Carbon footprint analysis of Saskatchewan and Canadian barley and oats production and comparison to international competitors

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Update: Addition of Canada without Saskatchewan estimates for barley and oats (throughout document - highlighted).

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1. Introduction

The production of commodity field crops, including barley and oats, makes a significant economic contribution to the Canadian economy (Statistics Canada 2024a). Within Canada, much of the production of these crops is concentrated in the Prairie provinces, including the province of Saskatchewan ((S&T)2 Consultants Inc. 2022a). A large portion of field crops produced in Canada are exported to international markets, making Canada a major contributor to international commodity field crop markets (Statistics Canada 2024b). In these international markets, sustainability is becoming increasingly important for market access, due to increasing customer awareness and preference for sustainably sourced foods (Xie et al. 2021; Noor et al. 2022; Yadav et al. 2022). As this trend continues, reliable and transparent sustainability assessment results will become increasingly valuable for agri-food producers and other value chain stakeholders. Particularly, it is important to develop an in-depth understanding of the environmental impacts and mitigation opportunities for crop production, as well as potential priority focus areas along supply chains for improvement. Comparisons among competitors will similarly become increasingly salient. Such information may help field crop producers and marketers develop and maintain a competitive advantage on the basis of superior sustainability outcomes (Tobi et al. 2019; Nassos and Avlonas 2020).

In the context of internationally-traded commodity field crops, there is the potential for large differences in the environmental impacts per unit of crops produced in different regions of the world. These differences may be driven by a variety of factors, including regional differences in soil, climate, and management practices (Abdalla et al. 2016; Kajsa et al. 2019). For example, field-level emissions of nitrous oxide (N_2O) are a major source of greenhouse gases (GHGs) in agriculture. The amounts of N_2O emissions from crop production may be influenced by many factors including the types, application methods, and amounts of nitrogenous fertilizers applied, the soil water content, and the availability of nitrogen in soils (Van Zandvoort et al. 2017), as well as other management and climate conditions (Kuang et al. 2021; Hassan et al. 2022). In addition to field-level emissions, there are differences in embodied emissions from the "life cycle" (i.e., supply chain) processes occurring upstream of field-level activities. Regional differences in field-level fertilizer-use efficiency (Liu et al. 2021), for example, may be compounded by regional differences in the impacts characteristic of fertilizer production, and the supporting electricity production grids (Kakanis 2021; Gong et al. 2022; Ouikhalfan et al. 2022).

In order to rigorously assess such potential differences between internationally-traded crops, it is necessary to use life cycle thinking-based tools (Pelletier 2015), which can be used to perform transparent and reproducible assessments of the cumulative resource demands and environmental emissions associated with the entire supply chain of a product or service. Life cycle assessment (LCA) is the most commonly applied life cycle thinking-based tool. LCA has been applied to a number of agri-food production systems, both within Canada (Dias et al. 2017; Pelletier 2017; Turner et al. 2022; Bamber et al. 2023, etc.) and internationally (Pelletier et al. 2014; Masuda 2016; Schmidt Rivera et al. 2017; Hietala et al. 2021, etc.). The performance of LCA, and derivative methods such as carbon footprinting methods, is supported by internationally accepted and standardized methodologies, including the ISO 14044 standard for LCA (ISO 2006a, b) and the ISO14067 standard for carbon footprinting (ISO 2018).

Within Canada and globally, it is estimated that one third of total anthropogenic GHG emissions are attributable to food systems (Crippa et al. 2021). Direct emissions from Canadian agricultural systems have increased by 26% over the past 30 years (Flemming et al. 2021). It is therefore vital to

identify the key drivers of GHG emissions from Canadian agriculture, and to compare them to those from international competitors. This will enable the development of an in-depth understanding of the sustainability challenges and areas for improvement in the Canadian field crop sector, as well as potential opportunities for competition on the basis of sustainability attributes. On this basis, the Global Institute for Food Security (GIFS) and the Saskatchewan Ministry of Agriculture commissioned a study to enable the comparison of the carbon footprints of barley and oats produced in Canada, Western Canada (the Prairie Provinces of Alberta, Saskatchewan, and Manitoba) and the province of Saskatchewan to the same crops grown by a subset of international competitors (Australia, France, Ukraine, Russia, Finland, Poland and Sweden). The results of this study may be used to support sustainability policy initiatives in both domestic and international contexts. The current documents report the methods, data sources and results of this study. These reports were developed in line with previous comparative carbon footprint studies conducted for GIFS by PRISM Consulting for canola, wheat, lentils and peas.

2. Methods

Development of carbon footprint models for the crop-region combinations of interest followed a staged approach. In brief, Stage 1 comprised a data mining and quality assessment exercise to identify sufficiently credible/rigorous data to support model development, and to select among available data sources in a transparent and reproducible manner. The outcome of Stage 1 described the methods, data sources, and results of the data quality assessment and selection process, which was shared with the Saskatchewan Ministry of Agriculture (Ministry) and GIFS for consultation (Stage 2) prior to proceeding to the modelling stage. Finally, in Stage 3 (the current report), carbon footprint models were developed for each of the crop-region combinations, and comparisons made between the magnitude and sources of GHG emissions associated with each.

2.1 Crop-region combinations included

In total, 12 crop production systems were proposed by the study commissioners for inclusion in this analysis (Table 1). Specifically, this included barley grown in Saskatchewan, the Canadian Prairie Provinces (average including Saskatchewan) Canada (average including Prairie Provinces), Canada without Saskatchewan, Australia, France, Ukraine, and Russia, as well as oats grown in Saskatchewan, Prairie Provinces, Canada, Australia, Finland, Poland, and Sweden.

Table 1. Crop-region combinations included in this analysis. Green fill represents combinations included, while grey fill represents crop-region combinations excluded.

	Barley	Oats
Saskatchewan		
Prairie Provinces		
Canada		
Canada without Saskatchewan		
Australia		
France		
Ukraine		
Russia		
Finland		
Poland		
Sweden		

These combinations were selected by the Ministry and GIFS because they represent priority field crops (i.e., on the basis of value and volume) for comparison with international competitors.

Between 2018/19 and 2022/23, Russia was the largest producer of barley, while Canada produced the largest volume of oats, across all of the regions considered in each analysis (Table 2). Estimates of production volumes for 2023 are not available for Ukraine and Russia from FAOSTAT or national statistical offices (Ukrstat, 2024; Rosstat, 2024), therefore data from 2018-2022 were used instead (FAOSTAT 2024). Only 4 year average data from 2020 to 2024 was reported for oats production in Australia by the Australian Bureau of Statistics (ABARES, 2024). Otherwise, all data presented in Table 2 represent a 5-year average yield from 2019-2023.

Table 2. Production estimates for each crop in the regions included in this analysis. Recent estimates of non-durum wheat production are not available for France or Germany.

	Production (tonnes)	
	Barley	Oats
Saskatchewan	3,622,241[a]	1,853,123[a]
Prairie Provinces	9,015,104[a]	3,529,017[a]
Canada	9,398,013[a]	3,912,752[a]
Australia	13,122,844[b]	1,414,957[b]
France	11,859,200[c]	/[d]
Ukraine	7,789,490[e]	/[d]
Russia	19,961,981[e]	/[d]
Finland	/[d]	1,067,380[f]
Poland	/[d]	1,525,600[c]
Sweden	/[d]	635,260[g]

[a] 5 year average (2019-2023) as reported by Statistics Canada, table 32-10-0359-01 (Statistics Canada, 2024)
[b] 5 year average for barley (2019-2023) and 4 year average for oats (2020-2024) as reported the Australian Bureau of Statistics (ABARES, 2024)
[c] 5 year average (2019-2023) as reported by EU Cereals production (European Commission, 2024)
[d] Crop-region combination not included in this analysis
[e] 5 year average (2018-2022) as reported by FAO (2024)
[f] 5 year average from (2019-2023) as reported by Natural Resources Institute Finland (LUKE, 2024)
[g] 5 year average from (2019-2023) as reported by Statistics Sweden (SCB, 2024)

2.2 Identification of potential data sources

    Calculation and comparison of carbon footprints across the crop-region combinations required the identification and compilation of data of sufficient quality to characterize crop management practices, soil/climate conditions, inputs, emissions and yields in each region. Specifically, data from the following categories were required for inclusion in all crop-region models:

- Yield

- Seed inputs
- Nutrient inputs/soil amendments including lime, manure, N fertilizers, P fertilizers, K fertilizers, and S fertilizers
- Pesticide inputs including herbicides, fungicides, and insecticides
- Energy use for irrigation
- Energy use for field activities
- Transportation of field inputs
- Post-harvest energy use
- Field level fluxes including direct and indirect N_2O emissions from N inputs, CO_2 emissions from lime and urea, and soil carbon changes from land use or management changes.

The following data points were excluded due to lack of relevance to the carbon footprints of field crop production:

- Infrastructure is excluded due to trivial contributions to GHG emissions when taken over the lifespan of the infrastructure
- Field level methane emissions from application of manure to agricultural fields are excluded, as field level emissions are negligible (Uddin et al. 2020), and calculation of them is not included in the IPCC methods (IPCC 2019).

Such data may be derived from various sources that differ in their scope, coverage, and quality. Potential sources include publicly-available and commercial life cycle inventory (LCI) databases, other publicly available databases such as those provided by national and international statistics agencies, peer-reviewed scientific literature, and reputable grey literature sources produced by governments and industry groups. Sources were only included if they presented quantitative values for the inventory data. They were excluded if they presented the sources of the inventory data without including the values.

A number of the countries of interest have developed country-specific, publicly available LCI databases. Specifically, country-specific, publicly available LCI databases have been developed for Canada (Fritter 2020), Australia (Grant 2016), France (Koch and Salou 2016), and Sweden (Swedish Life Cycle Center 2008), which provide varying degrees of sectoral coverage. In addition to these country-specific databases, commercial LCI databases such as EcoInvent (Moreno Ruiz et al. (2021) and Agri-Footprint (Blonk et al. 2022). were also searched. Each of these databases were first searched to determine if they included complete LCI datasets representative of each crop-region combination. To be considered, data sets had to be available as unit process data sets, rather than aggregated system process data sets. System process data sets were excluded because they represent the complete inventory of elementary flows associated with the supply chains of products, rather than as a set of linked processes with product flow inputs and outputs. Because of this, no individual LCI data points can be sourced, no modifications can be made to the data sets (i.e., changing electricity grid mixes to more appropriate mixes, etc.), and all granularity is lost with respect to the contributions to GHG emissions arising from the different life cycle stages of crop production.

Searches of peer reviewed scientific literature were also performed to identify possible sources that may provide data of higher quality. A topic search in the Web of Science Core Collection was performed for each crop-country combination using the following query: TS=(("life cycle assessment" OR "life cycle inventory" OR "life cycle analysis" OR "carbon footprint" OR LCA OR LCI) AND (barley OR oat) AND

(Canad* OR Saskatchewan OR Australia* OR France OR French OR Russia* OR Ukrain* OR Finland OR Finnish OR Swed* OR Poland OR Polish)). No temporal boundaries were placed on these literature searches because any potential data derived from them was subsequently assessed for data quality as described in section 2.3. The * was included as a wildcard search operator representing any group of characters, including no characters. Inclusion of this operator therefore means, for example, the term "Canad*" would return results related to "Canada", "Canadian", etc.

Grey literature from government and industry groups were similarly consulted to identify potential sources of high-quality data. Grey literature sources were identified through internet and website searches of each region's statistical databases and government agricultural departments. These included Statistics Canada and Agriculture and Agri-food Canada, the Australian Bureau of Statistics and Department of Agriculture, Fisheries and Forestry, the French Ministerial Statistical Service for Agriculture (AGRESTE), the Russian Institute for Agricultural Market Studies (IKAR), the State Statistics Service of Ukraine (Ukrstat), the Natural Resources Institute Finland (Luke), the Central Statistical Office of Poland, and Statistics Sweden (SCB). Additional searches were also performed to identify potential sources from industry groups representing field crop farmers in each region. These included the Canadian Roundtable for Sustainable Crops (CRSC), Grain Growers of Canada, Prairie Oat Growers Association, Cereal Growers of Canada, Cereals Canada, Barley Council of Canada, Saskatchewan Oats Development Commission, Saskatchewan Barley Development Commission, Canadian Barley Research Coalition, Alberta Grains, Manitoba Crop Alliance, and Alberta Oat Growers Commission, Grain Growers and Grain Producers of Australia, the Grains Research and Development Corporation, Australian Grain Note (AGNOTE), Local Agricultural Chambers (Chambres d'agriculture),Terres Inovia, Russian Grain Union, Ukrainian Grain Association (UGA), Central Union of Agricultural Producers and Forest Owners (MTK), Finnish Cereal Committee, Polish Grain Chamber, Swedish Grain & Flour Association, and Agricultural Societies.

It must be noted that data sets sourced from different LCI databases and literature sources may not be methodologically consistent due to differences in reporting guidelines, modelling protocols, and submission criteria (Turner et al. 2020). For example, land use changes and land occupation are modeled differently between Moreno Ruiz et al. (2021) and van Paassen et al. (2019). Therefore, it was necessary that all relevant data identified from the source documents be extracted and remodeled on a methodologically consistent basis to enable rigorous comparisons between results.

2.3 Data quality assessment

Following the identification of potential data sets and/or individual data points in LCI databases, peer-reviewed literature, and grey literature sources, all data points were screened using established LCI data quality screening methods to determine the quality of data available for modeling inputs to each cropping system. Data quality criteria were defined in accordance with the pedigree matrix proposed by Ciroth et al. (2016) (Table 3), with specific modifications (described below) as appropriate to the goals of the current analysis. 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. Each score in the pedigree matrix is associated with an additional uncertainty factor that combines with base sectoral uncertainty factors for each data point to generate the overall uncertainty distribution for that data point (Table 4), in accordance with equation 1 in Ciroth et al. (2016). The use of a pedigree matrix

for assessing data quality allows for assessment of parameter uncertainty, an important contributor to uncertainty in LCA studies (Bamber et al. 2020).

Table 3. 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 4. 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

When assessing the quality of yield data, the definitions associated with each data quality score for temporal correlation were altered to better reflect the potential for inter-annual variability in crop yields. Currently, the standard pedigree matrix as defined by Ciroth et al. (2016) assigns the highest quality score to data points for which there is less than 3 years of difference in the time periods of the study and the data set, with data quality decreasing as data sets get older. Use of this system, however, assumes that data points are representative of discrete moments in time, or periods of time that do not span data quality rankings. This is inappropriate when assessing data quality for yield estimates due to the potential for inter-annual variability in yields. This is a particularly salient issue for Canadian yield data, as 2021 yields for all crops included in this analysis were drastically reduced due to widespread drought across the Canadian prairie provinces (Agriculture and Agri-Food Canada 2021). Similar reductions in yield were also experienced for a number of crops around the world in 2021 (USDA 2022). Given the potential for interannual variability in yields, alterations have been made to the temporal correlation row of the pedigree matrix for assessment of yields as detailed in table 5.

Table 5. Alternative pedigree matrix definitions for assessment of the quality of 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 6 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 expertise and metrics that inform practices performed by farmers. The previous GIFS field crops carbon footprint study (Bamber et al. 2022b) 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 the completeness of a data point resulted in that data point being assigned a score of 5, as in the default pedigree matrix.

Table 6. 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

An additional change was also made to the pedigree matrix with respect to the assessment of reliability for each data point. In the default pedigree matrix, verified data based on measurements are assigned the highest quality score while non-verified estimates are assigned the lowest quality score. In the context of this analysis, however, verified measurements of farm level inputs and outputs should not be considered as the highest quality data unless replicates are taken from a sufficiently large sample of farms to be nationally representative. This is often not the case, particularly in the context of field-level emissions, such as nitrogenous emissions released from application of N fertilizers to agricultural fields (Klimczyk et al. 2021). Rather, well defined mathematical relationships are often used for estimation of field-level nitrogenous emissions at large scales, such as whole countries (Yeluripati et al. 2015). Many different models exist for the estimation of field-level nitrogenous emissions that may vary in their geographic scope, complexity, and types of nitrogenous emissions covered. These include the IPCC models which may be used to represent globally generic emissions using Tier 1 methods and default emissions factors or more nationally-resolved emissions using Tier 2 methods and regionalized

emissions factors (IPCC 2019). These models are widely accepted, as evidenced by their use in the National Inventory Reports (NIRs) of many countries included in this analysis (CCNUCC 2022; Environment and Climate Change Canada 2022; Federal Environment Agency 2022; Government of Australia 2022; U.S. Environmental Protection Agency 2022). In some cases, farm input data may also be modeled, particularly when measured data are unavailable.

Taking into account the preferability of modeled data in estimating emissions at the regional or national scale, and the potential for the use of modeled data for farm level inputs, the following changes were made to the reliability column of the pedigree matrix. First, nationally-resolved modelled emissions (such as those calculated using IPCC Tier 2 methods) were given a reliability score of 1 because these are the highest quality data practically available for modeling at large geographical scales such as the national scale. Generically modeled emissions (such as those calculated with IPCC Tier 1 methods) were given a reliability score of 2. Similarly, modeled inventory data were given a reliability score of 2. In all cases, reliability scores may be further decreased if the model inputs included in the data set themselves receive lower reliability scores. Finally, measured input and emissions data from a single or a small number of field sites (i.e., <10) or experimental sites were given a score of 4 for reliability, as these measures are poorly fit for use at the national scale.

When models were used to calculate LCI data points (e.g., N_2O emissions calculated using the IPCC methodology), the specificity of the emission factors (EFs) were assessed in combination with the geographical representativeness of the data entered into the model (e.g., N fertilizer application rate, etc.). The lowest geographical representativeness between the data entered into the model and the EF specificity was used as the limiting factor in assigning the pedigree score. For example, if the N fertilizer application rate was representative of the region under study, but a global EF for N_2O emissions was used (e.g., IPCC Tier 1), the value for N_2O emissions was assigned a geographical representativeness score of 2, representing "average data from larger area in which the area under study is included". If the EF used was representative of a different region (not globally representative), then scores of 3, 4, or 5 were assigned depending on the similarity of production conditions in that region to the region under study. In general, if a combination of sources were used for one data point (or several sources listed generally and the specific source for each data point was not indicated), then the pedigree scores were assigned based on the lowest quality source (Table 7).

Table 7. 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 8). Since this is a national-level carbon footprint study, the search of data sources was likely to produce data relevant to regions within a country, such as particular states in Australia or provinces in Canada. If the standard definitions for geographical correlation are used within the context of this study, such regional data would only be given a score of 3 since they are not representative of the entire region being modelled (Western Canada). 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 8).

Table 8. 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, for example, 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 sets for crop-region models

Once all potential data points were assigned data quality scores for their reliability, completeness, and temporal, geographic, and technological correlation, decisions were made regarding which of the identified sources were of the highest quality for use in model development. This choice was based on the calculation of the amount of uncertainty that would be introduced into the models

through the use of each specific data source. 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 3 and 4). 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 pedigree matrix scores. U_t represents the total geometric standard deviation of the uncertainty distribution of each inventory data point, from which Monte Carlo samples would be drawn during uncertainty propagation (Bamber et al. 2020). 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 crop/country combination 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). The choice of best fit data for modelling each data point for each crop-region combination therefore took into account these overall data quality scores. For the choice of data representing fertilizer and pesticide inputs, two options were possible for use as a data source: the combination of nutrient or total pesticide inputs with the distribution of types of fertilizers or pesticides applied, or the use of data characterizing the amounts of specific fertilizer and pesticide types. In these cases, the data chosen was that which had the lowest overall uncertainty score (i.e., highest overall data quality). Similarly, data on energy use related to field or post-harvest activities may be characterized by the total energy use, or the combination of energy use per activity and activity data (i.e., number of passes, etc.). For manure, data can be represented as the total amount of manure applied per total ha of harvested crop, or as the percent of crop receiving manure and the amount of manure applied per ha of crop receiving manure. The data with the highest overall quality was also chosen for these data points.

