Submitted: 01/17/2024
Accepted: 03/06/2025
Published: 03/31/2025

Research Article

Cassia Attard[1,2], Jasmine Boucley[1,2], Elianta Jaillet[1,2], Maxime Léger[1,2] and Eleanor Morrison[1,2]

Assessing Changes in Feed Security of the Québec Dairy Industry in 2050

[1] Department of Geography, McGill University, Montréal, QC, Canada

[2] Bieler School of Environment, McGill University, Montréal, QC, Canada

Keywords

Feed security, Dairy cattle diets, Québec dairy industry, Dairy land use, Climate adaptation

Email Correspondence

cassia.attard@mail.mcgill.ca

https://doi.org/10.26443/msurj.v1i1.225

Abstract

Understanding the effects of climate change is central to assessing the resilience of the agricultural sector in Québec. The dairy industry is vulnerable as climate change alters yields for cattle feed grown on-farm. Québec dairy farmers have adopted various strategies to mitigate greenhouse gas emissions on farms, incorporating sustainable agricultural practices such as improved waste and manure management, and altering cow diets to reduce enteric (digestive) methane production. The last of these practices –– altering cow diets that reduce enteric methane emissions –– is valuable, yet it introduces a tradeoff between emission reduction and climate adaptation. Indeed, diets that reduce methane emissions may require crops that are less resilient to future climate conditions, whereas climate-resilient feed crops may not offer the same methane-reduction benefits. In 2050, Québec dairy farmers may not be able to grow all feed crops on their land to support herd health and milk output, both metrics of feed security. Accordingly, this study assesses the regional feed security of the Québec dairy industry by modelling the impact of crop yield change in two climate scenarios and with three diet compositions in 2050. Results show that in 2050, methane-reducing corn-heavy diets will require more cropland than hay- or soy-based diets, presenting an environmental tradeoff between land use and methane emissions. The analysis reveals high projected intraprovincial variability in feed security, with Eastern Québec predicted to be more feed secure than Southwestern Québec. The importance of a sustainable and self-sufficient dairy industry is increasingly important in the face of climate change. More broadly, this research aims to identify potential approaches for farmers to support future successful dairy operations.

List of Abbreviations

Census Agricultural Region	CAR
Corn-Heavy Diet	CHD
Current Land Area	CLA
Future Land Area	FLA
Greenhouse Gas	GHG
Hay-Heavy Diet	HHD
Intergovernmental Panel on Climate Change	IPCC
Eastern Québec	QCE
Southwestern Québec	QCSW
Representative Concentration Pathway	RCP
Soy-Heavy Diet	SHD

Introduction

Assessing the resilience of key industries is crucial for informed decisions in the face of climate change. Agriculture, including dairy farming, is projected to be one of the industries most impacted by climate change in Canada. The province with the largest dairy industry is Québec, accounting for 46.7% of Canadian dairy farms[1]. Dairy farming accounts for 25% of Québec's agricultural revenue[2]. As the largest agricultural industry in Québec, it also contributes to the fulfillment of Québec's mission of being an economically and culturally self-sustaining province, averting reliance on interprovincial or international trade[2,3]. Existing dairy industry life cycle analyses (LCAs) and agri-food literature primarily acknowledge the climate impacts of greenhouse gas (GHG) emissions from enteric (digestive) fermentation from cattle in the Québec dairy industry[4,5]. Notable research has also been conducted by Cordeiro et al.[6] who assessed the feed security of beef production in the province of Alberta, and Thivierge et al. who simulated future climate impacts at the single-farm scale[7]. Yet, the literature does not account for future climate impacts on dairy production land, a gap which motivates this analysis. This paper seeks to analyze the current and future self-sufficiency of the Québec dairy industry and the potential impacts of climate fluctuations on the sector.

The dairy industry both contributes to and is impacted by climate change. Given this, methane mitigation strategies (MMS) for the beef and dairy industries have been developed by Agriculture and Agri-food Canada[8]. Greenhouse gas emissions of the dairy sector predominantly stem from methane production from enteric fermentation driven by a grass/hay dominant diet[4,5,9]. In accordance, the MMS outlines strategies whereby cattle diets are adapted to reduce enteric fermentation including substituting feed grasses for corn grain and silage or increasing oilseed additives (e.g. soy and canola) in feeds[8]. Several feed crops favored by the MMS are associated with the additional benefit of increased milk yield[9], an important environmental and economic indicator[10]. These suggested feed regimes have already taken effect across the province: Canadian Dairy Farmers estimated that in 2022, 74% of suggested MMS feed practices were already nationally adopted[11]. In Québec, current cow diets consist primarily of hay and are supplemented by corn and soy[4]. The current ratios of corn, grain, silage, and soy are in line with the MMS, though both corn and soy percentages could be further increased under MMS recommendations[11].

In addition to adopting GHG mitigation strategies, dairy farmers must also adapt to climate change-induced crop yield variability, as these fluctuations will affect farmers' ability to produce specific feed crops for their livestock[7]. Québec dairy farmers' heavy reliance on on-farm feed production makes them particularly vulnerable to climate-induced crop yield decreases and variability, with impacts varying in severity across different regions of the province[4]. In 2022, Québec dairy farms averaged 78 cows and produced about 770,000 litres of milk annually[12], typically operating as non-grazing farms with 92% of cows housed in tie-stalls and cows having an average lifespan of 6 years[4]. According to the Intergovernmental Panel on Climate Change's (IPCC) Representative Concentration Pathway (RCP) 4.5 and 8.5 emissions scenarios, by 2050, Québec will see an increase in average winter temperatures of 2.7 °C and 5.2 °C, and summer increases of 1.9 °C and 2.8 °C, respectively[13]. In these scenarios, the province's agriculture industry will experience nearly 50% longer warm growing seasons and increases in the frequency and intensity of precipitation events[14]. These climate changes will have mixed effects on common dairy cattle feed crops: for instance, soybean, corn, and timothy hay are predicted to benefit from longer frost-free growing seasons[15], whereas canola, wheat, and barley are expected to be negatively impacted[16]. Such variability in crop yields could affect feed security, i.e., the ability of farmers to consistently access adequate feed resources to support herd health and agri-food output (for instance, milk for dairy farmers)[6]. Feed security is an indicator of disruptions in the broader dairy production system. Coupled with climate stress and crop yield variability, the steady rise in Canadian demand for dairy products, including 1-3% increases in cheese, yogurt, and cream consumption in two-year periods[17], requires that cattle feed production meet demand. The combined pressures of changing crop yields and rising production demand may threaten Québec's feed security and ability to maintain a self-sustained dairy industry[18].

As crop yields decline on Québec farms due to climate change, farmers would need to expand their cropland to maintain feed production for their herds. This additional cropland could be diverted from other agricultural uses or newly created from forest or other natural ecosystems. From 2010 to 2015, 65% of land-use change in Southern Canada was forest-to-cropland conversion[19]. These conversions are associated with local biodiversity loss and fragmentation, decreases in natural carbon sequestration, and potential infringement of indigenous sovereignty[20]. Agricultural expansion also occurs at the cost of soil organic carbon sequestration[21]. In Canada and by 2070, unconverted pasture is projected to store 25.3% more carbon dioxide in unconverted pastures than in croplands[22]. As a result, greater cropland conversion resulting from preventing feed insecurity would have major implications for the environments surrounding dairy farms. Decisions about cropland conversion require consideration of the tradeoffs between using the land for dairying or other agricultural operations, and preserving natural ecosystems. Accordingly, this paper aims to assess the feed security of Québec's dairy industry, regionally and provincially, in a future climate-changed world.

