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SPECIAL FEATURE: CASE REPORT

Globally-Consistent National Pathways towards Sustainable Food and Land-use Systems

Pathways to sustainable land use and food systems in Canada

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Abstract

Meeting global sustainability targets under the United Nations Sustainable Development Goals and the Paris Agreement requires paying attention to major land-use sectors such as forestry and agriculture. These sectors play a large role in national emissions, biodiversity conservation, and human well-being. There are numerous possible pathways to sustainability in these sectors and potential synergies and trade-offs along those pathways. This paper reports on the use of a model for Canada's land use to 2050 to assess three different pathways (one based on current trends and two with differing levels of ambition for meeting sustainability targets). This was done as part of a large international consortium, Food, Agriculture, Biodiversity, Land and Energy (FABLE), which allows for incorporating international trade in meeting both national and global sustainability targets. The results show not only the importance of increasingly stringent policies in meeting the targets, but also the role that population and consumption (e.g., diets) play in meeting the targets. Both the medium and high ambition sustainability pathways can drastically reduce greenhouse gas emissions while protecting forestland.

Keywords Sustainable development goals · Scenario assessment · Land-use changes · GHG emissions · Food systems · Canada

Introduction

In 2015, the world's governments, through the United Nations, committed to a broad set of goals to ensure that basic human needs are met while also protecting the various natural systems that we depend upon (Hák et al. 2016). These 17 Sustainable Development Goals (SDGs) include alleviating poverty and sustainable economic growth (SDG 1, 8, 9), ending hunger (SDG 2), protecting life on land (SDG 15) and in water (SDG 14), and mitigating climate change (SDG 13). The latter goal goes hand-in-hand with the other major environmental commitment that governments made in 2015, to hold climate change to 2 °C (and aim for 1.5) as enshrined in the Paris Agreement. Meeting human needs in a sustainable fashion requires, in part, careful attention to how land is managed and used across multiple sectors. The main land-use sectors of agriculture and forestry are, however, facing major challenges globally. Unsustainable land-use practices and climate change have direct negative impacts on both human and natural systems but also threaten long-term productivity and the ability to meet human demand for food and products. Recent reports, for example, show a major biodiversity crisis with extinction threats rising due to factors such as habitat loss (IPBES 2019).

There is a great deal of debate about how exactly land-use sectors both contribute to sustainability problems and to the solutions to sustainability problems (Steffen et al. 2015; Haberl et al. 2007; Pradhan et al. 2017; Scherer et al. 2018; Fader et al. 2018; Roe et al. 2019; Bastin et al. 2019; IPCC 2019). Managing the land for meeting multiple Sustainable Development Goals (e.g., through improved food production, protection of biodiversity, contributing to economic well-being, carbon sequestration) implies a number of potential trade-offs and synergies between different goals (e.g., land for conservation vs. agricultural production). Different

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strategies and policies can result in very different outcomes in terms of those trade-offs (Bowen et al. 2017).

For Canada, the implications for land-use sectors of these goals is particularly important socially, environmentally and economically. Canada's land cover in 2010 was 5.8% cropland, 1.6% grassland, 38.1% forest, 0.1% urban and 54.3% other natural land (ESA 2010). Most of the agricultural area is located in the provinces of Alberta and Saskatchewan (with additional significant areas in Manitoba, Ontario, and pockets of agricultural production in other provinces) (Statistics Canada 2021a), while forests and other natural lands can be mostly found in British Columbia, Ontario, Manitoba, Quebec, and three northern Territories (Map 1). The main challenges for biodiversity conservation are related to energy production and mining (tar sands production in Alberta), forestry operations and an increase in fire frequency and intensity (wildfires in the west coast), and diseases that increase natural mortality and produce ecological imbalances (Axelson et al. 2009, Potapov et al. 2017).

Economically, the Canadian forest industry contributes over $20 billion to Canada's GDP, employs over 200,000 workers and harvests roughly 150 million cubic meters of roundwood per year (Natural Resources Canada 2018, Natural Resources Canada and Canadian Forest Service 2019). Agricultural production in Canada encompasses 55.2 million hectares (Mha), is worth $111 billion (6.7% of GDP), and is expected to expand to help Canada meet domestic and global demand for agricultural commodities (Bonti-Ankomah et al. 2017; Sarkar et al. 2018). These sectors face a number of climate change stressors: range shifts for various tree species, changes in precipitation and temperature affecting crop yields (Li et al. 2018), and increased risks of pests and forest fires, among others, which impact on people's health and wellbeing (Yusa et al. 2015).

Canada, being one of the largest exporters of agricultural products in the world, has projected to double its current agricultural productivity and incomes for small-scale producers by 2030 (Statistics Canada 2021b) in its quest to achieve the Zero hunger SDG mandate. This is expected to have an impact on Land Use, Land-Use Change and Forestry (LULUCF), given agriculture is one of the leading drivers of this change in Canada (Environment and Climate Change Canada 2021a, b). On the one hand, it is projected that afforestation and deforestation rates would continue to remain low, reducing the possible impact from land use changes (National Resources Canada 2020), which would translate to a net sink (overall emission reduction compared to what is released) for its land sector. However, in a recent inventory report by Environment and Climate Change Canada (2021a, b), this sector was revaluated and flagged as a net source of emission since 2015, with a difference of about 20 $MtCO_2e$ in recent years. This difference has been attributed to updates in modeling parameters and methods used, revisions of forest harvest activity and changes in how insect disturbances are captured (Climate Action Tracker 2021).

According to the Long-Term Low Emissions and Development Strategy (LT-LEDS), Canada has committed to reducing its GHG emissions by 80% by 2050 compared to 2005 (Environment and Climate Change Canada 2016). This includes emission reduction efforts from agriculture, forestry, and other land use (AFOLU). Envisaged mitigation measures from agriculture and land-use change include protecting and enhancing carbon sinks including forests, wetlands and agricultural lands; large-scale afforestation; increased use of long-lived harvested wood products; and increased utilization of waste wood biomass. Under its current commitments to the UNFCCC, Canada does not mention biodiversity conservation (Environment and Climate Change Canada 2016).

Table 1 summarizes Canada's Nationally Determined Contributions (NDCs) and LT-LEDS, and Table SI-1 in the Supplemental Information provides an overview of the biodiversity targets included in the National Biodiversity Strategies and Action Plan (NBSAP), as listed on the website of the Convention on Biological Diversity (CBD 2020). Moreover, Canada's NBSAP combines its 2020 Biodiversity Goals and Targets and the 2006 Biodiversity Outcomes Framework. However, NBSAPs' targets are seen as vague, unambitious, and ineffective (Hagerman and Pelai 2016; Lemieux et al. 2019).

As these goals and strategies are translated into concrete policies and actions at a domestic level there needs to be a mechanism for understanding the complex inter-linkages between the SDGs, climate action and different land-use options and decisions (Sachs et al. 2019). Integrated policies and strategies are lacking and no country has fully mapped out and integrated the pathways for meeting these goals over the long-term into policy. Approaches that capture the complex inter-linkages between the SDGs, climate action and different land-use decisions across multiple land-use sectors are needed (Steffen et al. 2015; Haberl et al. 2007; Pradhan et al. 2017; Scherer et al. 2018; Fader et al. 2018; Bastin et al. 2019; IPCC 2019).

