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RESEARCH ARTICLE

The Future of Northern Canadian Land Use in the Age of Climate Change

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ABSTRACT

Climate change and land use alterations are interdependent and change in one causes a change in the other. Climate change is projected to expand agricultural lands especially at higher latitudes like northern regions of Canada. However, the spatiotemporal extent of this land use change is not clear and will be affected by multiple factors. This research provides a descriptive modelling and analysis of climate change-driven agricultural expansions (CCDAEs) in northern Canada. We discuss the consequences of CCDAE progress in Canada's North in terms of climate change-driven soil loss, greenhouse gas (GHG) emissions, and associated environmental impacts. Results revealed that just over 135 million hectares of northern Canada's lands could change to agricultural lands through different CCDAE scenarios in four timeframes between 2025–2100. The scenarios were categorized to address Indigenous sovereignty on their treaty lands and sustainability of peatlands and mountain areas along with the most likely CCDAE patterns. The CCDAE is projected to cause $29 - 185 \times 10^3$ megaton (MT) soil loss, and $1.7 - 8.6 \times 10^5$ MT carbon dioxide equivalent GHG emissions in minimal/maximal situations. This huge CCDAEs in Canada's north will have considerable footprints on the environment, local communities, climate change mitigation plans, global food security, and local/national economic opportunities. Data and analyses can be used by provincial/territorial governments, policymakers, and environmental planners for future land use changes planning and infrastructure and rural development.

Keywords: Agricultural expansion, climate change, Land use, soil erosion.

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1. Introduction

Long-term shifts in temperatures and weather patterns are defined as climate change [1] affecting our planet, particularly at higher latitudes [2]. In Canada's northern regions, the climate is changing and is projected to continue changing at a rapid pace due to the cold-climate zone. Importantly, northern Canada's warming observations and projections revealed a rate of more than double the global warming average rate [3]. Relative to 1986–2005, the mean annual temperature of Canada is projected to increase by 1.8°C–6.3°C depending on the low and high emission scenarios by the end of the present century. This temperature rise will occur at 16.7%–23.8% higher rates (based on the low and high Representative Concentration Pathways (RCP) 2.6, and 8.5, respectively) in northern Canada [4]. A similar trend is projected for annual precipitation, where northern Canada will receive 9.4%–33.3% more precipitation relative to the current situation, while the entire country will receive 6.8%–24.2% more precipitation under RCP 2.6 (low emission scenario) and RCP 8.5 (high emission scenario), respectively [5]. Additionally, it is projected that extreme precipitation events will also increase in Canada [4], [5].

The changing climate, along with population growth, will accelerate the land use transition mainly from natural habitats to areas for human use and development [6]. Climate change-driven agricultural expansion (CCDAE) will be a general land use transformation trend in higher latitudes like Canada's North [2]. The northward expansion of agriculture [7] could considerably improve the global food chain and economic development [8] especially in rural and remote areas, while could seriously impact ecosystem services [2], [9]. More specifically, soil erosion (SE), carbon storage release, loss of biodiversity, and more greenhouse gas (GHG) emissions are associated with this land use change (LUC) [9], [10]. For instance, climate-driven LUC from forests and shrublands to croplands and bare lands (particularly in northern regions) can increase soil loss (SL) rates up to 10 t/ha/y–109 t/ha/y [7]. The climate change-driven (CCD) soil loss and the soil carbon loss rates in the case of agricultural expansion could be more catastrophic in wetlands and peatlands [11]. However, soil susceptibility to erosion in disturbed lands is much more than those in natural lands [7]. This is very significant for Canada, where one-third of global peatlands are in Canada's North, covering around 13% (i.e., 113 million hectares (ha)) [11] of the country's land area. This area stores 25% of the global peatlands' carbon, which is estimated around 150 billion tons [12]. Nowadays, although GHG emissions from high latitude soils have increased due to climate change and global warming, CCDAEs will intensify this release to an alarming level by the mid-century [9], [13].

Climate change, on the other hand, affected the frequency of wildfires in northern Canada and is projected to cause shorter fire cycles in the region [14]. Wildfires, as a critical factor of forest disturbance, affect the soil and forest stand function to stock and sequester carbon in biomass and soil profile [15], [16]. In addition, widespread wildfires are introduced as the main driver of decomposition and carbon emissions from frost stands in Canada's North [15]. However, ecosystem management efforts in the Canadian boreal based on ecological integrity and ecosystem services [14] could potentially mitigate carbon emissions into the atmosphere. Carbon is one of the key indicators to track and project the footprints of climate change and CCDAEs on the soils of Canada's North. Carbon is mainly stored in living forest ecosystems (above and below ground), in dead trees and woods, and as the organic matter of soil [15]. Then, the cumulative ecosystem disturbance [15] in Canada's North, including climate change forces and anthropogenic interventions, will determine the role of these ecosystems as carbon sinks or sources on a multi-decade scale. Some other local parameters like extreme precipitation events, soil texture [17], land physiography, vegetation cover, and managerial/agricultural practices [15] will also affect the ecosystem-atmosphere carbon exchange rate. The exchange rate and SL rate are highly correlated with the CCD forces and LUC [18]. Therefore, spatiotemporal agricultural and environmental monitoring could act as managerial tools in the context of climate change [19].

Climate change impacts, CCDAEs and other LUCs, SE, and wildfires are referred to as the main drivers of change in GHG emissions from Canada's North in the near term. Before the new Canada's actions against climate change, the GHG emission rate was projected to increase 12% above the 2005 level in the entire country by 2030. The most recent climate action, called Canadian Net-Zero Emissions Accountability Act (2021), will conduct Canada to bring down the emission rates to 40%–45% below 2005 records by the end of the present decade [20]. According to the data and the climate action plans, Canada is on the way to the net-zero emissions target by 2050. However, CCDAEs and other LUCs [9], [20], and the frequency and intensity of wildfires [15] are projected to act against this ambitious target. Meanwhile, the level of these drivers of change is also significantly correlated with the national and global emission and warming scenarios. In other words, the future of land use alterations and development plans in local and national scales is still debatable and subject to change due to the intensity of climate change and the future global food demand. Therefore, the levels of impacts of such changes are not solely credible through simple projections without considering all possible and likely CCDAE scenarios. These scenarios should be responsible for different levels of CCDAE which is not allocated so far or even not deemed in the future development plans. Moreover, The scenarios should also consider the role of agricultural practices and innovations to find the differences in GHG emissions, SE, and other impacts.

This research paper aims to investigate the impacts of climate change and its associated drivers of change on LUC, SL, and GHG emission trends in Canada's North. The land use alteration scenarios will have significant effects on GHG emission rates in the region. Thus, we plan to discuss decadal CCDLUC, decadal CCD soil loss (CCDSL), and their effects on the GHG emission rates based on the projected climate change scenarios. The environmental impacts of these changes and potential adaptation measures will also be discussed.

2. Data and Methods

2.1. Study Area

Most of the CCDAEs in Canada intersect with the Canadian Boreal zone. The total area of the Canadian Boral zone is 552 million ha, which includes 307 million ha of forests and woodlands (see Fig. 1). The area is also including lakes, rivers, wetlands, mountains, and coastal areas [21].

2.2. Data

We extracted data from various sources, including literature, Canadian and international climate reports, metadata platforms, international climate agreements, open-source data, and Canadian provincial and federal authorities'

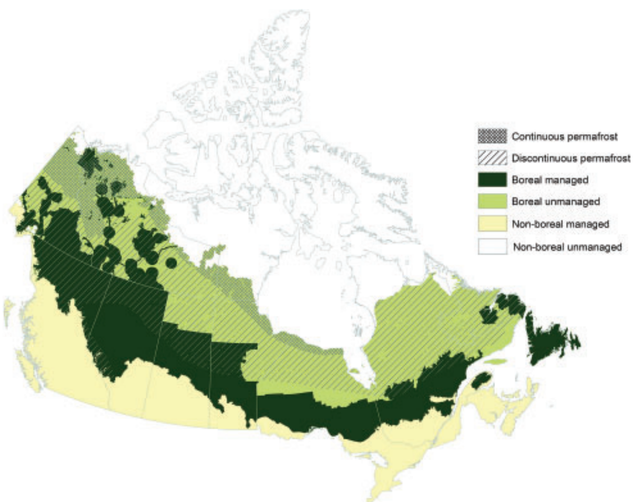

Fig. 1. Map of Canada's Boreal zone in light and dark green, adopted from [22].

web pages and reports. Links of the databases and other sources of data are provided in the supplementary data and reference lists.

