Carbon footprint analysis of Western Canadian beef production compared to international competitors – Part 2

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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. The large natural and naturalized pastures used for rearing beef cattle (Prairie grasslands) in Western Canada produce important societal and environmental benefits. Western Canadian beef cattle also feed mainly on biomass resources that are not digestible by humans in the cow-calf phase, transforming these resources into a nutrient dense protein high in available iron and vitamins.

However, beef is generally considered relatively resource and greenhouse gas-intensive among livestock food products (and livestock food products are in general more resource and greenhouse gas-intensive compared to plant-based food products). 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. Phase 1 of the study was completed in August 2024 and compared Western Canadian beef production to the system with backgrounding and feedlot finishing in USA, and grass-finished beef cattle in Brazil. This current report is the final deliverable of phase 2 and focuses on other key global competitors for Western Canadian beef in the international market, - namely Argentina, Australia, New Zealand, and France.

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. Data to characterize Australian beef production in Queensland and New South Wales was largely obtained from studies undertaken and published by FSA Consulting for Meat and Livestock Australia and was characterized by particularly poor data quality for temporal correlation. For Argentina and France, data was of largely good quality (some poor and average scores for temporal correlation in Argentina and New Zealand respectively) and relied significantly on each nation's national greenhouse gas inventory report submitted to the United Nations. For New Zealand, the other significant source of data was a carbon footprint study funded by Beef+Lamb New Zealand and the Ministry of Primary Industries. For France, data of largely good quality and was collected from published literature – primarily from a study led by Marco Berton at the University of Padova.

This carbon footprint study was based on the principles and methodological approaches of the ISO 14044 standard for Life Cycle Assessment and the ISO 14067 standard for carbon footprinting. Across the four 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 New Zealand beef (10.83 kg CO_2-eq.) was the lowest among the four countries considered in this phase, while Argentina (20.59 kg CO_2-eq.) was the highest per kilogram of live weight of finished beef cattle. All four countries considered in this phase however had carbon footprints higher than Western Canada (8.95 kg CO_2-eq.). The carbon footprints of 1 kilogram of live weight beef in Argentina, Australia, New Zealand, and France were 130%, 37.64%, 21.03%, and 40.70% higher than Western Canada respectively.

Most of the impacts were attributable to the cow-calf phase in Argentina and France (75.34% and 79.43% respectively), with backgrounding in Argentina (17.75%) and feedlot finishing in France (17.8%) being the next highest contributors in these countries. This distribution of impacts was somewhat comparable to Canada where the cow-calf phase accounted for 67% of the impacts, followed by feedlot finishing (25%). In New Zealand, the finishing phase accounted for the largest share of impacts (52.14%), due to assuming that the cow-calf phase ends at the time of weaning (at ~5 months of age), and the considerably long finishing period because of this assumption. In Australia, the long backgrounding (336 days) and finishing (263 days of grass finished cattle) periods resulted in these phases accounting for 21.62% and 28.44% of the impacts per kilogram of live weight respectively.

Looking at the sources of impacts across the different phases, enteric methane emissions accounted for the majority of GHG emissions in all four countries (57.17%-81.54%). The share of enteric methane emissions in Argentina (72.69%), Australia (72.48%), and New Zealand (81.54%) were all comparable to the share of enteric methane emissions to the overall carbon footprint of Western Canadian beef (79.90%). The share of enteric methane emissions was the lowest in Frace (57.17%) due to the low enteric methane conversion factor (Y_m) of the finishing diet (4.62-4.68%), higher finishing weights, and the significantly high share (31%) of impacts associated with feed inputs. Soil organic carbon (SOC) fluxes resulting from land use change was a significant contributor to the overall carbon footprint only in Argentina (3.55 kg CO_2-eq. per kg of live weight) among the countries modelled in this phase, accounting for 17.25% of the impacts.

Per kilogram of live weight, the carbon footprint estimates without the inclusion of soil carbon fluxes were 16.98 kg CO_2-eq., 12.31 kg CO_2-eq., and 10.70 kg CO_2-eq., and 12.75 kg CO_2-eq. for Argentina, Australia, New Zealand, and France respectively. These estimates without SOC for Argentina, Australia, New Zealand, and France were 79.88%, 30.42%, 13.34%, and 35.07% higher than Western Canada (9.44 kg CO_2-eq.). Across the two phases, Western Canada has the lowest carbon footprint estimate overall – both when including and SOC-related emissions per kilogram of liveweight. While Brazil (22.93 kg CO_2-eq.) had the highest overall impacts per kilogram of liveweight among the countries considered by a significant margin (11.3% higher than Argentina, the next highest), removing impacts of SOC emissions from land use change and land management resulted in Argentinian beef having the highest impacts (16.98 kg CO_2-eq.) – 3.03% higher than Brazil (16.48 kg CO_2-eq.).

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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).

Though the agri-food sector is economically and socially vital, it is also a key source of resource and environmental impacts. Livestock-based food production, in particular, is considered to be an important contributor 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).

Beef is generally considered to be relatively resource and GHG-intensive among food products from livestock (Steinfeld et al., 2006). Beef production accounts for about 25% of all agri-food GHG emissions in Canada (Canada Beef, 2022; Xu et al., 2021). The primary contributors to the carbon footprint of beef 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 (Nathan Pelletier et al., 2010; WRI, 2022).

Moreover, 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). Western Canadian beef cattle, particularly in the cow-calf phase, feed significantly on biomass resources that are not digestible by humans, transforming these resources into a nutrient dense protein high in available iron and vitamins (Peyraud & Peeters, 2016).

GHG emissions and other environmental impacts associated with beef production can also 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 study 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 established the project methods and focused 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.

Phase 1 (Arulnathan et al., 2024) of the project focussed on comparing Western Canadian beef production with its key global competitors from the Americas – the United States of America (USA) and Brazil. This was completed in August 2024. Phase 2 utilizes the methods established in Phase 1 and expands the analysis to other global competitors including beef production in Argentina, Australia, New Zealand, and France (as a representative producer from the European Union). Deliverable 1 for phase 2, which details the beef production systems to be modelled and compared, and the methods and results for identifying data sources based on the application of a transparent and consistent set of data quality considerations, was submitted in December 2024.

The current document represents Deliverable 2 of Phase 2, which details the methods and results of the carbon footprint analysis of beef production systems for the countries listed in Phase 2 – including the methods and results for identifying data sources for Phase 2. Unless specified otherwise, any mentions of deliverable 1 from here on refers exclusively to deliverable 1 of phase 2 of this project.

2 Methods

The estimation of the carbon footprint of beef production in each jurisdiction followed a stepwise 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 the most credible and representative 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 December 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, 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 Australia

Production in Eastern Australia, which includes the states of Queensland and New South Wales (NSW), was used to characterize Australian beef production. Eastern regions of Australia contribute approximately 70% of the total beef produced in the country. In 2024 and 2023, Queensland and NSW accounted for 46-48% and 21% of the national beef production respectively (ABS, 2024a). Similarly, about 60% of feedlots used for finishing beef cattle are in Queensland and 30% in NSW (ALFA, 2024).

Australia exported approximately 67% of the total beef produced in the country in 2022 (MLA, 2022). Cow-calf operations in Australia are primarily pasture-based and beef cattle are finished in intensive grain-based feedlots or on a less intensive, but longer, grass-based diet. Due to the availability of good quality data from export-specific operations (which is weighted between grass-based and feedlot finishing systems), an exports-specific Australian beef production system was modelled. Feedlots with grain-intensive diets have increasingly become an important source of beef that is exported from Australia – constituting 35% of total exports in 2021-2023 (ABARES, 2024; MLA, 2022). Therefore, a production weighted average was modelled by taking into account the two finishing systems (i.e., 65% grass-fed finishing beef and 35% feedlot finishing). There are three market specifications for grain-fed beef finished in feedlots in Australia: short-fed (i.e. 55-80 days on feed), mid-fed (i.e. 108-164 days), and long-fed (i.e. >300 days) (Wiedemann et al., 2017). Short-fed beef is destined for the domestic market, while mid- and long-fed beef is for the export market (MLA, 2024; Wiedemann et al., 2017). However, since the average period that cattle spend in feedlot in Australia is between 50-120 days (ALFA, 2024), only the mid-fed export system was considered.

2.1.2 Argentina

Similar to Australia, Argentina also has distinct cow-calf and finishing operations and significant proportions of beef cattle are finished on either grass or grain-based diets. Moreover, there is considerable heterogeneity in Argentinian beef production due to the differences in climate and technology adoption levels in different regions (MAyDS, 2022). On this basis, a production-weighted, national average model was developed, similar to the modelling of US beef production in (Arulnathan et al., 2024).

The cow-calf phase is characterized by different productivity levels: low, intermediate, and high. Numerous parameters determine the differences between each productivity level for each of the regions. Some of these include cattle performance, the amount of beef produced per land area (e.g. 40-100 kg/ha), stocking rates (e.g. 0.6-1 animal unit/ha), weaning rates (e.g. 40-78%), replacement rates (e.g. 14-22%), and mortality rates (2.5-5%) (MAyDS, 2022). The finishing phase is differentiated based on factors such as climate, phase duration, initial and end weights, steer or heifer systems, and feeding strategies (i.e. based on grazing with or without supplements, confined in feedlot, or a combination of both) (Arrieta et al., 2020; MAyDS, 2022).

2.1.3 France

France is the largest producer of beef in the European Union (EU) and has the largest inventory of cattle in the EU – accounting for just over 20% of all beef produced in the EU (TasteFrance, 2024). France is also home to over twice the number of beef cattle compared to the next highest country in the EU. A significant share (40-50%) of beef production in France is from culled dairy cows and beef cattle make up only 50% of the cattle inventory (compared to about 75% of the cattle inventory in the USA) (Hocquette et al., 2018). However, in line with the methodological choices made in Phase 1 of this study (Arulnathan et al., 2024) to only characterize dedicated beef production systems, culled dairy cow beef in France is excluded from this analysis.

Beef cattle production in France is largely concentrated in central and southwestern France, with the northwest of France accounting for much of the dairy production in the country. The region of Massif Central alone accounts for over 40% of the French national beef herd (Sanne, 2014). Production here is primarily made up of grass-based cow-calf operations that produce weaned cattle for finishing. These cow-calf operations are characterized by small herds (5-50 heads of cattle) that are raised on fodder (primarily grass) produced on-farm. The calves are then transported elsewhere – both within and outside France – for finishing on either low intensity grass or high intensity grain diets. Sometimes, the weaned cattle are retained in cow-calf operations on a grass-based diet for 50-90 days before being sold for finishing (a process similar in profile to backgrounding of beef cattle in Canada and the USA). While much of France's finishing farms (commonly called fattening farms in Europe) are located in north-western France, the majority of calves sold from cow-calf operations in central and southern France are moved to Italy for finishing. Just over 75% of all young beef cattle produced France end up in northern Italy for finishing on an intensive grain-based diet (FranceAgrimer, 2020). Accordingly, this system of grass-based cow-calf operations in central/southern France and grain-based finishing in northern Italy is modelled as the representative system for beef production in France.

2.1.4 New Zealand

New Zealand is among the top 10 exporters of beef in the world. One of the main reasons for the demand for New Zealand beef is a recognition of the lack of incidence of diseases such as foot and mouth disease (FMD), and bovine spongiform encephalopathy (BSE) in the country (BLNZ, 2017). New Zealand exports over half (60%) of the beef produced. About 95% of beef cattle is pasture-fed throughout their life and raised predominantly on the natural hilly grasslands of the North Island. The supplementation of diets using harvested forage or grain is minimal and only happens during the winter months. A distinguishing feature of New Zealand beef production is the combined rearing of beef cattle and sheep for better management of pasturelands (BLNZ, 2024, 2021). Most farms in New Zealand with beef cattle operations (both cow-calf and finishing) also raise sheep and hence this combined system is modelled as the representative system. However, only the resource use and emissions associated with cattle will be attributed to the beef produced (how the resources are attributed between sheep and cattle products is described in section 2.5.7.1.4). Finally, since beef cattle are raised and finished on pastures in New Zealand, the inventory data does not distinguish between cow-calf and finishing phases. Where required (for example, when determining average daily feed intake), differentiation between pre-weaning and post-weaning phases for calves is considered.

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). Further, 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 could be 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 – are 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. Open access LCI databases relevant to the agri-food sector specific to the countries considered are available (Grant, 2016; Koch and Salou, 2016) In addition, several other major commercial 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. For Australia and France, the country-specific AusLCI (Grant, 2016) and Agribalyse (Koch & Salou, 2016) databases was also considered.

In each of these databases, only datasets available as unit processes were considered. System processes – a type of aggregated 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.

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

4. 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”.
5. Country considered: Keywords used were “Australi*”, “Argentin*”, “France”, “French” and “New Zealand”.
6. 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 fewer keywords. For example, to identify beef LCA studies in Australia, the search query “life cycle assessment” AND “beef” AND “Australi*” 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 would likely not include data on the entire life cycle as required for this study and would 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 Stats NZ, Beef + Lamb NZ, France Agrimer, INRAE (Institut national de recherche pour l'agriculture, l'alimentation et l'environnement), Australian Bureau of Statistics (ABS), Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), and the National Directorate of Agriculture (Dirección Nacional de Agricultura - Argentina). These sources were searched for data related to cattle numbers and herd characterization data, timelines with respect to weaning and time spent in feedlots, pasture characteristics, pasture management, and composition of supplemental feeds and grain-based diets in feedlots. Similarly, for all major feed crops to be modeled, grey literature sources were searched for data related to production volumes and yields, land use, field activities and management practices, irrigation, and inputs of fertilizers and crop protection products.

While data for this study was extracted from multiple sources, it is important to note potential methodological inconsistency 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).

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

In order to best reflect study-specific goals, modifications were made to the score descriptors for the pedigree matrix where required. 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 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 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). Moreover, extreme weather events such as heatwaves or the outbreak of diseases also have the potential to influence cattle performance. Using data exclusively from such outlier years – even if it is for the most recent reporting period – can lead to flawed outcomes. 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 (Bamber et al., 2023) 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. 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 Intergovernmental Panel on Climate Change (IPCC) methods for estimating GHG emissions are widely used. They include either Tier 1 methods using default emission factors to characterize emissions generically, or Tier 2 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 (Citepa, 2023; DCCEEW, 2023; MAyDS, 2022; NZME, 2023).

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 and geographical correlation scores 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 nationally resolved emissions models, such as IPCC Tier 2	1
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, as seen in phase 1 of this project for the USA and Brazil (Arulnathan et al., 2024). 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. 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)	Conversion of other land use types to pasture (if any), pasture utilization and stocking rates, 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	All relevant greenhouse gas emissions associated with manure deposited on pasture and manure storage and application.
Soil carbon	Changes in soil organic carbon from land use, land use change, or 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 management changes

For both the beef production systems and feed crop production systems to be modelled, infrastructure is excluded since it makes a relatively trivial contribution to the GHG emissions of beef production when taken over the lifespan of the infrastructure. Also, field level emissions of methane from the application of manure to agricultural soils is also excluded since these are negligible and its calculation is not supported by the IPCC methods. In beef production systems, the production of growth supplements and medicines (such as antibiotics) are also excluded due to the complexity of modelling these inputs and the inability to obtain proprietary data to model their production.

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 are 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). 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, 2016) 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

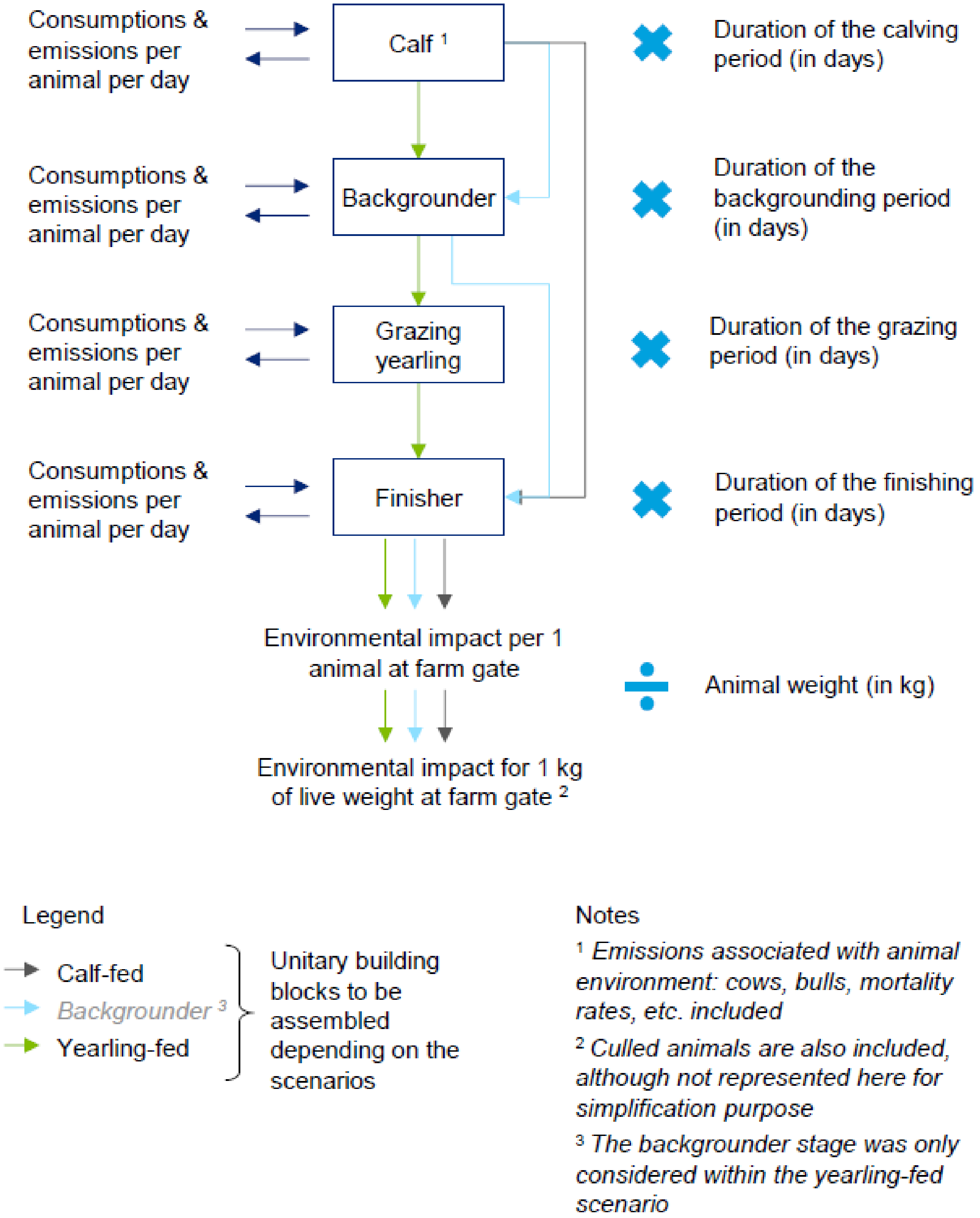
The intended audience of this study includes a number of governmental and industry stakeholders both within Canada, and internationally. These stakeholders include GIFS, the Government of Saskatchewan, as well as relevant representatives of the various countries to which comparisons are made in this 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 in phase 1 of this project (Arulnathan et al., 2024) and with beef carbon footprint and life cycle assessment studies in the literature (CRSB, 2023a; 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 102) 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 four 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 will vary based on the systems described in section 2.1. For example, New Zealand beef is largely from grass-finished cattle and the inventory data does not differentiate between cow-calf and finishing phases. On the other hand, France has distinct cow-calf and feedlot finishing operations. 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 cattle species, impacts were also characterised per kilogram of carcass weight. However, the study does not take into account the impacts associated with beef slaughter, with carcass weights only used to characterize impacts up to the farm-gate. This modelling framework is based on the approach detailed in the Canadian National Beef Sustainability Assessment (CRSB, 2023b). A representation of this framework is provided in Figure 1 below.



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 included 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 (if any), 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. For Europe, the transportation of feed imports was also considered. The geographical, temporal and technological boundaries were intended to be as representative of actual contemporary production conditions in the regions considered 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. However, if a feed ingredient contributing less than 0.1% contributed more to the feed composition in another phase, it was modelled across all applicable phases. 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 to soil. 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 amount of nitrogen available in the manure after the estimation of 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 and application of manure was modelled as described in section 2.5.9.4. No synthetic fertilizer credits for nutrients other than nitrogen contained in manure were applied.

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 Crop grains and co-products

Several feed crops considered resulted in multiple products such as grain and straw. This was the case for crops such as barley, sorghum, wheat, and corn (i.e., corn stover). In these systems, both grain and straw were considered co-products of the same production process. 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 sub-division or system expansion approach. If such approaches are 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 was determining the proportion of straw that is removed from agricultural fields. 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), the straw removal rate for wheat was based on Lafond et al. (2009) (except for Italy for which straw removal rates from Palmieri et al. (2017) was used), and straw removal rates from Agrifootprint was used for all other crop systems. Energy-based allocation factors from Agrifootprint were subsequently used to distribute the impacts of the crop production process between the identified co-products. These allocation factors were not applied for the production of silage or hay products since the entire crops are harvested to be used as feed inputs.

A second instance of allocation for the feed inputs modelled in this study were those that required further processing steps to produce suitable feed ingredients. Examples of such processed feed ingredients considered in this study were soybean meal, corn meal, sunflower pellets, corn distillers' grains (DDGs), sugarcane and sugar beet molasses. Inventories for all feed processing activities were taken from the Agrifootprint database (detailed in section 2.5.8) and allocation factors based on gross energy content of the co-products were taken directly from Agrifootprint.

2.5.7 Foreground data collection

Many 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 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 and are also submitted alongside this report.

2.5.7.1 Beef production

2.5.7.1.1 Australia

The data to represent the Australian beef production was mostly sourced from Wiedemann et al. (2016) and Wiedemann et al. (2017), which characterized a full cycle of production of grass- and grain-finished beef cattle for export in Queensland and New South Wales, respectively (Table 8). A score of 1 one was given for the reliability of cattle performance numbers, feeding strategies, and other production practices from the cow-calf to grass-finishing systems, because most of the data was based on national statistics, such as a survey of specialist beef producers conducted by the Australian Bureau of Agricultural and Resource Economics and Sciences . However, a completeness score of 3 was given to most of the data because it is representative of approximately 35% of the breeder herd in Australia (Wiedemann et al., 2016). Similarly, a score of 4 for temporal correlation was given to these data points because the data used in this analysis was from a 5-year period (i.e. from 2005-2010). More recent data to accurately represent the cattle systems was not accessible from national statistics. Furthermore, data from Wiedemann et al. (2017) that was used to characterize the feedlot finishing systems was of lower quality as it represented only seven feedlots in Eastern Australia. Therefore, a score of 4 was given for reliability and completeness. A score of 5 was given for the temporal correlation because the data is from 2007-2009. Lastly, it was not possible to find a high quality data source with respect to the dressing percentages of cattle in Australia. However, multiple sources reported similar values for both grass and grain-fed beef (Ataollahi et al., 2024; Mwangi et al., 2021; NSW DPI, 2007). Therefore, an average of these values was considered.

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

Data point	Source	R*	C*	Temp.*	G*	Tech.*
Cattle numbers (cow-calf stage)	Wiedemann et al. 2016 based on ABARES 2013 survey	1	3	4	1	1
Cattle performance (cow-calf to grass-fed finishing)	Wiedemann et al. (2016)	1	3	4	1	1
Cattle performance (feedlot finishing)	Wiedemann et al. (2017)	4	4	5	1	1
Dressing percentage	Ataollahi et al. (2024); NSW DPI (2007); Mwangi et al. (2021)	4	4	2	1	1
Breeding culling and weaning rates	Wiedemann et al. (2016)	1	3	4	1	1
Mortality rate (grass-finished beef)	Wiedemann et al. (2016)	1	3	4	1	1
Pasture management practices (grass-finished beef)	Wiedemann et al. (2016)	1	3	4	1	1
Feed supplement composition (grass-finished beef)	Wiedemann et al. (2016)	1	3	4	1	1
Feed composition (feedlot finishing)	Wiedemann et al. (2017)	4	4	4	1	1
Other material and energy inputs (grass-finished beef)	Wiedemann et al. (2016)	1	3	4	1	1
Energy inputs in feedlot system	Wiedemann et al. (2017)	4	4	4	1	1

Enteric methane	NIR - IPCC Tier 3 (pasture) and 2 (feedlot) methods	1	3	1	1	1
Manure-related emissions	NIR - IPCC Tier 2 (pasture) and 3 (feedlot) methods	1	3	1	1	1
Soil carbon (for pasture)	Obtained from the Australian NIR (DCCEEW, 2023)	1	1	1	1	1

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

2.5.7.1.2 Argentina

The data available to characterize the Argentinian beef production system was of relatively high quality (Table 9). Data was primarily sourced from the latest National Greenhouse Gas Inventory report (MAyDS, 2022). Most data points had high reliability scores because they were based on national statistics specific to the characterization of bovine stocks throughout the country from the National Agri-Food Health and Quality Service (SENASA). This information was based on official records of cattle stocks obtained through the traceability and identification systems implemented by SENASA, which track animal movements and inventories (MAGYP, 2022). A score of 1 was given for completeness for the data from MAyDS (2022) because detailed coverage of all registered production systems in every region in Argentina was available. However, most of the data that came from MAyDS (2022) was based on single year (2018) data, therefore a score of 4 was given for temporal correlation to cattle numbers and performance data. Data regarding the grazing pasture characteristics and management practices was obtained from Arrieta et al. (2020). In spite of the relatively lower data quality, it was the best available source found in the literature and characterized all of the different grazing/pasture lands in beef production regions reported in the NIR. However, one major gap was found regarding the feed intake during the feedlot finishing phase, therefore the average daily (Mathews & Vandeveer, 2007) feed intake was estimated based on the IPCC method (2019) using the average weight for steers and heifers provided by the NIR. The dressing percentage was based on the data found in the literature (Bognio et al., 2006; Garriz, 2012), and an average of the dressing percentage from each source was considered.

