

Agricultural Frontiers in Northern Ontario: Opportunities, Constraints, and Strategies for Crop Breeding and Agronomy

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Abstract

In Northern Ontario, agricultural production is constrained by cold climatic conditions and short growing seasons that limit crop suitability. However, climate change, which threatens global food security, may also create more favourable environmental conditions for growing grain and oilseed crops in northern latitudes. In this study, we quantify the extent to which climate change may create new opportunities for wheat, oats, rye, and canola production in Northern Ontario, Canada. We then assess how effective crop breeding and adaptive agronomic practices such as developing climate-resilient cultivars and implementing flexible management strategies can play a role. To do this, we used a GIS-based multi-criteria decision analysis to identify areas where climate change may create more suitable agricultural regions showing that despite shallow and heterogeneous soils, there will be new opportunities to expand grain and oilseed production into Northern Ontario. However, achieving this potential would require crop breeding for enhanced climate resilience along with more adaptive agronomic management practices. A second finding is that extending agriculture on new lands in higher latitudes may entail significant ecological trade-offs such as the carbon emissions that would be released after converting forests and wetlands into farmland. Therefore, the implication of this study is that although theoretically, climate change may create new opportunities for 'farming in the north,' realizing these opportunities will require a complex balance of crop breeding, careful agronomy, and an awareness of the ecological consequences of expanding farming's northern frontier.

Introduction

Northern Ontario is characterized by short growing seasons and cold weather conditions, which are not favourable environmental conditions for crop production. The conventional growing season begins when temperatures reach at least 5°C for five consecutive days after March 1 and ends when minimum temperatures fall below 2°C after August 1 (NRCan, 2025). However, these thermal constraints limit conducive environmental conditions for crop suitability, yield potential, and harvest timing (Manitoba Agriculture, n.d.). As a result, grains and oilseeds such as wheat, oats, rye, and canola are restricted to localized areas of Northern Ontario due to thermal limitations.

However, these constraints may shift due to climate change in the coming decades, and projected mean temperatures in Northern Canada are expected to increase by 2.1°C under RCP 2.6 and up to 7.8°C under RCP 8.5 by the late century (NRCan, n.d.). The increase in mean temperatures will contribute to extending growing degree days (GDD) and creating more favourable environmental conditions for crop production.

King et al. (2018) suggest that these trends may cause a northward shift of agricultural viability by over 900 km by 2099. Similar studies show consistent increases in the length of thermal and photosynthetic growing seasons over the last half century (Barichivich et al., 2013; Qian et al., 2012). Although the magnitude of this shift varies among models, there is general agreement that northern agricultural frontiers are likely to expand as temperatures rise (Hannah et al., 2020; Morgounov et al., 2018).

But while the idea of bringing new areas under farm management may offer potential economic and food production opportunities, realizing such benefits is far from clear. One challenge is that some areas identified as potential frontiers provide important ecological functions such as biodiversity habitat and carbon sequestration. These so-called frontiers are often the home to Indigenous communities with ancestral and legal ties with such areas. Hence, although there is some optimism in the literature that expanding agriculture into the north may create new food production opportunities (Chapagain, 2017), agricultural expansion may also drive environmental, cultural, and hydrological trade-offs. Furthermore, several frontier areas play an important role in providing ecosystem services to Indigenous communities. Wetlands and forests store considerable amounts of carbon and contribute to biodiversity conservation, water regulation, and other ecological functions. Therefore, agricultural activities in these areas will likely cause environmental and social trade-offs that should be considered within an ecological and social context (Foley et al., 2011). Considering such complex environmental and sociopolitical considerations means it is necessary to carefully evaluate the agricultural potential of northern agricultural frontiers against a range of possible criteria. These issues are all present in Northern Ontario, Canada, where warming regions are currently covered by forest and wetlands that sequester huge amounts of carbon and are the ancestral homes of a great number of Indigenous communities. Simultaneously, early work (e.g. Hannah et al., 2020) suggests that there is considerable potential to expand agriculture in Northern Ontario (see Fig. 1). As such, this paper aims to present an integrated assessment of how climatic, edaphic, topographic, and hydrological conditions may affect agricultural potential and how this may in turn have effects on ecosystem services and carbon emissions. Such analysis is necessary because populations in Ontario, Canada, and globally continue to grow, driving new demands for food and fuel and potentially intensifying pressures to develop any newly suitable land.