Climate change as a key driver of CCDAEs-along with other forces-will expand agricultural lands northward gradually in Canada. Therefore, we divided this progress into four timeframes ending by the year 2100 [23]. This expansion will mainly occur in the Canadian Boreal zone, including low-land forests, mountains, protected and conserved areas, Indigenous Treaties lands, and peatlands. Thus, data for these land use/land covers include total areas, areas intersecting with CCDAEs, total areas in each of the progress timeframes, SE rates, soil carbon stocks, above-ground biomass (AGB), and GHG emissions/sequestration rates obtained.

2.2.1. Climate Change-Driven Agricultural Expansion (CCDAE)

Data for potential CCDAEs extracted from [2]. They identified areas with no current agricultural land use becoming suitable for crop cultivation for at least one of the Canadian major commodity crops (i.e., corn, wheat, soy, and potatoes). They used climate projections from Natural Resources Canada (NRC) based on the Canadian Earth System Model (CanESM2), which is developed according to a moderate GHG emission scenario (Representative Concentration Pathway (RCP) 4.5). The NRC climate data were projected for the end of the present century. The projected temporal progress of CCDAEs in Canada's North was obtained from [23]. The authors applied ClimGen scenarios for seven global climate models (GCMs) and revealed that the leading edge of CCDAEs will move northwards up to 1200 km by the end of this century. In another word, 55%–89% of the boreal zone could become suitable for cultivation on a global scale [23].

2.2.2. Climate Data

Climate data and projections revealed that–in all emission scenarios–northern Canada will affect by climate change more than the southern part of the country. Specifically, winter temperatures are projected to warm up at a higher rate than summer ones. This warming up along with other climate-driven consequences (e.g., more growing degree days in summer and fewer freezing degree days in winter), will make more land suitable for cultivation [24]. Although Canada is going toward a Net-Zero emission target, we assumed a moderate climate change scenario (RCP 4.5) for further analyses according to the global efforts for climate change mitigation. The required data for analysis and discussions were collected from the Intergovernmental Panel on Climate Change (IPCC), the Government of Canada, and through literature.

2.2.3. Soil Data

Soil data include soil carbon amounts and estimations, and SL values were extracted from various sources, including Canada-USA digital soil mapping, North America inventory of soil survey, Status of the World's Soil Resources report by FAO (Food and Agriculture Organization of the United Nations), the European Soil Data Centre (ESDAC), and through literature. The acquired data were categorized based on the main land use/land cover types, including forestlands, shrublands, peatlands, bare lands, and croplands. In addition, soil carbon stocks, above-ground biomass (AGB), roots and other below-ground biomass (BGB), and dead plant matter (DPM) on the ground data were acquired for each land type.

2.2.4. Land Use and Land Cover Data

Land use and land cover data (i.e., peatlands, forests, croplands, etc.) were collected from various sources, including Canada's National Forest Inventory, Canada's Census data, Canadian Wetland Inventory [25], Canada Land Inventory, Canada's Annual Crop Inventory, Canadian Provincial and Territorial reports, and through recent literature. The data is then categorized based on the land types and temporal sequences.

2.3. Estimating CCDLUC and CCDSL

The projections for CCDLUC and CCDSL were divided into four timeframes according to the progress of CCDAEs in Canada's North. These projections were investigated in different scenarios and minimal-maximal situations. Descriptive modeling was implemented to reveal the accumulative consequences of changes in each category on an annual and timeframe basis. Then five family groups of land types (Family Group Scenarios (FGSs) A-E) were developed to analyze the most likely CCDAE progress in each timeframe. The FGSs are divided based on two assumptions: first, GHG emissions from soil carbon stock after land conversion, and emissions from agricultural activities, namely A1 to A4, and second, the mentioned emissions in the first assumption plus the emissions from burning DPM and BGB at new farms, namely A11 to A44 (Table I).

These FGSs are the areas outside the federally protected and conserved areas. We assumed that these protected areas are less likely converted to farmlands due to the sovereignty and management of governmental authorities [2], the country's commitments to protecting 30% of the planet's surface by 2030 [26], and other environmental protection considerations. There are some substantial reasons to exclude (or at least give special consideration to) some boreal areas from CCDAEs in Canada's North in FGSs development. First, although the northward expansion of CCDAEs in Canada's North is the potential to address some food insecurity in local communities, Indigenous sovereignty on their treaty lands should be addressed. Second, climate change will be more challenging in mountain areas and their local communities [27]. These mountain areas required adaptation plans to mitigate severe climate impacts, especially on ecosystem services and infrastructures [28]. Third, peatlands in both the northern and southern parts of the Canadian boreal zone are very sensitive to the global warming trend, which is more severe in Canada's North than the rest of the country. Therefore, CCDAEs could strongly affect Canadian peatlands and extremely accelerate SE [29], GHG emissions, and landscape change in this land type.

2.4. Modeling and Data Analysis

We developed a descriptive land use/land cover change model to reveal the consequences of CCDAE progress in

TABLE I: List of FGSs for the Progress of CCDAEs in the Canadian Boreal Zone from 2025 to 2100

FGS	Summary of scenario details and conditions			
	Traditional (Conventional) Agriculture (TA)		Conservative (Managed) Agriculture (CA)	
	Minimum*	Maximum*	Minimum*	Maximum*
A: All CCDAEs lands would convert to croplands (except for protected areas)	A1 (A11)	A2 (A22)	A3 (A33)	A4 (A44)
B: CCDAEs intersect with lowland forests, Indigenous Treaties lands, and peatlands	B1 (B11)	B2 (B22)	B3 (B33)	B4 (B44)
C: CCDAEs intersect with lowland forests and peatlands	C1 (C11)	C2 (C22)	C3 (C33)	C4 (C44)
D: CCDAEs intersect with lowland forests and Indigenous Treaties lands	D1 (D11)	D2 (D22)	D3 (D33)	D4 (D44)
E: CCDAEs intersect with lowland forests only	E1 (E11)	E2 (E22)	E3 (E33)	E4 (E44)

Note: *Including minimum and maximum SL value (SE rate), soil carbon stock, stand biomass, soil carbon loss in the first five years after land conversion to agriculture, gradual soil carbon loss after the initial five years, and carbon sink or release. *Same conditions, plus DPM and BGB for the second assumption (FGSs on the parentheses; A11, A22, etc.).

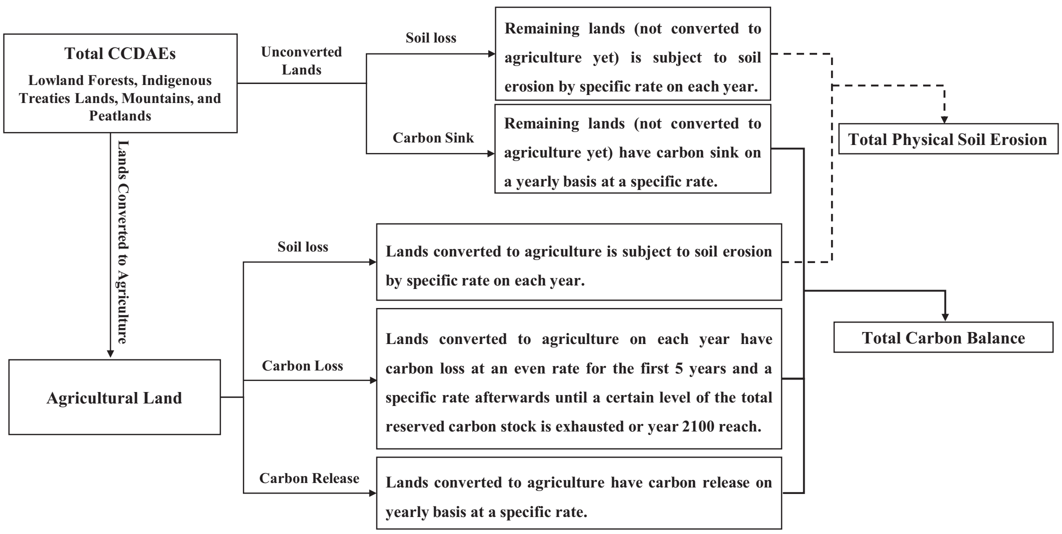

Fig. 2. Modeling flowchart for Canadian CCDAEs.