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

Data point	Source	R*	C*	Temp.*	G*	Tech.*
Cattle numbers	MAyDS (2022)	1	1	4	1	1
Dressing percentage	Bogno et al. (2006) & Garriz (2012)	3	5	5	1	1
Replacement rate	MAyDS (2022)	1	1	4	1	1
Weaning and mortality rates	MAyDS (2022)	2	1	4	1	1
Cattle performance (separately for cow-calf and finishing stages)	MAyDS (2022)	2	1	4	1	1
Pasture type, pasture management practices	Arrieta et al. (2020)	3	4	3	1	2
Energy inputs for pasture management	Arrieta et al. (2020)	4	4	2	3	2
Stocking rate	MAyDS (2022)	1	1	2	1	1
Feed composition	MAyDS (2022)	1	1	2	1	1
Finishing feed intake	IPCC (2019)	1	1	2	1	1
Manure management practices	MAyDS (2022)	1	1	2	1	1
Enteric methane	To be calculated based on IPCC Tier 2 methods	1	3	1	1	1
Manure-related emissions	To be calculated based on IPCC Tier 2 methods	1	3	1	1	1
Soil carbon (for pasture)	Obtained from the Argentinian NIR (MAyDS, 2022)	1	1	1	1	1

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

2.5.7.1.3 France

The data to characterize French beef production (cow-calf system in France and feedlot finishing in Italy) was sourced from a single study of generally good data quality (Table 10) – (Berton et al., 2017). The Agrifootprint (Blonk et al., 2023) and Agribalyse (Koch & Salou, 2016) LCI databases both had French beef production inventory datasets (primarily consisting of feed intake and feed composition data) but these datasets were of very poor data quality. The data in Agrifootprint depended heavily on personal communications with industry personnel and its representativeness was unknown. The Agribalyse dataset was based on primary data collected by the National Research Institute for Agriculture, Food and the Environment (INRAE), but the represented time period was 2005-2009 (which was beyond the 2010 cut-off applied to the literature review process described earlier in this report). Berton et al. (2017) reported more recent data from cow-calf operations in France from the INRAE Charolais farm network, which is made up of 40 farms in central and southern France. For the finishing phase in Italy, Berton et al. (2017) collected primary data from 14 fattening farms. These datasets had good reliability, geographical correlation, and technological correlation scores but average data quality for completeness and temporal correlation. A temporal correlation score of 3 was given due to the data being over 6 years old. Similarly, the two surveys that produced the primary data reported in Berton et al. (2017) had a completeness score of 3 since they were only collected from sites that represented <50% of the production system being characterized. The amount of dry matter intake from forage in the cow-calf phase was not collected from the INRAE network of farms since the pastures were considered to produce enough yield to meet the grazing requirements of the cow-calf herd. Hence average daily dry matter intake was calculated in Berton et al. (2017) based on feed intake capacity models developed by INRAE (Agabriel et al., 2015) . Supplemental feed rations for summer and winter periods in Berton et al. (2017) were based on a feed guidance handbook for suckler herds (Sauvant et al., 2023). As a result, the feed intake and feed composition data from the cow-calf phase had average reliability and poor completeness scores. The average daily weight gain used for feedlots was sourced from INRAE personnel and correlated to the live weight sale data to and from feedlots. Due to this data being partly based on expert opinion, a reliability score of 3 was given. Enteric methane and manure-related emissions were calculated based on IPCC Tier 2 methods as described in the French NIR (Citepa, 2023). Despite these calculations being based on data obtained from feed intake models in the cow-calf phase, a reliability score of 1 was given since the feed intake models used were developed for French cattle performance by INRAE (Agabriel et al., 2015). Soil organic carbon changes was derived from the French NIR in line with the methodology applied previously in phase 1 (Arulnathan et al., 2024).

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

Data point	Source	R*	C*	Temp.*	G*	Tech.*
Number of animals (cow-calf and finishing phases, calving, mortality and replacement rates)	Berton et al. (2017)	1	3	3	1	1
Phase durations	Berton et al. (2017)	1	3	3	1	1
Animal performance (feed consumption – cow-calf phase)	Berton et al. (2017)	3	4	3	1	1
Animal performance (feed consumption – finishing phase)	Berton et al. (2017)	1	3	3	1	1
Animal performance (weight gain – cow-calf phase)	Berton et al. (2017)	3	3	3	1	1
Animal performance (weight gain – finishing phase)	Berton et al. (2017)	1	3	3	1	1
Pasture stocking rate	Berton et al. (2017)	1	3	3	1	1
Feed composition (cow-calf phase)	Berton et al. (2017)	3	4	3	1	1
Feed composition (finishing)	Berton et al. (2017)	1	3	3	1	1
Other material and energy inputs	Berton et al. (2017)	1	3	3	1	1
Transportation	Berton et al. (2017)	1	3	3	1	1
Enteric methane	To be calculated using IPCC Tier 2 methods	1	3	1	1	1
Manure-related emissions	To be calculated using IPCC Tier 2 methods	1	3	1	1	1
Soil carbon (for pasture)	Obtained from the French National Inventory report (Citepa, 2023)	1	1	1	1	1

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

2.5.7.1.4 New Zealand

Data used for modelling beef production in New Zealand was obtained from three different sources (Mazzetto et al., 2023; NZME, 2023; Stats NZ, 2024a). In general, the data collected from all three sources was of high quality (Table 11). All data related to cattle numbers such as calving rates, replacement rates, bulls-to-cows ratio and mortality rates were obtained from

Stats NZ (Stats NZ, 2024a). This data was based on the most recent (2023) agricultural production statistics survey, which had a response rate of over 70% of all farms with more than $60,000 in sales. Stats NZ was also used to source the dressing percentage of beef cattle slaughtered and the finishing weight of steers and bulls sent for slaughter (Stats NZ, 2024b). Average weight of calves at birth in New Zealand was not reported in any of the literature reviewed and hence the method (9% of average adult cow weight) adopted by the New Zealand NIR (NZME, 2023) and Mazzetto et al. (2023) was used in this study as well. Similarly, the average daily feed intake of beef cattle was not explicitly reported in any of the literature reviewed (feed intake values reported in Agrifootprint were extrapolated from dairy cow feed consumption). Both the NIR and Mazzetto et al. (2023) adopted a Tier 2 feed intake estimation model for grazing beef cattle based on the metabolizable energy (ME) requirements for different functions (maintenance, live weight gain, lactation, gestation, etc.). This model (described in detail in section 2.5.10) was similarly used to calculate the feed intake for the current study. Since the birth weight of calves and feed consumption are based on empirical models and not on farm data, they are given a score of 4 for completeness (considered as derived from recommended practices). Feed composition data derived from Mazzetto et al. (2023) is given a score of 2 for reliability since it excluded the provision of supplemental inputs (such as kale and Swedish turnips during winter months due to their trivial share of total feed intake (hence assumed to have negligible impacts on the overall carbon footprint). Data on pasture stocking rates, fertilizer input to pastures, pasture renewal rates, and energy inputs were all sourced from Mazzetto et al. (2023) as well. The inventory data in Mazzetto et al. (2023) had high scores for reliability, completeness, geographical correlation, and technological correlation due to the data being compiled from Stats NZ and industry data provided by Beef + Lamb New Zealand (BLNZ). This data, however, only has a temporal correlation score of 3 due to the being from 2017-18. While the primary data used in Mazzetto et al. (2023) was collected from farms with both sheep and beef cattle, a combination of sub-division (for inputs such as energy use) and allocation using a biophysical relationship (dry matter intake) was used to report inventories specific for beef production. Enteric methane and manure-related emissions were calculated based on IPCC Tier 2 methods as described in the New Zealand NIR (NZME, 2023). Soil organic carbon changes was similarly derived from the New Zealand NIR in line with the methodology applied previously in phase 1 (Arulnathan et al., 2024).

Table 11: Data sources used to model New Zealand beef production, and their associated pedigree matrix scores

Data point	Source	R*	C*	Temp.*	G*	Tech.*
Number of animals (calving, mortality and replacement rates)	Stats NZ (2024a)	1	2	1	1	1
Phase duration	Mazzetto et al. (2023)	1	2	3	1	1
Dressing percentage	Stats NZ (2024b)	1	2	1	1	1
Animal start weights	Mazzetto et al. (2023)	3	4	3	1	1
Animal end weights – heifers and steers	Stats NZ (2024a)	1	2	1	1	1
Animal end weights – cows and bulls	Mazzetto et al. (2023)	1	2	3	1	1
Animal performance (feed consumption)	NZME (2023)	2	4	1	1	1
Animal performance (weight gain)	Mazzetto et al. (2023)	1	2	3	1	1
Pasture stocking rate	Mazzetto et al. (2023)	1	2	3	1	1
Pasture maintenance and renewal	Mazzetto et al. (2023)	1	2	3	1	1
Feed composition	Mazzetto et al. (2023)	2	2	3	1	1
Other material and energy inputs	Mazzetto et al. (2023)	1	2	3	1	1
Enteric methane	To be calculated using IPCC Tier 2 methods	1	2	1	1	1
Manure-related emissions	To be calculated using IPCC Tier 2 methods	1	2	1	1	1
Soil carbon (for pasture)	Obtained from the New Zealand NIR (NZME, 2023)	2	1	1	1	1

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

2.5.7.2 Highest quality data available for feed crop inputs

The major crops in the feed compositions for different stages of beef production in all of the countries considered are provided in Table 12 below. Sections 2.5.7.2.3, 2.5.7.2.4, and 2.5.7.2.5 provide data sources and data quality scores for the inventory data points for the feed crop inputs modelled for Australia, Argentina, and France respectively. For feed inputs that require further processing (such as soybean meal), inventory data from LCI databases was used (with modifications to ensure as much regionalization as possible). The feed processing datasets used in this study are listed in section 2.5.8. The impacts of crop production in New Zealand for supplemental feed inputs in the winter such as kale and Swedish turnips was not considered. This is because supplemental feed makes up a relatively trivial share of overall feed consumption and makes a materially non-significant contribution to the carbon footprint of New Zealand beef production according to Mazzetto et al. (2023). Moreover, no inventory datasets to model kale or turnip production in New Zealand were found in LCI databases and published literature. However, these inputs are considered in the feed intake calculations detailed in section 2.5.10 to ensure enteric methane emissions are estimated accurately.

Some of the countries considered imported significant proportions of various feeds from other countries. In such cases, the share of imports and the major countries from which the ingredient was imported is also specified in Table 12. If domestic production accounted for over 70% of national consumption, that ingredient was considered to be sourced only from domestic supply for beef production (unless trade or industry information specified that imports were used). For countries importing a specific ingredient from multiple countries, only the major sources were considered. For example, soybean meal used in the feedlot finishing phase in northern Italy was considered to be imported from Argentina and Brazil, since these two countries accounted for ~90% of Italian soy imports. For wheat used in Italy, France and Canada were considered since these two countries make up 40% of all wheat imports, and no other country accounted for more than 10%. All data related to shares of imported feed and countries sourced from were obtained from The Observatory of Economic Complexity database (OEC, 2024), which primarily uses Food and Agriculture Organization (FAO) data, to ensure consistency.

The ports of Marseille and Genoa were assumed to be the locations where feed inputs are delivered into the geographical boundaries of France and Italy, respectively. These ports were assumed based on their location in Southern France and Northern Italy, respectively, and their wide use for feed imports from South America (Mohit, 2021). In Argentina, the port of export was assumed to be Buenos Aires, and in Brazil, it was assumed to be the port of Paranaguá. Argentinian soy meal was generally considered to be transported by inland waterways from

Rosario to the port of Buenos Aires for ~300 kilometres (Lathuillière, 2022). Since no such average inland transportation distance could be found for Brazil, a similar 300 kilometres transportation distance was assumed by train to the port of Paranaguá. Canadian wheat imports to Italy were assumed to be transported by train from Regina to the port of Montreal and then shipped to Italy. Corn imports to Italy from Hungary and Ukraine were assumed to be transported by train from the cities of Pest and Cherasky, respectively. These cities were selected based on their location in the biggest corn production regions of each country (Derzhstat, 2024; KSH, 2024). All feed imported through ports into France and Italy are assumed to be transported inland for 150 kilometres by train before being trucked to their final destination.

Identification of literature sources for crops already considered in the GIFS field crops study (Bamber et al., 2023) or part 1 of this project (Arulnathan et al., 2024) was not repeated and only availability of new data sources since the completion of these projects was checked. However, the data quality assessment of these sources was verified and modified where necessary according to the goals of the current study.

Table 12: Major feed crops other than grazed forage modelled for Argentina, Australia, and France

Argentina	**Australia**	**France (FR)-Italy (IT)**
Corn	Barley	FR Harvested forage (hay)
Lucerne hay	Sorghum	FR Corn
Oats	Wheat	FR Wheat
Sunflower pellets	Canola	FR Soybean– 55% imported (84% from Brazil, 16% from Argentina)
Soybeans	Cottonseed	IT Corn – 60% imported (37% Hungary, 36% Ukraine, 27% Brazil)
Sorghum	Harvested forage (hay and silage)	IT Sugar beet
Wheat	Sugarcane	IT Barley
		IT Soybean– 70% imported (78% Argentina, 22% Brazil)
		IT Wheat – 51% imported (55% France, 45% Canada)
		IT Maize silage

2.5.7.2.1 Agrifootprint database

A large proportion of the data to be used for modelling feed crop production in the countries considered was sourced from the Agrifootprint database (Blonk et al, 2023). The datasets in the Agrifootprint database were developed based on consistent methodology and data sources across countries. To avoid repetition in sections 2.5.7.2.3 – 2.5.7.2.5, the data quality scores applied for data sourced from the Agrifootprint database are described here. When other sources are used for specific data points, descriptions are provided along with the data quality scores applied in the relevant sections.

Agrifootprint inventories used FAO yield data between 2014-2018. These yield values were largely not used in this study and were replaced by updated yield data from either the FAO statistical database (FAOstat, 2024) or national statistical databases. Agrifootprint used 2011 data from International Fertilizer Association (IFA) to determine inputs of nitrogen, phosphorus, potassium, and sulphur fertilizers for grain production and hence had poor scores for temporal correlation. Where possible, synthetic nutrient input data of higher data quality was sourced for this study. Agrifootprint used a combination of FAO statistics (crop cultivation and area harvested), and national fertilizer sales data from IFA (IFA, 2021) to determine amounts of specific synthetic fertilizer types applied for each crop. This data was of generally high data quality. Data for plant protection products in the Agrifootprint database had good data quality except for reliability and temporal correlation due to using expert assumptions regarding types of pesticides and relying on data from 2012-2016. All energy use data was based on a farm energy simulation tool (Schreuder et al., 2008) and hence had a poor score for completeness. The data for seed and transportation of field inputs were assumed to be 15 years-old based on time of publication and hence given a temporal correlation score of 4. For transportation, a 50 kilometres distance was assumed for all inputs, resulting in poor data quality scores for reliability and completeness as well.

2.5.7.2.2 Calculating emissions

For calculating field-level emissions associated with fertilizer application, IPCC Tier 2 methods were used for all crops. This is consistent with the methodology adopted in phase 1 of this project (Arulnathan et al., 2024) and the NIRs of all the countries considered (Citepa, 2023;

DCCEEW, 2023; MAyDS, 2022; NZME, 2023). For CO_2 emissions associated with the application of lime and urea, Tier 1 methods were used (consistent with the NIRs of all four countries considered) and hence has a reliability score of 2. Soil organic carbon changes were taken from the country-specific NIR – in line with the methods applied in phase 1 of this study (Arulnathan et al., 2024). Since these soil carbon estimates are not crop specific, they had a poor technological correlation score. Data quality scores associated with calculating emissions are not described for each crop to avoid repetition. Sections 2.5.7.2.3 – 2.5.7.2.5 provide the crop- and country-specific data sources and their respective data quality scores.

2.5.7.2.3 Australia

2.5.7.2.3.1 Barley

Data used to model Australian barley production was of relatively high quality (Table 13). Information on yield was taken from the historical report on agricultural commodities in Australia provided by the Australian Bureau of Statistics (ABS, 2024b), and was calculated using data from 2018 to 2022. The amounts of barley straw removed from the field was taken into account by first estimating the amount of straw produced using the barley grain-to-straw ratio provided by Gelaw et al. (2014) and proxy data based on the residue removal found in Blonk et al. (2023). The specific active ingredients in plant protection products used in Australia was taken from the Australian LCI database (Grant, 2016).

Table 13: Data sources used for modelling Australian barley production, and their associated pedigree matrix scores

Data point	Source	R*	C*	Temp.*	G*	Tech.*
Yield (grain)	ABS	1	1	1	1	1
Straw removal	Australian Government (2023)	1	1	2	1	3
Seed	Blonk et al. (2023)	2	3	4	1	1
Lime inputs	Blonk et al. (2023)	3	4	4	2	1
Fertilizer inputs	Blonk et al. (2023)	1	3	4	1	1
Herbicide, fungicide and insecticide inputs	Total amounts from Blonk et al. (2023), types from AusLCI	2	3	3	1	1

Irrigation energy	Blonk et al. (2023)	2	4	3	2	1
Field activities energy	Blonk et al. (2023)	2	4	3	2	1
Transportation	Blonk et al. (2023)	4	4	4	1	3
Post-harvest energy use	Blonk et al. (2023)	2	4	3	2	1
Direct and indirect N_2O emissions	Modelled using IPCC Tier 2 methods	1	3	2	1	1
CO_2 emissions from lime and urea	Modelled using IPCC Tier 1 methods	2	3	3	2	1
Soil carbon changes	Modelled using NIR data (DCCEEW, 2023)	1	1	1	1	4

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

2.5.7.2.3.2 Sorghum

Data for Australian sorghum production had generally good data quality scores for reliability, geographical correlation, and technological correlation, but average or poor scores for completeness and temporal correlation (Table 14). Yield data was taken from national statistics (ABS, 2023), but only data from 2021-2023 was found. Specific data on sorghum straw production and removal rates was not found, therefore proxy data was used to allocate between sorghum grain and straw (Blonk et al., 2023).

Table 14: Data sources used for modelling Australian sorghum production, and their associated pedigree matrix scores

Data point	**Source**	**R***	**C***	**Temp.***	**G***	**Tech.***
Yield (grain)	ABS	1	1	4	1	1
Seed	Blonk et al. (2023)	2	3	4	1	1
Lime inputs	Blonk et al. (2023)	3	4	4	2	1
Fertilizer inputs	Blonk et al. (2023)	1	3	4	1	1
Herbicide, fungicide and insecticide inputs	Blonk et al. (2023)	3	2	3	1	2
Irrigation energy	Blonk et al. (2023)	2	4	3	2	1
Field activities energy	Blonk et al. (2023)	2	4	3	2	1
Transportation	Blonk et al. (2023)	4	4	4	1	3
Post-harvest energy use	Blonk et al. (2023)	2	4	3	2	1
Direct and indirect N_2O emissions	Modelled using IPCC Tier 2 methods	1	3	2	1	1

COCO_2 emissions from lime and urea	Modelled using IPCC Tier 1 methods	2	3	3	2	1
Soil carbon changes	Modelled using NIR data (DCCEEW, 2023)	1	1	1	1	4

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

2.5.7.2.3.3 Wheat

Data for Australian wheat production was of generally good quality except for completeness and temporal correlation (Table 15). Average wheat yield was estimated using a 5-year average (2018-2022) from data from the Australian Bureau of Statistics (ABS, 2024). Proxy data for straw removal was used from Saskatchewan (Lafond et al., 2009), and data quality scores were adjusted accordingly. Specific active ingredients from the agricultural chemicals were taken from the ecoinvent dataset for Australian wheat production (Nemecek, 2007).

Table 15: Data sources used for modelling Australian wheat production, and their associated pedigree matrix scores

Data point	**Source**	**R***	**C***	**Temp.***	**G***	**Tech.***
Yield (grain)	ABS	1	1	1	1	1
Straw removed	Lafond et al. (2009)	2	4	5	3	1
Seed	Blonk et al. (2023)	2	3	4	1	1
Lime inputs	Blonk et al. (2023)	3	4	4	2	1
Fertilizer inputs	Blonk et al. (2023)	1	3	4	1	1
Herbicide, fungicide and insecticide inputs	Total amounts from Blonk et al. (2023), types from Nemecek (2007)	2	3	3	1	1
Irrigation energy	Blonk et al. (2023)	2	4	3	2	1
Field activities energy	Blonk et al. (2023)	2	4	3	2	1
Transportation	Blonk et al. (2023)	4	4	4	1	3
Post-harvest energy use	Blonk et al. (2023)	2	4	3	2	1
Direct and indirect N_2O emissions	Modelled using IPCC Tier 2 methods	1	3	2	1	1
CO_2 emissions from lime and urea	Modelled using IPCC Tier 1 methods	2	3	3	2	1
Soil carbon changes	Modelled using NIR data (DCCEEW, 2023)	1	1	1	1	4

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

2.5.7.2.3.4 Canola

Data for Australian canola production was of generally good quality except for completeness and temporal correlation (Table 16). Yield data from the Australian Oilseeds Federation Annual report (2021) was used. Seed and lime inputs, as well as post-harvesting data, were taken from (Alcock et al., 2022). The representativeness of this post-harvest energy use data was not known, and hence a score of 5 was given for completeness.

Table 16: Data sources used for modelling Australian canola production, and their associated pedigree matrix scores

Data point	Source to be used	R*	C*	Temp.*	G*	Tech.*
Yield	Australian Oilseeds Federation (2021)	1	3	1	1	1
Seed	Alcock et al. (2022)	2	3	2	1	1
Lime	Alcock et al. (2022)	2	3	2	1	1
All other nutrient inputs	Blonk et al. (2023)	1	3	4	1	1
All pesticides	Blonk et al. (2023)	3	2	3	1	2
Field activities energy use	Blonk et al. (2023)	2	4	3	2	1
Transportation	Blonk et al. (2023)	4	4	4	1	3
Post-harvest	Alcock et al. (2022)	2	5	2	1	1
Direct and indirect N_2O emissions	Modelled using IPCC Tier 2 methods	1	3	2	1	1
CO_2 emissions from lime and urea	Modelled using IPCC Tier 1 methods	2	3	3	2	1
Soil carbon changes	Modelled using NIR data (DCCEEW, 2023)	1	1	1	1	4

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

2.5.7.2.3.5 Cottonseed

The data used to model the Australian cottonseed production had relatively lower data quality due to the general lack of country-specific datasets (Table 17). However, the cottonseed products, such as white fluffy cottonseed and cottonseed meal, only contribute approximately 6% and 2% of the feed composition, respectively.

The cottonseed yield was estimated using the average yield data of cotton lint from 2021-2022 (ABS, 2023) and the proportion of cotton and cottonseed co-generation found in Nguyen et al. (2021). Seeding rates specific to seed cotton were not found for Australian production, therefore proxy data taken from the "seed-cotton production, conventional | seed-cotton | APOS, U - RoW" process in the ecoinvent database. Similarly, data on pesticides, transportation, and post-harvest data was not available for Australian seed cotton production, therefore, proxy data from the Agrifootprint US seed cotton production (Blonk et al. 2023) was used. Data quality scores were adjusted accordingly. Data regarding the fertilizer inputs and field operations energy consumption was taken from Nguyen et al. (2021).

Table 17: Data sources used for modelling Australian cottonseed production, and their associated pedigree matrix scores

Data point	Source	R*	C*	Temp.*	G*	Tech.*
Cotton yield	ABS	1	1	4	1	1
Cottonseed output	Nguyen et al. (2021)	1	1	2	1	1
Seed	Ecoinvent 3.10 database	2	5	5	5	1
Fertilizer inputs	Nguyen et al. (2021)	4	5	4	1	1
Herbicide, fungicide and insecticide inputs	Total amounts from Blonk et al. (2023), distribution from AusLCI	4	5	4	4	1
Field activities energy	Nguyen et al. (2021)	4	5	4	1	1
Transportation	Blonk et al. (2023)	4	5	4	4	1
Post-harvest energy use	Blonk et al. (2023)	2	5	3	5	1
Direct and indirect N_2O emissions	Modelled using IPCC Tier 2 methods	1	3	2	1	1
CO_2 emissions from lime and urea	Modelled using IPCC Tier 1 methods	2	3	2	2	1
Soil carbon changes	Modelled using NIR data (DCCEEW, 2023)	1	1	1	1	4

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

2.5.7.2.3.6 Lucerne hay

Due to lack of high-quality data, Australian lucerne production was characterized using lower quality data found in the literature, as well as proxy data available in commonly used LCI databases (Table 18). However, lucerne contributes only ~1% of the total feed composition. Yield, fertilizer and water inputs, as well as field operations data was taken from Mushtaq et al.

(2015), which had poor scores for reliability, completeness, and temporal correlation. Seeding rates, plant protection inputs, as well as energy consumption from field operations and post-harvest activities were based on proxy data from the US lucerne production model found in Agrifootprint (Blonk et al., 2023).