For field-level emissions and soil carbon changes, the available data points were also compared against a potential scenario of using the best available input data in conjunction with the best practices for emissions modelling. For this study, IPCC Tier 2 methods for modelling direct and indirect N_2O emissions, IPCC Tier 1 methods for modelling CO_2 emissions from lime and urea, and IPCC Tier 2 methods using the data available in the each country's NIR for soil carbon changes were considered to

be best practices (IPCC 2019). These methods are in line with those applied for calculation of GHG inventories in each country's NIR, and are internationally recognized (IPCC 2019). This choice is also in line with the guidelines for assessment of environmental performance of animal feed supply chains provided by UN FAO LEAP (FAO 2016), the most relevant guidance document from the partnership as the crops included in this analysis may be key contributors to livestock feeds (Pembleton et al. 2016; Begna et al. 2021; Cordeiro et al. 2022). The data quality for these scenarios was compared against the best available data points for these emissions from the identified sources. Therefore, for some crop-country combinations, the best available data for emissions may come from the best available data for fertilizer inputs, re-modelled using IPCC best practices (i.e. rather than coming directly from any of the identified data sources).

In instances of equivalent uncertainty scores for specific data points, data points coming from data sets from which other data points were already selected were preferentially selected based on the higher likelihood of methodological consistency in the generation of the data points.

3. Carbon footprint methodology

3.1 Intended applications, audience, and practitioners

The intended audience of this study includes a number of government and industry stakeholders both within Canada, and internationally. These stakeholders include GIFS, the Saskatchewan Ministry of Agriculture, as well as relevant representatives of government and industry in the various countries to which comparisons are made in this report. The results of this study are intended to be used to draw meaningful comparisons between the carbon footprints of oats and barley grown within Saskatchewan, Canada, and countries representing major competitors in international markets. These results may also be used to identify potential hotspots within the supply chains of these crops that may serve as priority targets for future GHG mitigation efforts.

3.2 Functional unit

Results for each crop-region combination are reported according to a functional unit of one kilogram of dried product (i.e., barley or oats) at farm gate.

3.3 System boundaries

The system boundaries for this analysis included all relevant material, energy, and emissions flows associated with production of commodity field crops in each of the crop-region combinations. These included farm-level inputs of fertilizers, plant protection products, seed, and energy for irrigation, field activities, and post-harvest activities (i.e., product drying). All on-farm activities were considered as foreground processes, while all processes occurring upstream of the farm (i.e. production of inputs) were considered as background processes. Transportation of material inputs to the field was also considered. The geographical, temporal and technological boundaries were intended to be representative of actual contemporary production conditions in Saskatchewan, Prairie Provinces, Canada, Australia, France, Russia, Ukraine, Finland, Poland, and Sweden as possible. Section 3.6 lists the sources for each data point and their associated data quality scores relative to this overarching goal.

3.4 Cut-off criteria and exclusions

Across all crop-country combinations, material inputs and associated GHG emissions attributable to production and maintenance of infrastructure 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; Meisterling et al. 2009; Bortolini et al. 2014). These impacts decrease further when amortized against total crop production over the lifespan of the infrastructure (Ghamkhar et al. 2022), which may be up to 30 years for some machinery (Lips 2017).

3.5 Allocation methods

3.5.1 Manure

Manure inputs to fields were generated from animal production systems, where the animals ate crops that were originally fertilized using synthetic fertilizers. Therefore, the nutrients present in manure originated from synthetic fertilizer production processes. Based on this reasoning, manure inputs were modelled as these original synthetic fertilizer production processes, rather than as a co-product of animal production systems. This removes the need for allocation between manure and all other co-products of these animal production systems. However, the nutrients present in the manure were considered recycled materials since they contributed to the growing of the first round of crops (that fed

the animals), then the second round of crops (that are receiving the manure). A 50/50 allocation of upstream impacts between the first use and second, recycled use of nutrients was assumed, in line with recommendations from AFNOR (2011).

3.5.2 Barley/oat grain and straw

Barley and oats cultivation results in two co-products – barley or oat grain, and straw. While some crop residues are commonly left on fields and/or incorporated into soils, a portion of barley and oat straw is often harvested and removed from fields to be used in other processes (Blonk et al. 2022). Therefore, straw is a co-product of barley and oats production systems. The ISO 14044 standard specifies a hierarchy of strategies for dealing with processes that produce multiple co-products (i.e., multi-functionality). First, if possible, it is required that allocation be avoided by taking a sub-division or system expansion approach. If such an approach is infeasible and allocation is unavoidable, ISO 14044 dictates 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). Sub-division is not possible in this context. Similarly, since the goal of the analysis is to compare among individual products (i.e not including their co-products), system expansion was similarly not possible. Allocation was therefore required.

The first step in developing allocation factors for grain and straw was determining the total amount (in weight) of straw that is generated from the production of barley and oats. These amounts were estimated using a grain-to-straw ratios for each crop from each country's NIR, as used in the calculation of N inputs from crop residues for N_2O emissions using IPCC Tier 2 methodology (described in detail in section 3.7.2). The second step was to determine the proportion of straw produced that is removed from agricultural fields – that is, the proportion of above-ground crop residues that are a co-product. Significant difficulty was encountered in finding high-quality, crop-country specific information detailing amounts of barley or oats residues baled and removed from fields in each country. Estimates in the literature regarding straw removal rates vary significantly across different countries (e.g., from 1.48% to 66.67% of residues removed) (Blonk et al. 2022; dos Santos et al. 2023; Searle and Bitnere, 2017). When available, data on removal rates were taken from each country's NIR (Table 9). However, when this was not provided and given the variations found in the literature, a standardized straw removal rate of 33.34% was applied to all countries for both barley and oats residues (Blonk et al. 2022), also in line with Lafond et al. (2009). This removal rate was then applied to the amount of straw produced per unit of grain yield (see Table 30). Given the high degree of variability in estimates of straw removal rates this assumption was the subject of sensitivity analyses, in addition to the quality scores assigned to the straw yield data for each crop-country combination.

Table 9. Fraction of removed and burnt crop residues based on the NIR from Australia, Poland, and Sweden

Country	Fraction of crop residue removed from field	Fraction of crop residue that is burnt
Australia[a]	8%	14%
Poland[b]	70%	0.4%
Sweden[c]	10%	0

[a](Commonwealth of Australia 2023)

Following the identification of the amounts of straw co-produced with grain and removed from field for use, it was necessary to choose an allocation method for partitioning impacts between co-products. LCI data for barley and oats cultivation were sourced from a variety of databases, reports, and literature sources that varied in their allocation strategies. In most cases, co-production of straw was ignored, and all impacts were allocated to production of grain (Heusala et al. 2019; Hietala et al. 2022; Kytta et al. 2020; Lehuger et al. 2011; Röös et al. 2015; Schwenke et al. 2018). When impacts were allocated between co-products both system expansion (dos Santos et al. 2023; Prade et al. 2017; Uusitalo and Leino 2019) and economic allocation was also applied (Leppakoski et al. 2022). Moreover, data from Blonk et al. (2022) include allocation factors for straw and grain based on dry matter (mass), gross chemical energy content, or economic value.

While economic allocation between barley/oat grain and straw has been commonly applied in the agri-food LCA literature, strong arguments have been made against its use (Pelletier and Tyedmers 2011) on the basis that economic value bears no relationship to and fundamentally misrepresents the actuals flows of resources and emissions characteristic of industrial activities. For this reason, economic allocation was not used in this analysis, and allocation factors were instead defined based on underlying biophysical relationships, consistent with the ISO allocation hierarchy (ISO 2006c). Arulnathan et al. (2022) provide an in-depth discussion of the use of external- or internal-causality in choice of biophysical relationships used as a basis for allocation between co-products. In doing so, they provide a strong argument for the use of chemical energy content as an underlying biophysical relationship upon which to define allocation factors, as the amounts of energy present in co-products should roughly reflect the relative proportions of input energy used by the crops in production of each co-product, while other relationships, such as mass, may not (for example, in the case of processed oil seed crops yielding oil and protein fractions) (Arulnathan et al. 2022).

Both mass and energy-based allocation methods were examined for their appropriateness to use in this analysis. To generate mass allocation factors between grain and straw, the percent of straw removed for each country was multiplied by the estimates of total above-ground biomass for each country (as described above), and the proportions of total co-produced mass were used as allocation factors. Definition of energy-based allocation factors accounted for two important considerations: first that estimates of the relative energy contents of grain and straw were available in consistent units for calculation of allocation factors; and second that factors may be regionally resolved, as energy content of grain and straw may be impacted by both varietal (Montero et al. 2016; Rodehutscord et al. 2016) and local climate and soil conditions (Montero et al. 2016; Hernández et al. 2019). Montero et al. (2016), for example, find that wheat straw produced in Baja, California has an average higher heating value of 14.86 MJ/kg DM, less than that of the higher heating value of 16.68 MJ/Kg DM predicted for wheat straw produced in China (Niu et al. 2014).

Accounting for both the necessary consistency in units and potential regional differences in energy contents, only the energy allocation factors presented by van Paassen et al. (2019) were deemed appropriate for use in this study. Both Havrysh et al. (2021) and Feedipedia (Heuzé et al. 2015, 2021) provide the necessary energy contents for calculating allocation factors, but neither provide this

information on a spatially resolved basis. To calculate energy allocation factors, the values presented by Van Paassen et al. (2019) were adjusted to account for the grain and crop residue yields used in this analysis. Upon calculation of these energy-based allocation factors it was determined that the energy- and mass-based allocation factors differed very little (i.e., around 1% difference between them). Given the small differences in allocation factors, mass- and energy-based allocation were considered equivalent in this analysis. The allocation factors used in this analysis were therefore based on mass (in kg) of co-products, and are presented in Table 10. Further, a sensitivity analysis was not performed around this choice of allocation method since the differences in resulting impacts would be trivial.

Table 10. Mass and energy allocation factors used for partitioning of impacts between barley grain and straw in this analysis, taking into account the proportions of straw removed from fields (Blonk et al. 2022 and Lafond et al. 2009)

Crop	Region	Mass allocation		Energy allocation[a]	
		Grain	Straw	Grain	Straw
Barley	Canada	0.74	0.26	0.73	0.27
Barley	Australia	0.79	0.21	0.78	0.22
Barley	France	0.71	0.29	0.70	0.30
Barley	Russia	0.71	0.29	0.70	0.30
Barley	Ukraine	0.73	0.27	0.72	0.28
Oats	Canada	0.73	0.27	0.73	0.27
Oats	Australia	0.76	0.24	0.76	0.24
Oats	Finland	0.61	0.39	0.62	0.38
Oats	Poland	0.88	0.12	0.89	0.11
Oats	Sweden	0.92	0.08	0.92	0.08

[a] Based on the gross energy content of barley/oat grains and straw (Blonk et al. 2022)
[b] Includes grain yield and the portion of straw left on field

3.6 Foreground data collection

A large number of potential data sources were identified for modeling different crop-region combinations. In total, 15 sources were identified for barley and 16 for oats. These sources included LCI databases, peer-reviewed literature, and government and industry group publications and statistics. Overall, the identified sources include the majority of all foreground data required for modeling the crop-region combinations included in this analysis. The following sections present the best identified data for modeling each crop-region combination and associated data quality scores. Preceding these sections, a single section is presented in which assumptions regarding manure inputs to foreground systems are described. This section is presented separately from each crop to avoid repetition between sections as the information therein is relevant for all crops receiving manure.

3.6.1 Manure inputs

Manure inputs were included in relevant crop-country combinations as inputs of organic fertilizers. As detailed previously in section 3.5.1, manure inputs were modeled as equivalent to the nutrient inputs

from the specific crop-region combination fertilizer mix, divided in half to reflect the prior applications of synthetic fertilizers to crops fed to the animal (i.e. 50/50 recycling allocation strategy), with the excreted nutrients by-passed by the animals' digestive systems. Application of this allocation principle required data regarding approximate N, P, and K contents of the manure inputs. In all cases, inputs of manure were stated to be from pigs and poultry (van Paassen et al. 2019). Exact nutrient contents of different manures are dependent on dietary compositions and the amounts of different nutrients being taken in by the animals, as well as the form in which manure is managed (Galassi et al. 2010; Horf et al. 2022). This is reflected, for example, in differences in estimates of nutrient composition of pig slurry from Saskatchewan (Government of Saskatchewan 2022), or other European countries, such as Germany (Kuhn et al. 2018), Denmark (Sommer et al. 2014), and Czechia (Hlisnikovský et al. 2022).

The following assumptions were made regarding nutrient compositions of different manures. N and P contents of pig manure for all European countries were assumed to be the same as those in Germany, in line with Kuhn et al. (2018), and assuming pig slurry has a density of 1000 kg/m^3, within one standard deviation of average pig slurry densities as reported by Moral and Paredes (2005). K contents of pig manure for all European countries were assumed to be the same as those reported by Moral and Paredes (2005). These nutrient contents were also applied to manure inputs in Russian and Ukrainian production systems and data quality scores were assigned accordingly. The Ukrainian State Statistics Service listed two types of manure applied to crops: poultry, and agricultural animal manure. In line with other countries included in the analysis, the unspecified agricultural animal manure was assumed to be pig manure. This assumption is justified in light of the relative production scale of the pork industry in Ukraine, which produced more than twice as much meat than the Ukrainian cattle industry in 2021, while the Ukrainian dairy industry has experienced sharp declines in size in recent years (FAOstat 2021). N, P, and K contents of pig manure for Canada were assumed to be the same as average values reported by the Government of Saskatchewan (2022), also assuming pig slurry has a density of 1000 kg/m^3 (Moral and Paredes 2005).

N, P, and K contents of Canadian and European poultry manures were assumed to be the same as those reported by Azeez and Van Averbeke (2010). While more regionalized nutrient contents could be determined for poultry manure from North American systems based on previously reported laying hen and broiler feed compositions (Pelletier 2008; Pelletier et al. 2014; Turner et al. 2022), the mix of manure attributable to different poultry species is unknown, making accurate calculations of appropriate manure nutrient contents difficult. Finally, nutrient contents for pig, and average nutrient contents for poultry manure for Australia were taken from the Australian Grains Research and Development Corporation (Griffiths 2014). All assumed manure nutrient contents are reported in Table 10. Large losses of nutrients may occur during manure storage, after excretion but before manure is applied to fields (Tittonell et al. 2010; Bai et al. 2016). To take these factors into account, all assumed manure nutrient contents reported in Table 11 are contents following losses from manure storage systems. Therefore, all losses during storage are allocated to the animal production system that produced the manure, not to the crop systems currently being modelled.

Table 11. Assumed percent nutrient contents of pig and poultry manure at time of application to field

	North America		Europe (including Russia)		Australia	
	Pig	Poultry	Pig	Poultry	Pig	Poultry
N	0.389	3.71	0.598	3.71	1.9	3
P	0.126	1.465	0.293	1.465	2.5	2.15
K	0.168	1.795	0.226	1.795	0.7	1.3

Based on the above information, data quality scores were assigned to those flows of synthetic fertilizers included in production models to represent the original nutrients found in the manure inputs, based on the quality of the sources from which nutrient contents were obtained. Rather than providing separate scores for pig and poultry manure, scores were assigned for each manure modeled as N fertilizers, P fertilizers, and K fertilizers. In each case, data quality scores were assigned to reflect the worst data quality between the sources considered, thereby providing a conservative view of data quality related to modeling of manure inputs. Data quality scores for manure inputs to each country are presented in Tables 11-13.

Manure nutrient contents were derived from the same sources for all Canadian crop production systems, so they all received the same data quality scores (Table 12). A score of 4 was given for reliability because it is unclear how many sites were sampled in determination of pig manure nutrient contents (Government of Saskatchewan 2022). A score of 5 was given for completeness because the assumed nutrient compositions of poultry manure are taken from a single large supplier with little relevance to the markets being modeled (Azeez et al. 2010). A score of 5 was given for temporal correlation because the data collected for determining pig manure nutrient contents were collected from 1998-2000 (Government of Saskatchewan 2022). A score of 5 was given for geographic correlation because the information on poultry manure nutrient content is based on estimates from a company in South Africa (Azeez et al. 2010). Finally, a score of 4 was given for technological correlation because manure is being modeled as upstream synthetic fertilizer inputs – that is, this data quality score does not reflect a limitation of the sources from which nutrient contents were taken, but rather a limitation of the modeling procedure used.

Table 12. Data quality scores for manure inputs to Canadian crop systems

	Reliability	Completeness	Temporal correlation	Geographic correlation	Technological correlation
Manure modeled as N fertilizer	4	5	5	5	4
Manure modeled as P fertilizer	4	5	5	5	4
Manure modeled as K fertilizer	4	5	5	5	4

For European cropping systems, a score of 4 was given for reliability as nutrient contents are derived from qualified estimates (Kuhn et al. 2018) (Table 13). Similarly, a score of 5 was given for

completeness as both the number of sites, and their relevance to the specific markets are unknown. A score of 5 was given to temporal correlation because estimates of pig manure K contents are from a paper published in 2005 (Moral and Paredes 2005) without any indication of when data was collected, so it was assumed to be 5 years prior to publication data, and because estimates of poultry manure nutrient contents were from 2006 (Azeez et al. 2010). Finally, a score of 4 was given for technological correlation for the same reasons as previously described for Saskatchewan and Canadian cropping systems.

Table 13. Data quality scores for manure inputs to European crop systems

	Reliability	Completeness	Temporal correlation	Geographic correlation	Technological correlation
Manure modeled as N fertilizer	4	5	5	5	4
Manure modeled as P fertilizer	4	5	5	5	4
Manure modeled as K fertilizer	4	5	5	5	4

Finally, for Australian cropping systems, a score of 4 was given for reliability as nutrient content estimates provided by the GRDC were assumed to be based on expert opinion because the original source from which they were derived is unavailable (Griffiths 2014) (Table 14). The unavailability of this source also resulted in a score of 5 for completeness. A score of 5 was given for temporal correlation, as the estimates of manure nutrient contents are based on data collected in 1992. A score of 5 was given for geographic correlation because no explicit information was available indicating the geographic scope of the data that was collected. Finally, a score of 4 was given for technological correlation for the same reasons as previously described for Saskatchewan, Canadian, and European cropping systems.

Table 14. Data quality scores for manure inputs to Australian crop systems

	Reliability	Completeness	Temporal correlation	Geographic correlation	Technological correlation
Manure modeled as N fertilizer	4	5	5	5	4
Manure modeled as P fertilizer	4	5	5	5	4
Manure modeled as K fertilizer	4	5	5	5	4

3.6.2 Barley data sources

3.6.2.1 Saskatchewan, Prairie Provinces, and Canada

Generally, data characterizing barley production in Saskatchewan and Prairie Provinces/Canada was of relatively high quality (Tables 15-16), although many sources received a score of 5 for completeness if they did not report the percentage of supply covered. However, this lack of reporting is common practice, so it does not necessarily indicate an issue with the dataset. A large portion of the Canadian data came from the sources used in the CRSC report on Canadian barley ((S&T)2 Consultants Inc. 2022b). This included fertilizers, pesticides, irrigation, field activities, and regionalized emissions factors for field-level emissions and soil carbon. Due to variable data quality and availability, some additional data were sourced from other sources, primarily Blonk et al. (2022). This included seed inputs, transportation of farm inputs, and post-harvest energy use. Yield data were sourced from Statistics Canada, using a 5-year average from 2019-2024, and the standard straw removal data from Blonk et al. (2022) was used.

Field-level emissions were calculated using IPCC Tier 1 and 2 methods, using nutrient input data and regionalized emissions factors from the CRSC report. Soil carbon change was also taken from the CRSC report, which was calculated in line with the Canadian NIR, using more regionalized factors, in accordance with IPCC Tier 2 methodology (however these estimates are not crop specific).

Table 15. Data sources used for modeling Saskatchewan barley production, and their associated pedigree matrix scores.

