State shifts and divergent sensitivities to climate warming across northern ecosystems

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Abstract

Northern ecosystems are among the most exposed to warming and their responses are difficult to anticipate due to the variable sensitivity of their biophysical components. Using an analysis based on expert assessment, we investigated heterogeneity in the sensitivity to climate-driven state shifts across the vast northern landscape, from the boreal to the polar biomes. Over a 3,700 km latitudinal gradient in northeastern North America, we identified 28 discontinuous states for six ecosystem components: permafrost, peatlands, lakes, snowpack, vegetation, and endothermic vertebrates. Sensitivities were quantified by the estimated time required to shift from an initial to a contrasting state in response to a 5°C step increase in mean annual air temperature. The inferred scenario reveals that multiple interconnected state shifts are likely to occur within a narrow subarctic latitudinal band at timescales of 10 to >100 years. However, response times decrease with latitude, with freshwater systems at high latitudes displaying heightened susceptibility to rapid state shifts (timescales of 1 to 10 years). The lack of coherence in response times between components and across latitudes will likely impair the integrity of northern ecosystems and generate heterogeneous range shifts, resulting in the reconfiguration of landscapes and ecosystems.

GLOSSARY

Cascading effect: Chain of events whereby an initial state shift in one ecosystem component triggers additional state shifts in other ecosystem components.

Contrasting state: State of a given ecosystem component characterized by marked differences in structure and function. In this study, it is one of the different states of a given component found along an extended latitudinal (temperature) gradient. For example, continuous vs. discontinuous permafrost, or boreal forest vs. shrub tundra vegetation.

Critical threshold: Point at which a system begins to shift from one state to another in response to an external driver. In this study, the southernmost modern-day position of a given state along a latitudinal gradient is considered a critical threshold, as all systems located further south (warmer climate) are characterized by another contrasting state or by a transition zone between contrasting states.

Ecosystem component: Biotic or abiotic constituent of an ecosystem. In this study, we focus on six key components of northern ecosystems at the landscape scale: permafrost, peatlands, lakes, winter snowpack, vegetation and endothermic terrestrial vertebrates.

Initial state: Contrasting state at a critical threshold and exposed to a sudden and persistent change in the environment.

Key determinant of response time: The main abiotic or biotic factor that determines the response time of an ecosystem component.

Sensitivity: Susceptibility of an ecosystem component to shift rapidly from its initial state to a resulting state following exposure to a sudden and persistent change in the environment. In this study, experts assess sensitivity using the response time (higher sensitivity = shorter response time) of a component located at a critical threshold and exposed to a hypothetical warming scenario (a sudden and persistent 5°C increase in mean annual air temperature).

State shift: The complete transition of an ecosystem component from an initial state to another contrasting state caused by an external driver.

Response time: Time required to shift from an initial to a contrasting state in an ecosystem component at a critical threshold, following a sudden and persistent change in the environment; in this study, response times are assessed by experts, using time intervals on a log temporal scale (high sensitivity: 1-10 years; moderate sensitivity: 10-100 years; low sensitivity: >100 years). Combination of more than one interval indicates higher uncertainty in response time estimates.

Resulting state: A contrasting state into which an ecosystem component is expected to shift, following exposure to a sudden and persistent change in the environment. In this study, the resulting states are limited to those that currently exist along a broad latitudinal gradient.

INTRODUCTION

Northern terrestrial ecosystems are considered among the most exposed and sensitive to climate warming[1-4]. However, their responses are difficult to anticipate due to the highly variable sensitivity of their components. Some components can respond rapidly to warming (e.g., arctic lakes can shift to a new state over a few years[5,6]), while others are likely to react very slowly (e.g., vegetation shifting from tundra to forest-tundra over decades[7-9]). A lack of coherence in response time between components and across latitudes can restructure ecosystems and transform landscapes by modifying the state combination of the coexisting components. The space for time substitution is therefore insufficient to anticipate the impact of global warming on these landscapes; we must better assess and integrate the heterogeneity between components of northern ecosystems responding on varying timescales.

The warming-induced state change of one ecosystem component can have abrupt and far-reaching impacts on other components. For instance, thawing permafrost can release massive amounts of carbon and nutrients, modify soil conditions for primary production, and affect geomorphological processes, hydrology, peatland dynamics, and human infrastructure[10-13]. A shift in vegetation state from polar to shrub tundra can radically transform terrestrial ecosystems with the addition of a third (vertical) dimension, offering new habitats and refuges for vertebrates and affecting microclimate and snowpack properties[14,15]. A change (or lack of change) in one component can trigger (or prevent) significant changes in another component. Such cascading effects strongly influence the heterogeneity in response times and hence must be fully integrated in ecosystem sensitivity analyses (**Fig. 1**).

Quantifying the local and latitudinal heterogeneity in the response times of interacting ecosystem components poses a significant challenge for traditional scientific approaches. The complex cascade of events spreading at relatively large spatial scales prevents experimental and reductionist studies. Furthermore, approaches that rely on massive datasets to assess sensitivity can currently be applied at large spatial scales for only a few components of the ecosystems[1,16,17]. Finally, cascading effects between biophysical components make their integration into global ecosystem simulation models difficult, if not impossible[18], where errors propagate and amplify uncertainty. In this context, searching for consensus among experts with a rigorous and transparent methodology is one of the best paths toward progress[19,20].

Here, we provide a conceptual approach based on expert elicitation to quantify the relative sensitivity of the interacting components of northern ecosystems across a broad latitudinal gradient. Using a consensus of specialists with complementary expertise and decades-long first-hand experience of northern regions, we assess where and at what rate state shifts of ecosystem components are most likely to occur under warmer conditions along a ≃100 km-wide, 3,700 km latitudinal gradient that extends from the boreal forest biome to the High Arctic (**Fig. 2**). This large study area located in eastern North America is among the last remaining wildernesses and a global rarity, as the ecosystem states found along the entire gradient are primarily the result of natural postglacial processes, with limited direct anthropogenic impacts. While considering cascading effects and interactions between components, we assess the heterogeneity in response times under the scenario of a 5°C increase in mean annual air temperature. This increase is well within the range of current warming scenarios for the Canadian Arctic (3 to 10°C by the end of the 21st century relative to the 1986-2005 reference period; shared Socioeconomic Pathway SSP1-2.6 and SSP5-8.5[21]).

RESULTS

We identified a total of 28 contrasting states along the latitudinal gradient (**Fig. 2, Tables 1 & 2**) for six key ecosystem components (permafrost, peatlands, lakes, winter snowpack, vegetation, and endothermic terrestrial vertebrates). For each ecosystem component, we identified a minimum number of contrasting states (between 4 and 6) along the gradient, characterized by marked differences in structure and function, implying that a state shift would strongly affect ecosystem properties. All states result from natural processes and are described in detail in the **Extended Data Figures (2-7)** and Supplementary Materials. We located the southernmost modern-day position of each state along the gradient. These critical thresholds (n = 22) were mostly located in the southern half of the gradient (16 in northern Québec; **Fig. 3**). We found that multiple critical thresholds emerged in the Subarctic region, between 55°N and 60°N. All ecosystem components were at critical thresholds within this region, characterized by the southern limit of continuous permafrost and of the shrub tundra. In the High Arctic, fewer thresholds emerged, and most were located slightly below 75°N, which corresponds to the southern limit of polar desert vegetation and intermittent ice-cover lakes.

The sensitivity of ecosystem components at critical thresholds, assessed using the time required to shift from an initial to a contrasting state (response time), ranged from high (1-10 years) to low (>100 years). Experts outlined that several factors, such as precipitation, topography, soil characteristics, solar radiation, and wind exposure can modulate the response time of components (**Extended Data Table 1**). Despite this uncertainty, the distribution of response times was not random among the observed critical threshold locations (**Fig. 3**). The mean latitude of critical thresholds associated with low sensitivity was lower than randomly expected ($p = 0.009$), while the opposite pattern was found for critical thresholds associated with high sensitivity (mean latitude higher than randomly expected ($p < 0.001$). Hence, even if low-latitude subarctic and boreal ecosystems are characterized by numerous critical thresholds, they should experience slower state shifts than some higher-latitude ecosystems close to critical thresholds and exposed to the same temperature increase.

The non-random latitudinal distribution of sensitivity likely reflects the predominance of cascading effects and strong interconnections among ecosystem components in the Boreal and Subarctic regions, as well as the relative effect of abiotic or biotic factors on response time along the gradient **(Fig. 2 & 3, Extended Data Table 1)**. The sensitivity of ecosystem components was often determined, at least partly, by the response time of another component (12 out of 22 state shifts). In most of these cases (8 out of 12), vegetation response time was a key determinant of the response time of other components such as permafrost, lakes, snowpack, and endothermic vertebrates. This underlines the ubiquitous cascading effects triggered by vegetation change, especially in the Subarctic and Boreal regions where marked changes in plant cover and vertical structure occur. It also indicates that the relatively low sensitivity of a biological component can drive lower sensitivity in other ecosystem components and increase the coherence in the response times of coexisting components.

When vegetation was not a key determinant of the sensitivity of other components (9 out of 17 cases), response times were mainly determined by the rate of warming-induced changes in the cryosphere, as in the case of all peatland state shifts driven by permafrost degradation (**Extended Data Table 1**). Changes in the cryosphere can trigger quick state shifts in some ecosystem components, as shown by lakes at high latitudes, which were the most sensitive components of northern landscapes to warming. For instance, a high arctic perennially ice-covered lake should shift to an intermittent ice-cover lake over a relatively short timescale (1-10 years). On the other hand, when exposed to the same temperature increase, a seasonally ice-covered lake located at lower latitudes should shift to a contrasting state at a slower rate (10 to >100 years) because the response time is partly conditioned by changes in catchment vegetation that increase dissolved organic matter content (**Extended Data Table 1 and Fig. 3**). Overall, the cascading effects of the most influential ecosystem components, vegetation and permafrost, appear to strongly drive the observed critical threshold locations and the heterogeneity in response times along the latitudinal gradient. By considering the effects of local environmental conditions that can modulate the response time of permafrost and vegetation to warming, especially precipitation, topography, and soil characteristics (**Extended Data Table 1**), we could thus greatly enhance the accuracy of estimates regarding the sensitivity of northern ecosystems to climate warming.

DISCUSSION

The identification and comprehensive understanding of regions ecologically sensitive to warming represent an urgent research priority on a global scale[1,20]. Our expert-based approach highlights clusters of critical thresholds and the strong heterogeneity in response times of ecosystem components to warming along a vast latitudinal gradient of global significance. Our analysis identifies not only regions that are likely the most susceptible to state shifts, but also provides insights into which ones should most rapidly shift to contrasting states under warmer climates, and why. Theoretical studies suggest that some systems close to critical thresholds could be more sensitive to external perturbations[17,22]. However, our study reveals that terrestrial northern ecosystems characterized by multiple biophysical components at critical thresholds could be relatively resistant to future warming due to the lower sensitivities of key ecosystem components that strongly affect the response times of others.

The strong heterogeneity in the sensitivity to warming across latitudes and between coexisting components highlighted in our study should contribute to asynchronous expansion or contraction of the geographic ranges of different states of ecosystem components and translate to novel restructuring of ecosystems. For instance, in a High-Arctic landscape, the remarkably short response time of intermittent ice-cover lakes may result in faster northward progression of seasonal ice-covered regimes compared to less sensitive coexisting component states, such as polar tundra vegetation, polar tundra winter snowpack, or polar tundra continuous permafrost. Additionally, a lack of coherence in the response times of biophysical ecosystem components to warming is expected to generate heterogeneous trends of biodiversity change across space and time[23,24].

The latitudinal southward decrease in sensitivity outlined in our study is consistent with the southward decrease in biodiversity response to climate change observed across northern ecosystems[25]. Moreover, the widespread northward (and alpine) advance of some terrestrial ecological boundaries appears much slower than the current warming rate[26-29]. Terrestrial species range shifts have been shown to be much slower than those of marine species, which better track climate-warming induced isotherm shifts[30]. The high level of heterogeneity in the response times of key ecosystem components assessed in our study can be an attribute of the terrestrial environment contributing to the contrast in responses of terrestrial vs marine ecosystems at vast spatial scales. Our results suggest that state shifts of certain terrestrial and freshwater systems at lower latitudes are mainly driven by the response times of biological components with relatively low sensitivities to warming. However, in the absence of less sensitive biological components dominating the landscape (established erect woody vegetation), biophysical systems near critical thresholds have the potential to transition more swiftly to contrasting states if the response times of their components are primarily governed by physical processes, such as rising ground and water temperatures.

Northern ecosystems are trending away from states experienced during the 20th century and arguably from the conditions that prevailed over the past several millennia[3,31]. Current empirical data are insufficient to develop models that can reliably predict when and where abrupt state shifts will occur across ecosystems under a warmer climate[20]. Our study was not designed to accurately predict the future state of northern ecosystems nor to determine exactly when state shifts will occur, but to assess the relative sensitivity and interplay of their different biophysical components. Under a warmer climate, novel states could also emerge, and several climate variables could modulate the response times of ecosystem components. For example, large changes in precipitation (from snow- to rain-dominated; rain-on-snow events) are likely to accompany future warming trends[32,33], amplifying the thermal effects on ecosystem change.

The multidisciplinary approach applied here, based on expert knowledge, allowed the analysis of complex natural ecosystems across vast spatial scales. This provided the opportunity to map the sensitivity of multiple components across northern landscapes and outlined the high degree of heterogeneity in response times between ecosystem components. This lack of coherence in response times to warming between components, and across latitudes, will likely impair the integrity of northern ecosystems by reshuffling the states of currently coexisting components and by generating heterogeneous rates of geographic range shifts. Such heterogeneity in sensitivity across northern ecosystems could ultimately lead to the restructuring, contraction, and expansion of biomes. Mapping sensitivity at large spatial scales is essential for predicting where and how ecosystem services will change in northern environments, and for defining implications for indigenous communities who have been part of and dependent upon these ecosystems for millennia.

REFERENCES

1. Seddon, A. W., Macias-Fauria, M., Long, P. R., Benz, D., & Willis, K. J. Sensitivity of global terrestrial ecosystems to climate variability. *Nature*, **531**(7593), 229-232 (2016).
2. Dai, A., Luo, D., Song, M., & Liu, J. Arctic amplification is caused by sea-ice loss under increasing CO2. *Nature communications*, **10**(1), 121(2019).
3. Post, E., Alley, R. B., Christensen, T. R., Macias-Fauria, M., Forbes, B. C., Gooseff, M. N., ... & Wang, M. The polar regions in a 2 C warmer world. *Science advances*, **5**(12), eaaw9883 (2019).
4. Rantanen, M., Karpechko, A. Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., ... & Laaksonen, A. The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment*, **3**(1), 168 (2022).
5. Bégin, P. N., Tanabe, Y., Kumagai, M., Culley, A. I., Paquette, M., Sarrazin, D., ... & Vincent, W. F. Extreme warming and regime shift toward amplified variability in a far northern lake. *Limnology and Oceanography*, **66**, S17-S29 (2021).
6. Saros, J. E., Arp, C. D., Bouchard, F., Comte, J., Couture, R. M., Dean, J. F., ... & Vincent, W. F. Sentinel responses of Arctic freshwater systems to climate: linkages, evidence, and a roadmap for future research. *Arctic Science, **9***(2) (2022).
7. MacDonald, G. M., Edwards, T. W., Moser, K. A., Pienitz, R., & Smol, J. P. Rapid response of treeline vegetation and lakes to past climate warming. *Nature*, **361**, 243-246 (1993).
8. Lavoie, C., & Payette, S. The long-term stability of the boreal forest limit in subarctic Quebec. *Ecology*, **77**(4), 1226-1233 (1996).
9. Payette, S., Couillard, P. L., Frégeau, M., Laflamme, J., & Lavoie, M. The velocity of postglacial migration of fire-adapted boreal tree species in eastern North America. *Proceedings of the National Academy of Sciences*, **119**(43), e2210496119 (2022).
10. Vincent, W. F., Lemay, M., & Allard, M. Arctic permafrost landscapes in transition: towards an integrated Earth system approach. *Arctic Science*, **3**(2), 39-64 (2017).
11. Heijmans, M. M., Magnússon, R. Í., Lara, M. J., Frost, G. V., Myers-Smith, I. H., van Huissteden, J., ... & Limpens, J. Tundra vegetation change and impacts on permafrost. *Nature Reviews Earth & Environment*, **3**(1), 68-84 (2022).
12. Hjort, J., Streletskiy, D., Doré, G., Wu, Q., Bjella, K., & Luoto, M. Impacts of permafrost degradation on infrastructure. *Nature Reviews Earth & Environment*, **3**(1), 24-38 (2022).
13. Miner, K. R., Turetsky, M. R., Malina, E., Bartsch, A., Tamminen, J., McGuire, A. D., ... & Miller, C. E. Permafrost carbon emissions in a changing Arctic. *Nature Reviews Earth & Environment*, **3**(1), 55-67 (2022).
14. Berteaux, D., Gauthier, G., Domine, F., Ims, R. A., Lamoureux, S. F., Lévesque, E., & Yoccoz, N.. Effects of changing permafrost and snow conditions on tundra wildlife: critical places and times. *Arctic Science*, **3**(2), 65-90 (2016).
15. Boelman, N. T., Gough, L., Wingfield, J., Goetz, S., Asmus, A., Chmura, H. E., ... & Guay, K. C. Greater shrub dominance alters breeding habitat and food resources for migratory songbirds in Alaskan arctic tundra. *Global Change Biology*, ***21***(4), 1508-1520, (2015)