Canada's North in terms of CCDSL and GHG emissions. A flow diagram of the modeling steps is shown in Fig. 2.

The model predicts temporal CCDAEs and the impacts of this CCDLUC on CCDSL and GHG emissions in each planned timeframe in each FGS. In addition to this, the model would consider the impacts of CCDBL on GHG emissions in each FGS. CCDBL includes three parts: AGB, DPM, and BGB. It is assumed that stored carbon in the cleared AGB would remain in the wood and wood products for the long term. However, there are two assumptions for the DPM and BGB; first, going through a natural decomposition process or as biomass for biofuel generation, and second, used as firewood or burned in farmlands which releases carbon into the atmosphere.

Then the obvious and potential impacts of the CCDAE progress will be compared to the non-CCDAE scenario. Finally, the minimum-maximum impacts of every scenario will be paralleled with Canada's climate change mitigation targets for each timeframe. These mitigation targets and adaptation strategies are set through Canada's 2030 Emissions Reduction Plan (to achieve 40%–45% emissions reductions below 2005 levels by 2030) [30], Canada's Climate Actions for a Healthy Environment and a Healthy Economy including a path forward on pricing carbon, The 2016 Pan-Canadian Framework on Clean Growth and Climate Change (PCF), and the Canadian Net-Zero Emissions Accountability Act. Net-Zero emissions refer to the situations that the economy has no GHG emission or offsets the emitted gases before releasing them into the atmosphere. The most common examples are tree planting or utilizing emerging technologies to capture GHG emissions [31].

3. Results and Descussions

3.1. *Estimates of Decadal Land Use Change*

The investigated data revealed that just over 185 million ha of Canadian non-agricultural lands would become suitable for cultivation by the end of this century. These lands are mainly intersected with the Canadian boreal zone and include lowland forests, mountains, peatlands, protected areas, and Indigenous Treaties lands (Table II).

The CCDAEs would expand northward in the Canadian boreal zone according to the fast pace warming climate in Canada's North. This progress is projected to cover 73% of all CCDAEs by 2100 (Tables III and IV).

TABLE II: Total Canadian CCDAEs by the End of the Year 2100, Modified after [2]

Total CCDAEs (ha)	Area	%
	185,050,300	100
Mountain	90,000,000	48.6
Protected and conservation areas	16,767,300	9
Indigenous treaties lands	6,568,800	3.5
Other lowland forests	71,714,200	38.9

TABLE III: Projected Progress of Canadian CCDAEs by 2100 (% of Total CCDAEs are Adopted from [23])

Canadian CCDAEs	Timeframe			
	2025–2055	2056–2070	2071–2085	2086–2100
Projected progress of CCDAEs (% of total CCDAEs)	55	62	69	73
Projected progress of CCDAEs (ha)	101,777,665	114,731,186	127,684,707	135,086,719
Projected CCDAEs for each period (ha)	101,777,665	12,953,521	12,953,521	7,402,012

TABLE IV: Land Types of the Projected Progress of Canadian CCDAEs by 2100, Modified after [2]

Projected progress of CCDAEs in the periods	Land type (ha)				
	Lowland forests	Indigenous treaties lands	Mountains	Peatlands	Total in each period (ha)
2025–2055	71,714,200	6,568,800	17,764,829	5,729,836	101,777,665
2056–2070	0	0	9,252,515	3,701,006	12,953,521
2071–2085	0	0	9,252,515	3,701,006	12,953,521
2086–2100	0	0	3,701,006	3,701,006	7,402,012
Total by land type (ha)	71,714,200	6,568,800	39,970,865	16,832,854	135,086,719

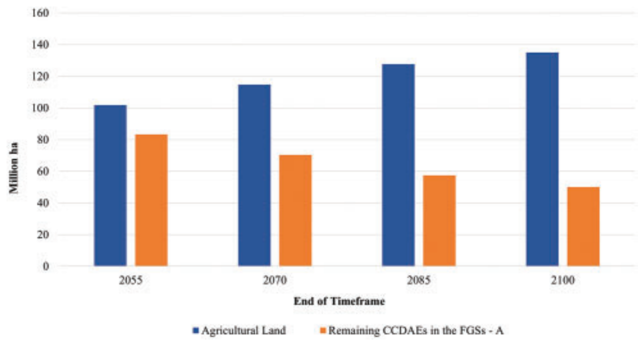

Fig. 3. CCDAEs progress in Canadian boreal–FGS: A.

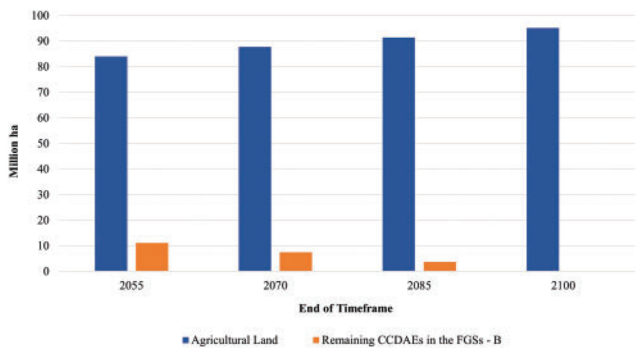

Fig. 4. CCDAEs progress in Canadian boreal–FGS: B.

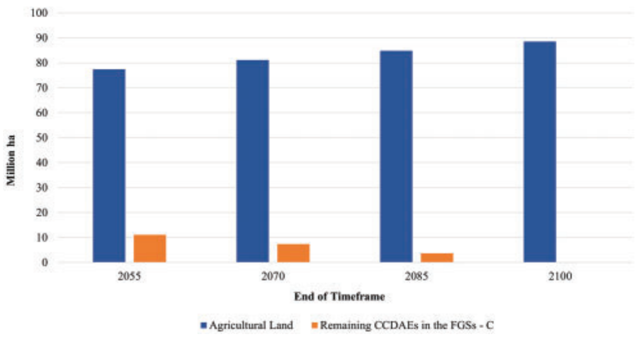

Fig. 5. CCDAEs progress in Canadian boreal–FGS: C.

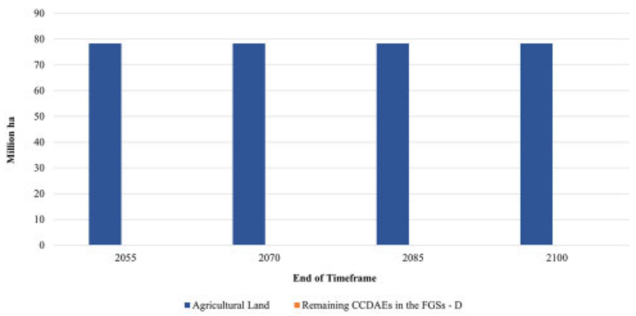

Fig. 6. CCDAEs progress in Canadian boreal–FGS: D.

The progress of the Canadian CCDAEs in each FGS and each timeframe are shown in Figs. 3–7. These figures include converted CCDAEs to agricultural lands and remaining Boreal areas waiting for conversion to farmlands in the next timeframe. Results revealed that all CCDAEs would convert to farmlands in the study period, except for the FGS-A, which 50 million ha are subject to LUC in the next century. The total converted land by the

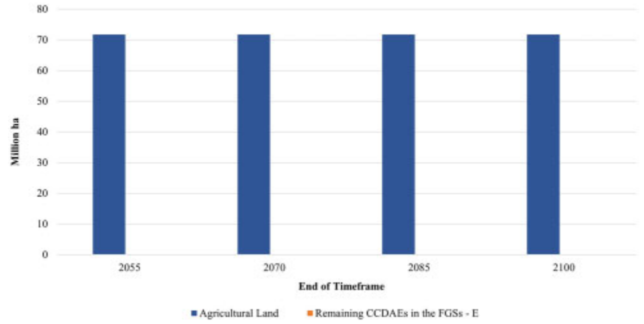

Fig. 7. CCDAEs progress in Canadian boreal–FGS: E.