Methods

The Model and Calculations

The Model

A feed insecurity model was made in Microsoft Excel. The model allows for the feed insecurity of sub-regions of Québec to be analyzed for two climate scenarios (RCPs 4.5 and 8.5) and with three different diets. The province is divided by Census Agricultural Regions (CARs), as data is most granular at this scale. As of 2024, data on future crop yield projections is available for two subregions of Québec: the East (QCE) and the Southwest (QCSW). As such, CARs are categorized into these two regions, informed by Thivierge and colleagues' map detailing Eastern and Southwestern Québec[7].

Diet Composition

In our analysis, feed insecurity is assessed for three different diets: a hay-heavy diet (HHD) (the current Québec cow diet), a soy-heavy diet (SHD) and a corn-heavy diet (CHD) (the current average US cow diet). These diets were chosen as realistic scenarios in which the fraction of each major feed crop varied. The relative composition of all three diets is shown in Table 1. "Current" refers to the best estimates as of 2024.

Table 1. Diet Composition (%) of the Three Modeled Diets. HHD sourced from Mc Geough et al.[4], CHD from Castillo-Lopez et al.[25], and SHD from Holtshausen et al.[5].

	Hay-Heavy Diet	Corn-Heavy Diet	Soy-Heavy Diet
Corn grain	11.86	16.30	11.56
Corn silage	23.51	36.40	17.11
Hay/Haylage	47.77	9.58	49.12
Soybean	11.66	9.58	13.26

Mc Geough and colleagues'[4] feed composition data is available by cow age category and is divided into 5 life stages. To obtain a lifetime average diet composition, feed components are weighted according to diet composition at each life stage and the duration of each life stage. For each crop, the weighted proportion of the diet ($\mathrm{WPD_{crop}}$) is calculated using Equation 1, where the proportion of the diet (PD) made up for by a given crop during a given life stage is multiplied by the fraction of life (FOL) spent in the given life stage, and where n refers to the life stages 1 to 5:

$$\mathrm{WPD_{crop}} = \sum_{n=1}^{5} \mathrm{PD_{stage\ n}} \times \mathrm{FOL_{stage\ n}}. \tag{1}$$

The average US dairy cattle diet found by Castillo-Lopez et al.[25] is used to simulate a corn-heavy diet. The diet developed by Holtshausen et al.[5] for their work on Québec dairy is used to simulate a soy-heavy diet. All diets are weighted by lifetime consumption.

Mass of Feed Required

The total energy intake of a cow during a given life stage ($\mathrm{TEI_{stage}}$) is the product of the *daily* energy intake during the given life stage ($\mathrm{DEI_{stage}}$) and the duration of the stage (t_{stage}), as shown by Equation 2. The lifetime average daily energy intake of a cow (ADEI), given by Equation 3, is the sum of total energy intake for each life stage, divided by the total lifespan of a cow (t_{total}). The average daily dietary energy ($\mathrm{ADDE_{crop}}$) provided by a given crop to a cow throughout its lifetime is the product of ADEI and WPD, as demonstrated by Equation 4. ADDE is found for each crop and each diet.

To find the mass of dry matter of a given crop ($\mathrm{DM_{crop}}$) required annually per cow for a given diet, the ADDE of the crop is first converted from units of MJ/day to Mcal/year, and then divided by digestible energy (DE), as shown by Equation 5. The annual crop production required ($\mathrm{CPR_{crop}}$) to meet feed demands is calculated using the dry matter required and the dry matter percentage of the crop ($\mathrm{DM\%_{crop}}$), as shown by Equation 6. CPR refers to the mass of wet feed of a given crop required annually per cow, and is calculated for each crop, for each of the three diets. Digestible energy (Mcal/kg) and dry matter percentage values for each crop are derived from the National Research Council's *Nutrient Requirements of Dairy Cattle*[26]:

$$\mathrm{TEI_{stage}\ (MJ)} = \mathrm{DEI_{stage}\ (MJ/day)} \times t_{\mathrm{stage}}\ \mathrm{(days)}, \tag{2}$$

$$\mathrm{ADEI\ (MJ/day)} = \sum \mathrm{TEI_{all\ stages}(MJ)}\ /\ t_{\mathrm{total}}\ \mathrm{(days)}, \tag{3}$$

$$\mathrm{ADDE_{crop}\ (MJ/day)} = \mathrm{ADDE\ (MJ/day)} \times \mathrm{WPD}, \tag{4}$$

$$\mathrm{DM_{crop}\ (kg/year/cow)} = \frac{\mathrm{ADDE_{crop}\ (Mcal/year)}}{\mathrm{DE\ (Mcal/kg)}}, \tag{5}$$

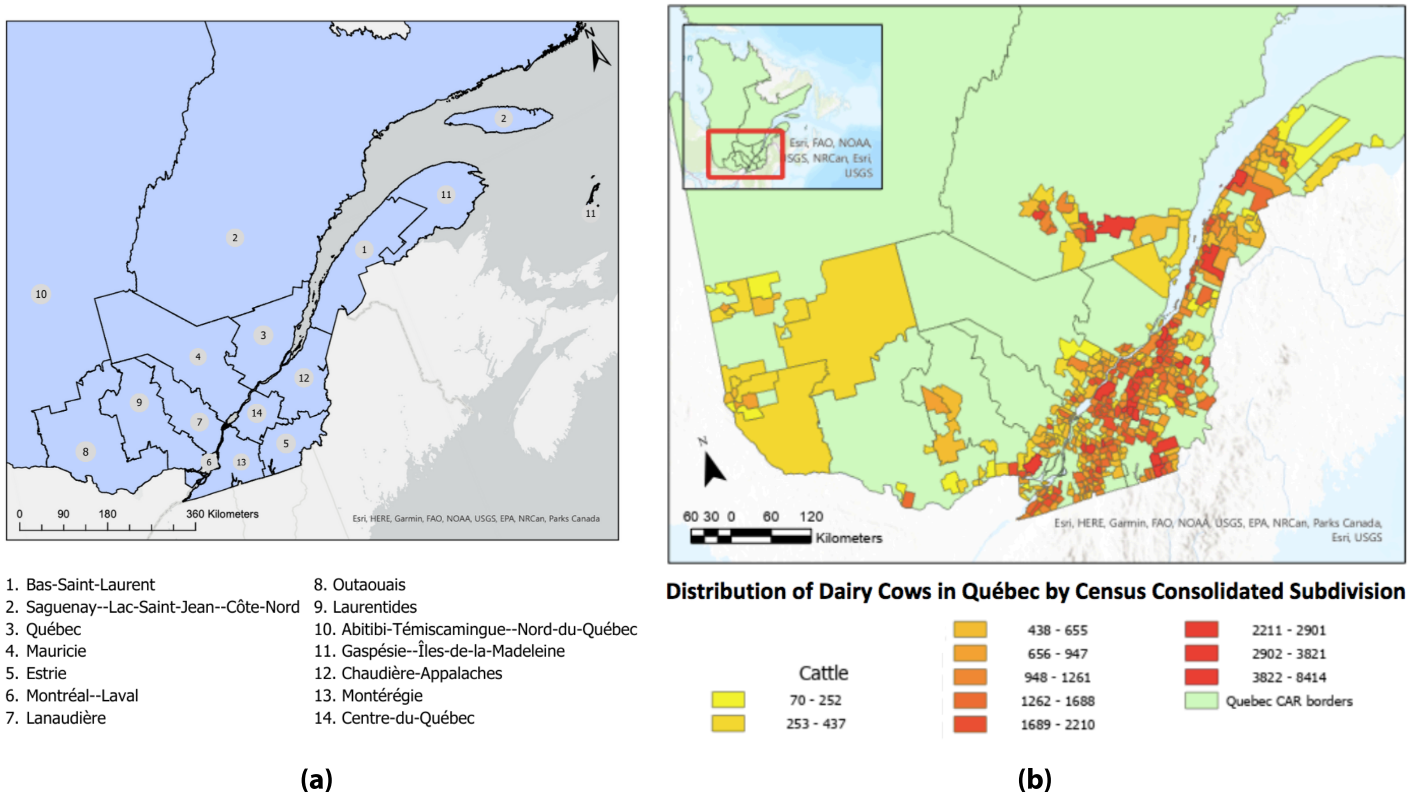


Figure 1. (a) Census Agricultural Regions in Québec. Showing the division of CARs. Data sourced from Statistics Canada[23]. **(b)** Distribution of dairy cows by CCS in Québec. Showing a visual of the distribution of cows by Census Consolidated Subdivisions, a subdivision of CARs. Data sourced from Statistics Canada[23,24].