In that context, the Food, Agriculture, Biodiversity, Land and Energy (FABLE) initiative aims to understand how countries can collectively transit towards more sustainable land-use and food systems, meeting at the same time the Sustainable Development Goals (SDGs) and the Paris Agreement. FABLE teams work through an iterative

Table 1 Summary of the mitigation target, sectoral coverage, and references to biodiversity and spatially explicit planning in current NDC and LT-LEDS

Canada climate commitments	Total GHG mitigation				Sectors included	Mitigation measures related to AFOLU (Y/N)	Mention of biodiversity (Y/N)	Inclusion of actionable maps for land-use panning[1] (Y/N)	Links to other FABLE targets
	Base line		Mitigation target						
	Year	GHG emissions (Mt CO_2e/years)	Year	Target					
NDC (2017)	2005	747	2030	30% reduction	Energy, industrial processed, agricultural, land-use change and forestry, and waste	N	N	N	Deforestation
LT-LEDS (2016)	2005	748	2050	80% reduction	Energy, industrial processed, agricultural, and waste	Y	N	N	Food security, water, and deforestation

"Total GHG Mitigation" and "Mitigation Measures Related to AFOLU" columns are adapted from Institute for Global Environmental Strategies (IGES) NDC Database (2021). We also compute the blue water footprint using the methodology of Mekonnen and Hoekstra (2010a, b, 2011). However, we do not report these results here in the interest of space

[1]We follow the United Nations Development Programme definition, "maps that provide information that allows planners to take action" (Cadena et al. 2019)

Source: Canada (2017)

process based on partial equilibrium models that take into account key determinants of global land-use projections: population, wealth, consumption preferences, agricultural productivity, land-use regulation, and trade, and their interactions (Stehfest et al. 2019). Twenty country-teams[1] that concentrate most on agricultural production, consumption and trade, and five "rest of continent" teams adjust different scenarios to ensure balanced trade flows and progressively align national pathways with these global targets, which account for food security, greenhouse gas emissions, and biodiversity (Mosnier 2020).

Along this process, teams engage national stakeholders and experts to review assumptions, seek technical advice, and build a shared vision of how to transform land use and food systems. FABLE teams work locally and have relationships with different stakeholders: industry, government, NGOs, farmers organizations, and researchers, who provide relevant data and feedback to define scenarios based on a bottom-up approach, which allows for better accounting for cross-scale interactions (Nilsson et al. 2017). This is the main value and difference of the FABLE initiative with other efforts that try to address similar challenges.

To assess how Canada could transition towards more sustainable land use and food systems, and simultaneously meet some key Sustainable Development Goals and the Paris Agreement, this paper reports on three scenarios that were built and projected to 2050 as part of the FABLE initiative. Each scenario has national level assumptions related to population, economic growth, agricultural production, and other relevant aspects. The next section describes the methods and the scenarios that were created to project possible futures for Canada by 2050. The subsequent section shows the main results of these projections, followed by which our main findings in light of the current literature are discussed. Finally, we propose some conclusions.

Materials and methods

The FABLE initiative is composed of a Secretariat plus 20 country-teams, which concentrate most on global agricultural production, consumption and trade, and five "rest of continent" teams (America, Asia, Africa, Oceania, and Europe) that process data for countries that are not directly involved in this partnership. The country teams are composed of people from different organizations, skills and

[1] Argentina, Australia, Brazil, Canada, China, Colombia, Ethiopia, Germany, Finland, India, Indonesia, Malaysia, Mexico, Norway, Russian Federation, Rwanda, South Africa, Sweden, United Kingdom and United States.

professions, allowing researchers from different backgrounds, hardware/software availability, resources, and skills to collaborate as a network, and assess common futures, which is a key characteristic of the FABLE initiative (FABLE 2020). At the same time, there is variability between the teams in terms of both data access and modeling tools used (GLOBIOM, MAgPIE, and the FABLE Calculator). This creates some methodological challenges for the FABLE Secretariat who integrate all modeling outputs.

The Canada team uses the FABLE Calculator developed by the International Institute for Applied Systems Analysis (IIASA) and the Sustainable Development Solutions Network (SDSN) to perform all calculations. The FABLE Calculator is an appropriate tool for this study compared to other modeling approaches, especially at an initial stage of work, because it does not require previous knowledge on specific software and licenses, as is the case of GLOBIOM, MAGPIE and other tools, and users can easily replace Tier 1 data with national or subnational statistics (Valin et al. 2013; Mosnier 2020). From this perspective, the FABLE Calculator is easier and cheaper to use than other platforms, and very flexible and transparent.

The FABLE Calculator

The FABLE Calculator is an Excel-based tool to model and project food and land use systems by 2050 at different levels (regional, national and subnational). This tool addresses the main aspects of these systems: food security and trade, land cover changes, biodiversity impacts, and GHG emissions from agriculture and land-use changes (Mosnier 2020). Databases for agricultural inputs and outputs, land-use, and other aspects are included in the Excel file, as well as the assumptions and formulas used for modeling, creating alternative scenarios, and visualizing the main results. From that perspective, the calculator is transparent in terms of the way it relates different kinds of data, as well as its limitations. The databases are pre-populated with data from FAOSTAT and the European Space Agency (ESA) but have been updated and modified with data from Canadian statistical sources as appropriate. The calculator is complemented by the Quality Assurance Tool, which was developed to check consistency of outputs and main results along its different formulas and tables. The calculator's open framework allows for frequent improvements suggested by the community of users (country team members, scholars, and experts). These improvements are assessed by IIASA and SDSN, and they are shared with the community through update packages, which are published regularly.

The calculator projects figures about land use and land-use changes, GHG emissions, biodiversity conservation, and other relevant indicators related to different SDGs by 2050, at 5-year periods, based on scenarios that combine shared socioeconomic pathways (population, economic growth and diets), international trade fluxes (imports and exports), agricultural productivity and efficiencies (crops and livestock, and losses along the food-supply chain), climate change scenarios, and public policies about forests and biodiversity protection. The calculator's users can combine different scenarios, and even create their own, based on a particular country's commitments, policies and potential futures in order to assess how these scenarios influence social and environmental goals. Calculations use historical data for the 2000–2015 period, and projections require several assumptions which are developed by each country team. Once scenarios are selected, all tables and formulas process the information to produce final outputs, which are later combined by the FABLE Secretariat and IIASA with the ones from the other country and "rest of continent" teams to balance the international trade fluxes by using partial equilibrium models. Once this is completed, adjusted values for different crops and agricultural products are given back to every country team to run the calculator again.

Metrics

This analysis considers three out of 17 SDGs related to food security, greenhouse gas emissions, and biodiversity protection. Table 2 shows the specific targets within those SDGs, and the metrics of these objectives.