Climatically suitable areas alone do not necessarily provide suitable conditions for successful crop production. For example, newly emerging agricultural frontiers in Northern Ontario will still experience challenges such as low temperatures, short growing seasons, soil fertility issues, and limited infrastructure (Ngongolo and Mmbando 2024). Therefore, opportunities for successful crop production will depend on climate change and developing crop varieties and agronomic practices adapted to northern conditions (Palmgren and Shabala 2024). Modern crop improvement and agronomic management technologies will likely translate the emerging suitable areas into resilient crop production. Therefore, there is a need for a research strategy that focuses on plant breeding, crop adaptation, and adaptive agronomy to ensure crop productivity.

Within these climatically suitable areas, soils and topography, acidity, and drainage will be used to assess agricultural suitability. Potential yields for wheat, oats, rye, and canola will be estimated, based on the crops' requirements and projected climatic conditions. The grain and oilseed crops were chosen because they are economically important crops in southern Ontario and thus likely to be interesting for any policymaker or landowner thinking about how to respond to changing climatic conditions.

The agricultural expansion opportunities identified in our study may not be considered as benefits of climate change (Quan et al., 2021). However, these opportunities require adaptation pathways that

emerge under changing environmental conditions (Fedele et al., 2019). Therefore, crop production in the newly emerging areas should be maintained in a way that supports ecological integrity and existing social and cultural values.

Previous studies have extensively focused on ecosystems and cultural services in evaluating the impact of expanding agricultural frontiers. However, there is limited information in the literature on the feasibility of integrating plant breeding and agronomy to support agricultural expansion in northern regions with short growing seasons, low temperatures, and marginal soils.

Therefore, we aim to address these questions: (1) where and to what extent climate change may create the potential for agricultural expansion in Northern Ontario; (2) what environmental and social trade-offs may be associated with agricultural expansion into Northern Ontario; and (3) how plant breeding and agronomic practices may contribute to mitigating these trade-offs and supporting sustainable crop production.

To answer these questions, we (1) use climate models to identify areas of the province that may reach sufficient growing degree days for grain and oilseed cultivation by 2099; (2) quantify the potential crop production, economic value and ecological and cultural trade-offs associated with agricultural expansion; and (3) discuss how crop breeding and agronomic intervention strategies may create additional opportunities for cropland expansion based on existing literature.

Data and methods

Data

We identified potential new agricultural frontiers and the suitability of growing grain and oilseed crops by 2099 within the Canadian province of Ontario by using three environmental variables (climate, soil, and terrain) and one anthropogenic variable (road accessibility). A summary of the data is presented in Table 1.

Base data layers, including administrative boundaries, waterbodies, and transportation networks, were obtained from Statistics Canada and Ontario government sources. Agricultural data consisted of historical crop statistics (1981–2023) and the 2023 Annual Crop Inventory, derived from satellite imagery and radar data with validated classification accuracy. Climate projections were obtained from the Ontario Climate Data Portal provided high-resolution, bias-corrected estimates of growing degree days, frost-free season, and precipitation across multiple IPCC scenarios (RCP2.6, RCP4.5, RCP 6.0 and RCP8.5). Topographic information was derived from the Provincial Digital Elevation Model, while soil characteristics were sourced from the Harmonized World Soil Database, with emphasis on topsoil properties relevant to plant growth.

Methods

We used a GIS-based multi-criteria decision analysis (MCDA) approach to identify emerging agricultural frontiers (EAFs) and the suitability of growing grain and oilseed crops by 2099 within the Canadian province of Ontario, projected harvest and economic value. The whole process was implemented in four steps using spatial datasets processed primarily in ArcGIS Pro and QGIS and statistical analysis, with all data standardized to a common projection and resolution.

Step 1: Identification of potential frontier zones or climate change-driven frontiers

Potential frontier zones are defined as locations that currently lack agricultural activity (based on the 2023 Annual Crop Inventory) and have insufficient growing degree days (GDD) for crop production under present conditions but would have sufficient GDD by 2099 to grow agricultural crops. GDD was selected as the primary climate variable and classified into four suitability categories. According to the Ontario Climate Data Portal (OCDP), GDD values greater than 1600 are highly suitable, 1200–1600 are moderately suitable, 1050–1200 are marginally suitable, and less than 1050 are not suitable for growing agricultural crops.

