Regional variations in life cycle greenhouse gas emissions of canola-derived jet fuel produced in western Canada

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Abstract
This study investigates the life cycle GHG emissions of jet fuel produced via the hydroprocessed esters and fatty acids (HEFA) pathway from canola grown in western Canada, with a focus on characterizing regional influences on emissions. We examine the effects of geographic variations in soil type, agricultural inputs, farming practices, and direct land use changes on life cycle GHG emissions. We utilize GREET 2016 but replace default feedstock production inputs with geographically representative data for canola production across eight western Canadian regions (representing 99% of Canada’s canola production) and replace the default conversion process with data from a novel process model previously developed in ASPEN in our research group wherein oil extraction is integrated with the HEFA-based fuel production process. Although canola production inputs and yields vary across the regions, resulting life cycle GHG emissions are similar if effects of land use and land management changes (LMC) are not included; 44–48 g CO₂e/MJ for the eight regions (45%–50% reduction compared to petroleum jet fuel). Results are considerably more variable, 16–58 g CO₂e/MJ, when including effects of land use and LMC directly related to conversion of lands from other uses to canola production (34%–82% reduction compared to petroleum jet fuel). We establish the main sources of emissions in the life cycle of canola jet fuel (N-fertilizer and related emissions, fuel production), identify that substantially higher emissions may occur when using feedstock sourced from regions where conversion of forested land to cropland had occurred, and identify benefits of less intense tillage practices and increased use of summerfallow land. The methods and findings are relevant in jurisdictions internationally that are incorporating GHG emissions reductions from aviation fuels in a low carbon fuel market or legislating carbon intensity reduction requirements.

KEYWORDS
aviation biofuel, biojet, canola, greenhouse gas emission, hydroprocessed esters and fatty acids (HEFA), life cycle assessment, renewable jet fuel, SAF, Sustainable Aviation Fuel
INTRODUCTION

Since 2009, the International Civil Aviation Organization (ICAO) has been working on the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) to mitigate emissions in the aviation sector. CORSIA is a market-based mechanism whereby the aviation sector compensates for its emissions by financially supporting eligible emissions reduction initiatives outside of aviation (e.g., through a carbon market). CO$_2$ emissions monitoring, reporting, and verification plans began on January 1, 2019 and will establish baseline emissions averaged from 2019 to 2020 (ICAO, 2019a). CORSIA complements the development of aviation biofuels as a means for significant emissions reductions in the sector because airline operators can claim emissions reductions by directly using certified lower carbon aviation fuel in their aircraft starting in 2021.

Regional policies and regulations such as those in the EU, California, and Canada also help reduce aviation greenhouse gas (GHG) emissions. A 2015 amendment to the EU Renewable Energy Directive (RED) allowed voluntary use of aviation biofuels to meet the RED target of at least 10% renewable energy sources in transportation by 2020 (European Environment Agency, European Aviation Safety Agency, & Eurocontrol, 2019). The California Air Resources Board amended the state's Low Carbon Fuel Standard (LCFS) in 2018 to allow fuel producers to voluntarily opt into the program and alternative aviation fuels to generate LCFS credits (CARB, 2019). In Canada, the Clean Fuel Standard (CFS) is being developed to accelerate deployment of fuels that will reduce emissions from the transport, industry, and building sectors, with a targeted annual reduction of 30 megatons of GHG emissions by 2030 (Government of Canada, 2019b).

Common elements in the EU, California, and Canadian approaches to emissions reductions are the quantification of a fuel's emission intensity on a life cycle basis, sectoral emissions targets, the generation of tradable credits to incentivize lower carbon fuels (i.e., carbon pricing), and a credit multiplier for aviation biofuels in some cases.

The policy and regulatory frameworks in various regions provide support for aviation biofuels but so far, few refineries commercially produce these fuels. The hydrotreated esters and fatty acids (HEFA) processing pathway is one of the few commercial successes in aviation biofuels, highlighted by AltAir/World Energy’s 45 million gallon per year of renewable jet and diesel facility in Paramount, California, where they convert waste fats, oils, and greases into fuels (Lane, 2018). HEFA fuels can also be derived from rapeseed as one of the viable near-term options for oilseed producing regions (e.g., the EU, China, Australia, and Canada). Canada is the top global exporter of a rapeseed variety called canola (yellow-seeded *Brassica juncea*; OECD & FAO, 2018), with China, Japan, the U.S., and Mexico currently importing much of the surplus Canadian canola seed, oil, and meal (Canola Council of Canada, 2019; USDA-FAS, 2019). Canadian canola yields have steadily improved, with average yields increasing from 1,250 kg/ha in 1990 to 2,325 kg/ha in 2018, and annual canola production for that period increasing from 3.2 to 20 million metric tons (MT; Statistics Canada, 2018c). Canola use outside of the food market is limited because of the priority placed on food applications; however, historical growth trends, the use of fallow land cropping, and the production of “off-specification” canola in Canada indicate that a certain level of canola could be dedicated to jet fuel production while maintaining the supply of canola for food applications. Canola use in HEFA fuel production can also diversify the market for canola, providing an outlet for increased canola supply due to yield growth that has outpaced demand in conventional markets.

There have been a small number of life cycle studies examining canola as a feedstock for renewable jet fuel production. Ukaew et al. (2016) and Shi et al. (2019) assessed the life cycle GHG emissions of HEFA jet fuel using canola/rapeseed grown in North Dakota, USA, and the US Northern Great Plains, respectively. They examined the impacts of crop price on cropping practices and calculated GHG emissions of 36–51 g CO$_2$e/MJ (Ukaew et al., 2016) and −55 to −107 g CO$_2$e/MJ (Shi et al., 2019) for canola-derived jet fuel based on energy allocation. The range of emissions was due to variations in soil carbon changes, which occurred because crop price influenced cropping decisions and subsequently led to carbon emissions or sequestration, depending upon the crop and land/crop management system displaced by canola. In Canada, Miller and Kumar (2013) compared canola and camelina produced in Alberta but focused on renewable diesel production without jet fuel co-production. They predicted GHG emissions from 33 to 94 g CO$_2$e/MJ for canola-derived diesel, using mass allocation. The range of emissions was a result of variations in oilseed yield, N$_2$O emissions factors, and land use change (LUC).

To our knowledge, there has not been a study of the life cycle GHG emissions of canola-derived jet fuel via the HEFA pathway from key canola producing regions in Canada based upon regional canola production data, while accounting for the soil carbon effects of land use and land management changes (LMC). We conduct a case study evaluating the life cycle GHG emissions of jet fuel production using canola from the gray, black, and brown soil zone regions within Manitoba (MB), Saskatchewan (SK), and Alberta (AB), provinces that represent 99% of Canada’s canola production since 2007. We use recent canola production data that are differentiated based on soil zone (MacWilliam, Sanscartier, Lemke, Wismer, & Baron, 2016), data on soil organic carbon (SOC) changes induced by LUCs directly related to conversion of lands from other uses to canola production and LMC (MacWilliam et al., 2016), and updated
process data from an integrated/co-located oil extraction and HEFA-based fuel production facility developed in our prior work (Chu, Vanderghem, MacLean, & Saville, 2017). We use the GREET 2016 fuel life cycle regulatory tool (Argonne National Laboratory, 2016) as a platform where we input our canola production and HEFA process data to investigate regional life cycle GHG emissions of canola-derived jet fuel. We also complete an analysis using the GHGenius 4.03a fuel life cycle model (Natural Resources Canada, 2013) to examine similarities/differences in predicted emissions and implications this may have for jurisdictions adopting these models for regulatory purposes. Canola-derived HEFA jet fuel as modeled in GREET 2016 and GHGenius 4.03a can provide life cycle GHG emissions based on nationally averaged data, whereas the present study explores GHG emissions at the soil zone geographic resolution. Analysis at the soil zone level provides greater precision in characterizing the biofuel's GHG emissions, and the approach we use is broadly applicable to other crops, regions, and jurisdictions that employ low-carbon fuel policies or more broadly aiming to characterize life cycle GHG emissions of bio-based products.