Table 18: Data sources used for modelling Australian cottonseed production, and their associated pedigree matrix scores

Data point	Source	R*	C*	Temp.*	G*	Tech.*
Yield	Mushtaq et al. (2015)	4	5	5	1	1
Irrigation water	Mushtaq et al. (2015)	4	5	5	1	1
Seed	Blonk et al. (2023)	2	5	5	5	1
Fertilizer inputs	Mushtaq et al. (2015)	3	3	5	3	4
Herbicide, fungicide and insecticide inputs	total amounts from Blonk et al. (2023), distribution from AusLCI and registered products	4	5	4	4	1
Field activities energy	Mushtaq et al. (2015)	4	5	4	1	1
Transportation	Blonk et al. (2023)	2	5	3	5	1
Post-harvest energy use	Blonk et al. (2023)	2	5	3	5	1
Direct and indirect N_2O emissions	Modelled using IPCC Tier 2 methods	1	3	2	1	1
Soil carbon changes	Modelled using NIR data (DCCEEW, 2023)	1	1	1	1	4

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

2.5.7.2.3.7 Sugarcane molasses

The modelling of sugarcane production in Australia to characterize molasses production was based on data of average data quality (Table 19). Yield data was obtained from ABS (2023) using a 3-year average from 2020-2022. Most other data was taken from Blonk et al. (2023), including seeding rates, fertilizer and plant protection products, and energy consumption from field and post-harvest activities. Data regarding the processing of sugarcane into sugar and molasses was taken from Renouf et al. (2011) but the input/output amounts are based on Blonk et al. (2023).

Table 19: Data sources used for modelling Australian sugarcane production, and their associated pedigree matrix scores

Data point	**Source**	**R***	**C***	**Temp.***	**G***	**Tech.***
Yield (sugarcane)	ABS	1	1	4	1	1
Seed	Blonk et al. (2023)	2	3	4	1	1
Lime inputs	Blonk et al. (2023)	3	4	4	2	1
Fertilizer inputs	Blonk et al. (2023)	1	3	4	1	1
Herbicide, fungicide and insecticide inputs	Blonk et al. (2023)	3	2	3	1	2
Irrigation energy	Blonk et al. (2023)	2	4	3	2	1
Field activities energy	Blonk et al. (2023)	2	4	3	2	1
Transportation	Blonk et al. (2023)	4	4	4	1	3
Sugarcane milling	Renouf et al. (2011)	4	5	4	1	1
Sugar and molasses outputs	Blonk et al. (2023)	3	5	5	4	1
Direct and indirect N_2O emissions	Modelled using IPCC Tier 2 methods	1	3	2	1	1
CO_2 emissions from lime and urea	Modelled using IPCC Tier 1 methods	2	3	2	2	1
Soil carbon changes	Modelled using NIR data (DCCEEW, 2023)	1	1	1	1	4

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

2.5.7.2.4 Argentina

2.5.7.2.4.1 Corn

Data to characterize Argentinian corn production was of relatively high quality (Table 20). Corn yield was estimated using a 5-year average (i.e. from 2019-2023) obtained from the Argentinian agricultural estimates provided by the National Directorate of Agriculture (NDA, 2024). Most of the cultivation data was obtained from the Argentinian corn production model found in Agrifootprint (Blonk et al., (2023). Data such as seeding rates, fertilizer and pesticides inputs, and post-harvest energy consumption were of relatively high quality. Transportation data was taken from Arrieta et al. (2020) but had poor quality with respect to completeness due to the unknown representativeness of the data.

Table 20: Data sources used for modelling Argentinian corn production, and their associated pedigree matrix scores

Data point	Source	R*	C*	Temp.*	G*	Tech.*
Yield	National Directorate of Agriculture	1	1	1	1	1
Seed	Blonk et al. (2023)	2	3	4	1	1
Lime inputs	Blonk et al. (2023)	3	4	4	2	1
Fertilizer inputs	Blonk et al. (2023)	1	3	4	1	1
Herbicide, fungicide and insecticide inputs	Blonk et al. (2023)	3	2	3	1	2
Irrigation energy	Blonk et al. (2023)	2	4	3	2	1
Field activities energy	Blonk et al. (2023)	2	4	3	2	1
Transportation	Arrieta et al. (2020)	1	5	2	1	2
Post-harvest energy use	Blonk et al. (2023)	2	4	3	2	1
Direct and indirect N_2O emissions	Modelled using IPCC Tier 2 methods	1	3	2	1	1
CO_2 emissions from lime and urea	Modelled using IPCC Tier 1 methods	2	3	3	2	1
Soil carbon changes	Modelled using NIR data	1	1	1	1	4

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

2.5.7.2.4.2 Sorghum silage and winter forage

The data to characterize the production of harvested forage in Argentina was of lower quality primarily due to poor representativeness and the lack of more recent data (Table 21). However, specific datasets for corn and sorghum silage, as well as for winter forages, were found in Arrieta et al. (2020), which developed these inventories to model feed inputs for finishing beef cattle. This dataset includes seeding rates, fertilizer and plant production products inputs, as well as energy inputs from field activities and transportation. A completeness score of 5 was given to the yield, seed, and transportation data due to the unknow representativeness of the sources. For fertilizer and pesticide inputs, only a small percentage of farms from a single region in Argentina were represented and hence a completeness score of 4 was given. A score of 4 was given to the reliability and completeness of the field energy inputs because the data was based on a small number of sites in Uruguay, which also contributed to the average score for geographical correlation.

Table 21: Data sources used for modelling Argentinian silage and winter forage productions, and their associated pedigree matrix scores

Data point	Source	R*	C*	Temp.*	G*	Tech.*
Yields	Arrieta et al. (2020)	2	5	4	1	1
Seed	Arrieta et al. (2020)	2	5	4	1	1
Fertilizer inputs	Arrieta et al. (2020)	3	4	3	1	2
Herbicide, fungicide and insecticide inputs	Arrieta et al. (2020)	3	4	3	1	2
Field activities energy	Arrieta et al. (2020)	4	4	2	3	2
Transportation	Arrieta et al. (2020)	1	5	2	1	2
Direct and indirect N_2O emissions	Modelled using IPCC Tier 2 methods	1	3	2	1	1
CO_2 emissions from lime and urea	Modelled using IPCC Tier 1 methods	2	3	3	2	1
Soil carbon changes	Modelled using NIR data	1	1	1	1	4

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

2.5.7.2.4.3 Oats

Similar to winter forage, the data to characterize Argentinian oat production was mostly obtained from Arrieta et al. (2020), which had poor quality for completeness and temporal correlation (Table 22). Proxy data from the Brazilian oat grain model in Agrifootprint (Blonk et al., 2023) was used to obtain the seeding rate and post-harvest energy use data due to the similar climatic and production conditions. Field activities energy data in Arrieta et al. (2020) was sourced from a small number of sites in Uruguay, which is why a score of 4 was given to the reliability and completeness and a 3 for geographical correlation.

Table 22: Data sources used for modelling Argentinian oats production, and their associated pedigree matrix scores

Data point	Source	R*	C*	Temp.*	G*	Tech.*
Yield	National Directorate of Agriculture	1	1	1	1	1
Seed	Blonk et al. (2023)	1	5	3	3	1
Fertilizer inputs	Arrieta et al. (2020)	3	4	3	1	2
Herbicides	Arrieta et al. (2020)	3	4	3	1	2

Field activities energy	Arrieta et al. (2020)	4	4	2	3	2
Post-harvest energy use	Blonk et al. (2023)	2	4	3	2	1
Direct and indirect N_2O emissions	Modelled using IPCC Tier 2 methods	1	3	2	1	1
CO_2 emissions from lime and urea	Modelled using IPCC Tier 1 methods	2	3	3	2	1
Soil carbon changes	Modelled using NIR data	1	1	1	1	4

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

2.5.7.2.4.4 Sunflower pellets

Data to characterize sunflower production required in sunflower oil extraction (of which sunflower pellets are a co-product) was largely based on lower quality data from Arrieta et al. (2020) due to the lack of other data sources (Table 23). However, this product constitutes a relatively minor share of the total feed composition (i.e. less than 6%). Yield data of better quality was obtained from the National Directorate of Agriculture for a 5-average (2019-2023). Agrifootprint data for the drying and processing of Argentinian sunflower seeds (Blonk et al., 2023) was used as a proxy to model the post-harvest energy inputs, including the energy requirements for sunflower oil extraction. Data sourced from Arrieta et al. (2020) had generally poor completeness scores due to either being based on data from a small number of sites or the representativeness of the data being unknown.

Table 23: Data sources used for modelling Argentinian sunflower pellets production, and their associated pedigree matrix scores

Data point	**Source**	**R***	**C***	**Temp.***	**G***	**Tech.***
Yield (pellets)	Blonk et al. (2023)	2	4	3	2	1
Yield (sunflower)	National Directorate of Agriculture	1	1	1	1	1
Seed	Arrieta et al. (2020)	2	5	4	1	1
Fertilizer inputs	Arrieta et al. (2020)	3	4	3	1	2
Herbicide, fungicide and insecticide inputs	Arrieta et al. (2020)	3	4	3	1	2
Field activities energy	Arrieta et al. (2020)	4	4	2	3	2
Transportation	Arrieta et al. (2020)	1	5	2	1	2
Post-harvest energy use	Blonk et al. (2023)	2	4	3	2	1
Direct and indirect N_2O emissions	Modelled using IPCC Tier 2 methods	1	3	2	1	1
CO_2 emissions from lime and urea	Modelled using IPCC Tier 1 methods	2	3	3	2	1

Soil carbon changes	Modelled using NIR data	1	1	1	1	4

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

2.5.7.2.4.5 Soybeans

Soybeans was not used in the production of Argentinian beef, but Argentina is a major exporter of soybean meal to Italy and France. Hence, best available data to model Argentinian soy production was collected and is reported here. Data to characterize soybean production was of good quality except for completeness and temporal correlation (Table 24). Soybean yield data was obtained from the Argentinian National Directorate of Agriculture (2024) using a 5-year average (from 2019-2023). All other data was obtained from Blonk et al. (2023).

Table 24: Data sources used for modelling Argentinian soybeans production, and their associated pedigree matrix scores

Data point	**Source**	**R***	**C***	**Temp.***	**G***	**Tech.***
Yield	National Directorate of Agriculture	1	1	1	1	1
Seed	Blonk et al. (2023)	2	3	4	1	1
Lime inputs	Blonk et al. (2023)	3	4	4	2	1
Fertilizer inputs	Blonk et al. (2023)	1	3	4	1	1
Herbicide, fungicide and insecticide inputs	Blonk et al. (2023)	3	2	3	1	2
Irrigation energy	Blonk et al. (2023)	2	4	3	2	1
Field activities energy	Blonk et al. (2023)	2	4	3	2	1
Transportation	Blonk et al. (2023)	4	4	4	1	3
Post-harvest energy use	Blonk et al. (2023)	2	4	3	2	1
Direct and indirect N_2O emissions	Modelled using IPCC Tier 2 methods	1	3	2	1	1
CO_2 emissions from lime and urea	Modelled using IPCC Tier 1 methods	2	3	3	2	1
Soil carbon changes	Modelled using NIR data	1	1	1	1	4

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

2.5.7.2.5 France

2.5.7.2.5.1 Wheat production in France

Most data sources for French wheat were generally of high data quality (Table 25) and were identified as part of the GIFS field crop carbon footprint study (Bamber et al., 2023). Proxy data from Saskatchewan were used for calculation of the amount of wheat straw removed. Data on the specific types of plant protection products came from Agreste (Agreste, 2022) for herbicides and fungicides, and (Nemecek 2007) for insecticides. The Nemecek insecticide data were valid from 2000-2004, extrapolated to the year 2021 (without an explanation of how this was done), and thus have a data quality score of 4 for temporal correlation. Some of the herbicides and fungicides indicated by the French Statistics and Forecasting Department – AGRESTE (Agreste, 2022) – did not have representative background production inventories in Ecoinvent, therefore they were modelled as the generic "pesticide, unspecified", which gave them a technological correlation of 4. For soil carbon change associated with wheat production in France, Muñoz et al. (2014) had data of higher quality than is achievable via modelling using the NIR values since it was modelled specifically for wheat, whereas the NIR is not crop specific. However, for consistency with the data available for all countries, we have chosen to model soil carbon changes according to the NIR model. Five-year (2018-2022) yield data was sourced from FAOStat. All other data was sourced from Blonk et al. (2023).

Table 25: Data sources used for modelling French wheat production, and their associated pedigree matrix scores

Data point	Source	R*	C*	Temp.*	G*	Tech.*
Yield (grain)	FAOStat	1	1	1	1	1
Straw removed	Lafond et al. (2009)	2	4	5	3	1
Seed	Blonk et al. (2023)	2	3	4	1	1
Lime	Blonk et al. (2023)	3	4	4	2	1
Fertilizers	Blonk et al. (2023)	1	3	4	1	1
Herbicide and fungicide inputs	Total amounts from Blonk et al. (2023), types from AGRESTE	1	3	2	1	4
Insecticide inputs	Total amounts from Blonk et al. (2023), types from Nemecek (2007)	2	3	4	1	1
Irrigation energy use	Blonk et al. (2023)	2	4	3	2	1

Field activities energy use	Blonk et al. (2023)	2	4	3	2	1
Transportation of field inputs	Blonk et al. (2023)	4	4	4	1	3
Post-harvest energy use	Blonk et al. (2023)	2	4	3	2	1
Direct and indirect N_2O emissions	To be modelled using IPCC Tier 2 methods	1	3	2	1	1
CO_2 emissions from lime and urea	To be modelled using IPCC Tier 1 methods	2	3	2	2	1
Soil carbon changes	To be obtained from NIR	1	1	1	1	4

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

2.5.7.2.5.2 Corn production in France

Data for corn production in France was of generally high quality (Table 26). Corn yield data in France (and many other feed inputs in France and Italy that are considered in this study) from the Eurostat database was of similarly high quality, but preference was given to FAOstat (5-year average for 2018-2022) for consistency. Amounts of fertilizer and plant protection products applied were sourced from AGRESTE (Agreste, 2022), which reported three-year averages (2018-2021). All other data was sourced from Blonk et al. (2023).

Table 26: Data sources used for modelling French corn production, and their associated pedigree matrix scores

Data point	**Source to be used**	**R***	**C***	**Temp.***	**G***	**Tech.***
Yield	FAOStat	1	1	1	1	1
Seed	Blonk et al. (2023)	2	3	4	1	1
Lime inputs	Blonk et al. (2023)	3	4	4	2	1
NPK fertilizer amounts	AGRESTE	1	3	2	1	1
NPK fertilizer types	Blonk et al. (2023)	2	2	2	1	2
Herbicide, insecticide, and fungicide inputs	AGRESTE	1	3	2	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	3
Post-harvest	Blonk et al. (2023)	2	4	3	2	1
Direct and indirect N_2O emissions	To be calculated using IPCC Tier 2 methods	1	3	2	1	1
CO_2 emissions from lime and urea	To be calculated using IPCC Tier 1 methods	2	3	3	2	1
Soil carbon changes	To be taken from NIR	1	1	1	1	4

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

2.5.7.2.5.3 Soybean production in France

Data quality for soybean production in France was of generally high quality (Table 27). Amounts of fertilizer and plant protection products applied were sourced from AGRESTE (Agreste, 2022), which reported three-year averages (2018-2021). Five-year (2018-2022) yield data was sourced from FAOStat (FAOstat, 2024). All other data was sourced from the Blonk et al. (2023).

Table 27: Data sources used for modelling French soybean production, and their associated pedigree matrix scores

Data point	**Source to be used**	**R***	**C***	**Temp.***	**G***	**Tech.***
Yield	FAOStat	1	1	1	1	1
Seed	Blonk et al. (2023)	2	3	4	1	1
Lime inputs	Blonk et al. (2023)	3	4	4	2	1
NPK fertilizer amounts	AGRESTE	1	3	2	1	1
NPK fertilizer types	Blonk et al. (2023)	2	3	2	1	2
Herbicide, insecticide, and fungicide inputs	AGRESTE	1	3	2	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	3
Post-harvest	Blonk et al. (2023)	2	4	3	2	1
Direct and indirect N_2O emissions	To be calculated using IPCC Tier 2 methods	1	3	2	1	1
CO_2 emissions from lime and urea	To be calculated using IPCC Tier 1 methods	2	3	3	2	1
Soil carbon changes	To be taken from NIR	1	1	1	1	4

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

2.5.7.2.5.4 Grass (for silage) production in France

All data except on field energy use for harvested forage production in France was sourced from the Blonk et al. (2023). Fuel use data for machinery used in the field was obtained from Fantin et al. (2017), which had a poor score for temporal correlation (data from 2013) and average score for completeness. Table 28 below provides the sources and data quality scores assigned for each data point to characterize French harvested forage production.

Table 28: Data sources used to model French silage production, and their associated pedigree matrix scores

Data point	Source to be used	R*	C*	Temp.*	G*	Tech.*
Yield	Blonk et al. (2023)	1	3	3	1	1
Seed	Blonk et al. (2023)	2	3	4	1	1
Lime inputs	Blonk et al. (2023)	3	4	4	2	1
NPK fertilizer amounts	Blonk et al. (2023)	1	3	4	1	1
NPK fertilizer types	Blonk et al. (2023)	2	3	2	1	2
Herbicide, insecticide, and fungicide inputs	Blonk et al. (2023)	3	2	3	1	2
Irrigation energy	Blonk et al. (2023)	2	4	3	2	1
Field activities energy use	Fantin et al. (2017)	1	3	4	1	1
Transportation	Blonk et al. (2023)	4	4	4	1	3
Post-harvest	Blonk et al. (2023)	2	4	3	2	1
Direct and indirect N_2O emissions	To be calculated using IPCC Tier 2 methods	1	3	2	1	1
CO_2 emissions from lime and urea	To be calculated using IPCC Tier 1 methods	2	3	3	2	1
Soil carbon changes	To be taken from NIR	1	1	1	1	4

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

2.5.7.2.5.5 Barley production in Italy

For barley production in Italy, 5-year average yield data (2018-2022) was sourced from FAOStat (FAOstat, 2024). Amounts of nitrogen, phosphorus, and potassium fertilizer inputs were sourced from the crop-specific fertilizer application data provided by the International Fertilizer Association (IFA). This data had only average data quality for reliability due to the use of information from experts alongside country-specific fertilizer application data. Transportation data from (Tricase et al., 2018) was preferred due to a marginally higher score for temporal correlation compared to the transportation data from Blonk et al. (2023). All other data was sourced from Blonk et al. (2023). Table 29 below provides the sources and data quality scores assigned for each data point to characterize Italian barley production.

Table 29: Data sources used to model Italian barley production, and their associated pedigree matrix scores

Data point	Source to be used	R*	C*	Temp.*	G*	Tech.*
Yield	FAOStat	1	1	1	1	1
Seed	Blonk et al. (2023)	2	3	4	1	1
Lime inputs	Blonk et al. (2023)	3	4	4	2	1
NPK fertilizer amounts	IFAStat	3	3	3	1	1
NPK fertilizer types	Blonk et al. (2023)	2	3	2	1	2
Herbicide, insecticide, and fungicide inputs	Blonk et al. (2023)	3	2	3	1	2
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	Tricase et al. (2018)	4	4	3	1	1
Post-harvest	Blonk et al. (2023)	2	4	3	2	1
Direct and indirect N_2O emissions	To be calculated using IPCC Tier 2 methods	1	3	2	1	1
CO_2 emissions from lime and urea	To be calculated using IPCC Tier 1 methods	2	3	3	2	1
Soil carbon changes	To be taken from NIR	1	1	1	1	4

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

2.5.7.2.5.6 Sugar beet production in Italy

Five-year (2018-2022) yield data was sourced from FAOStat (FAOstat, 2024). Amounts of fertilizer inputs were sourced from IFA (IFA, 2024). All other data was sourced from Blonk et al. (2023). Table 30 below provides the sources and data quality scores assigned for each data point to characterize Italian sugar beet production.

Table 30: Data sources used to model Italian sugar beet production, and their associated pedigree matrix scores

Data point	Source to be used	R*	C*	Temp.*	G*	Tech.*
Yield	FAOStat	1	1	1	1	1
Seed	Blonk et al. (2023)	2	3	4	1	1
Lime inputs	Blonk et al. (2023)	3	4	4	2	1
NPK fertilizer amounts	IFAStat	3	3	3	1	1
NPK fertilizer types	Blonk et al. (2023)	2	3	2	1	2
Herbicide, insecticide, and fungicide inputs	Blonk et al. (2023)	3	2	3	1	2
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	3
Post-harvest	Blonk et al. (2023)	2	4	3	2	1
Direct and indirect N_2O emissions	To be calculated using IPCC Tier 2 methods	1	3	2	1	1
CO_2 emissions from lime and urea	To be calculated using IPCC Tier 1 methods	2	3	3	2	1
Soil carbon changes	To be taken from NIR	1	1	1	1	4

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

2.5.7.2.5.7 Soybean production in Italy

Five-year (2018-2022) yield data was sourced from FAOStat (FAOstat, 2024). All other data was sourced from Blonk et al. (2023). Table 31 below provides the sources and data quality scores assigned for each data point to characterize Italian soybean production.

Table 31: Data sources used to model Italian soybean production, and their associated pedigree matrix scores

Data point	**Source to be used**	**R***	**C***	**Temp.***	**G***	**Tech.***
Yield	FAOStat	1	1	1	1	1
Seed	Blonk et al. (2023)	2	3	4	1	1
Lime inputs	Blonk et al. (2023)	3	4	4	2	1
NPK fertilizer amounts	Blonk et al. (2023)	1	3	4	1	1
NPK fertilizer types	Blonk et al. (2023)	2	3	2	1	2
Herbicide, insecticide, and fungicide inputs	Blonk et al. (2023)	3	2	3	1	2
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	3
Post-harvest	Blonk et al. (2023)	2	4	3	2	1
Direct and indirect N_2O emissions	To be calculated using IPCC Tier 2 methods	1	3	3	1	1
CO_2 emissions from lime and urea	To be calculated using IPCC Tier 1 methods	2	3	3	2	1
Soil carbon changes	To be taken from NIR	1	1	1	1	4

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

2.5.7.2.5.8 Wheat production in Italy

Straw removal rate for Italian wheat production was obtained from Palmieri et al. (2017) but had poor scores for completeness (based on data from a small number of sites) and temporal correlation (more than 10 years old). Data related to fuel use for field activities associated with wheat production in Italy was sourced from Fantin et al. (2017). This data was based on farm-level surveys and hence had good scores for reliability, geographical correlation, and technological correlation. However, the share of Italian wheat production represented in the survey was less than 1% and the data was over 10 years old. As a result, fuel use data from Fantin et al. (2017) had poor scores for completeness and temporal correlation. Five-year (2018-2022) yield data was sourced from FAOStat (FAOstat, 2024). All other data was sourced from Blonk et al. (2023). Table 32 below provides the sources and data quality scores assigned for each data point to characterize Italian wheat production.

Table 32: Data sources used to model Italian wheat production, and their associated pedigree matrix scores

Data point	Source to be used	R*	C*	Temp.*	G*	Tech.*
Yield	FAOStat	1	1	1	1	1
Straw removed	Palmieri et al. (2017)	2	4	4	1	1
Seed	Blonk et al. (2023)	2	3	4	1	1
Lime inputs	Blonk et al. (2023)	3	4	4	2	1
NPK fertilizer amounts	IFAStat	3	3	3	1	1
NPK fertilizer types	Blonk et al. (2023)	2	3	2	1	2
Herbicide, insecticide, and fungicide inputs	Blonk et al. (2023)	3	2	3	1	2
Irrigation energy	Blonk et al. (2023)	2	4	3	2	1
Field activities energy use	Fantin et al. (2017)	1	4	4	1	1
Transportation	Blonk et al. (2023)	4	4	4	1	3
Post-harvest	Blonk et al. (2023)	2	4	3	2	1
Direct and indirect N_2O emissions	To be calculated using IPCC Tier 2 methods	1	3	2	1	1
CO_2 emissions from lime and urea	To be calculated using IPCC Tier 1 methods	2	3	3	2	1
Soil carbon changes	To be taken from NIR	1	1	1	1	4

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

2.5.7.2.5.9 Corn production in Italy

Five-year (2018-2022) yield data was sourced from FAOStat (FAOstat, 2024). Data related to fuel use for field activities associated with corn production in Italy was sourced from Fantin et al. (2017). This data was based on farm-level surveys and hence had good scores for reliability, geographical correlation, and technological correlation. However, the share of Italian corn production represented in the survey was approximately 2% and the data was over 10 years old. As a result, fuel use data from Fantin et al. (2017) had an average score for completeness and a poor score for temporal correlation. All other data was sourced from Blonk et al. (2023). Table 33 below provides the sources and data quality scores assigned for each data point to characterize Italian corn production.

Table 33: Data sources used for modelling Italian corn, and their associated pedigree matrix scores

Data point	**Source to be used**	**R***	**C***	**Temp.***	**G***	**Tech.***
Yield	FAOStat	1	1	1	1	1
Seed	Blonk et al. (2023)	2	3	4	1	1
Lime inputs	Blonk et al. (2023)	3	4	4	2	1
NPK fertilizer amounts	IFAStat	3	3	3	1	1
NPK fertilizer types	Blonk et al. (2023)	2	3	2	1	2
Herbicide, insecticide, and fungicide inputs	Blonk et al. (2023)	3	2	3	1	2
Irrigation energy	Blonk et al. (2023)	2	4	3	2	1
Field activities energy use	Fantin et al. (2017)	1	3	4	1	1
Transportation	Blonk et al. (2023)	4	4	4	1	3
Post-harvest	Blonk et al. (2023)	2	4	3	2	1
Direct and indirect N_2O emissions	To be calculated using IPCC Tier 2 methods	1	3	2	1	1
CO_2 emissions from lime and urea	To be calculated using IPCC Tier 1 methods	2	3	3	2	1
Soil carbon changes	To be taken from NIR	1	1	1	1	4

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

2.5.7.2.5.10 Corn silage production in Italy

Similar to corn production, data related to fuel use for field activities associated with corn silage production in Italy was sourced from Fantin et al. (2017). Table 34 below provides the sources and data quality scores assigned for each data point to characterize Italian corn silage production.