In addition to the main SDG-based metrics discussed above, we also measure two other metrics of interest for understanding the implications of the pathways. The first is a self-sufficiency ratio that measures exports vs. imports of various food products to understand the dependence on global trade for both meeting internal dietary needs and for supplying food to other markets. The second is a diversity index to look at concentration in land-use for producing different crops and the concentration in exports and imports within certain commodities. For this, we use the Herfindahl–Hirschman Index (HHI), which is typically used to measure the degree of market competition using the number of firms and the market shares of each firm in a given market (Rhoades 1993). We apply this index to measure the diversity/concentration of:

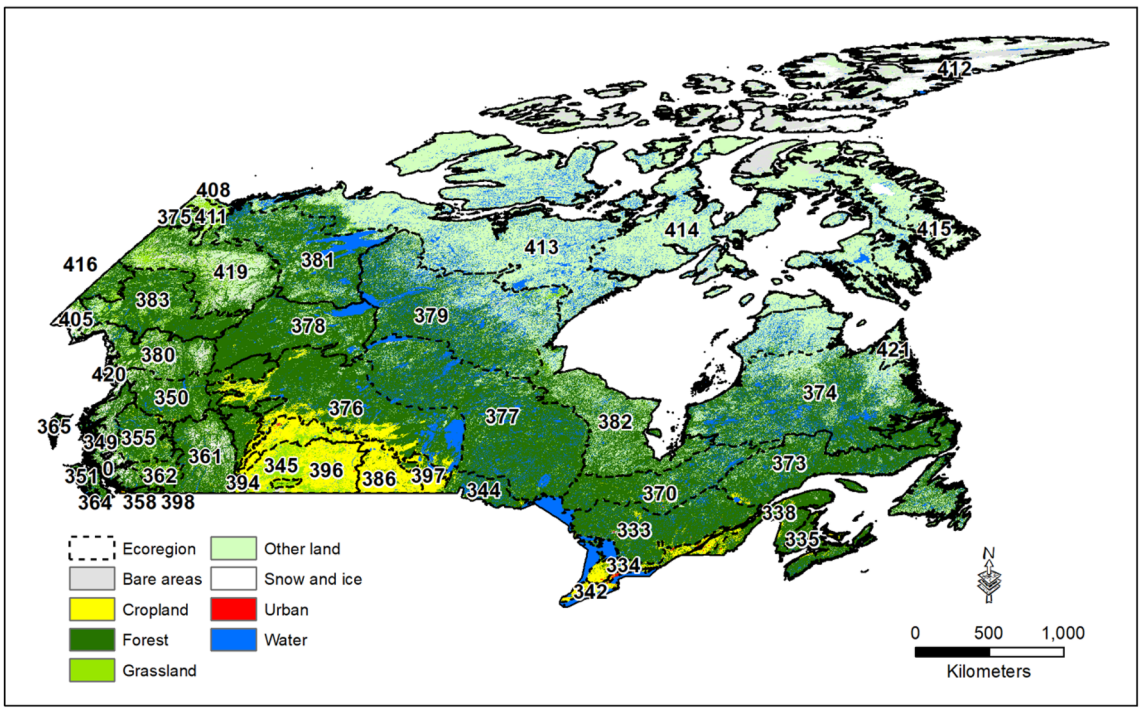
Cultivated area: where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
Exports and imports: where concentration refers to a situation in which a few commodities represent a large share

Table 2 Metrics used to include global targets into the calculator

SDGs	Targets	Metric
Food security	Average daily energy intake per capita is higher than the minimum requirement in all countries by 2030	Average kilocalories per capita per day
	Diet composition to achieve premature diet-related mortality below 5%	Average consumption of proteins and fats per capita per day by food group
GHG emissions[1]	GHG emissions from crops and livestock allow keeping the rise in average global temperatures to below 1.5 °C by 2050	Average CO_2e emissions per ton of crop and livestock produced and consumed (including exports, and wasted food)
	GHG emissions and removals from LULUCF are compatible with keeping the rise in average global temperatures to below 1.5 °C	Average CO_2e emissions per hectare of productive land expanded into forests or other lands, and removals per hectare of new forests
	Negative global GHG emissions from LULUCF by 2050	Average CO_2e balance between GHG emissions and removals related to LULUCF
Biodiversity protection[2]	No net loss of lands where natural processes predominate by 2030, and an increase of at least 20%,	Total area (hectares) of intact ecosystems outside protected areas by land use and ecoregion
	At least 30% of global terrestrial area is inside protected areas by 2030	Total area (hectares) inside protected areas
	Zero net deforestation by 2030	Total area (hectares) of forests cleared, and non-reforested

[1]GHG emissions that result from permafrost conversion to bog, fen lands and other land cover types, as also impacts on peatlands, have not been included in the FABLE Calculator yet. This process is relevant in Canada, especially because of climate change, and it can be producing significant amounts of methane and other gases (Chasmer et al. 2012)

[2]Agricultural expansion also affects wetlands, which are being drained in the Canadian prairies with severe ecological impacts (biodiversity, water quality and quantity, etc.) (Baulch et al. 2021). Wetlands are very critical ecosystems, but they were not included in this study because of the lack of adequate representation in the calculator and the difficulty of getting good statistics



Map 1 Land cover by aggregated land cover types in 2010 and ecoregions. Sources. Countries—GADM v3.6 (GADM 2020); ecoregions—Dinerstein et al. (2017); land cover—ESA CCI land cover 2015 (ESA 2017)

of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of the total exported and imported quantities.

We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, Sect. 5.3): diverse under 1500, moderate concentration between 1500 and 2500, and high concentration above 2500.

National pathways

Our Current Trends pathway corresponds to the lower boundary of feasible action. It is characterized by medium-speed population growth (from 38 million in 2020 to 49 million in 2050), no constraints in agricultural expansion, no afforestation target, no change in the extent of protected areas, low productivity increases in the agricultural sector, an evolution towards higher fat diets, and high speed of economic growth. This corresponds to a future based on current policy (as of 2010) and historical trends that would also see considerable growth in GDP and exports in the coming decades according to OECD (2020) and FAO (2020) database projections. We embed this Current Trends pathway in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m^2 (RCP 6), or a global mean warming increase likely between 2 and 3 °C above pre-industrial temperatures by 2100 (HadGEM2-ES climate model, and the GEPIC crop model without fertilization effect). Table SI-2 in the Supplemental Information summarizes the main assumption for all pathways, and provides references.

Our Sustainable Medium Ambition pathway represents a future in which significant efforts are made to adopt sustainable policies and practices, and corresponds to an intermediate boundary of feasible action. Compared to the Current Trends pathway, we assume that this future would lead to a higher afforestation rate, expansion of protected areas, improved crop and livestock productivities, expanded imports and exports, and greater biofuel consumption (Advanced Biofuels Canada 2019). It is also characterized by lower population and GDP growth rates, a lower deforestation rate, reduced calorie consumption, and a declining share of wasted food. This corresponds to a future based on the adoption and implementation of new ambitious policies about trade, immigration, and climate change that would also see considerable progress concerning biodiversity protection, first-generation biofuel consumption, sustainable forest management and agricultural performance (Bohnert et al. 2015; Mukhopadhyay et al. 2020; Prestele et al. 2016; Wulder et al. 2018). We embed this pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2 °C. At this level of warming, this scenario assumes a positive impact of climate change on crop and pastures productivities given resulting increases in growing season and suitable agricultural area (Assefa et al. 2018; Jing et al. 2017; Li et al. 2013; Lychuk et al. 2017; Qian et al. 2016; Ray et al. 2013; Thorpe et al. 2008; Thomas and Graf 2014), though we recognize that this may be overly optimistic and does not offset other damaging climate impacts (including to agriculture) even under an RCP 2.6 scenario.

