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Expansion of Agriculture in Northern Cold-Climate Regions: A Cross-Sectoral Perspective on Opportunities and Challenges

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Agriculture in the boreal and Arctic regions is perceived as marginal, low intensity and inadequate to satisfy the needs of local communities, but another perspective is that northern agriculture has untapped potential to increase the local supply of food and even contribute to the global food system. Policies across northern jurisdictions target the expansion and intensification of agriculture, contextualized for the diverse social settings and market foci in the north. However, the rapid pace of climate change means that traditional methods of adapting cropping systems and developing infrastructure and regulations for this region cannot keep up with climate change impacts. Moreover, the anticipated conversion of northern cold-climate natural lands to agriculture risks a loss of up to 76% of the carbon stored in vegetation and soils, leading to further environmental impacts. The sustainable development of northern agriculture requires local solutions supported by locally relevant policies. There is an obvious need for the rapid development of a transdisciplinary, cross-jurisdictional, long-term knowledge development, and dissemination program to best serve food needs and an agricultural economy in the boreal and Arctic regions while minimizing the risks to global climate, northern ecosystems and communities.

Keywords: boreal agriculture, Arctic agriculture, crops and agricultural practices, northern soils, policies for agriculture expansion, land-use conversion, social and cultural drivers

INTRODUCTION

Global warming has serious consequences for provision of goods and services from all ecosystems, and will affect social and economic sectors, including agriculture (Ray et al., 2019). In the cold-climate boreal and Arctic regions, herein referred to as northern regions (King et al., 2018), climate change is occurring at a historically unprecedented rate (Bush and Lemmen, 2019) substantially affecting regional land use and the interlinked socio-economic conditions for the 0.2 billion people currently living in northern countries (data.worldbank.org/).

Extended growing seasons allows for expansion of agriculture, introduction of crops historically cultivated in warmer regions, and crop diversification (Wiréhn, 2018). Following the assumptions of Cassidy et al. (2013) converting 10–20% of the northern areas potentially suitable for agriculture by 2100 (King et al., 2018) might feed 0.25 to 1 billion people, compensating for estimated reductions of food output in the Earth's most productive regions (Asseng et al., 2015). Thus, northern agriculture could become a net contributor to global food security.

Beside the global relevance, a primary driving force behind the growth of northern agriculture are policies designed to improve local food security and self-sufficiency in the short- to medium-term through crop diversification and adaptation. Finland, Sweden, and Denmark support agricultural intensification through the development of resilient farming systems and food value chains that consider changing dietary preferences and impact of land use and land use changes (LULUC) on biogeochemical cycles. Meanwhile, in the Canadian prairies and Mongolia, legislation favors the northward areal expansion of commercial agriculture, even in the absence of explicit policies or strong local population pressures. This creates opportunities for direct integration of new northern agricultural production in the global agricultural commodity markets. Given the potential for positive feedback loops in the global carbon cycles, consistent consistent agro-environmental policy goals regarding agricultural intensification and expansion (e.g., variable LULUC), are necessary.

This perspective addresses key issues associated with expansion and intensification of agriculture in northern regions, focusing on crop production, including forage, socio-economic frameworks and relevant policies. We highlight the context and consequences of agricultural expansion into the northern regions and identify scope, needs, and directions of integrated policies to support multi-disciplinary research and development for minimizing undesirable outcomes for local populations and ecosystems.

GEOECOLOGICAL CHANGES INDUCED BY CLIMATE CHANGE AFFECTING NORTHERN AGRICULTURE

By year 2100 the northern margin of the agricultural climate could shift further northwards by an average of 500 km, but as much as 1,200 km (King et al., 2018) (**Figure 1F**) overcoming the capacity of the boreal forest-tundra ecotone to shift northwards, estimated at 30–40 km per century (Evans and Brown, 2017) (**Figure 1G**). Boreal forests represent one third (12 million km^2) of the world's forests (Keith et al., 2009), storing 32% (272 $\pm$ 23 Pg) of the world's carbon forest stock (Pan et al., 2011) of which, soils store 163–254 Pg (Duarte-Guardia et al., 2020). Climate change (CC) and conversion to agriculture (**Figures 1A,B**) may turn them into net-emitters of greenhouse gases (GHG).