$$\text{CPR}_{\text{crop}}\ (\text{kg/year/cow}) = \frac{\text{DM}_{\text{crop}}\ (\text{kg/year/cow})}{\text{DM\%}_{\text{crop}}\ (\%)}. \tag{6}$$

Current & Future Number of Cows per CAR

The current number of cows in a given CAR is calculated from Statistics Canada heifer and dairy cattle data[24] by summing the number of heifers and dairy cattle per CAR. According to Alexandratos & Bruinsma[27], it can be assumed that the number of cows in each region increases by 0.3% annually. The number of cows per CAR in 2050 is calculated by Equation 7:

$$\text{Cows}_{2050} = \text{Cows}_{2021} \times (1 + 0.003)^{2050-2021}. \tag{7}$$

Current and Future Land Area Required

Data on the current land area (CLA) used to grow dairy feed crops in Québec is currently unavailable. Literature shows that most dairy producers in Québec grow the required amounts of feed on-farm[4,28]. As feed production mostly occurs on-farm and is currently sufficient for dairy production, we assume that all regions in Québec are currently feed secure. Current crop yield (CCY) data for each CAR is obtained froDiets and Feed Insecuritym the *Institut de la statistique du Québec*[29]. CLA within a given CAR is calculated for each diet scenario. The CLA required to grow the necessary amount of a crop for a given diet within a given CAR (for example the CLA required to grow all the corn grain for the hay-heavy diet in the Bas-St-Laurent CAR) is calculated with Equation 8. The total CLA required to grow feed for a given diet is the sum of the CLA for each individual crop. This total is calculated for each CAR using Equation 9:

$$\text{CLA}_{\text{crop}}\ (\text{ha}) = \frac{\text{Cows}_{2021} \times \text{CPR}_{\text{crop}}\ (\text{kg/year/cow})}{\text{CCY}_{\text{crop}}\ (\text{kg/ha/year})}, \tag{8}$$

$$\text{Total CLA}_{\text{CAR}}\ (\text{ha}) = \text{CLA}_{\text{corn grain}} + \text{CLA}_{\text{corn silage}} + \text{CLA}_{\text{hay}} + \text{CLA}_{\text{soy}}. \tag{9}$$

The total future land area (FLA) required to grow feed for all cows is calculated for each CAR, each diet, and both climate scenarios. Future crop yield changes are sourced from Thivierge et al.[7], which provides data for two greater regions in Québec: Eastern Québec (QCE) and Southwest Québec (QCSW). Future crop yields (FCY) under a given climate scenario are derived from current crop yields (CCY) and the predicted crop yield changes (ΔCY) for the given RCP, as shown by Equation 10. The FLA for a given crop under each RCP is then calculated with Equation 11. Lastly, using Equation 12, the total FLA required to grow feed for a given diet is calculated for each CAR by summing the FLA for each individual crop:

$$\text{FCY}_{\text{RCP,crop}}\ (\text{kg/ha}) = \text{CCY}_{\text{crop}}\ (\text{kg/ha}) + \Delta\text{CY}_{\text{RCP}}\ (\%), \tag{10}$$

$$\text{FLA}_{\text{RCP,crop}}\ (\text{ha}) = \frac{\text{Cows}_{2050} \times \text{CPR}_{\text{crop}}\ (\text{kg/year/cow})}{\text{FCY}_{\text{RCP,crop}}\ (\text{kg/ha})}, \tag{11}$$

$$\text{Total FLA}_{\text{CAR}}\ (\text{ha}) = \text{FLA}_{\text{corn grain}} + \text{FLA}_{\text{corn silage}} + \text{FLA}_{\text{hay}} + \text{FLA}_{\text{soy}}. \tag{12}$$

Feed Insecurity Indicator (FII)

The FII represents the percentage of land area change required to meet feed security. A negative FII indicates a decrease in land required—–land that could be diverted from cow feed production and reclaimed for other purposes such as reforestation—–whereas a positive FII indicates an increase

Table 2. Current Feed Crop Yields and Projected 2050 Feed Crop Yield Changes (%) by CAR. Current yield data obtained from Institut de la Statistique du Québec[29]. Predicted crop yield change data obtained from Thivierge et al.[7]

Census Agricultural Regions (CAR)	Current Yields (kg/ha)				Predicted 2050 Yield Change for RCPs 4.5 and 8 (%)							
	Corn Grain	Corn Silage	Soy	Hay	Corn Grain		Corn Silage		Soy		Hay	
					4.5	8	4.5	8	4.5	8	4.5	8
Bas-Saint-Laurent (QCE)	6500	27150	3110	4790	1.369	-8.22	83.50	76.70	34.78	43.48	15	22.73
Gaspésie – Îles-de-la-Madeleine (QCE)	6500	27150	3110	4790	1.369	-8.22	83.50	76.70	34.78	43.48	15	22.73
Saguenay – Lac-Saint-Jean – Côte-Nord (QCSW)	7680	35190	2050	3420	1.369	-8.22	14.77	16.78	34.78	43.48	15	7.32
Québec (QCSW)	8900	39800	2690	4980	1.369	-8.22	14.77	16.78	34.78	43.48	15	7.32
Mauricie (QCSW)	8900	39800	2690	4980	1.369	-8.22	14.77	16.78	34.78	43.48	15	7.32
Estrie (QCE)	8350	35490	2450	5390	1.369	-8.22	83.50	76.70	34.78	43.48	15	22.73
Lanaudière (QCSW)	9140	48130	3310	5930	1.369	-8.22	14.77	16.78	34.78	43.48	15	7.32
Outaouais (QCSW)	9260	47990	2710	4270	1.369	-8.22	14.77	16.78	34.78	43.48	15	7.32
Laurentides (QCSW)	9260	47990	2710	4270	1.369	-8.22	14.77	16.78	34.78	43.48	15	7.32
Abitibi-Témiscamingue – Nord-du-Québec (QCSW)	7880	19750	1980	2800	1.369	-8.22	14.77	16.78	34.78	43.48	15	7.32
Chaudière-Appalaches (QCE)	7520	32160	2690	5030	1.369	-8.22	83.50	76.70	34.78	43.48	15	22.73
Montérégie (QCE)	10690	40630	3130	6320	1.369	-8.22	83.50	76.70	34.78	43.48	15	22.73
Centre-du-Québec (QCE)	9030	41070	2780	5370	1.369	-8.22	83.50	76.70	34.78	43.48	15	22.73

in land required (conversion of land to cropland):

$$\text{FII} = \frac{\text{Total FLA (ha)}}{\text{Total CLA (ha)}}\% - 100\% \tag{13}$$

Assumptions

Our model functions under the following key assumptions:

[1] All CARs are currently perfectly feed secure.