16. Dakos, V., Carpenter, S. R., van Nes, E. H., & Scheffer, M. Resilience indicators: prospects and limitations for early warnings of regime shifts. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **370**(1659), 20130263 (2015).
17. Scheffer, M., Carpenter, S. R., Dakos, V., & van Nes, E. H. Generic indicators of ecological resilience: inferring the chance of a critical transition. *Annual Review of Ecology, Evolution, and Systematics*, **46**, 145-167 (2015).
18. Harfoot, M. B., Newbold, T., Tittensor, D. P., Emmott, S., Hutton, J., Lyutsarev, V., ... & Purves, D. W. Emergent global patterns of ecosystem structure and function from a mechanistic general ecosystem model. *PLoS biology*, **12**(4), e1001841 (2014).
19. Krueger, T., Page, T., Hubacek, K., Smith, L., & Hiscock, K. The role of expert opinion in environmental modelling. *Environmental Modelling & Software*, **36**, 4-18 (2012).
20. Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., ... & Lenton, T. M. Exceeding 1.5 C global warming could trigger multiple climate tipping points. *Science*, **377**(6611), eabn7950 (2022).
21. IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, doi:10.1017/9781009157896 (2021)
22. Scheffer, M., Bascompte, J., Brock, W. A., Brovkin, V., Carpenter, S. R., Dakos, V., ... & Sugihara, G. Early-warning signals for critical transitions. *Nature*, **461**(7260), 53-59 (2009).
23. Antão, L. H., Bates, A. E., Blowes, S. A., Waldock, C., Supp, S. R., Magurran, A. E., ... & Schipper, A. M. Temperature-related biodiversity change across temperate marine and terrestrial systems. *Nature ecology & evolution*, **4**(7), 927-933 (2020).
24. Feng, Y., Su, H., Tang, Z., Wang, S., Zhao, X., Zhang, H., ... & Fang, J. Reduced resilience of terrestrial ecosystems locally is not reflected on a global scale. *Communications Earth & Environment*, **2**(1), 88 (2021).
25. Antão, L. H., Weigel, B., Strona, G., Hällfors, M., Kaarlejärvi, E., Dallas, T., ... & Laine, A. L. Climate change reshuffles northern species within their niches. *Nature Climate Change*, **12**(6), 587-592 (2022).
26. Payette, S. Contrasted dynamics of northern Labrador tree lines caused by climate change and migrational lag. *Ecology*, *88*(3), 770-780 (2007).
27. Harsch, M. A., Hulme, P. E., McGlone, M. S., & Duncan, R. P. Are treelines advancing? A global meta-analysis of treeline response to climate warming. *Ecology Letters*, **12**(10), 1040-1049 (2009).
28. Lu, X., Liang, E., Wang, Y., Babst, F., & Camarero, J. J. Mountain treelines climb slowly despite rapid climate warming. *Global Ecology and Biogeography*, **30**(1), 305-315 (2021).
29. Maher, C. T., Dial, R. J., Pastick, N. J., Hewitt, R. E., Jorgenson, M. T., & Sullivan, P. F. The climate envelope of Alaska's northern treelines: implications for controlling factors and future treeline advance. *Ecography*, **44**(11), 1710-1722 (2021).
30. Lenoir, J., Bertrand, R., Comte, L., Bourgeaud, L., Hattab, T., Murienne, J., & Grenouillet, G. Species better track climate warming in the oceans than on land. *Nature ecology & evolution*, **4**(8), 1044-1059 (2020).

31. Fischer, H., Meissner, K. J., Mix, A. C., Abram, N. J., Austermann, J., Brovkin, V., ... & Zhou, L. Palaeoclimate constraints on the impact of 2 °C anthropogenic warming and beyond. *Nature geoscience*, **11**(7), 474-485 (2018).
32. McCrystall, M. R., Stroeve, J., Serreze, M., Forbes, B. C., & Screen, J. A. New climate models reveal faster and larger increases in Arctic precipitation than previously projected. *Nature communications*, **12**(1), 6765 (2021).
33. Bigalke, S., & Walsh, J. E. Future Changes of Snow in Alaska and the Arctic under Stabilized Global Warming Scenarios. *Atmosphere*, **13**(4), 541 (2022).

METHODS

A supertransect across northern ecosystems

The study region is a ~100 km-wide band of land extending from Matagami (49°45'N), located in the boreal forest biome of the James Bay region, to the polar desert of northern Ellesmere and Ward Hunt (83°04'N), the northernmost islands of the Canadian Arctic Archipelago (**Fig. 2**). Multidisciplinary environmental studies have been conducted by numerous teams at several sites along this gradient over the last 60 years[34-41], providing a legacy of in-depth knowledge of the biotic and abiotic components that make up the landscapes of this vast northern region. The current state of the various ecosystem components along the gradient is partly the result of the late Pleistocene and Holocene history of the region[42,43]. Mean annual air temperature along the gradient currently ranges from -25°C to 0°C, and annual precipitation from 100-200 mm to 800-1000 mm (according to CHELSA climate data, see **Fig. 2**)[38,44]. The study region encompasses other environmental variations with respect to hydrology, topography and geology. We restricted our analyses to low elevation areas (< 750 m), and excluded land currently covered by glaciers. Rocks found along the entire gradient belong to four broad geological provinces, mostly within the Canadian Shield (Superior and Churchill provinces) in the southern and central regions[45]. Hence, we assumed that geological differences across the study region have negligible effects on the location of critical thresholds (southern limits of contrasting states) and on the variation in sensitivity estimates. Moreover, it is a region with very sparse human population, negligible direct impact of human activities, and it is in one of the Earth's last remaining wildernesses[46,47]. The current state of ecosystems found along the gradient is thus essentially the result of natural postglacial processes. This makes the study region a global rarity that allowed us to focus on climatic impacts on the environment without the confounding effects of direct human pressures.

Expert elicitation

The aim of our expert elicitation process was twofold: 1) to identify the location of critical latitudinal thresholds between ecosystem component states, and 2) to assess the sensitivity of six key ecosystem components of northern landscapes: permafrost, peatlands, lakes, snowpack, vegetation and endothermic vertebrates. State shifts of these components can have strong impacts on ecosystem services (e.g., climate regulation, global biogeochemical cycles[48,49]) and on the culture, health and well-being of the indigenous communities inhabiting the study region (including food and water security, infrastructure, transportation, safety, health and traditional activities[12,50-52]).

We used structured expert elicitation inspired by the Delphi technique in which we combined multidisciplinary workshops with several rounds of expert assessments to ensure that all experts had the same interpretation of the questions and fully understood the aim of the project[53,54]. A set of 31 experts were chosen to cover a wide range of disciplines (geomorphology, hydrology, nivology, limnology, plant and animal ecology and plant paleoecology). For each component, we ensured that research conducted by experts covered the entire study region. Experts were separated into 6 groups (one per component, 2 to 8 experts per group). Facilitators then asked a series of questions to each group (**Table 2**). Experts first identified contrasting states found along the gradient. They provided detailed definitions for each contrasting state and justified their answers by providing detailed explanations (see **Extended Data Figures 2-7** for illustrations and Supplementary Materials for justifications). For each ecosystem component, experts determined the southernmost location (± 2.5 latitudinal degrees) of all contrasting states along the latitudinal gradient (e.g., the southern limit of continuous permafrost or the southern limit of shrub tundra vegetation; **Fig. 2**). Ecosystems located at these southern limits were considered to be at critical thresholds, as ecosystems located further south (i.e., under warmer conditions) were characterized by a contrasting state or by a transition zone between contrasting states.

Experts characterized the relative sensitivity of an ecosystem component at each critical threshold by estimating the time required (the response time, in years) necessary for a component located at the southern limit of its current state to shift to another existing contrasting state under a hypothetical warming scenario. To facilitate expert assessment, we used a marked temperature increase and broad time scales to quantify state shift response time. Models predicting future warming scenarios indicate large annual air temperature changes at the end of this century for northernmost latitudes, with projected changes 2 to 4 times greater in Arctic regions relative to global trends[4,21,55,56]. In the Canadian Arctic, this corresponds to increases of 3 to 10°C (shared Socioeconomic Pathway SSP1-2.6 and SSP5-8.5) by the end of the 21st century (relative to the 1986-2005 reference period[21]). We thus used a sudden and persistent 5°C increase in mean annual air temperature with respect to the 1986-2005 baseline period, and asked experts to categorize response times using time intervals on a log temporal scale (1-10 years, 10-100 years or >100 years). They considered known mechanisms, past changes and field studies, as well as known cascading effects and interactions between ecosystem components. Experts also identified the main sources of uncertainty in response times that could be partly generated by synergistic links between environmental variables with unknown trajectories that would ensue from warming (e.g., changes in precipitation type/patterns or fire regimes).

When the initial round of questions to experts was completed, facilitators summarized the answers (number of contrasting states, definitions, southern limits, response times and justifications) and shared them among the groups. Five multidisciplinary workshops were organized for discussions between experts, who subsequently revised their answers and improved their justifications in smaller groups. Several rounds of revisions were made for each ecosystem component until a consensus was reached among all experts.

Statistical analysis

We tested whether sensitivities (response time intervals) were randomly distributed among the observed critical threshold locations (n = 22 latitudes) with permutation tests. We first estimated the probability that the observed mean latitude of critical thresholds with low sensitivity (i.e., thresholds for which the maximum response time was >100 years, n = 8) was lower or higher than expected by chance. We computed the mean latitude for each possible permutation (n = 319,770). Using the mean and standard deviation of the resulting distribution of mean latitudes, we then calculated a *p*-value to determine if the observed mean latitude was unlikely to appear in a random situation. Following the same method, we estimated the probability that the observed mean latitude of critical thresholds with high sensitivity (i.e., critical thresholds for which the minimum response time was 1-10 years, n = 3; 1,540 permutations), was lower or higher than expected by chance.

REFERENCES

34. Fallu, M. A., & Pienitz, R. Diatomées lacustres de Jamésie-Hudsonie (Québec) et modèle de reconstitution des concentrations de carbone organique dissous. *Ecoscience*, **6**(4), 603-620 (1999).
35. Gauthier, G., Berteaux, D., Bêty, J., Tarroux, A., Therrien, J. F., McKinnon, L., ... & Cadieux, M. C. The tundra food web of Bylot Island in a changing climate and the role of exchanges between ecosystems. *Ecoscience*, **18**(3), 223-235 (2011).
36. Payette, S., & Saulnier-Talbot, É. Un demi-siècle de recherche au Centre d'études nordiques: un défi de tous les instants. *Écoscience*, **18**(3), 171-181 (2011).
37. Bhiry, N., Delwaide, A., Allard, M., Bégin, Y., Filion, L., Lavoie, M., ... & Vincent, W. F. Environmental change in the Great Whale River region, Hudson Bay: Five decades of multidisciplinary research by Centre d'études nordiques (CEN). *Ecoscience*, **18**(3), 182-203 (2011).
38. Vincent, W. F., Fortier, D., Lévesque, E., Boulanger-Lapointe, N., Tremblay, B., Sarrazin, D., ... & Mueller, D. R. Extreme ecosystems and geosystems in the Canadian High Arctic: Ward Hunt Island and vicinity. *Ecoscience*, **18**(3), 236-261 (2011).
39. Payette, S., & Delwaide, A. Tamm review: the North-American lichen woodland. *Forest Ecology and Management*, **417**, 167-183 (2018).
40. Saulnier-Talbot, É., Antoniades, D., & Pienitz, R. Hotspots of biotic compositional change in lakes along vast latitudinal transects in northern Canada. *Global Change Biology*, **26**(4), 2270-2279 (2020).
41. Royer, A., Domine, F., Roy, A., Langlois, A., Marchand, N., & Davesne, G. New northern snowpack classification linked to vegetation cover on a latitudinal mega-transect across northeastern Canada. *Écoscience*, **28**(3-4), 225-242 (2021).
42. Ritchie, J. C. *Post-glacial vegetation of Canada*. Cambridge University Press (2004).
43. Dalton, A. S., Margold, M., Stokes, C. R., Tarasov, L., Dyke, A. S., Adams, R. S., ... & Wright Jr, H. E. An updated radiocarbon-based ice margin chronology for the last deglaciation of the North American Ice Sheet Complex. *Quaternary Science Reviews*, **234**, 106223 (2020).
44. Karger, D. N., Conrad, O., Böhner, J., Kawohl, T., Kreft, H., Soria-Auza, R. W., ... & Kessler, M. Climatologies at high resolution for the earth’s land surface areas. *Scientific data*, **4**(1), 1-20 (2017).
45. Wheeler, J.O., Hoffman, P.F., Card, K.D., Davidson, A., Sanford, B.V., Okulitch, A.V., and Roest, W.R. Geological map of Canada; Geological Survey of Canada, Map 1860A. doi:10.4095/208175 (1996).

46. Watson, J. E., Evans, T., Venter, O., Williams, B., Tulloch, A., Stewart, C., ... & Lindenmayer, D. The exceptional value of intact forest ecosystems. *Nature ecology & evolution*, **2**(4), 599-610 (2018).
47. Hirsh-Pearson, K., Johnson, C. J., Schuster, R., Wheate, R. D., & Venter, O. Canada's human footprint reveals large intact areas juxtaposed against areas under immense anthropogenic pressure. *Facets*, **7**(1), 398-419 (2022).
48. Wik, M., Varner, R. K., Anthony, K. W., MacIntyre, S., & Bastviken, D. Climate-sensitive northern lakes and ponds are critical components of methane release. *Nature Geoscience*, **9**(2), 99-105 (2016).
49. Loisel, J., Gallego-Sala, A. V., Amesbury, M. J., Magnan, G., Anshari, G., Beilman, D. W., ... & Wu, J. Expert assessment of future vulnerability of the global peatland carbon sink. *Nature climate change*, **11**(1), 70-77 (2021).
50. White, D. M., Gerlach, S. C., Loring, P., Tidwell, A. C., & Chambers, M. C. Food and water security in a changing arctic climate. *Environmental Research Letters*, **2**(4), 045018 (2007).
51. Boulanger-Lapointe, N., Gérin-Lajoie, J., Siegwart Collier, L., Desrosiers, S., Spiech, C., Henry, G. H., ... & Cuerrier, A. Berry plants and berry picking in Inuit Nunangat: Traditions in a changing socio-ecological landscape. *Human Ecology*, **47**, 81-93 (2019).
52. Decaulne, A., Bhiry, N., Faucher-Roy, J., & Boily, C. P. The development of Kangiqsualujjuaq and the threat of snow avalanches in a permafrost degradation context, Nunavik, Canada. *Espace populations sociétés. Space populations societies*, (2020/3-2021/1) (2021).
53. Mukherjee, N., Huge, J., Sutherland, W. J., McNeill, J., Van Opstal, M., Dahdouh-Guebas, F., & Koedam, N. The Delphi technique in ecology and biological conservation: applications and guidelines. *Methods in Ecology and Evolution*, **6**(9), 1097-1109 (2015).
54. Dicks, L. V., Breeze, T. D., Ngo, H. T., Senapathi, D., An, J., Aizen, M. A., ... & Potts, S. G. A global-scale expert assessment of drivers and risks associated with pollinator decline. *Nature Ecology & Evolution*, **5**(10), 1453-1461 (2021).
55. AMAP, A. C. C. U. Key Trends and Impacts. *Summary for Policy-Makers, Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway*, 16 (2021).
56. Jansen, E., Christensen, J. H., Dokken, T., Nisancioglu, K. H., Vinther, B. M., Capron, E., ... & Stendel, M. Past perspectives on the present era of abrupt Arctic climate change. *Nature Climate Change*, **10**(8), 714-721 (2020).