While increasing atmospheric CO_2 concentrations promotes net primary productivity (Mekonnen et al., 2018), such gains are likely ephemeral as accelerated growth may overcome the soil's capacity to deliver nutrients, especially nitrogen (Hungate et al., 2003). Moreover, northern climatic change is non-linear, generating regional differences in its extent and pace, causing precipitation patterns to vary in space and time (King et al., 2018). Increasing occurrence of extreme events will affect plant performance, crop production and the agro-ecosystems' capacity to deliver ecosystem services (IPCC, 2018). Inner continental regions may experience droughts (King et al., 2018), favoring grassland at the expense of boreal forest (Davis and Shaw, 2001). Warmer and drier conditions reduce vitality of plants and increase their vulnerability to pests and diseases (Wiréhn, 2018). Conversely, narrow peri-oceanic northern regions might experience increased precipitations late into the season (King et al., 2018) affecting disease burden and impeding fall agricultural activities (Wiréhn, 2018).

GEOECOLOGICAL CHANGES INDUCED BY EXPANDING AND INTENSIFIED AGRICULTURE

Soils of the northern regions reflect the climates under which they evolved, making them unique in terms of utility and adaptation for agriculture (Jenny, 1941): common northern soils (FAO System of Soil Classification) are Podzols, Retisols, Cambisols, Histosols, Cryosols, and Andosols (Driessen et al., 2001). Converting these pristine soils to agriculture alter their properties affecting soil stability, increasing risks of soil erosion, accelerating GHG emission and loss of nutrients (FAO and ITPS, 2015). Evidently, agricultural expansion and intensification of