[2] All feed is grown on-farm.

[3] Future crop yields and milk output are not impacted by improvements in production technology.

[4] The number of cows per CAR will increase by 0.3%/year.

[5] Herds are not impacted by temperature fluctuations (e.g. heat stress).

Analytical Approach

To analyze the sensitivity of feed security to diet changes, the percent of a given crop in the diet composition is increased in 10% increments while decreasing other feed components proportionally.

Interregional variation is assessed to analyze the potential impact of feed insecurity on interprovincial trade. Nuanced analysis of intraprovincial variation and trade projections are outside the scope of this study. As simple metrics of variation, we use standard deviation (SD) and coefficient of variation (CV) from the mean of feed insecurity values across CARs. To note, CAR Montréal–Laval is omitted from all analyses as the region has no dairy farms.

The change in possible milk production is calculated assuming each cow produces 8,000 L of milk annually[30]. All maps were made using the GIS software ArcGIS Pro. Provincial and CAR shapefiles were sourced from Statistics Canada[23].

Results

HHD (Current Québec Diet) Scenario

Under the HHD scenario (current Québec diet), the study finds that all CARs will remain feed secure. The provincial average FII is -6.74% under RCP 4.5 and -10.04% under RCP 8.5. This equates to 39745 ha and 59183 ha, respectively, of reclaimed land area overall in the province. Despite Québec's average negative FII, only 6 of 11 CARs are found to have a negative FII (increased feed security). To meet feed demands, 7 of the 13 included CARs will require an increase in land for feed production by 2050.

The total land area required for feed production by 2050 will decrease in QCE, while increasing in QCSW. QCE is found to have an FII of -9.57% and -14.85% under RCPs 4.5 and 8.5, respectively. This equates to 43170 to 67043 ha of reclaimed land in QCE. Meanwhile, QCSW is found to have an FII of 2.48% and 5.70% under RCPs 4.5 and 8.5, respectively. This equates to 3425 to 7860 additional ha required in QCSW.

Under both RCP 4.5 and 8.5, the Montérégie region exhibits the largest absolute FIIs, while the Lanaudière region exhibits the largest positive FIIs (Table 3).

The Chaudière-Appalaches region sees the largest change in total land area requiring 11619.1 ha (RCP 4.5) to 18143.9 ha (RCP 8.5) less land for feed production by 2050. The Saguenay–Lac-Saint-Jean–Côte-Nord region exhibits the highest increase in total feed cropland area required, 917.1 ha (RCP 4.5) and 2280.3 ha (RCP 8.5).

CHD (Current US Diet) Scenario

In the CHD scenario, Québec is found to remain provincially feed secure under both RCPs, with an FII of -3.01% (8384 ha reclaimed) under RCP 4.5 and -3.18% (8858 ha reclaimed) under RCP 8.5. QCE will require less land to meet feed demands in 2050, with an FII of -6.20% (13552 ha reclaimed) and -6.87% (15003 ha reclaimed) under RCPs 4.5 and 8.5 respec-

Table 3. Québec 2050 Dairy Cow FII and Total Cropland Area Change. FII values expressed as a percentage are given per region (including the provincial, QCE and QCSW values), for each diet, at each RCP. For total cropland area change in Québec, negative numbers represent land reclaimed in 2050, while positive numbers indicate the additional cropland required to meet feed demands in 2050.

Regions	Hay-Heavy Diet RCP 4.5	Hay-Heavy Diet RCP 8.5	Corn-Heavy Diet RCP 4.5	Corn-Heavy Diet RCP 8.5	Soy-Heavy Diet RCP 4.5	Soy-Heavy Diet RCP 8.5
FII for Québec Dairy Cows in 2050						
Bas-Saint-Laurent (QCE)	-8.85%	-13.89%	-5.00%	-5.00%	-11.11%	-16.64%
Gaspésie – Îles-de-la-Madeleine (QCE)	2.17%	5.38%	8.00%	9.00%	-0.15%	2.61%
Saguenay – Lac-Saint-Jean – Côte-Nord (QCSW)	2.73%	5.83%	9.00%	11.00%	0.06%	2.66%
Québec (QCSW)	2.73%	5.83%	9.00%	11.00%	0.06%	2.66%
Mauricie (QCSW)	-9.77%	-15.06%	-7.00%	-7.00%	-11.81%	-17.49%
Estrie (QCE)	4.01%	7.29%	13.00%	15.00%	0.94%	3.67%
Lanaudière (QCSW)	2.73%	6.09%	10.00%	12.00%	0.30%	3.19%
Outaouais (QCSW)	2.73%	6.09%	10.00%	12.00%	0.30%	3.19%
Laurentides (QCSW)	0.77%	3.90%	2.00%	4.00%	-0.78%	2.01%
Abitibi-Témiscamingue – Nord-du-Québec (QCSW)	-8.85%	-13.89%	-5.00%	-5.00%	-11.11%	-16.64%
Chaudière-Appalaches (QCE)	-9.34%	-14.58%	-6.00%	-6.00%	-11.46%	-17.12%
Montérégie (QCE)	-10.38%	-15.72%	-8.00%	-9.00%	-12.16%	-17.88%
Centre-du-Québec (QCE)	-9.46%	-14.95%	-5.00%	-7.00%	-11.47%	-17.33%
Province of Québec	-6.74%	-10.04%	-3.01%	-3.18%	-6.46%	-9.98%
QCE	-9.57%	-14.85%	-6.20%	-6.87%	-9.07%	-14.64%
QCSW	2.48%	5.70%	8.58%	10.20%	2.01%	5.17%
Total Cropland Area Change in Québec in 2050 (ha)						
QC	-39745.2	-59183.0	-8383.5	-8857.8	-38655.3	-59743.9
QCE	-43170.3	-67042.6	-13552.4	-15003.2	-41492.7	-67024.2
QCSW	3425.1	7859.7	5168.9	6145.3	2837.4	7280.3

tively. QCSW will need to increase cropland, with an FII of 8.58% (additional 5169 ha required) and 10.2% (additional 6145 ha required) under RCP 4.5 and 8.5 respectively. Under this diet, Montérégie is the most feed secure CAR, and the least feed secure CAR is Lanaudière for both RCPs (Table 3). Overall, this diet scenario predicts the highest FIIs across both RCPs.

SHD Scenario

The SHD scenario results in an overall feed secure province, with FIIs of -6.46% (38655.3 ha reclaimed) and -9.98% (59743.9 ha reclaimed) under RCPs 4.5 and 8.5 respectively. In RCP 4.5, QCE is found to have a FII of -9.07% (41492.7 ha reclaimed) while QCSW is found to have an FII of 2.01% (additional 2837.4 ha required). In RCP 8.5, the FII is -14.64% (67024.2 ha reclaimed) for QCE and 5.17% (additional 7280.3 ha required) for QCSW. The most feed secure CAR for both RCPs is Montérégie and the least feed secure is Lanaudière (Table 3). This diet scenario leads to the most feed security, producing the lowest FIIs across all included CARs.

Discussion

Feed Security and Diet Composition

The results show a significant impact of diet composition on future feed security. The modeled outcome of the CHD scenario is least feed secure, while the SHD scenario is found to be the most feed secure.