2 | METHODOLOGY

Agronomic and HEFA production process data sources were surveyed with the aim of conducting a life cycle study on canola-derived jet fuel. We use Canadian canola production as a case study to explore the impacts of region-specific feedstock production conditions. Regionally specific canola data published in MacWilliam et al. (2016) and data from Statistics Canada (2018c) narrowed the focus to the three main Canadian canola-producing provinces of MB, SK, and AB. We linked feedstock production data from eight regions in these provinces to an integrated oil extraction and HEFA jet fuel process model previously developed within our group (Chu, 2014; Chu et al., 2017). The life cycle of jet fuel from canola/oil produced in the eight regions is analyzed using the canola to jet fuel pathway in GREET 2016 (Argonne National Laboratory, 2016), modified to incorporate the above feedstock, oil extraction, and process model data. Parameters for the canola to jet fuel pathway collected from the literature are entered as inputs in GREET 2016, after translating the data to GREET-equivalent units. The analysis also uses the GREET 2016 canola production LUC framework to evaluate the effects of land use directly related to conversion of lands from other uses to canola production and land management based on data presented in MacWilliam et al. (2016). We elaborate each aspect of the life cycle in the following sections.

This study mainly uses GREET 2016 (the most recent version available at the time of the analysis) as a platform to perform simulations for the eight western Canadian regions. As a comparative analysis, we highlight results from GHGenius 4.03a (Natural Resources Canada, 2013) when incorporating the same regional feedstock data and conversion process data for the canola HEFA pathway (see Section 3.5). Using GHGenius 4.03a presents results based on distinct modeling approaches and data in GHGenius 4.03a modeling approach, results, and a thorough comparison between GHGenius 4.03a and GREET 2016 when modeling the life cycle of canola-derived jet fuel.

GREET has been updated since our initial use of the 2016 version. However, these updates have had little impact on the canola-to-jet fuel pathway, and the newer versions of GREET would not have resulted in materially different results than obtained using GREET 2016, particularly given our use of user-defined or custom inputs related to the process, canola production, and utilities. Consequently, the use of GREET 2016 remains valid for estimation of GHG emissions of the canola-to-jet fuel pathway within the key regions in Canada. For details on the relevant updates and assessment of their impacts, see Section I in the Supporting Information.

2.1 | Life cycle assessment

The system boundary for the canola-derived jet fuel life cycle via the HEFA process includes canola production, canola seed transportation, oil extraction, jet fuel production, jet fuel transportation and distribution, and jet fuel use (Figure 1). These key processes are assumed to take place within each of the Canadian provinces where canola is produced. Parameters and data sources used in the life cycle processes are provided in Sections 2.2–2.7. The global warming potential, reported as grams of CO2 equivalent (g CO2e), is calculated using the 2013 Intergovernmental Panel on Climate Change (IPCC) 100-year global warming potentials (i.e., AR5 GWP100, with CO2 = 1, CH4 = 30 and N2O = 265; IPCC, 2013). The functional unit is 1 MJ of jet fuel (LHV) consumed in a passenger aircraft.

The life cycle GHG emissions of canola-derived jet fuel are compared with the life cycle GHG emissions of the default conventional jet fuel pathway in GREET 2016 (i.e., low sulfur fossil jet fuel). The GREET 2016 default specifications on conventional jet fuel are provided in the Supporting Information, Section F, along with a sensitivity analysis of life cycle GHG emissions based on variations in fossil fuel feedstock specifications, including Canadian feedstocks.

A process-level energy allocation approach, as described by Han, Elgowainy, Cai, and Wang (2013) and consistent with the ICAO methodology (ICAO, 2019b), is applied to allocate the GHG emissions among co-products according to the energy content of each product relative to the energy content of the full product slate. Canola oil and canola meal share the total GHG emissions burden from canola
production up to oil extraction. The GHG emissions of jet fuel production are shared between diesel, naphtha, and propane mix/LPG co-products. Energy allocation for the canola meal co-product may not be the best representation of its function because meal is produced for its nutritional value rather than energy (Wang, Huo, & Arora, 2011). Nevertheless, energy allocation is selected because it is appropriate for a fuel product system, generally provides a conservative estimate of life cycle GHG emissions, and is consistent with the ICAO methodology.

2.2 Canola production

Canola production data are derived from the results of a 2007–2011 Canola Council of Canada survey of canola growers, as presented in MacWilliam et al. (2016). Canola production data are provided for individual soil zone regions within MB, SK, and AB. The soil zones evaluated are the gray, black, and brown soil zones that traverse provincial boundaries. Reconciliation units (RUs) define soil zones within provincial boundaries. Soil zones, provincial boundaries, and RUs are illustrated in Figure 2. The gray soil zone RUs are RU23, RU28, and RU34, the black soil zone RUs are RU24, RU29, and RU35, and the brown soil zone RUs are RU30 and RU37.

From 2007 to 2011, canola production for these eight RUs averaged 6.8 million seeded hectares and 12.4 million dry MT, representing 99.0% of total Canadian canola production (Statistics Canada, 2018b). These values increased to 8.7 million hectares and 19 million dry MT based on 2014–2018 data, representing 99.2% of total Canadian canola production (Supporting Information, Section A.1).

Geographically differentiated material and energy inputs in canola production at RU-level resolution are presented in Table 1. For the synthetic N-fertilizer input values, N-fertilizer composition in each RU is also modified to customize the N-fertilizer mix used in each RU (see Table S5). RU-level data in Table 1 include canola yield and the percentage of each RU’s production relative to total canola production in the three western Canadian provinces. The canola production percentage in each RU is used as a weighting factor for determining Canadian-average values. Other canola properties not indicated in Table 1 but used in GREET 2016 simulations include oil and moisture contents. These are based on measurements made by the Canadian Grain Commission, which indicates average western Canadian canola having 44% oil and 8.5% moisture for “Canola, No. 1 Canada” in 2014 (used for all eight RUs; Canadian Grain Commission, 2014).

The default canola production model in GREET 2016 uses Canadian weighted-average values as inputs to canola production, which are derived from disaggregated/RU-level data in the Cai, Han, Elgowainy, and Wang (2015) GREET research note. Both Cai et al. (2015) and MacWilliam et al. (2016) are based on data from the 2011 Canola Council of Canada survey of
canola farmers (the report is not in the public domain) but data from MacWilliam et al. (2016) include a post-survey analysis that renders it slightly different from the disaggregated data in Cai et al. (2015). In addition, the present study also examines the impacts of SOC stock change at the RU-level using data in MacWilliam et al. (2016; refer to Section 2.4), which are not