Table 34: Data sources used for modelling Italian corn silage, and their associated pedigree matrix scores

Data point	Source to be used	R*	C*	Temp.*	G*	Tech.*
Yield	Blonk et al. (2023)	1	3	3	1	1
Seed	Blonk et al. (2023)	2	3	4	1	1
Lime inputs	Blonk et al. (2023)	3	4	4	2	1
NPK fertilizer amounts	Blonk et al. (2023)	1	3	4	1	1
NPK fertilizer types	Blonk et al. (2023)	2	3	2	1	2
Herbicide, insecticide, and fungicide inputs	Blonk et al. (2023)	3	2	3	1	2
Irrigation energy	Blonk et al. (2023)	2	4	3	2	1
Field activities energy use	Fantin et al. (2017)	1	3	4	1	1
Transportation	Blonk et al. (2023)	4	4	4	1	3
Post-harvest	Blonk et al. (2023)	2	4	3	2	1
Direct and indirect N_2O emissions	To be calculated using IPCC Tier 2 methods	1	3	2	1	1
CO_2 emissions from lime and urea	To be calculated using IPCC Tier 1 methods	2	3	3	2	1
Soil carbon changes	To be taken from NIR	1	1	1	1	4

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

2.5.7.2.5.11 Wheat production in Canada

Data characterizing Canadian-average production of non-durum wheat were also of generally high quality (Table 35). The data quality assessment and best available data sources for Canadian wheat production were identified as part of the previous GIFS field crop carbon footprint study (Bamber et al., 2023). Proxy data from Saskatchewan were used for calculation of the amount of wheat straw removed. Fertilizer application rates were reported in the CRSC report ((S&T)2 Consultants, 2022) from two sources: Pulse Canada surveys and provincial crop insurance surveys. The crop insurance survey data were multi-year averages, hence nutrient input data is of very good quality except for completeness (the crop insurance surveys are assumed to have a representativeness below 50%). Pesticide input data for Alberta was used for Canadian wheat production in the CRSC report. This data had 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. All other data was sourced from Blonk et al. (2023). Table 34 below provides the sources and data quality scores assigned for each data point to characterize Canadian wheat production.

Table 35: Data sources used for modelling Canadian wheat production, and their associated pedigree matrix scores

Data point	**Source**	**R***	**C***	**Temp.***	**G***	**Tech.***
Yield (grain)	StatsCan	1	2	1	1	1
Straw removed	Lafond et al. (2009)	2	4	5	1	1
Seed	CRSC report- wheat^	1	3	3	1	1
All fertilizer inputs	CRSC report- wheat^	1	3	2	1	1
All pesticide inputs	CRSC report- wheat^, fungicide and insecticide types from Nemecek (2007)	1	3	2	2	1
Irrigation energy	Blonk et al. (2023)	2	4	3	2	1
Fuel use for field activities	Blonk et al. (2023)	2	4	3	2	1
Transportation of field inputs	Blonk et al. (2023)	4	4	4	1	3
Post-harvest energy use	CRSC report- wheat^	3	4	2	1	1
Direct and indirect N_2O emissions	To be calculated using IPCC Tier 2 methods	1	3	2	1	1
CO_2 emissions from lime and urea	To be calculated using IPCC Tier 1 methods	2	3	3	2	1
Soil carbon changes	To be taken from NIR	1	1	1	1	4

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

2.5.7.2.5.12 Soybean production in Brazil

Data sources for soybean production in Brazil were identified in Bamber et al. (2023) and reported in the Phase 1 report of this study (Arulnathan et al., 2024). FAOStat for yield (2018-2022) and (Nemecek, 2007) for lime, other fertilizer inputs (micronutrients other than NPKS), and pesticide types were used. 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. 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). Table 36 below provides the sources and data quality scores assigned for each data point to characterize Brazilian soy production.

Table 36: Data sources used 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)	2	3	4	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	3	4	1	1
Herbicide, insecticide, and fungicide input amounts	Blonk et al. (2023)	3	2	3	1	2
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	3
Post-harvest	Nemecek (2007)	2	3	5	2	1
Direct and indirect N_2O emissions	To be calculated using IPCC Tier 2 methods	1	3	2	1	1
CO_2 emissions from lime and urea	To be calculated using IPCC Tier 1 methods	2	3	3	2	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.*

2.5.7.2.5.13 Corn production in Ukraine

High quality data related to amounts of fertilizer inputs, types of fertilizer inputs, and amounts of crop protection products applied for Ukrainian corn production were obtained from the Ukrainian National Statistical Service (Derzhstat, 2024).This data was assumed to represent less than 50% of Ukrainian corn production and hence was given a completeness score of 3. All other data was sourced from Blonk et al. (2023). Table 37 below provides the sources and data quality scores assigned for each data point to characterize Ukrainian corn production.

Table 37: Data sources used for modelling Ukrainian corn, and their associated pedigree matrix scores

Data point	Source to be used	R*	C*	Temp.*	G*	Tech.*
Yield	FAOStat	1	1	1	1	1
Seed	Blonk et al. (2023)	2	3	4	1	1
Lime inputs	Blonk et al. (2023)	3	4	4	2	1
NPK fertilizer amounts	National Statistics Service	1	3	1	1	1
NPK fertilizer types	National Statistics Service	1	3	1	1	1
Herbicide, insecticide, and fungicide inputs	National Statistics Service	1	3	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	3
Post-harvest	Blonk et al. (2023)	2	4	3	2	1
Direct and indirect N_2O emissions	To be calculated using IPCC Tier 2 methods	1	3	1	1	1
CO_2 emissions from lime and urea	To be calculated using IPCC Tier 1 methods	2	3	3	2	1
Soil carbon changes	To be taken from NIR	1	1	1	1	4

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

2.5.7.2.5.14 Corn production in Hungary

Five-year (2018-2022) yield data was sourced from FAOStat (FAOstat, 2024). Amounts of fertilizer inputs were sourced from IFA (IFA, 2024). All other data was sourced from Blonk et al. (2023). Table 38 below provides the sources and data quality scores assigned for each data point to characterize Hungarian corn production.

Table 38: Data sources used for modelling Hungarian corn, and their associated pedigree matrix scores

Data point	Source to be used	R*	C*	Temp.*	G*	Tech.*
Yield	FAOStat	1	1	1	1	1
Seed	Blonk et al. (2023)	2	3	4	1	1
Lime inputs	Blonk et al. (2023)	3	4	4	2	1
NPK fertilizer amounts	IFAStat	3	3	3	1	1
NPK fertilizer types	Blonk et al. (2023)	2	3	2	1	2
Herbicide, insecticide, and fungicide inputs	Blonk et al. (2023)	3	2	3	1	2
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	3
Post-harvest	Blonk et al. (2023)	2	4	3	2	1
Direct and indirect N_2O emissions	To be calculated using IPCC Tier 2 methods	1	3	3	1	1
CO_2 emissions from lime and urea	To be calculated using IPCC Tier 1 methods	2	3	3	2	1
Soil carbon changes	To be taken from NIR	1	1	1	1	4

**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 39 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 40 lists all processes used in modifications listed in Table 39 (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 39. 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 39: Inventory flows, the background 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		
Urea	urea production | urea | APOS, U – RER or RNA	electricity providers changed for each region
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 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 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
Monoammonium phosphate (MAP)	market for monoammonium phosphate | monoammonium phosphate | APOS, U – RNA or RER	electricity providers changed for each region
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)
Single superphosphate	single superphosphate production | single superphosphate | APOS, U – RER	electricity and phosphate rock providers changed for each region
Triple superphosphate	triple superphosphate production | triple superphosphate | APOS, U – RER	electricity, phosphate rock, and phosphoric acid providers changed for each region
Phosphate rock	phosphate rock beneficiation | phosphate	electricity providers changed for each region

	rock, beneficiated | APOS, U – RER	
Potassium chloride (potash)	potassium mining and benefication | potassium chloride | APOS, U - CA-SK	electricity providers changed for each region
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 potassium chloride providers changed for each region
Ammonium sulfate	ammonium sulfate production | ammonium sulfate | APOS, U – RER	ammonia providers changed to regionalized ammonia providers (modifications described above)
Sulfur	natural gas production | sulfur | APOS, U - CA-AB or DE	electricity providers changed for each region
Zinc	primary zinc production from concentrate | zinc | APOS, U – CA-QC	electricity and urea providers changed for each region
Lime	lime production, milled, loose | lime | APOS, U – CA-QC or CH	electricity providers changed for each region
Plant protection products		
Glyphosate	glyphosate production | glyphosate | APOS, U – RER	electricity providers changed for each region 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 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 ammonia and decarbonised water providers changed for each region
Glufosinate, chlorpyrifos, Methidathion	organophosphorus-compound production, unspecified | organophosphorus-	electricity providers changed for each region ammonia, decarbonised water and sulfur providers changed for each region

	compound, unspecified | APOS, U – RER	
MCPA, 2,4-D, Quizalofop-ethyl	phenoxy-compound production | phenoxy-compound | APOS, U – RER	electricity providers changed for each region 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 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 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 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 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 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
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 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 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 –	electricity and natural gas providers changed for each region

	CA-QC or Europe without Switzerland	
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	
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 (all Agrifootprint unless specified otherwise)		
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.
Canola meal	Crude rapeseed oil (solvent), at processing {CA} Energy, U	Electricity providers changed for each region.
Sugar beet pulp	Sugar pulp, at processing {IT} Energy, U - IT	Added to sugar beet production system modelled for Italy.
Corn meal	Maize gluten meal dried, at processing {FR} Energy, U - FR	Electricity and natural gas providers changed for each region.
Soybean meal	Crude soybean oil (solvent), at processing {IT} Energy, U AR, BR, FR, IT	For imports, soybean meal is considered to be produced in the country of origin and imported as soybean meal.
Sugarcane molasses	Sugar, from sugar cane, at processing {AU} Energy, U - AU	
Cottonseed meal	cottonseed oil mill operation | cottonseed meal | APOS, U - RoW (Ecoinvent)	Electricity and natural gas providers changed for each region.
Packaging processes		
Packaging film	packaging film production, low density polyethylene | packaging film, low	Electricity and natural gas providers changed for each region.

	density polyethylene | APOS, U - RER	

Table 40: Processes used for modification of background processes.

Modifications	Processes used for modifications
Electricity	- market for electricity, low voltage | electricity, low voltage | APOS, U – Australia - market group for electricity, low voltage | electricity, low voltage | APOS, U – Argentina - market for electricity, low voltage | electricity, low voltage | APOS, U – France - market group for electricity, low voltage | electricity, low voltage | APOS, U – New Zealand
Decarbonised water	- market for water, decarbonised | water, decarbonised | APOS, U – Rest of Europe
Processed feed inputs	- Maize distillers grains dried, at processing {US} Energy, U - Italy - Crude rapeseed oil (solvent), at processing {CA} Energy, U – Australia - Maize gluten meal dried, at processing {FR} Energy, U – Italy - Sugar, from sugar cane, at processing {AU} Energy, U – Australia - cottonseed oil mill operation | cottonseed meal | APOS, U – Australia
Packaging film	- packaging film production, low density polyethylene | packaging film, low density polyethylene | APOS, U – France

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 four 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 four countries estimated changes in carbon sequestration if the conversion is estimated to have happened within the last 20 years. All four NIRs follow the guidelines specified in the IPCC methods (IPCC 2019) and implement some form of 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:

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

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)

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 both land use change and grassland management that were calculated using the equations discussed above were taken directly from the respective NIRs (Citepa, 2023; DCCEEW, 2023; MAyDS, 2022; NZME, 2023).

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 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:

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

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 NIRs report 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 41 below.

Table 41: Emissions associated with soil organic carbon (SOC) fluxes per hectare of land use type derived from NIRs of Australia, Argentina, France, Italy, Ukraine, Hungary, and New Zealand

Source of soil organic carbon (SOC) changes	**CO_2-eq. emissions associated with SOC fluxes***	**Unit**
Australia		
SOC flux from cropland management (cropland remaining cropland)	77.181	kg/ha
SOC flux from grassland converted to cropland	30.697	kg/ha
Net cropland SOC flux	107.878	kg/ha
SOC from grassland management (grassland remaining grassland)	-2.368	kg/ha
SOC flux from land converted to grassland	-44.174	kg/ha

Net grassland SOC flux	-46.542	kg/ha
Argentina		
SOC flux from cropland management (cropland remaining cropland)	142.810	kg/ha
SOC flux from conversion to cropland	448.256	kg/ha
Net cropland SOC flux	591.066	kg/ha
Net grassland SOC flux	291.524	kg/ha
France**		
Net cropland SOC flux	274.018	kg/ha
Net grassland SOC flux	-196.158	kg/ha
Italy, Hungary, Ukraine**		
Net cropland SOC flux – Italy	112.760	kg/ha
Net cropland SOC flux – Hungary	23.529	kg/ha
Net cropland SOC flux - Ukraine	1380.118	kg/ha
New Zealand		
Net grassland SOC flux	188.768	kg/ha

**Negative value indicates sequestration. Positive value indicates emissions.*
***Emissions associated with SOC changes for crop imports from Brazil and Canada taken from part 1 of this study (Arulnathan et al., 2024)*

2.5.9.3 Enteric methane

For all of the beef production systems modelled, IPCC Tier 2 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 from Feedipedia reported in Table 43). 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 weres calculate 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 42 below.

Table 42: Methane conversion factors (Y_m) and their sources used for modelling enteric methane emissions

Region and source	**Cattle type**	**Y_m (% of GE)**
Australia	Cow-calf phase - Cows	6.15
	Cow-calf phase – Bulls	6.15
	Cow-calf phase – Calves	6.15
	Backgrounding- Calves	6.15
	Finishing – grass fed	6.15
	Finishing – grain fed	5.05
Argentina	Cow-calf phase – Cows	7
	Cow-calf phase – Bulls	7
	Cow-calf phase – Calves	7
	Grass finished – steers (including backgrounding)	6.3
	Grass finished – heifers (including backgrounding)	7
	Grain finished – steers and heifers (including backgrounding)	4
France	Cow-calf phase – Cows	6.5
	Cow-calf phase – Bulls	6.7
	Cow-calf phase – Calves	6.17
	Cow-calf phase – replacement heifers	6.17
	Backgrounding	6.17
	Finishing – steers	4.68
	Finishing – heifers	4.62
New Zealand	All beef cattle	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 (or Tier 1 if country-specific NIRs report using Tier 1 factors) approach, as done in the NIRs of the countries considered. Methane emissions from manure management as a result of anaerobic fermentation were estimated based on a Tier 2 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 N_2O emissions from manure deposited in pastures and manure management were calculated using a Tier 2 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, storage, and application result from volatilization of nitrogen as ammonia and nitrogen oxides, and nitrate leaching. Equation 10.26 of the IPCC (2019) guidelines was used to calculate indirect nitrous oxide emissions from volatilization, 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 43 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 43: Data used for estimating volatile organic solids excreted

Inputs	Dry matter (%)	GE (MJ/kg of DM)	TDN (%)	Ash (%)
Australia				
Pasture	22.7	18.0	62.2	9.7
Wheat	87	18.2	70.4	1.8
Sorghum	87.4	18.8	68.4	2.1
Barley	87.1	18.4	66.6	1.9
White fluffy cottonseed	90.9	20	81.8	7.4
Cottonseed meal	90.9	20	81.8	7.4
Canola meal	89	19.3	77.2	7.6
Hay	85	17.6	58.9	9
Straw	91	18.5	3.5	6.7
Silage	23.5	18.9	54.9	4.8
Cotton hulls	90.6	19.8	2.6	2.9
Molasses	73	14.7	43.1	14.6
Argentina				
Gatton pasture	31.3	18	58.4	9.5
Buffel grass pasture	30.1	18.3	57.5	9.1
Setaria grass	31.3	18	58.4	9.5
Weeping lovegrass	38.2	19.1	58.4	4.6

Oat/rye grass	16.8	17.8	71.7	10.7
Wheatgrass	29.5	17.9	63.1	8.2
Oats	26.3	18	56.3	10.1
Sorghum forage	28.1	18.1	60.5	9.1
Corn	87.2	18.7	89	1.4
Corn silage	32.5	18.8	54.7	3.7
Sorghum silage	28.4	18.1	58.9	8.8
Hay	85	17.6	58.9	9
France/Italy				
Hay	85	17.6	58.9	9
Wheat	87	18.2	70.4	1.8
Soybean	87	18.2	70.4	1.8
Corn silage	32.5	18.8	54.7	3.7
Grass silage	30.8	18.2	64.2	8.2
Pasture	18.75	17.9	65.3	10.2
Corn	87.2	18.7	89	1.4
Corn meal	95.6	20.7	71	2
Dried sugar beet pulp	88.8	17.1	70	7.1
Wheat straw	91	18.5	3.5	6.7
Sugar beet pulp	24.3	17.1	69	6.8
Soybean meal	88	19.7	91.1	7.3
Corn DDGS	89	21.4	83.3	5.4
Barley grain	87.1	18.4	66.6	1.9
New Zealand				
Pasture	16.8	17.8	10.7	71.7

2.5.9.5 N_2O emissions from feed crops

Modelling of N_2O 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 N_2O emissions were calculated using equation 11.2 of IPCC (2019) as follows

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

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}
- 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}
- 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)$^{-1}$

Indirect N_2O emissions from volatization of ammonia and nitrogen oxides were estimated according to equation 11.11 of IPCC (2019) as follows

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

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 N_2O 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 44 below summarizes all of the emission factors and fractions used for modelling emissions across all three countries considered.

Table 44: Emission factors and fractions used in calculating manure management and field-level crop-related emissions

Emission factors and fractions*	Australia	Argentina	France	New Zealand
Manure management				
B_o (Ch4/kg of VS)	0.24 (all cattle except calves that are grain finished), 0.19 (grain finished calves)	0.19	0.18 (all cattle except calves in finishing), 0.27 (calves in finishing)	0.19
MCF	0.01 (all cattle except calves that are grain finished), 0.0378 (grain finished calves)	0.0047 (cattle on grass), 0.01 (cattle on feed)	0.0047	0.00098
EF_{dir} (non pasture)	0.019	0.02	0.02	-
EF_{dir} (pasture)	0.004	0.004	0.0044	0.01
EF_{vol} (non pasture)	0.002	0.01	0.01	-
EF_{vol} (pasture)	0.002	0.01	0.00972	0.01
EF_{leach} (non pasture)	-	0.011	0.0075	-
EF_{leach} (pasture)	0.011	0.011	0.01	0.0075
$FRAC_{vol}$ (non pasture)	0.7	0.3	0.2	-

FRAC$_{vol}$ (pasture)	0.11	0.07 (all cattle except cows). 0.21 (cows)	0.01	0.1
FRAC$_{leach}$ (non pasture)	-	0.00035	0.095	-
FRAC$_{leach}$ (pasture)	0.24	0.24	0.24	0.08
Crop field-level emissions				
EF$_1$ – synthetic N application	0.002	0.01	0.01	0.0059*
EF$_1$- crop residues	0.01	0.006	0.00552 (France), 0.01 (Italy, Ukraine, Hungary)	0.01*
FRAC$_{GASF}$	0.11	0.1	0.067 (France), 0.0969 (Italy), 0.145 (Ukraine), 0.06 (Hungary)	0.1*
FRAC$_{GASM}$	0.21	0.21	0.21 (France, Italy), 0.2 (Ukraine), 0.1 (Hungary)	0.1*
EF$_4$ – indirect N volatization	0.002	0.01	0.00972 (France), 0.01 (Italy, Ukraine, Hungary)	0.01*
FRAC$_{LEACH}$	Barley (0.07), Sorghum (0.02), Wheat (0.06), Canola (0.07), Cotton (0.23), Sugarcane (0.16)	0.24	0.135 (France), 0.27 (Italy), 0.3 (Ukraine, Hungary)	0.08*
EF$_5$ – indirect N leaching	0.011	0.0075	0.011 (France, Ukraine), 0.0075 (Italy, Hungary)	0.0075*
Urea emissions factor	0.2	0.2	0.2	0.2*
Lime emission factor	0.12	0.12	0.12	0.12*

**For New Zealand, crop-related emissions are related to pasture management*

2.5.10 Estimating dry matter intake for New Zealand

The dry matter intake (DMI) estimates for New Zealand beef production was based on a Tier 2 methodology specified in the New Zealand NIR (NZME, 2023). The basic equation to calculate DMI is as follows.

$$DMI = \frac{ME_{total}}{ME_{diet}}$$

where,

DMI – dry matter intake (kg/animal/day),

ME_{total} – total metabolizable energy required per day per animal (MJ/d),

ME_{diet} – total metabolizable energy per kilogram of dry matter in the total diet, and

ME_{diet} were calculated based on the equation below using the metabolizable energy content values of New Zealand pasture forage and other supplemental ingredients and the feed composition specified in section 3.1.4.

$$ME_{diet} = \sum_{feed} ME_{feed} * \%Diet_{feed}$$

where,

ME_{feed} – metabolizable energy per kilogram of dry matter for each feed ingredient (MJ/kg),

$\%Diet_{feed}$ – proportion of each feed ingredient in the diet, and

ME_{total} is the sum of metabolic energy requirements of various functions of cattle such as lactation, gestation, growth, and maintenance. This is represented in the following equation

$$ME_{total} = ME_m + ME_p + ME_{lw} + ME_g$$

where,

ME_m is the metabolizable energy required for maintenance (MJ/day),

ME_p is the metabolizable energy required for production of milk in lactating cows (MJ/day),

ME_{lw} is the metabolizable energy required for live weight gain (MJ/day), and

ME_g is the metabolizable energy required for gestation or growth of the conceptus (MJ/day)

2.5.10.1 Metabolizable energy for maintenance

Metabolizable energy required for maintenance was calculated using the equation below.

$$ME_m = 1.4 * S * \frac{e^{-0.03A} * \ 0.28LW^{0.75}}{k_m} + 0.1 * ME_p$$

where,

S is a coefficient that differentiates between the basal metabolic rates of male and female cattle,

LW is the live weight of the animal in kilogram,

A is the age in years,

ME_p is the metabolizable energy required for production, and

K_m is the efficiency of utilizing metabolizable energy for maintenance.

2.5.10.2 Metabolizable energy for lactating cows

Metabolizable energy for milk production was calculated using the equation below.

$$\mathrm{ME}_p = \frac{Y * M_{GE}}{k_p}$$

where,

Y is the milk yield per lactating cow (kilogram/day),

M_{GE} is the gross energy content of milk (MJ/kilogram), and

K_p is is the efficiency of utilizing metabolizable energy for milk production.

2.5.10.3 Metabolizable energy for live weight gain

Metabolizable energy for growth of the animal was calculated using the equation below.

$$\mathrm{ME}_{lw} = \frac{(6.7 + R) + \frac{20.3 - R}{1 + \ e^{-6\,(P_{lw} - 0.4)}}}{k_{lw}} * LWG * 0.92$$

where

R is a coefficient for rate of change in live weight, LWG is the live weight gain (kilogram/day),

P_{lw} is the ratio of live weight to standard reference weights for mature cattle, and

K_{lw} is is the efficiency of utilizing metabolizable energy for growth.

2.5.10.4 Metabolizable energy for gestation

Metabolizable energy for gestating animals was calculated using the equation below.

$$\mathrm{ME}_{lw} = \frac{0.0201E_t + e^{-0.0000576D}}{0.133} * LW_c * 0.025$$

where,

LW_c is the live weight of calf at birth (kg),

E_t is the energy required in utero (MJ/day), and

D is the number of days the cow is pregnant.

2.5.11 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.

2.5.12 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 8-38). 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 6.1). 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 outputs. 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).

2.5.13 Sensitivity Analysis

Sensitivity analysis was performed to determine the sensitivity of the final results to any changes in methodological choices or to inventory data points that made significant contributions to the overall carbon footprint results. Given the huge significance of enteric methane emissions to New Zealand beef production (as seen in section 3.3) due to its pasture-based system, and the dependence of enteric methane emissions on the daily average feed intake values, a sensitivity analysis on the feed intake estimate was performed. The average daily feed intake value used for modelling Australian grass finished beef production (16.69 kilograms DM/animal unit) and Brazilian production (22.76 kilograms DM/animal unit) were used as an alternative to the value (15.25 kilograms DM/animal unit) determined using the models specified in section 2.5.10. These regions were used for alternate feed inputs values because Australia is the geographically closest region modelled to New Zealand and has a significant presence of grass-finished cattle, and Brazil was the only other fully pasture-based system modelled in this study across the two phases. It is important to recognize here that this sensitivity analysis is not intended to provide an alternate estimate of the carbon footprint of New Zealand beef, but rather to investigate the significance of feed intake estimates in the calculation of carbon footprints.

3 Results and Discussion

Table 45 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 3.1.1-3.1.4. Result for Western Canadian beef production from phase 1 (Arulnathan et al., 2024) are used here to provide a comparison to the inventory and impact assessment results for the regions modelled in phase 2.

Calving rates were comparable in Australia, France, and New Zealand (81-86%) to Western Canada (91%), but considerably lower in Argentina (67%). Replacement rate was the lowest in New Zealand (11%) and highest in France (25%), with the Western Canadian replacement rate (14%) falling within this range as well. Mortality rates of calves was generally low (2-4%) in all regions and comparable to Western Canada (1.2-3.3%), except in France (9.8%). The bulls to cow ratio was largely similar (1 bull for ~5 cows) across all the countries compared. Stocking rates were highest in New Zealand (3.2 animal units/hectare for cow calf, and 2.5 animal units/hectare for finishing) among the four countries. Stocking rates in France and Argentina were comparable (0.48 and 0.56 animal units per hectare, respectively), while the stocking rate in Australia was the lowest (0.1 animal units per hectare). The Western Canadian stocking rate (1.8 animal units/hectare) was higher than all countries except New Zealand.