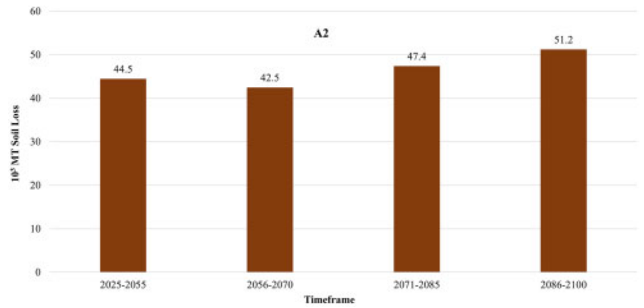

Fig. 8. Maximum physical SL-FGS: A2.

end of this century would be 135, 95.1, 88.5, 78.2, and 71.7 million ha in FGS A, B, C, D, and E, respectively. The whole forest lands in FGSs D and E would convert in the first timeframe and remain the same by the end of the study period.

3.2. *Estimates of Decadal SE*

Extracted SL data from the Canadian boreal zone were categorized based on minimum-maximum situations and used in the model (Table V). The Average soil carbon stock in the Canadian boreal zone is 210,000 and 810,000 kg C ha^{-1} for forests and peatlands respectively [22], [34].

Results of modeling for SL value (in megatone (MT)) in each CCDAE timeframe and for each FGS were considered and are available from the corresponding author, upon reasonable request. The maximum SL is projected to be just over 51 × 10^3 MT for the last timeframe (2086–2100) and 185 × 10^3 MT for the whole study period (2025–2100) in A2 (Fig. 8), while the minimum would be 7.1 × 10^3 MT for the last three timeframes and 29 × 10^3 MT for the whole period in E3 (Fig. 9). The maximum/minimum annual amount of SL at the end of the study period is projected to happen in the same FGSs, 3.5 × 10^3 and 0.48 × 10^3 MT, respectively. Results indicated that there are the lowest SL values in all minimum scenarios of conservative agriculture.

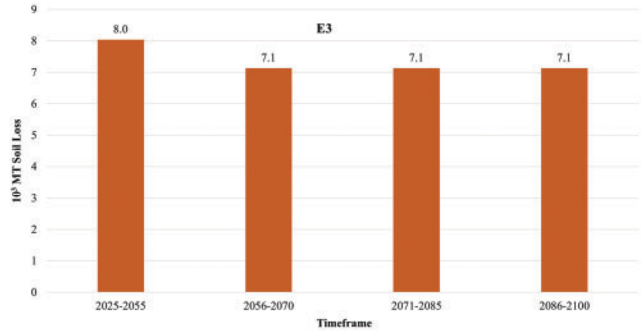

Fig. 9. Minimum physical SL-FGS: E3.

Results of the modeling also identified a massive difference in SL between FGSs and methods of agricultural activities where maximal expansion and conventional methods would result in seven times more SL than the minimal situations. Hence, if FGS E is the most likely scenario for Canadian CCDAEs, there will be just 0.48 × 10^3 MT annual SL in 2100 with an accumulative amount of 7.1 × 10^3 MT for the whole period of 2086–2100. This lowest projected level of SE would have a lower impact on the quality of fresh water and aquatic ecosystems, and fewer maintenance costs for the hydropower industry. The lowest level of SL would also minimize the fertility loss in farmland soils leading to a lower level of soil fertilizers application. These fertilizers were responsible for 21% [20] of total agricultural GHG emissions in Canada in 2020. The lowest level of soil deposit into streams and rivers would also minimize the CCDAE-driven risk of flooding in Canada's north despite the projected extreme precipitation events in the future [35].

One of the direct impacts of the Canadian CCDAEs-driven SL will be on water resources including surface water bodies and groundwater. The huge amount of SL (mentioned in the previous section) will transfer to rivers and lakes, which will affect the quality of freshwater. Agricultural fertilizers are also subject to accompanying soil particles and discharge to the water resources leading to more water pollution. In addition to these, SE and clear-cutting of forest/woodland stands (due to LUC) and projected extreme climatic events will increase the risk of flooding which is another driver of water pollution as well as limiting the nominal volume of dams. The latter will affect climate change adaptation plans in generating hydropower as a clean source of energy. These drivers of change will also affect the quality and quantity of groundwater and soil moisture at local and regional scales.

TABLE V: SE Rate by Land Use/Land Cover Type in Canada, Modified after [18], [32], [33]

SE rate in Canada	Bare lands/Fallow lands		Croplands		Shrublands/Woodlands		Forestlands		Peatlands	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
SE rate by Land use/Land cover (kg ha^{-1} y^{-1})	96,600	103,800	22,100	25,600	800	1800	400	900	−1,270	−1,270

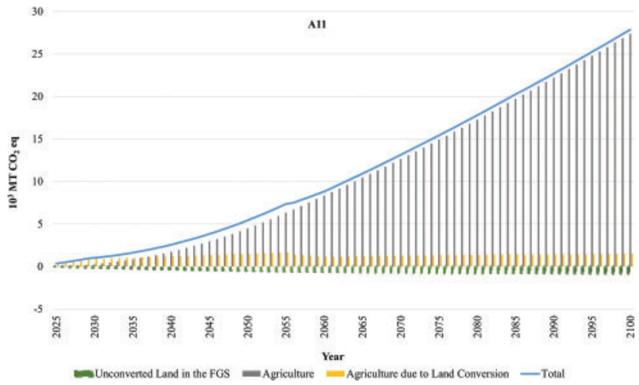

Fig. 10. Maximum GHG emissions–FGS: A11.

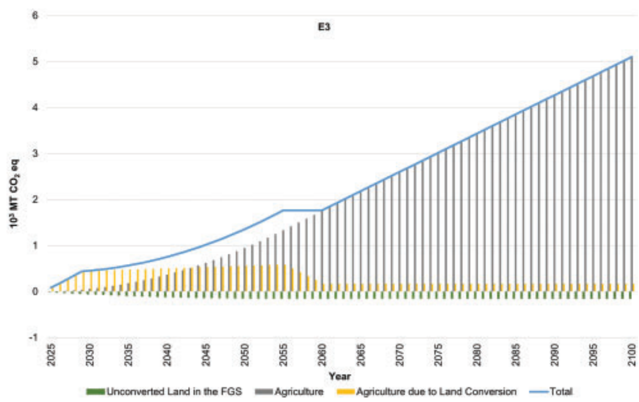

Fig. 11. Minimum GHG emissions–FGS: E3.

3.3. Impacts of the Projected Changes on GHG Emissions

Progress of CCDAEs in the Canadian boreal zone will impact the amount of GHG emissions across the country. This impact has two main sources; emissions due to land conversion and emissions due to new land use activities. Results revealed that the range of annual GHG emissions at the end of the study period would be $5.1 - 27.9 \times 10^3$ MT CO_2 eq in FGS A1-E4 and A11-E44. More specifically, in the highest level of CCDAEs progress (in both total land conversion and maximum conditions), FGS A11 (FGS A1 plus BGB and DPM-driven emissions (Fig. 10)) would lead to a total emission of 8.6×10 MT CO_2 eq in the whole study period and 776 MT CO_2 eq in 2028 which is solely higher than Canada's total GHG emission in 2020 (672 MT CO_2 eq). Likewise, FGS A22 represents the highest and fast paced emissions in the first timeframe, which solely surpass the current Canada's total GHG emissions in 2026 (682 MT CO_2 eq). On the other hand, the lowest level and minimum conditions of CCDAEs are projected to solely surpass Canada's 2020 emissions via a total emission of 708 MT CO_2 eq in FGS E3 (Fig. 11) in 2039. In both figures, green represents carbon sink, grey represents emissions from agricultural activities, and orange shows initial emissions from soil due to LUC.