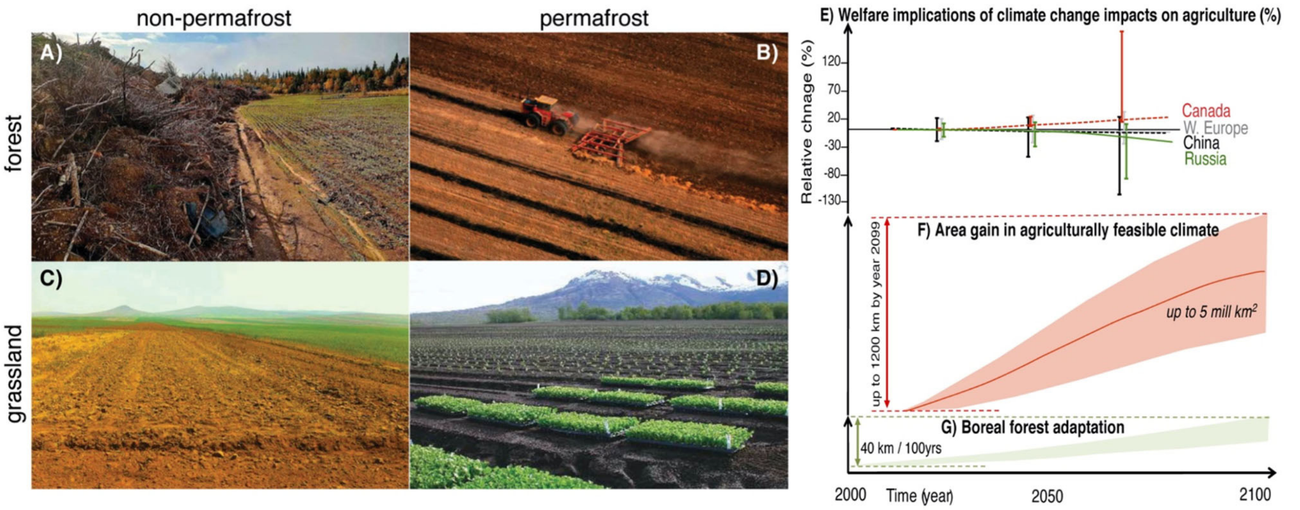

FIGURE 1 | Policies on agricultural land use and land use change in the northern regions respond to complex climatic, economic and societal circumstances. Shifts in land use to agriculture occur by converting boreal forests either on non-permafrost or permafrost lands or conversion of grasslands in regions contiguous to permafrost or on permafrost: **(A)** removal of boreal forest biomass and topsoil in Newfoundland, Canada, **(B)** former boreal forest, currently a tilled field, Alaska, USA, **(C)** large-scale plowing under of grassland, Mongolia, and **(D)** vegetables grown on former grasslands above permafrost, Alaska, USA; **(E)** The economic welfare implications of agriculture in the northern countries depend on a combination of agricultural productivity, market conditions, and export capacity/readiness of a particular region. The graphic summarizes the most likely relative change and the range of changes in economic welfare due to agriculture (adapted after Moore et al., 2017); **(F)** Climate change is expected to lead to an expansion of agriculturally feasible climate over an area of up to 5 million km^2 by the end of the twenty-first century, with linear northward shifts of up to 1,200 km (King et al., 2018); **(G)** At the same time, the estimated nortward shift of the boreal forest under climatic changes is limited to about 40 km over a century, significantly slower than the shift in climate (Davis and Shaw, 2001) **(G)**. All photographs by the authors (AU, MZ, AS).

agriculture reduces habitat and biodiversity, which reduces the ecosystems capacity to deliver ecosystem services (Cochran et al., 2013; Emmerson et al., 2016).

Conversion of northern lands to agriculture (**Figures 1A–D**) leads to rapid loss of carbon stored in biomass and accelerated mineralization of organic carbon from the upper 1 m of soil (Duarte-Guardia et al., 2020), as evident for the agricultural regions developed in the last 10,000 years (Sanderman et al., 2017). Notably, temperature-driven gains in net primary production cannot compensate for accelerated decomposition of soil organic carbon, diminishing the net sequestration of carbon of boreal regions (Lim et al., 2019). Northern peatlands store most of northern soils' carbon (Leifeld et al., 2019) and their capacity to sequester atmospheric CO_2 is partly due to the cold and poor drainage conditions.

Anthropogenic drainage drastically accelerates mineralization of peatland carbon from almost zero to 7.9 t CO_2-carbon ha^{-1} yr^{-1} (IPCC, 2014) turning carbon sinks into carbon sources. Only about 2% of the boreal peatlands are currently drained and farmed as croplands (Leifeld and Menichetti, 2018). Agricultural expansion into the vast peatlands of Asia (Minayeva et al., 2017) and North America (Vitt, 2016) would dramatically impact ecosystem structure with consequences felt globally (Leifeld et al., 2019). Farming above permafrost, and especially farming in the wake of permafrost melting, has been shown as possible and is predicted for Alaska and Siberia (Tchebakova et al., 2011), with predicted losses of carbon and land instability (Stevenson et al., 2014a,b) but, given the yet limited acreage, with long-term effects that still have to be fully quantified.

Soils also lose carbon as dissolved organic matter, which together with nutrients is more easily leached from agricultural plots than from natural lands. Farmlands converted from boreal forests are thus depleted in organic carbon and nutrients (Duarte-Guardia et al., 2020). When northern grasslands are cultivated (**Figures 1C,D**), the stores of historically accumulated soil organic carbon decompose rapidly leading to high nitrogen mineralization rates. This transient boost in soil fertility also favors leaching of dissolved nitrogen and the emission of nitrous oxide, a potent GHG (Grünzweig et al., 2004).

Given these considerable impacts of LULUC on the unique and diverse northern soils, the success of expanded and intensified agriculture in the northern regions will be strongly dependent on adapting land use, soil management (IPBES, 2019) and the protection of the critical carbon stock of intact peatlands (Leifeld et al., 2019). Specifically, conversion of boreal forests and grasslands dominated by low-fertility Podzols, a common target of land use conversion (LUC), requires long-term, intensive management to sustain soil fertility and health (Hutchinson, 1968). Podzols, mainly sandy soils with low water-holding capacity, are susceptible to aluminum and manganese toxicities due to their low pH (Sauer et al., 2007). Additionally, fertilizers and pesticides, typically required for intensive agriculture, may have serious consequences on ecosystem resilience (Balmer et al., 2019).