Step 2: Identification of potential new suitable areas to grow grain and oilseed

A GIS-weighted overlay approach was used to identify new areas suitable for growing grain and oilseed crops. In addition to GDD, three environmental variables (terrain slope, soil drainage, and soil acidity), were used. Slope is derived from elevation data and processed to reflect agricultural feasibility at a 1 km scale. Soil drainage and acidity are classified based on soil properties, with pH thresholds reflecting crop tolerance. Each variable was then classified, giving the score of 1 for not suitable, 2 for marginally suitable, 3 for moderately suitable, and 4 for highly suitable scores. To create the suitability model, a subjective weighting technique was used to assign appropriate weights to GDD, slope, acidity, and drainage. After assigning different weights to each factor and running the model for several iterations, GDD was finally assigned a weight of 40%, while the other three variables were each assigned 20%. This allowed the climate variable to be worth twice the individual slopes of soil drainage and soil acidity, but these three variables collectively weighed more, accounting for the “clay belt” and falling under potential future suitability.

Step 3: Identifying Areas Close to the Transportation Infrastructure

To capture the fact that areas with a better-developed transportation infrastructure are more likely to be developed by farmers, we calculated a second scenario that restricts agricultural frontiers to areas within 10-kilometer radius of all 2016 Canadian road infrastructure (Statistics Canada 2020) using Boolean raster algebra. The resolution and coordinate reference system were adjusted to match the crop

suitability grids produced in step 2, using nearest-neighbor resampling (Hijmans 2020). Given that the road network in 2099 will likely be different from today, for the rest of this paper, we present results both within this and within 10km radius of the contemporary road network – a lower-bound estimate – and within the frontier range – an upper-bound estimate.

Step 4: Estimating potential harvest and their values from the new suitable areas

Using the results of steps two and three, the potential harvest and their values are estimated. Provincial crop data were used to predict the potential production of the four crops studied (spring wheat, oats, rye, and canola) if all suitable land were used exclusively for each crop. Two predictions for each were made: one using average yields from 2019–2023, and another using predicted yields derived from linear yield trends from 2003 to 2023 extended out to 2099. Yields and costs per bushel were multiplied by suitable land area to estimate potential harvest and then converted to cash values for each crop.

Results

Expansion of climate change-driven agricultural frontiers

The total modelled area of suitable land for agricultural frontier under each climate scenario is detailed in Table 1. Compared to the total agricultural area in 2023, which was 80,553 km², the total amount of “suitable” land (i.e., classed as moderately or highly suitable) increases by 14% under RCP 2.6, versus over 626% under RCP 8.5. The distribution of suitability under each scenario is shown in Fig. 1. Compared to the 2023 distribution, RCP 2.6 shows little change in all categories. RCP 4.5 sees a small increase in highly suitable land, a strong increase in moderately suitable land, and a strong decrease in unsuitable land. RCP 6.0 is similar, with about the same amount of highly suitable land as RCP 4.5, but a strong increase in moderately suitable land and a decrease in mildly suitable land. Finally, RCP 8.5 displays no unsuitable land, far less mildly suitable land, and far more moderately suitable land. The locations of moderately and highly suitable land under each scenario are shown in Fig. 1. The same places that first become suitable as the climate frontier progresses north are largely the same places that become highly suitable under the most extreme scenario. Thus, an additional shapefile was created by determining a 2 km buffer around highly suitable areas under RCP 8.5, with a minimum area of 100 km².

[insert table 1 near here]

The results of the model were validated against the current agricultural land locations. The results show that 90% of existing agricultural land falls within the moderate-to-high suitability classes of the modelled results, while only 0.1% of existing cropland was classified as not suitable. Additionally, Fig. 1 depicts the percentage of land in each suitability category in 2023 used for crops, compared to the total percentage of the province with crop production. About 8% of the land area in Ontario is being used for crops, but of

the land classed as highly suitable, 95% of it contains cropland. This validates the model’s assessment of suitability by demonstrating that the current most suitable land in Ontario is already being used.

[Insert Fig. 1 near here]

[Insert Fig. 2 near here]

Provincial crop data were used to predict the potential production of the four crops in question (wheat, oats, rye, and canola) if all suitable land were to be used exclusively for each crop. Table 2 shows the potential harvest in billions of bushels under RCP 4.5 and 8.5, and the respective potential values.