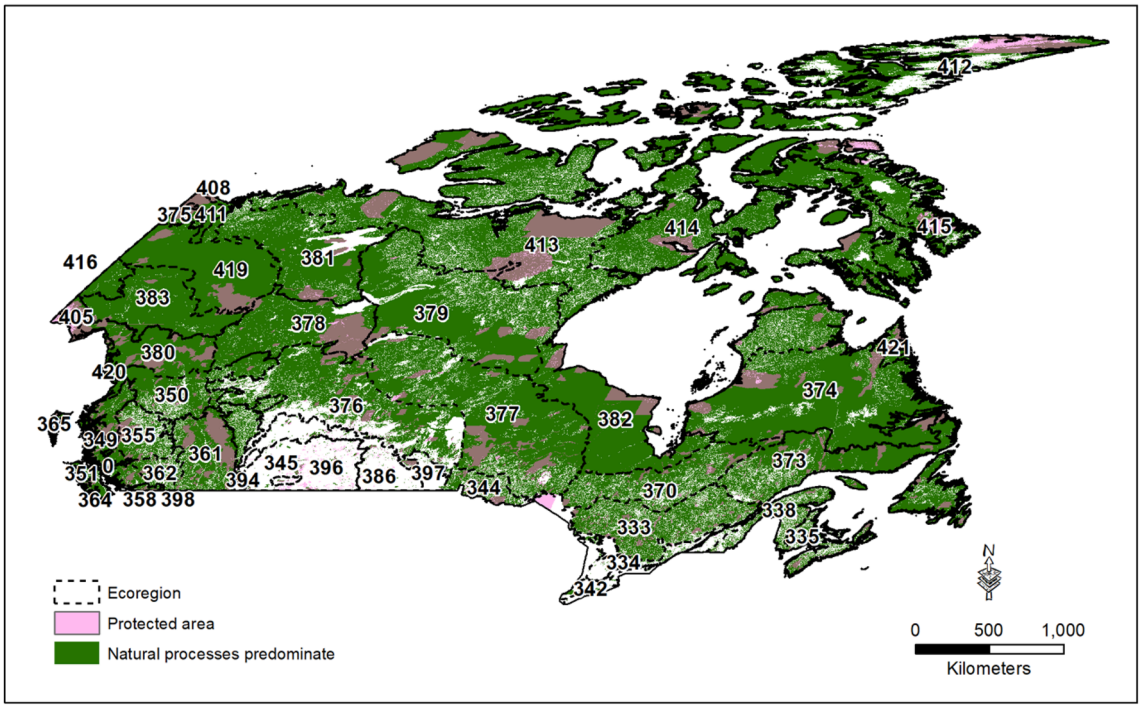
Our Sustainable High Ambition pathway represents a future in which even more significant efforts are made to adopt sustainable policies and practices, and corresponds to the highest boundary of feasible action. Compared to the Sustainable Medium Ambition pathway, we assume that this future would lead to even higher afforestation rates, expansion of protected areas, improvement of main crops' yields, and increased exports. This is coupled with lower GDP growth, reduced imports, and declining use of first-generation biofuel consumption. This corresponds to a future based on the adoption and implementation of very ambitious policies about biodiversity protection (Andrew et al. 2012; Schulte 2017) and climate change mitigation programs like the zero-emission vehicle (ZEV) target that includes subsidies and other support programs to increase the use of electric vehicles (Natural Resources Canada 2020a, b). As in the Sustainable Medium Ambition pathway, we embed this Sustainable High Ambition pathway in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6).

Results

Current land use and emissions

In Canada, lands where natural processes predominate[2] accounted for 80% of terrestrial land area in 2010, although only 17% of them are inside protected areas (UNEP-WCMC and IUCN 2020). This is mostly concentrated in a few ecoregions in the northern parts of the country (Map 2). Broadly, about 107 million hectares are under formal protection, which represents 11% of Canada's lands. This figure falls short of the post-2020 30% targeted by the Convention on Biological Diversity (CBD 2020).

[2] We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".



Map 2 Land where natural processes predominated in 2010, protected areas and ecoregions. Note: The 411-Brooks-British Range tundra ecoregion holds the greatest share of land where natural processes predominate, followed by the 419-Ogilvie–MacKenzie alpine tundra ecoregion and the 380-Northern Cordillera forests ecoregion. Moreover, the ecoregions with more than 30% of lands where natural processes predominate that are formally protected are the 405-Alaska-St. Elias Range tundra, the 365-Haida Gwaii conifer forests, the 408 Arctic foothills tundra, the 375 Interior Alaska-Yukon lowland taiga, the 421 Torngat Mountain tundra, the 361 Northern Rockies conifer forests, and the 415 Davis Highlands tundra. They will remain important for biodiversity into the future. By contrast, the 383-Watson Highlands taiga, the 345-Alberta-British Columbia foothills forests, the 416-Interior Yukon-Alaska alpine tundra, and other ecoregions may be at risk without action to better protect them. Sources. Countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International (2019), intact forest landscapes in 2016 – Potapov et al. (2017), and low impact areas – Jacobson et al. (2019)

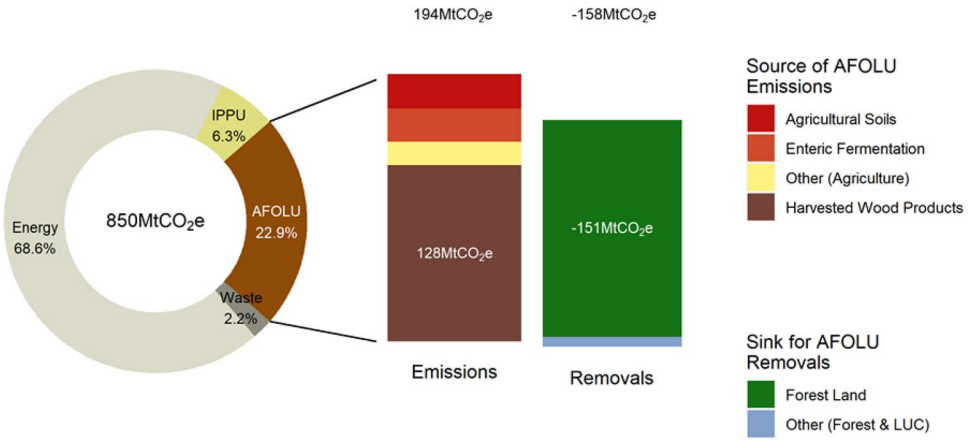


Fig. 1 Share of Canada's GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 2010. Source. Adapted from GHG National Inventory (UNFCCC 2020). *IPPU* industrial processes and product use

Most croplands do not maintain natural vegetation. In 2010, only 21% of these productive landscapes kept at least 10% of natural vegetation. These croplands (Smith et al. 2013a, b; Sloan et al. 2014) are mainly located in areas with lower agricultural production intensities, as is the case of the Canadian Aspen forests and parklands ecoregion (386 in Map 2), the Northern Shortgrass prairie ecoregion (396) and the Mid-Canada Boreal Plains forests ecoregion (376).