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Author contributions

ÉS-T, ÉD, DB, DG, GG, JB and WFV were responsible for conceptualization. ÉD and JB undertook data curation. ÉS-T, ÉD, JB, and KC developed the methodology. ÉD, JB and KC conducted the formal analysis. ÉD, JB, KC and MZCR were responsible for visualization. All co-authors contributed to data interpretation. ÉS-T, ÉD, JB wrote the original draft and all other authors reviewed and edited the final manuscript.

Competing interests

The authors declare no competing interests.

Supplementary information

The online version contains supplementary materials available at...

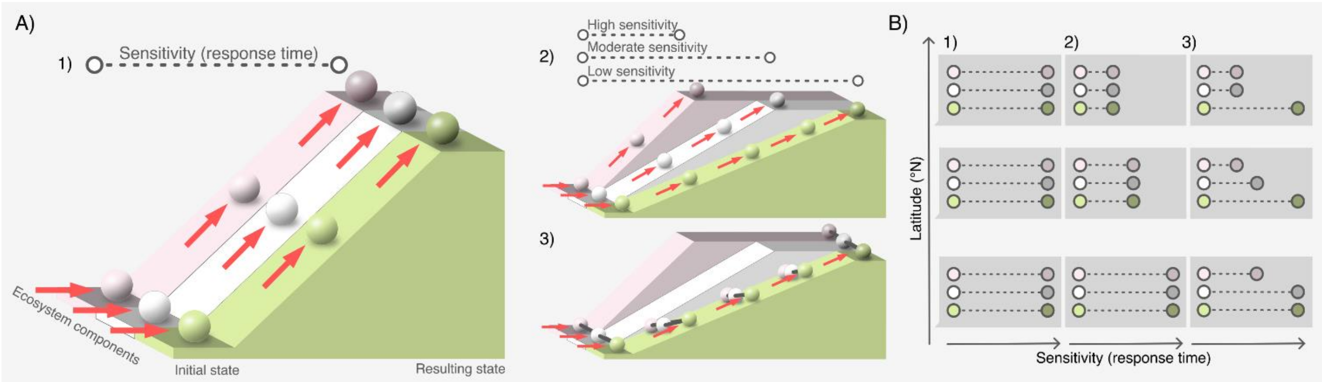


Fig. 1. Schematic representation of ecosystem components at critical thresholds (spheres located at the edge of a slope) and exposed to the same persistent environmental change (indicated by the red arrows). The sensitivity of the components to change is illustrated by the time required (response time) to shift from an initial to a resulting state. Response times can be independent and homogenous (A1) or heterogenous (A2) among coexisting components. Interconnections between components (a sphere pulling other components) can reduce the heterogeneity in response times among coexisting components (A3). Response times can be homogenous across latitude (B1), homogenous between coexisting components but heterogenous across latitude (B2), or heterogenous between components and across latitude (B3).

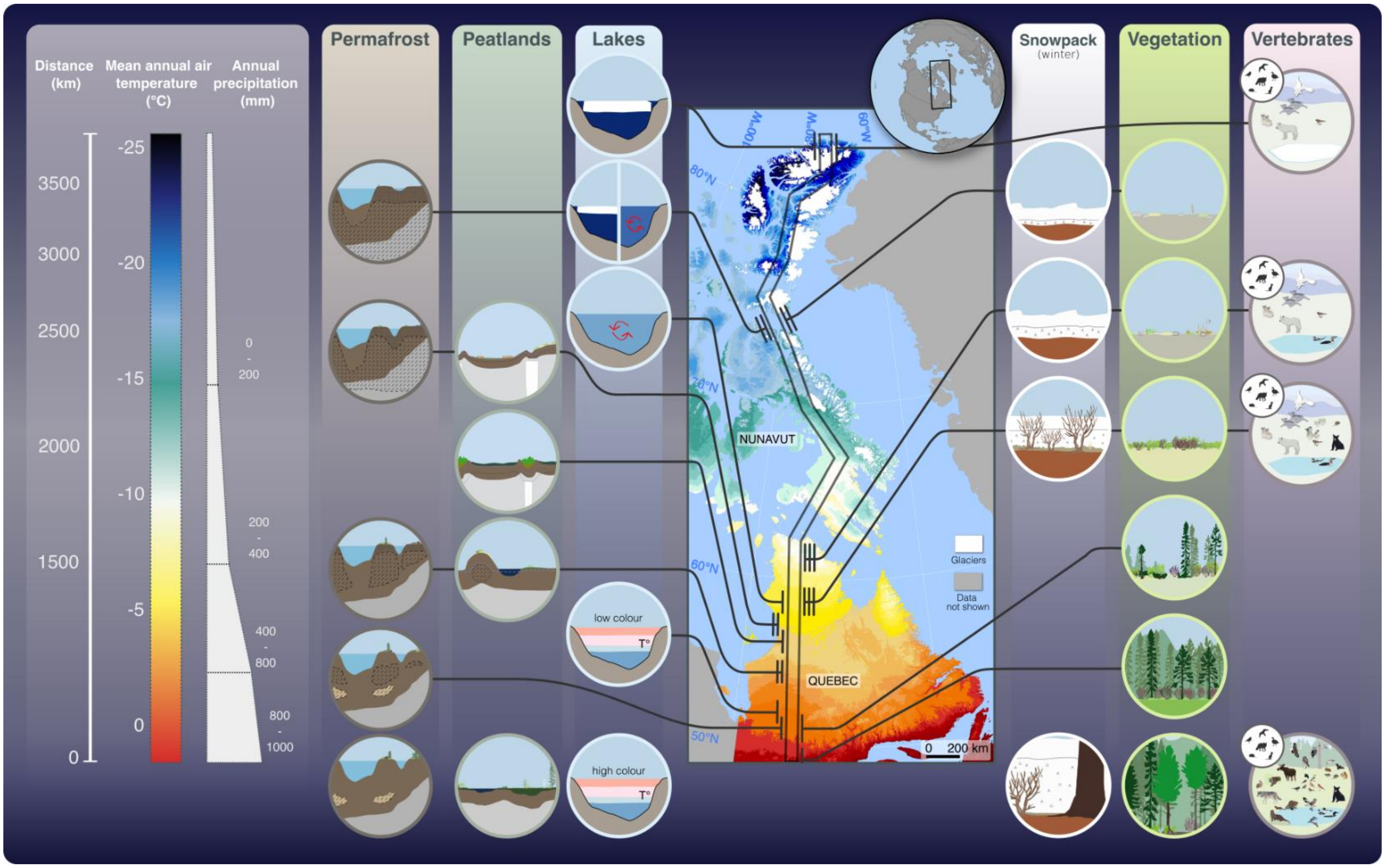


Fig. 2. Location and extent of the study region, a 100 km-wide strip of land covering a vast latitudinal gradient (3,700 km) in northeastern North America. Mean annual air temperature along the gradient currently ranges from 0°C to -25°C (see **Extended Data Fig. 1** for the July temperatures), while annual precipitation ranges from 800-1000 mm to 100-200 mm. Simplified illustrations of the current 28 contrasting states observed along the gradient for six ecosystem components (permafrost, peatlands, lakes, winter snowpack, vegetation and endothermic vertebrate assemblages) are presented alongside the map. Detailed illustrations are available in the **Extended Data Figures (2-7)**. The southern limit (± 2.5 degrees of latitude) of each state is identified along the latitudinal gradient.

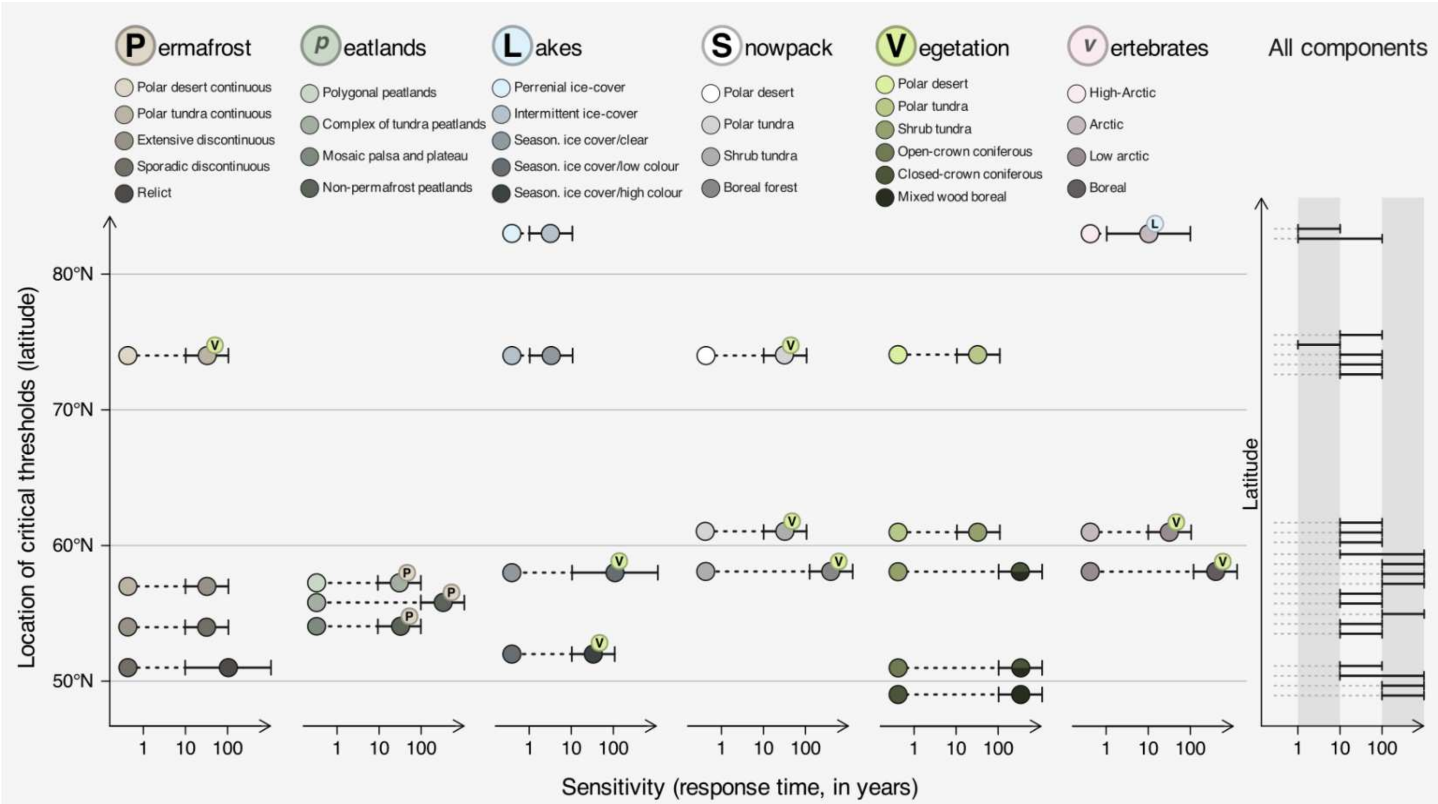


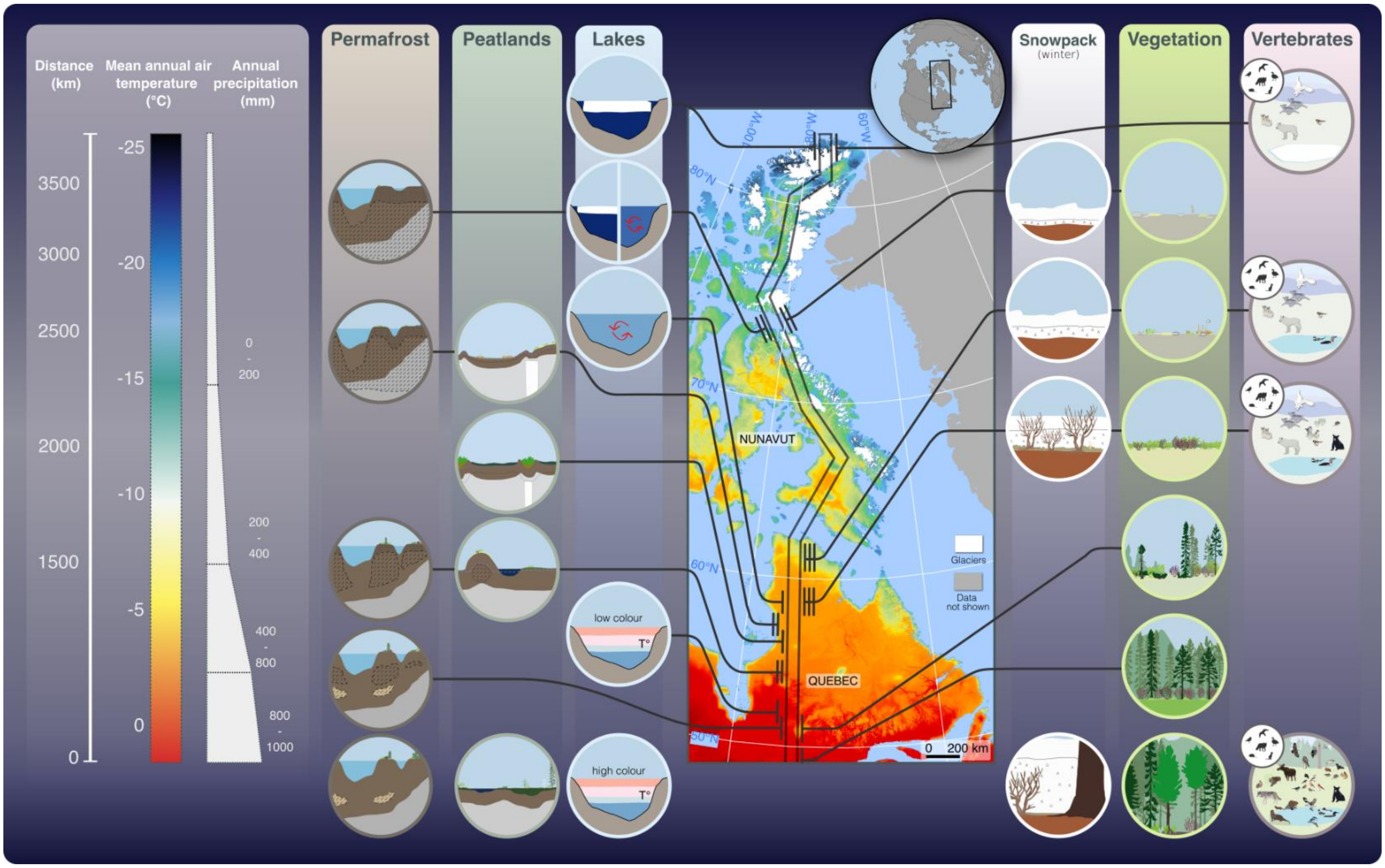
Fig. 3. Expert assessment of the sensitivity to state shifts of ecosystem components at critical thresholds identified along a 3,700 km latitudinal gradient in northeastern North America. The colours show contrasting states (initial and resulting) at each critical threshold. The response time is the estimated number of years (log scale) necessary for a component to shift from an initial to a resulting state under a warmer climate (i.e., a sudden and persistent 5°C increase in annual air temperature). The southernmost modern-day location of a given contrasting state is its critical threshold. Overlaid spheres with letters indicate that a warming-induced change of a given component (**L**: lakes, **P**: permafrost, **V**: vegetation) is the key determinant of the response time of another component. Sensitivity estimates of all components are combined in the right panel, where locations of critical thresholds are vertically jittered for visualisation purposes.

Table 1. Main characteristics used to discriminate contrasting states for six key ecosystem components of terrestrial landscapes along a ~100 km wide, 3,700 km latitudinal gradient across northeastern North America and examples of state shift impacts on ecosystem properties. See **Extended Data Figures (2-7)** and *Supplementary Materials* for detailed descriptions and illustrations of contrasting states.