Corn-Heavy Diets

In the CHD scenario, the average FIIs across CARs are 1.92% (σ 8.04%) for RCP 4.5 and 2.69% (σ 9.23%) for RCP 8.5. In contrast, the average FIIs across CARs under the HHD and SHD scenarios for both RCPs are negative, indicating greater feed security on average. Every included CAR presents a higher FII in the CHD scenario than the other diet scenarios.

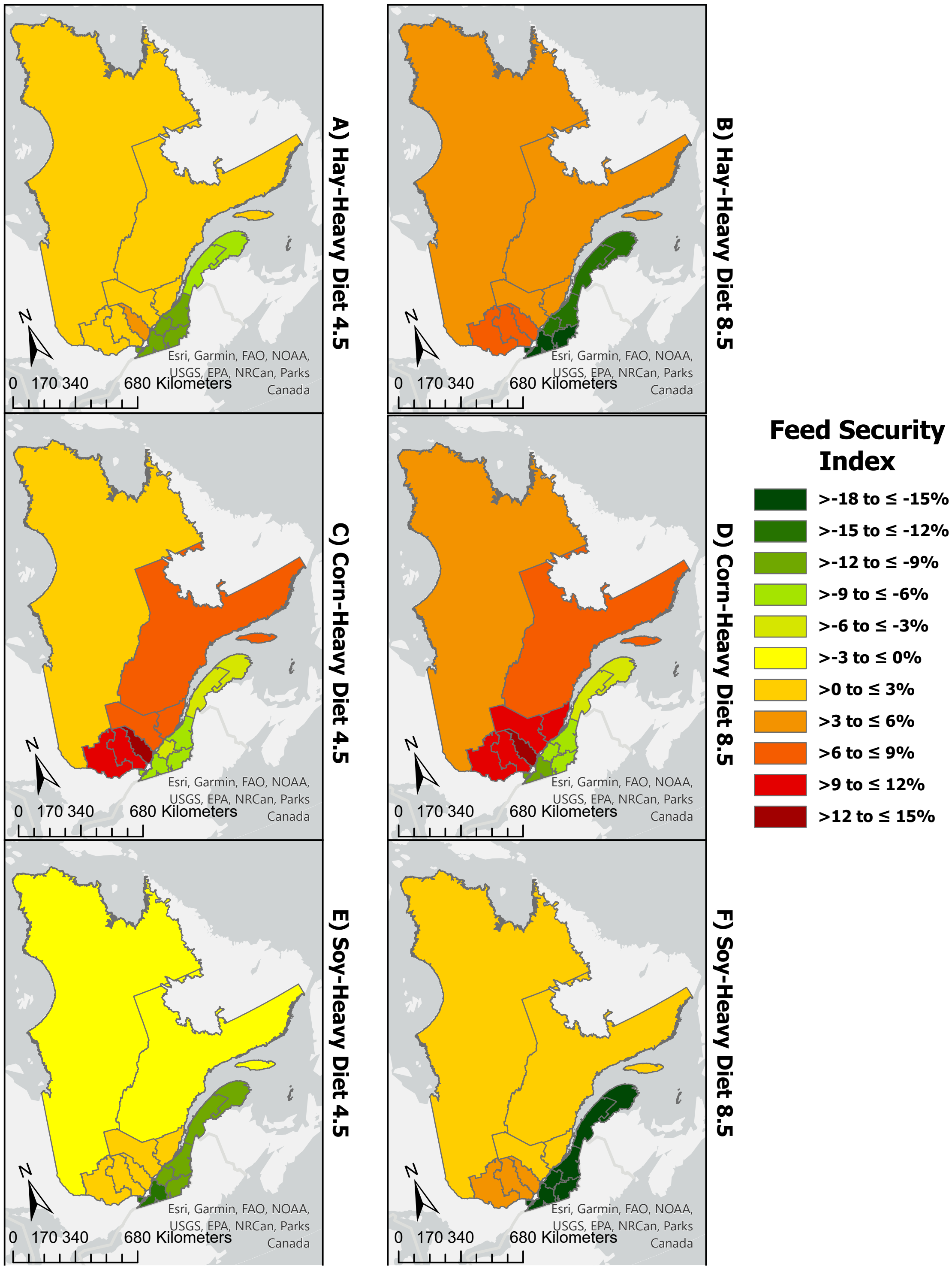
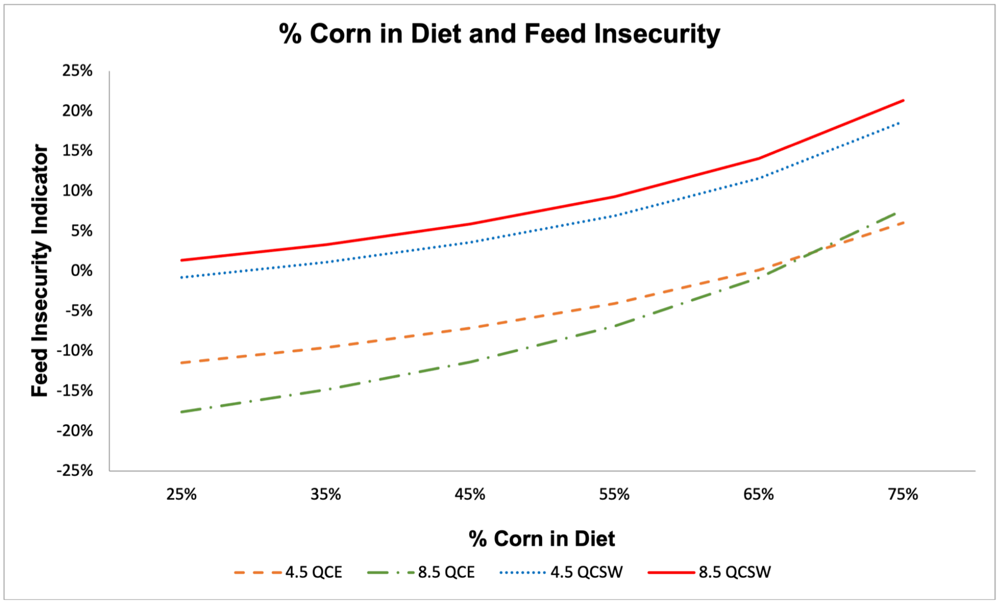


Figure 2. Feed Insecurity Indicator in Québec by CAR. Maps on the left correspond to RCP 4.5, and maps on the right correspond to RCP 8.5.

a)



b)