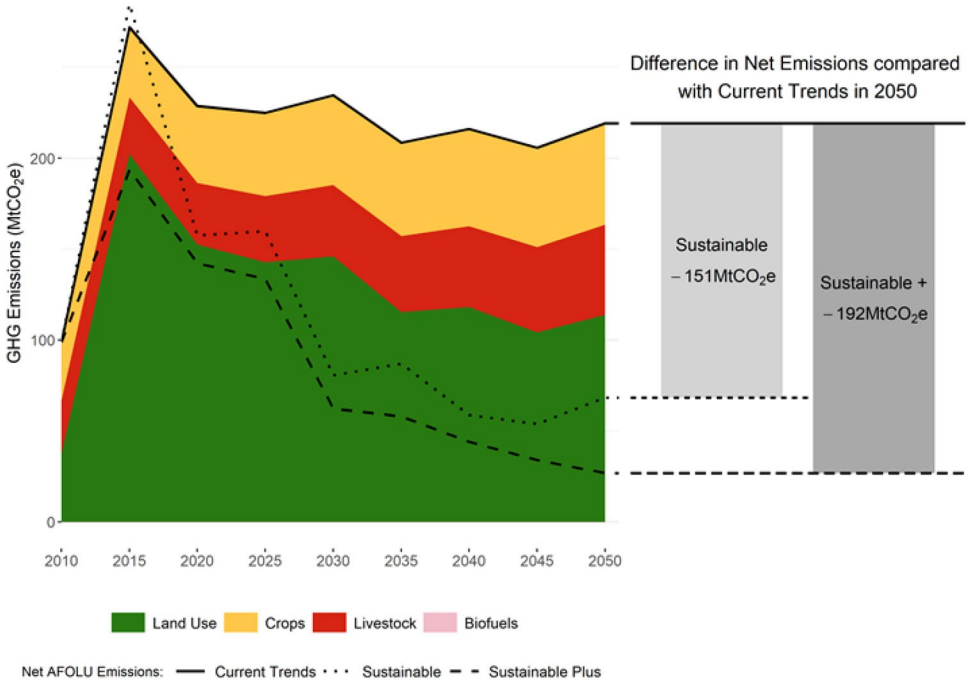


Fig. 2 Projected AFOLU emissions and reductions between 2010 and 2050 by main sources and sinks for the Current Trends pathway

GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) represented 23% of all Canada emissions in 2010 (Fig. 1). Harvested timber is the principal component of these emissions, which shows the relevance of the forest industry in Canada, followed by enteric fermentation, and agriculture soil management. Most of the enteric fermentation results from livestock, with over 10 million head of cattle for beef production and dairy (Environment and Climate Change Canada 2021b).

Pathways about land use and biodiversity

In the current trend scenario, projected land uses were based on shared socioeconomic pathways about population, GDP, diets, and other aspects. We assumed a medium-speed population growth, from 38 million in 2020 to 49 million in 2050, high speed of economic growth, a preference for higher fat diets, no-limits for land use changes, no significant afforestation programs, marginal augmentation to agricultural productivity, formally protected areas remaining on about 11% of total Canadian territory, and global warming between 2 and 3 °C higher than pre-industrial levels by 2100. Concerning land use, this scenario projects an increase in croplands, and a reduction in forest area by 2030 and continuing to 2050. The expansion of the planted area for rapeseed, wheat and barley explains 72% of total cropland expansion between 2010 and 2030. For rapeseed, 57% of the expansion is explained by an increase of exports, mainly to China, and 43% is due to an increase of domestic consumption (processed food). For wheat, 36% of expansion is due to an increase of exports and 64% an increase of domestic consumption (feeding animals, food, and biofuels). Finally, for barley, 98% results from an increase of domestic consumption for feeding animals.

Pasture expansion is mainly driven by the increase in internal food consumption of beef, milk, and derivatives, while livestock productivity per head increases and ruminant density per hectare of pasture remains constant over the period 2020–2030. Between 2030 and 2050, deforestation is explained by cropland and pasture expansion. This results in a reduction of land where natural processes predominate by 5% by 2030 and by 9% by 2050 compared to 2010, respectively.

In the Sustainable Medium Ambition and Sustainable High Ambition pathways, assumptions reflect a higher interest in biodiversity conservation and climate change mitigation (Prestele et al. 2016; Wulder et al. 2018). For the Sustainable Medium pathway, main assumptions include lower population and GDP growth rates, healthier diets (following the recommendations of the EAT-Lancet Commission), the prevention of deforestation by 2030, 1 million hectare afforested by 2050, protected areas increase from 11% of total land in 2010 to 17% in 2030, improved crop and livestock productivities, greater biofuel consumption, and a declining share of wasted food, in a context of 2 °C above pre-industrial temperatures by 2100. While for the Sustainable High pathway, afforested area increases by 2 million hectares and protected areas to 28%.

Compared to the Current Trends pathway, we observe the following changes regarding the evolution of land cover in Canada in the Sustainable Medium Ambition and

Table 3 Daily average fats, proteins and kilocalories intake under the Current Trends, Sustainable Medium Ambition, and Sustainable High Ambition pathways in 2030 and 2050

Considered aspects	2010	2030			2050		
	Historical diet (FAO)	Current trends	Sustainable medium ambition	Sustainable high ambition	Current trends	Sustainable medium ambition	Sustainable high ambition
Kilocalories *(MDER)*	2710 *(2104)*	2994 *(2092)*	2569 *(2092)*	2569 *(2092)*	3276 *(2086)*	2304 *(2086)*	2304 *(2086)*
Fats (g) *(recommended range)*	125 *(60–90)*	141 *(66–100)*	118 *(57–86)*	118 *(57–86)*	157 *(73–109)*	104 *(51–77)*	104 *(51–77)*
Proteins (g) *(recommended range)*	85 *(68–237)*	99 *(75–262)*	84 *(64–225)*	84 *(64–225)*	112 *(82–287)*	81 *(58–202)*	81 *(58–202)*

Values (for MDER) are in italics in order to distinguish them from the values assumed in the modeling

Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement per sex, age class, and activity level (U.S. Department of Health and Human Services and U.S. Department of Agriculture 2015) and the population projections by sex and age class (UN DESA 2017, 2019) following the FAO methodology (Wanner et al. 2014). For fats, the dietary reference intake is 20 to 30% of kilocalories consumption. For proteins, the dietary reference intake is 10 to 35% of kilocalories consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4 kcal/g of proteins

Sustainable High Ambition pathways: (i) a lower deforestation rate, (ii) a small increase in natural land, (iii) the stabilization or even a smaller area of agricultural land, and (iv) a higher afforested land. These differences are not only the natural result of changes in assumptions regarding land-use planning. They also arise from changes in internal demand for food due to changing diets, a reduction of population between the Current Trends and the sustainable pathways, and higher crop productivities (increased productivity leads to reduced land requirements to produce the same volume). This leads to an increase in the area where natural processes predominate: the area stops declining by 2025 and remains nearly constant (1% increase) between 2025 and 2050.

GHG emission pathways

Under the Current Trends pathway, annual GHG emissions from AFOLU increase to 235 Mt CO_2e/year in 2030, before reaching 219 Mt CO_2e/year in 2050 (Fig. 2). In 2050, methane produced by livestock is the largest source of emissions (35 Mt CO_2e/year) while forest regeneration acts as a sink (− 1 Mt CO_2e/year). Over the period 2020–2050, the strongest relative increase in GHG emissions is computed for livestock (47%) while a reduction is computed for deforestation (25%).