Data point	Source	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Yield (grain)	Statistics Canada (2024c)	1	2	1	1	1
Straw removal	Blonk et al. (2022)	2	5	3	2	3
Seed	Blonk et al. (2022)	1	3	4	5	1
Lime inputs	Blonk et al. (2022)	4	5	4	5	5
Fertilizer inputs	((S&T)2 Consultants Inc. 2022b)	4	5	5	1	4
Manure inputs	Amounts based on Blonk et al. (2022) and nutrient contents from Azeez and Van Averbeke (2010); Government of Saskatchewan (2022)	4	5	5	5	4

Data point	Source	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Herbicide, fungicide and insecticide inputs	((S&T)2 Consultants Inc. 2022b)	1	2	3	3	4
Irrigation energy	((S&T)2 Consultants Inc. 2022b)	1	5	2	1	1
Field activities energy	((S&T)2 Consultants Inc. 2022b)	2	5	3	1	4
Transportation	Blonk et al. (2022)	5	5	5	5	5
Post-harvest energy use	Blonk et al. (2022)	2	5	2	2	1
Direct and indirect N_2O emissions	Modelled using IPCC Tier 2 with N input data from ((S&T)2 Consultants Inc. 2022b)	4	5	5	1	4
CO_2 emissions from lime and urea	Modelled using IPCC Tier 1 with N input data from ((S&T)2 Consultants Inc. 2022b)	4	5	5	2	4
Soil carbon changes	Modelled using NIR data via ((S&T)2 Consultants Inc. 2022b)	1	1	1	1	4

Table 16. Data sources used for modeling Prairie Province and Canadian barley production, and their associated pedigree matrix scores.

Data point	Source	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Yield (grain)	Statistics Canada (2024c)	1	2	1	1	1
Straw removal	Blonk et al. 2022	2	5	3	2	3
Seed	Blonk et al. (2022)	1	3	4	5	1
Lime inputs	Blonk et al. (2022)	4	5	4	5	5

Data point	Source	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Fertilizer inputs	((S&T)2 Consultants Inc. 2022b)	4	5	4	1	4
Manure inputs	Amounts based on Blonk et al. (2022) and nutrient contents from Azeez and Van Averbeke 2010; Government of Saskatchewan 2022	4	5	5	5	4
Herbicide, fungicide and insecticide inputs	((S&T)2 Consultants Inc. 2022b)	1	2	3	3	4
Irrigation energy	((S&T)2 Consultants Inc. 2022b)	1	5	2	1	1
Field activities energy	((S&T)2 Consultants Inc. 2022b)	2	5	3	1	4
Transportation	Blonk et al. (2022)	5	5	5	5	5
Post-harvest energy use	Blonk et al. (2022)	2	5	2	1	1
Direct and indirect N_2O emissions	Modelled using IPCC Tier 2 with N input data from ((S&T)2 Consultants Inc. 2022b)	4	5	4	1	4
CO_2 emissions from lime and urea	Modelled using IPCC Tier 1 with N input data from ((S&T)2 Consultants Inc. 2022b)	4	5	4	2	4
Soil carbon changes	Modelled using NIR data via ((S&T)2 Consultants Inc. 2022b)	1	1	1	1	4

Data characterizing Australian barley production were of relatively high quality (Table 17), although many of the selected data sources were assigned completeness scores of 5 for not indicating the percentage of supply covered. The highest quality data characterizing yields was from the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES, 2024), although a score of 2 was given for temporal correlation, due to the lack of data reported from 2022 onwards.

The majority of Australian barley data were sourced from Blonk et al. (2022), since this is a consistent data source for agri-food LCI data, with relatively high data quality. There were very few other sources of LCI data for Australian barley, and they generally did not have similarly high data quality. Data on the total inputs of herbicides, fungicides and insecticides came from Blonk et al. (2022), however they did not provide crop- or country-specific data on the products or active ingredients that were applied. Therefore, assumptions have been made regarding Australian pesticide mixes. Specific types of herbicides and fungicides were estimated based on the proportions of inputs indicated in the barley production weighted average from the regional data sets from the AusLCI database (Grant, 2016). Insecticides are assumed to be an equal proportion mix of registered insecticides for control of aphids, armyworm, Helicoverpa spp., and blue oat mite (GRDC 2018), the predominant insect pests affecting Australian barley crops (Arthur et al. 2015; Ward et al. 2021).

Field-level emissions were modelled using IPCC Tier 1 and 2 methods, with input data from Blonk et al. (2022), and regional emissions factors from the Australian NIR. Soil carbon change data were calculated based on the data reported in the Australian NIR, in accordance with IPCC Tier 2 methodology (however, these estimates are not crop specific).

Table 17. Data sources used for modeling Australian barley production, and their associated pedigree matrix scores

Data point	Source	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Yield (grain)	ABARES	1	3	2	1	1
Straw removal	Australian Government (2023)	1	1	2	1	3
Seed	Blonk et al. (2022)	1	3	4	5	1
Lime inputs	Blonk et al. (2022)	4	5	4	5	5
Fertilizer inputs	Blonk et al. (2022)	2	5	4	1	4
Manure inputs	Amounts based on Blonk et al. (2022) and nutrient contents	4	5	5	5	4

Data point	Source	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
	from Griffiths (2014)					
Herbicide, fungicide and insecticide inputs	total amounts from Blonk et al. (2022), types from AusLCI	4	5	3	3	1
Irrigation energy	Blonk et al. (2022)	2	5	3	1	4
Field activities energy	Blonk et al. (2022)	2	5	3	1	4
Transportation	Blonk et al. (2022)	5	5	5	5	5
Post-harvest energy use	Blonk et al. (2022)	2	5	2	1	1
Direct and indirect N_2O emissions	Modelled using IPCC Tier 2 with N input data from Blonk et al. 2022	2	5	4	1	4
CO_2 emissions from lime and urea	Blonk et al. (2022)	2	5	4	2	4
Soil carbon changes	Modelled using NIR data (Government of Australia 2022)	1	1	1	1	4

3.6.2.3 France

Data sources used for modeling French barley production are presented in Table 18. These data are of similarly high quality, with the majority of data being sourced from Blonk et al. (2022). The yield value was calculated as a five-year average from 2020 to 2024 from the "Crop production in EU standard humidity" data browser (2024). As was done for Canada and Australia, total amounts of herbicide, fungicide, and insecticide inputs were sourced from Blonk et al. (2022). Information on pesticide types used in France were taken from FAOstat (2024) using an average consumption from 2018-2022.

The method for modeling soil carbon changes used by Ben Aoun et al. (2016) resulted in lower total uncertainty than those proposed to be used elsewhere herein. However, they used the CERES-EGC model (Gabrielle et al. 2006), a process-based model for simulation of soil carbon dynamics. Use of process-based models requires significant expertise to properly parametrize the models, and these models generally have large context-specific data requirements, making their implementation challenging (Adams et al. 2013). While the results of these models may provide more accurate estimates of soil carbon changes associated with French canola production in specific geographical/temporal contexts, the use of process-based models is outside the scope of the current analysis. Rather, use of the

methods proposed herein (which are consistent with the French NIR (CCNUCC 2022)) represent best practices for the current analysis, in accordance with IPCC Tier 2 methodology, despite that these estimates are not crop specific. Field-level emissions were calculated using IPCC Tier 1 and 2 methods, with nutrient inputs from Blonk et al. (2022) and regionalized EFs from the French NIR.

Table 18. Data sources used for modeling French barley production, and their associated pedigree matrix scores

Data point	Source	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Yield (grain)	Eurostat Database	1	3	1	1	1
Straw removal	Blonk et al. (2022)	2	5	3	2	3
Seed	Blonk et al. (2022)	1	3	4	5	1
Lime inputs	Blonk et al. (2022)	4	5	4	5	5
Fertilizer inputs	Blonk et al. (2022)	2	5	4	1	4
Manure (modelled as fertilizers)	van Paassen et al. (2019) for amounts, based on nutrient contents from Azeez and Van Averbeke (2010), Kuhn et al. (2018), and Moral and Paredes (2005)	4	5	5	5	4
Pesticide amounts	Blonk et al. (2022)	4	3	2	1	1
Fungicides, herbicides, and insecticides	FAOstat	1	3	1	1	4
Irrigation energy use	Blonk et al. 2022	2	5	3	1	4

Data point	Source	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Field activities energy use	Blonk et al. (2022)	2	5	3	1	4
Transportation of field inputs	Blonk et al. (2022)	5	5	5	5	5
Post-harvest energy use	Blonk et al. (2022)	2	5	2	1	1
Direct and indirect N2O emissions	Modelled using IPCC Tier 1 methods with N input data from Blonk et al. 2022	2	5	4	1	4
CO2 emissions from lime and urea	Blonk et al. (2022)	2	5	4	2	4
Soil carbon changes	Modelled using NIR values (CCNUCC 2022)	1	1	1	1	4

3.6.2.4 Russia

Generally, data characterizing barley production in Russia were of relatively high quality (Table 19). The five-year average yield (2019-2023) was calculated from FAOstat (2024). Inputs for seed, lime and fertilizer application, were sourced from Blonk et al. (2022).

Herbicide, insecticide and fungicide inputs amounts came from Blonk et al. (2022) for Russia. However, information on the types of pesticides applied to Russian barley could not be found. In the absence of this information, the pesticide distribution is assumed to be the same as that used in Ukraine, and applied to the amounts given by Blonk et al. (2022).

Energy use and transportation data were sourced from Blonk et al. (2022). However, these data points have generally lower data quality because they are fairly old, and often come from expert opinion or the sources are not indicated. Values for N_2O and CO_2 emissions from nutrient inputs were calculated using IPCC Tier 1 and 2 methods, and soil organic carbon (SOC) change data were sourced from the Russian NIR, in accordance with IPCC Tier 2 methodology (however, these estimates are not crop specific).

Table 19. Data sources used for modeling Russian barley production, and their associated pedigree matrix scores

Data point	Source to be used	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Yield (grain)	FAOStat	1	3	1	1	1

Data point	Source to be used	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Straw removal	Blonk et al. (2022)	2	5	3	2	3
Seed	Blonk et al. (2022)	1	3	4	5	1
Lime inputs	Blonk et al. (2022)	4	5	4	5	5
Manure nutrient contents	Amounts from Blonk et al. (2022), nutrient contents from Azeez and Van Averbeke (2010), Kuhn et al. (2018), and Moral and Paredes (2005)	4	5	5	5	4
Fertilizer inputs	Blonk et al. (2022)	2	5	4	1	4
Pesticide input amounts	Blonk et al. (2022)	4	3	2	1	1
Herbicide, insecticide, and fungicide input types	Ukrstat	1	1	3	3	3
Irrigation energy	Blonk et al. (2022)	2	5	3	1	4
Field activities energy use	Blonk et al. (2022)	2	5	3	1	4
Transportation	Blonk et al. (2022)	5	5	5	5	5
Post harvest	Blonk et al. (2022)	2	5	2	1	1
Field level emissions of N_2O	IPCC Tier 2 with inputs from Blonk et al. (2022)	2	5	4	1	4
CO_2 emissions from lime and urea	IPCC Tier 1 with inputs from Blonk et al. (2022)	2	5	4	2	4
Soil carbon changes	IPCC Tier 2 from NIR	1	1	1	1	4

3.6.2.5 Ukraine

Barley production data for Ukraine were also of relatively high quality (Table 20). The five-year average yield was based on data from the Ukrainian State Statistics Service (Ukrstat), covering the period 2017–2021. Data on seed and lime usage were sourced from Blonk et al. (2022), while fertilizer input data were obtained from UkrStat. Details on herbicide, insecticide, and fungicide application—including both the quantities applied and the types used—were also provided by Ukrstat. As with Russia, data on energy use and transportation came from Blonk et al. (2022), though these inputs are considered lower in reliability.

Emissions of N_2O and CO_2 from nutrient inputs were estimated using IPCC Tier 1 and 2 approaches. Changes in soil organic carbon (SOC) were derived from Ukraine's National Inventory Report (NIR), following IPCC Tier 2 guidance, though the values are not specific to barley.

Table 20. Data sources used for modeling Ukrainian barley production, and their associated pedigree matrix scores

Data point	Source to be used	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Yield (grain)	Ukrstat	1	3	1	1	1
Straw removal	Blonk et al. (2022)	2	5	3	2	3
Seed	Blonk et al. (2022)	1	3	4	5	1
Lime inputs	Blonk et al. (2022)	4	5	4	5	5
Manure nutrient contents	Inputs from Blonk et al. (2022) with nutrient contents from Azeez and Van Averbeke (2010), Kuhn et al. (2018), and Moral and Paredes (2005)	4	5	5	5	4
Fertilizer inputs	Ukrstat	1	3	1	1	3
Herbicide, insecticide, and fungicide input types and amounts	Amounts from Blonk et al. (2022), types from Ukrstat	4	3	2	1	3
Irrigation energy	Blonk et al. (2022)	2	5	3	1	4
Field activities energy use	Blonk et al. (2022)	2	5	3	1	4
Transportation	Blonk et al. (2022)	5	5	5	5	5
Post harvest	Blonk et al. (2022)	2	5	2	1	1

Data point	Source to be used	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Field level emissions of N_2O	IPCC Tier 1 with inputs from Ukrstat	2	1	1	1	3
CO_2 emissions from lime and urea	IPCC Tier 1 with inputs from Ukrstat	1	1	1	2	3
Soil carbon changes	IPCC Tier 2 from NIR	1	1	1	1	4

3.6.3 Oats data sources

3.6.3.1 Saskatchewan, Prairie Provinces, and Canada

The data sources used for Saskatchewan and Prairie Province/Canadian oats were of fairly high quality (Tables 21-22). However, ss with barley, many sources received a score of 5 for completeness if they did not indicate the percentage of supply covered. For Canada, the majority of data came from the sources used in the CRSC report on Canadian oats ((S&T)2 Consultants Inc. 2022b). This included data for seed, fertilizers, pesticides, field activities, and regionalized emissions factors for field-level emissions and soil carbon change. In the cases of missing or low quality data in the CRSC report, data were generally sourced instead from Blonk et al. (2022), including for lime, manure inputs, transportation of farm inputs, and post-harvest energy use. Yield data came from Statistics Canada, representing a 5-year average from 2019-2024, and the standard straw removal rate was applied to all Canadian regions (Blonk et al. 2022).

Field-level emissions were calculated using IPCC Tier 1 and 2 methods, with nutrient input data and regional EFs sourced from the CRSC report. Soil carbon change data were also sourced from the CRSC report, which were calculated in line with the IPCC Tier 2 methods used in the Canadian NIR, with regionalized EFs (however, these data were not crop-specific).

Table 21. Data sources used for modeling Saskatchewan oats production, and their associated pedigree matrix scores.

Data point	Source	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Yield (grain)	Statistics Canada (2024c)	1	2	1	1	1
Straw removal	Blonk et al. (2022)	2	5	3	2	3
Seed	((S&T)2 Consultants Inc. 2022b)	4	4	4	1	1
Fertilizer inputs	((S&T)2 Consultants Inc. 2022b)	4	5	5	1	4
Lime inputs	Blonk et al. (2022)	4	5	4	5	5

Data point	Source	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Manure inputs	Blonk et al. (2022) and nutrient contents from Azeez and Van Averbeke (2010); Government of Saskatchewan (2022)	4	5	5	5	4
Herbicide, fungicide and insecticide inputs	((S&T)2 Consultants Inc. 2022b)	1	2	3	3	4
Field activities energy	((S&T)2 Consultants Inc. 2022b)	2	5	3	1	4
Transportation	Blonk et al. (2022)	5	5	5	5	5
Post-harvest energy use	Blonk et al. (2022)	2	5	2	2	1
Direct and indirect N_2O emissions	Modelled using IPCC Tier 2 with N input data from ((S&T)2 Consultants Inc. 2022b)	4	5	5	1	4
CO_2 emissions from lime and urea	Modelled using IPCC Tier 1 with N input data from ((S&T)2 Consultants Inc. 2022b)	4	5	5	2	4
Soil carbon changes	Modelled using NIR data via ((S&T)2 Consultants Inc. 2022b)	1	1	1	1	4

Table 22. Data sources used for modeling Prairie Province/Canadian oats production, and their associated pedigree matrix scores.

Data point	Source	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Yield (grain)	Statistics Canada (2024c)	1	2	1	1	1
Straw removal	Blonk et al. (2022)	2	5	3	2	3
Seed	((S&T)2 Consultants Inc. 2022b)	4	4	4	1	1
Fertilizer inputs	((S&T)2 Consultants Inc. 2022b)	4	5	5	1	4
Manure inputs	Blonk et al. (2022) and nutrient contents from Azeez and Van Averbeke (2010); Government of Saskatchewan (2022)	4	5	5	5	4
Lime inputs	Blonk et al. (2022)	4	5	4	5	5
Herbicide, fungicide and insecticide inputs	((S&T)2 Consultants Inc. 2022b)	1	2	3	3	4
Irrigation energy	((S&T)2 Consultants Inc. 2022b)	1	5	2	1	1
Field activities energy	((S&T)2 Consultants Inc. 2022b)	2	5	3	1	4
Transportation	Blonk et al. (2022)	5	5	5	5	5
Post-harvest energy use	Blonk et al. (2022)	2	5	2	1	1
Direct and indirect N_2O emissions	Modelled using IPCC Tier 2 with N input data from ((S&T)2 Consultants Inc. 2022b)	4	5	5	1	4

Data point	Source	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
CO$_2$ emissions from lime and urea	Modelled using IPCC Tier 1 with N input data from ((S&T)2 Consultants Inc. 2022b)	4	5	5	2	4
Soil carbon changes	Modelled using NIR data via ((S&T)2 Consultants Inc. 2022b)	1	1	1	1	4

3.6.3.2 Australia

In general, the available LCI data for Australian oats production were of fairly high quality (Table 23). Yield data came from the Australian Bureau for Agricultural and Resource Economics and Sciences (ABARES), and represent a 4-year average from 2020-2024. Data on straw removal rate and burnt crop residues were sourced from the Australian NIR (Australian Government, 2023).

The sources of data for seed, lime inputs, and transportation from Blonk et al. (2022) are all around 10 years old at the time of writing this report. Data on post-harvest energy use has also been taken from Blonk et al. (2022). Specific types of herbicides and fungicides were estimated based on the proportions of inputs taken from the production weighted average of oats regional data sets found in the AusLCI database (Grant, 2016). Insecticides are assumed to be an equal proportion mix of registered insecticides for control of aphids, armyworm, Helicoverpa spp., and blue oat mite (GRDC 2018), the predominant insect pests affecting Australian barley crops (Arthur et al. 2015; Ward et al. 2021).

Field-level emissions were calculated using IPCC Tier 1 and 2 methods with nutrient input data from Blonk et al. (2022), and regional EFs from the Australian NIR. Soil carbon change was calculated based on the data reported in the Australian NIR, in line with IPCC Tier 2 methods (however, these data were not crop-specific).

Table 23. Data sources used for modeling Australian oats production, and their associated pedigree matrix scores

Data point	Source	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Yield (grain)	ABARES	1	3	2	1	1
Straw removal	Australian Government (2023)	1	1	2	1	3
Seed	Blonk et al. (2022)	1	3	4	5	1
Lime inputs	Blonk et al. (2022)	4	5	4	5	5

Data point	Source	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Fertilizer inputs	Blonk et al. (2022)	2	5	4	1	4
Herbicide, fungicide and insecticide inputs	Total amounts from Blonk et al. (2022), types from AusLCI	4	5	3	3	1
Irrigation energy	Blonk et al. (2022)	2	5	3	1	4
Field activities energy	Blonk et al. (2022)	2	5	3	1	4
Transportation	Blonk et al. (2022)	5	5	5	5	5
Post-harvest energy use	Blonk et al. (2022)	2	5	2	1	1
Direct and indirect N_2O emissions	Modelled using IPCC Tier 2 with N input data from Blonk et al. (2022)	2	5	4	1	4
CO_2 emissions from lime and urea	Blonk et al. (2022)	2	5	4	2	4
Soil carbon changes	Modelled using NIR data (Government of Australia 2022)	1	1	1	1	4

3.6.3.3 Finland

Data characterizing oats production for Finland were of relatively high quality (Table 24). 5-year average yield data were taken from Natural Resources Institute Finland (LUKE, 2024). Seed, transportation, and energy use data were taken from Blonk et al. (2022). Fertilizer and lime inputs came from Uusitalo and Leino (2019), based on data from LUKE (2024).