From a GHG emissions point of view, the modeled CCDAEs' progress would emit $1.7 - 8.6 \times 10^5$ MT CO_2 eq in the 76 years based on the developed FGSs. These enormous GHG emissions would be $2.2 - 11.4 \times 10^3$ MT CO_2 eq on an average annual basis. However, the CCDAE-driven annual emissions at the end of the present century would be $4.8 - 27.9 \times 10^3$ CO_2 eq. The CCDAE-driven emissions are the total balance between sink and release in each FGS where the sink comes from the remaining forests and peatlands in the FGS, and the release is due to land conversion and agricultural activities. Therefore, while the magnitude of land conversion and the methods of farming practices will characterize the amount of CCDAE-driven GHG emissions, the converted lands will decrease the total sink capacity of Canada's forests and peatlands compared to the current situations. In total, all projected GHG emissions will follow increasing trends where conservative agricultural methods could moderate the volume of annual emissions as well as the diagram slope.

The total CCDAEs accumulative GHG emissions in the study period is projected between 1.7×10^5 and 8.6×10^5 MT CO_2 eq in E4 and A11, respectively (Tables VI and VII). The minimum and maximum average annual GHG emissions for the first timeframe are projected to be 0.85 $\times 10^3$ and 3.2×10^3 MT CO_2 eq for FGSs E3 and A22, respectively.

3.4. Potential Impacts of the Projected Changes on the Environment

Progress of CCDAEs in Canada's North will have considerable consequences on ecosystem services in a wide range from altering microclimatic conditions to affecting air and water quality. The northward agricultural expansion will accelerate competition for habitat among all living creatures affecting species richness, species population dynamics, discontinuity of habitats, and increasing the number of vulnerable species. Therefore, some species will be endangered or at risk of extinction [36]. The progress of CCDAEs along with other impacts of climate change and warming trends will also higher the risk of an increase in invasive species, pests, and insect populations. Although forest fires are becoming more common in many areas across the globe, the synergistic effects of CCDAEs, climate change, and a warming trend will exacerbate the risk of forest fires in both frequencies and the length of fire seasons [37] in the Canadian boreal zone. Furthermore, LUC of boreal forests and peatlands to croplands will decrease the amount of generated oxygen on a large scale which impacts air quality and freshness. Besides, plowed land is the potential to release soil particles and lead to air pollution.

In a bigger frame, CCDAEs will decrease the total areas of Canada's forests and peatlands by 72–135 million ha based on the planned FGSs. Canada has 9% of the world's forests and covers 39% (347 million ha [38]) of Canada's land area. Therefore, if all CCDAEs occurred, the total area of Canada's forests in the next century will be between 212 (in FGS A) and 275 (FGS E) million ha. The sharp decline in the total forest areas acts as a strong driver of climate change affecting climate change mitigation efforts in Canada. All the above-mentioned parameters and other potential changes have cumulative impacts [37] and affect natural landscapes, the sustainability of ecosystems, and the survival of ecosystems' elements.

TABLE VI: GHG Emissions in FGSs without DPM and BGB as Sources of Emission

FGSs		Total accumulative balance of GHG emission by 2100 in MT	Average annual GHG emission (2025–2100) in MT (±SD)	Total accumulative GHG emission in each CCDAE timeframe in MT (Average annual ± SD)			
				2025–2055	2056–2070	2071–2085	2086–2100
A	A1	8.5×10^5	11.2×10^3 ($\pm 8.3 \times 10^3$)	8.7×10^4 ($2.8 \times 10^3 \pm 20.7 \times 10^2$)	15.2×10^4 ($10.1 \times 10^3 \pm 1.8 \times 10^3$)	25.2×10^4 ($16.8 \times 10^3 \pm 2.0 \times 10^3$)	36.3×10^4 ($24.2 \times 10^3 \pm 2.2 \times 10^3$)
	A2	8.1×10^5	10.7×10^3 ($\pm 7.8 \times 10^3$)	9.1×10^4 ($2.9 \times 10^3 \pm 18.9 \times 10^2$)	14.4×10^4 ($9.6 \times 10^3 \pm 1.7 \times 10^3$)	24.1×10^4 ($16.1 \times 10^3 \pm 2.0 \times 10^3$)	33.5×10^4 ($22.3 \times 10^3 \pm 2.1 \times 10^3$)
	A3	2.4×10^5	3.2×10^3 ($\pm 2.2 \times 10^3$)	3.2×10^4 ($1.0 \times 10^3 \pm 5.4 \times 10^2$)	4.0×10^4 ($2.7 \times 10^3 \pm 4.4 \times 10^2$)	6.8×10^4 ($4.6 \times 10^3 \pm 5.9 \times 10^2$)	10.0×10^4 ($6.5 \times 10^3 \pm 6.3 \times 10^2$)
	A4	2.1×10^5	2.8×10^3 ($\pm 1.8 \times 10^3$)	3.5×10^4 ($1.1 \times 10^3 \pm 3.9 \times 10^2$)	3.6×10^4 ($2.2 \times 10^3 \pm 3.5 \times 10^2$)	5.7×10^4 ($3.8 \times 10^3 \pm 5.3 \times 10^2$)	8.6×10^4 ($5.7 \times 10^3 \pm 5.8 \times 10^2$)
B	B1	6.7×10^5	8.8×10^3 ($\pm 6.3 \times 10^3$)	7.5×10^4 ($2.4 \times 10^3 \pm 17.5 \times 10^2$)	12.5×10^4 ($8.4 \times 10^3 \pm 1.4 \times 10^3$)	19.3×10^4 ($12.9 \times 10^3 \pm 1.4 \times 10^3$)	27.3×10^4 ($18.2 \times 10^3 \pm 1.6 \times 10^3$)
	B2	6.7×10^5	8.8×10^3 ($\pm 6.2 \times 10^3$)	8.5×10^4 ($2.7 \times 10^3 \pm 17.1 \times 10^2$)	11.8×10^4 ($7.8 \times 10^3 \pm 1.3 \times 10^3$)	19.3×10^4 ($12.9 \times 10^3 \pm 1.5 \times 10^3$)	27.4×10^4 ($18.2 \times 10^3 \pm 1.6 \times 10^3$)
	B3	2.1×10^5	2.7×10^3 ($\pm 1.8 \times 10^3$)	3.0×10^4 ($0.97 \times 10^3 \pm 5.2 \times 10^2$)	3.7×10^4 ($2.4 \times 10^3 \pm 3.6 \times 10^2$)	5.9×10^4 ($3.9 \times 10^3 \pm 4.6 \times 10^2$)	8.3×10^4 ($5.6 \times 10^3 \pm 4.8 \times 10^2$)
	B4	2.1×10^5	2.7×10^3 ($\pm 1.6 \times 10^3$)	3.8×10^4 ($1.2 \times 10^3 \pm 4.6 \times 10^2$)	3.5×10^4 ($2.4 \times 10^3 \pm 3.1 \times 10^2$)	5.6×10^4 ($3.7 \times 10^3 \pm 4.2 \times 10^2$)	7.7×10^4 ($5.1 \times 10^3 \pm 4.7 \times 10^2$)
C	C1	6.2×10^5	8.1×10^3 ($\pm 5.8 \times 10^3$)	6.9×10^4 ($2.2 \times 10^3 \pm 1.6 \times 10^3$)	11.6×10^4 ($7.7 \times 10^3 \pm 1.3 \times 10^3$)	17.8×10^4 ($11.9 \times 10^3 \pm 1.3 \times 10^3$)	25.2×10^4 ($16.8 \times 10^3 \pm 1.5 \times 10^3$)
	C2	6.2×10^5	8.1×10^3 ($\pm 5.7 \times 10^3$)	7.8×10^4 ($2.5 \times 10^3 \pm 1.6 \times 10^3$)	10.9×10^4 ($7.3 \times 10^3 \pm 1.2 \times 10^3$)	17.8×10^4 ($11.9 \times 10^3 \pm 1.4 \times 10^3$)	25.4×10^4 ($16.9 \times 10^3 \pm 1.5 \times 10^3$)
	C3	1.9×10^5	2.5×10^3 ($\pm 1.7 \times 10^3$)	2.8×10^4 ($0.89 \times 10^3 \pm 4.8 \times 10^2$)	3.4×10^4 ($2.3 \times 10^3 \pm 3.3 \times 10^2$)	5.5×10^4 ($3.6 \times 10^3 \pm 4.2 \times 10^2$)	7.7×10^4 ($5.1 \times 10^3 \pm 4.4 \times 10^2$)
	C4	1.9×10^5	2.5×10^3 ($\pm 1.5 \times 10^3$)	3.6×10^4 ($1.1 \times 10^3 \pm 4.2 \times 10^2$)	3.3×10^4 ($2.2 \times 10^3 \pm 2.9 \times 10^2$)	5.2×10^4 ($3.4 \times 10^3 \pm 3.9 \times 10^2$)	7.1×10^4 ($4.8 \times 10^3 \pm 4.4 \times 10^2$)
D	D1	6.1×10^5	8.0×10^3 ($\pm 5.6 \times 10^3$)	7.0×10^4 ($2.3 \times 10^3 \pm 1.6 \times 10^3$)	11.7×10^4 ($7.8 \times 10^3 \pm 1.2 \times 10^3$)	17.6×10^4 ($11.7 \times 10^3 \pm 1.2 \times 10^3$)	24.3×10^4 ($16.2 \times 10^3 \pm 1.3 \times 10^3$)
	D2	5.9×10^5	7.8×10^3 ($\pm 5.5 \times 10^3$)	7.5×10^4 ($2.4 \times 10^3 \pm 1.6 \times 10^3$)	10.6×10^4 ($7.1 \times 10^3 \pm 1.1 \times 10^3$)	17.2×10^4 ($11.5 \times 10^3 \pm 1.3 \times 10^3$)	24.1×10^4 ($16.0 \times 10^3 \pm 1.3 \times 10^3$)
	D3	1.9×10^5	2.5×10^3 ($\pm 1.6 \times 10^3$)	2.9×10^4 ($0.92 \times 10^3 \pm 4.9 \times 10^2$)	3.4×10^4 ($2.3 \times 10^3 \pm 3.2 \times 10^2$)	5.3×10^4 ($3.6 \times 10^3 \pm 3.9 \times 10^2$)	7.4×10^4 ($4.9 \times 10^3 \pm 3.9 \times 10^2$)
	D4	1.8×10^5	2.4×10^3 ($\pm 1.4 \times 10^3$)	3.3×10^4 ($1.1 \times 10^3 \pm 4.8 \times 10^2$)	3.2×10^4 ($2.1 \times 10^3 \pm 2.8 \times 10^2$)	5.1×10^4 ($3.4 \times 10^3 \pm 3.8 \times 10^2$)	6.9×10^4 ($4.6 \times 10^3 \pm 3.9 \times 10^2$)
E	E1	5.6×10^5	7.3×10^3 ($\pm 5.1 \times 10^3$)	6.5×10^4 ($2.1 \times 10^3 \pm 1.5 \times 10^3$)	10.7×10^4 ($7.1 \times 10^3 \pm 1.1 \times 10^3$)	16.1×10^4 ($10.7 \times 10^3 \pm 1.1 \times 10^3$)	22.3×10^4 ($14.9 \times 10^3 \pm 1.2 \times 10^3$)
	E2	5.4×10^5	7.2×10^3 ($\pm 5.0 \times 10^3$)	6.9×10^4 ($2.2 \times 10^3 \pm 1.5 \times 10^3$)	9.7×10^4 ($6.5 \times 10^3 \pm 1.0 \times 10^3$)	15.8×10^4 ($10.5 \times 10^3 \pm 1.2 \times 10^3$)	22.0×10^4 ($14.7 \times 10^3 \pm 1.2 \times 10^3$)
	E3	1.7×10^5	2.3×10^3 ($\pm 1.5 \times 10^3$)	2.6×10^4 ($0.85 \times 10^3 \pm 4.5 \times 10^2$)	3.1×10^4 ($2.1 \times 10^3 \pm 2.9 \times 10^2$)	4.9×10^4 ($3.3 \times 10^3 \pm 3.6 \times 10^2$)	6.8×10^4 ($4.5 \times 10^3 \pm 3.6 \times 10^2$)
	E4	1.7×10^5	2.2×10^3 ($\pm 1.3 \times 10^3$)	3.1×10^4 ($0.98 \times 10^3 \pm 4.4 \times 10^2$)	2.9×10^4 ($1.9 \times 10^3 \pm 2.6 \times 10^2$)	4.6×10^4 ($3.1 \times 10^3 \pm 3.4 \times 10^2$)	6.3×10^4 ($4.2 \times 10^3 \pm 3.6 \times 10^2$)