In comparison, the Sustainable Medium Ambition pathway leads to a reduction of AFOLU GHG emissions by 69% and the Sustainable High Ambition pathway to a reduction by 88% by 2050 compared to Current Trends (Fig. 2). The potential emissions reductions under the Sustainable Medium Ambition pathway is dominated by a reduction in GHG emissions from deforestation and livestock production. Agricultural expansion would not affect forests beyond 2030, and a lower population growth rate by 2050 and a healthier diet are the most important drivers of this reduction. Under the Sustainable High Ambition pathway, GHG emissions from agriculture (crops), and land-use change are further reduced thanks to a higher afforestation rate and a lower consumption of first-generation biofuels.

Food security pathways

Under the Current Trends pathway, compared to the average Minimum Dietary Energy Requirement (MDER) at the national level, our computed average calorie intake is 43% higher in 2030 and 57% higher in 2050 (Table 3). The current average intake is mostly satisfied by red meat, poultry, milk, eggs, roots and sugar, and animal products represent 21% of the total calorie intake. We estimate that the consumption of animal products and in particular milk will increase by 57% between 2020 and 2050. The consumption of red meat, poultry, and cereals will also increase while pulses, roots, and nuts consumption will decrease. As a result, 2050 consumption of red meat, poultry, eggs, sugar, roots, and milk is higher and consumption of pulses and nuts is lower than the EAT-Lancet recommendations (Willett et al. 2019) (Fig. 3). Moreover, fat intake per capita exceeds the dietary reference intake (DRI) in 2030 and 2050, while protein intake remains in the recommended range. This can be explained by high consumption of red meat, milk, pork, and poultry (Table 3).

Under the Sustainable Medium Ambition pathway, we assume that diets will transition towards higher consumption of pulses and vegetables in general. Similar assumptions are made under the Sustainable High Ambition pathway. The ratio of the computed average intake over the MDER

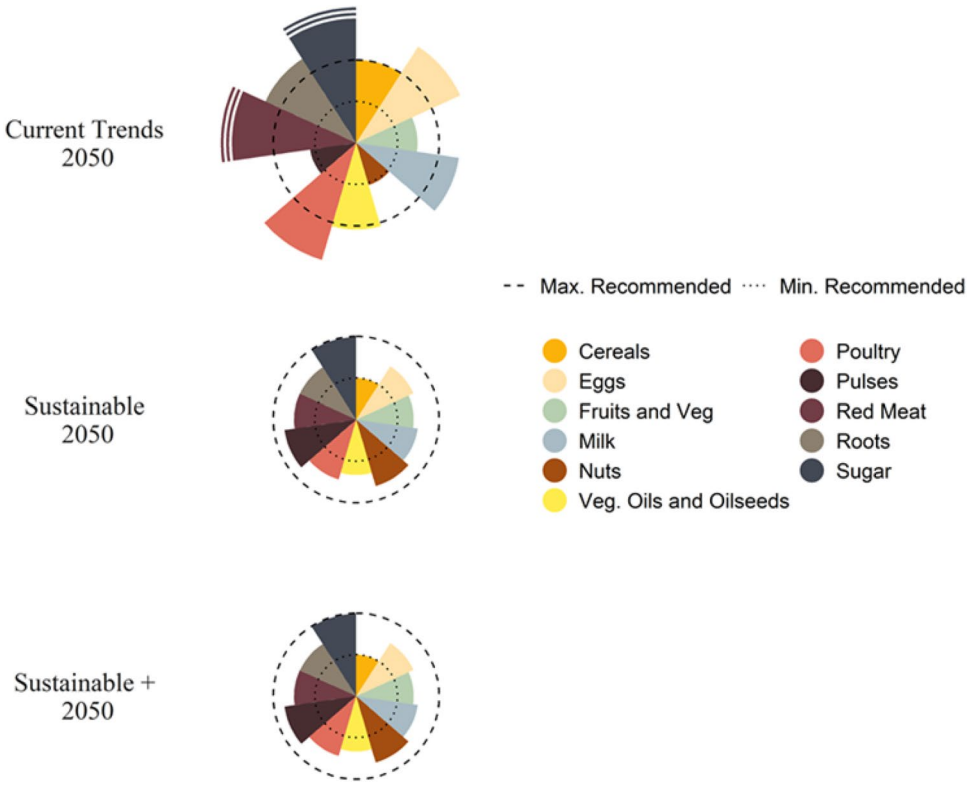


Fig. 3 Comparison of the computed daily average kilocalories intake per capita per food category across pathways in 2050 with the EAT-Lancet recommendations. Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e., the rings); therefore, the different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring and if it is higher, it is displayed on the maximum ring. The discontinuous lines that appear at the outer edge of sugar and red meat indicate that the average kilocalorie consumption of these food categories is significantly higher than the maximum recommended

decreases to 86% in 2030 and 70% in 2050 under the Sustainable pathways. Compared to the EAT-Lancet recommendations, only the consumption of animal fat remains outside of the recommended range with the consumption of pulses and nuts being now within the recommended range (Fig. 3). Moreover, the fat intake per capita will still exceed the dietary reference intake (DRI) in 2030, showing some improvement compared to the Current Trends pathway.

Self-sufficiency and commodity diversity

Under the Current Trends pathway, we project that Canada would be self-sufficient in cereals, oilseeds and vegetable oils, poultry meat, pulses, read meat (beef, goat and lamb), and roots and tubers in 2050, with self-sufficiency by product group increasing for the majority of products from 2010 to 2050 (Fig. 4). The product groups where the country depends the most on imports to satisfy internal consumption are beverages, spices and tobacco, fruits, and vegetables and this dependency will remain stable until 2050 given the lack of suitable growing conditions for many of these products within Canada. Under the Sustainable Medium Ambition and the Sustainable High Ambition pathways, Canada remains self-sufficient in the same eight product groups, but with higher self-sufficiency levels by 2050. This is explained by changes in volume of imports and exports, productivity, and change in diets.

Wheat and rapeseed were, by far, the main crop sown in 2010, followed by barley, soybeans, lentils, corn (for feed) and oats. Among these, rapeseed, wheat, barley, and soybeans are the main crops exported by Canada. According to the HHI Index, the planted crop area is moderately concentrated in 2010 as are exports.