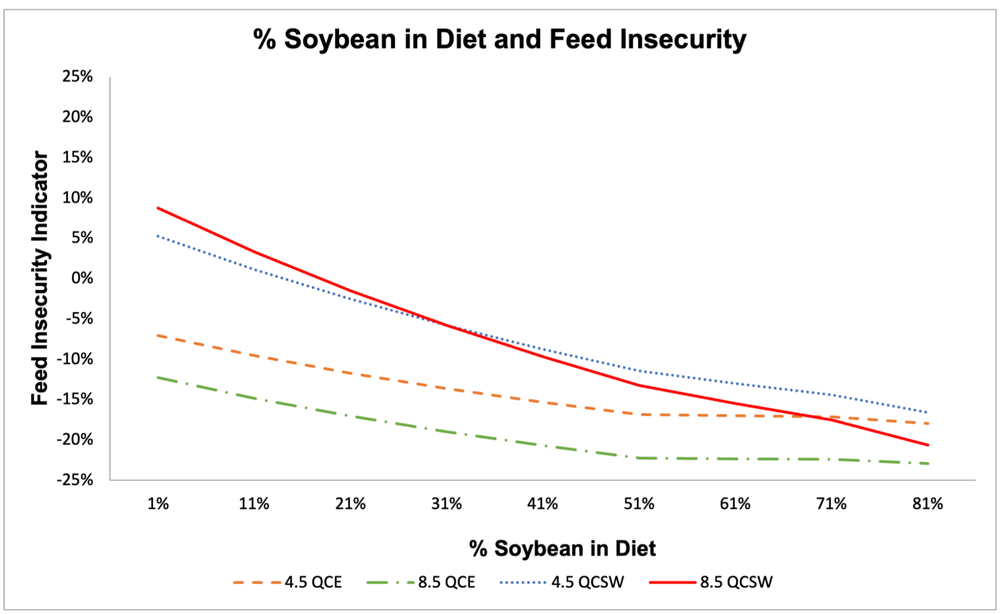


Figure 3. (a) Relationship Between Proportion of Corn (%) in Dairy Cow Diet (Sum of Silage and Grain) and Feed Insecurity. Corn includes both grain and silage. The percentage of corn in the HHD (current Québec dairy cow diet) is 36%. Correlation between percent corn in the diet and FII in QCE and QCSW is $R^2 = 0.958$ for RCP 4.5 QCE, $R^2 = 0.958$ for RCP 8.5 QCE, $R^2 = 0.9432$ for RCP 4.5 QCSW, and $R^2 = 0.9443$ for RCP 8.5 QCSW. (b) Relationship Between Proportion of Soybean (%) in Dairy Cow Diet and Feed Insecurity. The percentage of soybeans in the HHD (current Québec dairy cow diet) is 11.66%. Correlation between percent soybean in the diet and FII in QCE and QCSW is $R^2 = 0.9082$ for RCP 4.5 QCE, $R^2 = 0.8921$ for RCP 8.5 QCE, $R^2 = 0.9722$ for RCP 4.5 QCSW, and $R^2 = 0.9765$ for RCP 8.5 QCSW.

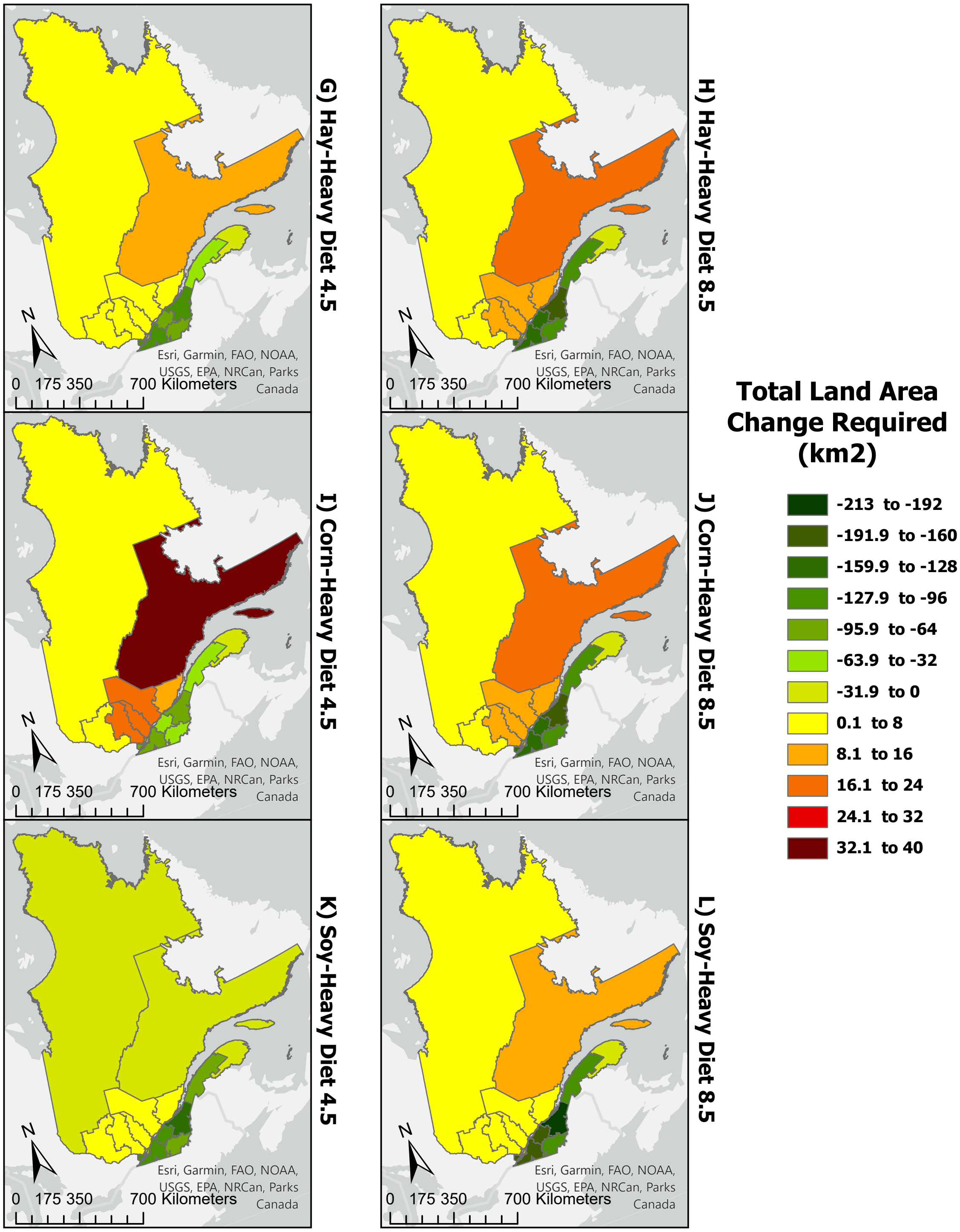


Figure 4. Total land area change required per CAR (km^2). Maps show the total land area change required in Québec by CARs. Maps on the left correspond to RCP 4.5, and maps on the right correspond to RCP 8.5.

This demonstrates that a corn-heavy diet renders regions at higher risk of feed insecurity than other diets. This is primarily a result of the projected change in corn grain yields, which increase only modestly under RCP 4.5 and decrease under RCP 8.5 (Table 2). Other crop yields considered in this study, including corn silage, are projected to increase under both RCPs. While corn grain comprises 44% of the corn intake in the CHD (corn silage comprising 56%), its baseline yield is considerably lower than that of corn silage, requiring 330% more land on average in Québec (Table 2). Thus, the decrease in corn grain yield counteracts the increases in corn silage yield. This leads us to conclude that the proportion of corn grain in the diet is among the largest risk factors of projected feed insecurity in Québec.

Despite this diet scenario presenting the highest feed insecurity indicators across all included CARs, Québec dairy farmers will experience a province-wide increase in feed security. However, due to high intraprovincial variation in feed security, not all feed will be able to be produced on-farm.

The choice to increase corn feed demonstrates a tradeoff in the environmental sustainability of the dairy industry. Hassanat et al.[9] found that when fed a high-starch, corn-based diet, there was a quadratic reduction in methane production in Québec dairy cows. This study also found that methane reductions only occurred when corn comprised >50% of the diet by weight, suggesting a critical proportion higher than the current Québec diet which contains 36% corn[9]. Lastly, Hassanat et al.[9] revealed increased milk yield under a corn-heavy diet: When comparing a no-corn diet to a 50% corn diet, the study found a 10% increase in milk yield in the cattle fed a corn-heavy diet. Similarly, Guyader et al.[31] found an 8.7% increase in milk yield in Québec dairy cattle when barley feed was replaced with corn. This indicates a tradeoff between methane-reducing strategies and land use expansion for agriculture.