For pesticide inputs, data on the total amounts of herbicides, fungicides, and insecticides were taken from Blonk et al. (2022), and data on the specific types of plant protection products came from FAOStat (2024) based on Finland's use of herbicides, insecticides, fungicides, and other plant protection products between 2018-2022. These data points were given a technological correlation score of 4 because they are not crop specific.

Field-level emissions were calculated using IPCC Tier 1 and 2 methods with nutrient input data from Uusitalo and Leino (2019), and regional EFs from the Finnish NIR. Soil carbon change was calculated

based on the data reported in the Finnish NIR, in line with IPCC Tier 2 methods (however, these data were not crop-specific).

Table 24. Data sources used for modeling Finnish oats production, and their associated pedigree matrix scores

Data point	Source to be used	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Yield (grain)	LUKE	1	2	1	1	1
Straw removal	Blonk et al. (2022)	2	5	3	2	3
Seed	Blonk et al. (2022)	1	5	4	5	1
Lime inputs	Uusitalo and Leino (2019)	1	3	5	1	1
Manure inputs and nutrient contents	Blonk et al. (2022) for amounts, and Azeez and Van Averbeke (2010), Kuhn et al. (2018), and Moral and Paredes (2005)	4	5	5	5	4
Fertilizer inputs	Uusitalo and Leino (2019)	1	3	5	1	1
Herbicide, insecticide, and fungicide input amounts	Blonk et al. (2022)	4	3	2	1	1
Herbicide, insecticide, and fungicide input types	FAOStat	1	3	1	1	4
Irrigation energy	Blonk et al. (2022)	2	5	3	1	4
Field activities energy use	Blonk et al. (2022)	2	5	3	1	4
Transportation	Blonk et al. (2022)	5	5	5	5	5
Post harvest	Blonk et al. (2022)	2	5	2	1	1
Field level emissions of N_2O	IPCC Tier 2 with inputs from Uusitalo and Leino (2019)	1	3	5	1	1

Data point	Source to be used	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
CO_2 emissions from lime and urea	IPCC Tier 1 with inputs from Uusitalo and Leino (2019)	1	3	5	2	1
Soil carbon changes	IPCC Tier 2 from NIR	1	1	1	1	4

3.6.3.4 Poland

Data for oats production in Poland were of relatively high quality (Table 25). Five-year average yield data (2019–2023) were sourced from the Central Statistical Office of Poland (2024). All on-farm input values, including seeds, fertilizers, and lime, were taken from Blonk et al. (2022).

For pesticide inputs, data on the total amounts of herbicides, fungicides, and insecticides were taken from Blonk et al. (2022), and data on the specific types of plant protection products came from FAOStat (2024) based on the use of herbicides, insecticides, fungicides, and other plant protection products in Poland between 2018-2022. These data points were given a technological correlation score of 4 because they are not crop specific.

Field-level emissions were calculated using IPCC Tier 1 and 2 methods with nutrient input data from Blonk et al (2022). Soil carbon change was calculated based on the data reported in the Polish NIR, in line with IPCC Tier 2 methods (however, these data were not crop-specific).

Table 25. Data sources used for modeling Polish oats production, and their associated pedigree matrix scores

Data point	Source to be used	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Yield (grain)	Statistics Poland	1	3	1	1	1
Straw removal	Ministry of Climate and Environment (2023)	1	5	1	1	1
Seed	Blonk et al. (2022)	1	3	4	5	1
Lime inputs	Blonk et al. (2022)	4	5	4	5	5
Manure inputs and nutrient contents	Blonk et al. (2022) for amounts, and Azeez and Van Averbeke (2010), Kuhn et al. (2018), and Moral and Paredes (2005)	4	5	5	5	4

Data point	Source to be used	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Fertilizer inputs	Blonk et al. (2022)	2	5	4	1	4
Herbicide, insecticide, and fungicide input amounts	Blonk et al. (2022)	4	3	2	1	1
Herbicide, insecticide, and fungicide input types	FAOStat	1	3	1	1	4
Irrigation energy	Blonk et al. (2022)	2	5	3	1	4
Field activities energy use	Blonk et al. (2022)	2	5	3	1	4
Transportation	Blonk et al. (2022)	5	5	5	5	5
Post harvest	Blonk et al. (2022)	2	5	2	1	1
Field level emissions of N_2O	IPCC Tier 2 with inputs from Blonk et al. (2022)	2	5	4	1	4
CO_2 emissions from lime and urea	IPCC Tier 1 with inputs from Blonk et al. (2022)	2	5	4	2	4
Soil carbon changes	IPCC Tier 2 from NIR	1	1	1	1	4

3.6.3.5 Sweden

Data on oats production in Sweden were similarly of good quality (Table 26). The average yield over five years was based on data from Statistics Sweden (SCB, 2024). All relevant farm inputs, such as seeds, fertilizers, and lime were sourced from Blonk et al. (2022).

Total quantities of herbicides, insecticides, and fungicides were taken from Blonk et al. (2022), and the specific types of plant protection products used in Sweden came from FAOStat (2024), covering usage between 2018 and 2022. Since this data represents general agricultural use rather than oat-specific data, they were assigned a technological correlation score of 4.

Field emissions were estimated using IPCC Tier 1 and 2 methods, based on input data from Blonk et al. (2022) and regional emission factors from the NIR. Soil carbon stock changes were estimated from Sweden's NIR using IPCC Tier 2 approaches, though these values were not crop-specific.

Table 26. Data sources used for modeling Swedish oats production, and their associated pedigree matrix scores

Data point	Source to be used	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Yield (grain)	Statistics Sweden	1	3	1	1	1
Straw removal	Swedish Environmental Protection Agency (2023)	1	5	4	1	1
Seed	Blonk et al. (2022)	1	3	4	5	1
Lime inputs	Blonk et al. (2022)	4	5	4	5	5
Manure inputs and nutrient contents	Blonk et al. (2022) for amounts, and Azeez and Van Averbeke (2010), Kuhn et al. (2018), and Moral and Paredes (2005)	4	5	5	5	4
Fertilizer inputs	Blonk et al. (2022)	2	5	4	1	4
Herbicide, insecticide, and fungicide input amounts	Blonk et al. (2022)	4	3	2	1	1
Herbicide, insecticide, and fungicide input types	FAOStat	1	3	1	1	4
Irrigation energy	Blonk et al. (2022)	2	5	3	1	4
Field activities energy use	Prade et al. (2017)	2	5	3	1	4
Transportation	Blonk et al. (2022)	5	5	5	5	5
Post harvest	Blonk et al. (2022)	2	5	2	1	1
Field level emissions of N_2O	IPCC Tier 2 with inputs from Blonk et al. (2022)	2	5	4	1	4
CO_2 emissions from lime and urea	IPCC Tier 1 with inputs from Blonk et al. (2022)	2	5	4	2	4
Soil carbon changes	IPCC Tier 2 from NIR	1	1	1	1	4

3.7 Background data providers

The ecoinvent database version 3.10 was chosen for all background data providers. A single background data source was chosen to ensure methodological consistency for all background data. The ecoinvent database was chosen since it contains background datasets for all relevant data categories at the appropriate levels of regional specificity (country-level as well as for the province of Saskatchewan). It is also one of the most commonly used background databases for LCA practitioners. Table 27 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 28 lists all processes used in the modifications. These tables were split in order to avoid redundancy, as electricity providers were changed across many of the background processes listed in Table 27. In general, processes were modified to use electricity providers specific to the country or province modelled, unless otherwise indicated in the table. In some cases, production processes representing specific pesticide active ingredients are unavailable in ecoinvent v.3.10. 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 27. LCI flows, the processes used to model them from ecoinvent v.3.10, and any modifications made to those processes.

Data point	Process (from ecoinvent v.3.10)	Modifications
Seed		
Barley seed	barley seed production, for sowing | barley seed, for sowing | APOS, U - GLO	electricity and barley providers changed for each region
Oat seed	oat seed production, for sowing | oat seed, for sowing | APOS, U - RoW	electricity and oats providers changed for each region
Fertilizers (including manure modelled as upstream synthetic fertilizer production)		
Urea	urea production | urea | APOS, U – RER or RNA	electricity providers changed for each region for CA, the national average electricity mix was used since urea is produced in many Canadian provinces (Cheminfo Services Inc. 2016)
Ammonia	ammonia production, steam reforming, liquid | ammonia, anhydrous, liquid | APOS, U – RER or RNA	electricity and natural gas providers changed for each region
Ammonium nitrate	ammonium nitrate production | ammonium nitrate | APOS, U – RER or RNA	electricity providers changed for each region for CA, the national average electricity mix was used since ammonium nitrate is produced in many Canadian provinces (Cheminfo Services Inc. 2016) ammonia providers changed to regionalized ammonia providers (modifications described above)
Ammonium chloride	ammonium chloride production | ammonium chloride | APOS, U - GLO	ammonia and electricity providers changed for each region

Data point	Process (from ecoinvent v.3.10)	Modifications
Calcium ammonium nitrate	calcium ammonium nitrate production	calcium ammonium nitrate – RNA or RER	electricity providers changed for each region for CA, the national average electricity mix was used since ammonium nitrate is produced in many Canadian provinces (Cheminfo Services Inc. 2016) ammonia providers changed to regionalized ammonia providers (modifications described above)
Calcium nitrate	calcium nitrate production	ammonium nitrate	APOS, U - RER	ammonia provider changed for each region
Urea ammonium nitrate (UAN)	urea ammonium nitrate production	urea ammonium nitrate mix	APOS, U – RNA or RER	ammonium nitrate provider changed to regionally modified ammonium nitrate process for each region (described above) electricity providers changed for each region for CA, the national average electricity mix was used since urea ammonium nitrate is produced in many Canadian provinces (Cheminfo Services Inc. 2016)
Monoammonium phosphate (MAP)	market for monoammonium phosphate	monoammonium phosphate	APOS, U – RNA or RER	ammonia, electricity, and phosphate rock providers changed for each region for CA and SK, process was modelled as taking place in AB since that is the only location of a production facility for MAP (Cheminfo Services Inc. 2016)
Diammonium phosphate (DAP)	diammonium phosphate production	diammonium phosphate	APOS, U – RNA or RER	electricity providers changed for each region ammonia providers changed to regionalized ammonia providers (modifications described above) for CA and SK, process was modelled as taking place in AB since that is the only location of a production facility for MAP (Cheminfo Services Inc. 2016), and no information was provided for production locations for DAP
Single superphosphate	single superphosphate production	single superphosphate	APOS, U - RER	electricity and phosphate rock providers changed for each region for CA and SK, process was modelled as taking place in AB since that is the only location of a production facility for MAP (Cheminfo Services Inc. 2016), and no information was provided for production locations for superphosphate
Triple superphosphate	triple superphosphate production	triple superphosphate	APOS, U - RER	electricity, phosphate rock, and phosphoric acid providers changed for each region for CA and SK, process was modelled as taking place in AB since that is the only location of a production facility for MAP (Cheminfo Services Inc. 2016), and no information was provided for production locations for superphosphate
Phosphate rock	phosphate rock beneficiation	phosphate	electricity providers changed for each region

Data point	Process (from ecoinvent v.3.10)	Modifications
	rock, beneficiated | APOS, U - RER	
Potassium chloride (potash) – SK, CA, US	potassium mining and benefication | potassium chloride | APOS, U - CA-SK	electricity providers changed for each region for CA, process was modelled as SK since that is the only location for a production facility of potash, and SK was modelled as SK (Cheminfo Services Inc. 2016)
Potassium chloride (potash) – FR, RU, UA	potassium chloride production | potassium chloride | APOS, U	electricity providers changed for each region
Potassium sulfate	potassium sulfate production | potassium sulfate | APOS, U - RER	electricity providers changed for each region for CA, process was modelled as SK since that is the only location for a production facility of potassium, and SK was modelled as SK (Cheminfo Services Inc. 2016) potassium chloride providers changed for each region (SK for both SK and CA)
Potassium nitrate	potassium nitrate production | potassium nitrate | APOS, U - RER	potassium chloride changed for each region
Ammonium sulfate	ammonium sulfate production | ammonium sulfate | APOS, U - RER	ammonia providers changed to regionalized ammonia providers (modifications described above) electricity providers changed for each region for CA, the national average electricity mix was used since ammonium sulfate is produced in several Canadian provinces (Cheminfo Services Inc. 2016)
Sulfur	natural gas production | sulfur | APOS, U - CA-AB or DE	electricity providers changed for each region for CA and SK, the AB electricity mix was used since sulfur is mainly produced in AB (Prud'homme 2013)
Zinc	primary zinc production from concentrate | zinc | APOS, U – CA-QC	electricity and urea providers changed for each region for CA, the national average electricity mix was used since zinc is produced in several Canadian provinces, for SK the MB electricity mix was used since SK does not produce zinc and MB is the largest producer (World Atlas 2022)
Lime	lime production, milled, loose | lime | APOS, U – CA-QC or CH	electricity providers changed for each region for CA, the national average electricity mix was used since lime is produced in several Canadian provinces, and SK used for SK (Vagt 2015)
Plant protection products		
Glyphosate	glyphosate production | glyphosate | APOS, U - RER	electricity providers changed for each region US national electricity grids were used for CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al. 2022a)

Data point	Process (from ecoinvent v.3.10)	Modifications
		ammonia and decarbonised water providers changed for each region
Pyroxasulfone, Metolachlor, S-Metolachlor	acetamide-anillide-compound production, unspecified | acetamide-anillide-compound, unspecified | APOS, U - RER	electricity providers changed for each region US national electricity grids were used for CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al. 2022a) ammonia, sulfur and decarbonised water providers changed for each region
Sulfentrazone, propiconazole, prothioconazole, epoxiconazole, tebuconazole, metconazole, Tetraconazole, Carfentrazon-ethyl, metribuzin, terbuthylazine, metamitron, metribuzin, Prometryn	triazine-compound production, unspecified | triazine-compound, unspecified | APOS, U - RER	electricity providers changed for each region US national electricity grids were used for CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al. 2022a) ammonia and decarbonised water providers changed for each region
Glufosinate, chlorpyrifos, Methidathion, Dimethoate, Malathion, Pirimiphos-methyl, Fenitrothion, Organophosphate ester	organophosphorus-compound production, unspecified | organophosphorus-compound, unspecified | APOS, U - RER	electricity providers changed for each region US national electricity grids were used for CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al. 2022a) ammonia, decarbonised water and sulfur providers changed for each region
MCPA, 2,4-D, Quizalofop-ethyl, 2-Methyl-4-chlorophenoxyacetic, Aryloxyphenoxyprop Spiroxamine ionate	phenoxy-compound production | phenoxy-compound | APOS, U - RER	electricity providers changed for each region US national electricity grids were used for CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al. 2022a) ammonia and decarbonised water providers changed for each region
Bromoxynil, Azoxystrobin, Dimoxystrobin, chlorothalonil, ethaboxam	nitrile-compound production | nitrile-compound | APOS, U - RER	electricity providers changed for each region US national electricity grids were used for CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al. 2022a) ammonia and decarbonised water providers changed for each region
Bentazon	benzo[thia]diazole-compound production | benzo[thia]diazole-compound | APOS, U - RER	electricity providers changed for each region US national electricity grids were used for CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al. 2022a) ammonia, sulfur and decarbonised water providers changed for each region

Data point	Process (from ecoinvent v.3.10)	Modifications
Fluroxypyr, Diflufenican, Boscalid, Fluxapyroxad, Clopyralid, Picloram, Aminopyralid, Flumetsulam, Pyriproxyfen, Fipronil,	pyridine-compound production | pyridine-compound | APOS, U - RER	electricity providers changed for each region US national electricity grids were used for CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al. 2022a) ammonia and decarbonised water providers changed for each region
Triallate	[thio]carbamate-compound production | [thio]carbamate-compound | APOS, U - RER	electricity providers changed for each region US national electricity grids were used for CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al. 2022a) ammonia, sulfur and decarbonised water providers changed for each region
Diquat, paraquat	bipyridylium-compound production | bipyridylium-compound | APOS, U - RER	electricity providers changed for each region US national electricity grids were used for CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al. 2022a) ammonia, sulfur and decarbonised water providers changed for each region
Ethalfluralin, Trifluralin, Pendimethalin	dinitroaniline-compound production | dinitroaniline-compound | APOS, U - RER	electricity and ammonia providers changed for each region US national electricity grids were used for CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al. 2022a)
Deltamethrin, cyhalothrin-lambda, Bifenthrin, Alpha-cypermethrin, Beta-cypermethrin, Zeta-cypermethrin, Cypermethrin, Etofenprox, Beta-Cyfluthrin, Permethrin, Cynodon-ethyl, Esfenvalerate, Gamma-cyhalothrin, Tau-fluvalinate, Tefluthrin	pyrethroid-compound production | pyrethroid-compound | APOS, U - RER	electricity providers changed for each region US national electricity grids were used for CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al. 2022a) ammonia and decarbonised water providers changed for each region
Atrazine	atrazine production | atrazine | APOS, U - RER	electricity and ammonia providers changed for each region
Dimethanamid-P	dimethenamide production | dimethenamide | APOS, U - RER	electricity, ammonia, sulfur and decarbonised water providers changed for each region
Napropamide	napropamide production | napropamide | APOS, U - RER	electricity, sulfur, and decarbonised water providers changed for each region

Data point	Process (from ecoinvent v.3.10)	Modifications
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, captan, folpet	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
Diazoles	diazole-compound production | diazole-compound | APOS, U - RER	ammonia and electricity providers changed for each region
Tebufenpyrad	pyridazine-compound production | pyridazine-compound | APOS, U - RER	ammonia, electricity, sulfur, and decarbonised water providers changed for each region
Oxyfluorfen	diphenylether-compound production | diphenylether-compound | APOS, U - RER	ammonia, electricity, sulfur, and decarbonised water providers changed for each region
Imazalil, Imazalil sulfate	imidazole production | imidazole | APOS, U - RER	ammonia and electricity providers changed for each region
Dimethomorph, Diazines	morpholine production | morpholine | APOS, U - GLO	ammonia and electricity providers changed for each region
Iron sulfate	iron sulfate production | iron sulfate | APOS, U - RER	electricity providers changed for each region
Copper sulfate	copper sulfate production | copper sulfate | APOS, U - GLO	copper oxide and electricity providers changed for each region
Sulfonylurea, Urea derivates	[sulfonyl]urea-compound production | [sulfonyl]urea-compound | APOS, U - RER	ammonia, electricity, sulfur, and decarbonised water providers changed for each region
Bixafen, Isopyrazam, Sedaxane, Penflufen	pyrazole production | pyrazole | APOS, U - RER	electricity providers changed for each region
All other active ingredients	pesticide production, unspecified | pesticide, unspecified | APOS, U - RER	electricity providers changed for each region US national electricity grids were used for CA and SK since the majority of pesticides used in Canada are sourced from the US (Bamber et al. 2022a)

Data point	Process (from ecoinvent v.3.10)	Modifications
		ammonia, urea, sulfur and decarbonised water providers changed for each region
Energy providers		
Diesel	diesel, burned in agricultural machinery | diesel, burned in agricultural machinery | APOS, U - GLO	infrastructure and machinery flows removed
Electricity	market for electricity, low voltage | electricity, low voltage | APOS, U (for each region)	processes for each region used without modifications
Natural gas (heat)	heat production, natural gas, at boiler condensing modulating >100kW | heat, district or industrial, natural gas | APOS, U – CA-QC or Europe without Switzerland	electricity and natural gas providers changed for each region
Transportation		
Truck transportation	market for transport, freight, lorry 7.5-16 metric ton, EURO4 | transport, freight, lorry 7.5-16 metric ton, EURO4 | APOS, U - RER	

Table 28. Processes used for modification of background processes

Modifications	Processes used for modifications
Electricity	- market for electricity, low voltage | electricity, low voltage | APOS, U – Saskatchewan, - market group for electricity, low voltage | electricity, low voltage | APOS, U – Canada, - market for electricity, low voltage | electricity, low voltage | APOS, U – Australia - market for electricity, low voltage | electricity, low voltage | APOS, U – France - market for electricity, low voltage | electricity, low voltage | APOS, U – Russia - market group for electricity, low voltage | electricity, low voltage | APOS, U – Ukraine - market for electricity, low voltage | electricity, low voltage | APOS, U – Finland - market for electricity, low voltage | electricity, low voltage | APOS, U – Poland - market for electricity, low voltage | electricity, low voltage | APOS, U – Sweden
Barley seed	- barley seed production, for sowing | barley seed, for sowing | APOS, U – Saskatchewan - barley seed production, for sowing | barley seed, for sowing | APOS, U – Canada - barley seed production, for sowing | barley seed, for sowing | APOS, U – Australia - barley seed production, for sowing | barley seed, for sowing | APOS, U – France - Russia: barley seed production, for sowing | barley seed, for sowing | APOS, U – GLO

