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RESEARCH ARTICLE

Agriculture in boreal and Arctic regions requires an integrated global approach for research and policy

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Abstract

Under food security concerns and accelerated global warming, northern regions are becoming new agricultural frontiers. While diverse regional, national, and local policies support northern agricultural intensification and expansion through land use conversion, the scope and environmental consequences of northern agriculture are yet to be fully understood. As northern agriculture is poised to increase its role in both the local and global food production, its sustainable growth depends on a comprehensive understanding of opportunities and challenges. To evaluate the current perception of the status of northern agricultural research and the extent to which there is a need for a coordinated approach to its growth, we developed a targeted survey delivered online. Questions are aimed at revealing similarities and discrepancies in the awareness of northern agriculture and obtaining feedback on the need for a global synchronization of research and development. Out of 309 respondents, a curated dataset of 238 respondents was employed for analysis. This included respondents with knowledge and expertise in boreal and/or Arctic agriculture (41%), of temperate and/or alpine agriculture (37%), and other respondents (22%). Most are involved in agricultural (60%) or applied environmental (23.5%) sciences. Results revealed that scientists working in the northern regions are cautiously optimistic about climate change–driven expansion of northern agriculture while also realistic about the need for environmentally sustainable agricultural systems. Respondents with limited exposure to northern agriculture were more pessimistic about its expansion. Surprisingly, there was a limited and inconsistent knowledge of extant networks and research entities focusing on northern agriculture research. Nevertheless, there was a strong consensus that a concerted approach among multiple disciplines and across global regions would benefit northern agriculture and its ongoing growth. The survey's results illuminate for the very first time the need for better coordination and a greater emphasis on northern agriculture under climate change.

Keywords Agriculture · Climate change · Boreal · Arctic · Survey · Research priorities

1 Introduction

While global warming effects are predicted to threaten the productivity of established agricultural regions due to erratic precipitation patterns and drastic temperature changes (Challinor et al. 2014), accelerated climatic shifts in the boreal and Arctic regions create the conditions for an expansion of agricultural lands into these cold northern regions (King et al. 2018). Evidently, global warming has already lengthened the growing season and led to a greening of circumpolar regions including the introduction of crops not historically cultivated in these areas (Herrington et al. 1997; Piao et al. 2006). Despite the yet limited understanding of the impacts of agriculture on the boreal and Arctic northern ecosystems, and indeed a limited understanding of the governing factors, including unpredictable temperature and precipitation patterns (Semenov et al. 2014; Höglind et al. 2013), northward agricultural expansion is already occurring and is supported by various regional and national policies. While this occurs through both intensification and acquiring of new areas (Fig. 1), agricultural growth in combination with less adapted practices, however, risks losses of

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carbon and biodiversity while affecting the water and energy cycles (Williams et al. 2013; Poore and Nemecek 2018; Dainese et al. 2019; Duarte-Guardia et al. 2020).

Drivers fostering agricultural growth in the circumboreal and the Arctic regions include an increased interest in stronger local food security and sufficiency (Hohle et al. 2016; Chuluunbaatar et al. 2017; Government of Newfoundland and Labrador 2017; Ivanov and Lazhentsev 2015; Belyaeva and Bokusheva 2018) and a goal for the northern communities to play a greater role in the global food economy (Chapagain 2017). Policies in support of expanding agriculture, including land use conversion from boreal forests, wetlands, and grasslands can be found in northern jurisdictions from Mongolia, to Russia and across Canada (Stevenson et al. 2014; Government of Mongolia 2018; Government of Yukon 2016; Government of Newfoundland and Labrador 2017; Government of Ontario 2011; Belyaeva and Bokusheva 2018; Schou et al. 2017). In other jurisdictions, such as in China, Norway, or Finland, northern agriculture is mainly expressed in adapting current agriculture to climate change (Niemi and Väre 2018; Government of Norway 2017; Delang and Yuan 2015). This is partly due to the limited land available for further agricultural expansion in these regions (Hohle et al. 2016). Major players in agricultural production, such as Canada and the USA (Hohle et al. 2016; Niemi and Väre 2019), but also smaller and new entrants, such as Greenland or Iceland (Lehmann et al. 2017; Reykdal et al. 2016), see fewer but larger farms that cause a northward shift of commodity crops, as already observable (Landbrugskommissionen 2014). These approaches at the frontier of agriculture are short or medium term oriented and focused on agricultural intensification and expansion and its commercial success, at the expense of forest and natural land (Cho and McCarl 2017). The negative consequences of intensification and land use change (e.g., conversion from forest to agriculture) are recognized but less prioritized and not consistently included in planning (Tscharntke et al. 2012). Still, the effects of intensification, particularly of the areal expansion of northern agriculture, are associated with negative environmental impacts, from regional to global. Most conspicuous is the effect on greenhouse gas (GHG) balances. Conversion of northern natural lands to agricultural uses involves the removal of aboveground biomass and to variable extents of the organic matter rich topsoil (Fig. 1). This leads to an immediate and long-term loss of carbon adding to the historical soil carbon debt incurred when lands are converted to agriculture (Hannah et al. 2020).

Northern land use change and agricultural intensification are linked to drastic impacts on natural habitats, biodiversity (microbial communities, invertebrates, and vertebrates), and ecosystem services such as provision of genetic diversity and regulating and maintaining chemical, biological, and physical soil processes (IPBES 2019). Boreal agricultural land use and its alteration of hydrology further impacts lake CO_2 and C dynamics with undesired trophic effects (Tscharntke et al. 2012; Hobson et al. 2002). This is particularly problematic since, for example, the self-recovery potential for boreal spring ecosystems is very low (Jyrkänkallio-Mikkola et al. 2017). As future agricultural extensification and intensification will affect the environment, the agriculture in the northern regions will also have to consider impacts on productivity due to climate change–induced impacts on ecosystem, nutrient, water, and soil management (Työ- ja elinkeinoministeriö 2019). Facing these opportunities and the related challenges, the scientific community is expected to develop comprehensive, multi-regional, and cross-disciplinary research that addresses the complex challenges associated with the northward expansion of agriculture and its impacts on the economy, environment, and society.