Harvest under RCP 4.5 range from 0.75 billion to 2.8 billion bushels (if land within 10 km of an existing road ends up being cultivated) and from 1.8 billion to 6.8 billion bushels when we assume all potential frontier land was cultivated. Under RCP 8.5, the results range from 2.8 billion to 10.4 billion and 6.8 billion to 25.6 billion, respectively. Oats consistently have the highest yields in terms of volume, while canola currently has the lowest according to averages. Compared to the approximately 1.4 billion bushels of field crops harvested in Ontario in 2023, there exists the potential to increase production by up to 18 times. Crop values under RCP 4.5 range from \$4.6 billion to \$26.3 billion using suitable land near roads, and from \$11.3 billion to \$64.1 billion using all suitable land. Under RCP 8.5, results range from \$17.2 billion to \$97.5 billion and from \$42.2 billion to \$239.9 billion, respectively. Canola consistently has the highest value potential, while rye has the lowest value potential using current yield averages under projected yield trends. Compared to the approximately \$6.7 billion value of field crops in Ontario in 2023, there is the potential to increase total cash receipts from field crops by up to 35 times.

[Insert Table 2 near here]

Ecological and cultural trade-offs

Using the results of Steps One and Two, analysis was conducted under RCP 4.5 and 8.5 to quantify and describe the potential ecosystem service characteristics of suitable agricultural frontier areas if all suitable land were transformed for cultivation. Provisioning services were represented by crop harvest and value, regulating and supporting services by soil carbon, wetland coverage, provincially tracked species, and protected area coverage, and cultural services by First Nations communities and historical Treaties.

The CO₂-equivalent of carbon stored in suitable frontier areas exceeded Canadian’s annual emissions. Wetlands covered approximately 58% and 53% of suitable frontier areas under RCP 4.5 and RCP 8.5, respectively. Suitable frontier areas also contained provincially tracked species, including threatened and endangered species, and overlapped with woodland caribou range. Protected and significant areas accounted for a proportion of suitable frontier areas.

The last variable assessed relates to cultural ecosystem services, particularly Indigenous relationships with the land. The RCP 8.5 suitable areas are shown overlapping with First Nations Treaties and

communities. Most of the highly suitable land falls within the James Bay, Robinson-Superior, and North-West Angle Treaties. First Nations communities near the highly suitable land include: Grassy Narrows First Nation, Lac Seul, Apitipi Anicinapek Nation, McDowell Lake, Moose Cree First Nation, Wabauskung First Nation, Biigtigong Nishnaabeg, and Wabigoon Lake Ojibway Nation.

Discussion

Our findings demonstrate that the projected expansion of agriculture in Northern Ontario presents both significant potential and important risks under future climate scenarios. Specifically, (1) emerging agricultural frontiers are likely to expand in Northern Ontario under future climate scenarios. (2) The suitable areas for crop production are estimated to increase significantly under RCP 8.5, suggesting an increase of approximately seven times greater than the 2023 agricultural area. RCP8.5 represents an upper-end climate change and indicates maximum expansion of suitable land. (3) The expansion of suitable land is not uniform across the area and is in specific frontier zones with ecological and cultural trade-offs. (4) There is a potential for economic returns associated with the expansion of suitable land. This northward shift to crop suitability is consistent with previous assessments indicating that warming climates are associated with increased agricultural expansion in boreal regions (KC et al., 2021), especially for cereal and oilseed production. Therefore, the newly emerging suitable lands should not be considered an extension of existing agricultural systems, but as an agroecosystem that requires customized genetic and crop management solutions with bottom-up and top-down approaches to support resilient crop production system.

Consequently, advanced plant breeding and adaptive agronomic practices (is crop management practices adjusted to changing environmental conditions to optimize crop performance) used in developing resilient grain and oilseed crops will determine sustainability of frontier agriculture. The development of crop varieties adapted to emerging agricultural frontiers characterized by shallow soils, short growing seasons, and low temperature stress are the backbone for realizing the productive potential of EAFs.

Our findings also suggest that breeding gains and resilient crop production of grains and oilseeds in EAFs will not be fully achieved without adaptive agronomic practices. Practices such as optimized sowing dates, adaptive nutrient management, soil organic amendments, and residue retention will help the performance of frontier-adapted genotypes by mitigating soil and climatic constraints (Hatfield and Walthall, 2015; Cassman and Grassini, 2020). Therefore, developing cereal and oilseed crops through a breeding program for EAFs in Ontario should be conducted jointly with adaptive agronomic practices to respond to conditions of environmental instability and produce maximum yield and resilient crop (Table 3).