Modifications	Processes used for modifications
	- Ukraine: barley seed production, for sowing | barley seed, for sowing | APOS, U - GLO
Oat seed	- oat seed production, for sowing | oat seed, for sowing | APOS, U – Saskatchewan - oat seed production, for sowing | oat seed, for sowing | APOS, U – Canada - oat seed production, for sowing | oat seed, for sowing | APOS, U – Australia - oat seed production, for sowing | oat seed, for sowing | APOS, U – Finland - oat seed production, for sowing | oat seed, for sowing | APOS, U – Poland - oat seed production, for sowing | oat seed, for sowing | APOS, U – Sweden
Natural gas	- market group for natural gas, high pressure | natural gas, high pressure | APOS, U – Canada - market for natural gas, high pressure | natural gas, high pressure | APOS, U – Australia - market for natural gas, high pressure | natural gas, high pressure | APOS, U – Alberta - market for natural gas, high pressure | natural gas, high pressure | APOS, U – Finland - market for natural gas, high pressure | natural gas, high pressure | APOS, U – France - market for natural gas, high pressure | natural gas, high pressure | APOS, U – Poland - market for natural gas, high pressure | natural gas, high pressure | APOS, U – Russia - market for natural gas, high pressure | natural gas, high pressure | APOS, U – Sweden
Phosphate rock	- market for phosphate rock, beneficiated | phosphate rock, beneficiated | APOS, U – Europe - market for phosphate rock, beneficiated | phosphate rock, beneficiated | APOS, U – United States - phosphate rock beneficiation | phosphate rock, beneficiated | APOS, U | - Australia - phosphate rock beneficiation | phosphate rock, beneficiated | APOS, U | - France
Phosphoric acid	- phosphoric acid production, dihydrate process | phosphoric acid, fertiliser grade, without water, in 70% solution state | APOS, U – United States - phosphoric acid production, dihydrate process | phosphoric acid, fertiliser grade, without water, in 70% solution state | APOS, U – Rest of World - phosphoric acid production, dihydrate process | phosphoric acid, fertiliser grade, without water, in 70% solution state | APOS, U - Europe
Potassium chloride	- potassium mining and benefication | potassium chloride | APOS, U | - Australia - potassium mining and benefication | potassium chloride | APOS, U – Saskatchewan - potassium chloride production | potassium chloride | APOS, U | - France - potassium mining and benefication | potassium chloride | APOS, U | - United states - potassium chloride production | potassium chloride | APOS, U – Russia - potassium chloride production | potassium chloride | APOS, U – Ukraine - potassium chloride production | potassium chloride | APOS, U – Rest of Europe
Urea	- Urea production | urea | APOS, U | - Canada
Ammonia	- ammonia production, steam reforming, liquid | ammonia, anhydrous, liquid | APOS, U | - Australia - ammonia production, steam reforming, liquid | ammonia, anhydrous, liquid | APOS, U | - United States - ammonia production, steam reforming, liquid | ammonia, anhydrous, liquid | APOS, U | - France - ammonia production, steam reforming, liquid | ammonia, anhydrous, liquid | APOS, U | - Russia - ammonia production, steam reforming, liquid | ammonia, anhydrous, liquid | APOS, U | - Ukraine

Modifications	Processes used for modifications
	- ammonia production, steam reforming, liquid | ammonia, anhydrous, liquid | APOS, U | - Rest of Europe
Decarbonised water	- market for water, decarbonised | water, decarbonised | APOS, U – Rest of World - market for water, decarbonised | water, decarbonised | APOS, U – Canada - market for water, decarbonised | water, decarbonised | APOS, U – United States - market for water, decarbonised | water, decarbonised | APOS, U – France - market for water, decarbonised | water, decarbonised | APOS, U – Russia
Sulfur	- market for sulfur dioxide, liquid | sulfur dioxide, liquid | APOS, U - Europe - market for sulfur dioxide, liquid | sulfur dioxide, liquid | APOS, U – Rest of World - natural gas production | sulfur | APOS, U – United States - natural gas production | sulfur | APOS, U – France - natural gas production | sulfur | APOS, U – Russia - natural gas production | sulfur | APOS, U – Ukraine
Ammonium nitrate	- ammonium nitrate production | ammonium nitrate | APOS, U | - Saskatchewan - ammonium nitrate production | ammonium nitrate | APOS, U | - Canada - ammonium nitrate production | ammonium nitrate | APOS, U | - France - ammonium nitrate production | ammonium nitrate | APOS, U | - United States - ammonium nitrate production | ammonium nitrate | APOS, U | - Australia - ammonium nitrate production | ammonium nitrate | APOS, U | - Russia - ammonium nitrate production | ammonium nitrate | APOS, U | - Ukraine - ammonium nitrate production | ammonium nitrate | APOS, U | - Rest of Europe

3.7 Emissions modelling

3.7.1 Soil carbon change

The estimates of soil carbon change from each country's NIR were used (or the CRSC reports for Canada, since they included more regional granularity and were based on the same methods as the Canadian NIR). These values were calculated by dividing the total soil carbon change for each country's cropland (cropland remaining cropland and land converted to cropland) by the total area of cropland (remaining and converted) in each country. These area-based estimates were then scaled by the yield of each crop in each country to give carbon sequestration or emission estimates per functional unit of 1 kg of crop. Apart from the differences in yield, these values are 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 at a crop-specific level. For estimates of net carbon sequestration, these were modelled 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.

3.7.2 N_2O emissions

In order to ensure methodological consistency for all crop-country combinations, the modelling practices employed in each country's NIR were used, with all deviations documented (Table 29).

Direct N_2O

Direct N_2O emissions were calculated in accordance with the IPCC (2019) equation 11.2 such that

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

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}

EF_{1i} represents emissions factors developed for N_2O emissions from synthetic fertilizers, organic N application, N inputs from crop residues, and mineralization of N due to losses of soil organic matter in kg N_2O-N (kg N input)$^{-1}$

F_{CR} represents the annual amount of N in above and belowground crop residues, including N-fixing crops, and from forage/pasture renewal, returned to soils in kg N year^{-1}

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}

The input values for synthetic fertilizer and manure came from the inventory values, as described in section 3.6. The F_{SOM} values were calculated using the estimates of soil carbon change, as described in section 3.7.1. For any countries that had net carbon losses from the soil (rather than sequestration), these carbon losses were used to calculate the losses of N based on the N:C ratio of 0.1 (Cetipa 2022; Commonwealth of Australia 2022; Environment and Climate Change Canada 2022; Federal Environment Agency 2022). Inputs of N from crop residue were calculated for each crop-country combination, as described below in section 3.7.3.

For Canada, Prairie Provinces, and Saskatchewan, the direct N_2O emission factors estimated in the CRSC carbon footprint methodology report were used ((S&T)2 Consultants Inc. 2021), since they are based on the Canadian NIR, calculated at a sub-regional level, then aggregated to the provincial and national scale. The Canadian, Prairie Province, and Saskatchewan emission factors are production weighted averages of the Reconciliation Unit (RU) factors presented in the CRSC reports. Since the production volumes in each RU differ by crop, the emission factors also differ due to the differences in production weighted averages.

The values for the direct N_2O emission factors for Australia, France, Finland, Poland, Sweden, Russia, and Ukraine were taken from each country's NIR (Citepa, 2022; Commonwealth of Australia, 2022; Statistics Finland, 2023, Ministry of Environmental Protection and Natural Resources of Ukraine, 2023; Polish Ministry of Climate and Environment, 2023; Russian Federation, 2022; Swedish Environmental Protection Agency, 2023). The Australian and Russian NIRs presented country-specific Tier 2 emission factors, whereas the French, Ukrainian, Finnish, Polish, and Swedish NIRs used default IPCC Tier 1 values (IPCC, 2006;2019).

Indirect N_2O

Indirect N₂O emissions come from both volatilization (or gasification) of applied N as NH_3 and NO_x, and leaching as NO_3, followed by subsequent emissions of N₂O from each of these N compounds. Indirect N₂O emissions from volatilization or gasification were calculated according to equation 11.11 from IPCC (2019), such that

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

where

$N_2O_{(ATD)} - N$ represents the annual amount of $N_2O - N$ produced from atmospheric deposition of N volatilised from managed soils in kg N₂O–N yearr^{-1}

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^{-1}

$Frac_{GASM}$ 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)$^{-1}$ with values taken from table 11.3 in IPCC (2019)

EF_4 represents emission factor for N₂O emissions from atmospheric deposition of N on soils and water surfaces, in [kg N–N₂O (kg NH₃–N + NO$_x$–N volatilised)$^{-1}$] with values taken from table 11.3 in IPCC (2019)

Indirect emissions of N₂O from N leaching and runoff were calculated according to equation 11.10 from IPCC (2019) for regions where leaching/runoff occurs such that

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

where

$N_2O_{(L)}$–N represents the annual amount of N₂O–N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs, in kg N₂O–N year^{-1}

F_{SN} represents the annual amount of synthetic fertilizer N applied to soils in regions where leaching/runoff occurs, in kg N year^{-1}

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^{-1}

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^{-1}

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^{-1} calculated according to equation 11.8 in IPCC (2019)

$Frac_{Leach}$ 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)$^{-1}$ with values taken from table 11.3 in IPCC (2019)

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)$^{-1}$ with values taken from table 11.3 in IPCC (2019)

For Canada, as per the CRSC methodology report ((S&T)2 Consultants Inc 2021), the IPCC Tier 1 methodology was followed for indirect N_2O emissions from volatilization. Regionalized Tier 2 values for $Frac_{LEACH}$ were taken from the CRSC methodology report ((S&T)2 Consultants Inc 2021), and aggregated to Saskatchewan and national averages based on the relative proportions of production for each crop in each region. The Tier 1 value for EF_5 was used. For Australia, France, Finland, Poland, Sweden, Russia, and Ukraine, the values for $Frac_{GAS}$, $Frac_{LEACH}$, EF_4 and EF_5 were taken from each country's NIR (Citepa, 2022; Australian Government, 2023; Statistics Finland, 2023, Ministry of Environmental Protection and Natural Resources of Ukraine, 2023; Polish Ministry of Climate and Environment, 2023; Russian Federation, 2023; Swedish Environmental Protection Agency, 2023). The Ukrainian NIR provided a country-specific value for $Frac_{GASF}$, and all other values were default Tier 1. All values used in the Russian NIR for indirect N_2O emissions were default Tier 1 values.

Table 29. Emission factors and fractions used to model N_2O emissions according to the NIR for each country.

Region	EF1 (kg N_2O-N kg N applied^{-1})	$Frac_{GASF}$ (kg N volatilized kg N applied^{-1})	$Frac_{GASM}$ (kg N volatilized kg N applied^{-1})	EF4 (kg N_2O-N (kg NH_3-N + NOx-N volatilized)$^{-1}$)	$Frac_{LEACH}$ (kg N leached kg N applied^{-1})	EF5 (kg N_2O-N kg N leached^{-1})
Saskatchewan	Oats[a]: synthetic N = 0.004, crop residue N = 0.0034 Barley[a]: synthetic N = 0.0041, crop residue N = 0.0034	0.1[b]	0.2[b]	0.01[b]	Oats[c]: 0.154 Barley[c]: 0.142	0.0075[d]
Prairie Provinces	Oats[a]: synthetic N = 0.005, crop residue N = 0.0042 Barley[a]: synthetic N = 0.0055, crop residue N = 0.0046	0.1[b]	0.2[b]	0.01[b]	Oats[c]: 0.162 Barley[c]: 0.150	0.0075[d]

Region	EF1 (kg N_2O-N kg N applied^{-1})	$Frac_{GASF}$ (kg N volatilized kg N applied^{-1})	$Frac_{GASM}$ (kg N volatilized kg N applied^{-1})	EF4 (kg N_2O-N (kg NH_3-N + NOx-N volatilized)$^{-1}$)	$Frac_{LEACH}$ (kg N leached kg N applied^{-1})	EF5 (kg N_2O-N kg N leached^{-1})
Canada	Oats[a]: synthetic N = 0.0056, crop residue N = 0.0047 Barley[a]: synthetic N = 0.0058, crop residue N = 0.0048	0.1[b]	0.2[b]	0.01[b]	Oats[c]: 0.171 Barley[c]: 0.155	0.0075[d]
Canada without Saskatchewan	Oats[a]: synthetic N = 0.0073, crop residue N = 0.0061 Barley[a]: synthetic N = 0.0070, crop residue N = 0.0059	0.1[b]	0.2[b]	0.01[b]	Oats[c]: 0.189 Barley[c]: 0.165	0.0075[d]
Australia	Crop residue and organic: 0.01[e] Synthetic fertilizer (irrigated): 0.0085[f] Synthetic fertilizer non-irrigated: 0.002[f] Mineralization: 0.002[g]	0.11[h]	0.21[h]	Irrigated: 0.0085[i] Non-irrigated: 0.002[i]	0.24[h]	0.011[h]
France	Humid climate – synthetic N: 0.016[h], other N inputs: 0.006[h] Dry climate – all N inputs: 0.005[h]	0.11[h]	0.21[h]	Humid climate: 0.014[h] Dry climate: 0.005[h]	0.24[h]	0.011[h]

Region	EF1 (kg N_2O-N kg N applied^{-1})	Frac$_{GASF}$ (kg N volatilized kg N applied^{-1})	Frac$_{GASM}$ (kg N volatilized kg N applied^{-1})	EF4 (kg N_2O-N (kg NH_3-N + NOx-N volatilized)$^{-1}$)	Frac$_{LEACH}$ (kg N leached kg N applied^{-1})	EF5 (kg N_2O-N kg N leached^{-1})
Ukraine	Synthetic N, crop residue, organic, and mineralization: 0.01[e]	0.145[j]	0.2[j]	0.01[e]	0.3[e]	0.0075[e]
Russia	Synthetic N - Chernozems soils: 0.0126[k], soddy-podzolic soils: 0.0238[k], other: 0.012[k] Crop residue, organic, and mineralization: 0.01[e]	0.11[e]	0.21[e]	0.01[e]	0.3[e]	0.0075[e]
Finland	Synthetic N, crop residue, organic, and mineralization: 0.01[e]	0.015[l]	0.085[l]	0.01[e]	0.144[l]	0.011[h]
Poland	Synthetic N, crop residue, organic, and mineralization: 0.01[e]	0.11[e]	0.21[e]	0.01[e]	0.3[e]	0.0075[e]
Sweden	Synthetic N, crop residue, organic, and mineralization: 0.01[e]	0.0194[m]	0.1577[m]	0.01[e]	0.1334[m]	0.0075[e]

[a] CRSC methodology report ((S&T)2 Consultants Inc. 2022c) Table 5-3, production-weighted for each crop based on RU-level production and EFs

[b] CRSC methodology report ((S&T)2 Consultants Inc. 2022c) section 5.3.2, based on IPCC Tier 1 default factor

[c] CRSC methodology report ((S&T)2 Consultants Inc. 2022c) Table 5-4, production-weighted for each crop based on RU-level production and Frac$_{LEACH}$ factors

[d]CRSC methodology report ((S&T)2 Consultants Inc. 2022c) section 5.2, based on IPCC Tier 1 default factor
[e]Default Tier 1 factor (IPCC 2006) Tables 11.1 and 11.3
[f](Commonwealth of Australia 2023) (Table 5.19)
[g](Commonwealth of Australia 2023) Section 3.D.a.5
[h]Default Tier 1 factor (IPCC 2019) Tables 11.1 and 11.3
[i]Same as EF1 (Commonwealth of Australia 2023)
[j]Ministry of Environmental Protection and Natural Resources of Ukraine. 2023
[k]Russian Federation. 2023
[l]Statistics Finland. 2023
[m]Swedish Environmental Protection Agency. 2023

3.7.3 N inputs from crop residues

Retention of crop residues on agricultural fields after crop harvesting may impart benefits to agricultural soils. Potential benefits include limiting soil water evaporation, reducing risks of soil erosion by wind and water, and increases in soil carbon stocks and sequestration (Ranaivoson et al. 2017). These benefits may be accompanied, however, by increased emissions of N_2O resulting from microbial N mineralization and nitrification of residues, the rate of which is dependent on the N content of crop residues (Chen et al. 2013; Abalos et al. 2022). Accurate modeling of N_2O emissions therefore requires information related to crop residue yields and associated management practices, such as their removal from fields, as well as the N content of these residues. Crop residue-related management practices, yields, and N contents for each crop-country combination were mostly sourced from each country's NIR (Table 30). When specific data on (above- or belowground) residue-to-grain, moisture content, or residue removal rates was not available in the NIR, the default IPCC (2019) values were used specifically for barley/oats.

Table 30. Factors used to calculate N inputs from crop residues for each crop-country combination.

	Moisture content (%)	Aboveground crop residues (kg DM/kg yield)	Belowground crop residues (kg DM/kg yield)	Aboveground residues N content (kg/kg residue)	Belowground residues N content (kg/kg residue)
Oats Canada	13[a]	1.12[b]	0.91[b]	0.0068[b]	0.0138[b]
Barley Canada	13[a]	1.08[b]	0.43[b]	0.0081[b]	0.0124[b]
Oats Australia	12[c]	1.24[c]	0.40[c]	0.006[c]	0.01[c]
Barley Australia	12[c]	1.42[c]	0.61[c]	0.006[c]	0.01[c]
Barley France[d]	11	1.2	0.48	0.007	0.014
Barley Ukraine[e]	14	1.4	0.8	0.005	0.012
Barley Russia[f]	11	1.2	0.26	0.007	0.014
Oats Finland[g]	14	2.17	0.39	0.007	0.008

	Moisture content (%)	Aboveground crop residues (kg DM/kg yield)	Belowground crop residues (kg DM/kg yield)	Aboveground residues N content (kg/kg residue)	Belowground residues N content (kg/kg residue)
Oats Poland[h]	14	1.1	0.38	0.0075	0.0075
Oats Sweden[i]	14	0.89	0.25	0.0073	0.008

[a](Canadian Grain Commission 2021)
[b](Thiagarajan et al. 2018)
[c](Commonwealth of Australia 2023) Table A5.5.9.1
[d]Citepa. 2023
[e]Ministry of Environmental Protection and Natural Resources of Ukraine. 2023
[f]Default IPCC values (2019)
[g]Statistics Finland. 2023
[h]Polish Ministry of Climate and Environment. 2023
[i]Swedish Environmental Protection Agency. 2023

3.8 Impact assessment methods

The carbon footprint of each crop-country model was calculated using the GWP100 impact category from the IPCC 2021 AR6 methodology (Cilleruelo 2022). This method is based on the most recent Assessment Report (AR6) released by the IPCC (IPCC 2022), which reports all characterization factor values used in calculation of global warming impacts.

3.9 Calculation of production weighted average global carbon footprints

As a point of comparison, global, production weighted average carbon footprints were calculated for each crop to compare with the carbon footprint results from Saskatchewan cropping systems. These were calculated by first determining the proportion of total production represented by each country included in the analysis, as reported in Table 2. These proportions were then multiplied by the calculated impact assessment results (both with and without soil carbon change), and the products summed. Importantly, calculation of these production weighted average carbon footprints did not include the impacts attributable to Saskatchewan cropping systems. They did, however, include the impacts attributable to Canadian production systems.

3.10 Data quality and uncertainty assessment

Data quality indicator scores were computed for each LCI data point based on the pedigree matrix scores assigned during the data quality assessment stage (reported in Tables 11-21). 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, as described in section 2.4. 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. 2020). These uncertainty values were sourced from Frischknecht et al., (2005), which provides generic base uncertainty factors specific to sector or type of flow (Table 31). These generic factors were used since data were collected from various sources and it was not possible to consistently calculate the stochastic 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. The 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. 2020).