To gauge the perception of the scientific community concerning the opportunities and risks associated with an enhanced boreal and Arctic agriculture, we developed and conducted a targeted online survey. The survey aimed to reveal similarities and discrepancies in the current awareness of northern agriculture and to obtain feedback concerning the need for a global synchronization of research and development efforts, supporting the effective and sustainable

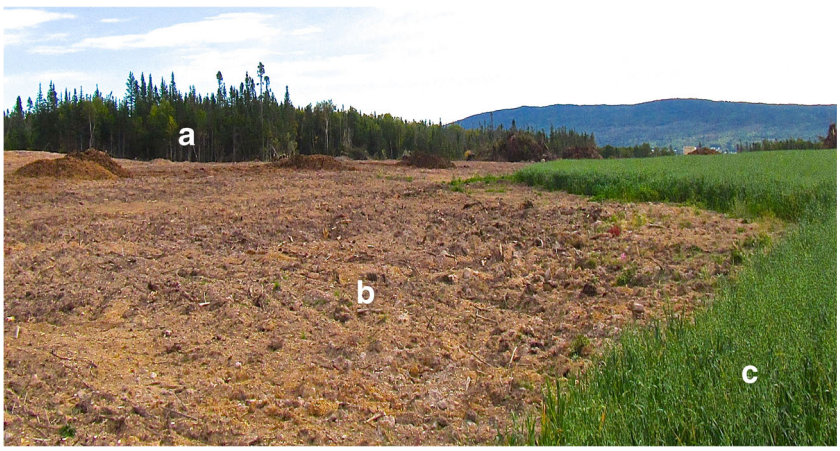

Fig. 1 Agriculture in the northern regions, driven mainly by local food security and sufficiency concerns, may expand substantially through conversion of boreal forest (**a**) to agricultural land (**b**) that can be cropped employing intensive or extensive agricultural practices (**c**). Image taken in 2019 by A. Unc in Newfoundland, Canada

adaptation to the new climate change–driven realities while upholding environmental standards.

2 Methods

2.1 Survey setup and delivery

An online survey was designed and conducted by Memorial University of Newfoundland (MUN), Natural Resource Institute of Finland (Luke), and University of Alberta (UA) (Table A1 Supplementary material). The survey had 49 questions, including background examination of researcher affiliation and professional interest, climate change and boreal and Arctic agriculture perception, and the perceived need for a boreal and Arctic research network. Assuming that agriculture includes both plant and livestock production, the survey design of this study was less specific to ensure inclusion of multiple farming systems. The survey included multiple choice questions (single answer or multiple answers), yes/no answer questions, and ranked opinions on a Likert scale (i.e., a 1 to 5 rating scale, from strongly disagree to strongly agree) (Table A1 Supplementary material). The respondents were offered the option of free feedback twice during the survey.

The survey was released on January 4th and was available until January 31st 2019. Invitations were sent through the Canadian Society of Soil Science, Global Soil Biodiversity Initiative, DSSAT, and Canadian Agricultural Economics Society, USDA, and the Critical Zone Network. Other researchers identified through their affiliation to northern agriculture research networks or departments from around the circumboreal region were invited directly via email; this included invitations sent to department heads at universities and institutes known to carry work relevant to the matter at issue. Respondents were encouraged to forward the survey to others; therefore, it is unknown how many people received the survey and thus a response rate could not be calculated. The survey indicated that it might be completed in approximately 10 to 15 min. However, no time limit was imposed and is expected that most respondents spent longer on answering the survey. Respondents could withdraw from the survey at any point.

2.2 Data curating

Several criteria were employed to select relevant responses: (1) respondents who declared themselves as located in a northern region while declaring an address in a country without a boreal, Arctic, or similar alpine ecosystems (i.e., location mismatch) were eliminated; (2) those with qualifications that were non-verifiable, or those whose identity could not be verified (i.e., declared and verifiable contact information did not match) were eliminated from the dataset; and (3) respondents that only responded to a limited number of the quantitative questions (e.g., mainly responded to the commentary sections or did not answer the Likert questions), which could have had an unduly effect on the strength of the statistical analyses, were also eliminated from the dataset. Of the total of 309 survey respondents, 238 passed quality control criteria. Respondents in the curated set were from 50 countries (Fig. 2). All analyses were carried out on anonymized datasets.

To ensure strength of the statistical analyses (Table 1), the response profiles were mainly analyzed according to (1) professional connection to boreal and Arctic agricultural research and (2) the region of activity. Respondents were grouped according to their professional connection as self-identified at questions 6 and 7 of the survey as listed in Table A1 Supplementary material (Figs. 3 and 4, Tables 1 and 2, and Table A2 Supplementary material).

A summary of the respondents by countries based on the type of the agriculture in each country is presented in Fig. 2: northern countries (that have boreal and/or Arctic agriculture, even if they might also have agriculture in other regions), countries that have temperate zone and/or alpine agriculture (temperate and alpine agriculture countries), and other countries.

Analyses were carried out on respondents grouped along the self-declared climatic zone and professional focus of activity (employing responses to questions 3 and 4 of the survey (Table A1 Supplementary material) and the classification in Fig. 4: boreal and Arctic agriculture (BAag), temperate and/or alpine agriculture (TAag), and other (Oag)). Note that there is not a perfect overlap between country classification (Fig. 2) and climatic zone: some researchers might not be located in northern countries but carry out work relevant to the boreal and Arctic agriculture, while other researchers located in a northern country might carry out research focused on other climatic zone than the boreal and Arctic, for example, working on temperate zone agriculture. Thus, despite overwhelming responses from Canada (Fig. 2), the statistical assessment remained unbiased as analyses were mainly carried out between groupings based on climatic zone; ~66% of the researchers that declared a boreal and Arctic focus were not Canadians. The datasets without Canadians offered similar trends, albeit with a weaker statistical strength directly related to the modified size of the dataset (data not shown). This classification allowed for a more accurate description of the respondents' relationship to the climatic zone of professional interest (see Fig. 3).