Under the Current Trends pathway, we project medium concentration of crop exports and planted area, and low concentration of imports in 2050, trends which stabilize over the period 2010–2050. This indicates moderate levels of diversity across the national production system

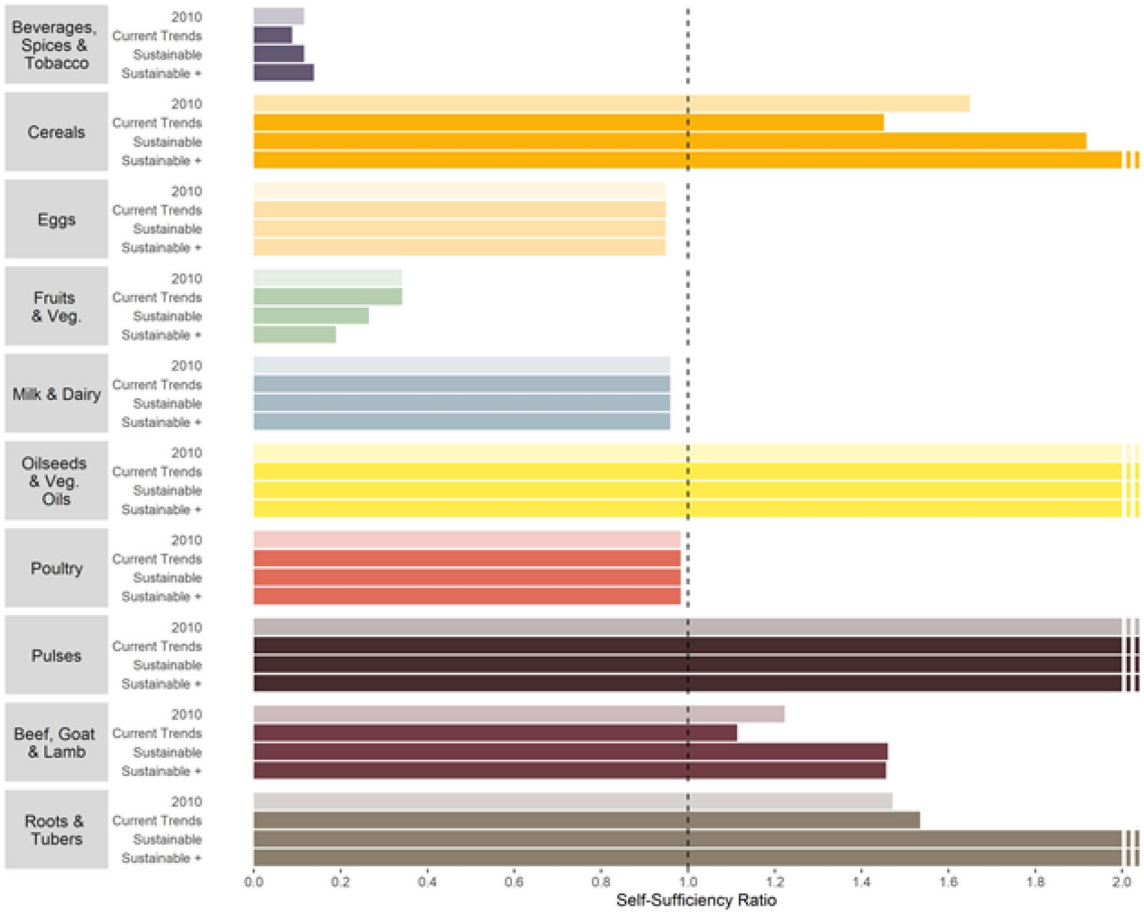


Fig. 4 Self-sufficiency per product group in 2010 and 2050. Notes. In this figure, self-sufficiency is expressed as the ratio of total internal demand over total internal production. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1. The discontinuous lines on the right side of this figure, as appear for cereals and oilseeds and vegetable oils, pulses, roots and tubers, indicate a high level of self-sufficiency in these categories

and exports. Under the Sustainable Medium Ambition pathway, we project a similar scenario, although a higher concentration of the planted area is possible, which is explained by a higher international demand of some specific crops from China and other important markets. Finally, under the Sustainable High Ambition pathway, we find medium and low concentration in exports and imports in 2050, respectively, indicating similar levels of diversity across the national production system as in the Current Trends pathway.

Discussion

The results above present three different land-use pathways out to 2030 (the timeline for the SDGs) and then beyond to 2050 for Canada. These result from country-level modeling coupled with results from global projections performed by 20 countries and "rest of continent" teams in the context of the FABLE initiative. These results come from the last joint-scenarios exercise, performed in 2020, and show possible futures based on what every country is projecting to produce, consume and trade (imports and exports) in the coming decades, adjusted by using partial equilibrium models, and their consequences on land use, as a result of different combinations of policies, demographic changes, social processes (diets, lifestyles, etc.), and climate change (FABLE 2020).

These pathways are driven by a set of assumptions around factors such as GDP and population growth, as well as scenario choices related to both dietary choices and land-use decisions (e.g., protected areas), and they are not intended to be precise nor comprehensive, as many aspects were not considered in our projections (pests, impacts on permafrost and wetlands, etc.). The main value of this global exercise is showing how different pathways of land use and food systems, built collectively by groups of experts worldwide, can impact on Canada's SDGs and climatic goals, and how

some measures can help (or not) to achieve more sustainable results.

Each of the pathways for Canada was assessed against metrics derived from three SDGs for health and nutrition, greenhouse gas emissions and biodiversity protection. In addition, the results show impacts on the resilience of Canada's agricultural system as measured by both self-sufficiency and diversity of crop production and markets.

Our results are consistent with prior work about the relevance of diets on achieving a more sustainable society (Macdiarmid et al. 2012; Eker et al. 2019). Diets are a key driver of land-use in the agricultural sector with spillover effects into other land uses and outcomes. A significant change in consumption is possible to achieve healthier diets and more sustainable land and food systems (Willett et al. 2019). Our findings are similar to Mora et al. (2020), who estimated a lower average calorie intake for the US–Canadian population when a healthy diet is projected, which would imply a higher demand for fruits, vegetables, and cereals (the first two food groups are mostly imported by Canada).

However, this is not only about energy content; it is also about food quality and environmental impacts. For Canada, a diet based on nuts, pulses, a higher consumption of fruits and vegetables, and a lower consumption of ultra-processed food and meat would reduce GHG emissions, and other negative impacts. Yet, it is important to clarify that there is not a single diet to recommend worldwide, as there is not enough agricultural land on the planet to supply these products to 8 billion people. Cultural and economic variations, and different local food sources should be taken into account to define country-specific (or even lower spatial scale) diets that can compatibilize people's health (healthier meals) and lower social and environmental impacts in the context of climate change (Rizvi et al. 2018).

Moreover, the population scenarios vary by about 10 million people by 2050 (50 million under the Current Trends vs. 40 million for the sustainable scenarios). This population is highly concentrated along the US border, which means significant areas of the country have not been extensively industrialized or urbanized. The lack of access to large territories has already created de facto protected areas, especially in the boreal forest (between 50 and 80% of the total area) (Andrew et al. 2012). This could allow Canada to reach the 30% goal suggested by the UN Convention on Biological Diversity, which is being suggested by the House of Commons, who recommended "*more ambitious targets for protected areas than those established in the Aichi Target 11"* (Schulte 2017).

However, new policies around protected areas and further analysis within the context of FABLE need to account for Indigenous land rights over much of the territory that would be considered for protection. Whether formal protected areas administered outside Indigenous governance regimes are either feasible or even desirable requires careful consideration, as Canada engages in processes of reconciliation and decolonization, including implementing the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) (Wong et al. 2020). In this context, reaching conservation goals should be part of a wider conversation inside Canadian society that also includes reconciliation and recognition of land rights (Zurba et al. 2019).

Population growth along with levels of types of consumption (e.g., diets) are key factors because they determine the size of the economy, and the resulting pressure on food and land systems, energy consumption, and natural resources depletion. Diet and lifestyles (sedentarism and other unhealthy behaviors) determine land-use outcomes as it can be clearly seen in modeling results. A high consumption of red meat, pork, and ultra-processed food significantly increases Canada's GHG emissions and is related to a higher share of wasted food (throughout the distribution supply chain), which has been also highlighted by other authors (Government of Canada, Environment and Climate Change Canada, Waste Reduction and Management Division 2019; Fardet and Rock 2020; Auclair and Burgos 2021).