Table 31. Base uncertainty factors for the inherent stochasticity in combustion (c), process (p) and agricultural (a) processes, based on the sector of the activity. Source: Frischknecht et al. (2005).

Input/output group	c	p	a
Demand of:			
Thermal energy, electricity, semi-finished products, working material, waste treatment services	1.05	1.05	1.05
Transport services (tkm)	2.00	2.00	2.00
Infrastructure	3.00	3.00	3.00
Resources:			
Primary energy carriers, metals, salts	1.05	1.05	1.05
Land use, occupation	1.50	1.50	1.50
Land use, transformation	2.00	2.00	2.00
Pollutants emitted to water:			
BOD, COD, DOC, TOC, inorganic compounds (NH_4, PO_4, NH_3, Cl, Na, etc.)		1.50	
Individual hydrocarbons, PAH		3.00	
Heavy metals		5.00	1.80
Pesticides			1.50
NO_3, PO_4			1.50
Pollutants emitted to soil:			
Oil, hydrocarbon total		1.50	
Heavy metals		1.50	1.50
Pesticides			1.20
Pollutants emitted to air:			
CO_2	1.05	1.05	
SO_2	1.05		
NMVOC total	1.50		
NOx, N_2O	1.50		1.40
CH_4, NH_3	1.50		1.20
Individual hydrocarbons	1.50	2.00	
PM>10	1.50	1.50	
PM10	2.00	2.00	
PM2.5	3.00	3.00	
Polycyclic aromatic hydrocarbons (PAH)	3.00		
CO, heavy metals	5.00		
Inorganic emissions, others		1.50	
Radionuclides (e.g., Radon-222)		3.00	

3.11 Sensitivity analysis

Sensitivity analyses were performed to determine the sensitivity of the final results to any methodological choices that were based on assumptions, and that made significant contributions to the overall carbon footprint results. These were determined in consultation with representatives from GIFS and the Ministry, and based on the carbon footprint and contribution analysis results. Topics for the

sensitivity analysis included the assumed crop residue straw-to-grain ratios and removal rates, and uncertainty ranges for N_2O emissions, since these were the most influential sensitivity analyses in the previous Saskatchewan crop carbon footprint report (Bamber et al. 2022b). Other sensitivity analyses were performed in the previous report, specifically for assumptions around cut-off criteria and exclusions, manure nutrient contents, allocation methods, and impact assessment methods, but these were not influential on the carbon footprint results, therefore they were not repeated in this report.

3.11.1 Residue removal

Similar to straws of other cereals, oats and barley straw may also be retained or removed from fields. Oats and barley straw is commonly used for animal bedding and has also shown potential as a substrate for bioenergy production (Zhao et al. 2018; Szufa et al. 2020). Oats straw may also be used as livestock feed as is it generally considered to be of higher nutritional quality than barley or wheat straw (Government of Saskatchewan 2024). In contrast, retention of oats straw on fields may be associated with reductions in runoff and soil erosion (Cerdà et al. 2017), and may provide benefits to the soil microbiome (Kimeklis et al. 2023). The only estimates of sustainable oats and barley residue harvest rates that could be found were for European Union countries. Scarlat et al. (2010) estimate that 40% of oats and barley residues may be harvested sustainably in EU countries. This estimate is much lower than that suggested by Borrega et al. (2022), who estimate the residue biomass potential for Finnish oats and barley to be about 4000 kg per hectare. This corresponds to a residue removal rate of approximately 92%, assuming average yields for Finnish oats production in 2023 as reported by the Finnish national statistics database (LUKE, 2024) and using the aboveground residue yields from Thiagarajan et al. (2018). Since Borrega et al. (2022) seek to estimate total biomass potential, however, it is unlikely that their estimate corresponds to a sustainable residue removal rate. In the absence of more granular data for each country, the standard 33.34% removal rate has been used first as a sensitivity analysis for all aboveground oats and barley residues from countries with an alternate removal rate. A second analysis was then performed by applying a 40% straw removal rate to all crop-countries. This latter rate is slightly higher than the estimated sustainable residue removal rate used in the Agrifootprint Database (Blonk et al. 2022).

3.11.2 Crop residue yields and N contents

Large differences were observed in the above and below ground crop residue yields and N contents across the regions included in this analysis. Given the potentially important role that N from crop residues may play in determining field level nitrogenous emissions, a sensitivity analysis was conducted to explore how these regional differences may be impacting results. Specifically, average values for above and below ground residue yields and N contents were calculated for each crop (Table 32), and these values were used in calculations of the N inputs from crop residues for each crop-region combination. Use of these alternative crop residue yields and N contents alters both the field level emissions due to differences in the N contribution made by crop residues to each system, and alters the allocation factors associated with removed crop residues in the barley and oats production systems. The allocation factors used in this sensitivity analysis were calculated following the procedure outlined in section 3.5.2, using the assumed straw removal rate.

Table 32. Average crop residue yields and N content values used for sensitivity analyses, including the new allocation factors used

Crop	Moisture content (%)	Aboveground crop residues (kg DM/kg yield)	Belowground crop residues (kg DM/kg yield)	Aboveground residues N content (kg/kg residue)	Belowground residues N content (kg/kg residue)	Allocation factors	
						Grain	Straw
Barley	12	1.26	0.58	0.007	0.012	0.704	0.296
Oats	13	1.30	0.47	0.007	0.009	0.697	0.303

3.11.3 N$_2$O emissions modelling

For each emission factor or fraction used in the N$_2$O emission calculations, a sensitivity analysis was conducted to use instead the minimum and maximum values from the uncertainty ranges given (Tables 33-34). These were obtained from the NIRs or IPCC reports that reported the uncertainty associated with each factor.

Table 33. Lowest N$_2$O emission factors used for barley and oats sensitivity analyses (values marked with * did not vary from the baseline analysis)

Region	EF1 for synthetic N (kg N$_2$O-N kg N applied^{-1})	EF1 for crop residues (kg N$_2$O-N kg N applied^{-1})	EF1 for manure inputs (kg N$_2$O-N kg N applied^{-1})	EF1 for N mineralization (kg N$_2$O-N kg N applied^{-1})	EF4 (kg N$_2$O-N (kg NH$_3$-N + NOx-N volatilized)$^{-1}$)	EF5 (kg N$_2$O-N kg N leached^{-1})
Saskatchewan	0.0026	0.0022	0.0022	-	0.0064	0.0048
Prairie Provinces	0.0035 (barley), 0.0032 (oats)	0.0029 (barley), 0.0027 (oats)	0.0029 (barley), 0.0027 (oats)	-	0.0064	0.0048
Canada	0.0037 (barley), 0.0036 (oats)	0.0031 (barley), 0.003 (oats)	0.0031 (barley), 0.003 (oats)	-	0.0064	0.0048
Australia	0.002* (non-irrigated land) 0.0085* (irrigated land)	0.002	0.002 (dairies, feedlots, poultry), 0.0039* (piggeries)	0.002*	0.002* (non-irrigated land) 0.0085* (irrigated land)	0
France	0.013 (humid zone), 0 (dry zone)	0.013 (humid zone), 0 (dry zone)	0.013 (humid zone), 0 (dry zone)	0.0005	0.0057	0

Region	EF1 for synthetic N (kg N_2O-N kg N applied^{-1})	EF1 for crop residues (kg N_2O-N kg N applied^{-1})	EF1 for manure inputs (kg N_2O-N kg N applied^{-1})	EF1 for N mineralization (kg N_2O-N kg N applied^{-1})	EF4 (kg N_2O-N (kg NH_3-N + NOx-N volatilized)$^{-1}$)	EF5 (kg N_2O-N kg N leached^{-1})
Ukraine	0.003	0.003	0.003	0.003	0.002	0.0005
Russia	0.0126* (Chernozems soils), 0.0238* (soddy-podzolic soils), 0.012* (other)	0.003	0.003	0.003	0.002	0.0005
Finland	0.003	0.003	0.003	0.003	0.002	0
Poland	0.003	0.003	0.003	0.003	0.002	0.0005
Sweden	0.003	0.003	0.003	0.003	0.002	0.0005

Table 34. Highest N_2O emission factors used for barley and oats sensitivity analyses (values marked with * did not vary from the baseline analysis)

Region	EF1 for synthetic N (kg N_2O-N kg N applied^{-1})	EF1 for crop residues (kg N_2O-N kg N applied^{-1})	EF1 for manure inputs (kg N_2O-N kg N applied^{-1})	EF1 for N mineralization (kg N_2O-N kg N applied^{-1})	EF4 (kg N_2O-N (kg NH_3-N + NOx-N volatilized)$^{-1}$)	EF5 (kg N_2O-N kg N leached^{-1})
Saskatchewan	0.005	0.004	0.004	-	0.0129	0.0097
Prairie Provinces	0.007 (barley), 0.006 (oats)	0.006 (barley), 0.005 (oats)	0.006 (barley), 0.005 (oats)	-	0.0129	0.0097
Canada	0.007	0.006	0.006	-	0.0129	0.0097
Australia	0.002* (non-irrigated land) 0.0085* (irrigated land)	0.018	0.018 (dairies, feedlots, poultry), 0.0039* (piggeries)	0.018	0.002* (non-irrigated land) 0.0085* (irrigated land)	0.02
France	0.019 (humid zone), 0.011 (dry zone)	0.011	0.011	0.011	0.014	0.02
Ukraine	0.03	0.03	0.03	0.03	0.05	0.025

Region	EF1 for synthetic N (kg N_2O-N kg N applied^{-1})	EF1 for crop residues (kg N_2O-N kg N applied^{-1})	EF1 for manure inputs (kg N_2O-N kg N applied^{-1})	EF1 for N mineralization (kg N_2O-N kg N applied^{-1})	EF4 (kg N_2O-N (kg NH_3-N + NOx-N volatilized)$^{-1}$)	EF5 (kg N_2O-N kg N leached^{-1})
Russia	0.0126* (Chernozems soils), 0.0238* (soddy-podzolic soils), 0.012* (other)	0.03	0.03	0.03	0.05	0.025
Finland	0.03	0.03	0.03	0.03	0.05	0.02
Poland	0.03	0.03	0.03	0.03	0.05	0.025
Sweden	0.03	0.03	0.03	0.03	0.05	0.025

4. Results and discussion

4.1 Life cycle inventory

4.1.1 Barley

France had the highest barley yields (5,970 kg/ha), followed by the Prairie Provinces (3,519.8 kg/ha), Ukraine (3,434 kg/ha), and Canada (3,325 kg/ha with SK, 3,396 kg/ha without SK). Australia had the lowest (2,400 kg/ha) (Table 35). Seed inputs ranged from 0.03-0.07 kg/kg, depending on the region. Australia had the highest lime input (0.17 kg/kg) and France the lowest (0.07 kg/kg yield). France had the highest N fertilizer application rates (0.03 kg/kg), and the remaining countries had similar N application rates (0.02-0.03 kg/kg). P fertilizer application rates were fairly similar in Canada, Australia, and France, ranging from 0.01-0.02 kg/kg, as opposed to Ukraine and Russia which had lower P application rates (0.005 and 0.004 kg/kg, respectively). K and S fertilizer rates were more variable, with K fertilizer application rates ranging from 0.001 g kg/kg in Australia to 0.006 kg/kg in France, and S fertilizers ranging from 0 kg/kg in Australia, France, and Russia, to 0.002 kg/kg in all Canadian regions. Manure applications also varied significantly across regions. Australia had the lowest total manure application rate (0.0001 kg/kg yield), and France had the highest (0.22 kg/kg). Generally, the amount of applied pig manure was higher than poultry manure (i.e. 3-4 times higher in most countries, except Australia). Total pesticide active ingredient application rates were highest in Australia and France (0.002 kg/kg) followed by Ukraine (0.001 kg/kg). Russia had the lowest pesticide inputs (0.0003 kg/kg), followed by all Canadian regions (0.0004 kg/kg).

Irrigation energy varied significantly across all countries, from 0 MJ in Saskatchewan and Australia, to 0.036 MJ/kg in Ukraine. Ukraine had the highest energy use for field activities (1.472 MJ/kg), followed by Russia (1.137 MJ/kg). All Canadian regions had the lowest (~0.3 MJ/kg). Generally, all Canadian regions

had the lowest post-harvest energy use (0.030-0.035 MJ/kg), and Ukraine and Russia had the most (0.108 MJ/kg). All transportation distances were assumed to be the same (30 km for manure and 50 km for all other inputs) due to lack of region-specific data.

Canada and Australia had the lowest N_2O emissions (0.0002 kg/kg), due to soil, climate and management differences, particularly a lack of mineralized N from soil carbon losses in Canada, compared to the other countries. Ukraine had the largest amount of soil carbon losses and N_2O emissions. Australia had the highest levels of field-level CO_2 emissions (0.087 kg/kg) since they had the highest inputs of lime, as opposed to France which had the lowest inputs of lime (0.036 kg/kg). All Canadian regions, and Russia had similar amounts of field CO_2 emissions (0.062-0.069 kg/kg). Canadian (with and without Saskatchewan), Prairies, and Saskatchewan soils are sequestering carbon (-0.151, -0.087, -0.167, and -0.24 kg CO_2/kg, respectively), while all other countries have net carbon emissions from soils. Ukraine had the highest emissions from soil carbon loss (0.402 kg CO_2/kg), and Russia had lower emissions (0.0003 kg CO_2/kg).

Table 35. Summary of life cycle inventory data for barley production

Input	Saskatchewan	Prairie Provinces	Canada	Canada without Saskatchewan	Australia	France	Ukraine	Russian Federation
Yield (kg/ha)	3,118	3,520	3,325	3,396	2,400	5,970	3,434	2,571
Seed (kg/kg)	0.055	0.048	0.051	0.0507	0.071	0.029	0.05	0.067
Lime (kg/kg)	0.128	0.114	0.120	0.1178	0.166	0.067	0.116	0.156
N fertilizers (kg/kg)	0.028	0.024	0.025	0.025	0.028	0.056	0.030	0.020
P fertilizers (kg/kg)	0.011	0.009	0.010	0.009	0.021	0.009	0.005	0.004
K fertilizers (kg/kg)	0.003	0.003	0.003	0.003	0.001	0.006	0.005	0.002
S fertilizers (kg/kg)	0.002	0.002	0.002	0.002	0	0	7.6E-5	0
Pig manure (kg/kg)	0.089	0.079	0.084	0.082	3.6E-05	0.175	0.093	0.157
Poultry manure (kg/kg)	0.025	0.022	0.023	0.023	2.1E-05	0.049	0.035	0.047
Total pesticide AI (kg/kg)	0.0004	0.0004	0.0004	0.0004	0.002	0.002	0.001	0.0003
Irrigation energy (MJ/kg)	0	3.6E-06	3.8E-06	3.7E-06	0	0.006	0.036	0.033
Field activities energy (MJ/kg)	0.326	0.304	0.340	0.338	1.06	0.657	1.472	1.137
Post-harvest energy (MJ/kg)	0.035	0.030	0.032	0.032	0.045	0.027	0.108	0.108
Transportation (kg*km/kg)	12.1	10.6	11.3	11.0	10.9	13.7	11.7	15.2

Input	Saskatchewan	Prairie Provinces	Canada	Canada without Saskatchewan	Australia	France	Ukraine	Russian Federation
Field-level N_2O emissions (kg/kg)	0.0003	0.0003	0.0002	0.0003	0.0002	0.0006	0.0011	0.0004
Field-level CO_2 emissions (kg/kg)	0.069	0.062	0.065	0.064	0.087	0.036	0.058	0.069
Soil carbon change (kg CO_2/kg)	-0.241	-0.167	-0.151	-0.087	0.058	0.023	0.402	0.0003

4.1.2 Oats

Poland had the highest oat grain yields (4,200 kg/ha), followed by Sweden (3,892 kg/ha) (Table 36). The Prairies, Finland, Canada (with and without Saskatchewan), and Saskatchewan had similar yields (3,407.4, 3,398, 3,239.6, 2979.4, and 3,154.8 kg/ha, respectively), and Australia had the lowest (1,600 kg/ha). Australia had the highest lime input (0.25 kg/kg) and Poland the lowest (0.095 kg/kg yield). Australia also had the highest seeding rate (0.166 kg/kg). However, seed inputs were fairly similar between the rest of the regions, ranging from 0.06-0.08 kg/kg. Australia had the highest lime application rate (0.25 kg/kg) due to the low yield. Lime application was similar in the rest of the regions (0.095-0.12 kg/kg). N fertilizer application rates ranged from 0.021 kg/kg in the Prairies region to 0.058 kg/kg in Sweden. Finland and Sweden had relatively low P fertilizer application rates (0.005-0.006 kg/kg) compared to all other regions (0.008-0.023 kg/kg). K fertilizer application rates were different between regions, with K rates ranging from 0.0015 kg/kg in Australia to 0.008 kg/kg in Poland. S inputs were only applied in the Canadian regions (0.001 kg/kg). Pig manure application rates were the lowest in Australia (0.054 kg/kg), similar in the Canadian regions (0.082-0.088 kg/kg), and highest in Finland, Sweden, and Poland (0.32-0.35 kg/kg). Poultry manure application rates were lowest in Canada (0.022-0.025 kg/kg), followed by Australia, Sweden, and Finland (0.032-0.036 kg/kg), with the highest application rates in the Poland (0.067 kg/kg). Pesticide application rates ranged from 8.0E-5 kg/kg in Poland, to 0.0005 kg/kg in Canada (without Saskatchewan).

The Canadian regions had the lowest irrigation energy inputs (4.3E-7 MJ/kg to 4.8E-7 MJ/kg), followed by Finland (8.2E-6 MJ/kg), and Australia had the highest (0.145 MJ/kg). Australia and the Poland had the highest energy use for field activities (1.58 and 1.21 MJ/kg), followed by Finland (1.1 MJ/kg), Sweden (1.02 MJ/kg), and the Canadian regions had the lowest (0.287-0.36 MJ/kg). Finland had the lowest post-harvest energy use (0.04 MJ/kg) and Poland had the highest (0.198 MJ/kg). The remaining regions had the same amount of post-harvest energy use (0.108 MJ/kg). Like barley, all transportation distances were assumed to be 30 km for manure and 50 km for all other inputs. Sweden had the most inputs transported to farm (19.6 kg*km/kg), and the Prairies had the least (10.7 kg*km/kg).

Canada, the Prairie Provinces, Saskatchewan, and Australia had the lowest N_2O emissions, due to their soil, climate, and management conditions (0.0003 kg/kg). This was followed by Canada without Saskatchewan, and Poland (0.0004 kg/kg), then Sweden (0.0005 kg/kg), and Finland had the highest emissions (0.0009 kg/kg). Finland, Sweden, and Poland had similar field-level CO_2 emissions (0.044-0.046

kg/kg), as did the Prairies, Saskatchewan, and Canada (with and without Saskatchewan) (0.059, 0.063, 0.065, and 0.067 kg/kg, respectively). Australia had the highest CO_2 emissions due to higher inputs of lime and urea (0.125 kg/kg). Canadian (with and without Saskatchewan), Prairie, and Saskatchewan soils had net carbon sequestration (-0.074 to -0.298 kg CO_2/kg). All other soils had net CO_2 emissions, ranging from 0.029 kg/kg in Poland to almost 0.1 kg/kg in Finland. Australia and Sweden had similar soil carbon losses (0.087 kg/kg and 0.098 kg/kg).