INDUCED ALTERATION OF LOCAL CROPPING SYSTEMS

Under the exceptionally rapid warming of northern regions, temperate crops and cold adapted varieties of crops from temperate or tropical climates, such as maize (*Zea mays* L.), are projected to shift further north (Cho and Mccarl, 2017; Bunge, 2018; Manners and Van Etten, 2018). Warmer nights accelerate plant metabolism without a concurrent capture of solar radiation, reducing grain yield and quality (García et al., 2015; Gol et al., 2017). A 2001 assessment concluded that soybean production [*Glycine max* L. (Merr.)] was not feasible in Newfoundland, Canada (Spaner et al., 2001), yet by 2018 the local government was promoting soybean as an "excellent" rotation crop (Tingskou, 2018). Barley (*Hordeum vulgare* L.) production in Alaska peaked at 7 Gg in 2017. In Iceland the median barley yields fluctuate around 3.2 Mg ha^{-1} (Hilmarsson et al., 2017), after being virtually non-existent before 1995. By 2100 wheat (*Triticum aestivum* L.) yield is predicted to increase by >50%, in northern regions matching a decrease in the southern regions (Asseng et al., 2015; Chenu et al., 2017). Evidence is mounting that crop diversity and agricultural management (e.g., sowing and harvest time) in northern regions will change further, requiring varieties adapted to northern photoperiods and increased mean temperatures (Nikolaeva and Desyatkin, 2015).

Changing precipitation patterns also favor shift of crops: in Alberta, Canada increased droughts will induce northward shift of barley (Masud et al., 2018) while agricultural expansion into northern Russia will compensate for drought-related declines in cereal productivity in the southern regions (Belyaeva and Bokusheva, 2018). More frequent winter and spring freeze-thaw events will increase greenhouse gas emissions and affect crop health (Christensen et al., 2016). Increased risks of emerging pests and diseases coincide with weather extremes (IPCC, 2018) and alteration of seasonal weather patterns. These risks already manifest as declines in crop resilience and increased reliance on insecticides (Wiréhn, 2018; Kahiluoto et al., 2019). Meta-analyses of European wheat yields for 2002–2009 revealed that breeding programs and cultivar selection practices are ill-prepared for climatic uncertainty and variability (Kahiluoto et al., 2019).

Crops adapted to changed conditions must be developed, preferably based on local varieties and/or wild relatives resilient to site-specific climatic extremes typical of northern regions; this requires access and maintenance of seed banks. An analysis of Nordic wild plant species closely related to crops and thus with traits of potential value for food security and climate change adaptation includes an ever growing list of wild species related to food crop groups such as in decreasing order of their abundance: forages, fruits and berries, spices, nuts, and cereals (Fitzgerald et al., 2019; Palmé et al., 2019). Broad-based cultivar evaluation trials are necessary to increase the probability of adaptation by current agricultural crops, including forage crops, and new varieties to northern regions (Schlautman et al., 2018).

EXPECTED ALTERATION OF SOCIO-ECONOMIC CONDITIONS

Climate change-driven changes in the economic welfare associated with agriculture, drivers for expanding agricultural activities, depend on a combination of agricultural productivity, market conditions and export capacity/readiness of a region (Moore et al., 2017) (**Figure 1E**). Historically, expansion of agrarian practices into northern communities led to a loss of traditional food supply practices, environmental degradation, and to reliance on costly imported food (Spiegelaar and Tsuji, 2013). While perceived or actual decreases in global agricultural productivity support decisions to expand northern farmland and intensify production, perceived new market opportunities may also support expansion and intensification policies. However, intensification on current farmlands, proposed for increasing food production (Hohle et al., 2016), is limited in scope: e.g., only 34% of European farmlands, most of them in Eastern and Southern Europe, may be amenable to sustainable intensification (Scherer et al., 2018). Moreover, greater yields through intensification do not necessarily preclude further conversion of land to farmlands (Ewers et al., 2009). As larger farms tend to be financially more efficient, farm sizes increase (Statistics Canada, 2017; Eurostat, 2019), especially at the shifting interface between the intensely cropped temperate regions and adjacent boreal agroecosystems (Hobson et al., 2002).