2.3 Statistical analyses

The analysis was conducted in R vs. 3.5.3 using the Psych package (https://cran.r-project.org/web/packages/psych/psych.pdf). A polychoric correlation matrix was created

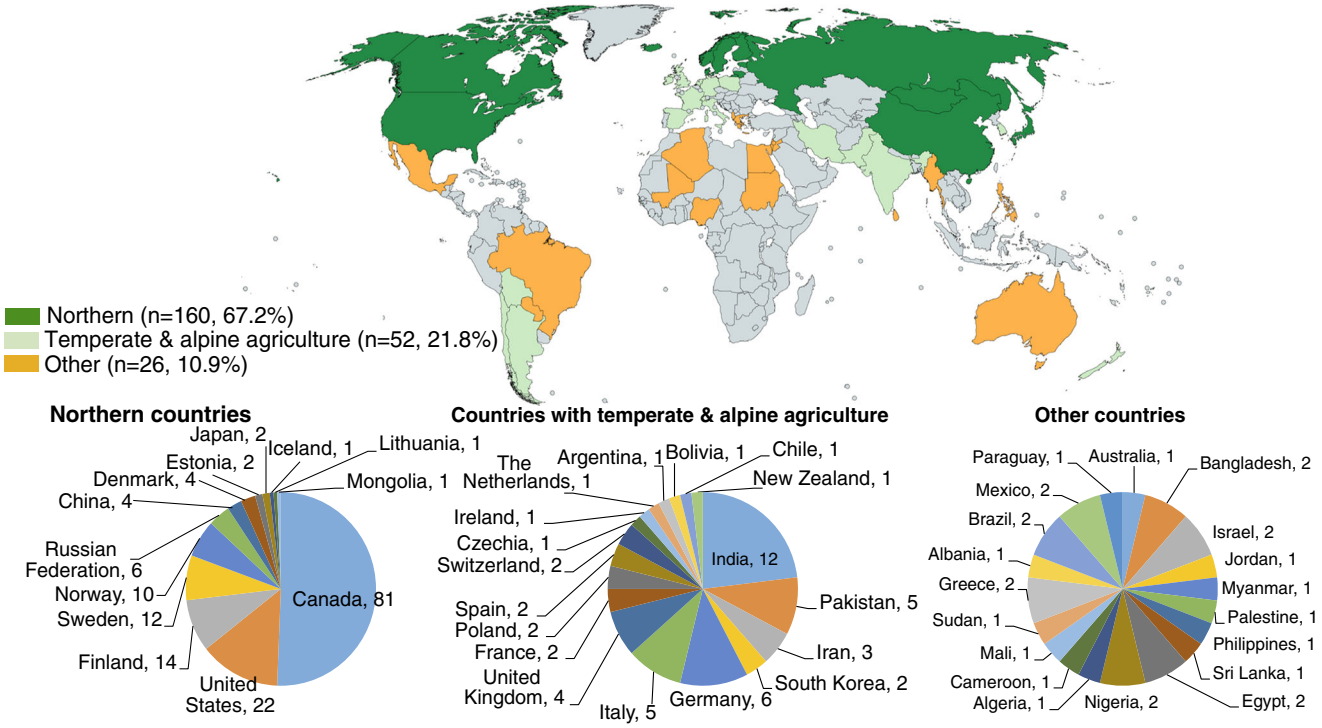

Fig. 2 Distribution of survey respondents based on declared country. "Countries with temperate and alpine agriculture" group includes all countries that do have temperate and/or alpine agriculture and no boreal and/or Arctic agriculture. While the "Northern countries" group includes the countries that do have boreal and/or Arctic agriculture, they might also have agriculture in other climatic zone, e.g., the USA Canada

for all Likert and binomial questions for regional agriculture groups (BAag, TAag, and Oag) and for professional categories (respondents with research directly relevant to boreal or Arctic agriculture research, respondents with agricultural research that could have a boreal or Arctic focus, respondents with non-agricultural research that could support boreal or Arctic agriculture research, respondents with no connection to boreal or Arctic agriculture research, and respondents with no connection to research). Respondents did not always answer all questions, so n varied between questions. Moreover, a few questions had uniform responses from nearly all respondents. These questions were eliminated from all correlation matrices so that the matrices could be compared; e.g., 230 respondents answered with "Yes" to the question "Is there a need for interdisciplinary research?" (4 replied "No" and 4 did not reply) so this question was excluded from the polychoric matrices for all professional categories. Polychoric correlation matrices for regional or professional category were then compared to each other using Pearson correlation (i.e., correlation between two matrices); a t-test (α=0.05) was applied to determine significance (Tables A2 and A3 Supplementary material).

The standard deviations of each combination of questions from the polychoric correlation matrices for the regional and professional categories were calculated separately; the standard deviations were compared for regional and professional categories, respectively, to determine the overall similarity of responses between questions. A Kruskal–Wallis analysis was performed to estimate statistical significance of the responses to Likert-scaled questions as summarized in Fig. 4 (Table 2). A post hoc Dunn's multiple comparison test was used to determine to source of dissimilarity for each question (Table 2).

The data were analyzed for respondents' regional and professional connection to boreal and Arctic agricultural research but not explicitly for country of origin as mean error distance indicated that the confidence for smaller country-based datasets was not at an acceptable level (Table 2). The sample sizes for most countries were not enough to allow an 80% confidence (z-score=1.28) that the mean was within a ±30% error range. Therefore, analyses were focused on regional and professional categories.