Table 36. Summary of life cycle inventory data for oats production

Input	Saskatchewan	Prairie Provinces	Canada	Canada without Saskatchewan	Australia	Finland	Poland	Sweden
Yield (kg/ha)	3,154.8	3,407.4	3,239.6	2979.4	1,600	3,398	4,200	3,892
Seed (kg/kg)	0.084	0.078	0.082	0.089	0.166	0.078	0.063	0.068
Lime (kg/kg)	0.127	0.117	0.123	0.134	0.25	0.101	0.095	0.103
N fertilizers (kg/kg)	0.022	0.021	0.022	0.024	0.031	0.029	0.030	0.058
P fertilizers (kg/kg)	0.007	0.008	0.008	0.009	0.023	0.005	0.01	0.006
K fertilizers (kg/kg)	0.003	0.003	0.003	0.003	0.0015	0.006	0.008	0.002
S fertilizers (kg/kg)	0.001	0.001	0.001	0.002	0	0	0	0
Pig manure (kg/kg)	0.088	0.082	0.086	0.093	0.054	0.353	0.32	0.338
Poultry manure (kg/kg)	0.025	0.022	0.024	0.024	0.032	0.036	0.067	0.035
Total pesticide AI (kg/kg)	0.0004	0.0004	0.0004	0.0005	0.001	0.0003	8.0E-5	0.0002
Irrigation energy (MJ/kg)	4.6E-07	4.3E-7	4.3E-07	4.8E-07	0.145	8.2E-6	0.001	0.0004
Field activities energy (MJ/kg)	0.320	0.287	0.312	0.360	1.577	1.099	1.208	1.02
Post-harvest energy (MJ/kg)	0.108	0.108	0.108	0.108	0.108	0.04	0.198	0.108
Transportation (kg*km/kg)	11.5	10.7	11.2	12.1	18	18.8	18.8	19.6
Field-level N_2O emissions (kg/kg)	0.0003	0.0003	0.0003	0.0004	0.0003	0.0009	0.0004	0.0005
Field-level CO_2 emissions (kg/kg)	0.063	0.059	0.065	0.067	0.125	0.044	0.046	0.045
Soil carbon change (kg CO_2/kg)	-0.298	-0.232	-0.188	-0.074	0.087	0.999	0.029	0.098

4.2 Life cycle impact assessment

4.2.1 Barley

Best practice is to present the LCIA results both with and without soil carbon change. Therefore, Figure 1 shows the carbon footprint results (allocated based on the mass relationship between grain and straw harvested), excluding soil carbon changes, for barley production in Saskatchewan (SK), Prairie Provinces (PP), Canada (CA), Canada without Saskatchewan (CA w/o SK), Australia (AU), France (FR), Russia (RU), and Ukraine (UA), broken down by the contribution of each major LCI data category. For Canada (with and without Saskatchewan), the Prairies, and Saskatchewan, the main contributors to the carbon footprint of barley production were fertilizer inputs (21-24%), and associated CO_2 (27-30%) and N_2O emissions (27-35%). For Saskatchewan, most N_2O emissions came from a combination of N applied in synthetic fertilizer, crop residues, and manure inputs, with almost 70% from direct N_2O emissions from N application. There are no net soil carbon losses on Saskatchewan soils that could lead to N losses. The impacts of upstream fertilizer production were predominantly due to CO_2 emissions in the production of ammonia to produce N fertilizers. CO_2 from the combustion of diesel for field activities contributed 11% of the impacts in the Prairies and Canada (with and without Saskatchewan), and 12% in Saskatchewan. The Prairie region had slightly lower emissions than Saskatchewan and the Canadian average, due to lower overall inputs and associated N_2O emissions.

For Australia, field-level CO_2 emissions accounted for 27% of the carbon footprint and N_2O emissions were 20%. Approximately 58% of the N_2O emissions were from crop residues, 20% from synthetic fertilizers and 2% from soil carbon change. Indirect N2O emissions account for 20% of impacts. Field activities accounted for 26% of Australian GHG emissions, which is much higher than the Canadian energy impact, due to the higher levels of field activities. Fertilizer inputs also accounted for 20% of emissions, comparable to the Canadian regions. Overall, Australian barley had a 51% higher carbon footprint than Saskatchewan barley (not including SOC changes), due to higher amounts of inputs required. Most differences between regions were statistically significant, except for Prairies and Canada, and Australia, France, and Russia (as indicated by the separate letters above each bar on the graph).

Barley production in France had 49% higher impacts than Saskatchewan. This is due to the much higher field-level N_2O emissions. Fertilizer production (22%) and field-level N_2O emissions (48%) were the largest contributors to the carbon footprint of French barley. Fifty-two percent of field-level N_2O emissions for French barley came from the application of synthetic N fertilizers, 22% came from leached N/runoff, 15% from crop residues, and 7% from volatilization. Field activities contributed 15% of the life cycle GHG emissions, and field-level CO_2 emissions from lime and urea contributed 10%. All other impacts and activities contributed 2% or less.

Russia and Ukraine had similar production inventories; however, the carbon footprint varies significantly due to the higher amounts of soil carbon losses from Ukraine compared to the other regions. In Ukraine, 53% of the emissions were attributed to field-level N_2O, compared to 33% in Russia. For Russia, 39% of N_2O emissions came from synthetic fertilizer, 30% from crop residues, 10% from manure, and 20% from indirect N_2O (i.e. leaching and volatilization). As for Ukraine, the contribution to the total N_2O emissions was similar for soil carbon loss, crop residues, and synthetic N application (between 18-21%). Field energy inputs were also a major contributor to impacts in both countries (26% in Russia and 21% in Ukraine). Fertilizer application also had similar contributions in Russia and Ukraine (12% and 9%, respectively).
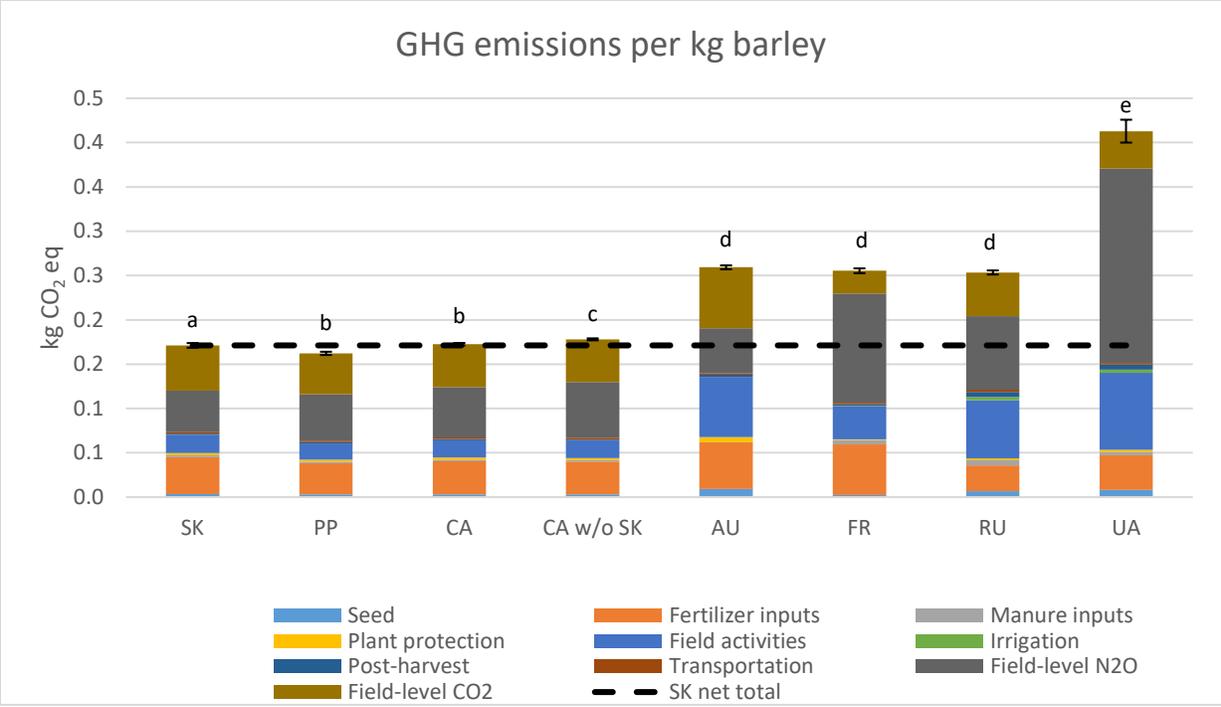
Figure 1. Contribution analysis of main LCI data categories to the overall carbon footprints (without soil carbon change) of barley produced in SK, PP, CA, CA w/o SK, AU, FR, RU, and UA (kg CO₂ eq per kg barley).

Canadian soils are the only cropland soils that are sequestering carbon, due to a combination of soil, climate and management factors (Figure 2). The soil carbon sequestration estimates for Saskatchewan were higher than the Prairie, and national average (particularly without Saskatchewan), since there are some regions in Canada that do not sequester as much carbon, and some that have net CO_2 emissions. All other countries have net CO_2 emissions from their cropland soils. Ukraine has by far the highest level of emissions. This is due to the soil and climate conditions in the region, as well as the intensity of field operations. Russia had much lower levels of CO_2 emissions, likely due to differences in soil, climate and management factors. According to the Russian NIR (Russian Federation, 2023), the majority (70%) of the estimate soil carbon losses from cropland are due to land remaining cropland, with the remainder from land converted to cropland.

Including the impacts of soil carbon changes, Saskatchewan barley had the lowest life cycle GHG emissions of all regions studied (-0.045 kg CO₂e/kg), due to the carbon sequestration. The Prairie Provinces and Canada had fairly similar overall impacts (0.04 and 0.06 kg CO₂e/kg), increasing to 0.11 kg CO₂e/kg for the Canadian average without Saskatchewan. Impacts from the national barley model including soil carbon changes are significantly higher than those of Saskatchewan barley despite the closer impacts of other production-related emissions from systems. Russian, French, and Australian barley have similar overall impacts including soil carbon losses (0.25-0.3 kg CO₂e/kg).
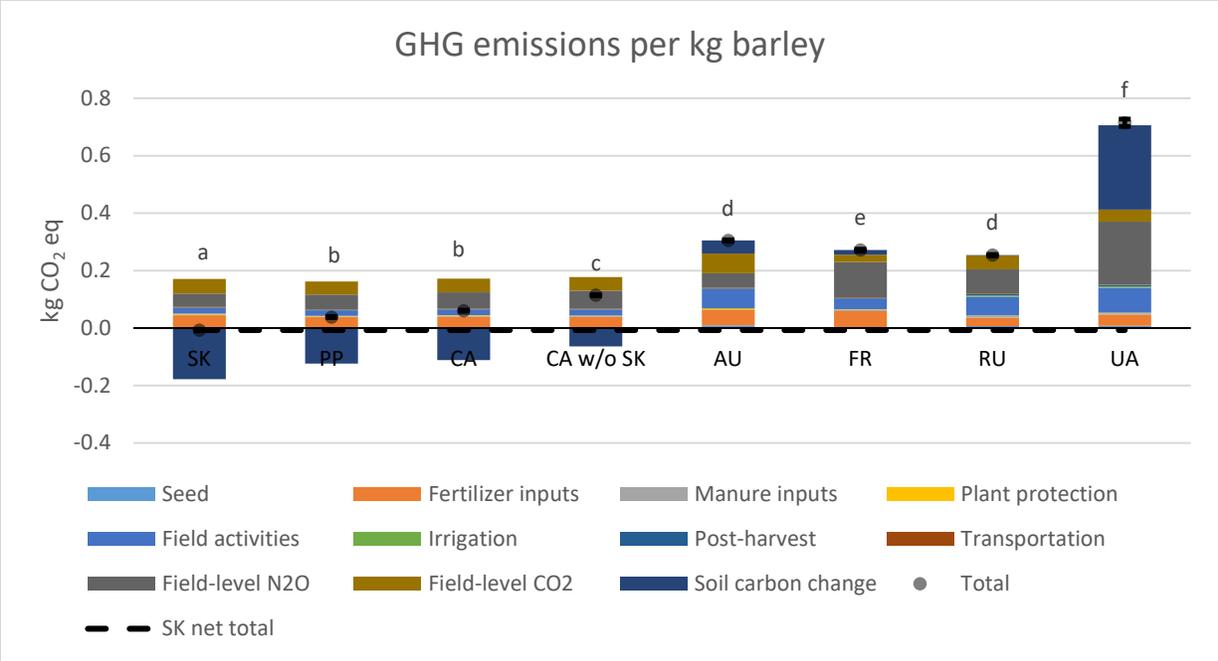
Figure 2. Contribution analysis of main LCI data categories to the overall carbon footprints (with soil carbon change) of barley produced in SK, PP, CA, CA w/o SK, AU, FR, RU, and UA (kg CO$_2$ eq per kg barley).

Both including and excluding soil carbon changes, Saskatchewan barley has a much lower carbon footprint than the global weighted average of all countries included in this analysis (35-102% lower), especially when soil carbon changes are included (Table 37).

Table 37. Global average carbon footprint values (with and without soil carbon change) compared to Saskatchewan carbon footprint values for barley grain production.

	Global average	Saskatchewan
kg CO$_2$e per kg barley (without soil carbon change)	0.262	0.171
kg CO$_2$e per kg barley (with soil carbon change)	0.296	-0.007

4.2.2 Oats

Figure 3 shows the LCIA results, without soil carbon change, for the production of 1 kg of oat grain (allocated based on the mass relationship between grain and straw harvested) for Saskatchewan (SK), Prairie Provinces (PP), Canada (CA), Canada without Saskatchewan (CA w/o SK), Australia (AU), Finland (FI), Poland (PL), and Sweden (SE). The results are broken down into the contributions from transportation, seed, fertilizer inputs, manure inputs, plant protection products, field activities, irrigation, post-harvest drying, and field-level CO$_2$ and N$_2$O emissions. For Canadian (with and without Saskatchewan), Prairie, and Saskatchewan oats, the associated field-level N$_2$O emissions (30-40%) and field-level CO$_2$ (23-27%) were the highest contributors to the life cycle GHG emissions, followed by fertilizer inputs (19-22%). Around 35% of the N$_2$O emissions came from synthetic N fertilizer, 31% from

crop residues, and 32% were indirect N_2O emissions. There were no net carbon losses in Saskatchewan and Canadian soils, therefore there are no N_2O emissions from this source. Field activities contributed 10-11% of the GHG emissions of Saskatchewan, Prairie, and Canadian (with and without Saskatchewan) oats. All other inputs and activities contributed 3% or less. Overall, the Canadian average oat production had 7% higher impacts than Saskatchewan (or 24% higher without Saskatchewan), and the Prairies impact were less than 1% higher. All other countries had significantly higher impacts of production than Saskatchewan. In fact, all differences were statistically significant, except for between Saskatchewan and Canada.

Australian oats had more than double the impacts compared to Saskatchewan oats (129% higher). The major contributors to the impacts were field activities energy use and field-level CO_2, which all had similar percentage contributions to the overall impacts of Australian oats (24-25%). These were followed by N_2O emissions (17%) and impacts from fertilizer use (15%). Fifty-four percent of the N_2O emissions for Australian wheat were due to crop residues. Sixteen percent were from the use of synthetic N fertilizers, 8% from manure inputs, and almost 20% from indirect N_2O emissions. Australian oat seed made a 7% contribution to the overall carbon footprint, which is significantly more than the other regions. All other inputs and activities contributed to less than 5% of the overall carbon footprint of Australian oats.

Finnish oats had 61% higher impacts than Saskatchewan oats, due to higher inputs of fertilizer and manure and the much higher field-level N_2O emissions, which are the largest contributor to the carbon footprint of Finnish oats production (55%). Forty-six percent of these N_2O emissions are due to N mineralization from soil carbon loss. Twenty percent are from crop residues, 13% from synthetic fertilizer inputs, and 6% are from manure inputs. After N_2O emissions, field activities are the next highest contributor to the carbon footprint of Finnish oats (20%). Fertilizer inputs and field-level CO_2 emissions from lime inputs contributed 10% each, and all other inputs and activities contributed 2% or less.

Oat production in Poland had 93% higher GHG emissions than Saskatchewan. This is due to higher levels of field activities, post-harvest energy use, and field-level N_2O emissions. Field-level N_2O emissions (29%) and field activities (26%) were the largest contributors to the carbon footprint of Polish oats. Fourty-two percent of field-level N_2O emissions came from the application of synthetic N fertilizers, 17% came from manure inputs, 14% from crop residues, and 3% from soil carbon losses. Fertilizer inputs contributed 17% of the life cycle GHG emissions of Polish oats production, field-level CO_2 emissions from lime and urea contributed 12%, and manure inputs and post-harvest energy use contributed to 6% and 4%, respectively. All other impacts and activities contributed 1% or less.

The carbon footprint of Swedish oats is 106% higher than Saskatchewan oats. Field-level N_2O emissions are the major contributor to the carbon footprint of Swedish oats production (38%),followed by field activities energy use (21%) and fertilizer inputs (20%). Most of the N_2O emissions are due to the application of synthetic N fertilizers (49%). Twenty-three percent came from crop residues, 10% from manure application, and 8% from soil carbon losses. Field-level CO_2 emissions contributed 12% to the overall carbon footprint of Swedish oats. The remaining activities contributed to less than 3%.

Figure 3. Contribution analysis of main LCI data categories to the overall carbon footprints (without soil carbon change) of oat produced in SK, PP, CA, CA w/o SK, AU, FI, and PL (kg CO2 eq per kg barley).

Saskatchewan soils had the highest levels of carbon sequestration per kg of oats (Figure 4). Average Prairies and Canadian (with and without Saskatchewan) soils are also sequestering carbon, albeit at a lower rate. All other regions have net carbon emissions from agricultural soils. Poland has the lowest levels of emissions, followed by Australia and Sweden. When the impacts of soil carbon changes are included in the overall carbon footprint, Saskatchewan oats production has the lowest impacts (-0.046 kg CO_2e/kg), followed by Prairie (0.004 kg CO_2e/kg) and Canadian production (0.047 kg CO_2e/kg with Saskatchewan, 0.160 kg CO_2e/kg without). All other regions have much higher impacts than Saskatchewan, since they have higher life cycle impacts of production, and have net carbon emissions from soils. Of all other regions, Poland, Sweden, and Australia have the lowest impacts (0.36 kg CO_2e/kg, 0.44 kg CO_2e/kg, and 0.46 kg CO_2e/kg, respectively). Finnish oats have the highest combined impacts (0.88 kg CO_2e/kg).
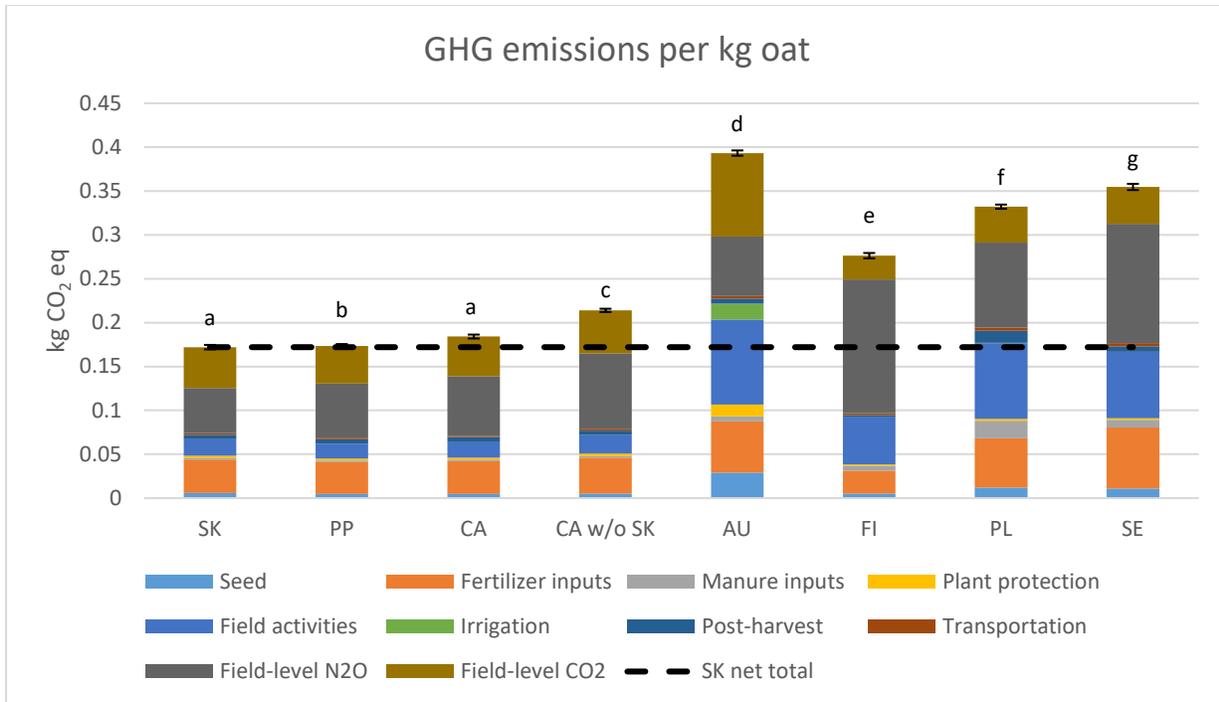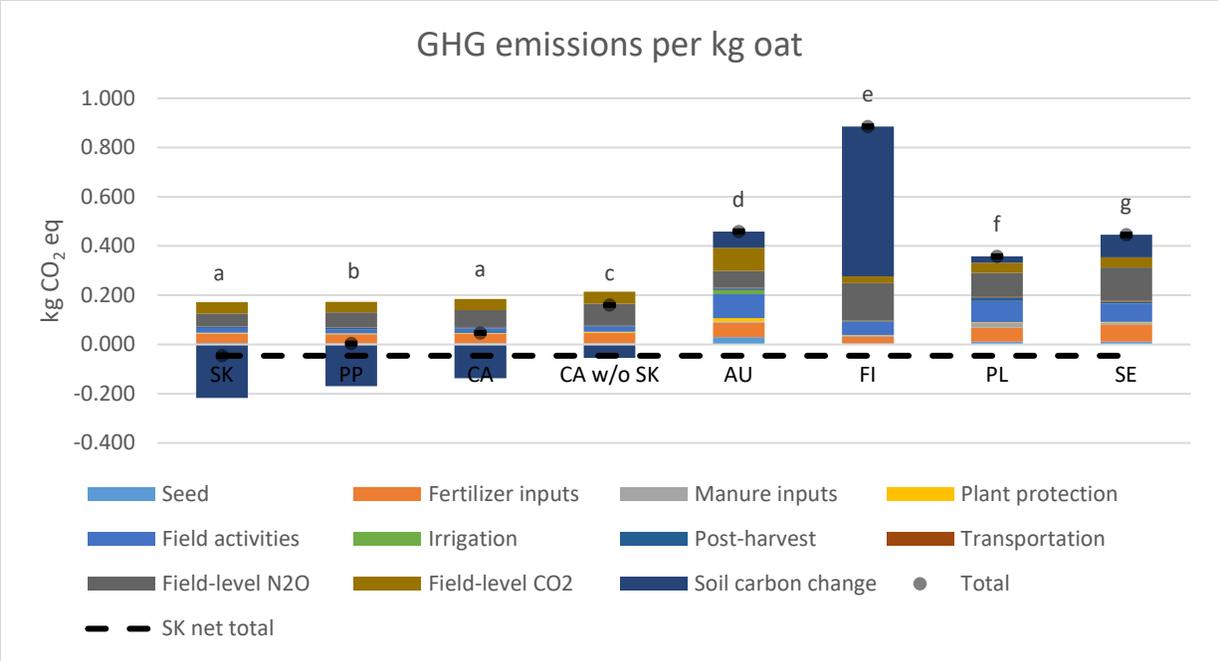
Figure 4. Contribution analysis of main LCI data categories to the overall carbon footprints (with soil carbon change) of oats produced in SK, PP, CA, CA w/o SK, AU, FI, and PL (kg CO2 eq per kg oats).