In this context, there are notable political ambitions to increase self-sufficiency of regions that currently import most of their food, such as Alaska, Greenland, or Newfoundland (**Figure 2**). For historical and cultural reasons northern regions generally lack markets for high value field crops since traditional food often integrates wild food and livestock (Huntington and Fox, 2005). While there are examples of specialist northern food exports (e.g., meat, mushrooms, berries), the contribution of northern agriculture to global commodity markets is not yet readily apparent, especially when its expansion occurs adjacent to current production regions (ESTR Secretariat, 2014). Current production levels in many northern regions are limited to the demands of relatively small local populations, reflected in the local agri-food value chains (Stevenson et al., 2014a). The adoption rate of new, climate-adapted cropping systems is limited by available physical and technical infrastructure, and financial resources that can support an expanding agricultural sector (Freshwater, 2017). Private industry is often fiscally better situated to invest in infrastructure for agricultural expansion. This has been observed in Québec, Canada (Québec Secrétariat Au Plan Nord, 2015), where industry, rather than local populations, is initiating most agricultural expansion. In Manitoba, Canada private investment led to a five-fold increase of soybean acreage between 2009 and 2018 (Manitoba Agricultural Services Corporation, 2019). Examples from Russia illustrate that inadequacies of infrastructure limit northern regions' contributions to regional and national food security and sufficiency (Swinnen et al., 2017; Belyaeva and Bokusheva, 2018).

Discontinuously inhabited regions far from the current agricultural regions may be pressured to adopt farming systems