Weights at the end of the cow-calf phase varied considerably across the four countries, with Australian calves at the end of the cow-calf phase having weights that were closest to Western Canada (226.8 kilograms for calves going to backgrounding, 260.8 kilograms for calves going to feedlot). Weight of calves reported at the end of the cow calf phase in Australia (263 kilograms) was considerably higher than the other regions (~165 kilograms in New Zealand and Argentina and 200 kilograms in France). The duration of the cow-calf phase in each country did not clearly correlate with the end weights specified, however. Despite having the highest weights at the end, the cow-calf phase in Australia was among the shortest (155 days). As a result, the average daily weight gain modelled for Australia was significantly higher (1.47 kilograms/animal/day) than the other three countries (0.5-0.75 kilograms/animal/day). When the cow-calf and backgrounding phases are considered together, the average daily weight gain in Australia (0.7 kg/day) was comparable to the other regions modelled (0.85 kg/day in Western Canada for example). Given that both these phases are pasture based, the high average daily weight gain in the cow-calf phase is unlikely to have significantly altered the results other than some potential differences in what share of total impacts from the cow-calf and backgrounding phases are attributed to each phase. It is also important to note that the data sources used for New Zealand did not distinguish between cow-calf and finishing phases (since the beef cattle are largely finished on pasture in the same farms where they were born). Instead, the cow-calf phase is considered to end at the time of weaning – reported to be around 5 months of age and at an average weight of 165 kilograms. Cumulative feed intakes per animal unit in the cow-calf phase was highest in France and lowest in New Zealand, and correlated closely with the duration of the phase in each country.

The characteristics of the backgrounding phase were also considerably varied across regions. Both Australia and Argentina reported long backgrounding phases (209-336 days), France had a relatively short backgrounding phase (68 days), and New Zealand did not have one. The Western Canadian backgrounding duration (259 days in the yearling-fed system) was different from all these countries, highlighting the diversity in production practices among the regions modelled. These differences in length of the backgrounding phase were directly reflected in the feed intake per animal unit modelled. Weight at the end of the backgrounding phase was the highest in Australia (421 kilograms) and France (365-377 kilograms), and relatively lower in Argentina (277-334 kilograms). The weights at the end of the backgrounding phase in Western Canada (358.96 kilograms for calves going directly to feedlot and 453.59 kilograms for calves put on an extended pasture-based yearling phase) was comparable to France and Australia. This highlights that there exists a potential narrow range (~350 to 450 kilograms), especially in countries that have significant share of grain-finished beef cattle, after which beef calves are sent for finishing. It is important to note here that, due to lack of direct linkage between the cow-calf herds in France and the feedlots in Italy from which data were collected in the source used in this study (particularly related to start and end weights), the authors (Berton et al., 2017) used a cluster analysis of body weight of calves (validated by industry experts) at different times of the year in France to estimate average weights at the beginning and end of phases. As a result, there is some uncertainty in the reported durations and average daily weight gains for the French cow-calf and backgrounding phases.

Reported finishing weights were highest in France/Italy (731 kilograms), and comparable to grain finished beef cattle in Australia (652 kilograms), and Western Canada (653-680 kilograms). Australian (552 kilograms) and New Zealand (449-570 kilograms) finishing weights were comparable for cattle finished on pasture, and Argentina had the lowest average finishing weights (227-334 kilograms). This resulted in considerable variation with respect to estimated 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 45: Simplified inventory table for cow-calf, backgrounding, and finishing phases of beef production in the regions modelled and compared to Western Canada

Data point	Western Canada	Australia	Argentina	France	New Zealand	Unit
Cow calf phase						
Calving rate	91	80	67.35	86	81	%
Replacement rate	14	18	16.75	25	11	%
Mortality rate	Calves -3.3%; Cows 1.5%; Bulls-1.2%;	2	4.2	9.8	2.25	%
Cows to bull ratio	19	20	21	20	18.18	number of cows per bull
Start weight	44.9	35	35	62	52	kg
End weight	226.8 for calves going to backgrounding , 260.8 for calves going to feedlot	263	164	200	165	kg
Duration of cow calf phase	205	155	210	240	150	days

Feed intake	6713.49	6700.35	7599.71	10280.77	5270.96	kilogram DM/animal unit
Stocking rate	1.8	0.1	0.56	0.48	3.2	cow-calf pair/hectare
Enteric methane	154.39	133.39	162.37	208.90	80.83	kg CH_4/animal unit
Backgrounding						
Start weight	226.8	263	164	200	NA	kg
End weight	358.96 for calves going direct to feedlot, 453.59 for calves put on pasture as yearlings	421	334.25 (steers), 277.35 (heifers)	377 (male), 365 (female)	NA	kg
Duration	151 days backgrounding, 108 yearling phase	336	324 (steers), 209 (heifers)	68	NA	days
Feed intake	857.89	2744.16	2209.04	295.42	NA	kilogram DM/animal unit
Enteric methane	20.03	54.63	45.83	5.83	NA	kg CH_4/animal unit
Finishing						
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	421	334.25 (steers), 277.35 (heifers)	377 (male), 365 (female)	165	kg
End weight	653 for calves direct from cow-calf, 680 for calves after backgrounding and yearling phases	552 (grass finished), 652 (grain finished)	404 (steers), 335 (heifers)	731	449 (female), 570 (male)	kg

Duration	270 for calves from cow-calf, 214 for calves from backgrounding, 140 for calves after time on pasture as yearlings	243 (grass finished), 125 (grain finished)	139 (steers), 100 (heifers)	226	690 (female), 810 (male)	days
Feed intake	1831.795	1831 (grass finished), 475 (grain finished)	772.64	801 (female), 1595 (male)	4833.57	kilogram DM/animal unit
Enteric methane	36.01	37.95	15.45	33.23	100.49	kg CH_4/animal unit
Dressing percentage	60	54.35	58	60	58	%

3.1.1 Australia

As specified in section 2.1.1, 65% of beef cattle in Australia was grass finished and 35% grain finished. The finishing feedlot grain diet in Australia includes a variety of feed ingredients (Table 46). The main ingredients were wheat and sorghum (i.e. approximately 30% each), followed by barley grain, cottonseed products (i.e. white fluffy cottonseed and cottonseed meal), and silage products (i.e. 9% approx.). Other agri-food co-products and residues are also part of the feed composition in lower quantities, such as canola oil, hay, straws, cotton hulls, and sugarcane molasses. .

Table 46: Average composition of one tonne of finishing feed for Australian beef production

Feed composition (unit)	Amount	Unit
Wheat	295.8	Kilogram/tonne
Sorghum	289.4	Kilogram/tonne
Barley	94.7	Kilogram/tonne
White fluffy cottonseed	63.4	Kilogram/tonne
Cottonseed meal	23.9	Kilogram/tonne
Canola meal	0.9	Kilogram/tonne
Hay*	33.6	Kilogram/tonne
Straw*	3.2	Kilogram/tonne
Silage***	85.1	Kilogram/tonne

Cotton hulls	17.2	Kilogram/tonne
Canola oil	12.2	Kilogram/tonne
Molasses	21.9	Kilogram/tonne
Wet supplement	58.7	Kilogram/tonne

**Lucerne hay*
***Includes wheat and sorghum straw.*
**** Includes sorghum and wheat silage.*

All other material and energy inputs to characterize the beef production system in Australia is provided in Table 47 below relative to one animal unit.

Table 47: Energy and material inputs per animal unit for Australian beef production

Data point	**Unit**	**Value**
Cow-calf phase (365 days)		
Electricity	14.50	kWh
Diesel	19.33	L
Petrol	4.83	L
Backgrounding phase		
Electricity	13.35	kWh
Diesel	17.80	L
Petrol	4.45	L
Finishing phase (grass-fed)		
Electricity	24.25	kWh
Diesel	32.34	L
Petrol	8.08	L
Finishing phase (feedlot)		
Electricity	118.60	kWh
Diesel	33.53	L
Petrol	17.51	L
Natural gas	0.30	MJ
Pasture		
P fertilizer	11	kg

The enteric methane and methane from manure management emissions for the different cattle types across the three phases of the Australian beef production process are provided in Table 48 below. These values (reported on a per animal unit basis) were determined based on the proportion of each cattle type in a reference animal unit and number of days spent in each phase. The Australian NIR reported production-weighted emission factors for different manure management systems used in Queensland and New South Wales (as reported in Table 44) and these were used directly for estimating feedlot methane and nitrous oxide emissions.

Table 48: Methane emissions in Australian beef production in kg CH_4 per animal unit

	Enteric methane	**Manure management**
Cow-calf phase		
Cows	112.83	3.36
Bulls	6.90	0.21
Calves	13.66	0.41
Backgrounding phase		
Calves	54.63	1.63
Finishing phase		
Calves (grass-fed)	29.93	1.08
Calves (grain-fed)	8.02	0.87

The direct and indirect nitrous oxide emissions from manure management for the different cattle types across the three phases of the Australian beef production process are provided in Table 49 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 emissions per animal unit.

Table 49: Manure related N_2O emissions each cattle type for Australian beef production in kg emission/head/day

	Direct N_2O emissions (kg/head/day)	**Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x (kg/head/day)**	**Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^- (kg/head/day)**
Cows	1.38E-03	7.56E-05	9.09E-04
Bulls	1.50E-03	8.26E-05	9.91E-04
Calves	4.30E-04	2.37E-05	2.84E-04
Calves- backgrounding	9.88E-04	5.43E-05	6.52E-04
Calves (grass-fed finish)	1.41E-03	7.731E-05	9.28E-04
Calves (grain-fed finish)	5.80E-03	4.28E-04	-

3.1.2 Argentina

The inventory of Argentinian beef production was calculated using a production-weighted average of beef production that includes all Argentinian regions listed in Table 50. The region of Conurbano (Greater Buenos Aires) was excluded due to the non-significant contribution to the national herd (MAyDS, 2022).

Table 50: Number of cattle heads by region and contribution to the Argentine national herd

Region	**Number of animals**	**Contribution (%)**
North Pampas	7,330,695	14
West Pampas	5,676,272	11
Southeast Pampas	8,107,201	16
Southwest Pampas	4,903,440	10
Northeast	12,840,589	25
Northwest	6,250,284	12
Semi-Arid	4,264,335	8
Patagonia	1,513,389	3
Greater Buenos Aires	8,603	1
National herd	50,894,808	100

To build the Argentinian beef production inventory reported in Table 45, in addition to regional weighting, the cow-calf phase inventory was also weighted by the three types of breeding systems from each region: low, intermediate, and high productivity. Data for the finishing phase was calculated by aggregating all of the diverse finishing systems from each region for both male (steers) and female (heifers) calves. These systems include different feeding strategies such as all grazing with no supplemental feed, pasture finishing with supplements, a combination of grazing and feedlot (grain-fed beef), or only confinement in feedlot (MAyDS, 2022). The weighted average compositions of the pasture diets in different phases and the grain finishing diet for Argentinian beef production are provided in Tables 51 and 52, respectively.

Table 51: Weighted average composition of pasture diets in different phases of Argentinian beef production

Input	Cow-calf phase	Steers in backgrounding and finishing phases	Heifers in backgrounding and finishing phases	Unit
Natural grassland	0.85	0.33	0.26	kg/kg DM
Mixed pastures	0.01	0.23	0.25	kg/kg DM
Gatton pasture	0.02	0.07	0.07	kg/kg DM
Buffel grass pasture	0.01	0.03	0.03	kg/kg DM
Setaria grass	0.01	0.10	0.10	kg/kg DM
Weeping lovegrass	0.01			kg/kg DM
Oat/rye grass	0.00	0.07	0.07	kg/kg DM
Wheatgrass	0.04			kg/kg DM
Sorghum silage	0.01			kg/kg DM
Winter forage	0.02	0.09	0.13	kg/kg DM
Sorghum forage	0.03	0.05	0.05	kg/kg DM
Oats		0.03	0.03	kg/kg DM

Table 52: Weighted average composition of finishing diets for steers and heifers in Argentinian beef production

Input	Steers in backgrounding and finishing phases	Heifers in backgrounding and finishing phases	Unit
Corn	0.63	0.70	kg/kg DM
Corn silage	0.14	0.18	kg/kg DM
Sorghum silage	0.04	0.01	kg/kg DM
Supplements	0.18	0.10	kg/kg DM
Hay	0.01	0.01	kg/kg DM

The enteric methane and methane from manure management emissions for the different cattle types across the three phases of the Argentinian beef production process are provided in Table 53 below. These values (reported on a per animal unit basis) were determined based on the proportion of each cattle type in a reference animal unit and number of days spent in each phase.

Table 53: Methane emissions in Argentinian beef production in kg CH_4 per animal unit

	Enteric methane	Manure management
Cow-calf phase		
Cows	148.35	1.57
Bulls	0.46	0.08
Calves	14.01	0.15
Backgrounding phase		
Steers	23.25	0.29
Heifers	21.39	0.24
Finishing phase		
Steers	8.29	0.14
Heifers	5.50	0.08

The direct and indirect nitrous oxide emissions from manure management for the different cattle types across the three phases of the Argentinian beef production process are provided in Table 54 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 emissions per animal unit.

Table 54: Manure related N2O emissions each cattle type for Argentinian beef production in kg emission/head/day

	Direct N_2O emissions (kg/head/day)	**Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x (kg/head/day)**	**Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^- (kg/head/day)**
Cows	7.24E-04	3.80E-04	4.78E-04
Bulls	9.82E-04	1.72E-04	6.48E-04
Calves	1.95E-04	3.41E-05	1.28E-04
Steers-backgrounding	4.41E-03	6.80E-04	4.86E-04
Heifers-backgrounding	3.52E-03	5.43E-04	3.88E-04
Steers-finishing	5.87E-03	9.06E-04	6.47E-04
Heifers-finishing	4.35E-03	6.70E-04	4.79E-04

3.1.3 France

The feed compositions in the French cow-calf and backgrounding phases are provided in Table 55. The diets in the cow-calf phase are distinguished between cows, bulls, calves, and replacement heifers (after weaning). The cow-calf phase diets for each of these cattle types was determined as an average of the diets specified for each calving season (the number of calves born in each calving season was not specified and hence a production weighted average could not be determined).

Table 55: Feed composition (kg inclusion/kg of diet) for the cow-calf and backgrounding phases of French beef production

	Backgrounding	**Cow-calf phase**			
		Cows	**Bulls**	**Calves**	**Replacement heifers**
Hay	0.44	0.26	0.52	0.03	0.39
Wheat	0.07	0.09	0.01	0.07	0.04
Soy meal	0.02	0.03	0.00	0.02	0.01
Corn silage	0.00	0.01	0.00	0.00	0.00
Grass silage	0.01	0.04	0.00	0.00	0.02
Pasture grass	0.46	0.58	0.46	0.87	0.53

The finishing diet for French beef cattle in Northern Italy is provided in Table 56.

Table 56: Feed composition (kg inclusion/kg of diet) for the finishing of French beef cattle in Northern Italy

Feed ingredient	**kg inclusion/kg of diet**
Corn	0.18
Protein supplement	0.1
Corn meal	0.08
Dried sugar beet pulp	0.07
Wheat straw	0.04
Hay	0.03
Sugar beet pulp	0.03
Soybean meal	0.02
Corn DDGS	0.02

Corn silage	0.41
Barley grain	0.02

All other material and energy inputs to characterize the beef production system in France are provided in the Table 57 below relative to one animal unit.

Table 57: Energy and material inputs per animal unit for French beef production

Input	Amount	Unit
Cow-calf and backgrounding		
Electricity	106.08	kWh
Fuel- model as gasoline	67.97	litres
Bedding straw-model as wheat straw	156.54	kg
Finishing		
Bedding straw	34.67	kg
Bedding saw dust	3.09	kg
Fuel- model as gasoline	30.96	litres
Electricity	16.09	kWh
Transportation (calves from France to Northern Italy)	350	kms

Since the French beef production phases in both southern France and Northern Italy involve significant imports of feed, the following transportation distances were modelled (Table 58) for the shares of specific feed ingredients listed as being imported in Table 12. These transportation distances are in addition to the 50 kilometres of transport to farm (by truck) assumed for all feed inputs to French beef production.

Table 58: Transportation distances and types modelled for feed imports to France and Italy

Feed import route	Train/barge-before port (kms)	Maritime shipping (nautical kms)	Train-after port (kms)
Feed imports from outside mainland Europe			
Brazil to France	300 (train)	8351	150
Argentina to France	300 (barge)	9622	150
Canada to Italy	2000 (train)	6228	150
Brazil to Italy	300 (train)	8603	150
Argentina to Italy	300 (barge)	9875	150
Feed imports from within mainland Europe			

Ukraine to Italy	2200 (train)
Hungary to Italy	970 (train)
France to Italy	400 (train)

The enteric methane and methane from manure management emissions for the different cattle types across the three phases of the French beef production process are provided in Table 59 below. These values (reported on a per animal unit basis) were determined based on the proportion of each cattle type in a reference animal unit and number of days spent in each phase.

Table 59: Methane emissions in French beef production in kg CH_4 per animal unit

	Enteric methane	**Manure management**
Cow-calf phase		
Cows	168.78	1.62
Bulls	9.05	0.09
Calves	14.80	0.20
Heifers for replacement	16.27	0.17
Backgrounding phase		
Steers	3.88	0.04
Heifers	1.95	0.02
Finishing phase		
Steers	11.01	0.24
Heifers	22.22	0.48

The direct and indirect nitrous oxide emissions from manure management for the different cattle types across the three phases of the French beef production process are provided in Table 60 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 emissions per animal unit.

Table 60: Manure related N2O emissions each cattle type for French beef production in kg emission/head/day

	Direct N_2O emissions (kg/head/day)	**Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x (kg/head/day)**	**Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^- (kg/head/day)**
Cows	1.97E-03	4.13E-04	1.07E-03
Bulls	2.21E-03	4.63E-04	1.20E-03
Calves	3.55E-04	7.46E-05	1.94E-04
Heifers for replacement	1.25E-03	2.62E-04	6.81E-04
Steers-backgrounding	8.37E-04	1.76E-04	4.57E-04
Heifers-backgrounding	8.20E-04	1.72E-04	4.47E-04
Steers-finishing	5.75E-03	5.75E-04	2.15E-05
Heifers-finishing	4.50E-03	4.50E-04	1.69E-05

3.1.4 New Zealand

As specified previously in Section 2.5.7.1.4, New Zealand beef cattle are exclusively finished on pasture, and minor supplemental feed inputs such as kale and Swedish turnips are not modelled. The other energy and material inputs used in New Zealand beef production are specified in Table 61. These inventory data points were provided in the source material cumulatively for the entire lifespan of beef cattle, and hence were divided between the cow-calf and finishing stages based on the weaning age – as specified in section 3.

Table 61: Energy and material inputs per animal unit for New Zealand beef production

Input	**Amount**	**Unit**
Electricity	7.09	kWh
Diesel	2.69	Litres
Petrol	0.96	Litres
Aviation fuel	0.54	Litres
Pasture management		
Pasture renewal rate	1.60	%
N fertilizer input to pastures	12.10	Kg N/hectare/year

P fertilizer input to pastures	11.40	Kg P/hectare/year
K fertilizer input to pastures	4.90	Kg K/hectare/year
Lime input to pastures	42	Kilogram/hectare/year

The feed intake estimates calculated for New Zealand beef production – based on equations specified in section 2.5.10 are specified in Table 62 below. The detailed calculations used to obtain the values in Table 62 are provided in the supplementary information section 6.4.

Table 62: Feed intake and metabolizable energy intake estimates for New Zealand beef production

Cattle type	**DMI (kg/day)**	**Metabolizable Energy - total (MJ/day)**
Cows	5.56	57.80
Bulls	7.53	78.22
Calves-pre wean	3.28	34.09
Calves-post weaning (female)	5.57	57.88
Calves-post weaning (male)	6.92	71.89

The enteric methane and methane from manure management emissions for the different cattle types across the two phases of the New Zealand beef production process are provided in Table 63 below. These values (reported on a per animal unit basis) were determined based on the proportion of each cattle type in a reference animal unit and number of days spent in each phase.

Table 63: Methane emissions in New Zealand beef production in kg CH_4 per animal unit

Cattle type	**Enteric methane**	**Manure management**
	Cow-calf phase	
Cows	66.09	0.91
Bulls	4.47	0.06
Calves	10.26	0.14
	Finishing phase	
Heifers	35.01	0.48
Steers	65.49	0.90

The direct and indirect nitrous oxide emissions from manure management for the different cattle types across the two phases of the New Zealand beef production process are provided in

Table 64 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 emissions per animal unit.

Table 64: Manure related N_2O emissions each cattle type for New Zealand beef production in kg emission/head/day

	Direct N_2O emissions (kg/head/day)	**Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x (kg/head/day)**	**Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^- (kg/head/day)**
Cows	3.12E-03	3.12E-04	1.87E-04
Bulls	5.01E-03	5.01E-04	3.01E-04
Calves	7.84E-04	7.84E-05	4.70E-05
Heifers-finishing	2.67E-05	2.67E-06	1.60E-06
Steers-finishing	2.65E-03	2.65E-04	1.59E-04

3.2 Inventory data for feed crop inputs

This section provides inventory tables for all crop production and feed processing relevant for each country considered (Tables 65 to 100). These inventory tables are based on data extracted from the data sources specified in section 2.5.7.2 for each crop in each region.

3.2.1 Australia

The inventory data tables for all major feed crop inputs (and feed processing inventories where relevant) to Australian beef production are provided below.

3.2.1.1 Barley

Table 65: Inventory data for 1 kilogram of barley production in Australia

Inputs	**Amount**	**Unit**
Seed	0.0718	kg
Lime	0.1667	kg
Potassium chloride	0.0011	kg
Potassium chloride	0.0001	kg
Potassium sulfate	0.0002	kg

Ammonia, anhydrous, liquid	0.0005	kg
Ammonium nitrate	0.0001	kg
Ammonium sulfate	0.0045	kg
Calcium ammonium nitrate	0.0001	kg
Urea	0.0188	kg
Urea ammonium nitrate mix	0.0043	kg
Diammonium phosphate	0.0124	kg
Monoammonium phosphate	0.0001	kg
Single superphosphate	0.0086	kg
Triple superphosphate	0.0002	kg
Field activities energy	1.0600	MJ
Total pesticides	0.0009	kg
Post-harvest energy	0.0451	MJ
Transportation	0.0162	t*km
Outputs	**Amount**	**Unit**
Barley grain	1.0000	kg
Straw	0.2728	kg
Carbon dioxide	0.0870	kg CO_2
Direct N_2O emissions	2.95E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	4.91E-06	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	3.54E-05	kg N_2O
SOC change	0.0459	kg CO_2

3.2.1.2 *Sorghum*

Table 66: Inventory data for 1 kilogram of sorghum production in Australia

Inputs	**Amount**	**Unit**
Lime	0.1000	kg
Potassium chloride	0.0008	kg
Potassium sulfate	0.0002	kg
Ammonia, anhydrous, liquid	0.0004	kg
Ammonium sulfate	0.0034	kg
Calcium ammonium nitrate	0.0001	kg
Urea	0.0142	kg
Urea ammonium nitrate mix	0.0032	kg
NPK (15-15-15) fertiliser	0.0003	kg
Diammonium phosphate	0.0093	kg
Single superphosphate	0.0065	kg
Triple superphosphate	0.0001	kg
Field activities energy	0.6400	MJ
Irrigation energy	0.0453	MJ

Total pesticides	0.0005	kg
Post-harvest energy	0.1082	MJ
Seed	0.0049	kg
Transportation	0.0072	t*km
Outputs	**Amount**	**Unit**
Sorghum grain	1.0000	kg
Straw	1.1739	kg
Carbon dioxide	0.0850	kg CO_2
Direct N_2O emissions	3.21E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	1.48E-05	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	2.14E-05	kg N_2O
SOC change	0.0267	kg CO_2

3.2.1.3 Wheat

Table 67: Inventory data for 1 kilogram of wheat production in Australia

Inputs	**Amount**	**Unit**
Lime	0.1880	kg
Potassium chloride	0.0018	kg
Potassium sulfate	0.0003	kg
Ammonia, anhydrous, liquid	0.0008	kg
Ammonium sulfate	0.0066	kg
Calcium ammonium nitrate	0.0001	kg
Diammonium phosphate	0.0143	kg
Urea	0.0277	kg
Urea ammonium nitrate mix	0.0063	kg
NPK (15-15-15) fertiliser	0.0003	kg
Single superphosphate	0.0100	kg
Triple superphosphate	0.0002	kg
Field activities energy	1.1919	MJ
Irrigation energy	0.0154	MJ
Total pesticides	0.0007	kg
Glyphosate	0.0004	kg
Phenoxy-compound	0.0002	kg
Post-harvest energy	0.1082	MJ
Transportation	0.0165	kg*km
Seed	0.0718	kg
Outputs	**Amount**	**Unit**
Wheat grain	1.0000	kg
Straw	0.1100	kg

Carbon dioxide	0.1025	kg CO_2
Direct N_2O emissions	2.91E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	6.95E-06	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	3.84E-05	kg N_2O
SOC change	0.0504	kg CO_2