A comparative LCA is beyond the scope of this work. However, we note that if cropland increases in proximity to existing dairy farms, most of this land use change will occur in Southern Québec (Figure 1). Changes in land use in Southern Québec have implications on the mitigation of greenhouse gas emissions, as most terrestrial carbon (forest biomass and soil organic carbon) is found in this part of the province[32]. Thus, increases in the dairy feed cropland to provide a CHD could disturb Québec's most dense forest and soil carbon areas.

Soy-Heavy Diets

In the SHD scenario, the average feed insecurity indicators across included CARs for RCP 4.5 and 8.5 are -5.26% (σ 6.05%) and -6.39% (σ 10.41%), respectively. Every CAR presents a lower feed insecurity indicator in the SHD scenario than the other diet scenarios.

This demonstrates that a soy-heavy diet renders regions less at risk of feed insecurity than other diets. This is largely because soy yield is projected to increase significantly (Table 2). An additional factor is the decreased corn consumption in the SBD, which also predicts improved feed security.

A SHD may present a similar greenhouse gas-related environmental tradeoff. Soybean meal, particularly when compared to canola meal, has been shown to increase enteric fermentation (methane emissions) and nitrous oxide emissions from manure[5,33]. Canola is the most available and equivalent protein soy replacement for Canadian dairy cattle; canola yields are projected to decline in Canada in the face of climate change[16]. This leads us to predict that replacing soybean with canola to reduce methane emissions would increase feed insecurity and drive larger land use demands. However, further research must be done to examine the impact of climate change on feed security to determine the tradeoff of GHG emissions and land use.

Feed Security and Intraprovincial Regional Variation

According to Statistics Canada[34], total cropland area in Québec is 1,942,491 ha. Thus, the increase in dairy cattle feed security seen across these various diet and RCP scenarios represents a 2-3% reduction in total required cropland in the province (8383.5 to 59743.9 ha) by 2050.

The impacts of climate change are non-uniform in Québec; therefore, feed security is predicted to vary regionally. Under all scenarios, QCE is more feed secure than QCSW. This is because corn silage and hay yields are projected to increase dramatically more in QCE than QCSW (Table 2) due to greater increases in mean temperature, annual precipitation, and changes in planting dates for various crops[7].

Feed Security and Intraprovincial Trade

Currently, the literature indicates that feed for dairy cattle in Québec is grown on-farm[4,28]. However, climate change is projected to increase geographical variation in crop yields across the province. This increased variation, which would project some CARs with a feed surplus and others with a feed deficit, will likely drive intraprovincial trade. Intraprovincial trade, rather than sourcing feed from elsewhere within Canada, is particularly likely given the province's desire to maintain a self-sustaining dairy industry.

Standard deviation (SD) and coefficient of variation (CV) are interpreted as simple metrics of intraprovincial variation. The SD for all diet and RCP scenarios is high, with the CV ranging from 192% to 418%. These values indicate substantial variation across CARs, leading us to predict greater trade of feed crops in 2050.

Increased transportation for trade will lead to increased GHG emissions from the dairy sector. These emissions will be particularly significant if the variation occurs largely east-to-west, implying long-haul transports from QCE to QCSW.

The CHD scenario demonstrates the highest CV values: 418% and 342.90% under RCP 4.5 and 8.5, respectively. This demonstrates an increased trade demand under this diet scenario compared to a HHD or SHD, highlighting an additional environmental tradeoff of the CHD: while it may reduce enteric fermentation, it would increase both transportation and land use requirements.

Possible Milk Production

As Québec becomes more feed secure, increased crop production could feed more cattle. If the current HHD remains, in 2050 Québec will be able to produce enough crops on existing land to feed an additional 38,906 dairy cows under RCP 4.5 and 54,026 dairy cows under RCP 8.5. This equates to approximately 61,000,000 and 436,000,000 additional liters of milk annually, 0.84% and 1.17% of current Québec milk production[17].

Conversely, regions that experience feed insecurity will be unable to support the current number of dairy cattle without expanding land use. QCSW, which is predicted to face feed insecurity in 2050, will be unable to support 2,635 of the region's projected dairy cattle if land use remains stagnant. This equates to a loss of 21,082,847 liters of milk annually from the QCSW region.

Trade or land use expansion must account for this loss to prevent adverse economic and social outcomes of dairy production decline.

Greater Implications

Although this study focused on the tradeoffs between feed security and methane reduction, it is important to note the broader, additional implications of different diets in dairying. Such implications include impacts on biodiversity, pesticide use, water use, and water pollution. Most notably, the production of soy- and corn-heavy diets requires significantly greater pesticide use[35].

Additionally, the study highlights the possibility for feed strategies to reduce methane emissions from the dairy industry. The IPCC's policy recommendations describe the potential of consumer plant-based diets for climate change mitigation and adaptation[36]. Future work would benefit from assessing the impact of these diets on methane emissions.

Limitations

The model's assumptions inherently restrict the accuracy of the outcomes. To ensure model consistency, both crop yield and milk yield are assumed fixed. For model simplicity, we assume that crop yield would not be impacted by factors other than climate change. In tandem, milk yield is also kept constant across RCPs, despite the likelihood that heat stress will reduce milk yield in a warming future[37]. Further LCAs which aim to quantify future GHG emissions should consider accounting for not only yield and land-use change, but also increased transport emissions.

The limited availability and geographical scope of data also constrains our results. Two RCP pathways, 2.6 and 6, are not employed in this study as crop projections aligned with these scenarios are currently not found in literature. Thivierge and colleagues' predicted temperature and yield increases do not consider all possible extreme climate weather events[7]. Projected crop yields also compartmentalized data only into two regions: QCE and QCSW. Because of this, QCE and QCSW data was coarsely applied to their respective CARs.

Conclusion

The feed supply of the Québec dairy industry will endure various impacts of climate change. This study predicts that as crop yields fluctuate with warming and increased precipitation, Québec will become more feed secure, requiring 2-3% less cropland in 2050 to feed the projected dairy cattle than at the time of writing. Meanwhile, regional variation in crop production is projected to increase. If land use remains stagnant, Eastern Québec will produce a feed surplus while Southwestern Québec will be in feed deficit. This intraprovincial variability will drive feed crop trade, fundamentally changing the current on-farm feed production system and driving an increase in industry GHG emissions from transportation. This study also revealed that diet has a profound impact on feed security. Corn-heavy diets are projected to render Québec more feed insecure than other diets would, requiring 374% to 573% more land for crop production than soy- or hay-heavy diets, as soy and hay yields will be favorably impacted by climate change. Corn-heavy diets are also projected to drive the largest regional crop yield variation, increasing trade requirements and thereby transport emissions. While corn-based diets are recommended for methane reduction, they create an environmental tradeoff by requiring greater land use. Further research on Québec dairy's environmental sustainability should consider predicted land use changes. In the context of Québec's dedication to methane reduction strategies, further investigations of the GHG tradeoffs of various diets would be pertinent to determine the most sustainable diets.

Acknowledgement

This study would not have been possible without Dr. Graham MacDonald, Associate Professor of Geography at McGill University, whose insight and expertise in agricultural systems and modelling was invaluable.