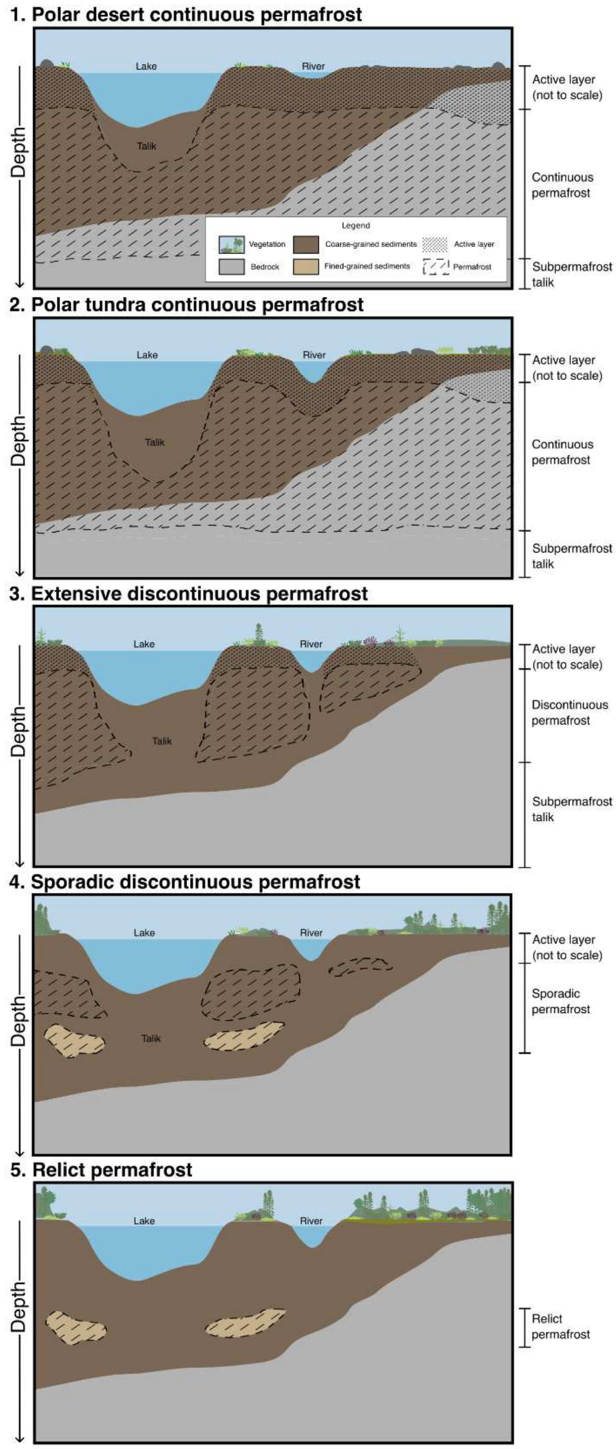
Ecosystem component	Discriminating characteristics	Ecosystem properties affected by state shift
Permafrost (5 states)	- Extent in the landscape - Temperature, thickness, connectivity, water and ice content of the different layers	- Surface/subsurface hydrology and biological activity - Surface energy budget - Nutrient cycle
Peatlands (4 states)	- Surface morphology - Permafrost dynamics - Hydrology - Vegetation (functional groups)	- Nutrient cycle - Greenhouse gas balance - Hydrological cycle - Biodiversity
Lakes (5 states)	- Extent of ice cover - Water mixing and stratification regime - Light and oxygen availability - Dissolved organic matter content	- Nutrient cycles - Greenhouse gas balance - Primary productivity - Biodiversity
Vegetation (6 states)	- Extent of vegetation cover - Vegetation height - Plant growth forms	- Habitat structure - Surface energy budget - Nutrient cycle - Hydrological cycle - Biodiversity
Snowpack (4 states)	- Snowpack thickness - Stratigraphy (density, ice crystal type, grain size and hardness of different layers)	- Surface energy budget - Surface/subsurface hydrology - Biodiversity
Vertebrates (4 states)	- Occurrence and relative abundance of functional groups	- Diseases, propagules, and energy transport - Nutrient cycle - Plant succession

Table 2. Questions asked by facilitators during the expert elicitation process. Each question aimed to assess a specific metric, expressed in predetermined units.

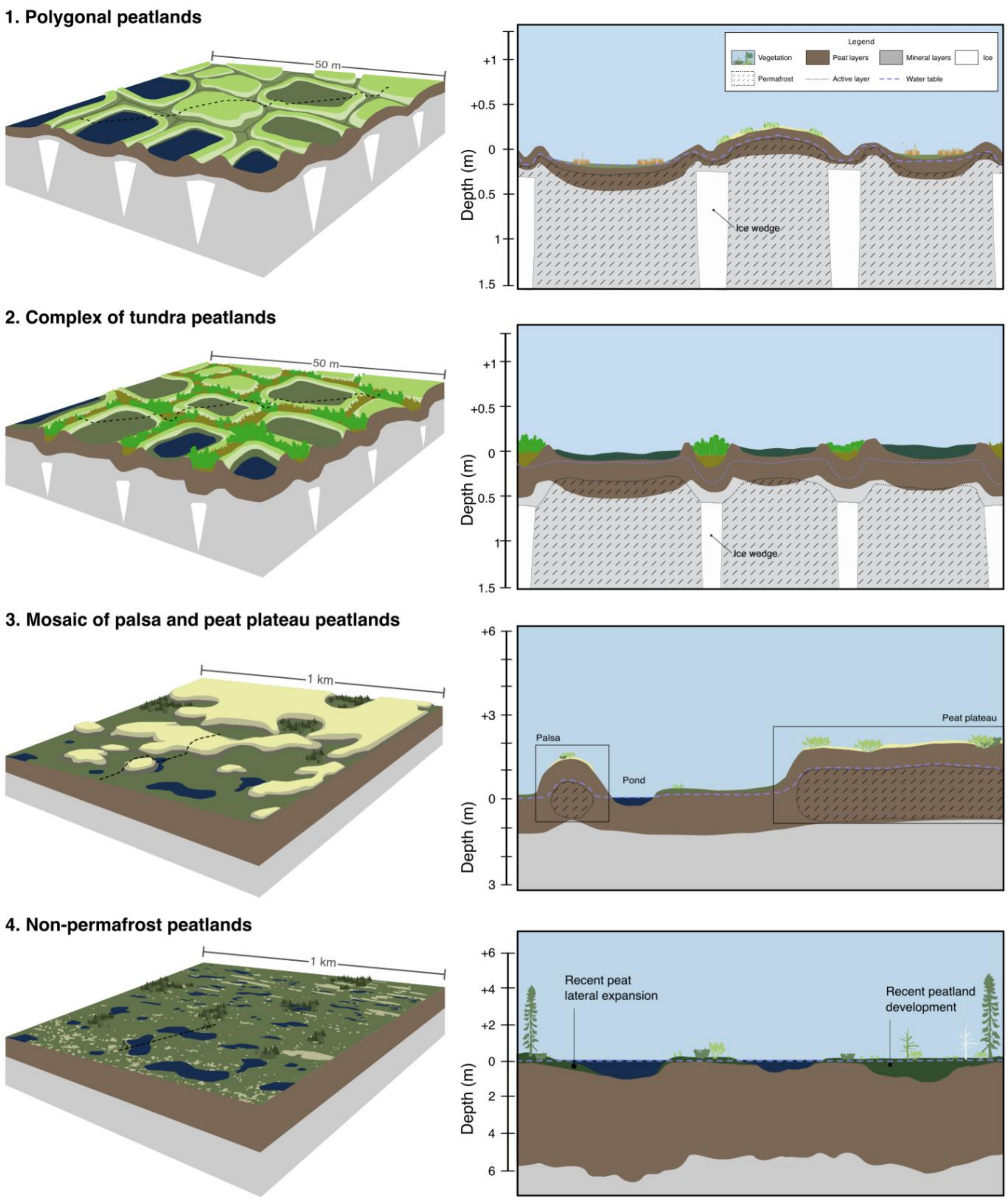
Question	Metric	Units
What is the minimum number of contrasting states, characterized by marked differences in structure and function, that you can distinguish along the latitudinal gradient (~100 km-wide transect)?	Number and definition of contrasting states	Number
Where is the southern limit of each contrasting state located along the gradient?	Latitude	Degrees (±2.5°N)
At the southern limit of a given state, how long would it take to shift to another, existing state (currently found along the gradient) if the ecosystem was exposed to a sudden and persistent 5°C increase in mean annual temperature?	Sensitivity (Response time)	High (1-10 years) Moderate (10-100 years) Low (>100 years)



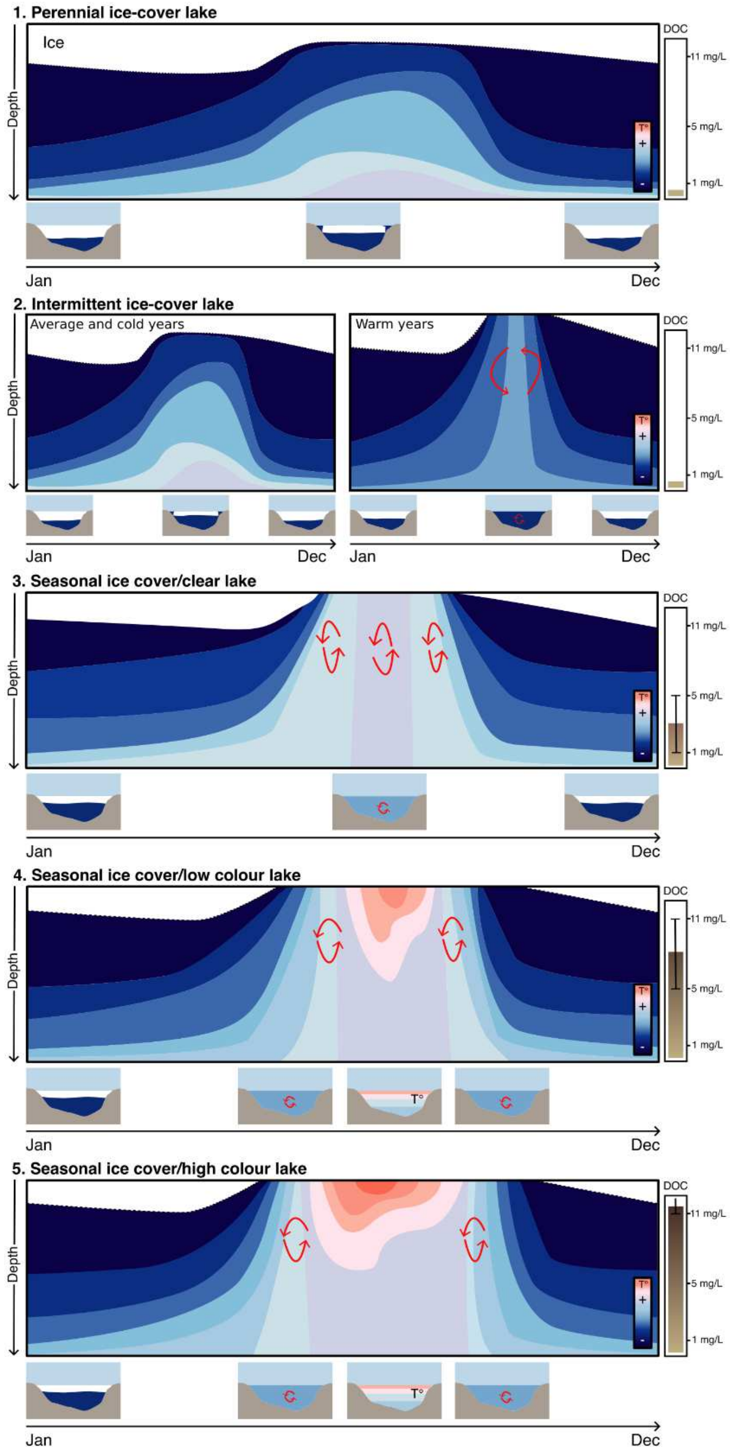
Extended data Fig. 1 | Map showing the location and extent of the study region in northeastern North America. Mean July daily air temperatures along the gradient are shown. Simplified illustrations of the current 28 contrasting states observed along the gradient for six ecosystem components are presented alongside the map. The southern limit (± 2.5 degrees of latitude) of each state is identified along the latitudinal gradient.



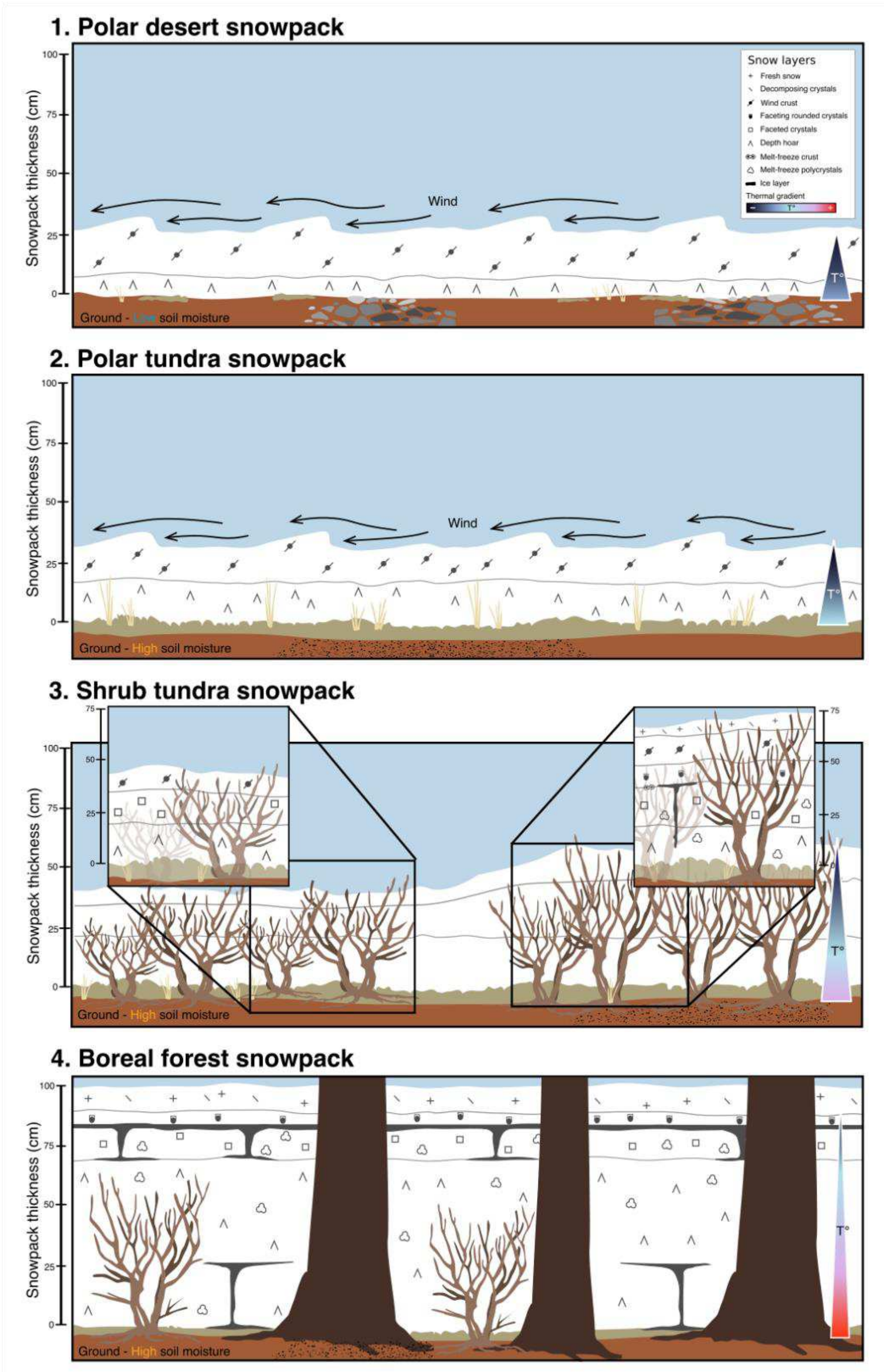
Extended Data Fig. 2 | Permafrost is defined as rock or soil that remains below 0°C for at least two consecutive years. Along the latitudinal gradient, it ranges from 1) an extensive continuous thick permafrost to 5) a relict permafrost located in underground isolated patches. Permafrost contrasting states are primarily based on the extent of frozen ground across the landscape (30 km X 30 km). States are also described using the characteristics (temperature, permafrost thickness, water and ice contents) of their different layers (active layer, perennially frozen ground and taliks).