3 Results and discussion

3.1 Future challenges prioritized by experts

At the onset of the survey setup, we anticipated that responses from professionals across the boreal and Arctic regions would reflect the regional policies driving the development directions of northern agriculture. About 5% of the respondents identified themselves as working in boreal and/or Arctic regions, with

Table 1 Statistical strength at 90% and 80% confidence levels for average the Likert responses across grouping by self-declared country of origin, region, and professional connection

Category		90% confidence, z-score=1.64		80% confidence, z-score=1.28	
		CI95 for the error range (%)	Error range from the mean (%)	CI95 for the error range (%)	Error range from the mean (%)
Countries	Canada*	1.4%	7.6%	1.1%	5.9%
	US	2.6%	14.6%	2.1%	11.4%
	Finland	3.3%	18.3%	2.6%	14.3%
	India	3.6%	19.8%	2.8%	15.4%
	Sweden	3.6%	19.8%	2.8%	15.4%
	Norway	3.9%	21.6%	3.1%	16.9%
	Germany	5.1%	27.9%	4.0%	21.8%
	Russian Federation	5.1%	27.9%	4.0%	21.8%
	Italy	5.5%	30.6%	4.3%	23.9%
	Pakistan	5.5%	30.6%	4.3%	23.9%
	China	6.2%	34.2%	4.8%	26.7%
	Denmark	6.2%	34.2%	4.8%	26.7%
	UK	6.2%	34.2%	4.8%	26.7%
Agricultural regions	Boreal and Arctic	1.3%	7.0%	1.1%	5.8%
	Temperate and Alpine	1.3%	7.3%	1.0%	5.7%
	Other	1.7%	9.5%	1.3%	7.4%
Relationship to boreal and/or Arctic agriculture	My research is directly relevant to BAag	1.7%	9.6%	1.4%	0.9%
	My research is agric. research that can have a BAag focus	1.3%	7.1%	1.0%	0.6%
	My research is non-agric., but can offer support to BAag	1.8%	9.9%	1.4%	0.9%
	No connection to BAag research	2.2%	12.3%	1.7%	1.1%
	No connection to research	3.2%	17.7%	2.5%	1.6%

*e.g., for the Canadian dataset, there is a 90±1.4% confidence that the average mean of responses to a Likert-ranked question has an error of 7.6%

another 36% working in boreal regions; these two groups were combined in a boreal and Arctic group (BAag) (41%). A substantial proportion of respondents are researchers that carry out agricultural or related environmental works in regions similar or adjacent to boreal regions, i.e., in temperate regions close to the temperate–boreal ecotone and/or alpine regions (TAag) (37%). The presence of a substantial "Other" group of respondents (Oag), professionally not involved with the northern regions (22%), allowed for a comparison of the perception of northern agriculture between professionals with a diverse range of exposure to northern agricultural development.

All respondents agreed that global warming–driven expansion of boreal and Arctic agriculture is likely (Fig. 4a). While professionals directly or indirectly involved in boreal and Arctic regions' agriculture recognize that this is already happening, non-researchers and scientists that do not have expertise in agricultural research tended to project the likelihood of northern agriculture as a more distant event, towards the end of the century (Figure 4a). There was strong agreement between all respondents that climate change affects agriculture in boreal and Arctic regions (Fig. 4a). This was particularly distinct for researchers that are directly and indirectly involved or have self-identified as having skills relevant to agriculture in boreal and Arctic regions. These results confirmed the assumption that researchers working in agriculture and related fields already experienced climate change–related challenges (Lehosmaa et al. 2018). Agricultural researchers see moderate disadvantages while they clearly identify the corresponding opportunities to increase agricultural productivity (i.e., yields) (Figure 4b, Table 2, and Figure A1 Supplementary material). On the other hand, the non-scientist or scientists not involved in agriculture or environment were more likely to identify climate change effects on agriculture as mainly negative and ranked lower any climate change related opportunity (Figures 3b and 4a). The survey revealed distinct views and varying perceptions of the impact of global warming on agricultural performance among academic disciplines, and the participants' relation to agriculture in northern

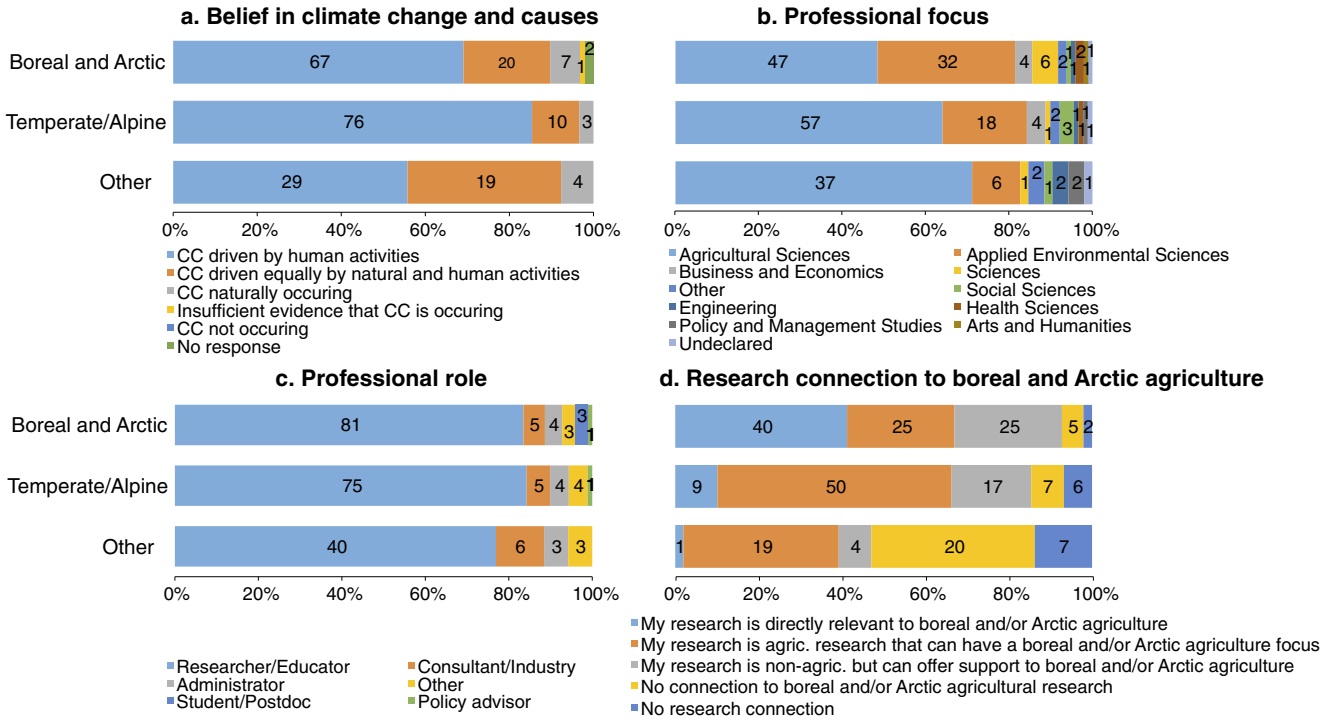

Fig. 3 Characterization of respondents' in each agricultural region; boreal and Arctic (BAag), *n*=97; temperate and alpine (TAag), *n*=89; other (Oag), *n*=52. Note that respondents from countries that have multiple climatic zones or with professionals active in different climatic zones have self-identified as active in diverse regions: Canada—BAag (*n*=36) and TAag (*n*=45); China—BAag (*n*=2), TAag (*n*=1), and Oag (*n*=1); Denmark—BAag (*n*=2) and TAag (*n*=2); Finland—BAag (*n*=13); Sweden—BAag (*n*=10) and TAag (*n*=2); United Kingdom—BAag (*n*=2) and TAag (*n*=2); and TAag (*n*=1); and United States of America BAag (*n*=11) and TAag (*n*=11). Respondents from all other countries were classified as described in Figure S1. *CC* climate change