**Canola production data used in this study, based on canola production data at the reconciliation unit (RU) level from MacWilliam et al. (2016)**

| Input                     | Unit          | RU23 Gray | RU24 Black | RU28 Gray | RU29 Black | RU30 Brown | RU34 Gray | RU35 Brown | RU37 Brown |
|---------------------------|---------------|-----------|------------|-----------|------------|------------|-----------|------------|------------|
| Diesel                    | L/dry MT      | 24.6      | 21.7       | 22.1      | 20.7       | 20.8       | 20.9      | 20.6       | 21.8       |
| Electricity               | kWh/dry MT    | 2.2       | 2.2        | 2.2       | 2.2        | 2.2        | 2.2       | 2.2        | 2.2        |
| Synthetic N-fertilizer    | kg N/dry MT   | 71.2      | 64.3       | 55.6      | 57.3       | 57.0       | 57.0      | 61.4       | 52.3       | 49.4       |
| Manure                    | kg N/dry MT   | 0.0       | 0.7        | 1.8       | 0.1        | 0.3        | 0.2       | 1.2        | 1.6        |
| K₂O-fertilizer            | kg K₂O/dry MT | 4.2       | 3.0        | 4.0       | 1.8        | 2.3        | 6.4       | 5.5        | 2.8        |
| P₂O₅-fertilizer           | kg P₂O₅/dry MT | 16.9    | 16.8       | 18.5      | 16.6       | 18.5       | 20.7      | 14.8       | 21.0       |
| S-fertilizer              | kg S/dry MT   | 12.0      | 11.6       | 13.2      | 13.5       | 9.3        | 12.6      | 11.5       | 9.7        |
| Herbicide + fungicide     | g a.i./dry MT | 502       | 436        | 393       | 389        | 365        | 414       | 333        | 400        |
| Pesticide                 | g a.i./dry MT | 0.30      | 1.83       | 4.29      | 4.90       | 3.11       | 0.79      | 3.50       | 4.37       |
| Canola yield              | dry MT/ha/year| 1.68      | 1.80       | 1.68      | 1.61       | 1.51       | 1.65      | 1.86       | 1.58       |

Abbreviation: a.i., active ingredient.

*Values indicated as amount per hectare are converted to amount per dry metric ton of canola using the RU’s canola yield.
available in the default canola pathway in GREET 2016 nor in the Cai et al. (2015) GREET research note.

2.3 | Emissions from nitrogen sources

GHG emissions from N-fertilizer use and from crop residue decomposition are included in the life cycle and are calculated using the default approach in GREET 2016, which is a simplified version of the IPCC methodology for National Greenhouse Gas Inventories (de Klein et al., 2006; IPCC, 2006). The GREET 2016 calculation uses weighted average parameters representing average canola production conditions in western Canada (Cai et al., 2015) and these parameters are common across the RUs we examine. The GREET 2016 approach has RU-level differences based on the N-fertilizer input for each RU, which is the only input we provide that is used in calculating GHG emissions from N-fertilizer use and crop decomposition. Nominally, a unique set of parameters and N₂O emission factors would be used to characterize regions with different climatic and soil conditions using the full set of equations in the IPCC methodology. A supplementary analysis in Section A.3 (Supporting Information) compares N₂O emissions using the GREET 2016 approach and RU-differentiated N₂O emissions using the full set of equations from the IPCC methodology, populated with parameters for individual RUs from MacWilliam et al. (2016). The calculations in the Supporting Information also provide a breakdown of N₂O emissions arising from synthetic N-fertilizer, organic N-fertilizer, crop residue decomposition, volatilization, and leaching/runoff. We retain use of the simplified calculation of N-based emissions in GREET 2016 because modifications to this area would entail substantive changes to the model.

2.4 | Direct LUC and LMC

GHG emissions or sequestration from LUC and LMC attributable to canola production are examined in this study using annual LUC and LMC emissions or sequestration data from individual RUs for the 2007–2011 timeframe, as reported in MacWilliam et al. (2016). These data represent immediate and residual LUC and LMC values annually estimated in the National Inventory Report that Environment and Climate Change Canada (ECCC) submits to the United Nations Framework Convention on Climate Change (UNFCCC; Environment Canada, 2013b; MacWilliam et al., 2016). LUC values factor in biomass and SOC stock changes from direct LUCs (e.g., grassland to cropland and forest to cropland conversions) and residual N₂O emissions from soil disturbance. If a conversion event occurred within 20 years from the inventory reporting year, land that has remained cropland in this period will still indicate LUC due to long-term accounting of SOC losses and organic matter decay. LMC values factor in SOC stock changes from annual and perennial cropping changes, changes in tillage (e.g., between intensive, reduced, and no-tillage practices), and changes in summerfallow land use. Additional details on LUC and LMC estimation are included in Supporting Information, Section A.4.

LUC and LMC data used in this study were developed from the IPCC Good Practice Guidance for LUC (IPCC, 2003) and IPCC Guidelines for National GHG Inventories (IPCC, 2006). LUC and LMC values in the Canadian National Inventory Report (Environment Canada, 2013a) are indicated at the ecozone resolution (Canadian Soil Information Service, 2013) wherein the gray, black, and brown soil zone RUs (Figure 2) are captured collectively under the Boreal Plains, Subhumid Prairie, and Semiarid Prairie ecozones, respectively. Analyses in MacWilliam et al. (2016) developed emissions/sequestration values at the higher-resolution RU-level from ecozone values in the National Inventory Report (Environment Canada, 2013a). LUC values from the National Inventory Report do not include estimates of emissions expected to occur elsewhere in the world as a consequence of LUCs induced by canola production (i.e., induced land use change or ILUC, a combination of direct and indirect LUC effects), unlike California’s LCFS which use the Global Trade Analysis Project and Agro-Economic Zone models to calculate ILUC (CARB, 2016).

In MacWilliam et al. (2016), annual LUC and LMC values were normalized and attributed to canola as one of the crops produced in each of the RUs using annual statistics on canola production, land area seeded with canola, land area seeded with annual crops, and land area in summerfallow in each of the RUs. In the current study, we use 5-year averaged LUC and LMC values for canola (Table 2) based on annual RU-level LUC and LMC values for canola from 2007 to 2011 in MacWilliam et al. (2016). A positive LUC or LMC indicates net emissions while a negative value indicates net carbon sequestration.

GREET 2016 does not model LUC and LMC for the canola-derived jet fuel pathway but includes a placeholder for LUC emissions. The 5-year averaged and normalized LUC and LMC values in Table 2 are entered in the LUC value placeholder in GREET 2016. We determine life cycle GHG emissions of canola-derived jet fuel for each of the RUs with and without LUC and LMC effects.

2.5 | Oil extraction and jet fuel production

As of 2018, there were 14 commercial oilseed extraction (crushing) facilities that processed 46% of the 20 million MT
of canola produced in Canada (Canadian Oilseed Processors Association, 2019). The oil extraction process in Canada (Canola Council of Canada, 2017) matches the assumptions used in our prior work (Chu, 2014; Chu et al., 2017) and employed in the present study. However, there are currently no renewable jet fuel production facilities in Canada (Natural Resources Canada, 2018) and thus, a hypothetical HEFA jet fuel production facility is modeled in the current study. Background information on the development of these processes is described below and the resulting parameters entered in GREET 2016 are listed in Table 3 (see also Table S12).

A co-located canola oil extraction and jet fuel production facility is used in the present analysis based on Chu (2014) and Chu et al. (2017). The co-located oil extraction and fuel production facility reduces overall energy demand through heat integration and elimination of an intermediate oil transportation step. Oil extraction is based on a combined mechanical and hexane extraction to maximize oil recovery while jet fuel production is modeled via the HEFA process (i.e., decarboxylation, decarbonylation, and hydrodeoxygenation via a NiMo catalyst). The published results are based on camelina, carinata, and used cooking oil feedstocks (Chu, 2014; Chu et al., 2017). However, Chu developed the oil extraction process based on industry data for mechanical and solvent extraction of canola oil. Chu also developed the jet fuel production process from mechanistic models for fatty acid conversion reactions and Aspen Plus process simulations that used canola oil as a benchmark.