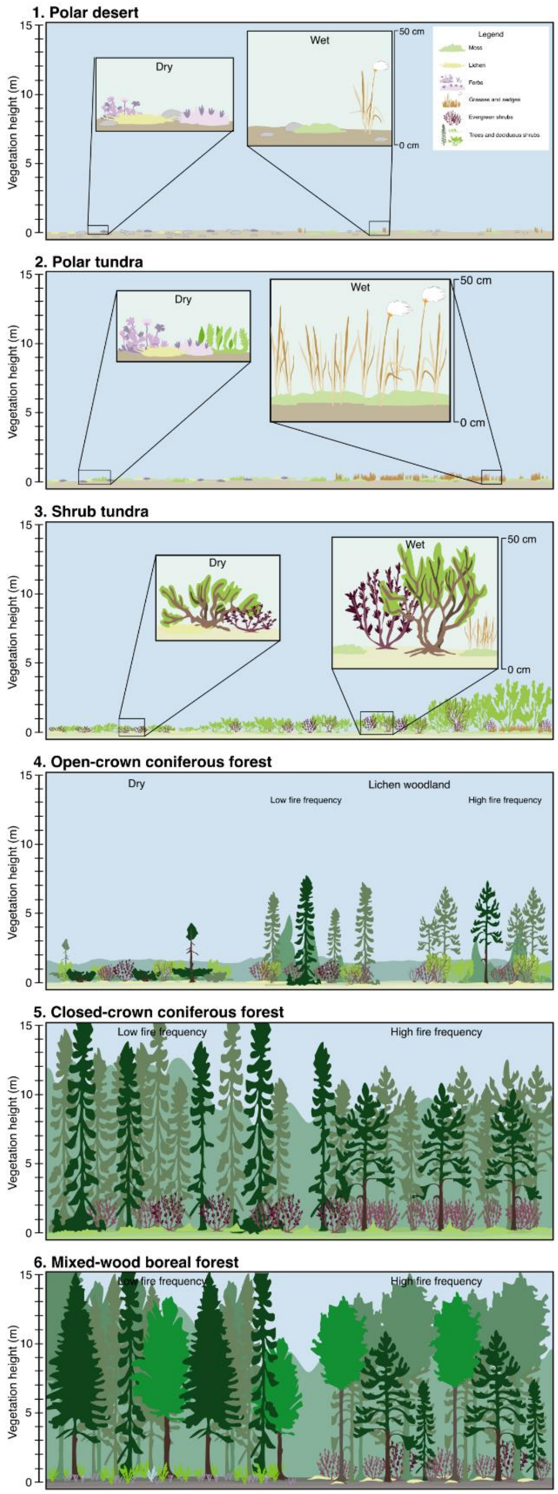
Extended Data Fig. 3 | Peatlands are terrestrial ecosystems in which waterlogged conditions prevent plant material from fully decomposing. Along the latitudinal gradient, they range from 1) polygonal peatlands shaped by the dynamics of ice-wedge networks to 4) peatlands completely devoid of permafrost. The contrasting peatland states are defined by their surface morphology, the water and permafrost table dynamics, including the thickness of the active layer, as well as vegetation communities.



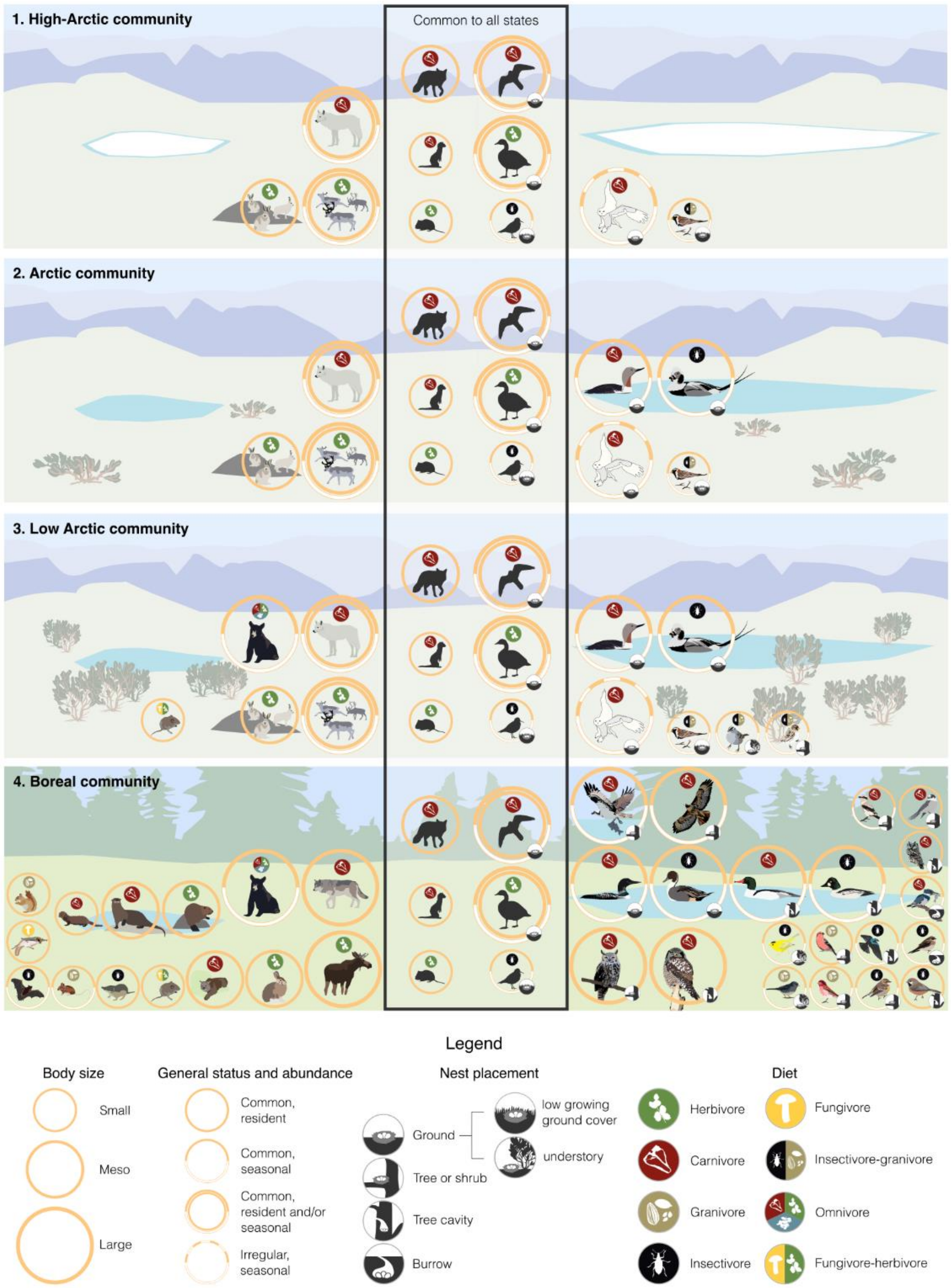
Extended Data Fig. 4 | Along the latitudinal gradient, freshwater lakes (the typical lake for the study region has an average area of 24 ha and a mean depth of 4.0 m – see Supplementary Materials) range from 1) perennially frozen clear lakes to 4) lakes with seasonal ice cover and high dissolved organic matter content. Lake contrasting states are defined by the extent of ice cover, the stratification of the water column and the mixing regime, the oxygen and light availability, as well as the dissolved organic matter content (given as dissolved organic carbon, or DOC).



Extended Data Fig. 5 | Winter snowpack covers the study region for 6 to 10 months of the year. Snowpack contrasting states are described based on the depth of snow and snowpack stratigraphy, describing ice crystal type, grain size and hardness of the different snow layers of the snowpack in a landscape (30 km X 30 km) characterized by a flat terrain with mesic conditions. Along the transect, the snowpack ranges from a 1) two-layer poorly insulating, thin, hard and dense polar desert snowpack to a 4) multi-layer, very thick and insulating boreal forest snowpack.



Extended Data Fig. 6 | Along the latitudinal gradient, vegetation ranges from 1) very sparse and low polar desert vegetation to 4) dense and tall, closed canopy boreal forest vegetation. Vegetation contrasting states are defined by the dominant structural characteristics of vegetation cover, namely height and growth form (herbs, forbs, shrubs, coniferous and deciduous trees), found on a landscape (30 km × 30 km) characterized by a flat terrain with mesic conditions.



Extended Data Fig. 7 | Along the latitudinal gradient, endothermic terrestrial vertebrate communities range from an assemblage of 1) few functional groups in the High-Arctic to the 4) highly functionally diverse boreal vertebrate community. Contrasting states are defined by the occurrence and relative abundance of mammalian and avian functional groups present and active in the landscape (100 km x 100 km, a scale that encompasses summer home ranges of most taxa) throughout the annual cycle. Functional traits known to affect species interaction strength, dynamics of vertebrate communities and ecosystem processes were used to characterise functional groups (e.g., body size, nest placement, diet, hunting mode and sociality).

Extended Data Table 1 | Key determinants of the sensitivity of the contrasting states of each ecosystem component to a hypothetical warming scenario assessed by expert knowledge. The sensitivity is quantified by response time, which is the estimated time required for a component at critical threshold to shift from an initial state to another, existing contrasting state following an exposure to a sudden and persistent 5°C increase of mean annual temperature. Key determinants are the main abiotic or biotic factors (in **boldface**) that determine the response time of a component. Local conditions that can modulate response time (i.e., increase or decrease response time within the selected time interval) are also indicated.

Permafrost					
State shift		Sensitivity (Response time, in years)	Key determinants of response time		Local conditions modulating response time
From	To		Direct effects of air temperature on	Indirect effects of air temperature via	
1. Polar desert continuous permafrost	**2.** Polar tundra continuous permafrost	10-100	NA	**Vegetation state shift** (triggers snowpack state shift)	See vegetation (polar desert to polar tundra)
2. Polar tundra continuous permafrost	**3.** Extensive discontinuous permafrost	10-100	- Permafrost thickness - Permafrost extent	NA	- Vegetation cover - Snowpack properties - Soil characteristics - Topography - Precipitation - Ground ice content
3. Extensive discontinuous permafrost	**4.** Sporadic discontinuous permafrost	10-100	- Permafrost thickness - Permafrost extent	NA	- Vegetation cover - Snowpack properties - Soil characteristics - Topography - Precipitation - Ground ice content
4. Sporadic discontinuous permafrost	**5.** Relict permafrost	10-100 to >100	- Permafrost thickness - Permafrost extent	NA	- Vegetation cover - Snowpack properties - Soil characteristics - Topography - Precipitation - Ground ice content - Permafrost depth - Fire regime
Peatlands					
State shift		Sensitivity (Response time, in years)	Key determinants of response time		Local conditions modulating response time
From	To		Direct effects of air temperature on	Indirect effects of air temperature via	
1. Polygonal peatlands	**2.** Complex of tundra peatlands	10-100	NA	Permafrost degradation	- Soil characteristics - Topography - Precipitation - Ground ice content - Plant species colonization rate
2. Complex of tundra peatlands	**4.** Non-permafrost peatlands	>100	NA	Permafrost degradation	- Soil characteristics - Topography - Precipitation - Ground ice content

					- Plant species colonization rate
3. Mosaic of palsa and peat plateau peatlands	**4.** Non-permafrost peatlands	10-100	NA	Permafrost state shift	- Plant species colonization rate - See permafrost (extensive discontinuous to sporadic discontinuous).
Lakes					
State shift		Sensitivity (Response time, in years)	Key determinants of response time		Local conditions modulating response time
From	To		Direct effects of air temperature on	Indirect effects of air temperature via	
1. Perennial ice cover lake	**2.** Intermittent ice-cover lake	1-10	- Lake ice cover - Lake water temperature	NA	- Exposure to solar radiation and wind
2. Intermittent ice-cover lake	**3.** Seasonal ice cover/clear lake	1-10	- Lake ice cover - Lake water temperature	NA	- Exposure to solar radiation and wind
3. Seasonal ice cover/clear lake	**4.** Seasonal ice cover/low colour lake	10-100	NA	**- Vegetation densification** **- Changes in plant assemblages** - Permafrost degradation	- Catchment soil characteristics and hydrology
4. Seasonal ice cover/low colour lake	**5.** Seasonal ice cover/high colour lake	10-100	NA	**- Vegetation densification** **- Changes in plant assemblages** - Permafrost degradation	- Catchment soil characteristics and hydrology
Snowpack					
State shift		Sensitivity (Response time, in years)	Key determinants of response time		Local conditions modulating response time
From	To		Direct effects of air temperature on	Indirect effects of air temperature via	
1. Polar desert snowpack	**2.** Polar tundra snowpack	10-100	NA	**Vegetation state shift**	See Vegetation (polar desert to polar tundra).
2. Polar tundra snowpack	**3.** Shrub tundra snowpack	10-100	NA	**Vegetation state shift**	See Vegetation (polar tundra to shrub tundra).
3. Shrub tundra snowpack	**4.** Boreal forest snowpack	>100	NA	**Vegetation state shift**	See Vegetation (shrub tundra to forest).
Vegetation					
State shift		Sensitivity (Response time, in years)	Key determinants of response time		Local conditions modulating response time
From	To		Direct effects of air temperature on	Indirect effects of air temperature via	
1. Polar desert vegetation	**2.** Polar tundra vegetation	10-100	**Plant growth, survival and reproduction**	NA	- Precipitation - Topography - Soil characteristics - Exposure to solar radiation and wind

2. Polar tundra vegetation	**3.** Shrub tundra vegetation	10-100	**Plant growth, survival and reproduction**	NA	- Precipitation - Topography - Soil characteristics - Exposure to solar radiation and wind - Plant species colonization rate - Herbivory
3. Shrub tundra vegetation	**5.** Closed-crown coniferous forest **6.** Mixed wood boreal forest	>100	**Plant growth, survival and reproduction**	NA	- Precipitation - Topography - Soil characteristics - Exposure to solar radiation and wind - Plant species colonization rate - Herbivory - Frequency and intensity of disturbances (fire, insects)
4. Open-crown coniferous forest	**5.** Closed-crown coniferous forest **6.** Mixed wood boreal forest	>100	**Plant growth, survival and reproduction**	NA	- Precipitation - Topography - Soil characteristics - Exposure to solar radiation and wind - Plant species colonization rate - Herbivory - Frequency and intensity of disturbances (fire, insects)
5. Closed-crown coniferous forest	**6.** Mixed wood forest	>100	**Plant growth, survival and reproduction**	NA	- Precipitation - Topography - Soil characteristics - Exposure to solar radiation and wind - Plant species colonization rate - Herbivory - Frequency and intensity of disturbances (fire, insects)
Vertebrates					
State shift		Sensitivity (Response time, in years)	Key determinants of response time		Local conditions modulating response time
From	To		Direct effects of air temperature on	Indirect effects of air temperature via	
1. High-Arctic vertebrates	**2.** Arctic vertebrates	1-10 to 10-100	NA	Lake state shift	- Vertebrate species colonization rate - Species interactions - See Lakes (perennial ice cover to intermittent ice cover).
2. Arctic vertebrates	**3.** Low Arctic vertebrates	10-100	NA	**Vegetation state shift**	- Vertebrate species colonization rate - Species interactions - See Vegetation (polar tundra to shrub tundra).
3. Low Arctic vertebrates	**4.** Boreal vertebrates	>100	NA	**Vegetation state shift**	- Vertebrate species colonization rate - Species interactions - See Vegetation (shrub tundra to forest).

Supplementary material

Permafrost

Permafrost is defined as rock or soil that remains below 0°C for at least two consecutive years. Along the transect, it ranges from an extensive continuous thick permafrost to a relic permafrost located in underground isolated patches.

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Introduction

Permafrost provides a foundation for ecosystems and infrastructure in northern regions and its structural role can directly affect other ecosystem components (e.g., formation and drainage of lakes, release of nutrients and contaminants, production and emission of greenhouse gases) (Shur et al. 2007; French 2017; Hughes-Allen et al. 2021).

Permafrost is a thermodynamic phenomenon, and its main characteristics are temperature, followed by ice content and ground thermal properties, which are partly affected by both the mineral and organic matter content. Permafrost contrasting states are primarily based on the extent of frozen ground across the landscape. States are also described using the characteristics (temperature, permafrost thickness, water and ice contents) of their different layers (active layer, perennially frozen ground and taliks).

Permafrost research in the eastern Canadian Arctic reveals that permafrost properties change markedly with latitude and associated climatic conditions (Fortier & Allard 2005, Fortier et al. 2008, Verpaelst et al. 2017, Coulombe et al. 2019). Permafrost state is a function not only of Holocene post-glacial dynamics but also of previous glaciations (French 2017). The Canadian permafrost region is sub-divided in zones sharing common permafrost attributes, mostly climate-dependent (Heginbottom et al. 1995; O'Neill et al. 2020). The boundaries between these zones are generally diffuse and gradual along the latitudinal gradient (Brown 1967). The following five permafrost contrasting states are currently encountered from North to South along the latitudinal gradient covered by our study: 1. polar desert continuous permafrost, 2. polar tundra continuous permafrost, 3. extensive discontinuous permafrost, 4. sporadic discontinuous permafrost, and 5. relict permafrost. We defined the southern limit of a permafrost contrasting state as the southernmost modern-day position of a landscape (30 km X 30 km) dominated by this state along our latitudinal gradient. The southern limit of relict permafrost is not encompassed by our gradient. Southern limits identified along the transect were considered critical thresholds.