Either including or excluding soil carbon changes, Saskatchewan oats production had lower impacts (36-115% lower) than the global production weighted average of all countries (Table 38).

Table 38. Global average carbon footprint values (with and without soil carbon change) compared to Saskatchewan carbon footprint values for oats grain production.

	Global average	Saskatchewan
kg CO$_2$e per kg oats (without soil carbon change)	0.269	0.172
kg CO$_2$e per kg oats (with soil carbon change)	0.305	-0.046

4.3 Sensitivity analysis

4.3.1 Residue removal rate and allocation ratio

4.3.1.1 Barley

Australian barley had a different straw removal rate than the standard applied to the other regions due to the specific removal data found in each country's NIR (Table 39). Therefore, for compatibility, a 33.34% residue removal rate was applied to this country. This represents a reduction of impacts for Australian barley of 4%. However, impacts remain higher that Saskatchewan barley by 45%. When using a 33.34% straw removal rate, the Prairie Provinces had the lowest carbon footprint, followed by

Saskatchewan, Canada, Australia, Russia, France, and Ukraine. In the results from using a standard 40% straw removal rate, the impacts decreased for all Canadian regions and Russia by 6%, and for Australia and France by 17% and 5%, respectively. Ukraine was the only country with an increase (9% of impacts).

Table 39. Barley straw sensitivity analysis assuming removal rates of 33.34% and 40%.

Region	Baseline result without soil carbon change (kg CO_2 eq)	Result with 33.34% of straw removal rate (kg CO_2 eq)	% change from baseline	Result with 40% of straw removal rate (kg CO_2 eq)	% change from baseline	Original ranking (lowest to highest CF)	New ranking (lowest to highest CF)
SK	0.171	0.171	0	0.162	-6	2	2
PP	0.162	0.162	0	0.153	-6	1	1
CA	0.173	0.173	0	0.163	-6	3	3
AU	0.259	0.248	-4	0.216	-17	6	4
FR	0.255	0.255	0	0.242	-5	5	6
RU	0.253	0.253	0	0.238	-6	4	5
UA	0.413	0.413	0	0.448	+9	7	7

4.3.1.2 Oats

Australia, Poland, and Sweden had different straw removal rates than the standard rate applied to the other regions due to the specific removal data found in each country's NIR. Therefore, for compatibility, a 33.34% residue removal rate was applied to these countries as well (Table 40). This represents a reduction of impacts for Swedish and Australian oats of 18% and 11%, respectively. However, impacts remain higher than Saskatchewan oats by 70-102%. For Poland the impact of oats production increased by 7%. In the results from using a standard 33.34% straw removal rate in all regions, Saskatchewan had the lowest carbon footprint, followed by the Prairie Provinces, Canada, Finland, Sweden, Australia, and Poland. When using a 40% straw removal rate, the impacts of all Canadian regions decreased by 5-6%, for Sweden by (22%), Australia (17%) and Finland by 5%. However, the impacts increased for Polish oats by 6%.

Table 40. Oats straw sensitivity analysis assuming removal rates of 33.34% and 40%.

Region	Baseline result without soil carbon change (kg CO_2 eq)	Result with 33.34% of straw removal rate (kg CO_2 eq)	% change from baseline	Result with 40% of straw removal rate (kg CO_2 eq)	% change from baseline	Original ranking (lowest to highest CF)	New ranking (lowest to highest CF)
SK	0.172	0.172	0	0.163	-5	1	1
PP	0.174	0.174	0	0.162	-6	2	2
CA	0.184	0.184	0	0.174	-5	3	3
AU	0.393	0.348	-11	0.326	-17	7	6
FI	0.276	0.276	0	0.255	-8	4	4
PL	0.332	0.356	+7	0.351	+6	5	7

Region	Baseline result without soil carbon change (kg CO₂ eq)	Result with 33.34% of straw removal rate (kg CO₂ eq)	% change from baseline	Result with 40% of straw removal rate (kg CO₂ eq)	% change from baseline	Original ranking (lowest to highest CF)	New ranking (lowest to highest CF)
SE	0.355	0.292	-18	0.278	-22	6	5

4.3.2 Crop residue yields and N contents

Using the same average crop residue yield and N content for all countries changed the total carbon footprint of barley between -11 and +5% (Table 38). Due to these relatively small changes, there were only small variations in the new ranking, with impacts from Saskatchewan barley remaining as the lowest and Ukrainian barley with the highest carbon footprint. For oats, the total carbon footprint values changed by -23 to +11% (Table 41). Similarly, only small differences were found in the new ranking of impacts from all regions.

Table 41. Barley sensitivity analysis assuming an average crop residue yield and N contents for all countries.

Region	Baseline result without soil carbon change (kg CO₂ eq)	Field-level N2O (kg CO2 eq)	Result without soil carbon change (kg CO₂ eq)	% change from baseline	Original ranking (lowest to highest CF)	New ranking (lowest to highest CF)
SK	0.171	0.048	0.167	-3	2	3
PP	0.162	0.054	0.158	-2	1	1
CA	0.173	0.056	0.166	-11	3	2
AU	0.259	0.061	0.240	+5	6	4
FR	0.255	0.123	0.254	-1	5	5
RU	0.253	0.093	0.261	+3	4	6
UA	0.413	0.206	0.393	-5	7	7

Table 42. Oats sensitivity analysis assuming an average crop residue yield and N contents for all countries.

Region	Baseline result without soil carbon change (kg CO₂ eq)	Field-level N2O (kg CO2 eq)	Result without soil carbon change (kg CO₂ eq)	% change from baseline	Original ranking (lowest to highest CF)	New ranking (lowest to highest CF)
SK	0.172	0.042	0.157	-9	1	2
PP	0.174	0.048	0.154	-11	2	1
CA	0.184	0.053	0.164	-11	3	3
AU	0.393	0.055	0.353	-10	7	7
FI	0.276	0.165	0.306	+11	4	6

Region	Baseline result without soil carbon change (kg CO$_2$ eq)	Field-level N2O (kg CO2 eq)	Result without soil carbon change (kg CO$_2$ eq)	% change from baseline	Original ranking (lowest to highest CF)	New ranking (lowest to highest CF)
PL	0.332	0.098	0.283	-15	5	5
SE	0.355	0.107	0.272	-23	6	4

4.3.3 N$_2$O emissions modelling

4.3.3.1 N$_2$O emissions based on the lowest EF

Modelling the N$_2$O emissions as the lowest possible values based on the ranges presented resulted in overall reductions in the carbon footprint of barley ranging from a 8% reduction for Australia to a 30% reduction for France (Table 43). For oats, using the lowest possible N$_2$O values resulted in reductions ranging from 10% for Saskatchewan and Australia to 41% for Finland (Table 44).

Table 43. Barley sensitivity analysis results for lowest N$_2$O values in range.

Region	Baseline result without soil carbon change (kg CO$_2$ eq)	Field-level N2O (kg CO2 eq)	Result without soil carbon change (kg CO$_2$ eq)	% change from baseline	Original ranking (lowest to highest CF)	New ranking (lowest to highest CF)
SK	0.171	0.030	0.155	-9	2	3
PP	0.162	0.032	0.142	-12	1	1
CA	0.173	0.038	0.154	-11	3	2
AU	0.259	0.022	0.238	-8	6	6
FR	0.255	0.047	0.180	-30	5	4
RU	0.253	0.044	0.215	-15	4	5
UA	0.413	0.059	0.314	-24	7	7

Table 44. Oats sensitivity analysis results for lowest N$_2$O values in range.

Region	Baseline result without soil carbon change (kg CO$_2$ eq)	Field-level N2O (kg CO2 eq)	Result without soil carbon change (kg CO$_2$ eq)	% change from baseline	Original ranking (lowest to highest CF)	New ranking (lowest to highest CF)
SK	0.172	0.034	0.154	-10	1	2
PP	0.174	0.038	0.150	-14	2	1
CA	0.184	0.044	0.160	-13	3	3
AU	0.393	0.029	0.355	-10	7	7
FI	0.276	0.039	0.164	-41	4	4

Region	Baseline result without soil carbon change (kg CO₂ eq)	Field-level N2O (kg CO2 eq)	Result without soil carbon change (kg CO₂ eq)	% change from baseline	Original ranking (lowest to highest CF)	New ranking (lowest to highest CF)
PL	0.332	0.027	0.262	-21	5	6
SE	0.355	0.038	0.256	-28	6	5

4.3.3.2 N₂O emissions based on the highest EF

Using the highest N₂O values resulted in increases in carbon footprint values for barley ranging from 7% in Saskatchewan to 127% in Ukraine (Table 45). For oats, using the highest N₂O values resulted in increases ranging from 10% in Saskatchewan and Prairie Provinces to 102% in Finland (Table 46).

Table 45. Barley sensitivity analysis results for highest N₂O values in range.

Region	Baseline result without soil carbon change (kg CO₂ eq)	Field-level N2O (kg CO2 eq)	Result without soil carbon change (kg CO₂ eq)	% change from baseline	Original ranking (lowest to highest CF)	New ranking (lowest to highest CF)
SK	0.171	0.059	0.183	+7	2	2
PP	0.162	0.069	0.178	+10	1	1
CA	0.173	0.073	0.189	+9	3	3
AU	0.259	0.087	0.296	+14	6	4
FR	0.255	0.199	0.332	+30	5	5
RU	0.253	0.197	0.367	+45	4	6
UA	0.413	0.681	0.936	+127	7	7

Table 46. Oats sensitivity analysis results for highest N₂O values in range.

Region	Baseline result without soil carbon change (kg CO₂ eq)	Field-level N2O (kg CO2 eq)	Result without soil carbon change (kg CO₂ eq)	% change from baseline	Original ranking (lowest to highest CF)	New ranking (lowest to highest CF)
SK	0.172	0.070	0.190	+10	1	1
PP	0.174	0.080	0.191	+10	2	2
CA	0.184	0.090	0.206	+12	3	3
AU	0.393	0.117	0.443	+13	7	4
FI	0.276	0.434	0.558	+102	4	6
PL	0.332	0.311	0.546	+64	5	5
SE	0.355	0.418	0.637	+80	6	7

4.4 Limitations of the analysis

LCA has limitations. While the impacts of these limitations may be somewhat mitigated through performance of in-depth sensitivity analyses, some limitations remain. The most obvious of these is the use of secondary data sourced from LCI databases, published literature, and government and industry sources as the basis for the analyses. LCA is data intensive, and the robustness of models and associated results and interpretations are intrinsically linked to the quality of the data used in model development (Ciroth et al., 2016). While much of the data used in this analysis are of high quality, many data points were of relatively lower quality with respect to the completeness criteria, either due to small sample sizes, or a lack of reporting on the percentage of supply covered. This lack of reporting is, unfortunately, quite common in the LCA literature (Turner et al., 2020). Completeness scores could also be improved through the collection of primary data based on large, representative samples across industries. Doing so, however, would require significant effort and resources.

An additional key limitation of LCA is related to the models and assumptions used for estimation of LCI data. These include those for estimation of field level emissions, manure nutrient inputs, crop residue yields, etc. While the use of modeled values is necessary given the infeasibility of primary data collection, the potential biases that may be inherent to these models should not be ignored. The impact of these biases has been taken into account through the performance of uncertainty analysis.

5   Conclusions

This analysis provides estimates of life cycle GHG emissions for barley and oats produced in Saskatchewan, the Canadian Prairies, and Canada (as a whole, and without Saskatchewan), and compares them with emissions from the same crops grown in Australia, Europe, and other major producing regions. Specifically, barley systems are compared with those in Australia, France, Russia, and Ukraine, while oats production systems are compared with those in Australia, Finland, Poland, and Sweden.

Across both crops, production systems in Saskatchewan, the Prairie Provinces, and Canada (both with and without Saskatchewan), perform favourably in comparison to international counterparts, consistently showing the lowest GHG emissions per kilogram of product. For example, barley production in Saskatchewan had the lowest carbon footprint when including soil organic carbon (SOC) changes, at -0.007 kg CO_2 eq, while the Canadian Prairies and Canada also reported low emissions of 0.039 and 0.061 kg CO_2 eq, respectively. In contrast, higher emissions were observed in Russia (0.254 kg CO_2 eq), France (0.272 kg CO_2 eq), Australia (0.305 kg CO_2 eq), and especially Ukraine, which had the highest footprint at 0.706 kg CO_2 eq. A similar trend was seen in oats production, where Saskatchewan again showed the lowest footprint at -0.046 kg CO_2 eq when including SOC, followed by the Prairies (0.004 kg CO_2 eq) and Canada (0.047 kg CO_2 eq). Emissions from other major oat-producing regions were notably higher, with Poland at 0.358 kg CO_2 eq, Sweden at 0.445 kg CO_2 eq, Australia at 0.459 kg CO_2 eq, and Finland the highest at 0.885 kg CO_2 eq.

Similarly, without accounting for SOC changes, the carbon footprint of barley ranged from 0.162 kg CO_2 eq/kg in the Prairies, 0.171 kg CO_2 eq in Saskatchewan, and 0.173-0.178 kg CO_2 eq in Canada (with and without SK), compared to higher emissions in Russia (0.253 kg CO_2 eq), France (0.255 kg CO_2 eq), Australia (0.259 kg CO_2 eq), and Ukraine 0.413 kg CO_2 eq).

For oats, Canada also showed a favourable performance, with emissions of 0.172 kg CO_2 eq/kg in Saskatchewan, 0.174 kg CO_2 eq/kg in the Prairies, and 0.184-0.214 kg CO_2 eq/kg in Canada (with and without Saskatchewan). This is in contrast to emissions from Finland (0.276 kg CO_2 eq), Poland (0.332 kg CO_2 eq), Sweden (0.355 kg CO_2 eq), and Australia (0.393 kg CO_2 eq).

Overall, the results showed limited sensitivity to methodological decisions made in the study. For all crop-region combinations, key hotspots in the supply chain included field-level nitrous oxide (N_2O) emissions, fertilizer use, and/or field activities energy use—which may offer opportunities for targeted sustainability improvements.

Although this analysis focuses on barley and oats as key crops within the Saskatchewan field crop sector, future work could expand the analysis to include other economically significant crops. Such comparisons could help build a more comprehensive understanding of how Saskatchewan's crop production systems align with or differ from those of international competitors, and identify potential areas for further improvement.

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Appendix 1. Detailed results for baseline analyses

Table A1 Detailed contribution analysis describing contributions to total GHG emissions (kg CO_2 eq) per kilogram of barley produced in the baseline models.

Input	SK	PP	CA	CA w/o SK	AU	FR	RU	UA
Seed	0.003	0.003	0.003	0.003	0.009	0.002	0.007	0.008
Fertilizer inputs	0.042	0.035	0.037	0.037	0.053	0.057	0.029	0.039
Manure inputs	0.002	0.002	0.002	0.002	0.000	0.005	0.006	0.004
Plant protection	0.003	0.002	0.002	0.002	0.006	0.001	0.002	0.002
Field activities	0.020	0.018	0.019	0.020	0.068	0.038	0.066	0.087
Irrigation	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.003
Post-harvest	0.002	0.002	0.001	0.001	0.003	0.001	0.006	0.006
Transportation	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Field-level N_2O	0.046	0.053	0.057	0.063	0.051	0.123	0.083	0.219
Field-level CO_2	0.051	0.046	0.049	0.048	0.069	0.026	0.049	0.042
Soil carbon change	-0.178	-0.124	-0.112	-0.064	0.046	0.016	0.000	0.293
Total result (Including SOC)	-0.007	0.039	0.061	0.113	0.305	0.272	0.254	0.715

Table A2 Detailed contribution analysis describing contributions to total GHG emissions (kg CO_2 eq) per kilogram of oat produced in the baseline models.

Input	SK	PP	CA	CA without SK	AU	FI	PL	SE
Seed	0.006	0.005	0.005	0.005	0.029	0.005	0.012	0.011
Fertilizer inputs	0.038	0.036	0.037	0.041	0.058	0.026	0.056	0.070
Manure inputs	0.002	0.002	0.002	0.002	0.006	0.006	0.020	0.009
Plant protection	0.003	0.002	0.002	0.003	0.013	0.001	0.002	0.002
Field activities	0.019	0.017	0.018	0.021	0.097	0.054	0.086	0.076
Irrigation	0.000	0.000	0.000	0.000	0.018	0.000	0.000	0.000
Post-harvest	0.005	0.005	0.005	0.005	0.006	0.002	0.014	0.006
Transportation	0.002	0.002	0.002	0.002	0.003	0.002	0.004	0.004
Field-level N_2O	0.052	0.062	0.068	0.086	0.068	0.152	0.097	0.136
Field-level CO_2	0.046	0.043	0.045	0.049	0.095	0.027	0.041	0.042
Soil carbon change	-0.218	-0.170	-0.137	-0.054	0.066	0.609	0.026	0.090
Total result (Including SOC)	-0.046	0.004	0.047	0.160	0.459	0.885	0.358	0.445