For the jet fuel production process, a mass balance and process modeling using the reaction mechanisms would ideally be performed based on the fatty acid profile of the oil feedstock to determine the hydrogen requirement and an accurate product distribution. Chu (2014) and Chu et al. (2017) adopted such an approach, considering the

| TABLE 2 | Five-year averaged land use change (LUC) and land management change (LMC) data<sup>a</sup> and resulting LUC and LMC emissions/sequestration for the reconciliation units (RUs) |
|---------|---------------------------------|
| Land seeded to annual crops (1,000 ha) | 492 | 2,840 | 1,603 | 1,685 | 1,810 | 2,322 | 1,255 | 1,735 | 1,299 |
| Land seeded to canola (1,000 ha) | 192 | 1,063 | 531 | 1,153 | 1,698 | 598 | 928 | 647 |
| Canola production (1,000 MT) | 646 | 1,631 | 1,685 | 1,810 | 2,322 | 1,255 | 1,735 | 1,299 |
| LUC: grassland↔cropland | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 1 |
| LUC: forest↔cropland | 417 | 64 | 440 | 62 | 0 | 663 | 52 | 0 |
| LUC: residual N<sub>2</sub>O | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| LMC: annual↔perennial | −94 | −117 | −66 | −132 | −234 | −141 | −62 | −111 |
| LMC: reduction in summerfallow | −142 | −137 | −72 | −233 | −350 | −131 | −116 | −213 |
| LMC: change in tillage practice | −44 | −109 | −116 | −258 | −206 | −106 | −187 | −134 |
| Total LUC and LMC | 137 | −300 | 187 | −560 | −787 | 286 | −314 | −457 |

<sup>a</sup>Used for allocating regional LUC and LMC emissions/sequestration to canola among annual crops.

<sup>b</sup>Some zero values are due to rounding down.

| TABLE 3 | Mass and energy balance from the integrated oil extraction and jet fuel production process presented in Chu (2014) and Chu et al. (2017) |
|---------|-------------------------------------------------|
| Oil extraction & Max jet production | Per MT oil |
| Inputs | |
| Canola seed (kg DM) | 2,089 | N/A |
| Oil (kg) | N/A | 1,000 |
| Hydrogen (kg) | N/A | 25.8 |
| Hexane (kg) | 2.92<sup>a</sup> | N/A |
| Natural gas (MJ) | 2,160 | 3,025 |
| Electricity (kWh) | 118 | 62.8 |
| Oil loss (%) | 1 | N/A |
| Outputs | |
| Oil (kg) | 1,000 | N/A |
| Meal (kg) | 1,095<sup>b</sup> | N/A |
| CO<sub>2</sub> (kg) | N/A | 95.3 |
| CO (kg) | N/A | 2.50 |
| Water (kg) | N/A | 34.2 |
| LPG/propane (kg) | N/A | 78.6 |
| Naphtha (kg) | N/A | 145 |
| Jet fuel (kg) | N/A | 537 |
| Diesel (kg) | N/A | 132 |

<sup>a</sup>Hexane input to top up solvent losses.

<sup>b</sup>Meal composition: 40% fiber, 59% protein, <1% oil, <1% water.
fatty acid profiles of camelina, carinata, and used cooking oil, and observed that the hydrogen demand varied by only 4 kg per ton of oil, and the aggregate yield of kerosene and diesel differed by no more that 8 kg per ton of oil. The oil profile had a greater effect on the proportion of feed oil that was converted into light hydrocarbons and naphtha (difference up to 20 kg per ton of oil). Overall, there was a very small impact on HEFA process performance, product distribution, utility demand, and hydrogen demand. Consequently, given the similarity in fatty acid composition (see Table S11) and oil content (44%) between carinata and canola, we are confident that the prior results from Chu (2014) and Chu et al. (2017) would be applicable to this study. We also performed a further analysis of hydrogen consumption for different feedstocks, and found that differences are small unless there is a substantial difference in fatty acid profile (e.g., canola oil to highly saturated fatty acid palm oil; see Table S13 for details). Thus, the jet fuel production process model for carinata is used to model the conversion of canola oil to jet fuel. We use the dataset that maximizes the production of jet fuel range hydrocarbons without complete cracking of the diesel range hydrocarbons. In this process, the fuel product slate is comprised of middle distillate range hydrocarbons (>C15), jet fuel range hydrocarbons (C10–C15), naphtha range hydrocarbons (C5–C9), and liquefied petroleum gas (C1–C4). The light hydrocarbons are treated as co-products of the jet fuel production process and are not used internally as fuel to generate process heat nor as a source of hydrogen, two potential uses of these co-products that could reduce natural gas and hydrogen requirements.

Electricity consumption reflects the electricity grid mix according to the province where the RU is located. Forecasted electricity data for each province in 2020 are used (National Energy Board, 2016). Depending on the RU being simulated, the corresponding electricity grid composition for MB, SK, or AB is entered in the GREET 2016 user-defined mix for stationary electricity use (see Table S14).

Natural gas and hydrogen have been identified as key sources of GHG emissions in oilseed-derived jet fuel production (Chu et al., 2017; Han et al., 2013; Ukaew et al., 2016). The assumptions for these two inputs and corresponding emissions factors are in Table S15. No changes are implemented in GREET 2016 for the natural gas and hydrogen pathways used in the canola-derived jet fuel life cycle.

2.6 | Transportation

Transportation steps modeled in the canola-derived jet fuel system include the transportation of canola seeds and transportation and distribution of jet fuel, all based on default assumptions in the canola jet fuel pathway in GREET 2016. In using the oil extraction and fuel production model by Chu (Chu, 2014; Chu et al., 2017), oil transport from an oil extraction facility to a fuel production facility is eliminated because oil is extracted and converted in an integrated facility. Transportation parameters and assumptions are provided in Table S16.

2.7 | Jet fuel use

Pump-to-wake GHG emissions for jet fuel use are calculated from the combustion of 1 MJ of jet fuel in a conventional jet engine. Biogenic carbon emitted as CO₂ upon biofuel jet combustion is assumed to be balanced by CO₂ uptake during crop growth. In GREET 2016, crop CO₂ uptake is modeled as the CO₂ equivalent value of the carbon contained in the neat canola-derived jet fuel and is included as a credit in the well-to-pump stage of the canola-derived jet fuel life cycle. The well-to-pump biogenic CO₂ credit from canola-derived jet fuel negates the pump-to-wake CO₂ emissions component of the jet engine combustion emissions.

3 | RESULTS AND DISCUSSION

3.1 | Life cycle GHG emission estimates

Based upon the feedstock production and HEFA process data input into GREET 2016, life cycle GHG emissions of canola-derived jet fuel are estimated to range from 44 to 48 g CO₂e/MJ for the eight RUs examined in Canada (Figure 3). These results exclude LUC and LMC effects. Without LUC and LMC, canola production comprises 56%–65% of life cycle GHG emissions (24–31 g CO₂e/MJ), with fuel production comprising 28%–33% (13–14 g CO₂e/MJ), and oil extraction 6%–10% (3.1–4.2 g CO₂e/MJ). Fossil jet fuel life cycle GHG emissions of 88 g CO₂e/MJ, estimated using GREET 2016 and its default specifications, suggests GHG emissions reductions of 45%–50% for canola-derived jet fuel from the eight RUs. The carbon intensity of the crude oil source can substantially affect the GHG emissions estimated for fossil jet fuel and the corresponding emissions reduction provided by canola-derived jet fuel (see Supporting Information, Section F). Some policies lessen uncertainties from variations in feedstock types and associated GHG emissions reductions of alternative fuels by prescribing benchmarks for fossil fuels used in their jurisdiction. For example, Canada's CFS proposes life cycle GHG emissions of 92 g CO₂e/MJ (LHV basis) for fossil jet fuel whereas ICAO prescribes a value of 89 g CO₂e/MJ (ECCC, 2019; ICAO, 2019b). This approach shifts the focus of analyses to the alternative jet fuel’s emissions and variabilities therein.
Canadian production-weighted emissions for key life cycle stages, including LUC and LMC, for canola-derived jet fuel are shown in Figure 4. Production-weighted values are determined as the sum-product of the eight RUs’ GHG emissions and the fraction of canola production in the RU relative to total western Canada production (Table 1). The “error bars” convey the range of emissions from the eight RUs. Emissions from transportation, jet fuel combustion, and biogenic carbon are not shown in Figure 4 based on their low contributions to life cycle emissions and/or low degree of variation across the RUs. There are notable variations in life cycle GHG emissions across the eight RUs (Figure 4) and the greatest sources of variability are in the LUC and LMC emissions, which subsequently drive the wide range in life cycle GHG emissions. In contrast, life cycle GHG emissions without LUC and LMC for each RU as shown in Figure 3 indicate relatively consistent life cycle GHG emissions across the RUs in spite of variations in agricultural inputs and seed yield (Table 1). Life cycle GHG emissions without LUC and LMC (Figure 3) would be consistent with soil and biomass carbon stocks reaching a future equilibrium state (e.g., most of the available fallow land has become productive land, different types of tillage practices employed in a region are being maintained, and there are no more net changes in land use between forest lands, perennial lands, and croplands in a region). The default IPCC soil and biomass carbon accounting methods assume that changes in SOC from LUC and LMC occur over a 20-year time period, after which a new equilibrium state will have been reached (IPCC, 2003). In the present study, LMC carbon sequestration benefits may still be derived for canola produced from some of the RUs examined (i.e., RUs that present life cycle GHG emissions less than the hypothetical equilibrium state shown in Figure 3 as 44–48 g CO₂e/MJ). However, these benefits would need to be validated for current applicability.