3.5. Impacts of CCDAEs on Canada's Climate Change Mitigation Goals and Commitments

Canada's total GHG emissions decreased to 672 MY CO_2 eq in 2020, showing a net decrease of 9.3% from 2005 [20]. Climate change mitigation efforts and plans are set to achieve the emission reduction target of 40%–45% by 2030 and a net-zero level by 2050 [39]. The share of agriculture and land use, land use change, and forestry (LULUCF) are projected to be steady at around 71–73 MT CO_2 eq in emissions and 14–30 MT CO_2 eq in removals by 2030 [39]. However, CCDAEs will change this trend as an extra and emerging source of emissions. Results of our study revealed that these extra emissions are projected to be between 453–1484 MT of CO_2 eq in FGSs by 2030 and between 1353–5337 MT CO_2 eq in FGSs by 2050. This trend will continue where the extra emissions rich 5102–25,869 MT CO_2 eq in 2100. Statistical results in showed that agricultural GHG emissions due to land conversion would have a dominant role in total emissions in the first timeframe mainly due to the initial plowing of converted forests and peatlands. The first plowing would trigger a considerable amount (25%–40%) of stored carbon in the soil in the first five years after land conversion causing a jump in the total amount of GHG emissions in every FGS. The results characterized that this change would be more visible in FGSs D1-4 and E1-4 as all CCDAEs would convert during the first timeframe. The BGB and DPM-related emissions would also worsen this case in FGSs D11-44 and E11-44 because the burning of BGB and DPM would release carbon into the atmosphere right after land conversion and before or after initial plowing.

The average annual CCDAE-driven emissions between 2025–2055 (first timeframe) in minimal situations are projected to be 846 MT CO_2 eq which is nearly 26% more than total Canada's 2020 emissions level reaching a rough