At each critical threshold, we determined the sensitivity of the permafrost state to a hypothetical warming scenario. We assessed the sensitivity using the estimated time required (the response time, in years) for an initial permafrost state to shift to another existing state if exposed to a sudden and persistent 5°C increase in mean annual temperature. We considered that a state shift is reached when more than 50% of the landscape is covered by the resulting state.

Permafrost state shifts at critical thresholds are expected to be mainly driven by the effects of changes in air temperature on ground temperature, as well as on vegetation and snowpack characteristics. Local conditions such as soil characteristics, topography, precipitation, ground ice content, vegetation cover, snowpack properties and fire regime (French 2017) can modulate response time of state shifts (increase or decrease response time within the assessed time interval).

1. Polar desert continuous permafrost

(Coldest permafrost, covering ≥ 90% of the landscape)

The polar desert continuous permafrost state is characterized by extensive frozen ground beneath the exposed land surface (≥ 90% of the landscape). This very cold (< -10°C) permafrost can be more than 600 m thick (Smith et al. 2003, Taylor et al. 1982), and generally has a very low unfrozen water content. Shallow isolated or closed taliks can be present under lakes that do not freeze to the bottom (generally with a depth > 3-4 m). Frost cracking and ice-wedge polygons are common, but ice wedges are generally narrow (~ 1 m wide). The active layer is thin in surface sediments (< 1 m), with a very low moisture content, and even thinner in patchy wetlands, where the organic layer acts as a thermal buffer (especially when dry) during the summer (Woo & Young 1998). Freeze-back of the active layer is fast (a few weeks) and dominated by upward freezing. The ground ice content is low (ice-poor) in dry zones and can be high (ice-rich) in humid zones and areas affected by Holocene marine transgression (Couture & Pollard 1998, Hodgson 1982, Hodgson & Nixon 1998, Paquette et al. 2021). Thermokarst processes are limited in magnitude and extent. This state coincides with the High Arctic zone corresponding to the polar desert vegetation class of Bliss and Matveyeva (1992).

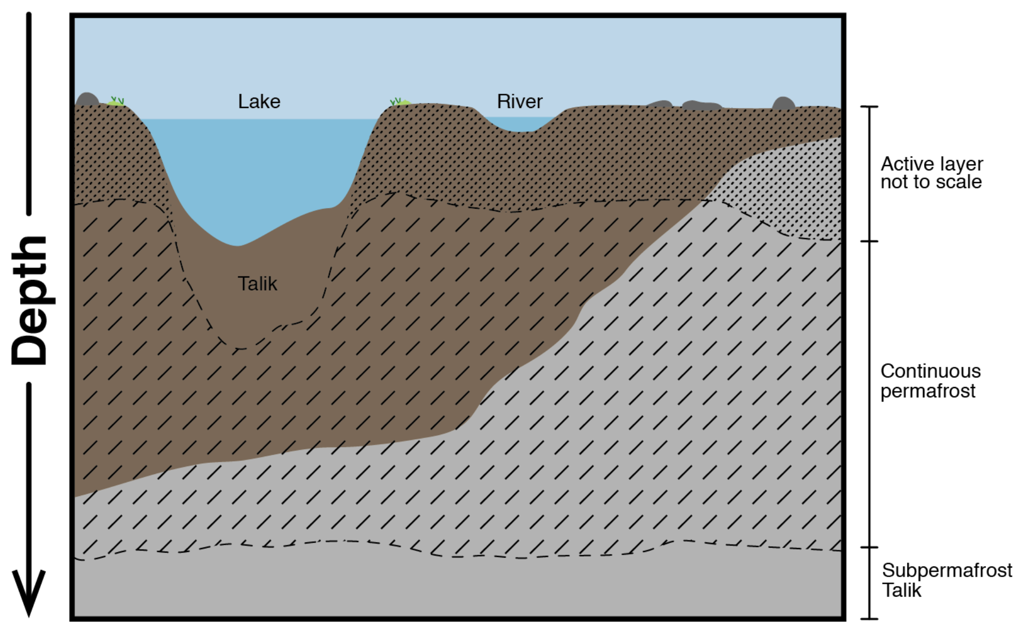
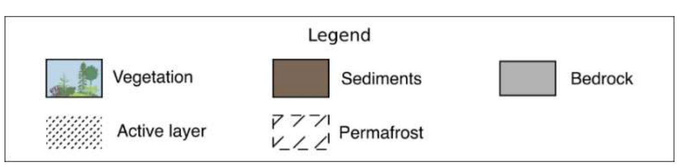


Fig. S1. Schematic representation of polar desert continuous permafrost.



Modern day southern limit: 74 ± 2.5 °N

State shift from <u>Polar desert continuous permafrost</u> to <u>Polar tundra continuous permafrost</u> under a T+5°C scenario

Response time: 10-100 years

Justification of response time: State shift is mostly linked to a slightly reduced active layer thickness and a warmer permafrost temperature once the surface is colonized by vegetation. These changes are driven by the effect of temperature on vegetation state shift that subsequently affects soil moisture, thermal properties and snowpack properties. An increase in vegetation cover partly insulates the ground surface from solar radiation during the summer (keeping it cool), but also increases heat loss in winter. However, the presence of a basal depth hoar in the snowpack contributes to insulation of the ground from cold temperature (although to a lesser extent compared to the summer vegetation effect). Ultimately, these changes modify the annual thermal regime of the ground, resulting in a thinner active layer, even with slightly higher ground temperatures. Response time should thus be mostly determined by vegetation state shift from polar desert vegetation to polar tundra vegetation, triggering a snowpack state shift from polar desert snowpack to polar tundra snowpack.

2. Polar tundra continuous permafrost

(Cold permafrost, covering ≥ 90% of the landscape)

The polar tundra continuous permafrost state is characterized by extensive frozen ground beneath the exposed land surface (≥ 90% of the landscape). This cold permafrost (around –10 to –5 °C) is several hundred meters thick and has a low unfrozen water content. Taliks are usually present under lakes but are usually isolated or closed and shallow. Frost cracking and ice-wedge polygons are widespread. Polygonal wetlands can be affected by ice-melting to form thermokarst lakes (Bouchard et al. 2020). Lake drainage triggers re-aggradation of permafrost in exposed sediments, re-activation of ice wedge growth and sometimes the development of pingos (Mackay 1986, Samsonov et al. 2016). The active layer is thin (< 0.7 m) where the organic cover is continuous, and thinner in well-drained sites compared to humid sites and sites with erect shrubs. Volumetric water content in the soil of the active layer depends on topographic position, with upslope, well drained sites having a low water table, while low-lying and low slope gradient areas often show water saturation close to the surface. Freeze-back of the active layer is fast (weeks to month) and dominated by both downward freezing and upward freezing. The ground ice content varies between ice-poor well-drained areas to ice-rich humid areas, except in the upper part of permafrost where the permafrost material is ice-rich in both cases. The carbon content of this type of permafrost is generally low.

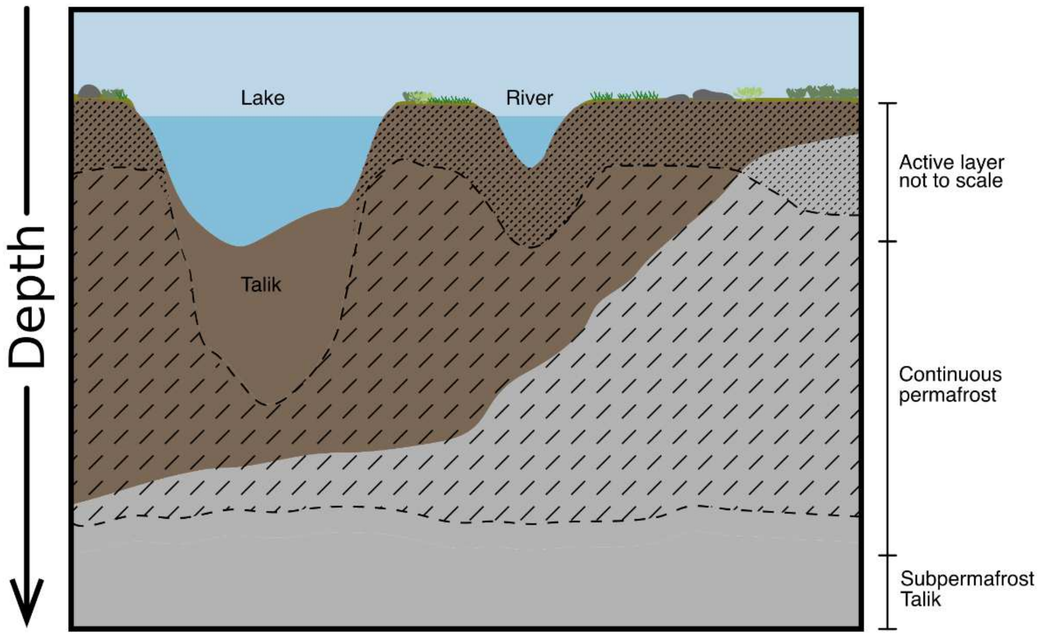
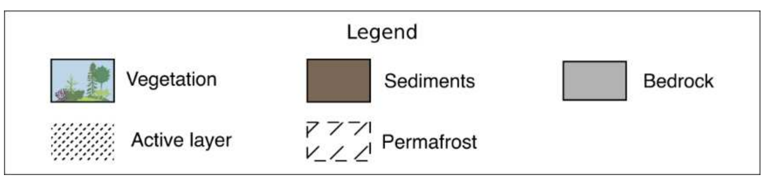


Fig.S2. Schematic representation of polar tundra continuous permafrost.



Modern day southern limit: 57 ± 2.5 °N

State shift from <u>Polar tundra continuous permafrost</u> to <u>Extensive discontinuous permafrost</u> under a T+5°C scenario

Response time: 10-100 years

Justification of response time: State shift is mostly caused by a reduction of perennially frozen ground extent in the landscape, and an increase of active layer thickness and permafrost temperature. Although state shift is partly linked to the vegetation state shift from polar tundra to shrub tundra and a shift from polar tundra snowpack to shrub tundra snowpack, as vegetation and snowpack properties are affecting the thermal regime of the ground (see Vegetation and Snowpack sections), response time is mostly determined by the direct effect of air temperature on permafrost warming, resulting in permafrost degradation (reduction in extent and thickness).

3. Extensive discontinuous permafrost

(Relatively warm permafrost, covering 50-90% of the landscape)

The extensive discontinuous permafrost state is characterized by an extensive, but reduced presence of frozen ground beneath the exposed land surface (50-90% of the landscape). This relatively warm permafrost (around –5 to –2 °C) is tens of meters thick and has a low to medium unfrozen water content in fine-grained sediments. Under lakes and rivers that do not freeze to the bottom, taliks are wide and can be interconnected, allowing heat, water and solute transfers (McKenzie et al. 2021). Frost cracking occurs occasionally, and ice-wedge polygons are common but growing slowly as they are mostly inherited from past colder climates. The active layer is thin (< 1 m) where the organic cover is continuous and thicker (< 2 m) in wetlands and sites with erect shrubs. Well-drained sites with mesic vegetation have an even thicker active layer (< 3 m). The active layer in low-lying and low slope sites is often nearly water saturated. Subsurface flow in sloping terrain creates wet conditions and increases the thickness of the active layer under rills, streams, water tracks and wetlands. Freeze-back of the active layer is slow (a few months) and dominated by downward freezing. The ground ice content can be high in fine-grained sediments while it is low in coarse sediments. Ground ice of the upper portion of ice-rich permafrost has thawed. Carbon content of this permafrost is generally higher than the polar tundra and polar desert continuous permafrost. Thermokarst mass movements, thermokarst basins (drained lakes) and thermokarst lakes are common and actively expanding (Grosse et al. 2013; Bouchard et al. 2016).

Modern day southern limit: 54 ± 2.5 °N

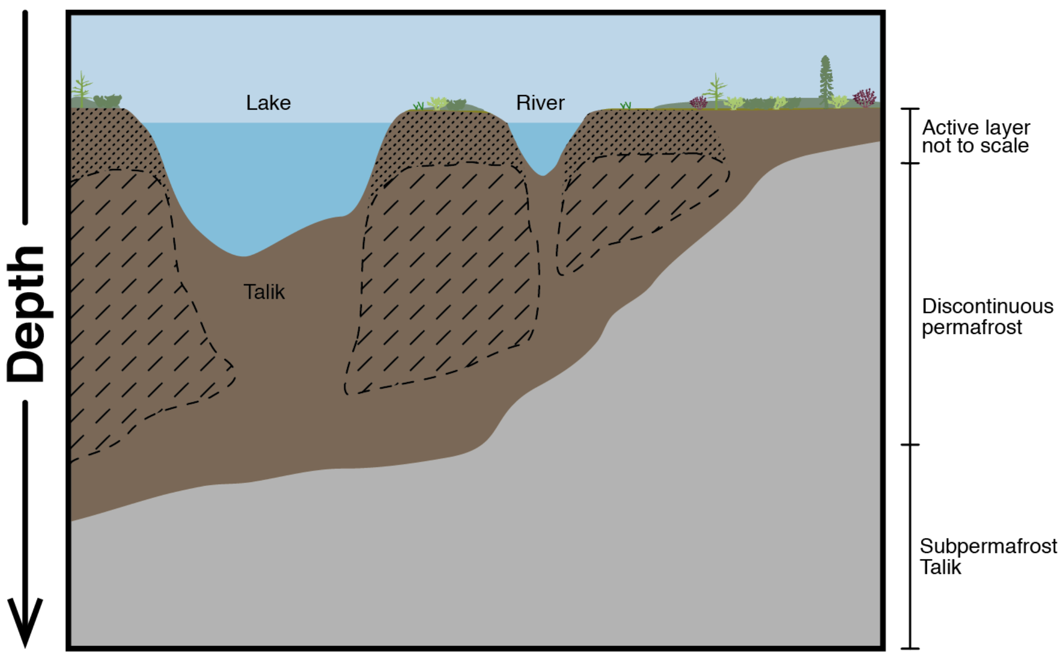
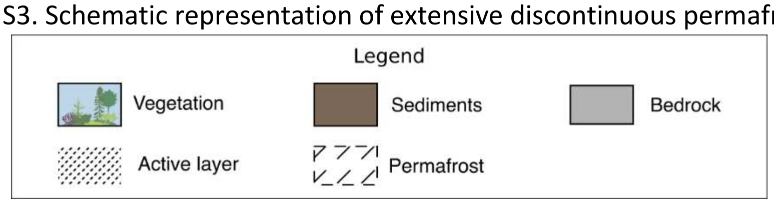


Fig. S3. Schematic representation of extensive discontinuous permafrost.



State shift from <u>Extensive discontinuous permafrost</u> to <u>Sporadic discontinuous permafrost</u> under a T+5°C scenario

Response time: 10-100 years

Justification of response time: State shift is mostly linked to an important decrease in frozen ground extent in the landscape, an increased sub-surface hydrological connectivity, and increase in permafrost temperature. Response time should mostly be determined by the direct effect of air temperature on permafrost warming, resulting in its degradation (reduction in extent and thickness).

4. Sporadic discontinuous permafrost

(Warmest permafrost, covering 0-50% of the landscape)

The sporadic discontinuous permafrost state is characterized by a limited presence of frozen ground beneath the exposed land surface (0-50% of the landscape). This near-thawing point (i.e., near 0 °C) permafrost is a few meters thick and has a high unfrozen water content in fine-grained sediments. Permafrost is often dependent on micro-climatic conditions (slope aspect, topographic conditions, elevation, wind exposure, etc.) and is generally absent or relict in coarse-grained sediments and bedrock, unless covered by thick organic deposits. Taliks are present under lakes and rivers and connected laterally allowing heat, water and solute transfers. Some taliks may be open and penetrate permafrost completely, connecting suprapermafrost water and subpermafrost water (McKenzie et al. 2021). Cryopeg can be present in layers and pockets. The active layer is thick (> 1 m) and supra-permafrost talik may be present. Subsurface flow in sloping terrains is common and low-sloping and flat areas have thicker active layer (1- >3 m) or no permafrost. Freeze back of the active layer is very slow (several months) and dominated by downward freezing. The upper portion of ice-rich permafrost has thawed. The ground ice content is variable but can be high in remaining fine-grained sediments. The carbon content of the permafrost is generally similar or higher than in extensive discontinuous permafrost, depending on the dynamics of organic matter accumulation. Thermokarst processes are actively transforming the landscape.