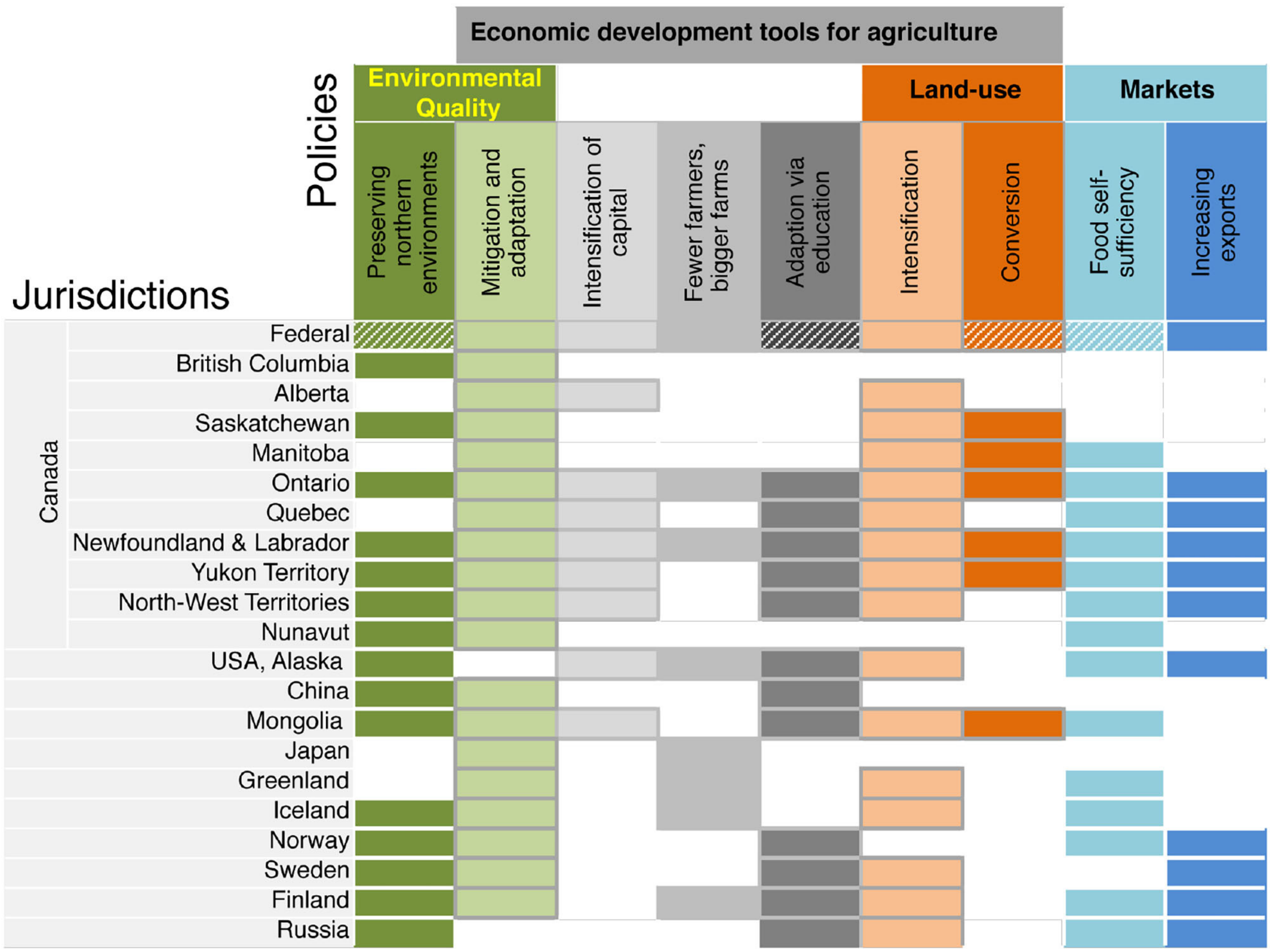

FIGURE 2 | Trends and agricultural policy preparedness for northern climatic shifts (Government of Sweden, 1993; Government of Saskatchewan, 1999, 2018, 2019; Tsogtbaatar, 2002; Ott, 2005; Yang et al., 2007; Government of the Russian Federation, 2009, 2018a,b, 2019; Deng et al., 2010; Gouvernement Du Québec, 2010, 2018, 2019; Government of Norway, 2010, 2017; Manitoba Agricultural Services Corporation, 2010, 2019; Ahern et al., 2011; Government Offices of Sweden, 2011, 2015; Government of Nunavut, 2011; Government of Ontario, 2011, 2016, 2018a,b; Government of Yukon, 2012, 2016, 2018a,b; Hammond et al., 2013; The Conservation of Arctic Flora and Fauna, 2013; Alaska Farm Bureau, 2014; ESTR Secretariat, 2014; Forbord et al., 2014; Government of Finland, 2014a,b, 2015, 2019; Nunavut Food Security Coalition, 2014; Stevenson et al., 2014c; United States Department of Agriculture, 2014, 2019; Government of Japan, 2015, 2018; Government of British Columbia, 2016, 2019; Government of Iceland, 2016, 2018; Government of Northwest Territories, 2016, 2018, 2019; Hohle et al., 2016; Naalakkersuisut (Government of Greenland), 2016, 2018; Parliament of Mongolia, 2016; Research Department of Arion Bank, 2016; State Council of the People's Republic of China, 2016; State Great Khural of Mongolia, 2016; Statistics Canada, 2016, 2017; Agriculture and Agri-Food Canada, 2017, 2019; Chuluunbaatar et al., 2017; Government of Alberta, 2017, 2018; Government of Manitoba, 2017a,b,c,d; Government of Newfoundland and Labrador, 2017a,b,c,d,e, 2018a,b; Lehmann et al., 2017; Luke Finland, 2017; Research Northwest and Hershfield, 2017; Schou et al., 2017; Government of Canada, 2018; National Research Council of Canada, 2018; Niemi and Väre, 2018, 2019; Government of Alaska, 2019; Hokkaido Agricultural Administration Department, 2019; Manitoba Agriculture and Resource Development, 2019; National Statistics Office of Mongolia, 2019).

that will shift the local practices away from traditional or indigenous food production affecting labor structure. Labor involvement in agriculture varies: <5% of the population in the Scandinavian countries or Canada (Government of Ontario, 2011; The World Bank Group, 2019) is employed directly in agriculture; conversely, in Russia agriculture employs >50% of the population in Yamalo-Nenets and Nenets autonomous regions or Yakutia (Forbes et al., 2009).

We must note that given the vital role that land plays for sustainable economic development of northern Indigenous peoples, the impact of Indigenous land claims, and the particularities of the fragmented land tenure in the North (OECD, 2020), are unfortunately not unequivocally discernible in agricultural policies targeting northern expansion. This is a necessary discussion, that requires a detailed assessment, as any agricultural development requires clear integration of Indigenous peoples' rights to decide on the ways land is managed.