regions. However, addressing climate change–induced impacts on agriculture require concerted efforts at global, regional, national, and local levels to build policy pathways and to implement tailored measures accounting for multiple domains of interest, such as nutrition, environment, economic, social, and resilience and their conflicting interactions.

Despite the differences in the strength of the response among different groups of respondents, all shared a surprisingly similar view of northern agriculture on the environment (Fig. 4c); nevertheless, respondents from boreal and Arctic regions were less concerned about climate change–induced impacts on the environment (Figs. 3c and 4b). There was a moderately strong and uniform agreement among respondents that agricultural expansion and intensification in boreal and Arctic regions increases the risks of GHG emissions, which is in line to recent research results (King et al. 2018; Peltonen-Sainio and Jauhiainen 2020; Peltonen-Sainio et al. 2020). The impact of an expanding agriculture on environmental quality and biodiversity at local and global scales ranked particularly high by respondents having no connection to research and to a lesser extent by researchers (Fig. 4c). The loss of biodiversity and impaired environmental quality (both local and global) induced by agriculture has been discussed in the scientific and popular literature for several decades with particular prominence in recent years (Tubiello et al. 2015). In respect to the survey results however, it is obvious that the stronger the professional involvement with applied and northern agriculture of a responder, the more positive the view on the expanding northern agriculture. Non-researchers and researchers having no connection to agriculture in boreal and Arctic regions ranked the negative effects on biodiversity and environmental quality of agricultural expansion particularly higher than other respondents (Table 2, Fig. 4c, and Figure A1 Supplementary material). Consistently, all survey respondents agreed that growth of boreal and Arctic agriculture would increase emissions of GHG and negatively affect biodiversity but also the energy cycles and water quality and availability issues. Based on these well-acknowledged facts, growth of agriculture in boreal and Arctic regions should consider foreseeable impacts on the environment as addressed by local, national, regional (e.g., European Union), and international institutions (e.g., UN) demanding for targeted approaching appropriate to manage contradictory interactions between agricultural development and environmental conservation.

Overall, perceptions of adaptability, science and policy measures in place were remarkably uniform (Fig. 4d, Figure A1 Supplementary material). There is a general agreement that boreal and Arctic agriculture must be developed