3.2.1.4 Canola meal and oil

Table 68: Inventory data for 1 kilogram of canola production in Australia

Inputs	**Amount**	**Unit**
Lime	0.1900	kg
Field activities energy	1.7910	MJ
Potassium chloride	0.0043	kg
Potassium sulfate	0.0008	kg
Ammonia, anhydrous, liquid	0.0013	kg
Ammonium sulfate	0.0104	kg
Calcium ammonium nitrate	0.0002	kg
Diammonium phosphate	0.0170	kg
Urea	0.0434	kg
Urea ammonium nitrate mix	0.0099	kg
NPK (15-15-15) fertiliser	0.0015	kg
Single superphosphate	0.0118	kg
Triple superphosphate	0.0003	kg
Post-harvest energy	0.0500	MJ
Total pesticides	0.0028	kg
Cyclic N-compound	0.0003	kg
Glyphosate	0.0051	kg
Phenoxy-compound	0.0025	kg
Seed	0.0021	kg
Transportation	0.0203	kg*km
Outputs	**Amount**	**Unit**
Canola	1.0000	kg
Carbon dioxide	0.1154	kg CO_2
Direct N_2O emissions	3.12E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	1.05E-05	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	5.21E-05	kg N_2O
SOC change	0.0777	kg CO_2

Table 69. Inventory data for the processing of 1 kg of canola into canola meal and oil

Inputs	**Amount**	**Unit**
Canola	1	kg
Electricity	0.149	kWh
Heat from natural gas	0.808	MJ
Outputs	**Amount**	**Unit**
Canola meal	0.574	kg
Canola oil	0.413	kg

3.2.1.5 Cottonseed

Table 70: Inventory data for 1 kilogram of cottonseed production in Australia

Inputs	**Amount**	**Unit**
NPK (15-15-15) fertiliser	0.0019	kg
NPK (26-15-15) fertiliser	0.0018	kg
Potassium chloride	0.0081	kg
Potassium nitrate	0.0005	kg
Potassium sulfate	0.0023	kg
Ammonia, anhydrous, liquid	0.0026	kg
Ammonium sulfate	0.0079	kg
Monoammonium phosphate	0.0100	kg
Potassium nitrate	0.0002	kg
Urea	0.0716	kg
Urea ammonium nitrate mix	0.0127	kg
Monoammonium phosphate	0.0146	kg
Single superphosphate	0.0026	kg
Triple superphosphate	0.0003	kg
Field activities energy	1.7767	MJ
Irrigation energy	0.0497	MJ
Total pesticides	0.0118	kg
Seed	0.0040	kg
Transportation	0.0325	t*km
Outputs	**Amount**	**Unit**
White fluffy cottonseed	1.0000	kg
Carbon dioxide	0.0525	kg CO_2
Direct N_2O emissions	5.57E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	1.52E-05	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	2.59E-04	kg N_2O
SOC change	0.0465	kg CO_2

Table 71. Inventory data for the processing of 1 kilogram of cottonseed meal

Inputs	**Amount**	**Unit**
Cottonseed	0.648	kg
Activated bentonite	0.0001	kg
Electricity	0.020	kWh
Heat from natural gas	0.040	MJ
Hexane	6.31E-5	kg
Phosphoric acid	0.0001	kg
Tap water	0.0002	kg
Outputs	**Amount**	**Unit**
Cottonseed meal	1	kg

3.2.1.6 Lucerne hay

Table 72. Inventory data for 1 kilogram of lucerne hay

Inputs	**Amount**	**Unit**
Ammonium sulfate	0.221	kg
Field activities energy	1.098	MJ
Total herbicides	0.0005	kg
Seed	0.001	kg
Post-harvest energy	0.108	MJ
Transportation	0.005	t*km
Outputs	**Amount**	**Unit**
Lucerne hay	1	kg
Direct N_2O emissions	3.83E-04	kg N_2O
SOC change	-007.91	kg CO_2

3.2.1.7 Sugarcane and molasses

Table 73: Inventory data for 1 kilogram of sugarcane production in Australia

Inputs	**Amount**	**Unit**
Lime	0.0040	kg
Potassium chloride	0.0013	kg
Potassium sulfate	0.0002	kg
Ammonia, anhydrous, liquid	0.0001	kg
Ammonium sulfate	0.0005	kg
Calcium ammonium nitrate	0.0000	kg
Urea	0.0021	kg
Urea ammonium nitrate mix	0.0005	kg
NPK (15-15-15) fertiliser	0.0001	kg
Diammonium phosphate	0.0006	kg

Single superphosphate	0.0004	kg
Triple superphosphate	0.0000	kg
Field activities energy	0.0402	MJ
Irrigation energy	0.0404	MJ
Total pesticides	0.0001	kg
Seed	0.0109	kg
Transportation	0.0010	t*km
Outputs	**Amount**	**Unit**
Sugarcane	1	kg
Carbon dioxide	0.0025	kg CO_2
Direct N_2O emissions	2.17E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	4.98E-07	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	3.73E-05	kg N_2O
SOC change	0.0167	kg CO_2

Table 74. Inventory data for the processing of 1 kg of sugarcane into sugar and molasses

Inputs	**Amount**	**Unit**
Sugarcane	1	kg
Flocculant	1.20E-07	kg
Lime	0.0005	kg
Phosphoric acid	0.00004	kg
Outputs	**Amount**	**Unit**
Sugar	0.132	kg
Molasses	0.310	kg

3.2.2 Argentina

The inventory data tables for all major feed crop inputs (and feed processing inventories where relevant) are provided below.

3.2.2.1 Corn

Table 75: Inventory data for 1 kilogram of corn production in Argentina

Inputs	**Amount**	**Unit**
Lime	0.0600	kg
Total fertilizers	0.0262	kg
Ammonium sulfate	0.0005	kg
Calcium ammonium nitrate	0.0006	kg
Diammonium phosphate	0.0050	kg
NPK (15-15-15) fertiliser	4.95E-05	kg
Potassium chloride	3.15E-05	kg

Potassium sulfate	7.15E-06	kg
Single superphosphate	0.0016	kg
Triple superphosphate	0.0006	kg
Urea	0.0076	kg
Urea ammonium nitrate mix	0.0076	kg
Urea ammonium nitrate mix	0.0028	kg
Field activities energy	0.3468	MJ
Irrigation energy	0.0124	MJ
Seed	0.0057	kg
Total pesticides	0.0046	kg
Post-harvest energy	0.1082	MJ
Transportation	0.0283	t*km
Outputs	**Amount**	**Unit**
Corn grain	1.0000	kg
Corn stover	0.1500	kg
Carbon dioxide	0.0056	kg CO_2
Direct N_2O emissions	1.67E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	7.00E-06	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	4.93E-05	kg N_2O
SOC change	0.0885	kg CO_2

3.2.2.2 *Sorghum (forage)*

Table 76: Inventory data for 1 kilogram of sorghum production in Argentina

Inputs	**Amount**	**Unit**
Lime	0.1000	kg
Total fertilizers	0.0390	kg
Ammonium sulfate	0.0009	kg
Calcium ammonium nitrate	0.0010	kg
Diammonium phosphate	0.0126	kg
NPK (15-15-15) fertiliser	0.0000	kg
Potassium chloride	2.90E-05	kg
Potassium sulfate	6.57E-06	kg
Single superphosphate	0.0040	kg
Triple superphosphate	0.0015	kg
Urea	0.0139	kg
Urea ammonium nitrate mix	0.0051	kg
Field activities energy	0.5575	MJ
Irrigation energy	0.0117	MJ
Total pesticides	0.0008	kg
Post-harvest energy	0.1082	MJ

Seed	0.0049	kg
Transportation	0.0072	t*km
Outputs	**Amount**	**Unit**
Sorghum forage	1.0000	kg
Carbon dioxide	0.0016	kg CO_2
Direct N_2O emissions	1.35E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	1.96E-06	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	4.03E-05	kg N_2O
SOC change	0.1449	kg CO_2

3.2.2.3 Oats

Table 77: Inventory data for 1 kilogram of oat production in Argentina

Inputs	**Amount**	**Unit**
Total fertilizers	0.0260	kg
Ammonium nitrate	0.0007	kg
Ammonium sulfate	0.0002	kg
Calcium ammonium nitrate	0.0008	kg
Monoammonium phosphate	0.0028	kg
Potassium nitrate	2.61E-05	kg
Urea	0.0190	kg
Urea ammonium nitrate mix	0.0026	kg
Field activities energy	0.1242	MJ
Seed	0.1356	kg
Total pesticides	0.0004	kg
Post-harvest energy	0.1082	MJ
Outputs	**Amount**	**Unit**
Oat grain	1.0000	kg
Carbon dioxide	0.0139	kg CO_2
Direct N_2O emissions	2.58E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	1.69E-05	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	7.56E-05	kg N_2O
SOC change	0.3031	kg CO_2

3.2.2.4 Sunflower pellets

Table 78: Inventory data for 1 kilogram of sunflower seed production in Argentina

Inputs	**Amount**	**Unit**
Total fertilizers	0.0136	kg

Ammonium nitrate	0.0003	kg
Ammonium sulfate	0.0001	kg
Calcium ammonium nitrate	0.0004	kg
Monoammonium phosphate	0.0013	kg
Potassium nitrate	1.17E-05	kg
Urea	0.0085	kg
Urea ammonium nitrate mix	0.0012	kg
Monoammonium phosphate	7.01E-07	kg
Single superphosphate	2.48E-07	kg
Triple superphosphate	1.16E-07	kg
Ammonium sulfate	0.0008	kg
Field activities energy	0.5957	MJ
Total pesticides	0.0030	kg
Post-harvest energy	0.0542	MJ
Seed	0.0176	kg
Transportation	0.1274	MJ
Outputs	**Amount**	**Unit**
Sunflower seeds	1.0000	kg
Carbon dioxide	0.0062	kg CO_2
Direct N_2O emissions	1.89E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	7.44E-06	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	5.58E-05	kg N_2O
SOC change	0.5576	kg CO_2

Table 79. Inventory data for the processing of 1 kg of sunflower seeds into pellets and oil

Inputs	**Amount**	**Unit**
Sunflower seeds	1	kg
Electricity	0.027	kWh
Heat from natural gas	0.500	MJ
Outputs	**Amount**	**Unit**
Sunflower pellets (meal)	0.350	kg
Sunflower oil	0.285	kg
Hulls	0.248	kg

3.2.2.5 Soybeans

Table 80: Inventory data for 1 tonne of soybeans production in Argentina

Data point	**Value**	**Unit**
Cultivated land	0.38	ha
Seed	65.41	kg
N fertilizers	7	kg
P fertilizers	35.77	kg
K fertilizers	0.38	kg
NPK compound (15-15-15)	0.49	kg
Limestone	400	kg
Fungicides	0.08	kg
Herbicides	5.72	kg
Insecticides	0.06	kg
Irrigation energy use	12.79	MJ
Field activities energy use	1,958	MJ
Transportation	25.75	t-km
Post-harvest energy use	324.47	MJ
Outputs	**Amount**	**Unit**
Soybean	1000	kg
Carbon dioxide	67.96	kg CO_2
Direct N_2O emissions	0.16	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	0.002	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	0.06	kg N_2O
SOC change	223.89	kg CO_2

Table 81: Inventory data for processing 1 kilogram of soybean into soybean meal and oil in Argentina

Inputs	**Amount**	**Unit**
Base oil	0.000020	kg
Electricity	0.20	MJ
Heat, natural gas	1.20	MJ
Hexane	0.0008	kg
Soybeans, dried	1	kg
Water	0.00025	m3
Outputs	**Amount**	**Unit**
Soybean oil	0.19	kg

Soybean hulls	0.074	kg
Soybean meal	0.71	kg

3.2.3 France

The inventory data tables for all major feed crop inputs (and feed processing inventories where relevant) to French beef production are provided below.

3.2.3.1 French wheat

Table 82: Inventory data for 1 kilogram of wheat production in France

Input	**Unit**	**Amount**
Seed	0.02	kg
Lime	0.06	kg
Calcium Ammonium nitrate	0.050	kg
Ammonium nitrate	0.073	kg
Ammonium sulfate	0.005	kg
Diammonium phosphate	0.008	kg
Urea ammonium nitrate	0.014	kg
Urea	0.048	kg
Single superphosphate	0.002	kg
Triple superphosphate	0.014	kg
Potassium Chloride	0.023	kg
Potassium sulfate	0.028	kg
PK-custom	0.120	kg
NPK custom mix	0.114	kg
Total pesticide inputs	2.10E-04	kg
Irrigation energy	0.002	MJ
Field activities energy	0.56	MJ
Post-harvest energy	0.53	kWh
Transportation	14.06	kg-km
Outputs	**Amount**	**Unit**
Wheat grain	1	kg
Straw	0.08	kg
Carbon dioxide	0.060	kg CO_2
Direct N_2O emissions	8.33E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	7.16E-05	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	1.99E-04	kg N_2O
SOC change	0.039	kg CO_2

3.2.3.2 French corn

Table 83: Inventory data for 1 kilogram of corn production in France

Inputs	**Amount**	**Unit**
Calcium Ammonium nitrate	0.010	kg
Ammonium nitrate	0.015	kg
Ammonium sulfate	0.001	kg
Diammonium phosphate	0.005	kg
Urea ammonium nitrate	0.007	kg
Urea	0.010	kg
Single superphosphate	0.002	kg
Triple superphosphate	0.004	kg
Potassium chloride	0.001	kg
Potassium sulfate	0.002	kg
PK-custom	0.005	kg
NPK custom mix	0.010	kg
Field activities energy	0.473	MJ
Irrigation energy	0.131	MJ
Seed	0.004	kg
Total pesticides	0.000	kg
Post-harvest energy	0.164	MJ
Transportation	0.006	t*km
Outputs	**Amount**	**Unit**
Corn grain	1	kg
Corn stover	0.150	kg
Carbon dioxide	0.028	kg CO_2
Direct N_2O emissions	3.07E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	1.71E-05	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	7.66E-05	kg N_2O
SOC change	0.032	kg CO_2

3.2.3.3 French soybean

Table 84: Inventory data for 1 kilogram of soybean production in France

Inputs	Amount	**Unit**
Calcium Ammonium nitrate	0.0005	kg
Ammonium nitrate	0.0008	kg
Ammonium sulfate	0.0001	kg

Diammonium phosphate	0.0001	kg
Urea ammonium nitrate	0.0003	kg
Urea	0.0005	kg
Single superphosphate	0.0069	kg
Triple superphosphate	0.0033	kg
Potassium Chloride	0.0019	kg
Potassium sulfate	0.0047	kg
PK-custom	0.0100	kg
NPK custom mix	0.0180	kg
Field activities energy	1.4054	MJ
Irrigation energy	0.6672	MJ
Total pesticides	0.0009	kg
Post-harvest energy	0.3245	MJ
Seed	0.0267	kg
Transportation	0.0139	t*km
Outputs	Amount	**Unit**
Soybean	1.0000	kg
Carbon dioxide	0.0721	kg CO_2
Direct N_2O emissions	1.50E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	1.12E-06	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	3.99E-05	kg N_2O
SOC change	0.1117	kg CO_2

Table 85: Inventory data for processing 1 kilogram of soybean to produce soybean meal and oil in France

Inputs	**Amount**	**Unit**
Base oil	0.00002	kg
Electricity	0.10	MJ
Heat, natural gas	0.83	MJ
Hexane	0.00058	kg
Soybeans, dried	1	kg
Water	0.00025	m3
Outputs	**Amount**	**Unit**
Soybean oil	0.19	kg
Soybean meal	0.78	kg

3.2.3.4 French harvested forage

Table 86: Inventory data for 1 kilogram of harvested forage production in France

Input	**Amount**	**Unit**
Yield	1.0000	kg
Seed	0.0002	kg
Lime	0.0128	kg
Ammonium nitrate	0.0008	kg
Ammonium sulfate	0.0001	kg
Calcium ammonium nitrate	0.0006	kg
Diammonium phosphate	0.0002	kg
Urea ammonium nitrate	0.0012	kg
NPK compound (NPK 15-15-15)	0.0003	kg
PK compound (NPK 0-22-22)	0.0003	kg
Potassium chloride (NPK 0-0-60)	0.0006	kg
Potassium sulfate (NPK 0-0-50)	0.0001	kg
Single superphosphate, (NPK 0-21-0)	0.0001	kg
Triple superphosphate (NPK 0-48-0)	0.0001	kg
Urea	0.0005	kg
Herbicides	3.19E-06	kg
Field activities energy use	0.0930	MJ
Transportation	0.0009	t-km
Packaging	3.19E-08	kg
Irrigation water	0.0003	m3
Outputs	**Amount**	**Unit**
Harvested forage	1.0000	kg
Carbon dioxide	0.0060	kg CO_2
Direct N_2O emissions	1.30E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	8.79E-07	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	3.46E-05	kg N_2O
SOC change	-0.0063	kg CO_2

3.2.3.5 Italian Barley

Table 87: Inventory data for 1 kilogram of barley production in Italy

Inputs	**Amount**	**Unit**
Seed	0.0408	kg
Lime	0.0947	Kg
N fertilizers	0.0182	kg
P fertilizers	0.0040	kg
K fertilizers	0.0050	kg

Inputs	**Amount**	**Unit**
Fungicide	0.0002	kg
Herbicide	0.0002	kg
Insecticide	0.0001	kg
Field activities energy	1.2162	MJ
Post-harvest energy	0.0388	MJ
Transportation	0.0093	t-km
Outputs	**Amount**	**Unit**
Barley grain	1.0000	kg
Straw	0.4077	kg
Carbon dioxide	0.0550	kg CO_2
Direct N_2O emissions	5.03E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	2.77E-05	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	1.23E-04	kg N_2O
SOC change	0.0267	kg CO_2

3.2.3.6 Italian sugar beet

Table 88: Inventory data for 1 kilogram of sugar beet production in Italy

Inputs	**Amount**	**Unit**
Seed	3.57E-05	kg
Lime	7.14E-03	kg
N fertilizers	1.61E-03	kg
P fertilizers	1.16E-03	kg
K fertilizers	8.93E-04	kg
Fungicide	8.60E-05	kg
Herbicide	3.64E-05	kg
Insecticide	5.18E-06	kg
Irrigation energy	3.49E-02	MJ
Field activities energy	1.54E-01	MJ
Transportation	7.24E-04	t-km
Outputs	**Amount**	**Unit**
Sugar beet	1	kg
Carbon dioxide	0.004	kg CO_2

Inputs	Amount	Unit
Direct N_2O emissions	5.50E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	2.44E-06	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	1.13E-04	kg N_2O
SOC change	0.002	kg CO_2

Table 89. Inventory data for the processing of 1 kg of sugar beet into sugar, pulp, and molasses

Inputs	Amount	Unit
Sugar beet	1	kg
Electricity	0.009	kWh
Heat from natural gas	0.194	kWh
Lime	0.015	kg
Outputs	**Amount**	**Unit**
Sugar	0.128	kg
Sugar beet pulp	0.385	kg
Molasses	0.040	kg

3.2.3.7 Italian soybean

Table 90: Inventory data for 1 kilogram of soybean production in Italy

Inputs	Amount	Unit
Seed	0.0188	kg
Lime	0.1152	kg
Ammonium nitrate	0.0026	kg
Ammonium sulfate	0.0037	kg
Calcium ammonium nitrate	0.0072	kg
Diammonium phosphate	0.0052	kg
Urea ammonium nitrate	0.0007	kg
NPK compound (NPK 15-15-15)	0.0124	kg
PK compound (NPK 0-22-22)	0.0007	kg
Potassium chloride (NPK 0-0-60)	0.0023	kg
Potassium sulfate (NPK 0-0-50)	0.0018	kg
Single superphosphate, (NPK 0-21-0)	0.0010	kg
Triple superphosphate (NPK 0-48-0)	0.0012	kg
Urea	0.0225	kg
Fungicides	0.0004	kg
Herbicides	0.0003	kg
Insecticides	4.03E-05	kg

Field activities energy use	1.3480	MJ
Irrigation energy	0.3558	MJ
Transportation	0.0098	t-km
Post-harvest energy use	0.0364	MJ
Outputs	**Amount**	**Unit**
Soybean	1.0000	kg
Carbon dioxide	0.0633	kg CO_2
Direct N_2O emissions	5.03E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	2.88E-05	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	1.24E-04	kg N_2O
SOC change	0.0325	kg CO_2

Table 91: Inventory data for producing soybean meal in Italy

Inputs	**Amount**	**Unit**
Base oil	0.00002	kg
Electricity	0.10	MJ
Heat, natural gas	0.83	MJ
Hexane	0.00058	kg
Soybeans, dried	1	kg
Water	0.00025	m3
Outputs	**Amount**	**Unit**
Soybean oil	0.19	kg
Soybean meal	0.78	kg

3.2.3.8 Italian wheat

Table 92: Inventory data for 1 kilogram of wheat production in Italy

Input	**Unit**	**Amount**
Seed	0.0390	kg
Lime	0.1020	Kg
N fertilizers	0.0265	Kg
P fertilizers	0.0074	kg
K fertilizers	0.0010	kg
Fungicide	0.0001	kg
Herbicide	0.0001	kg
Insecticide	0.0001	kg
Irrigation energy	0.0420	MJ
Field activities (diesel)	0.0413	kg
Post-harvest energy	0.0276	MJ

Transportation	0.0149	t-km
Outputs	**Amount**	**Unit**
Wheat grain	1.0000	kg
Straw	0.1230	kg
Carbon dioxide	0.0643	kg CO_2
Direct N_2O emissions	4.82E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	4.03E-05	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	1.28E-04	kg N_2O
SOC change	0.0288	kg CO_2

3.2.3.9 *Italian corn*

Table 93: Inventory data for 1 kilogram of corn production in Italy

Input	**Unit**	**Amount**
Seed	0.004	kg
Lime	0.040	kg
N fertilizers	0.016	kg
P fertilizers	0.002	kg
K fertilizers	0.003	kg
Fungicide	2.27E-04	kg
Herbicide	8.63E-05	kg
Insecticide	4.46E-05	kg
Irrigation energy	0.100	MJ
Field activities (diesel)	0.030	litres
Post-harvest energy	0.011	MJ
Transportation	0.006	t-km
Outputs	**Amount**	**Unit**
Corn grain	1.000	kg
Corn stover	0.150	kg
Carbon dioxide	0.030	kg CO_2
Direct N_2O emissions	3.88E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	2.51E-05	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	9.75E-05	kg N_2O
SOC change	0.011	kg CO_2

Table 94. Inventory data for the production of 1 kilogram of dried corn meal

Inputs	**Amount**	**Unit**
Corn	16	kg
Electricity	6.624	kWh
Heat from natural gas	3.376	MJ
Sulfur dioxide	2.251	kg
Outputs	**Amount**	**Unit**
Dried corn meal	1	kg

Table 95. Inventory for the production of corn DDGs in Italy

Inputs	**Amount**	**Unit**
Corn	1	kg
Electricity (ethanol production)	0.065	kWh
Heat from natural gas (ethanol production)	2.921	MJ
Electricity (DDGs)	0.038	kWh/kg distillers’ grains
Heat from natural gas (DDGs)	1.909	MJ/kg distillers’ grains
Outputs	**Amount**	**Unit**
Dried distillers’ grains	0.452	kg

3.2.3.10 Canadian wheat

Table 96: Inventory data for 1 kilogram of wheat production in Canada

Input	**Amount**	**Unit**
Seed	0.03	kg
Lime	0	kg
N fertilizers	0.04	kg
P fertilizers	0.01	kg
K fertilizers	0.006	kg
S fertilizers	0.007	kg
Total pesticide AI	0.001	kg
Irrigation energy	0.004	MJ
Field activities energy	0.76	MJ
Post-harvest energy	0.003	MJ
Transportation	8.90	kg-km
Outputs	**Amount**	**Unit**
Wheat grain	1.0000	kg
Straw	0.1230	kg
Carbon dioxide	0.020	kg CO_2
Direct N_2O emissions	4.53E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	3.09E-05	kg N_2O

Input	Amount	Unit
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	1.44E-04	kg N_2O
SOC change	-0.078	kg CO_2

3.2.3.11 Brazilian soybean

Table 97: Inventory data for 1 kilogram of soybean production in Brazil

Input	**Amount**	**Unit**
Seed	0.0196	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	**Amount**	**Unit**
Soybean	1	kg
Carbon dioxide - SOC flux	0.39	kg CO_2
Carbon dioxide from lime and urea application	0.04	kg CO_2
Direct N_2O emissions	1.82E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	6.69E-06	kg N_2O

Input	**Amount**	**Unit**
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	4.63E-05	kg N_2O

Table 98: Inventory data for producing soybean meal in Brazil

Inputs	**Amount**	**Unit**
Base oil	0.000020	kg
Electricity	0.20	MJ
Heat, natural gas	1.20	MJ
Hexane	0.0008	kg
Soybeans, dried	1	kg
Water	0.00025	m^3
Outputs	**Amount**	**Unit**
Soybean oil	0.19	kg
Soybean hulls	0.074	kg
Soybean meal	0.71	kg

3.2.3.12 Ukrainian corn

Table 99. Inventory data for 1 kilogram of corn production in Ukraine

Input	**Unit**	**Amount**
Seed	0.005	kg
Lime	0.058	kg
Anhydrous Ammonia	0.014	kg
Amonium nitrate	0.012	kg
Ammonium sulfate	0.007	kg
Diammonium phosphate	0.036	kg
Urea ammonium nitrate	0.026	kg
Urea	0.030	kg
Single superphosphate	0.001	kg
Triple superphosphate	0.001	kg
Monoammonium phosphate	0.003	kg
Potassium Chloride	0.070	kg
NPK custom mix	0.089	kg
PK-custom	0.057	kg
Total pesticides	2.02E-04	kg
Irrigation energy	0.164	MJ
Field activities energy	0.753	MJ
Post-harvest energy	0.016	MJ
Transportation	0.005	t-km
Outputs	**Amount**	**Unit**

Corn grain	1.000	kg
Corn stover	0.150	kg
Carbon dioxide	0.047	kg CO_2
Direct N_2O emissions	6.74E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	1.07E-04	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	3.11E-04	kg N_2O
SOC change	0.198938	kg CO_2

3.2.3.13 Hungarian corn

Table 100. Inventory data for 1 kilogram of corn production in Hungary

Inputs	**Amount**	**Unit**
Seed	0.005	kg
Lime	0.058	kg
N fertilizers	0.017	kg
P fertilizers	0.003	kg
K fertilizers	0.004	kg
Fungicide	1.23E-04	kg
Herbicide	1.45E-04	kg
Insecticide	2.18E-05	kg
Field activities energy	0.762	MJ
Irrigation energy	0.002	MJ
Post-harvest energy	0.108	MJ
Transportation	0.006	t*km
Outputs	**Amount**	**Unit**
Corn grain	1.000	kg
Corn stover	0.150	kg
Carbon dioxide	0.028	kg CO_2
Direct N_2O emissions	3.78E-04	kg N_2O
Indirect N_2O emissions from volatization of nitrogen as NH_3 and NO_x	1.64E-05	kg N_2O
Indirect N_2O emissions from leaching and run off of nitrogen as NO_3^-	1.07E-04	kg N_2O
SOC change	0.003	kg CO_2

3.3 Impact assessment

3.3.1 Beef production systems

Overall, the carbon footprint of New Zealand beef (10.83 kg CO_2-eq.) was the lowest among the four competitor countries considered in this phase, while Argentina (20.59 kg CO_2-eq.) was the highest per kilogram of live weight of finished beef cattle. All four countries considered in this phase, however, had carbon footprints higher than Western Canada (8.95 kg CO_2-eq.). The carbon footprints of 1 kilogram of live weight beef in Argentina, Australia, New Zealand, and France were 130%, 37.64%, 21.03%, and 40.70% higher than Western Canada, respectively. The carbon footprint of Australian (12.32 kg CO_2-eq.) and French (12.59 kg CO_2-eq.) beef production was 13.7% and 16.3% higher than that of beef from New Zealand (lowest footprint among the regions modelled in this phase), respectively (Figure 2). The carbon footprint of Argentinian beef production was about 90% higher than New Zealand beef production on a live weight basis. These large differences were primarily driven by the soil organic carbon losses associated with land conversion to grasslands, the relatively long duration of cow-calf and backgrounding phases, and the considerably lower finishing weights in Argentina. This is despite the enteric methane conversion factor (Y_m) for finishing in Argentina being the lowest (and equal to Western Canada) among the countries considered. However, the finishing period in Argentina is much shorter than the cow-calf and backgrounding phases, and these pasture-based phases are characterized by both higher methane conversion factors (Y_m of 7%) and the longer durations spent on feed that is lower in quality compared to the finishing diets.