[Insert Table 3 near here]

Breeding efficiency can be improved for EAFs in Ontario through international collaboration to have access to diverse pre-breeding materials from stress-prone areas and expose them to different

environmental stresses (cold, acidic soils, nutrient limitations) where selection pressure is high, not only in Canada but also across the border, to help select grain and oilseed varieties that carry desirable traits needed in EAFs for adaptation and production. Therefore, productivity in EAFs will depend not on genetics or agronomy alone but on optimizing genotype × management interactions.

The use of genomics-assisted breeding approaches, such as marker-assisted selection and genomic selection, facilitates the quick identification and incorporation of complex traits, including drought tolerance, nutrient use efficiency, early maturity, and resilience to low-temperature stress (Hickey et al., 2017; Varshney et al., 2020; Vikram et al., 2024). Furthermore, the use of genomic prediction models helps screen a large breeding population's performance under diverse environmental conditions, which reduces breeding cycles and increases selection accuracy for complex traits (Amoah et al., 2019). This is due to the complexity of genetic interactions, the polygenic nature of most agronomic traits, and the unpredictability of environmental conditions influencing crop development. These tools are very important in newly emerged agricultural frontiers, where strong genotype-by-environment interactions can obscure trait performance under conventional selection environments.

In our study, five highly suitable areas for expansion of agriculturally suitable land have been identified in the West, Upper Central, Lower Central, Upper Eastern, and Lower Eastern regions of Ontario. The volumes of crop production in the five highly suitable areas under RCP 8.5 suggest that harvest of wheat, oats, rye, and canola could increase to 18-fold (6.8–25.6 billion bushels) and economic value to 35-fold (\$42.2 - \$240 billion) relative to 2023 (Table 2). Oats have the highest potential for increased crop production, and canola could contribute to the greatest economic value (Table 2). Model validation confirms that 90% of 2023 farmland is in alignment with predicted moderately or highly suitable land. The level of confidence and alignment of farmland with the projected land suitability will help investment in infrastructure, market access, and adaptive crop production practices. However, such development should be pursued in line with land-use governance, Indigenous consultation and consent frameworks, and market/price signals that would need to align for frontier development to proceed responsibly. Therefore, investment should prioritize existing farmland that corresponds with future land suitability rather than encouraging unplanned frontier expansion. Areas targeted for agricultural expansion should be planned through the development of targeted infrastructure and locally appropriate management strategies that consider both ecological and cultural considerations. Such an approach would improve the efficiency of public investment while reducing unnecessary environmental and cultural impacts.

Expanding agricultural land in Northern Ontario creates possible challenges with regulating and supporting ecosystem services. Soil organic carbon (SOC) that has been stored in the EAFs exceeds Canada's total annual emissions in 2023 (702 Mt CO₂-e), and a partial conversion could release greenhouse gases at a national scale. Similarly, wetlands cover 53–58% of suitable frontier land, which provide important services, such as carbon sequestration, water filtration, and flood regulation. If these ecosystems are converted into suitable land for crop production purposes, it would reduce these functions and degrade water quality, consistent with findings on wetland ecosystem vulnerability (ECCC, 2019).

Conclusion

There is significant frontier potential, particularly under higher-emissions scenarios, but it comes with important ecological, economic, and cultural trade-offs and breeding alongside agronomy are necessary, though not sufficient, tools for reconciling these opportunities and trade-offs. Future agricultural frontiers should be considered distinct agroecosystems rather than simple extensions of existing agricultural systems. Its successful development will require customized genetic solutions, adaptive agronomic practices, and careful consideration of ecological and social conditions. Responsible agricultural expansion in Northern Ontario requires balancing production opportunities with ecological and cultural considerations. Therefore, climate change may create new theoretical opportunities for farming in the north but realizing them responsibly requires a complex balance of breeding, agronomy, and ecological awareness.

Declarations

Competing interests

The authors declare that they have no competing interests.

Author Contribution

Author Contributions J.S.: writing—review, editing and original draft preparation. K.B.K.C.: Methodology, data interpretation, and review and editing of the manuscript. E.D.G.F.: Supervision, conceptualization, and review and editing of the manuscript. All authors read and approved the final manuscript.