The life cycle GHG emissions of canola-derived jet fuel can vary substantially depending on whether direct LUC and/or LMC are accounted for, as illustrated for the eight RUs in Figure 5. When both LUC and LMC effects are included in the canola to jet fuel pathway simulations in GREET 2016, life cycle GHG emissions across the RUs are estimated to
range from 16 to 58 g CO2e/MJ. Comparing scenarios without LUC and LMC to those include both LUC and LMC, life cycle GHG emissions increase by 5.3–11 g CO2e/MJ in the gray soil zone RUs (11%–23% increase) and decrease by 11–30 g CO2e/MJ in the black and brown soil zone RUs (25%–65% reduction).

With LUC and LMC included in the life cycle, gray soil zone regions present the highest GHG emissions for canola-derived aviation biofuel (52–58 g CO2e/MJ from RU23, RU28, and RU34), followed by the black soil zone regions (25–34 g CO2e/MJ from RU24, RU29, and RU35), and then the brown soil zone regions (16–26 g CO2e/MJ from RU30 and RU37). A Canadian production-weighted average life cycle GHG emissions for canola-derived jet fuel is estimated at 34 g CO2e/MJ, which reflects the greater proportion of canola production and lower GHG emissions in the brown and black soil zones. Similarly, soil-zone-weighted average life cycle GHG emissions are 54 g CO2e/MJ (gray), 30 g CO2e/MJ (black), and 20 g CO2e/MJ (brown). Although it may appear to be attractive to focus jet fuel production in black and brown soil zones, caution is required in case this could lead to more food-derived canola production in the gray soil zones, resulting in higher GHG emissions for food-related applications of canola. In this instance, the net GHG emissions reduction benefit from biofuels may be partially negated. In the sections that follow, we discuss the relevance of each of the key emissions sources in the life cycle of canola-derived jet fuel.

3.2 | Canola production: Material inputs, energy inputs, and N-based emissions

GHG emissions resulting from material inputs, energy inputs, and N-based emissions in canola production are shown in Figure 6 based on data entered in GREET 2016. GHG emissions of 10–13 g CO2e/MJ for the eight RUs are from material and energy inputs to canola production and 14–18 g CO2e/MJ from N-based emissions. These emissions comprise 23%–28% and 31%–37% of life cycle GHG emissions across the RUs, respectively (life cycle without LUC and LMC). GHG emissions from material inputs to canola production consist of the production and transport of nitrogen, phosphate, and potassium fertilizers, and herbicides and pesticides while GHG emissions from energy inputs are solely from diesel production and combustion in farm equipment. The MacWilliam et al. (2016) feedstock production data source also includes sulfur fertilizer and seed inputs, which are not included in simulations because they are not standard inputs in the GREET 2016 canola production model. With the same reasoning, only N-based emissions resulting from the application of synthetic N-fertilizers and from crop decomposition are accounted for, while excluding organic N-fertilizers from the MacWilliam et al. (2016) dataset.

Results in Figure 6 illustrate that in canola production, the most significant source of GHG emissions is synthetic N-fertilizer and related N-fertilizer use emissions, collectively contributing 16–23 g CO2e/MJ across the eight RUs. These emissions consist of 6.0–9.2 g CO2e/MJ from fertilizer production, 8.4–12 g CO2e/MJ from the direct and indirect emissions upon fertilizer application, and 0.98–2.3 g CO2e/MJ from carbon fixed in urea that eventually oxidizes to CO2. For canola production overall, the GHG emissions across the RUs are relatively consistent, but with slightly higher overall emissions from MB RUs (RU23 and RU24) and slightly lower emissions from the Black and Brown RUs in AB (RU35 and RU37). The GHG emissions trend across the RUs closely reflects the trend in N-fertilizer input values across RUs (Table 1).

3.3 | Direct LUC and LMC

Substantial emissions and variations in emissions are found to occur due to LUC and LMC, as illustrated in Figures 4 and 5. LUC and LMC contributions are broken down in Figure 7 to show the effects in each RU. Net GHG emissions from LUC and LMC range from 5.3 to 11 g CO2e/MJ for gray soil
zone RUs, −11 to −21 g CO₂e/MJ for black soil zone RUs, and −18 to −30 g CO₂e/MJ for brown soil zone RUs.

Findings of the LUC analyses in MacWilliam et al. (2016) indicate high LUC emissions from the gray soil zones (RU23, RU28, and RU34), attributed to canola being grown on cropland converted from forest land. In black soil zone regions (RU24, RU29, and RU35), forest conversion is considerably less compared to prior decades, while insignificant forest conversion is reported for brown soil zones (RU30 and RU37). These findings are reflected in Figure 7, which are consistent with broader analyses in the Canadian National Inventory Report (Environment Canada, 2013a, 2013b). From the National Inventory Report, there are substantial forest LUC emissions from the Boreal Plains ecozone (i.e., gray soil zones) when compared with LUC emissions from the Subhumid and Semiarid Prairie ecozones (i.e., black and brown soil zones). The Boreal Plains encompasses 16% of Canada’s forest land, whereas the Subhumid and Semiarid Prairie landscapes have substantially less forest land area (1% and 0.01%, respectively in 2011; Environment Canada, 2013a). LUC emissions in
Semiarid Prairie RUs (see Figure 7) are from grassland to cropland conversion. Overall, the 2011 National Inventory Report indicates that agriculture comprises a declining but substantial cause of forest area conversion (e.g., 43% across Canada in 2011, of which 56% occurred in the Boreal Plains and 13% in the Subhumid Prairies; Environment Canada, 2013a). Resulting LUC emissions in the 2011 National Inventory Report are comprised of immediate emissions from conversion (58%) and residual emissions from LUC events in the last 20 years (42%; Environment Canada, 2013b).

In contrast with LUC effects of canola production, LMC effects show only SOC sequestration. Canadian National Inventory Report records since 1990 indicate increases in SOC resulting from increasing adoption of LMC practices of reduced tillage intensity, re-establishment of perennial vegetation, and increased photosynthetic activities from reduction in summerfallow (Campbell, McConkey, Zentner, Selles, & Curtin, 1996; Environment Canada, 2013b; Janzen et al., 1998; McConkey et al., 2003). Census of Agriculture data (Statistics Canada, 2016) indicate the general movement toward reduced tillage and no-till practices across canola growing regions (Table S10). Simultaneously, there are decreasing trends of land in summerfallow (Statistics Canada, 2014a, 2018a) and land seeded to wheat (Statistics Canada, 2014b) while land seeded to canola or used as pasture are increasing (Figures S3 and S4). These supporting data are consistent with findings in MacWilliam et al. (2016), which indicate carbon sequestration in all canola-producing RUs from varying levels of adoption of LMC practices.