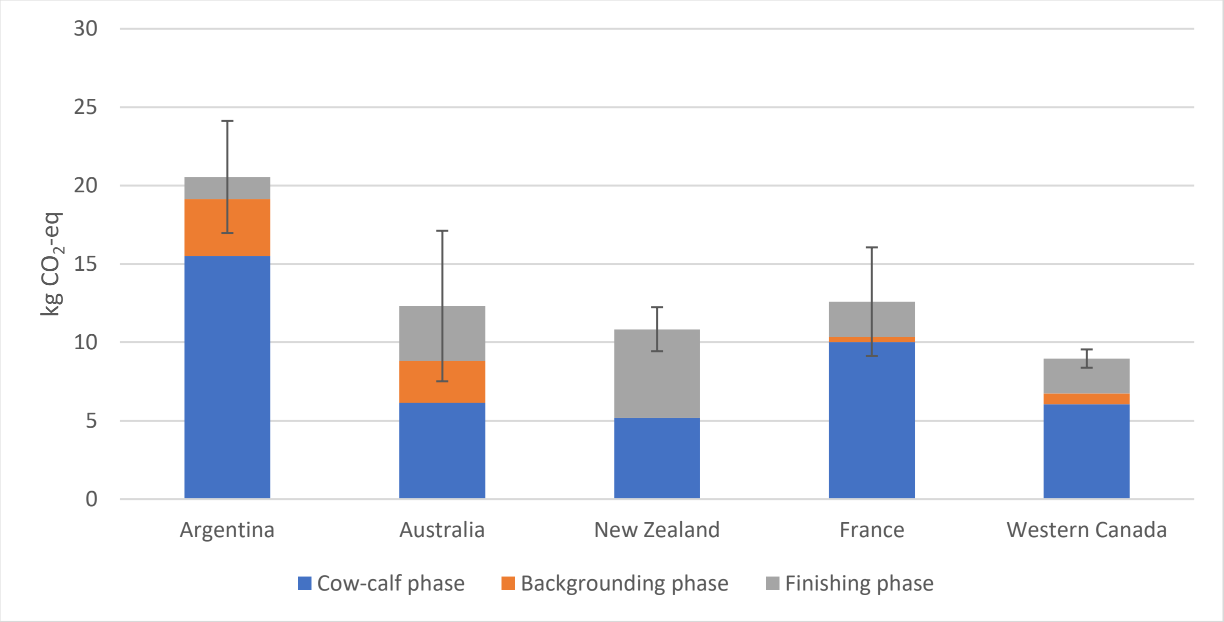


Figure 2: Carbon footprint of 1 kg of live weight beef produced – contributions by phase of production. Error bars represent one standard deviation from the mean.

The contributions of the different stages of the beef production process were varied across the four countries modelled in this phase (Figure 2). The majority of the impacts were attributable to the cow-calf phase in Argentina and France (75.34% and 79.43% respectively), with backgrounding in Argentina (17.75%) and feedlot finishing in France (17.8%) being the next highest contributors in these countries. This distribution of impacts was somewhat comparable to Canada where the cow-calf phase accounted for 67% of the impacts, followed by feedlot finishing (25%). In Argentina, 22.9% of the impacts in the cow-calf phase was attributable to changes in soil organic carbon (SOC) resulting from land use change and land management. In New Zealand, the finishing phase accounted for the largest share of impacts (52.14%), followed by the cow-calf phase (47.86%). The higher share of impacts associated with the finishing phase in New Zealand was due to assuming that the cow-calf phase ends at the time of weaning (at ~5 months of age), and the considerably long finishing period because of this assumption. This assumption was necessary due to the lack of distinction between the cow-calf and finishing periods in New Zealand beef production inventory data collected, since it is all pasture-based, and beef cattle often spend their entire lives on the same farm before slaughter. In Australia, the long backgrounding (336 days) and finishing (263 days of grass finished cattle) periods resulted in these phases accounting for 21.62% and 28.44% of the impacts per kilogram of live weight respectively. The significance of the backgrounding phase in Australia and Argentina was in stark contrast to Western Canada, where the backgrounding phase only accounted for 8% of the overall carbon footprint.

Looking at the sources of impacts across the different phases (Figure 3), enteric methane emissions accounted for the majority of GHG emissions in all four countries (57.17%-81.54%). The share of enteric methane emissions in Argentina (72.69%), Australia (72.48%), and New Zealand (81.54%) were all comparable to the share of enteric methane emissions to the overall carbon footprint of Western Canadian beef (79.90%). The share of enteric methane emissions was the lowest in Frace (57.17%) due to the low enteric methane conversion factor (Y_m) of the finishing diet (4.62-4.68%), and the higher finishing weights. The share of enteric methane emissions was the highest in New Zealand due to the high enteric methane conversion factor (Y_m) for pasture-based diets, and the lack of any other significant source of impacts other than manure-related emissions. While the share of enteric methane emissions in each country was different – for example 81.54% in New Zealand and 72.48% in Australia – the actual enteric methane emissions per kilogram of liveweight in these two countries was similar (8.83 and 8.93 kg CO_2-eq respectively). The enteric methane emissions for France per kilogram of liveweight was the lowest (7.20 kg CO_2-eq) while the enteric methane emissions in Argentina (14.97 kg CO_2-eq) were almost double (108% higher) that of France. The enteric methane conversion factors (Y_m) were similar across the countries for both pasture-based diets (6.15%-7%), and grain-based diets (4%-5.05%) with the duration of different phases and the finishing weights being more influential factors in determining the amount of enteric methane emissions per kilogram of live weight. Overall, the actual enteric methane emissions for all four countries were higher than Western Canada. The difference in enteric methane emissions was almost negligible between Western Canada and France (0.6%) reflecting the grain-based finishing systems and high finishing weights in both countries. In contrast, the long cow-calf and backgrounding phase (with associated high Y_m values) and lower finishing weights meant that enteric methane emissions in Argentina were about 109% higher than in Western Canada.

Feed consumption was the second highest source of impacts in France (31%) and the third highest contributor in the Australia (13.19%) – similar to Western Canada (11.5%). The impacts of feed ingredients in French beef production (3.9 kg CO_2-eq per kg of live weight) was at least 3 times higher than all the other regions modelled in this phase and Western Canada due to the significant inclusion of supplemental feed ingredients in the cow-calf phase, the high amount of feed imports from regions that have significant land use-related impacts (Brazil), and the relatively lower yields in French and Italian feed production. In New Zealand, the contribution of feed inputs was relatively minor (0.22%) since this only takes into account the relatively minor inputs of energy and fertilizers that are used for the ~2% of pastures that are renewed annually. In Argentina, too, the share of feed inputs was minor (2.9%) due to the relatively short finishing period of 68 days. 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 second highest contributor in Argentina (20.16%), and a slightly bigger (1.44%) contributor to emissions in New Zealand.

The carbon footprints of all feed inputs to the feed compositions of beef production in each country are provided in Table 101 relative to one kilogram of yield for the respective crop.

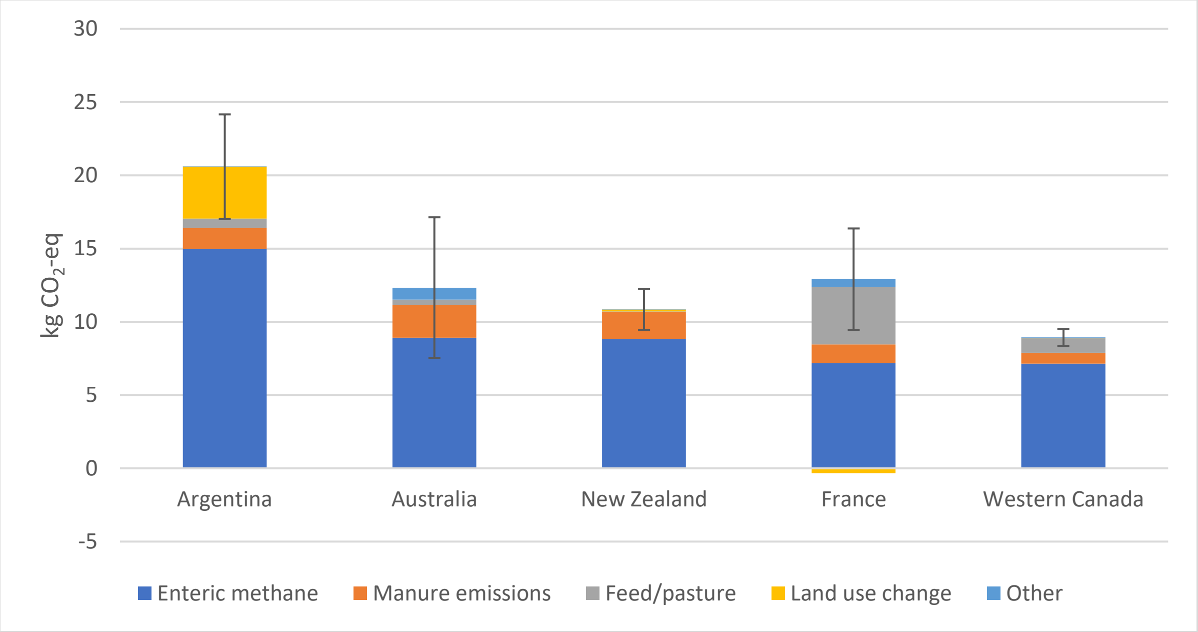


Figure 3: Carbon footprint of 1 kg of live weight beef produced – contributions by source of impacts. Error bars represent one standard deviation from the mean.

Table 101: Carbon footprints per kilogram of feed inputs in each country modelled

Country	**Feed input**	**Kg CO_2-eq.**
Argentina	Corn	0.202
	Oats	0.520
	Sorghum forage	0.302
	Sunflower pellets	0.575
	Soybean	0.480
Australia	Barley	0.273
	Canola meal	0.537
	Canola oil	1.199
	White fluffy cottonseed	0.929
	Cottonseed meal	0.710
	Sorghum	0.239
	Sugarcane molasses	0.580
	Wheat	0.452
	Lucerne hay	0.226
France	Corn	0.334
	Corn meal	0.787
	Harvested forage	0.058
	Wheat	0.926
	Soybean meal	0.480
Italy (FR)*	Barley	0.322
	Corn	0.318

	Corn meal	0.787
	Soybean meal	0.437
	Sugar beet pulp	0.222
	Dried distillers’ grains	1.120
	Wheat	0.371
Ukraine (FR)	Corn	0.860
Hungary (FR)	Corn	0.328

**Italy (FR) refers to the crops produced and used for finishing beef cattle in Italy as part of French beef production*

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 four regions (7-17%) (Figure 3). Manure management impacts were largely similar across all regions per kilogram of liveweight, with France (1.26 kg CO_2-eq. per kg of live weight) being the lowest and Australia (2.22 kg CO_2-eq.) the highest. This was reflective of the relatively minor variations in emission factors for manure-related emissions between the regions, which were already specified in Table 44. Manure-related emissions in all four regions were however considerably higher (72-202%) than Western Canada (0.734 kg CO_2-eq.). This was primarily down to the country-specific Tier 2 emission factor for direct N_2O emissions from the Canadian NIR which was considerably lower than the equivalent emission factors for the countries modelled in this phase – as discussed in detail in the phase 1 report (Arulnathan et al., 2024).

A limitation in the manure management emissions reported here (and for all regions modelled in phase 1) is that it only accounted for a nitrogen fertilizer credit equivalent to the amounts of N remaining in manure after storage and application losses, and no credits for other nutrients remaining in manure – such as P (Phosphorus). While the inclusion of credits for nutrients other than nitrogen has the potential to lower carbon footprint estimates for all countries with feedlot finishing further (since only manure for feedlots is stored and applied to cropland and manure deposited in pastures directly are not given any credits), the potential differences are unlikely to drastically alter the individual estimates for or comparative differences between these countries (For example, a simple phosphorus fertilizer credit based on a 2.9% phosphate run-off rate resulted in the carbon footprint estimate of France decreasing by ~0.6%).

Soil organic carbon fluxes resulting from land use change was a significant contributor to the overall carbon footprint only in Argentina (3.55 kg CO_2-eq. per kg of live weight), accounting for 17.25% of the impacts. Brazil (3.63 kg CO_2-eq. per kg of live weight) was the only other region across the two phases with comparable impacts associated with land use change. These impacts in Argentina were primarily a result of forest land being converted to pastures and rangeland for beef production. Based on the Argentinian NIR, there was a net soil organic carbon loss of 291.52 kg CO_2-eq. per hectare of grassland in Argentina. With a stocking rate of almost 2 hectares per animal unit, land use-related emissions were highly influential to the carbon footprint estimate for Argentina. Land use change also made a small contribution to New Zealand beef production emissions (1.22%), resulting from land conversions to pastures or rangeland. France and Australian pastureland sequestered small amounts of carbon (0.32 and 0.02 kg CO_2-eq. per hectare, respectively) according to the NIRs of those countries, while France also had a small amount of land use change-related emissions of carbon (0.16 kg CO_2-eq. per kg of live weight) as a result of feed imports from Argentina and Brazil. 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, there was no emissions associated with land use change for Western Canadian beef.

As in the case of Western Canadian beef, energy inputs and transportation made trivial contributions (< 0.1%) to the overall carbon footprint of New Zealand and Argentinian beef, but meaningful amounts to Australian (0.82 kg CO_2-eq.) and French (0.55 kg CO_2-eq.) beef production per kilogram of liveweight. In both Australia and France, these impacts were largely due to the inputs of electricity and other energy sources in feedlots.

Figures 4 and 5 present the carbon footprint of beef production in the four regions considered in this phase and Western Canada 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 dressing percentages were fairly similar (58-60%) between Argentina, France, and New Zealand – and comparable to the dressing percentage for Western Canada (60%). On the other hand, the dressing percentage for Australian beef was comparatively lower (54.35%). The carbon footprint of one kilogram of carcass weight beef in Western Canada (14.88 kg CO_2-eq.) was lower than all four regions considered in this phase, with carbon footprints being 1.9%, 20.17%, 20.58%, and 96.51% higher in New Zealand, France, Australia, and Argentina respectively.

Table 102 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. As in phase 1, a conversion factor of 1.4 was used to convert impacts per kilogram of carcass weight to impacts per kilogram of boneless meat.

Table 102: Carbon footprint (kg CO_2-eq.) of beef produced characterized relative to different reference units.

Reference unit	**Western Canada**	**Argentina**	**Australia**	**New Zealand**	**France**
1 Animal Unit (AU)	7061.4 (788.98 kg finishing weight)	8601.05 (417.72 kilograms live weight/AU)	8698.93 (706.13 kilograms live weight/AU)	6204.53 (572.77 kilograms live weight/AU)	12101.28 (961 kilograms live weight/AU)
1 kg of live weight	8.95	20.59	12.32	10.83	12.59
1 kg of carcass weight	14.88	29.24	17.94	15.17	17.88
1 kg of boneless meat	20.84	40.93	25.12	21.23	25.03

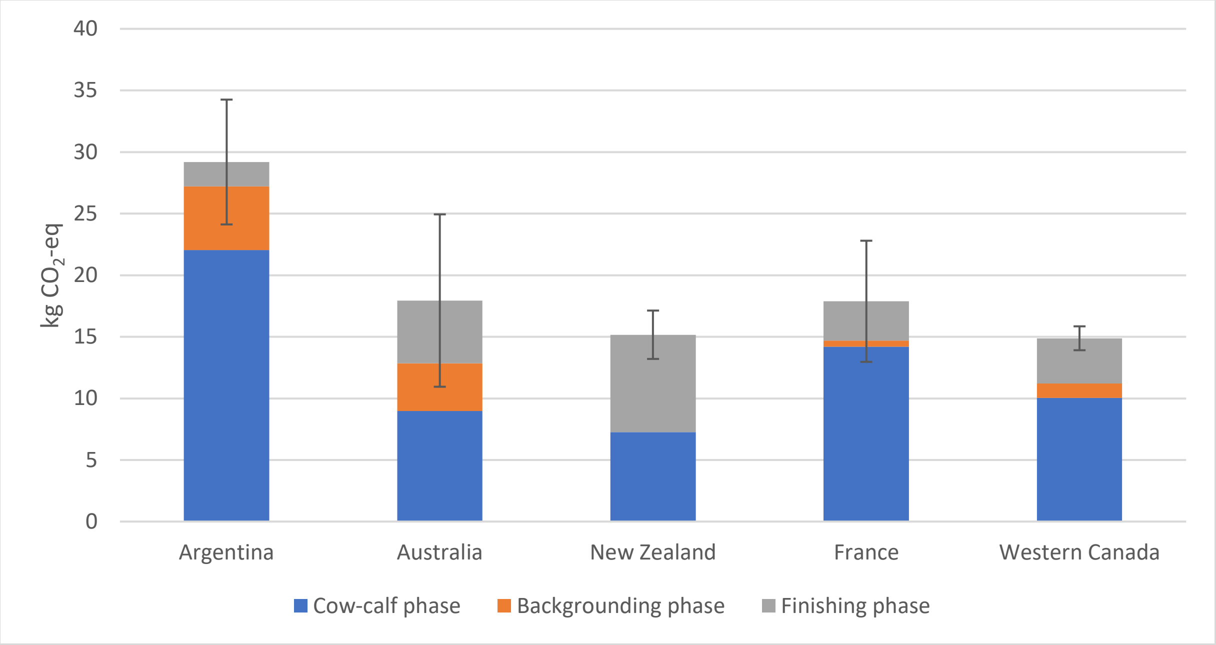


Figure 4: Carbon footprint of 1 kg of carcass weight beef produced – contributions by phase of production. Error bars represent one standard deviation from the mean.

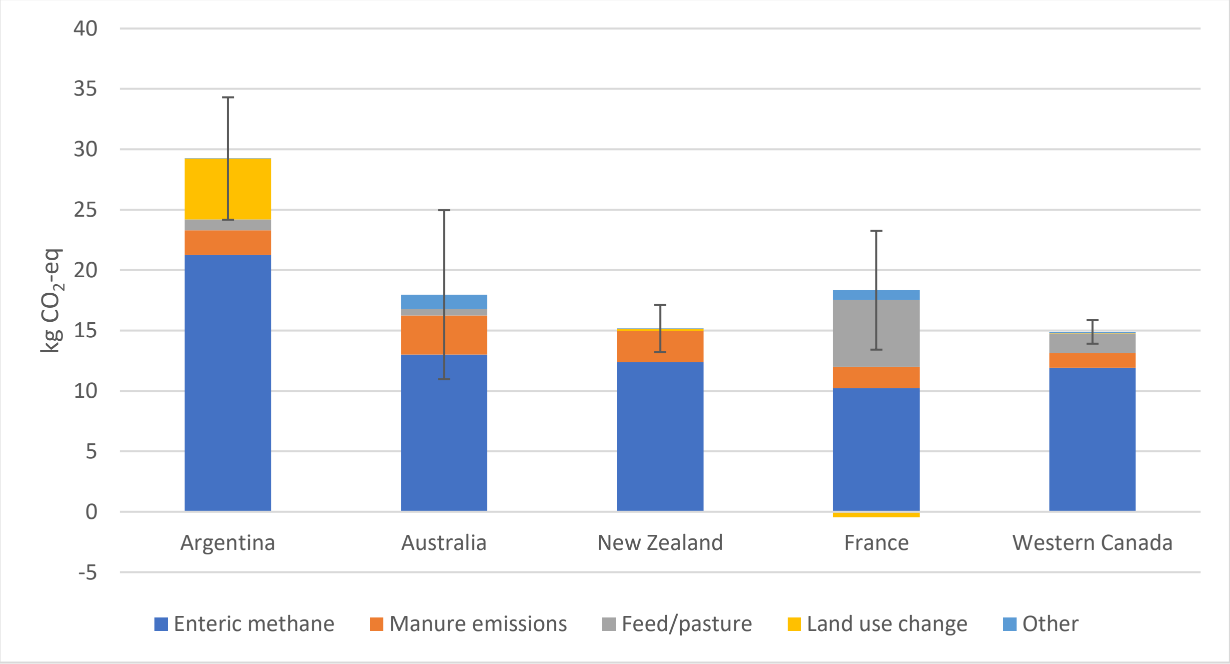


Figure 5: Carbon footprint of 1 kg of carcass weight beef produced – contributions by source of impacts. Error bars represent one standard deviation from the mean.

Finally, Figure 6 represents the carbon footprint of producing beef per kilogram of live weight without the contributions of soil organic carbon fluxes. Similar to Western Canada (6%), the removal of SOC fluxes only led to slight changes on the carbon footprint of Australian (0.05%), New Zealand (1.22%), and French (1.27%) beef. The carbon footprint of Argentinian beef production however reduced considerably (17.52%) when soil organic carbon losses due to land use change and land management were excluded. As a result, the carbon footprint of Argentinian beef was much closer to the other countries considered, with a maximum difference of 59% compared to New Zealand per kilogram of live weight, as opposed to the almost 90% difference when SOC impacts are included. Per kilogram of live weight, the carbon footprint estimates without the inclusion of soil carbon fluxes were 16.98 kg CO_2-eq., 12.31 kg CO_2-eq., and 10.70 kg CO_2-eq., and 12.75 kg CO_2-eq. for Argentina, Australia, New Zealand, and France respectively. Without the inclusion of SOC fluxes, the carbon footprint of 1 kilogram of liveweight beef in Argentina, Australia, New Zealand, and France was 79.88%, 30.42%, 13.34%, and 35.07% higher than Western Canada (9.44 kg CO_2-eq.).

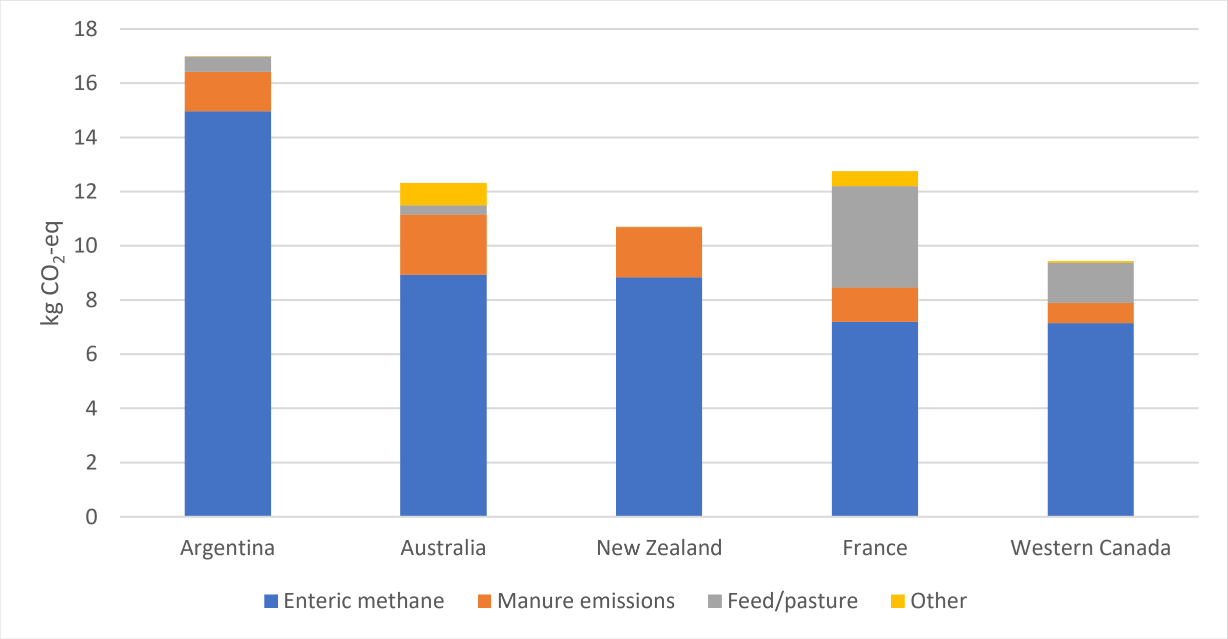


Figure 6: Carbon footprint of 1 kilogram of live weight beef produced without SOC contributions

The impact assessment results represented in Figures 2-6 and discussed in section 3.3 are provided in the supplementary information section 6.2.