TABLE VII: GHG Emissions in FGSs Including DPM and BGB as Sources of Emission

FGSs		Total accumulative GHG emission by 2100 in MT	Average annual GHG emission (2025–2100) in MT (±SD)	Total accumulative GHG emission in each CCDAE timeframe in MT (Average annual ± SD)			
				2025–2055	2056–2070	2071–2085	2086–2100
A	A11	8.6×10^5	11.4×10^3 ($\pm 8.4 \times 10^3$)	9.5×10^4 ($3.1 \times 10^3 \pm 20.7 \times 10^2$)	15.2×10^4 ($10.2 \times 10^3 \pm 1.8 \times 10^3$)	25.3×10^4 ($16.9 \times 10^3 \pm 2.1 \times 10^3$)	36.4×10^4 ($24.2 \times 10^3 \pm 2.2 \times 10^3$)
	A22	8.2×10^5	10.8×10^3 ($\pm 7.7 \times 10^3$)	9.9×10^4 ($3.2 \times 10^3 \pm 18.9 \times 10^2$)	14.5×10^4 ($9.7 \times 10^3 \pm 1.7 \times 10^3$)	24.2×10^4 ($16.1 \times 10^3 \pm 2.0 \times 10^3$)	33.6×10^4 ($22.4 \times 10^3 \pm 2.1 \times 10^3$)
	A33	2.5×10^5	3.3×10^3 ($\pm 2.2 \times 10^3$)	3.9×10^4 ($1.3 \times 10^3 \pm 5.4 \times 10^2$)	4.1×10^4 ($2.8 \times 10^3 \pm 4.4 \times 10^2$)	6.9×10^4 ($4.6 \times 10^3 \pm 5.9 \times 10^2$)	10.0×10^4 ($6.7 \times 10^3 \pm 6.3 \times 10^2$)
	A44	2.2×10^5	2.9×10^3 ($\pm 1.7 \times 10^3$)	4.3×10^4 ($1.4 \times 10^3 \pm 3.9 \times 10^2$)	3.7×10^4 ($2.3 \times 10^3 \pm 3.5 \times 10^2$)	5.8×10^4 ($3.9 \times 10^3 \pm 5.3 \times 10^2$)	8.6×10^4 ($5.8 \times 10^3 \pm 5.8 \times 10^2$)
B	B11	6.7×10^5	8.9×10^3 ($\pm 6.2 \times 10^3$)	8.1×10^4 ($2.6 \times 10^3 \pm 17.5 \times 10^2$)	12.6×10^4 ($8.4 \times 10^3 \pm 1.4 \times 10^3$)	19.3×10^4 ($12.9 \times 10^3 \pm 1.4 \times 10^3$)	27.3×10^4 ($18.2 \times 10^3 \pm 1.6 \times 10^3$)
	B22	6.8×10^5	8.9×10^3 ($\pm 6.2 \times 10^3$)	9.1×10^4 ($2.9 \times 10^3 \pm 17.1 \times 10^2$)	11.8×10^4 ($7.9 \times 10^3 \pm 1.3 \times 10^3$)	19.3×10^4 ($12.9 \times 10^3 \pm 1.5 \times 10^3$)	27.4×10^4 ($18.2 \times 10^3 \pm 1.6 \times 10^3$)
	B33	2.2×10^5	2.8×10^3 ($\pm 1.8 \times 10^3$)	3.6×10^4 ($1.2 \times 10^3 \pm 5.2 \times 10^2$)	3.7×10^4 ($2.5 \times 10^3 \pm 3.6 \times 10^2$)	5.9×10^4 ($3.9 \times 10^3 \pm 4.6 \times 10^2$)	8.4×10^4 ($5.6 \times 10^3 \pm 4.8 \times 10^2$)
	B44	2.1×10^5	2.8×10^3 ($\pm 1.5 \times 10^3$)	4.5×10^4 ($1.4 \times 10^3 \pm 4.6 \times 10^2$)	3.5×10^4 ($2.4 \times 10^3 \pm 3.1 \times 10^2$)	5.6×10^4 ($3.7 \times 10^3 \pm 4.2 \times 10^2$)	7.7×10^4 ($5.2 \times 10^3 \pm 4.7 \times 10^2$)
C	C11	6.2×10^5	8.2×10^3 ($\pm 5.8 \times 10^3$)	7.5×10^4 ($2.4 \times 10^3 \pm 1.6 \times 10^3$)	11.6×10^4 ($7.7 \times 10^3 \pm 1.3 \times 10^3$)	17.8×10^4 ($11.9 \times 10^3 \pm 1.3 \times 10^3$)	25.2×10^4 ($16.8 \times 10^3 \pm 1.5 \times 10^3$)
	C22	6.3×10^5	8.2×10^3 ($\pm 5.7 \times 10^3$)	8.4×10^4 ($2.7 \times 10^3 \pm 1.6 \times 10^3$)	10.9×10^4 ($7.3 \times 10^3 \pm 1.2 \times 10^3$)	17.9×10^4 ($11.9 \times 10^3 \pm 1.4 \times 10^3$)	25.4×10^4 ($16.9 \times 10^3 \pm 1.5 \times 10^3$)
	C33	2.0×10^5	2.6×10^3 ($\pm 1.6 \times 10^3$)	3.4×10^4 ($1.1 \times 10^3 \pm 4.8 \times 10^2$)	3.4×10^4 ($2.3 \times 10^3 \pm 3.3 \times 10^2$)	5.5×10^4 ($3.6 \times 10^3 \pm 4.2 \times 10^2$)	7.7×10^4 ($5.2 \times 10^3 \pm 4.4 \times 10^2$)
	C44	2.0×10^5	2.6×10^3 ($\pm 1.4 \times 10^3$)	4.1×10^4 ($1.3 \times 10^3 \pm 4.2 \times 10^2$)	3.3×10^4 ($2.2 \times 10^3 \pm 2.9 \times 10^2$)	5.2×10^4 ($3.5 \times 10^3 \pm 3.9 \times 10^2$)	7.2×10^4 ($4.8 \times 10^3 \pm 4.4 \times 10^2$)
D	D11	6.1×10^5	8.1×10^3 ($\pm 5.5 \times 10^3$)	7.7×10^4 ($2.5 \times 10^3 \pm 1.6 \times 10^3$)	11.7×10^4 ($7.8 \times 10^3 \pm 1.2 \times 10^3$)	17.6×10^4 ($11.7 \times 10^3 \pm 1.2 \times 10^3$)	24.3×10^4 ($16.2 \times 10^3 \pm 1.3 \times 10^3$)
	D22	6.0×10^5	7.9×10^3 ($\pm 5.4 \times 10^3$)	8.1×10^4 ($2.6 \times 10^3 \pm 1.6 \times 10^3$)	10.6×10^4 ($7.1 \times 10^3 \pm 1.1 \times 10^3$)	17.2×10^4 ($11.5 \times 10^3 \pm 1.3 \times 10^3$)	24.1×10^4 ($16.0 \times 10^3 \pm 1.3 \times 10^3$)
	D33	2.0×10^5	2.6×10^3 ($\pm 1.5 \times 10^3$)	3.5×10^4 ($1.1 \times 10^3 \pm 4.9 \times 10^2$)	3.4×10^4 ($2.3 \times 10^3 \pm 3.2 \times 10^2$)	5.3×10^4 ($3.6 \times 10^3 \pm 3.9 \times 10^2$)	7.4×10^4 ($4.9 \times 10^3 \pm 3.9 \times 10^2$)
	D44	1.9×10^5	2.5×10^3 ($\pm 1.3 \times 10^3$)	3.9×10^4 ($1.3 \times 10^3 \pm 4.8 \times 10^2$)	3.2×10^4 ($2.1 \times 10^3 \pm 2.8 \times 10^2$)	5.1×10^4 ($3.4 \times 10^3 \pm 3.8 \times 10^2$)	6.9×10^4 ($4.6 \times 10^3 \pm 3.9 \times 10^2$)
E	E11	5.6×10^5	7.4×10^3 ($\pm 5.1 \times 10^3$)	7.0×10^4 ($2.3 \times 10^3 \pm 1.5 \times 10^3$)	10.7×10^4 ($7.1 \times 10^3 \pm 1.1 \times 10^3$)	16.1×10^4 ($10.7 \times 10^3 \pm 1.1 \times 10^3$)	22.3×10^4 ($14.9 \times 10^3 \pm 1.2 \times 10^3$)
	E22	5.5×10^5	7.2×10^3 ($\pm 4.9 \times 10^3$)	7.5×10^4 ($2.4 \times 10^3 \pm 1.5 \times 10^3$)	9.7×10^4 ($6.5 \times 10^3 \pm 1.0 \times 10^3$)	15.8×10^4 ($10.5 \times 10^3 \pm 1.2 \times 10^3$)	22.0×10^4 ($14.7 \times 10^3 \pm 1.2 \times 10^3$)
	E33	1.8×10^5	2.4×10^3 ($\pm 1.4 \times 10^3$)	3.2×10^4 ($1.0 \times 10^3 \pm 4.5 \times 10^2$)	3.1×10^4 ($2.0 \times 10^3 \pm 2.9 \times 10^2$)	4.9×10^4 ($3.3 \times 10^3 \pm 3.6 \times 10^2$)	6.8×10^4 ($4.5 \times 10^3 \pm 3.6 \times 10^2$)
	E44	1.7×10^5	2.3×10^3 ($\pm 1.2 \times 10^3$)	3.6×10^4 ($1.2 \times 10^3 \pm 4.4 \times 10^2$)	2.9×10^4 ($1.9 \times 10^3 \pm 2.6 \times 10^2$)	4.6×10^4 ($3.1 \times 10^3 \pm 3.4 \times 10^2$)	6.3×10^4 ($4.2 \times 10^3 \pm 3.6 \times 10^2$)