Compared to a scenario that does not account for LUC and LMC (Figure 3), direct LUC emissions of 0.05–25 g CO₂e/MJ (Figure 7a) increase the life cycle GHG emissions of canola-derived jet fuel by 33%–54% in the gray soil zone RUs and by 5% in the black soil zone RUs, both primarily from emissions related to forest conversion, while emissions related to grassland conversion in the brown soil zone RUs are negligible. LMC values of −10 to −30 g CO₂e/MJ (Figure 7b) reduce life cycle emissions by 22%–65%, depending on the agricultural practices in the RU. Gray soil zone RUs have the highest LUC emissions and lowest carbon sequestration values from LMC, leading to the highest life cycle GHG emissions across the eight RUs. Gray soil zone LUC emissions of 16–25 g CO₂e/MJ associated with canola production represent the highest source of GHG emissions in the life cycle of canola-derived jet fuel, followed by N-based emissions (14–18 g CO₂e/MJ) and HEFA jet fuel production emissions (13–14 g CO₂e/MJ).

Carbon sequestration resulting from LMC practices counterbalances a substantial portion of LUC emissions in gray soil zone RUs, though still resulting in net emissions from LUC and LMC (5.3–11 g CO₂e/MJ). In contrast, LUC and LMC in black and brown soil zone RUs imply net carbon sequestration (−11 to −30 g CO₂e/MJ). The greatest benefits from LMC practices are attained in the black and brown soil zone RUs in SK, wherein LMC sequestration values are primarily from summerfallow reduction (see Figure S2) and degree of adoption of lower intensity tillage practices (see Tables S9 and S10; Figures S5 and S6).

While there are reported soil carbon benefits and N₂O emissions reduction from the adoption of lower intensity tillage practices, tillage practice changes have also been studied for potential adverse impacts on crop yields, field emissions, and soil carbon (Bilandžija, Zgorelec, & Kisić, 2016; Liu, Mosier, Halvorson, & Zhang, 2006; van Kessel et al., 2013). The meta-analysis by van Kessel et al. (2013), for example, determined that the greatest benefit from implementing reduced or zero tillage is the statistically significant reduction in N₂O emissions, but only after at least 10 years of continuous implementation. Reduced crop yield resulted after implementation of reduced or zero tillage, most significantly in dry climatic regions, counterbalancing some of the benefits of less intense tillage practices. Crop yield did not recover to levels attained with conventional tillage and the authors suggested that nitrogen deficiency was the cause.

Minimizing emissions from direct LUC and maximizing carbon sequestration benefits from LMC practices have the potential to substantially reduce the life cycle GHG emissions of canola-derived jet fuel. However, the LUC and LMC values determined in this study, originally derived from the 1990–2011 Canadian National Inventory Report to UNFCCC (Environment Canada, 2013a, 2013b), may not be applicable in other regulatory regimes. For example, Canada's CFS, as currently written, includes direct LUC aspects in life cycle accounting but excludes indirect LUC (Government of Canada, 2019a), similar to the approach in this study. This approach is different from the economic-equilibrium-based approach to LUC, as used in California's LCFS (CARB, 2016) and in the aviation biofuel pathways assessed in ICAO's CORSIA (ICAO, 2019b), which currently show emissions of 21–28 g CO₂e/MJ from ILUC for rapeseed from the EU. While there is an analogous feedstock class with an ILUC value in the list of CORSIA aviation biofuels, ILUC has regional dependencies and is modeled based upon intricate linkage to other oilseeds traded globally, primarily in the food and feed markets. Net emissions reductions or sequestration benefits are realized regardless of canola's use in the food market or as biofuel feedstock but GHG emissions reductions would only be required for canola-derived jet fuel. There is a benefit in estimating direct LUC, which are assessed at the RU geographic resolution and can subsequently be tailored to develop local strategies for managing emissions. In contrast, ILUC accounts for impacts to the rest of the world, which may be challenging to disaggregate into applicable local strategies for emissions management.

### 3.4 Oil extraction and fuel production

GHG emissions from oil extraction and fuel production are comparable across RUs and comprise a substantial 16–18 g CO₂e/MJ
(33%–41% of life cycle GHG emissions, without LUC and LMC). GHG emissions sources in oil extraction and fuel production are concentrated among a few process inputs, as shown in Figure 8. Natural gas is the main source of emissions from oil extraction at 2.8 g CO₂e/MJ (67%–91% of oil extraction GHG emissions), followed by electricity at 0.08–1.2 g CO₂e/MJ (3%–28%). In fuel production, hydrogen is the main source of emissions, comprising 7.2–7.5 g CO₂e/MJ (54%–57% of fuel production GHG emissions), followed by natural gas at 5.5 g CO₂e/MJ (40%–43%). Variability in emissions across RUs in both oil extraction and fuel production is due to the significant level of hydroelectricity in MB’s RU23 and RU24 at 87% grid hydroelectricity (Table S14). This represents about 2 g CO₂e/MJ lower life cycle GHG emissions and counterbalances higher GHG emissions from feedstock production in MB RUs (based on Figure 6).

3.5 Life cycle results from GHGenius 4.03a

Using GHGenius 4.03a and equivalent inputs and model assumptions to those used in GREET 2016, life cycle GHG emissions for canola-derived jet fuel are estimated to range from 33 to 38 g CO₂e/MJ for the eight RUs (without LUC and LMC effects) or 11 to 43 g CO₂e/MJ (including LUC and LMC, see Table 4). Life cycle GHG emissions from GHGenius 4.03a follow the same trend across RUs as the GREET 2016 results (i.e., gray > black > brown), but with 5–15 g CO₂e/MJ less GHG emissions from GHGenius 4.03a compared to GREET 2016 estimates (see Figures S9–S11). We apply the methods in Section 2 to GHGenius 4.03a, but note a few distinctions in the Supporting Information, Section H.1 to better match the GREET 2016 modeling approach and provide consistent results.

We explored underlying causes for differences in predicted emissions between GHGenius 4.03a and GREET 2016 with a comparative analysis across life cycle stages and individual emissions sources (Supporting Information, Section H.2). Key areas that differ are LUC/LMC, oil extraction, and N-based emissions. Equivalent LUC/LMC emissions per unit feedstock values are entered in GHGenius 4.03a and GREET 2016 but resulted in 27% lower emissions/carbon sequestration per unit MJ of jet fuel in GHGenius 4.03a compared with corresponding RUs in GREET 2016. For natural gas, there is no notable difference in fuel production emissions between the models, but in oil extraction, there is three-fold higher emissions using GREET 2016. Emissions factor differences are partly responsible for differences in emissions seen from results determined from each input in feedstock production, which is also true for N-based emissions. Besides emissions factor differences and differences in modeling approach, systematically lower emissions from GHGenius 4.03a are determined to be largely due to differences in applying energy allocation compared to calculations within GREET 2016. Despite lower magnitude emissions estimated using GHGenius 4.03a compared with GREET 2016, the magnitudes of most emissions sources and life cycle emissions across RUs in GHGenius 4.03a follow the same trend as those estimated using GREET 2016.

FIGURE 8 Breakdown of greenhouse gas emissions for the reconciliation units (RUs) associated with (a) canola oil extraction and (b) jet fuel production
When determining life cycle GHG emissions reductions of canola-derived jet fuel (inclusive of LUC and LMC emissions), GHG emission reductions of 34%–82% across RUs are determined using GREET 2016 and 59%–90% using GHGenius 4.03a. Emissions reductions are determined using the life cycle GHG emissions of fossil jet fuel, estimated at 88 and 106 g CO₂e/MJ using the default settings in GREET 2016 and GHGenius 4.03a, respectively.