References

1. Canadian Dairy Commision. Number of Farms with Shipments of Milk on August 1st. https://agriculture.canada.ca/en/market-information-system/rp/index-eng.cfm?action=gR&r=220&signature=2BB1B27ED46C50FE77D7BC142B757B69&pdctc=&pTpl=1#wb-cont (2023).
2. Agriculture and Agri-Food Canada. Overview of Canada's agriculture and agri-food sector (2023); https://agriculture.canada.ca/en/sector/overview
3. Ministère de l'Agriculture, des Pêcheries et de l'Alimentation (MAPAQ). *Agir, pour une agriculture durable — Plan 2020-2030 [Acting, for sustainable agriculture – 2020-2030 plan]* (2020).
4. Mc Geough, E. et al. Life-cycle assessment of greenhouse gas emissions from dairy production in Eastern Canada: A case study. *J. Dairy Sci.* **95,** 5164–5175 (2012). https://doi.org/10.3168/jds.2011-5229
5. Holtshausen, L., Benchaar, C., Kröbel, R. & Beauchemin, K. A. Canola meal versus soybean meal as protein supplements in the diets of lactating dairy cows affects the greenhouse gas intensity of milk. *Animals* **11,** 1636 (2021). https://doi.org/10.3390/ani11061636
6. Cordeiro, M. et al. Assessing feed security for beef production within livestock-intensive regions. *Agric. Syst.* **196,** 103348 (2022). https://doi.org/10.1016/j.agsy.2021.103348
7. Thivierge, M.-N. et al. Projected impact of future climate conditions on the agronomic and environmental performance of Canadian dairy farms. *Agric. Syst.* **157,** 241–257 (2017). https://doi.org/10.1016/j.agsy.2017.07.003
8. Agriculture and Agri-Food Canada. Reducing Methane Emissions from Livestock (2019); https://agriculture.canada.ca/en/science/story-agricultural-science/scientific-achievements-agriculture/reducing-methane-emissions-livestock
9. Hassanat, F. et al. Replacing alfalfa silage with corn silage in dairy cow diets: Effects on enteric methane production, ruminal fermentation, digestion, N balance, and milk production. *J. Dairy Sci.* **96,** 4553–4567 (2013). https://doi.org/10.3168/jds.2012-6480
10. Lorenz, H., Reinsch, T., Hess, S. & Taube, F. Is low-input dairy farming more climate friendly? A meta-analysis of the carbon footprints of different production systems. *J. Clean. Prod.* **211,** 161–170 (2019). https://doi.org/10.1016/j.jclepro.2018.11.113
11. Dairy Farmers of Canada. *Net Zero by 2050: Best Management Practices Guide to Mitigate Emissions on Dairy Farms* (2023).
12. Les Producteurs de Lait du Québec. *Supply Management and Collective Milk Marketing* (2023).
13. Environment Canada. *Climate data and scenarios for Canada: Synthesis of recent observation and modelling results* (2016).
14. Li, G. et al. Indices of Canada's future climate for general and agricultural adaptation applications. *Clim. Chang.* **148,** 249–263 (2018). https://doi.org/10.1007/s10584-018-2199-x
15. Alberti-Dufort, A. et al. Quebec; Chapter 2 in *Canada in a Changing Climate: Regional Perspectives Report*. (eds Warren, F., Lulham, N., Dupuis, D. & Lemmen, D.). Government of Canada (2022).

16. Qian, B. et al. Simulated canola yield responses to climate change and adaptation in Canada. *Agron. J.* **110,** 133–146 (2018). https://doi.org/10.2134/agronj2017.02.0076

17. Les Producteurs de Lait du Québec. *Rapport Annuel 2022 [Annual Report 2022]* (2022).

18. Ouranos. *Vers l'adaptation. Synthèse des connaissances sur les changements climatiques au Québec. Édition 2015 [Toward adaptation. Synthesis of knowledge on climate change in Québec. 2015 Edition]* (2015).

19. Government of Canada. Land-use change (2022); https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/land-use-change.html

20. KC, K. B. et al. Opportunities and trade-offs for expanding agriculture in Canada's North: an ecosystem service perspective. *Facets* **6,** 1728–1752 (2021). https://doi.org/10.1139/facets-2020-0097

21. Wei, X., Shao, M., Gale, W. & Li, L. Global pattern of soil carbon losses due to the conversion of forests to agricultural land. *Sci. Rep.* **4,** 4062 (2014). https://doi.org/10.1038/srep04062

22. Jiang, R. et al. Impacts of land use conversions on soil organic carbon in a warming-induced agricultural frontier in Northern Ontario, Canada under historical and future climate. *J. Clean. Prod.* **404,** 136902 (2023). https://doi.org/10.1016/j.jclepro.2023.136902

23. Statistics Canada. 2021 Census –- Boundary Files (2021); https://www12.statcan.gc.ca/census-recensement/2021/geo/sip-pis/boundary-limites/index2021-eng.cfm?year=21

24. Statistics Canada. Table 32-10-0370-01 Cattle inventory on farms, Census of Agriculture, 2021. https://doi.org/10.25318/3210037001-eng (2022).

25. Castillo-Lopez, E. et al. Performance of dairy cows fed silage and grain produced from second-generation insect-protected (Bacillus thuringiensis) corn (MON 89034), compared with parental line corn or reference corn. *J. Dairy Sci.* **97,** 3832–3837 (2014). https://doi.org/10.3168/jds.2014-7894

26. National Research Council. in *Nutrient Requirements of Dairy Cattle: Seventh Revised Edition, 2001.* 281–289 (The National Academies Press, 2001). https://doi.org/10.17226/9825.

27. Alexandratos, N. & Bruinsma, J. *World agriculture towards 2030/2050: the 2012 revision* ESA Working paper No. 12-03. Rome, FAO (2012). https://doi.org/10.22004/ag.econ.288998

28. Guyader, J., Little, S., Kröbel, R., Benchaar, C. & Beauchemin, K. *Carbon footprint of dairy production systems in Québec: Barley versus corn silage* in Abstracts of the 2017 American Dairy Science Association® Annual Meeting, June 25–28, 2017, Pittsburgh, PA. *J. Dairy Sci.* **100** Suppl. 2 (2017). https://doi.org/10.1016/S0022-0302(20)30813-4

29. Institut de la statistique du Québec. Area of field crops, yield per hectare and production, by combined administrative regions, Québec, 2007-2023 (in French only). https://statistique.quebec.ca/en/produit/tableau/3786 (2023).

30. Fédération des producteurs de lait du Québec. *The journey of MILK from the farm to your table* (2014).

31. Guyader, J., Little, S., Kröbel, R., Benchaar, C. & Beauchemin, K. A. Comparison of greenhouse gas emissions from corn-and barley-based dairy production systems in Eastern Canada. *Agric. Syst.* **152,** 38–46 (2017). https://doi.org/10.1016/j.agsy.2016.12.002

32. Sothe, C. et al. Large soil carbon storage in terrestrial ecosystems of Canada. *Glob. Biogeochem. Cycles* **36,** e2021GB007213 (2022). https://doi.org/10.1029/2021GB007213

33. Benchaar, C., Hassanat, F., Beauchemin, K., Gislon, G. & Ouellet, D. Diet supplementation with canola meal improves milk production, reduces enteric methane emissions, and shifts nitrogen excretion from urine to feces in dairy cows. *J. Dairy Sci.* **104,** 9645–9663 (2021). https://doi.org/10.3168/jds.2020-20053

34. Statistics Canada. Over one-third of dairy cows were reported in Québec (2011); https://www150.statcan.gc.ca/n1/pub/95-640-x/2011001/p1/prov/prov-24-eng.htm

35. Nehring, R. et al. *Pesticide Use in US Agriculture: 21 Selected Crops, 1960-2008. EIB-124* U.S. Department of Agriculture, Economic Research Service (2014).

36. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2023).

37. West, J. W. Effects of heat-stress on production in dairy cattle. *J. Dairy Sci.* **86,** 2131–2144 (2003). https://doi.org/10.3168/jds.S0022-0302(03)73803-X