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Data Availability

The datasets used in this study were obtained from publicly available sources cited in the manuscript. The study used derived GIS datasets and model outputs generated during the analysis. Availability of these derived datasets can be clarified by contacting the corresponding author.

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Tables

Tables 1-3 are available in the Supplementary Files section.

Figures

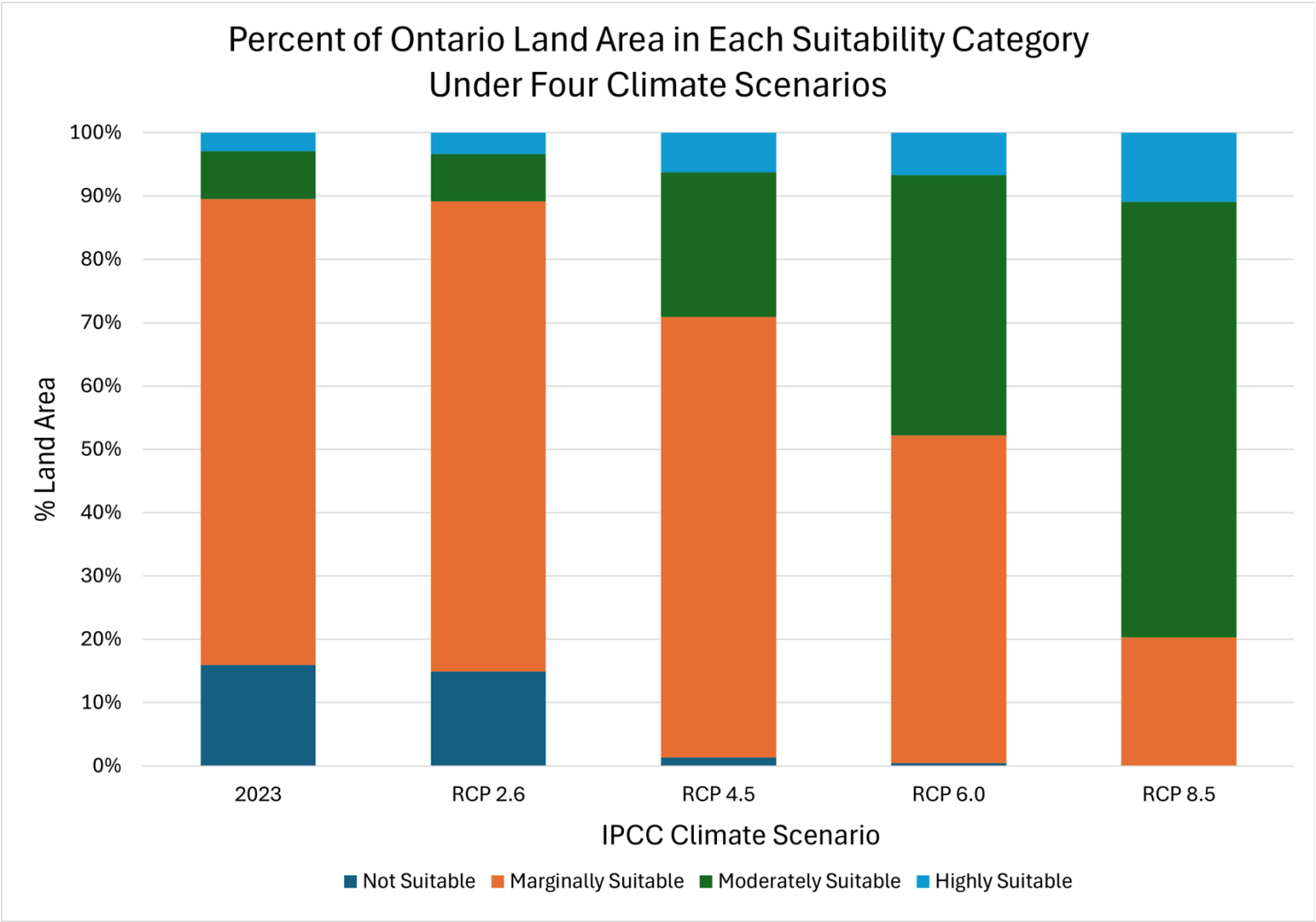


Figure 1

The proportion of modelled suitability of Ontario frontier areas under each IPCC scenario