Differences between GHGenius and GREET estimates of fuel life cycle GHG emissions have been assessed in recent studies (e.g., IEA, 2018; Obnamia, Dias, MacLean, & Saville, 2019; Pereira et al., 2019). For certain fuel pathways, model harmonization was shown to lead to less than a 9% difference between estimated life cycle GHG emissions such as with sugarcane ethanol (Pereira et al., 2019), corn ethanol (Pereira et al., 2019), and corn stover ethanol (Obnamia et al., 2019). For soybean biodiesel, a residual 6%–23% difference between model estimates remained after harmonization, with GHGenius estimating the highest emissions (IEA, 2018). In the present study, differences between GHGenius emissions estimates for canola-derived jet fuel remain, with GREET 2016 estimating 19%–33% higher life cycle GHG emissions compared to corresponding RUs in GHGenius 4.03a. The use of canola toward renewable jet fuel production means that there may be uneven treatment when assessed under different policies and regulatory frameworks (e.g., domestic vs. international LCA approaches), which may estimate different life cycle GHG emissions for the same renewable jet fuel product.

### 4 | CONCLUSIONS

The range of life cycle GHG emissions for canola-derived jet fuel across eight Canadian regions is estimated using GREET 2016 as 16–58 and 11–43 g CO₂e/MJ using GHGenius 4.03a. When excluding LUC and LMC effects, life cycle GHG emissions across the eight RUs fall within narrower ranges (44–48 g CO₂e/MJ using GREET 2016 and 33–38 g CO₂e/MJ using GHGenius 4.03a). These results indicate that SOC changes from regionally specific LUC and LMC influence life cycle GHG emissions, to a greater extent than regional differences in agricultural inputs and yields for canola. Canola produced in any of the regions examined has the potential to provide meaningful GHG emissions reductions compared to fossil jet in the near term (with or without inclusion of LUC and LMC emissions). The use of canola also benefits from the technical and economic viability of the HEFA pathway. However, if canola were to be used to produce jet fuel in the longer term, it is advantageous to reduce the GHG impacts from the production and use of N-fertilizer, natural gas, and hydrogen. Alternatives to conventional sources of natural gas would directly influence (and potentially reduce) emissions from the production of ammonia-based fertilizers (most N-fertilizers) and hydrogen derived from steam methane reforming. In the foreseeable future, it is likely that canola used for biofuel production would be sourced from existing production (i.e., feedstock that can result in lower carbon intensity), exclude extensification, and account for practices that increase SOC levels.

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DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available in the supplementary material of this article.

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REFERENCES
Argonne National Laboratory. (2016). GREET: Greenhouse gases, regulated emissions, and energy use in transportation (version GREET1 fuel cycle 2016 excel model) [computer software]. Retrieved from https://greet.es.anl.gov/

Bilandžija, D., Zgorelec, Ž., & Kisić, I. (2016). Influence of tillage practices and crop type on soil CO2 emissions. Sustainability, 8(1), 90. https://doi.org/10.3390/su8010090

Cai, H., Han, J., Elgowainy, A., & Wang, M. Q. (2015). Research note: Parameters of canola biofuel production pathways in GREET. Retrieved from https://greet.es.anl.gov/publications

Campbell, C., McConkey, B., Zentner, R., Selles, F., & Curtin, D. (1996). Long-term effects of tillage and crop rotations on soil organic C and total N in a clay soil in southwestern Saskatchewan. Canadian Journal of Soil Science, 76, 395–401. https://doi.org/10.4141/cjss96-047

Canadian Grain Commission. (2014). Western Canadian canola – Scientific analysis of harvest and export quality. Retrieved from https://www.graincanada.gc.ca/canola/hqcm-mqrc-eng.htm

Canadian Oilseed Processors Association. (2019). Overview of Canada’s oilseed processing sector: June 2019. Retrieved from https://copacanada.com/industry-profile/

Canadian Soil Information Service. (2013). National ecological framework. Retrieved from http://sis.agr.gc.ca/cansi/nsdb/ecostat/index.html

Canola Council of Canada (2017). Steps in oil and meal processing. Retrieved from https://www.canolacouncil.org/oil-and-meal/what-is-canola/how-canola-is-processed/steps-in-oil-and-meal-processing/

Canola Council of Canada. (2019). Canola market statistics. Retrieved from https://www.canolacouncil.org/markets-stats/markets/

CARB. (2016). LCFS land use change assessment. Retrieved from https://www.arb.ca.gov/fuels/lcfs/iluc_assessment/iluc_assessment.htm

CARB. (2019). Final regulation order. Title 17, California code of regulations. Subchapter 10. Climate change. Article 4. Regulations to achieve greenhouse gas emissions reductions. Subarticle 7. Low carbon fuel standard. Retrieved from https://ww2.arb.ca.gov/rulemaking/2018/low-carbon-fuel-standard-and-alternative-diesel-fuels-regulation-2018

Chu, P. L. (2014). Environmental and financial performance: Aviation biofuels. Master’s thesis, University of Toronto TSPACE Research Repository. hdl.handle.net/1807/82631

Chu, P. L., Vanderghem, C., MacLean, H. L., & Saville, B. A. (2017). Process modeling of hydroxodeoxygenation to produce renewable jet fuel and other hydrocarbon fuels. Fuel, 196, 298–305. https://doi.org/10.1016/j.fuel.2017.01.097

de Klein, C., Novoa, R. A., Ogle, S., Smith, K. A., Rochette, P., Wirth, T. C., & Williams, S. A. (2006). N2O emissions from managed soils, and CO2 emissions from lime and urea application, chapter 11. In S. Eggleston, L. Buendia, K. Miwa, T. Ngara, & K. Tanabe (Eds.), 2006 IPCC guidelines for national greenhouse gas inventories (Vol. 4, Agriculture, Forestry, and Other Land Use). Hayama, Japan: Institute for Global Environmental Strategies.

ECCC. (2019). Clean fuel standard: Proposed regulatory approach. Retrieved from https://www.canada.ca/en/environment-climate-change/services/managing-pollution/energy-production/fuel-regulations/clean-fuel-standard/regulatory-approach.html

Environment Canada. (2013a). National inventory report 1990–2011: Greenhouse gas sources and sinks in Canada – Canada’s submission to the United Nations framework convention on climate change – Common reporting format. Retrieved from https://unfccc.int/process/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories/submissions-of-annual-greenhouse-gas-inventories-for-2017/submissions-of-annual-ghg-inventories-2013

Environment Canada. (2013b). National inventory report 1990–2011: Greenhouse gas sources and sinks in Canada – Canada’s submission to the United Nations framework convention on climate change – Part 1. Retrieved from https://unfccc.int/process/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories/submissions-of-annual-greenhouse-gas-inventories-for-2017/submissions-of-annual-ghg-inventories-2013

European Environment Agency, European Aviation Safety Agency, & Eurocontrol. (2019). European aviation environmental report. Retrieved from https://ec.europa.eu/transport/sites/transport/files/2019-aviation-environmental-report.pdf

Government of Canada. (2019a). Canada gazette, part I, volume 153, number 3: Government notices. Ottawa, Canada: Queen’s Printer for Canada. Retrieved from http://gazette.gc.ca/rp-pr/p1/2019/2019-01-19/html/notice-avis-eng.html

Government of Canada. (2019b). Clean fuel standard. Retrieved from https://www.canada.ca/en/environment-climate-change/services/managing-pollution/energy-production/fuel-regulations/clean-fuel-standard.html

Han, J., Elgowainy, A., Cai, H., & Wang, M. Q. (2013). Life-cycle analysis of bio-based aviation fuels. Bioresource Technology, 150, 447–456. https://doi.org/10.1016/j.biortech.2013.07.153