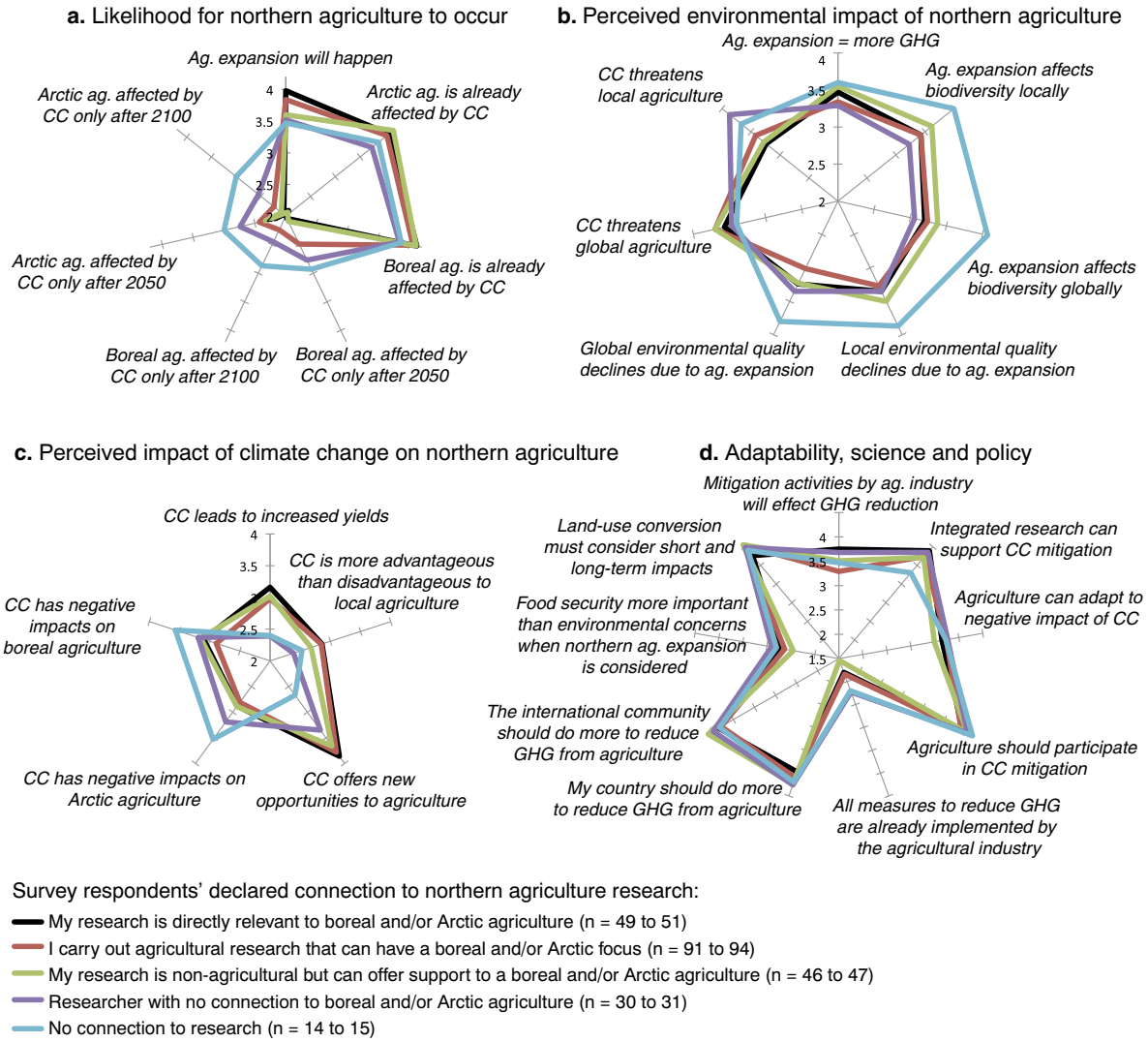

Fig. 4 Summary of survey responses addressing perception of northern agriculture and its context. Values represent the mean of responses, which were ranked between 1 (strongly disagree) and 5 (strongly agree). Variation in the number of respondents (*n*) is due to the variable rates of response (*n*=238) to each question; *GHG* greenhouse gases, *CC* climate change. The similarity in the responses between respondent groups, as classified according to their declared connection to northern agriculture, is summarized in Figure A1 Supplementary material

with attention to environmental impacts. Despite the variability in perception of opportunities and challenges, all respondents agreed to the need for climate change mitigation and adaptation strategies. Current measures to reduce GHG were identified as insufficient while national and international efforts to reduce GHG (IPBES 2019) were supported. Interestingly, all groups consistently rated environmental concerns higher than food security (Fig. 4d). Hence, ensuring sustainable development of agriculture in the boreal and Arctic regions should address competing interactions between agricultural and environmental domains rather than focusing solely on food security. Consequently, the respondents supported the need for an assessment of short- and long-term consequences accompanying agricultural land use and land use conversion, as for instance demanded by the European Commission (Tubiello et al. 2015).

3.2 Prioritization of the relevance of research topics

Given the inter- and multi-disciplinary nature of agricultural research and development (Saskia et al. 2019), we also asked the respondents to identify the most relevant research topics (identified as scientific disciplines in the questionnaire) that ought to lead the research into an expanded northern agriculture. Since familiarity to agriculture and to boreal and Arctic agriculture was assumed to be key to the prioritization of the research topics identified as most relevant to northern agricultural research, answers were itemized by respondent's self-declared region of professional focus (i.e., BAag, TAag, or Oag; Fig. 5). Respondents from each climatic zone recognized environmental sciences as the most relevant field of research for the newly expanded northern agriculture; large vote counts were received for *ecosystem sustainability, natural resource*

Table 2 Statistical significance of the differences in Likert-ranked survey questions among respondent with variable professional connection to boreal agriculture (Fig. 4)

Questions (Likert)	Dunn's post hoc test					
	Connection to boreal and/or Arctic agricultural (BAag) research#					Alpha (p_{H0})
	A	B	C	D	E	
Expansion of agric. into boreal and Arctic regions is in our future	4.0$^{a##}$	3.8^{ab}	3.6^{b}	3.5^{b}	3.5^{ab}	0.10
Climate change will affect agric. in the Arctic zone only after 2050	2.2^{a}	2.4^{ab}	2.3^{ab}	2.7^{b}	3.0^{b}	0.10
Climate change will affect agric. in the Arctic zone only after 2100	2.0^{a}	2.2^{ab}	2.1^{a}	2.5^{bc}	3.0^{c}	0.10
Climate change effects on the Arctic zone are already visible	4.1^{ab}	4.0^{a}	4.2^{a}	3.7^{b}	3.9^{ab}	0.10
Climate change will affect agric. in the boreal zone only after 2050	2.0^{a}	2.5^{bc}	2.1^{ab}	2.8^{c}	2.9^{c}	0.05
Climate change will affect agric. in the boreal zone only after 2100	1.9^{a}	2.2^{abc}	1.9^{ab}	2.5^{bc}	2.9^{c}	0.05
Climate change effects on the boreal zone are already visible	4.1	4.1	4.1	3.8	3.9	0.10
Expansion of BAag results in a net increase of global GHG emissions	3.5	3.3	3.6	3.3	3.6	0.10
Expansion of BAag affects global biodiversity negatively	3.2^{a}	3.2^{a}	3.4^{a}	3.1^{a}	4.1^{b}	0.10
Expansion of BAag results in a global decline in environmental quality (soil, water, and air)	3.2^{ab}	3^{a}	3.2^{ab}	3.4^{ab}	3.8^{a}	0.05
Expansion of BAag affects local biodiversity negatively	3.4^{ab}	3.4^{ab}	3.6^{ab}	3.2^{a}	4^{b}	0.10
Expansion of BAag results in a local decline in environmental quality (soil, water, and air)	3.4	3.3	3.5	3.4	3.9	0.10
Climate change is both a threat and an advantage to agric. in my region	3.6	3.7	3.7	3.5	3.4	0.10
Climate change is a great threat to agric. in my region	4.3	4.3	4.3	4.2	4.5	0.10
Mitigation actions made by agricultural sector could have a significant effect to the climate emission reduction globally	4.1	4.0	4.1	3.8	3.9	0.10
Climate change will bring more advantages than disadvantages to the agricultural sector in my region	3.9^{a}	3.8a	3.7^{ab}	3.4^{bc}	2.7c	0.05
The agricultural yields in my region will get bigger due to climate change	3.2^{a}	3^{a}	3^{a}	2.4^{b}	2.4^{ab}	0.05
Climate change will affect agric. in the Arctic zone negatively	2.9^{ab}	2.8^{a}	2.9^{ab}	3.2^{ab}	3.5^{b}	0.10
Climate change will affect agric. in the boreal zone negatively	3.1	2.9	3.2	3.2	3.6	0.10
Climate change is a threat to agric., globally	3.2^{a}	3.4^{ab}	3.3^{a}	3.9^{b}	3.7^{ab}	0.05
Climate change creates new possibilities for agric. in my region	2.9	2.8	2.7	2.4	2.5	0.10
Agric. offers more solutions than challenges for GHG emission reduction	3.3	3.5	3.2	3.5	3.7	0.10
Agric. can adapt to the negative effects of climate change	3.6	3.7	3.5	3.8	3.7	0.10
The agricultural sector should participate in climate change mitigation	4.4	4.4	4.6	4.5	4.7	0.10
My country should do more than is currently being done to reduce GHG emissions from agric.	4	4.1	4.2	4.3	4.2	0.10
Food security concerns are more important than environmental concerns when deciding on land use conversion for agricultural uses in the boreal and Arctic regions	2.7	2.6	2.4	2.9	2.8	0.10
All necessary measures to reduce greenhouse gas emissions are already done in the agricultural sector	1.8^{ab}	1.8^{ab}	1.5^{a}	2.2^{b}	2.2^{ab}	0.05
Mitigation actions made by agricultural sector will have a significant effect to the climate emission reduction in my region	3.7^{a}	3.3^{b}	3.5^{ab}	3.7^{ab}	3.5^{ab}	0.10
The international community should do more than is currently being done to reduce GHG emissions from agric.	4.4	4.3	4.6	4.5	4.3	0.10
Integrated scientific research can provide the baseline for protocols and guidelines to avoid and attenuate the environmental impact of boreal agric.	4.4^{a}	4.2^{a}	4.2^{ab}	4.4a^{b}	3.8^{b}	0.10
Decision-making for land conversion should require a scientific assessment about potential short and long-term consequences	4.3	4.5	4.6	4.5	4.4	0.10