While CC impacts on traditional economies (e.g., reindeer herding) are acknowledged (Kelman and Næss, 2013), factors affecting local human migration have rarely been implemented into socio-economic population projections and models considering also increasing costs of agricultural land (Smas, 2018; FCC, 2021), hampering long-term infrastructure planning. Currently, northern population size is relatively stable, with urbanization increasing, albeit slower than elsewhere (Smas, 2018). However, food security concerns in new and expanded settlements support increasingly localized production around these urban clusters in Russia (Ivanov and Lazhentsev, 2015). Long distances limiting efficient distribution of commodities in North America lead to increased interest in local agriculture (Stevenson et al., 2014a). Moreover, changing food preferences in urbanized northern pockets increase and diversify local demand for food production, favoring high cash-value crops readily marketable by small farms (Government of Newfoundland and Labrador, 2017d). Consequently, northern expansion of agriculture cannot be attributed to notable population shifts. Regulatory support for new agricultural activities mostly targets increasing local food supply in remote communities (**Figure 2**). Climate driven migration into the northern regions is rarely considered in models (Mulligan et al., 2014), yet this knowledge is crucial for anticipatory policies that consider both the migration driven by socio-economic factors and that driven by CC (Missirian and Schlenker, 2017).

CURRENT POLICIES ADDRESSING CLIMATE CHANGE AND AGRICULTURE

Figure 2 summarizes the scope of extant policy types, to the best knowledge of all authors. Policies supporting northern expansion and intensification of agriculture address the improvement of food security, self-sufficiency and quality, and support agricultural development and economic diversification (Ivanov and Lazhentsev, 2015; Government of Northwest Territories, 2016; Government of Yukon, 2016; Government of Newfoundland and Labrador, 2017d; Hamilton, 2017). Northern regional governments view the increasingly favorable growing conditions as an opportunity to encourage agricultural growth (**Figure 2**). Some policies support conversion of boreal forests into cropland (**Figure 2**), while other focus on sustainable intensification through adaptation where expansion is anticipated or occurring (Hohle et al., 2016). For example, Siberia, described as a dormant breadbasket, is currently at ≤50% of its estimated production potential achievable by various means including recovering abandoned, former agricultural lands (Swinnen et al., 2017). While sustainable intensification aims to mitigate environmental impacts (Burney et al., 2010), expansion (**Figures 1A–D**) and intensification, focused principally on opportunities for production, can nevertheless result in inadequately quantified externalities (Balmford et al., 2018).

Divergent effects of CC on agricultural regions (Moore et al., 2017) are likely reflected as varied regional decision-making and policies (**Figure 2**). Additionally, though not exclusive to agriculture, northern countries have agreed to participate in the 2015 Paris Agreement (UN Framework Convention on Climate Change, 2015) to mitigate CC and limit global warming by 2100. Denmark signed but with territorial exclusion in respect of Greenland. However, policies related to boreal and Arctic expansion of agriculture necessitating conversion of northern ecosystems remain unique to jurisdictions fully located within these ecosystems. Notably, policies in Canada, Greenland, Iceland, Mongolia and USA support agricultural expansion (**Figure 2**), including financial support to enhance agricultural productivity in support of economic diversification (Landbrugskommissionen, 2014; Stevenson et al., 2014a; National Statistics Office of Mongolia, 2019), including conversion of natural areas to agriculture (Government of Newfoundland and Labrador, 2017c) while addressing local and global environmental concerns (Agriculture and Agri-Food Canada, 2015). Conversely, Chinese scientists are focusing on adapting cropping systems to a changing climate, including growth of irrigated agriculture, instead of expansion for which there is limited geographic scope (Yang et al., 2007). Russia established a program dedicated to maintaining former agricultural soils by minimizing nutrient leaching and secondary fallowing of arable lands to avoid natural re-initialization of podsolization and reversion of lands to forest (Government of the Russian Federation, 2009). Agricultural policies in Finland and Sweden follow the European Union's Common Agricultural Policy (CAP) (Swinbank, 2011). CAP promotes agricultural productivity and rural development while supporting agroecological practices, including organic farming, and ensuring that agricultural products are available to consumers (European Union Parliament, 2013). However, national interests and supporting policies may differ: in Finland the national objectives are founded on the view that permanent competitive disadvantage due to natural changes must be compensated to maintain self-sufficiency in nutritional food and to preserve production (Niemi and Väre, 2018). With limited suitable land, the Norwegian government prioritizes sustainable intensification (Hohle et al., 2016). Sweden is prepared to liberalize EU agricultural policy, by reducing aid and making agriculture more market-oriented (Government Offices of Sweden, 2017). In this diverse and regionalized policy context, small farms accessing newly available northern agricultural lands might drive the initial expansion of agriculture, but the global trend of fewer and larger farms cannot be dissociated from northern agricultural expansion and adaptation (Hobson et al., 2002; Forbord et al., 2014).