3.3.2 Uncertainty analysis

The results of the Monte Carlo simulations showed that uncertainty was highest in Australia, followed by Argentina and France. Uncertainty was the lowest in New Zealand, but the uncertainty in the carbon footprint estimates of all four countries considered in this phase were higher compared to Western Canada. The inventory data for beef production in Australia was characterized by poor temporal correlation for most data points. In addition, most of the inventory data also had average completeness scores, and the feedlot cattle performance and feed data had poor scores for both reliability and completeness. All these factors combined resulted in the high uncertainty observed for the Australian beef carbon footprint. The high uncertainty for the Argentinian estimate was likely due to the poor temporal data quality for most cattle performance and herd composition inventory data points. In France, very few beef production inventory data points had poor data quality scores, but a vast majority of the data was characterized by average completeness and temporal correlation scores. In addition, feed inputs accounted for a higher share of the carbon footprint in France compared to the other countries considered, and the feed inventory data for France (and Italy) was significantly characterized by average or poor scores for both completeness and temporal correlation (see section 2.5.7.2 for data quality scores of feed inputs). The New Zealand inventory only had a few data points with average temporal correlation scores, and this is reflected in the much lower uncertainty observed compared to the other three countries modelled.

T-tests were performed comparing the Argentinian beef production system against the other three regions using the results of each model's Monte Carlo simulation. In all three comparisons, the two-tail P-values were less than the assumed significance level ($\alpha = 0.05$), indicating that the null hypothesis (that there is no difference in the observed datasets) needs to be rejected and that there is a strong statistical significance in the observed differences between these systems. These statistically significant differences are further emphasized by the t-stat value falling well outside the two-tail t-critical value in each of these t-tests. An ANOVA comparing all four 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 (843.17) being higher than the F critical value (2.61) at $\alpha = 0.05$. The 95% confidence interval of the Monte Carlo

Simulation results were +/- 0.011, 0.024, 0.005, and 0.034 from the respective means for Argentina, Australia, New Zealand, and France respectively. The results table for the T-test is provided in supplementary information section 6.3 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.

3.3.2.1 Sensitivity analysis

The only sensitivity analysis performed involved replacing the feed intake values estimated for New Zealand with the feed intake value from Australia (geographically closest region modelled to New Zealand and with significant presence of grass-finished cattle) and Brazil (the only other fully pasture-based system modelled in this study). With the use of the Australian feed intake value, the carbon footprint of New Zealand beef increased by 6.4% to 11.52 kg CO_2-eq per kilogram of live weight. With the use of the Brazilian feed intake value, the impacts of New Zealand beef increased by approximately 19% to 12.88 kg CO_2-eq. The Brazilian feed intake value was about 49% higher but only resulted in an overall increase in carbon footprint of 19%. This shows that accurate data on feed intake values in important (and in the case of New Zealand, data collection on feed intake should be prioritized in the future since no feed intake data was found during the review of literature), it also further emphasizes that the relatively lower carbon footprint of New Zealand beef is also the result of the production process not containing any other major sources of emissions beyond enteric methane and manure deposition on pasture, and the high finishing weights.

3.3.3 Comparison of results to other studies

The carbon footprint estimates obtained in this study for Australia, France, and New Zealand matched closely with the carbon footprint estimates from the major data sources used for these countries. Wiedemann et al. (2016) estimated that the carbon footprint of 1 kilogram of boneless meat in Eastern Australia to be 23.4 to 27.2 kg CO_2-eq., which is comparable to the 25.12 kg CO_2-eq. carbon footprint estimate from this study. The estimate of carbon footprint (10.07 kg CO_2-eq.) for New Zealand beef per kilogram of live weight by Mazzetto et al. (2023) was slightly lower than the estimate in this study (10.83 kg CO_2-eq.). Similarly, for France, the estimate in this study (12.59 kg CO_2-eq.) was slightly lower than, but still comparable to, the 13.0-14.1 kg CO_2-eq. estimate by Berton et al. (2017) per kilogram of live weight. For Argentina, the main source of inventory data was the Argentinian NIR and this did not provide estimates of carbon footprint relative to animal units or live/carcass weights (NIRs usually report data cumulatively for the entire sector). Viglizzo and Ricard (2024) estimated the carbon footprint of Argentinian beef to be 7,671 kilograms of CO_2-eq. per animal. This is about 11% lower than the estimate per animal unit (table 90) in this study. Arrieta et al. (2020) estimated the carbon footprint of Argentinian beef to be between 18.7 kilograms of CO_2-eq. and 27 kilograms of CO_2-eq. per kilogram of liveweight. The estimate in this study per kilogram of live weight (20.59 kilograms of CO_2-eq.) is well within this range, though it is significantly higher (by ~15%) than the weighted average carbon footprint estimate for Argentinian beef calculated by Arrieta et al. (2020). Overall, the carbon footprint estimates for all four regions modelled were found to be quite similar – and when different, largely within a ~15% range – to other studies in literature.

3.3.4 Comparison to regions modelled in Phase 1

Figures 7 and 8 (only liveweight, with and without SOC impacts) and Table 103 (all reference units, including SOC impacts) below provide a comparison of the carbon footprint estimates for all the seven regions modelled across the two phases of this study. Western Canada has the lowest carbon footprint estimate overall – both when including (8.95 kg CO_2-eq.) and excluding (9.44 kg CO_2-eq.) SOC-related emissions per kilogram of liveweight. Impacts of beef produced in USA and New Zealand were the next lowest when SOC impacts were included, and quite similar to each other (10.96 and 10.83 kilograms of CO_2-eq. respectively) per kilogram of live weight – despite have vastly different production systems and lifespans of beef cattle. While Brazil (22.93 kg CO_2-eq.) had the highest overall impacts per kilogram of liveweight among the countries considered by a significant margin (11.3% higher than Argentina, the next highest), removing impacts of SOC emissions from land use change and land management resulted in Argentinian beef having the highest impacts (16.98 kg CO_2-eq.) – 3.03% higher than Brazil (16.48 kg CO_2-eq.).

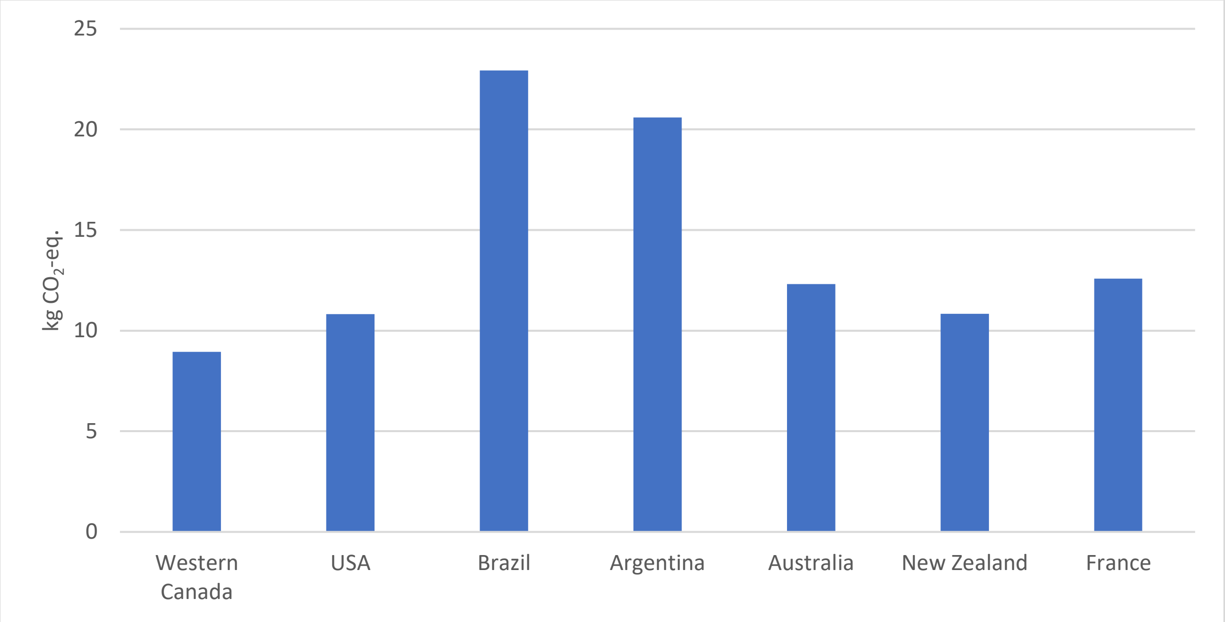


Figure 7: Carbon footprint estimates per kilogram of liveweight for all seven regions modelled across the two phases – including SOC-related impacts.

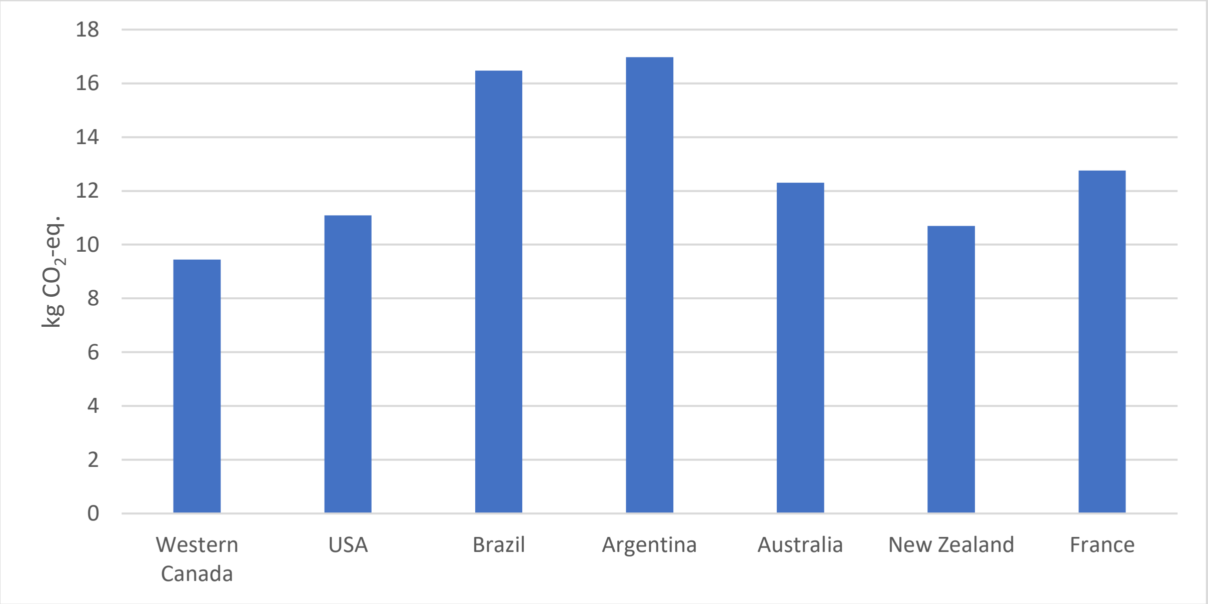


Figure 8: Carbon footprint estimates per kilogram of liveweight for all seven regions modelled across the two phases – excluding SOC-related impacts.

Table 103: Impacts relative to different reference units for all 7 regions modelled across the two phases

Reference unit	**1 Animal unit**	**1 kg of live weight**	**1 kg of carcass weight**	**1 kg of boneless meat**
Western Canada	7061.40	8.95	14.88	20.84
USA	7293.00	10.96	18.15	25.42
Brazil	15822.21	22.93	41.68	60.3
Argentina	8601.04	20.59	29.24	40.93
Australia	8698.93	12.32	17.94	25.12
New Zealand	6204.53	10.83	15.17	21.23
France	12101.28	12.59	17.88	25.03

4 Conclusions

Overall, the carbon footprint of New Zealand beef production was lowest among the four competitor countries considered in Phase 2. Considering all of the regions modelled across the two phases, Western Canada has the lowest carbon footprint estimate overall – both when including (8.95 kg CO_2-eq.) and excluding (9.44 kg CO_2-eq.) SOC-related emissions per kilogram of liveweight beef products. Impacts of beef produced in USA and New Zealand were the next lowest when SOC impacts were included (10.96 and 10.83 kilograms of CO_2-eq. respectively). At the other end of the scale, the carbon footprint of Brazilian beef was the highest when SOC-related emissions were included (22.93 kg CO_2-eq.), and Argentina the highest without SOC-related emissions (16.98 kg CO_2-eq.) The carbon footprints of US, Brazilian, Argentinian, Australian, New Zealand, and French beef were 22.5%, 156%, 130%, 37.64%, 21.03%, and 40.70% higher, respectively, compared to Western Canadian beef.

The South American regions modelled had either significant (Argentina) or fully (Brazil) pasture-finished beef cattle. These two countries were characterized by either very long backgrounding and finishing phases (Brazil), or much lower finishing weights (Argentina) compared to the other regions modelled. In addition, the soil organic carbon (SOC)-related impacts for both regions were significant. As a result of these factors (including the higher enteric methane emissions resulting from prolonged intake of low-quality pasture diets), the carbon footprint estimates for the South American regions modelled were the highest. While Australia (~70% grass finished) and New Zealand (100% grass finished) also had primarily grass-finished cattle, the carbon footprint estimates for the Oceanic countries were considerably lower compared to South America. This directly correlated with the higher feed consumption (22.8-23.7 kg DM/animal unit in South America and 15.3-16.7 kg DM/animal unit in Oceania) in both countries, the long finishing phase (480 days) in Brazil, and low finishing weight (~417 kilograms) in Argentina. In addition to the Y_m value for pasture intake being the highest for Argentina (7%), the amount and duration of feed intake along with finishing weights were also highly influential in determining the enteric methane emissions – which was the largest contributor to the carbon footprint estimate across all the regions modelled.

Manure management and feed use were significant contributors in most regions, while in the South American countries, impacts associated with land use change were also highly influential. Feed consumption was the second highest source of impacts in France (31%) and this share of feed related impacts were significantly higher than Australia (13.5%) – the region with the next highest share of feed-related impacts. The impacts of feed ingredients in French beef production (3.9 kg CO_2-eq per kg of live weight) was at least 3 times higher than all the other regions modelled in this phase and Western Canada due to the significant inclusion of supplemental feed ingredients in the cow-calf phase, the high amount of feed imports from regions that have significant land use-related impacts (Brazil), and the relatively lower yields in French and Italian feed production.

For Argentina and Brazil, 18.8% and 29% of the carbon footprint estimates were attributable to soil organic carbon fluxes resulting from land use change and land management. While the carbon footprint estimates for Brazil and Argentina were 156% and 130% higher than that of Western Canada, the difference fell to 75% and 80%, respectively, when SOC-related impacts were excluded. Finally, in Western Canada, US, Argentina, and France, most of the emissions were attributable to the cow-calf phase, whereas in the other countries, the impacts were much more broadly distributed across the different phases (due to the prolonged length of backgrounding and/or finishing phases in these countries).

In conclusion, the results of this analysis highlight the significant differences in carbon footprint estimates of beef produced in different regions, the overall better performance of Western Canadian beef compared to other regions, the comparable performance between US and New Zealand (the two regions with the next lowest carbon footprints) beef despite their very different production characteristics, the high impacts of South American beef production, and the significance of not characterizing carbon footprint estimates on an animal unit basis due to the widely different feed intake amounts and finishing weights observed in the regions modelled.

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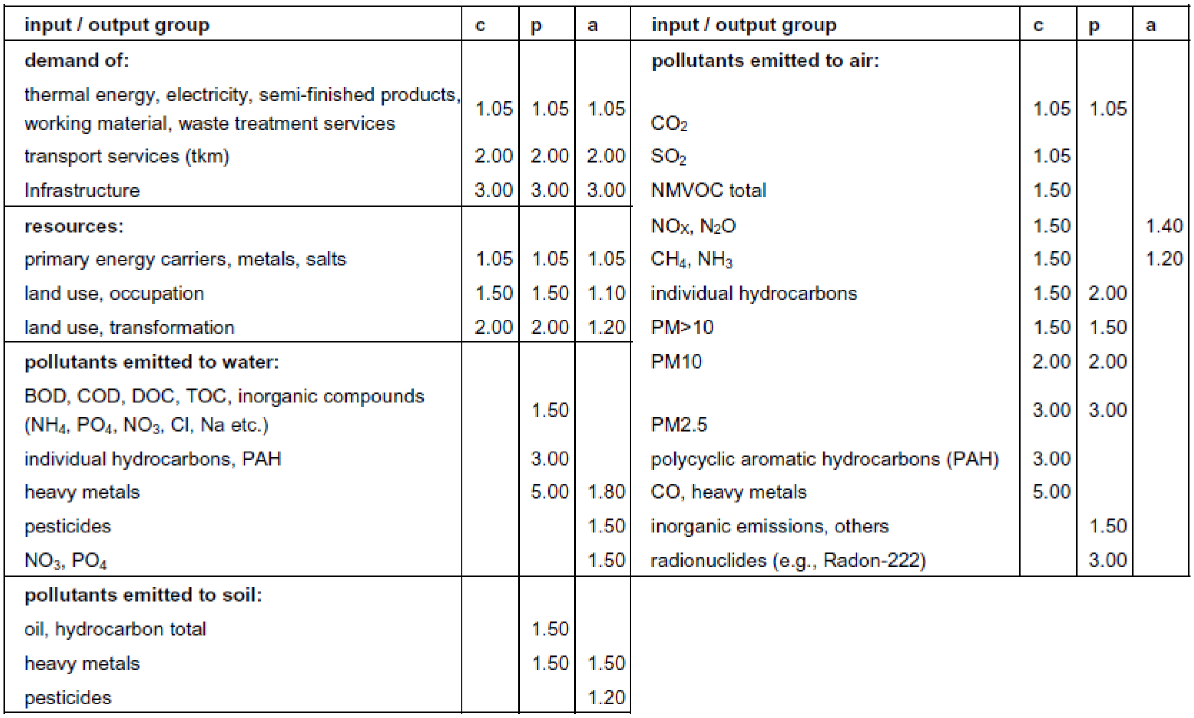
6 Supplementary Information

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



input / output group	c	p	a	input / output group	c	p	a
demand of:				**pollutants emitted to air:**			
thermal energy, electricity, semi-finished products, working material, waste treatment services	1.05	1.05	1.05	CO_2	1.05	1.05	
transport services (tkm)	2.00	2.00	2.00	SO_2	1.05		
Infrastructure	3.00	3.00	3.00	NMVOC total	1.50		
resources:				NO_X, N_2O	1.50		1.40
primary energy carriers, metals, salts	1.05	1.05	1.05	CH_4, NH_3	1.50		1.20
land use, occupation	1.50	1.50	1.10	individual hydrocarbons	1.50	2.00	
land use, transformation	2.00	2.00	1.20	PM>10	1.50	1.50	
pollutants emitted to water:				PM10	2.00	2.00	
BOD, COD, DOC, TOC, inorganic compounds (NH_4, PO_4, NO_3, Cl, Na etc.)		1.50		PM2.5	3.00	3.00	
individual hydrocarbons, PAH		3.00		polycyclic aromatic hydrocarbons (PAH)	3.00		
heavy metals		5.00	1.80	CO, heavy metals	5.00		
pesticides			1.50	inorganic emissions, others		1.50	
NO_3, PO_4			1.50	radionuclides (e.g., Radon-222)		3.00	
pollutants emitted to soil:							
oil, hydrocarbon total		1.50					
heavy metals		1.50	1.50				
pesticides			1.20				

6.2 Impact assessment results of the beef production systems modelled per kilogram of live weight (LW)/carcass weight (CW)

Table 6.2.1: Carbon footprint estimates per kilogram of live weight (by phase)

	Argentina	Australia	New Zealand	France
Cow-calf phase	15.51494	6.152916	5.18397	10.00261
Backgrounding phase	3.66052	2.662965	0	0.347034
Finishing phase	1.415214	3.503274	5.648543	2.242736

Table 6.2.2: Carbon footprint estimates per kilogram of live weight (by source)

	Argentina	Australia	New Zealand	France
Enteric methane	14.96825	8.92849	8.832358	7.198998
Manure emissions	1.443794	2.21669	1.844367	1.261389
Feed/pasture	0.632903	0.366142	0.023903	3.904368

Land use change	3.545728	-0.01517	0.131829	-0.32186
Other	0.0001	0.823008	5.53E-05	0.549487

Table 6.2.3: Carbon footprint estimates per kilogram of carcass weight (by phase)

	Argentina	**Australia**	**New Zealand**	**France**
Cow-calf phase	22.03121	8.961722	7.257558	14.2037
Backgrounding phase	5.197938	3.878609	0	0.492789
Finishing phase	2.009604	5.102519	7.90796	3.184686

Table 6.2.4: Carbon footprint estimates per kilogram of carcass weight (by source)

	Argentina	**Australia**	**New Zealand**	**France**
Enteric methane	21.25491	13.00435	12.3653	10.22258
Manure emissions	2.050188	3.228608	2.582114	1.791173
Feed/pasture	0.898723	0.533286	0.033465	5.544203
Land use change	5.034934	-0.0221	0.18456	-0.45705
Other	0.000142	1.198711	7.74E-05	0.780272

6.3 Results of MC simulation (including T-test and ANOVA) per representative animal unit

Per representative animal unit	**Argentina**	**Australia**	**New Zealand**	**France**
Impact category	IPCC 2021 GWP 100	IPCC 2021 GWP 100	IPCC 2021 GWP 100	IPCC 2021 GWP 100
Reference unit	kg CO_2 eq	kg CO_2 eq	kg CO_2 eq	kg CO_2 eq
Mean	8601.05	8698.93	6204.53	12101.28
Standard deviation	1470.451	3383.347	468.8144	6672.12
Standard error	46.499	106.991	14.825	210.991
Minimum	5629.286	2900.651	4978.91	4498.599
Maximum	18334.56	37416.71	7895.107	56605.97

Median	8397.688	8042.525	6194.255	10287.18
5% Percentile	6607.157	4617.165	5448.739	6535.341
95% Percentile	11303.67	14871.14	6992.866	23660.15
95% Confidence interval (+/- mean)	0.010596	0.024106	0.004683	0.034173
p-value	<0.001 (ANOVA)	6.4E-212	2.3E-201	2.5E-183
t-statistic	-	-39.3505	-35.4287	-35.8854
t-critical	-	1.962129	1.961513	1.962281

6.4 Data estimated for feed intake values for New Zealand

$ME_{maintenance}$	**Cows**	**Bulls**	**Calves-pre wean**	**Calves-post wean female**	**Calves-post wean male**
K	1.4	1.4	1.4	1.4	1.4
S	1	1.15	1	1	1.15
Live weight	432	683	109	307	368
Age	4	4	0.5	1	1.1
ME of diet (MJ/kg of dry matter)	10.39	10.39	10.39	10.39	10.39
Q_m	0.56	0.56	0.56	0.56	0.56
k_m	0.70	0.70	0.70	0.70	0.70
LW km portion	33.61	47.39	13.29	28.47	32.51
ME_{main}(MJ/day)	**47.06**	**76.30**	**18.61**	**39.85**	**52.35**

$ME_{production}$	**Cows**
Annual milk yield (kg)	824.00
Milk per day (Y) kg/day	2.26
Fat content of milk (kg/100 litres)	5.04
100 litres to kg	103.00
Fat content (%)	0.05
Protein content (kg/100litres)	3.95
Protein content(%)	0.04
GE of milk (MJ/kg)	0.97
Q_m	0.56
k_t	0.62
$ME_{production}$ (MJ/day)	**3.56**

ME_{growth}	**Cows**	**Bulls**	**Calves-pre wean**	**Calves-post wean female**	**Calves-post wean male**
kgnl	0.442	0.442	0.442	0.442	0.442
Days	365	365	150	690	810
Total weight gain	36	13	113	284	405
LWG per day (kg/day)	0.099	0.036	0.753	0.412	0.500
EBC	0.091	0.033	0.693	0.379	0.460
LW_x (current live weight in kg)	432	683	109	307	368
SRW (kg)	550	770	660	550	770
SRW portion of R	454.289	584.693	520.856	454.289	584.693
R	-1.000	-1.000	-0.999	-0.999	-0.999
P_{lw}	0.785	0.887	0.165	0.558	0.478
P_{lw} portion of Meg	19.381	20.212	4.183	15.355	13.095
ME_{growth} (MJ/day)	**5.145**	**1.919**	**15.486**	**18.025**	**19.545**

$ME_{gestation}$	**Cows**
Days-prg	115.25
e^{prg} portion of Et	0.994
E^t	10.421
E^t k_c portion	1.565
$ME_{gestation}$ (MJ/day)	**2.034**