[#] Self-reported connection to boreal and/or Arctic agricultural research (Table A1 Supplementary material, question 7): A, "My research is directly relevant to boreal and/or Arctic agriculture"; B, "My research is agricultural research that can have a boreal and/or Arctic agriculture focus"; C "My research is non-agricultural, but can offer support to boreal and/or Arctic agriculture"; D "No connection to boreal and Arctic agricultural research"; E, "No connection to research"

[##] The means followed by the same letter are not statistically different at alpha or 0.05 or 0.1 (declared in the last column); no letters were added to the questions where all means are statistically similar, even at an alpha of 0.1.

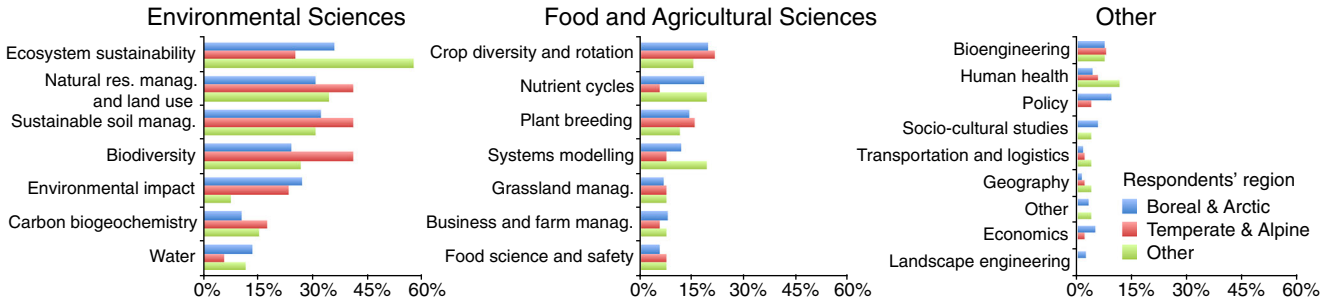

Fig. 5 Research areas identified as most relevant to northern agricultural research. Respondents' region as self-declared region of professional interest, not by country (i.e., BAag, TAag, or Oag)

management and land use, sustainable soil management, biodiversity, and *environmental impact* (up to 60%). The *impact on environment* ranked higher than the concerns on *carbon biogeochemistry* and *water*. TAag participants voted less strongly for the need for *ecosystem sustainability*, most likely because in countries with temperate agriculture, ecosystem concerns are already implemented in national policies (Davidson 2016). Higher awareness of biodiversity loss among TAag respondents may be due to the same stronger exposure to relevant policies and research (Swinbank 2016). Thus, both environmental and agricultural foci were highlighted as most relevant, confirming the urgent need for increased support for agro-ecological research and development as demanded by global policies at multiple levels (e.g., Farm-to-Fork strategy of the European Commission (Ellis 2019)).

Among food and agricultural research areas (Question 15, Table A1 Supplementary material), most votes were received for *crop diversity*, *nutrient cycles*, and *plant breeding* (Fig. 5). The TAag group selected *nutrient cycles* research less often (<10%) than the other two groups. This might be linked to the established nutrient cycle policies, effective in almost every participating temperate and/or alpine agriculture country: e.g., the European Nitrate Directive, issued almost 30 years ago, and the European Water Framework Directive show partially positive results now (European Union 2020). We interpret this also as a signal of a strong level of expertise in standard production focused sciences, i.e., greater certainty in the adaptability of agronomic knowledge and tools, while environmental impacts are perceived as uncertain in scope, more difficult to manage and thus requiring further in-depth consideration (European Commission 2018; EU Water Framework Directive (WFD) 2000; European Nitrate Directive 1991). Other sciences, such as *bioengineering*, *human health*, *policy*, and *socio-cultural studies* ranked consistently low, which could be partly due to the fewer participants from these fields among the survey respondents (see Fig. 3, Professional focus). For example *bioengineering* was selected by only 3 out of 141 respondents of the Agricultural Sciences group, but by 2 out of 4 of the Engineering group.

The response profile of the respondents (i.e., the proportion of respondents selecting each research topic) that declared Agricultural Sciences as professional focus (Table A1 Supplementary material, question 6) was correlated with the response profile of Applied Environmental Sciences and General Sciences groups (R=0.71 and R=0.65, respectively). On the other hand, the response profile of the Applied Environmental Sciences group was correlated with the profiles of Engineering (R=0.56), General Sciences (R=0.73), and Social Sciences (R=57); Business response profile was correlated to Engineering (R=0.72). All correlations listed here are significant at p_{H0}<0.05. Similarly, the closeness of the respondents, and thus reasonably arguable their familiarity, to the boreal and/or Arctic agricultural research, as self-reported was also reflected in the response profiles (Tables A2 and A3 Supplementary material).