Obviously, urban-centric policies created in southern regions are inappropriate without consideration for the particularities of northern communities (Freshwater, 2017). The mismatch is exacerbated if industry directed agricultural expansion fails to incorporate local practices that require intentional incentives and policies; local knowledge systems better adapted to the regional environment can be more suitable for meeting values identified by local populations. Instead, it is argued that northern farmers often focus on regulations, administrative activities, and global market prices, rather than adaptation (Neset et al., 2019). Hence, policy makers in northern regions must understand the full context of these new opportunities and challenges to foster support for farmers, access to infrastructure and assistance with adaptation (Stevenson et al., 2014b).

IMPLICATIONS FOR FUTURE RESEARCH AND POLICIES

Climate change is predicted to accelerate socio-economic changes that drive northern LULUC following similar historical trends in the temperate regions (Cassidy et al., 2013; Ostberg et al., 2015). The greatest challenge is the careful consideration of all options for minimizing the divergence between the goals of mitigating CC, protecting nature, reversing degradation of ecosystems, and accounting for diversity in agricultural systems while addressing local food needs, and commoditizing production. Development and implementation of integrative policies considering multiple scopes, needs, and directions required to ensure a sustainable development of northern agri-food systems must consider that:

1) The scope of direct interventions is defined in space and time by the (i) northern geographical areal presently and potentially available for agriculture, and (ii) by the speed at which CC impacts LULUC. Major challenges for advancing research and policies are, (i) heterogeneity in socio-economic and environmental conditions between and within regions (e.g., between Finnoscandia, Canadian prairies or Russia, or between Canadian provinces and territories), (ii) growing urban populations, and (iii) fragmented research support systems, development models and policies focusing on regional and local concerns and opportunities while neglecting global challenges.
2) Cross-sectoral needs create both challenges and opportunities. Critical knowledge gaps exist concerning if and how northern regions can incorporate, adapt or develop practices as the acknowledged northward shift of the agricultural zone allows agricultural expansion, intensification and diversification. Therefore, multi-fold challenges and opportunities for the agricultural sector must account for divergences between sustainable development goals addressing food security/self-sufficiency, mitigating CC and preserving biodiversity, particularly addressing effects of CC and LUC on carbon, nutrient and water cycles, while addressing negative (e.g., drought risk, diseases) and positive (e.g., crop diversification) impacts on agricultural production, through designing and testing agricultural practices for sustainability. These require research capacities and site-specific, long-term agricultural experiments, currently scarce in the northern regions (Sandén et al., 2018). Accounting for the multi-sectoral nature of the agri-food sector requires multi-disciplinary research and development along the entire agri-food value chains.

Development toward sustainable and resilient northern agri-food systems must avoid repeating the failures of agricultural practices in temperate and tropical regions that prioritize production over nature. Wherever northern agricultural expansion is considered necessary, development ought to guarantee the adoption of locally adapted plant varieties, sustainable agro-ecological and soil management practices. This includes developing science based, adaptable policies balancing growth opportunities of an expanding and intensified agriculture with local, regional and global food security goals. An example is the possibility for conversion of marginal lands naturally low in organic matter to promote net carbon fixation for carbon trading (Burney et al., 2010; Morgan et al., 2015; Hohle et al., 2016) while producing agricultural products (Purola et al., 2018); contrastingly, protect organic carbon rich peatlands, while supporting adapted land use systems (e.g., paludiculture).

Thus, widespread LULUC in the north could lead to undesirable ecological and socio-economic consequences. Sustainable agricultural expansion and intensification across northern regions requires deliberate planning based on factual research to achieve positive social benefits and neutral environmental impacts.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

AU and NB conceived the review. AU wrote the first version and managed contributions. NB, DA, SB, DC, LF, DN, MO, and DP carried out major revisions. AU, EA, SA, SB, DC, MG, CK, AK, PL, DMc, DMi, HN, JN, MO, JO, DP, SQ, AS, JW, and MZ contributed technical and policy information. AU, DA, NB, JV, and EY contributed to figures and related data integration. All authors advised on the content and revised the manuscript. Photographs by AU (**Figure 1A**), MZ (**Figures 1B**, **2B**), and AS (**Figure 1C**).

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