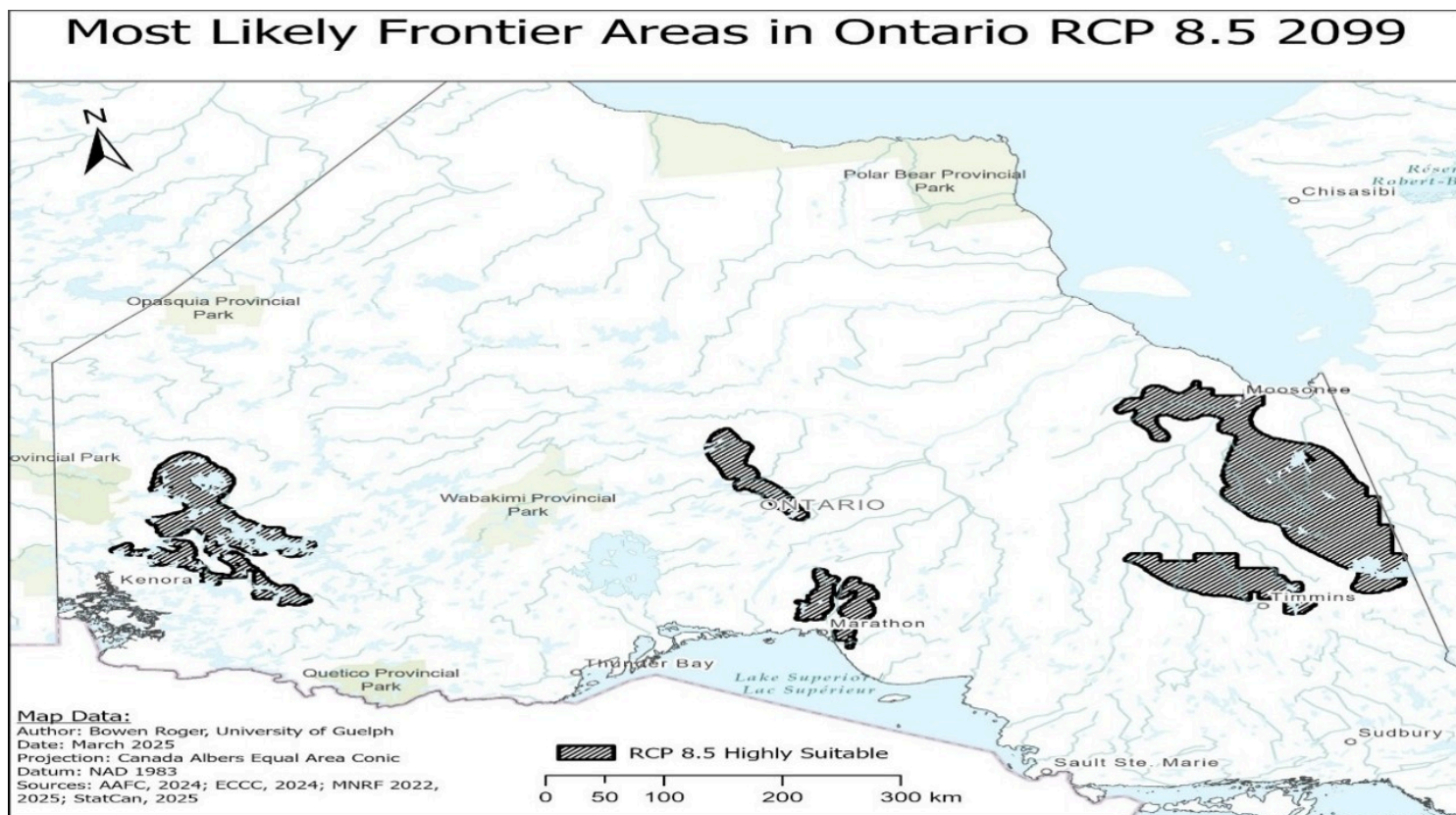


Figure 2

The five largest areas that have been projected to be highly suitable for crop land in Ontario that include West (Between Lac Seul, Red Lake, and Trout Lake), Upper Central (Between Albany River Provincial Park and Wababimigo Lake), Lower Central (North of Lake Superior, between Pukaskwa National Park and Kagiano Lake), Upper Eastern (North of the clay belt, between Lake Abitibi and Moosonee) and Lower Eastern (South of the clay belt, between Timmins and Kapuskasing)

Supplementary Files

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