Regardless of the overwhelming support for environmental sciences expressed by the respondents, this survey revealed the relevance of agricultural research for achieving transformative adaptation of agri-food systems in the boreal and Arctic regions to global warming–induced changes and other shocks (e.g., pandemic events (Bilotta et al. 2015)). To archive the balance between agricultural development and adaptation on one side and the serious environmental concerns on the other, research and development of resilient agri-food systems in the boreal and Arctic regions must be interdisciplinary to ensure greatest benefits for both the environment and communities (Udmale et al. 2020).

3.3 Boreal and Arctic agricultural network

Given the expected complexity and partially contrasting interests and foreseeable adverse environmental impacts associated with expansion and intensification of boreal and Arctic agriculture, as confirmed for the very first time by the survey results discussed above, we also inquired about the need for a common approach to accelerate knowledge acquisition, demonstration and replication (i.e., scalability + transferability) for achieving sustainable agriculture in boreal and Arctic regions. The results of this survey clearly show that perception of opportunities and challenges associated with the growth of northern agriculture are dependent on the level of familiarity with the northern regions of each respondent, which highlights

the need of knowledge development to support evidence-based policy making.

The majority of the respondents (>80%) declared that they are not aware of an existing network supporting multi-disciplinary and multi-national agricultural research and development in the boreal and Arctic regions (Table A4 Supplementary material). Surprisingly, 79% of the researchers working in the boreal and/or Arctic regions were also not aware of an existing research network addressing the same issues. Most respondents that did name a network (32 out of 238) identified a single option, which is an indication of the limited acknowledgment of these networks by non-members; 27 extant or putative institutions, networks, or research groups that either carry out relevant activities or have the capacity to do so were named; these included Universities and governmental departments (Table A4 Supplementary material). The available identification information for these respondents suggests either a direct relationship or geographical proximity to the named network or institution. We should also note that we are not aware of any respondent to be associated with a research council or research funding entities. The lack of consistency in the identification of such networks suggests that their scope, to the extent that they are focused on boreal and Arctic agriculture, and even their existence are not widely known. It also suggests strong local foci, which clearly neglects the advantage of multilateral networks required to combat effects of global warming, land use, and land use change. Thus, despite differences in the perception of immediacy, opportunities, and impacts of the boreal and Arctic agriculture throughout the survey, results pointed clearly to the need of an integrated approach, addressing the complex challenges related with northern agriculture and arguably competing associated interests. Compared to the current fragmentation of policies and networks the herein proposed integrated approach can spur accelerated development of regional and national activities (Tscharntke et al. 2012) mainly through supporting platforms that facilitate connectivity (Wagner et al. 2015) and thus allow for the timely exchange of information and common education activities (Fielke et al. 2020; Neef and Neubert 2011). Furthermore, such a network can enhance the necessary integration and exchange of knowledge across the northern research community and ensure transparency leading to development of evidence-based policies and thus support collaborative governance (Jacob and Meek 2013).

4 Conclusion

This is the first time that the perception of the research professionals on the future of northern agriculture across the circumboreal and Arctic regions has been comprehensively gauged. The responses advance comprehensive new evidence to the understanding of the current status and future directions of agriculture in the northern regions, which may encourage increased support for work on critical northern agriculture issues. While most of the respondents self-identified as agri-food researchers, 40% were other researchers or non-researchers. Results show that global warming–induced northward shift of agricultural zone is recognized as occurring. Nevertheless, its urgency and related opportunities are more strongly perceived by researchers directly involved in boreal and Arctic research. There are opportunities to enhance the relevance of northern agriculture, but there is also a foreseeable risk to accelerate global warming through massive loss of soil carbon and biodiversity (Dubrovina 2018; Simola 2018; Bradshaw and Warkentin 2015; Emmerson et al. 2016; ESTR Secretariat 2014).

Northern agricultural developments are obvious to the professionals directly involved in relevant activities, while they are less acknowledged and understood outside the region. This leads to a lower level of support and scrutiny than for developments in current agricultural regions, especially for jurisdictions where northern agriculture is seen as yet marginal in terms of policy, and of interest only to local governance. On the other hand, there was an overwhelming support for a concerted and science supported approach towards northern agriculture. This was perceived as essential to facilitate coherent research and policy development in support of both the development of northern agriculture and mitigation and adaptation measures to minimize its environmental impacts. This might be achieved through coordination of different initiatives, networks, universities, institutes, and organizations. Agriculture is uniquely couched in the socioeconomics and environmental and as such, it is evident that stronger public and political awareness, both locally and globally (Davidson 2016; Busch and Lacy 1983), is essential for increased support to address issues that clearly affect more than just the local food security and sufficiency.

The respondents identified the need for interdisciplinary and cross-regional coordination. Opportunities and risks associated with a developing northern agriculture are subject to complex interactions and governed by conflicting interests, and a pan-global approach is recommended. The survey results highlighted for the very first time the need for a global boreal and Arctic agricultural network, ideally under the umbrella of an international organization, FAO, for example. This might build on an existing network, be developed as an umbrella entity, or as a new structure.

Author contribution Survey design: AU, NB, JS, DA, SQ, LG; Survey delivery: JS; Data analysis: DA, EHY, AU; Initial draft AU, DA; Manuscript writing: DA, AU, NB, EHY; Manuscript corrections: JS, LG, SQ.

Availability of data and material Summary data available upon request only within the scope obligated and permitted by the legislation, according to the Privacy Notice.

Code availability Not applicable.

Declarations

Conflicts of interest The authors declare no competing interests

Ethics approval A Privacy Notice was approved by the Natural Resource Institute Finland (LUKE) where the survey distribution was managed; the rights of data subjects are based on articles 15–22 of the EU GDPR (2016/679).

Consent to participate The rights of data subjects are based on articles 15–22 of the EU GDPR (2016/679) (https://www.luke.fi/en/data-protection-and-privacy/rights-of-data-subject/). Respondents were able to withdraw at any point during the survey.

Consent for publication As per the LUKE Privacy Notice anonymized data may be used for scientific purposes (i.e., peer reviewed).

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