level of 1518 MT CO_2 eq as Canada's average annual GHG emissions in the first timeframe. This timeframe corresponds to Canada's 2030 GHG emissions target and the 2050 Net-Zero Emissions Accountability Act. With the assumption of conservative agricultural practices, all FGSs in the first timeframe will impact Canada's emissions targets at the nearly same level, while the increasing trend in the rest of the timeframes would be considerably higher in FGS A. These CCDAE-driven emission levels indicate the importance of innovation in agricultural practices and improvements in cultivation techniques' efficiency. Furthermore, Canada is strongly working on limiting GHG emissions from agricultural fertilizers which were responsible for 21% of total emissions from Canada's agriculture sector in 2020 [20]. The projected decrease in fertilizer-driven emissions by 2030 and 2050 would have the same decreasing effect on the projected total emissions of this study as our emissions data were based on the current level of Canada's agricultural emissions. However, this projected mitigation in fertilizer-driven GHG emissions would partially adjust the results of GHG emissions in this study. Different levels of emissions in FGSs acknowledge the importance of conservative agricultural practices, especially in plowing frequencies and methods. These practices would moderate the amount of GHG emissions, especially in the first timeframe, giving more time to policymakers to adapt to the emerging CCDLUC.

3.6. Discussion

Canada is among the largest exporters of agricultural products in the world responsible for 6.8% of the nation's gross domestic product (GDP) in 2021 [40]. Based on the current data, Canada has 62.2 million ha of agricultural land covering 6.3% of total Canada's land [40]. Results of our study indicated that Canada's agricultural lands are projected to increase by an extra 7.2%–13.5% of total Canada's lands through CCDAEs. This expansion would develop total Canadian agricultural lands to 133.9–197.3 million ha in the future. This huge expansion could substantially elevate Canada's global position in the growing and on-demand market of agriculture and agri-foods. Current agri-food crises around the world and the potential impacts of climate change on global food production in the future along with the growing world's population may act as encouraging factors to expand farmlands leading to CCDAEs becoming more acceptable, especially in northern countries like Canada. United Nations population data about the world population is projected to increase to 9.7 billion by 2050 and 10.4 billion by 2100 [41]. From another aspect, global warming, extreme climate events, and water scarcity are affecting agri-food production across the globe. This trend will attract more attention to upper latitudes where CCDAEs are making more areas suitable for agriculture. Canada and Russia will have a vast amount of CCDAEs in the future creating new opportunities to address some agri-food insecurity worldwide. However, the environmental consequences of CCDAEs will be enormous, leading to more climate change disturbances. These consequences include a wide range of impacts from habitat and biodiversity loss to more GHG emissions. More air and water pollution such as sediment flow into water bodies (from SE), leaching chemicals (mainly from fertilizers and manures) to downstream water resources, and gases and fine particles into the air will also expect due to the progress of CCDAEs. The CCDAEs are projected to convert 71.7–135 million ha of Canada's Boreal zone, including lowland forests, mountains, peatlands, and Indigenous Treaties Lands, to agricultural lands in different FGSs. Among all land cover types in Canada's Boreal, peatlands and mountains are identified as the most vulnerable areas to land use alteration and climate change, indicating the importance of environmental protection in these two resources. Therefore, protection efforts should consider the sustainability of ecological systems and local communities. Researchers believe that mountain areas are pioneered to affecting by the earliest and greatest impacts of climate change [28]. However, Canada is the home of the largest intact forest areas in the world, representing 25% of the total intact forest of the world [42] which acts as an important carbon sink hotspot.

As mentioned in the potential impacts on the environment, the progress of CCDAEs without considering different FGSs and methods of agricultural practices will impact the ecological capability of surrounding unconverted boreal lands in terms of ecological values and ecosystem services. Moreover, this northward expansion will develop infrastructure and road networks in the Canadian Boreal zone which will cause more ecological discontinuity. These effects, in addition to the mentioned environmental impacts of CCDAEs, will put more pressure on the biodiversity and sustainability of marginal forests and peatlands amid climate change. Due to the considerable concerns about the current and projected climate change impacts on traditional lifestyles and resource development of the local communities of Canada's north [43], we presented all our results in five different FGSs. Mountain areas were excluded in the first step due to their high level of vulnerability to climate change impacts. The same reason was used in the third step for Canadian Boreal zone peatlands and their related permafrost [29], [33]. This research developed two parallel FGSs (D & E) for lowland forests' conversion to be accompanied by Indigenous Treaties Lands in one scenario and solely in the other scenario to ensure that Indigenous sovereignty on their lands is addressed for future development plans. In Canada, First Nations Land Management Act transferred the land administration to the First Nations, including legislation and management with respect to land, the environment, and resources [44], [45]. Hence, Indigenous policymakers have the option to plan for the potential CCDAEs, which are projected to be just over 6.5 million ha. Although this expansion could potentially provide more opportunities for local economic growth and food security, impacts on traditional food systems [2] and CCDAEs' environmental consequences should be considered.

In total, federal and provincial/territorial governments and Indigenous authorities in Canada will determine the intensity and the volume of CCDAEs in Canada's north. Thus, the magnitude of the projected land use changes and farming practices are the key elements to confine the environmental consequences of CCDAEs. These consequences are considered important drivers of climate change [46], proving interactions between climate change and CCDAEs.

4. Conclusion

Future climate change-driven Land use alterations in Canada's north will have considerable footprints on the environment, local communities, climate change mitigation plans, and local/national economic opportunities. These effects include both advantages and disadvantages, which are extensively stated in this study. Some of these impacts, like species distinction and soil carbon stock release, are almost irreversible, even in the long term. Likewise, natural landscape alteration is hard to recover in the short term. On the other hand, Increasing economic opportunities in Canada's northern rural areas will lead to a rise in agri-food production, which will be in high demand in the future.United Nations emphasized that food supply and food security will be strictly under the pressure of climate change in the next three decades [47]. These pressures will affect both crop yield and the availability of land and water for croplands around the world. This trend is going to make more and more current farmlands unsuitable for agriculture and is capable to give a justification for CCDAEs in northern regions despite all projected impacts on the environment and communities. In addition, innovations and improvements in the efficiency of agricultural methods, tools, materials, and crop selection could diminish some more of the negative effects of CCDAEs.

In conclusion, CCDAEs in Canada, as a likely scenario in the future, need multisectoral conversations between local communities, provincial/territorial governments, Indigenous authorities, the federal government, and other stakeholders to determine the volume (LUC intensity in every FGSs) and geographical progress of the CCDAEs over time. Accordingly, the CCDAEs' impacts on Canada's climate change mitigation targets and commitments may conceivably be considered a global issue that can have international solutions, as Canada's CCDAEs will help overcome future global food crises. IPCC is among the international stewardship committees qualified to assess the CCDAEs' trade-offs for the whole planet. This assessment should provide more details in every aspect of outcomes, co-benefits, and trade-offs for the total Canadian CCDAEs or each specific FGS from a global perspective. Furthermore, some of the Canadian CCDAEs' trade-offs, especially GHG emissions, could be compensated via carbon offset in other parts of the world through international collaborations. This research paper tried to fill some knowledge gaps in CCDLUC and its correlated impacts in Canada's north by implementing descriptive modeling. The results and detailed discussions of this study could be beneficial for various sectors at local, national, and international scales. These sectors represent a wide range of beneficiaries, including farmers, economists, policymakers, governments, environmental scientists, First Nations, researchers, and decision-making committees. However, future studies are essential to characterize the impacts of the CCDAEs on global warming trends, water resources, and wildfires. Moreover, the geographical pattern of this northward expansion should be investigated in a spatiotemporal manner to locate the potential CCDAEs with the minimum trade-offs in each FGS across the country. We also suggest further research projects on finding solutions to mitigate the ecological side effects of this northward agricultural expansion, especially on biodiversity loss and natural landscape degradations.

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Conflict of Interest

The authors have no relevant financial or non-financial interests to disclose.

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