ICAO. (2019a). CORSIA frequently asked questions. Retrieved from https://www.icao.int/environmental-protection/CORSIA/Pages/CORSIA-FAQs.aspx

ICAO. (2019b). ICAO CORSIA implementation elements: CORSIA eligible fuels – CORSIA default life cycle emissions values for CORSIA eligible fuels. Retrieved from https://www.icao.int/environmental-protection/CORSIA/Pages/CORSIA-Eligible-Fuels.aspx

IEA. (2018). IEA bioenergy task 39: Comparison of biofuel life cycle analysis tools phase 2, part 1: FAME and HVO/HEFA. Retrieved from http://task39.ieabioenergy.com/publications/

IPCC. (2003). Good practice guidance for land use, land-use change and forestry. Retrieved from https://www.ipcc-nggip.iges.or.jp/public/ggplulucf/ggplulucf_contents.html

IPCC. (2006). 2006 IPCC guidelines for national greenhouse gas inventories. Prepared by the National Greenhouse Gas Inventories Programme. Retrieved from https://www.ipcc-nggip.iges.or.jp/publications/2006gl/index.html

IPCC. (2013). Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. Retrieved from https://www.ipcc.ch/report/ar5/wg1/
Janzen, H., Campbell, C., Izaurralde, R., Ellert, B., Juma, N., McGill, W., & Zentner, R. (1998). Management effects on soil C storage on the Canadian prairies. *Soil & Tillage Research*, 47, 181–195. https://doi.org/10.1016/S0167-1987(98)00105-6

Lane, J. (2018). The paramount deal: World Energy takes off with audacious $72M acquisition of AltAir and the Paramount oil refinery. *Biofuels Digest*. Retrieved from http://www.biofuelsdigest.com/bdigest/2018/03/19/the-paramount-deal-world-energy-takes-off-with-audacious-72m-acquisition-of-altair-and-the-paramount-oil-refinery/

Liu, X. J., Mosier, A. R., Halvorson, A. D., & Zhang, F. S. (2006). The impact of nitrogen placement and tillage on NOx, N2O, CH4 and CO2 fluxes from a clay loam soil. *Plant and Soil*, 280(1–2), 177–188. https://doi.org/10.1007/s11104-005-2950-8

MacWilliam, S., Sanscartier, D., Lemke, R., Wismer, M., & Baron, V. (2016). Environmental benefits of canola production in 2010 compared to 1990: A life cycle perspective. *Agricultural Systems*, 145, 106–115. https://doi.org/10.1016/j.agsy.2016.03.006

McConkey, B., Liang, B., Campbell, C., Curnin, D., Moulin, A., Brandt, S., & Lafond, G. (2003). Crop rotation and tillage impact on carbon sequestration in Canadian prairie soils. *Soil & Tillage Research*, 74, 81–90. https://doi.org/10.1016/S0167-1987(03)00121-1

Miller, P., & Kumar, A. (2013). Development of emission parameters and net energy ratio for renewable diesel from Canola and Camelina. *Energy*, 58, 426–437. https://doi.org/10.1016/j.energy.2013.05.027

National Energy Board. (2016). Canada's energy future 2016: Province and territory outlooks. Retrieved from https://www.neb-one.gc.ca/cn/energy/transp/altair-and-the-paramount-oil-refinery/2018/03/19/the-paramount-deal-world-energy-takes-off-with-audacious-72m-acquisition-of-altair-and-the-paramount-oil-refinery/

Obnamia, J. A., Dias, G. M., MacLean, H. L., & Saville, B. A. (2019). Management effects on soil C storage on the Canadian prairies. *Soil & Tillage Research*, 187(6), 18764. https://doi.org/10.1016/j.still.2019.06.018

O'Neill, R. J., Campbell, C., Izaurralde, R., Ellert, B., Juma, N., McGill, W., & Zentner, R. (1998). Management effects on soil C storage on the Canadian prairies. *Soil & Tillage Research*, 47, 181–195. https://doi.org/10.1016/S0167-1987(98)00105-6

Shi, R., Archer, D. W., Pokharel, K., Pearlson, M. N., Lewis, K. C., Pereira, L. G., Cavalett, O., Bonomi, A., Zhang, Y., Warner, E., & Chum, H. L. (2019). Comparison of biofuel life-cycle GHG emissions assessment tools: The case studies of ethanol produced from sugar-cane, corn, and wheat. *Renewable and Sustainable Energy Reviews*, 110, 1–12. https://doi.org/10.1016/j.rser.2019.04.043

Shi, R., Archer, D. W., Pokharel, K., Pearlson, M. N., Lewis, K. C., Ukaew, S., & Shonnard, D. R. (2019). Analysis of renewable jet from oilseed feedstocks replacing fallow in the U.S. northern great plains. *ACS Sustainable Chemistry & Engineering*, 7(23), 18753–18764. https://doi.org/10.1021/acssuschemeng.9b02150

Statistics Canada. (2014a). *Statistics Canada. (2014b). Snapshot of Canadian agriculture – Spring wheat and canola area in Canada: Crops in Canada from census years 1956 to 2006*. Retrieved from https://www150.statcan.gc.ca/n1/ca-ra2006/articles/snapshot-portrait-eng.htm

Statistics Canada. (2016). *Table: 32–10-0162-01 (formerly CANSIM 004–0010) Selected land management practices and tillage practices used to prepare land for seeding, historical data*. Retrieved from https://www150.statcan.gc.ca/t1/tbl1/en/cv?recreate.action?pid=3210016201&selectedNodeIds=1D8,1D9,1D10,2D5,2D6,2D7,2D8&check2d=0D1,2D1&refPeriods=1981010120160101&dimensionLayouts=0D1,2D1,2D1&refPeriods=1981010120160101&dimensionLayouts=0D1,2D1,2D1&refPeriods=1981010120160101&dimensionLayouts=0D1,2D1,2D1&refPeriods=1981010120160101&dimensionLayouts=0D1,2D1,2D1

Statistics Canada. (2018a). *Change in summerfallow area by census division (CD) from 2011 to 2016*. Retrieved from https://www150.statcan.gc.ca/n1/pub/95-634-x/2017001/article/54903/catm-cfra233-eng.htm

Statistics Canada. (2018b). *Table 32–10-0359-01 estimated areas, yield, production, average farm price and total farm value of principal field crops, in metric and imperial units*. Retrieved from Statistics Canada https://www150.statcan.gc.ca/t1/tbl1/en/view.action?pid=3210035901

Statistics Canada. (2018c). *Table: 32–10-0359-01 (formerly CANSIM 001–0017) estimated areas, yield, production, average farm price and total farm value of principal field crops, in metric and imperial units*. Retrieved from Statistics Canada https://www150.statcan.gc.ca/t1/tbl1/en/view.action?pid=3210035901

Ukaew, S., Shi, R., Lee, J. H., Archer, D. W., Pearlson, M., Lewis, K. C., ... Shonnard, D. R. (2016). Full chain life cycle assessment of greenhouse gases and energy demand for canola-derived jet fuel in north Dakota, United States. *ACS Sustainable Chemistry & Engineering*, 4(5), 2771–2779. https://doi.org/10.1021/acssuschemeng.6b00276

USDA-FAS. (2019). *Oilseeds: World markets and trade*. Retrieved from https://www.fas.usda.gov/data/oilseeds-world-markets-and-trade

Wang, M. Q., Huo, H., & Arora, S. (2011). Methods of dealing with co-products of biofuels in life-cycle analysis and consequent results within the U.S. context. *Energy Policy*, 39(10), 5726–5736. https://doi.org/10.1016/j.enpol.2010.03.052

**SUPPORTING INFORMATION** Additional supporting information may be found online in the Supporting Information section.

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