Modern day southern limit: 51 ± 2.5 °N

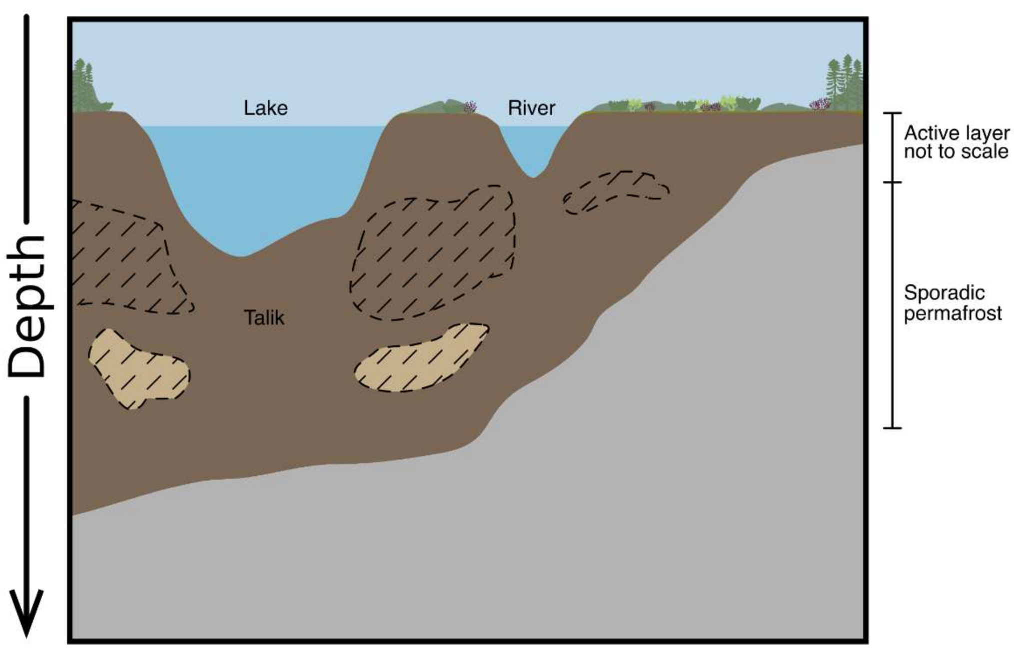


Fig. S4. Schematic representation of sporadic discontinuous permafrost.

State shift from <u>Sporadic discontinuous permafrost</u> to <u>Relict permafrost</u> under a T+5°C scenario

Response time: 10-100 to >100 years

Justification of response time: State shift is mostly linked to an important decrease in frozen ground extent in the landscape, and an increase in permafrost temperature. Response time should mostly be determined by the direct effect of air temperature on permafrost warming, resulting in permafrost degradation (reduction in extent and thickness). As remaining permafrost gets deeper, response time increases (French 2017).

5. Relict permafrost

(Isolated bodies of near 0°C permafrost)

The relict permafrost state is characterized by an occasional presence of permafrost in isolated underground bodies. This permafrost is a relic of past climatic conditions and cannot form under present climatic conditions. Permafrost is undergoing its final decay, as its temperature is now in disequilibrium with the mean annual ground surface temperature above 0°C. Permafrost exists in isolated bodies, its temperature is at the thawing point and has a high unfrozen water content in fine-grained sediments. A supra-permafrost talik and lateral talik separate the permafrost bodies. The ground ice content varies and can be high in remaining frozen fine-grained sediments whereas it is low to absent in coarse-grained sediments and bedrock. The carbon content of the permafrost is generally higher than in sporadic discontinuous permafrost depending on the dynamics of organic matter accumulation.

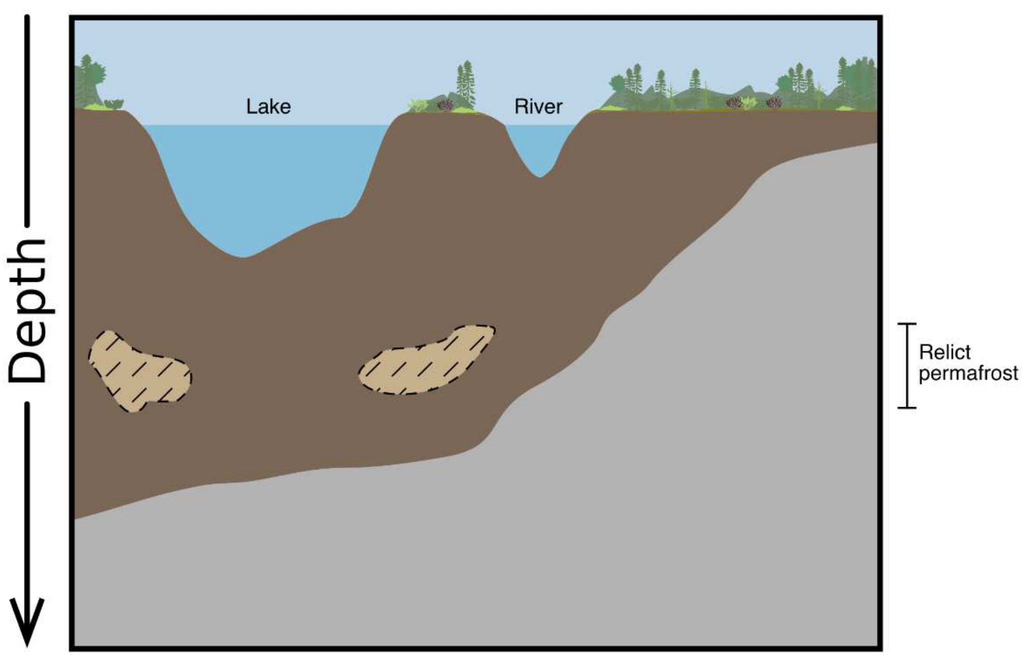
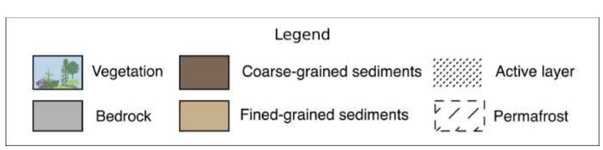


Fig. S5. Schematic representation of relict permafrost.



Glossary

Definitions come mainly from the National Snow and Ice Data Center's cryosphere glossary (https://nsidc.org/learn/cryosphere-glossary).

Active layer: Surface layer of earth material within the permafrost that thaws and refreezes each year.

Cryopeg: An unfrozen layer of perennially cryotic ground, in which freezing is prevented by freezing-point depression due to the presence of dissolved-solids (ex. salts) in the pore water.

Cryotic ground: Soil or rock at temperatures of 0°C or lower.

Downward Freezing: the advance of a freezing front downwards from the ground surface during annual freezing of the active layer.

Free water: Portion of the pore water that is free to move between interconnected pores under the influence of gravity

Frost mound: Any mound-shaped landform produced by ground freezing combined with accumulation of ground ice due to groundwater movement or the migration of soil moisture.

Frozen ground: Soil or rock in which part or all the pore water has changed to ice.

Ground ice: All types of ice formed in freezing or frozen ground. Ground ice occurs in pores, cavities, voids or other openings in soil or rock and includes massive ice.

Ice-rich permafrost: Permafrost containing excess ice (ground-ice content greater than the saturated moisture content of thawed soil).

Ice wedge: A massive, generally wedge-shaped body with its apex pointing downward, composed of foliated or vertically banded, commonly white, ice

Ice-wedge polygon: A polygon outlined by ice wedges underlying its boundaries.

Massive ice: A comprehensive term used to describe large masses of ground ice, including ice wedges, pingo ice, buried ice and large ice lenses.

Permafrost: Rock or soil that remains below 0°C for at least two consecutive years.

Permafrost base: The lower boundary surface of permafrost, above which temperatures are perennially below 0°C (cryotic) and below which temperatures are perennially above 0°C (non cryotic).

Permafrost degradation: A naturally or artificially caused decrease in the thickness and/or areal extent of permafrost.

Permafrost region: A region in which the temperature of some or all of the ground below the seasonally freezing and thawing layer remains continuously at or below 0°C for at least two consecutive years.

Permafrost table: The upper boundary surface of permafrost.

Permafrost thickness: The vertical distance between the permafrost table and the permafrost base

Permafrost zone: A major subdivision of a permafrost region.

Pingo: A perennial frost mound consisting of a core of massive ice, produced primarily by injection of water and covered with soil and vegetation.

***Pore water:** Water occurring in the pores of soils and rocks. Pore water includes free water and interfacial (adsorbed) water.

Rill: Shallow channel cut into the soil by flowing water with a width and depth that do not exceed a few tens of centimeters.

Subpermafrost water: water occurring in the noncryotic ground below the permafrost.

Suprapermafrost water: water occurring in unfrozen ground above perennially frozen ground.

Talik: A layer or body of unfrozen ground in a permafrost area. Taliks may have temperatures above 0°C (non cryotic) or below 0°C (cryotic, forming part of the permafrost). Several types of taliks can be distinguished on the basis of their relationship to the permafrost (ex. closed, open, lateral, isolated taliks), and on the basis of the mechanism responsible for their unfrozen condition (hydrochemical, hydrothermal and thermal taliks).

> **Isolated talik**: A talik entirely surrounded by perennially frozen ground
>
> **Lateral talik**: A talik overlain and underlain by perennially frozen ground
>
> **Open talik**: A talik that penetrates the permafrost completely, connecting suprapermafrost water and subpermafrost water.

Thermal regime of the ground: A general term encompassing the temperature distribution and heat flows in the ground and their time-dependence.

Thermokarst: The process by which characteristic landforms (depressions, lakes, irregular topography, etc.) result from the thawing of ice-rich permafrost or the melting of massive ice.

Unfrozen water content: The amount of unfrozen (liquid) water contained in frozen soil or rock. The unfrozen water content can include free water that can be moved by gravity, and/or interfacial (adsorbed) water that cannot be moved by gravity.

Upward Freezing: the advance of a freezing front upwards from the permafrost table during annual freezing of the active layer.

Volumetric (total) water content: The ratio of the volume of the water and ice in a sample to the volume of the whole sample, expressed as a proportion or as a percentage.

References

Bliss, L.C., & Matveyeva N.V. Circumpolar arctic vegetation. in *Arctic ecosystems in a changing climate: An ecophysiological perspective*. San Diego, United States (eds Chapin III, F.S., Jefferies, R.L., Reynolds, J.F., Shaver G.R., Svoboda, J.) 59-89 (Academic Press Inc, 1992).

Bouchard, F., Fortier, D., Paquette, M., Boucher, V., Pienitz, R., & Laurion, I. Thermokarst lake inception and development in syngenetic ice-wedge polygon terrain during a cooling climatic trend, Bylot Island (Nunavut), eastern Canadian Arctic. *The Cryosphere*, **14,** 2607–2627, (2020).

Bouchard, F., MacDonald L. A., Turner, K. W., Thienpont, J. R., Medeiros A. S., Biskaborn, B. K., Korosi, J., Hall R. I., Pienitz, R., & Wolfe, B. B. Paleolimnology of thermokarst lakes: a window into permafrost landscape evolution. *Arctic Science*. **3**(2), 91-117, (2016).

Brown, R.J.E. Permafrost Map of Canada. National Research Council Canada, Pub. NRC 9769 and Geological Survey of Canada, Map 1246A. (1967).

Coulombe, S., Fortier, D., Lacelle, D., Kanevskiy, M., & Shur, Y. Origin, burial and preservation of late Pleistocene-age glacier ice in Arctic permafrost (Bylot Island, NU, Canada), *The Cryosphere*, **13**, 97–111, (2019).

Couture, N. J., & Pollard, W. H. An assessment of ground ice volume near Eureka, Northwest Territories. *Proceedings of the 7th International Permafrost Conference*, Yellowknife, NT. (1998).

Fortier, D. & Allard, M. Frost-cracking Conditions, Bylot Island, Eastern Canadian Arctic Archipelago. *Permafrost and Periglacial Processes*, **16**, 145–161. (2005).

Fortier, R., LeBlanc, A.-M., Allard, M., Buteau, S., & Calmels, F. Internal structure and conditions of permafrost mounds at Umiujaq in Nunavik, Canada, inferred from field investigation and electrical resistivity tomography. *Canadian Journal of Earth Sciences* 2008, **45**(3), 367–387, (2008).

French, H.M. *The Periglacial Environment, 4th Edition*. (Wiley-Blackwell, 2017).

Grosse, G., Jones, B., & Arp, C. Thermokarst lakes, drainage, and drained basins. *Treatise on Geomorphology*, **8**, 325-353, (2013).

Heginbottom, J. A., Dubreuil, M-A., & Harker, P. A. Canada - Permafrost. Ottawa, Canada: Natural Resources Canada, National Atlas of Canada, 5th edition, Plate 2.1 (MCR No. 4177; scale 1:7 500 000), http://atlas.gc.ca/english/products/thematic/pfrost/english/html/epfrost.html (1995).

Hodgson, D.A. Surficial materials and geomorphological processes, western Sverdrup and adjacent islands, district of Franklin in Geological Survey of Canada, P.N, (1982).

Hodgson, D.A., & Nixon, F.M. Ground ice volumes determined from shallow cores from western Fosheim Peninsula, Ellesmere Island, Northwest Territories in Geological Survey of Canada, Bulletin 507, (1998).

Hughes-Allen, L., Bouchard, F., Laurion, I., Séjourné, A., Marlin, C., Hatté, C., Costard, F., Fedorov, A., & Desyatkin, A. Seasonal patterns in greenhouse gas emissions from thermokarst lakes in Central Yakutia (Eastern Siberia). Limnology and Oceanography, **66**(S1), S98-S116, (2021).

Mackay, J. Growth of Ibyuk Pingo, Western Arctic Coast, Canada, and Some Implications for Environmental Reconstructions. *Quaternary Research,* **26**(1), 68-80, (1986).

McKenzie, J. M., Kurylyk, B. L., Walvoord, M. A., Bense, V. F., Fortier, D., Spence, C., & Grenier, C. Invited perspective: What lies beneath a changing Arctic? *The Cryosphere*, **15**, 479–484, (2021).

O'Neill, H.B., Wolfe, S.A., & Duchesne, C. Ground ice map of Canada in Geological Survey of Canada, Open File 8713, (2020).

Paquette, M., Fortier, D., & Lamoureux, S.F. Cryostratigraphical studies of ground ice formation and distribution in a High Arctic polar desert landscape, Resolute Bay, Nunavut. *Canadian Journal of Earth Sciences*. 59(11), 759-771, (2021).

Samsonov, S. V., Lantz, T. C., Kokelj, S. V., & Zhang, Y. Growth of a young pingo in the Canadian Arctic observed by RADARSAT-2 interferometric satellite radar. *The Cryosphere*, **10**, 799–810, (2016).

Smith, S. L., M. M. Burgess, & A. E. Taylor. High Arctic permafrost observatory at Alert, Nunavut–analysis of a 23 year data set. *Proceedings of the Eighth International Conference on Permafrost.* (2003).

Shur, Y.L., & Jorgenson, M.T. Patterns of Permafrost Formation and Degradation in Relation to Climate and Ecosystems. *Permafrost and Periglacial Processes*, **18,** 7–19, (2007).

Taylor, A., Brown, R.J.E., Pilon, J., & Judge, A.S. Permafrost and the shallow thermal regime at Alert, N.W.T. *Proceedings of the Fourth Canadian Permafrost Conference* (1982).

Verpaelst, M., Fortier, D., Kanevskiy, M., Paquette, M., & Shur, Y. Syngenetic dynamic of permafrost of a polar desert solifluction lobe, Ward Hunt Island, Nunavut. *Arctic Science*, **3**(2), 301-319, (2017).

Woo, M.-K., & Young, K.L. Characteristics of patchy wetlands in a polar desert environment, Arctic Canada. *Proceedings of the Seventh International Conference on Permafrost*. (1998).

Peatlands

Peatlands are terrestrial ecosystems in which waterlogged conditions prevent plant material from fully decomposing. Along our transect, they range from peatlands shaped by the dynamics of ice-wedge networks to peatlands completely devoid of permafrost.