According to Molotoks et al. (2021), Canada's low to moderate population growth and higher crop yields due to climate change would imply undernourishment will not be an issue in the future, unlike most of the countries worldwide where food systems will be highly stressed because of overpopulation and the negative consequences of environmental degradation. In this context, Canada's relevance as a global food supplier could significantly increase, which would have geopolitical consequences for the country in the future (larger immigration pressure, higher political influence, among others).

In provinces where agriculture is concentrated—Alberta, Saskatchewan, Manitoba, and Ontario—and continuously expanding, agricultural productivity could temporarily improve under climate change through a longer growing season due to better environmental conditions (Qian et al. 2010, 2016), but gains could be offset by climate related stresses (e.g., wildfire risk, droughts) that were not modeled as of yet (Asong et al. 2018). Increasing crop productivity is also important to reduce the impacts of agriculture. Harvesting more tons per hectare has a key role in reducing GHG emissions and agricultural expansion. Here is where improved crop genetics and better management practices can significantly contribute to increase agriculture's performance and reduce uncertainty (Abberton et al. 2016; Bailey-Serres et al. 2019; Bevan et al. 2017; Carpenter 2010; Rivers et al. 2015).

Our results also show that forests have a key role in reducing greenhouse gas emissions, protecting biodiversity, and preserving fresh water supply. From this perspective, preventing agricultural expansion into forest areas through deforestation bans beyond 2030 could have a significant

impact on Canada's contribution to climate change mitigation (Prestele et al. 2016).

Also, developing a national afforestation program, as the Bonn Challenge has recommended, would be a good complement for a higher protection of Canadian ecoregions. Some initiatives, like the Caribou Habitat Restoration Project, Afforestation Ontario, and the National Greening Program, are already promoting afforestation on private and public lands as a way to recover ecosystem services (Government of Ontario 2017; Habitat Conservation Trust Foundation 2020; MacDonald et al. 2020; Mansuy et al. 2020).

Canada's varied ecological zones suitable for different resources and small population imply high levels of per-capita natural resources availability (fisheries, agricultural lands, forests, etc.). Canada can be self-sufficient in a number of commodities, such as cereals, fish, red meat, many vegetables, and other food groups, at least in terms of availability (as affordability, and other aspects were not considered in this assessment), as well as in timber, energy, water and other goods and services. However, the high import dependency of Canada on fresh fruits and vegetables, mainly from the US, can become a barrier to sustain healthier diets, especially in the context of global crises like COVID-19 (Richards and Rickard 2020). At the same time, it should be noted that while production of several commodities can exceed their internal demand, for many of them there is a two-way trade such that Canada both exports and imports within the same category of goods. This is, in part to deal with seasonal production, which also has to be taken into account as part of Canadian vulnerability. Additionally, the fact that most of the harvesting depends on temporary-foreign workers increases the exposure of Canada's land and food systems to external/global crises (Weiler et al. 2017).

The COVID-19 crisis exposed the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems (Rivera-Ferre et al. 2021). We examined two indicators to gauge Canada's resilience to agricultural-trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade. Canadian agricultural production is moderately concentrated in a group of crops: rapeseed, wheat, barley, soybeans, and lentils. This concentration implies some risks for Canada, as any disease infestation, abiotic stress, and negative environmental event affecting these five crops could produce significant impacts on the SDGs and beyond (Ijaz et al. 2019).

Moreover, international trade is another key driver related to the use of ecosystems. The Canadian internal market for agricultural products is small compared to the country's productive capacity and much of Canada's production is oriented towards the international market, especially the U.S. and China. This implies a high level of economic dependency and vulnerability, which has been evident in the past cases of political tension between Canada and its trade partners (Bratt 2021; Georges 2017). Diversifying agricultural production and the number of trade partners would allow for potentially greater resilience and independence in Canada's policy development around climate change, land use and environmental and social sustainability.

Conclusions

By comparing three different pathways (Current Trends, Sustainable Medium Ambition, and Sustainable High Ambition scenarios), we assessed the effect that changes on population, GDP, agricultural production, international trade, and diet would have on Canada's greenhouse gas emissions, biodiversity, and resilience of the food and land systems. This paper demonstrates the potential impact that different policies could have for increasing Canada's contribution to climate change mitigation, biodiversity conservation and solving other global challenges as laid out in the Sustainable Development Goals and other international initiatives.

There are some areas of limitation that are the basis of future work on the model. First, Canada has a supply management system in place for some agricultural products. This still needs to be incorporated into the model as a constraint on production. Second, the model does not represent wetlands as well as it should and improvements need to be made to better account for the impact of wetlands and wetlands area changes on outcomes. Third, the FABLE Calculator was developed in such a way that the initial focus was on agricultural production. Forests are primarily impacted by changes in agricultural land, decisions around protected areas, and decisions around afforestation/deforestation. Forest products and forest production are not as well represented. The Canada team has been developing a Forest Products Module for the calculator and, when completed, it will be available to all of the country teams.

Despite these limitations, the analysis demonstrates how policies could contribute to improved sustainability in Canada's land-use sectors, by reducing GHG emissions, biodiversity loss, and other negative environmental impacts by: banning deforestation beyond 2030; promoting afforestation for carbon sequestration and biodiversity conservation in the context of initiatives like the Bonn Challenge (IUCN 2015); increasing protected areas (Aichi Biodiversity Targets and beyond), especially in less protected ecoregions, and considering a broader range of conservation tools, including other effective area-based conservation measures (OEABCMs) (MacKinnon et al. 2015); sowing higher productivity crops

and improving livestock genetics and pastures productivity; improving Canadians' diet according to the EAT-Lancet Commission (Willett et al. 2019); and increasing the use of zero-emission vehicles instead of crop-based biofuels. These measures could be particularly important when considering options for NDC enhancement.

However, it is not clear that even by implementing these measures, Canada will be able to fulfill its long-term goals (LT-LEDS) and other international commitments (Environment and Climate Change Canada 2016). Our projections show similar results as other works (Mora et al. 2020), in terms of how important people's diets and lifestyles can become to reduce negative environmental impacts (land use and GHG emissions). From this perspective, even if the Canadian government does its job by promoting these policies, the effect will only be seen if the population actually responds by reducing consumption of animal protein and ultra-processed foods, and engaging in other critical behaviors. At the same time, it is necessary to recognize, as with the larger question of pro-environmental behavior, that individual choices are constrained by larger systems that impact factors such as what foods are available and at what price. These in turn are not only impacted by the Government's policies (as noted above) but also by corporate actors that make investment and purchasing decisions as well as investments in influencing policy. This represents a huge challenge for the Canadian society as a whole.

Finally, we recognize that this analysis was conducted within the context of a dominant economic paradigm that assumes continued economic growth and then views sustainability from the lens of how to reduce future demand and meet that demand with the least impact. Therefore, our sustainability scenarios are largely based on some changes in demand (e.g., diets) and more intensive production (e.g., crop yields) with a continued reliance on global markets for both imports and exports. However, there may be other approaches to sustainability worth analyzing, which could arise from a deeper knowledge about what sustainability means for Canadians.

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