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Introduction

Peatlands are terrestrial ecosystems characterized by waterlogged conditions, in which the accumulation of plant material through time exceeds decomposition (Charman 2002). Such conditions lead to an accumulation of partially decomposed plant material that forms peat. The thickness of peat deposits varies between 30 cm and several meters, depending on the geographic location, hydrogeomorphic context and time since initiation (Payette & Rochefort 2001). Given the process of peat accumulation, peatlands have acted as important carbon (C) sinks over the Holocene and contributed to global climate regulation through carbon sequestration and storage (Loisel et al. 2021). However, uncertainty remains concerning how their carbon balance is expected to change in response to climate warming (Gallego-Sala et al. 2018). The magnitude and direction of the response of high latitude peatlands under a warmer climate is of consideration for their predicted carbon balance. In addition to carbon sequestration, peatlands provide other important ecosystem services by supporting biological habitat, biodiversity and species at risk (Daba & Dejene 2018). They also play an important role in the hydrological cycle through water flow and retention (Price 2003).

The contrasting peatland states distributed along the gradient encompassed by our study are defined by their surface morphology, the water and permafrost table dynamics, including the thickness of the active layer, as well as vegetation communities which are typically dominated by mosses, graminoids (sedges and grasses), shrubs and scattered trees (south of the treeline).

The following four peatland types are currently encountered from North to South along the latitudinal gradient covered by our study: 1) Polygonal peatlands, 2) Complex of tundra peatlands, 3) Mosaic of palsa and peat plateau peatlands, and 4) Non-permafrost peatlands. We defined the southern limit of a peatland contrasting state as the southernmost modern-day position of a dominant peatland type at the landscape scale (30km X 30km). The southern limit of non-permafrost peatlands goes far beyond the studied gradient. The southern limits of all peatland states identified along the transect are considered critical thresholds.

At each critical threshold, we determined the sensitivity of a peatland state to a hypothetical warming scenario. We assessed its sensitivity using the estimated time required (the response time, in years) for an initial peatland state to shift to another existing state if exposed to a sudden and persistent 5°C increase in mean annual temperature. A state shift is reached when the resulting state becomes the dominant peatland type among existing peatlands at the landscape scale.

Peatland state shifts at critical thresholds are expected to be mainly driven by the effects of changes in mean air temperature on permafrost degradation. Local conditions such as precipitation, snow cover thickness, ground ice content, thermal conductivity of peat and topography, which affect hydrology and vegetation, can modulate the response time of peatlands to state shifts (increase or decrease response time within the selected time interval) (Seppälä 1990, Schuur et al. 2008, Jorgensen et al. 2015, Minayeva et al. 2010).

1. Polygonal peatlands

Polygonal peatlands contain perennially frozen peat and the permafrost active layer is usually located in the mineral-peat layers (30-40 cm, e.g., Vardy et al. 2005). These peatlands have a variety of geometrical networks of flat, low-centre (or raised-edge) or high-centre polygons (Tarnocai & Zoltai 1988, Jorgensen et al. 2015) that are delineated and influenced by ice wedges arranged in a polygonal pattern (Schuur et al. 2008; Jorgensen et al. 2015, Liljedahl et al. 2016). During the summer, ponds may form in the middle of low-centre polygons, in contrast to high-centre polygons that develop well-drained mounds, often surrounded by troughs. Vegetation composition and distribution are determined by local hydrology, soil and microtopography. Plant communities vary from sedges (*Carex* sp., *Eriophorum* sp.) and mosses (*Aulacomnium* spp., *Scorpidium scorpioides, Warnstorfia fluitans*) in wet low-centre polygons to shrubs (*Rubus chamaemorus*, *Rhododendron tomentosum, Salix* spp., *Betula glandulosa*) and patchy lichen cover in dry high-centre polygons and ridges (Ouzilleau Samson et al. 2010; Gagnon and Allard 2020).

Modern day southern limit: 57± 2.5 °N

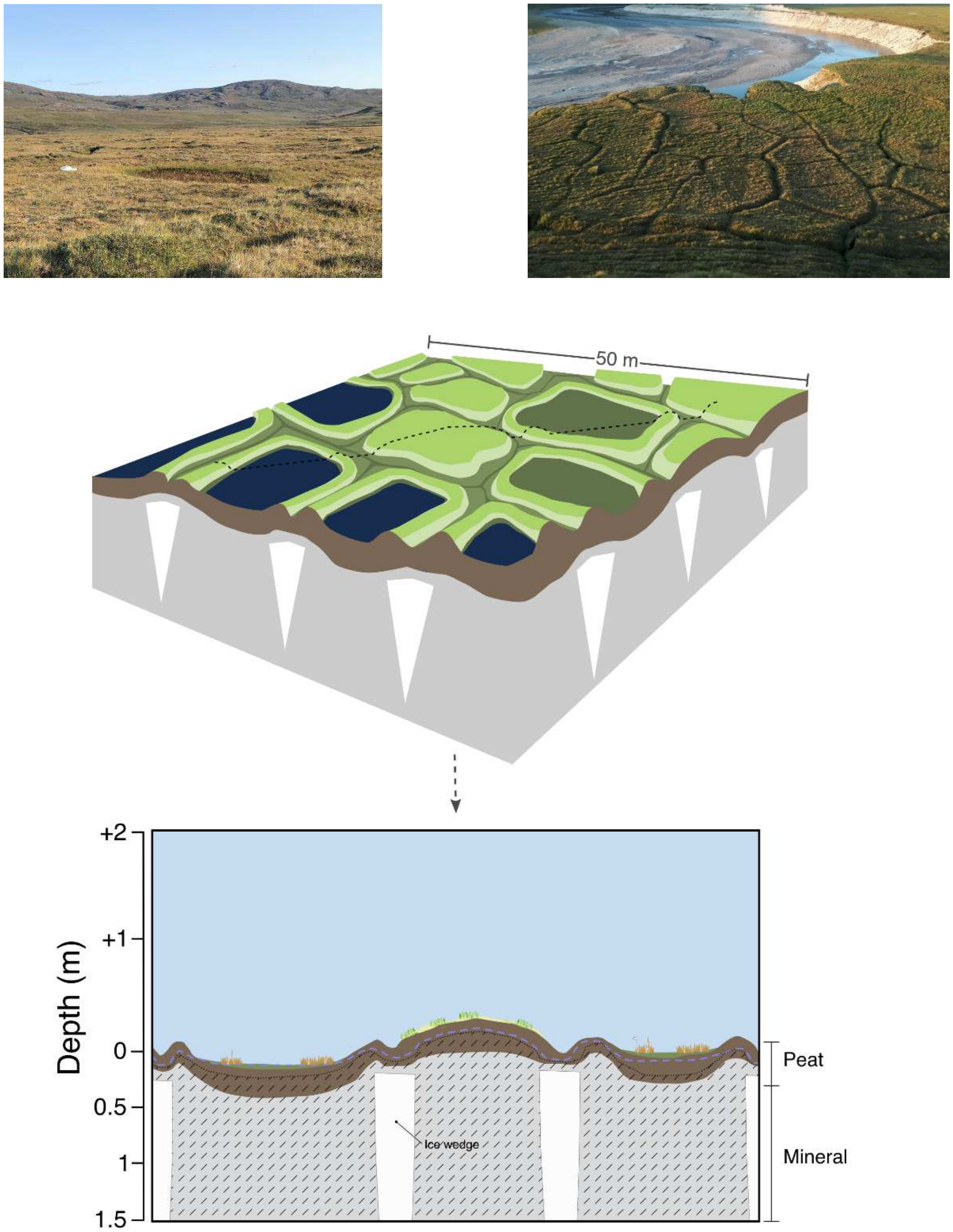
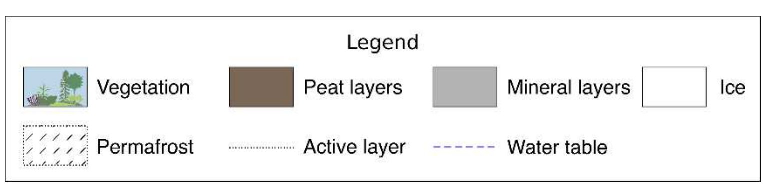


Fig. S6. Schematic representation of polygonal peatlands.



State shift from _Polygonal peatlands_ to _Complex of tundra peatlands_ under a T+5°C scenario.

Response time: 10-100 years

Justification of response time: Transition to a complex of tundra peatlands is linked to the deepening of the active layer that leads to the melting of the upper portion of ice wedges. This transition involves the combination of two processes linked to permafrost degradation: 1) initial thaw of ice wedges forming linear depressions surrounding low- or high-centred polygons that creates environments with improved drainage, and 2) ice wedge melt leading to ground subsidence and flattening of the terrain that creates poorly drained environments. The areas with a better drainage favour the development of shrub species, whereas poorly drained areas favour the development of hygrophilous species such as *Sphagnum* spp. and mosses (*Aulacomnium palustre*, *Aulacomnium turgidum*, *Scorpidium revolvens*, *Warnstorfia fluitans*) (Jorgensen et al. 2015, Liljedahl et al. 2016, Kanevskiy et al. 2022). Response time is thus mostly determined by permafrost warming and its subsequent degradation (Koven et al. 2015).

2. Complex of tundra peatlands

This complex state, associated with a thicker active layer, includes a variety of geometrical networks delineated by degraded ice wedges. It is characterized by assemblages of poorly drained areas in flat or subsided terrain and areas with a better drainage above degraded ice wedges. Wet or saturated soils are colonised by hygrophilous species (e.g., *Comarum palustre*, *Micranthes foliolosa*), *Sphagnum* spp. and mosses (*Aulacomnium palustre*, *Aulacomnium turgidum*, *Scorpidium revolvens*, *Warnstorfia fluitans*) and characterized by an increase in peat accumulation (Jorgensen et al, 2001). Alternatively, sectors with better drainage exhibit an increase in shrub cover (e.g., *Rubus chamaemorus*, *Betula glandulosa*, *Salix* spp.) (Couillard & Payette 1985, Ouzilleau Samson et al. 2010, Gagnon & Allard 2020).

Modern day southern limit: 56 ± 2.5 °N

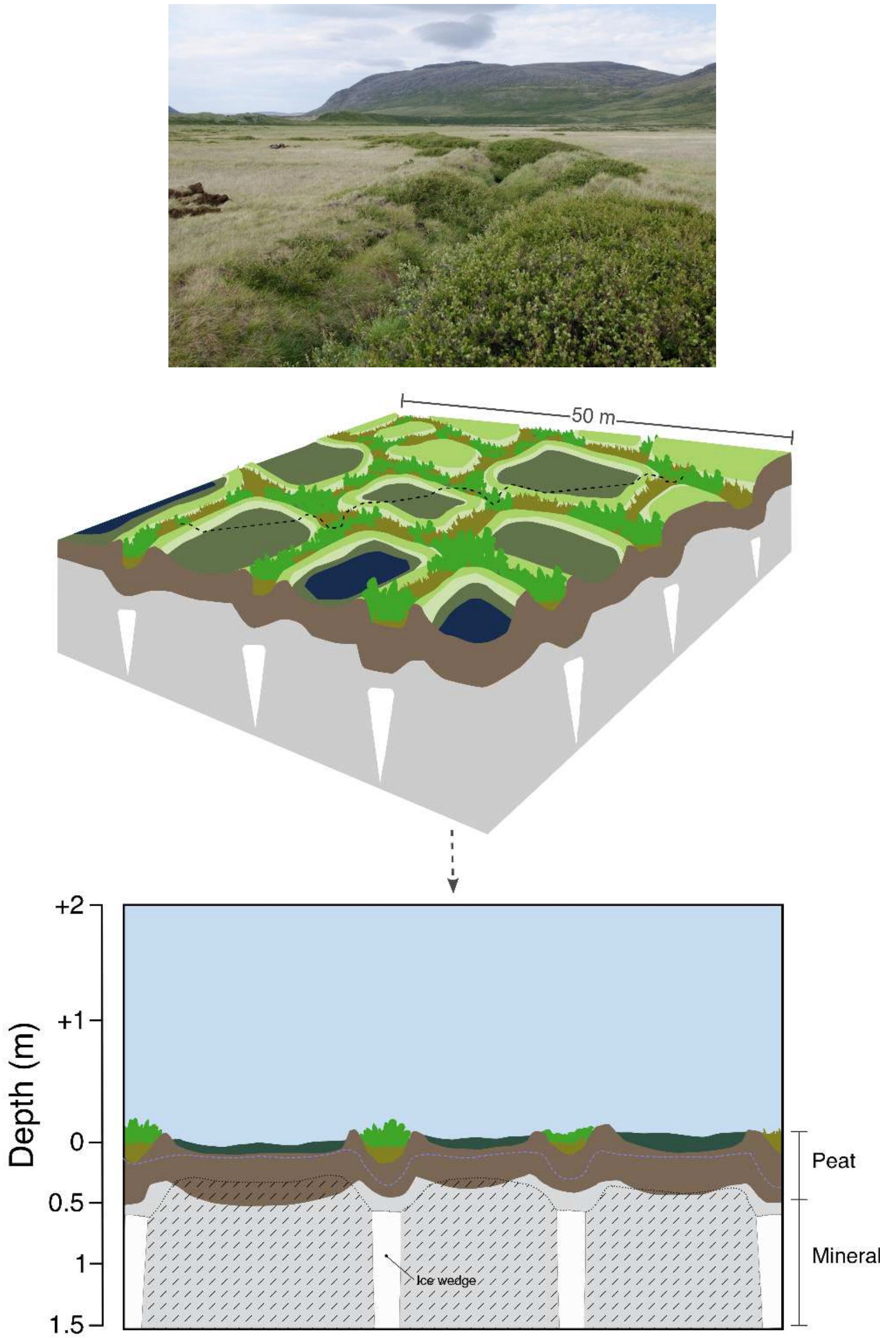
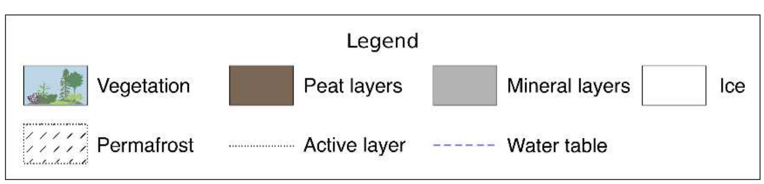


Fig. S7. Schematic representation of complex of tundra peatlands.



State shift from *Complex of tundra peatlands* to *Non-permafrost peatlands* under a T+5°C scenario

Response time: >100 years

Justification of response time: The progressive degradation of permafrost in tundra peatlands involves two main divergent hydrological pathways, dependent on ecogeomorphological conditions, and leading to either 1) non-permafrost peatlands or 2) well-drained non-peatland environment. Response time should be mainly driven by the direct effect of air temperature on permafrost warming, causing its degradation. As permafrost underlying peatlands thaws locally, soil conditions in some areas can become saturated, triggering wetland formation and peat accumulation increase with gradual ice melt. Areas where the water coming from permafrost thaw drains freely will develop xeric to mesic soil conditions that favour the expansion of shrubs and grasses (Lantz 2017, Lawrence & Slater 2005).

N.B. Neither this state nor the preceding one can shift to a mosaic of palsa and peat plateau peatlands. In fact, palsa and peat plateaus formed during cooler climate conditions in areas where peat deposits had previously accumulated (>50-60 cm). During the deglaciation, newly deglaciated lands and a warmer climate created suitable conditions for peatland initiation and peat accumulation. Due to their latitude, Subarctic regions accumulated significantly more peat than arctic regions. From the Neoglacial onward (about 3500 BP), the global climate became colder and initiated ice formation in the peat and the underlying sediment, which caused the peat surface to rise (Payette et al. 2004, Bhiry et al. 2007).

3. Mosaic of palsa and peat plateau peatlands

A mosaic of palsa and peat plateau peatlands consists of a patchwork of permafrost peatlands mixed with non-permafrost peatlands and thermokarst ponds. These permafrost peatlands are characterized by peat plateaus, residual peat plateaus or palsas that are not in equilibrium with the present-day climatic conditions. Palsa and peat plateau peatlands are underlain by permafrost and elevated above the surrounding water table. They contain perennially frozen peat and their dry surface is colonized by xeric and mesic plant communities dominated by lichens (*Cladonia stellaris*), shrubs (*Betula glandulosa*, *Vaccinium vitis-idaea*, *Rhododendron groenlandicum*), and occasionally trees (mainly *Picea mariana*) (Langlais et al. 2021).

In this state, permafrost peatlands are distributed over the landscape along thermokarst ponds and non-permafrost peatlands (Payette et al. 2004, Sannel & Kuhry 2011). Wet areas surrounding ponds and over the non-permafrost terrain are mainly colonized by bryophytes (e.g *Sphagnum fuscum*) and sedges (*Carex spp.).*

Modern day southern limit: 54 ± 2.5 °N

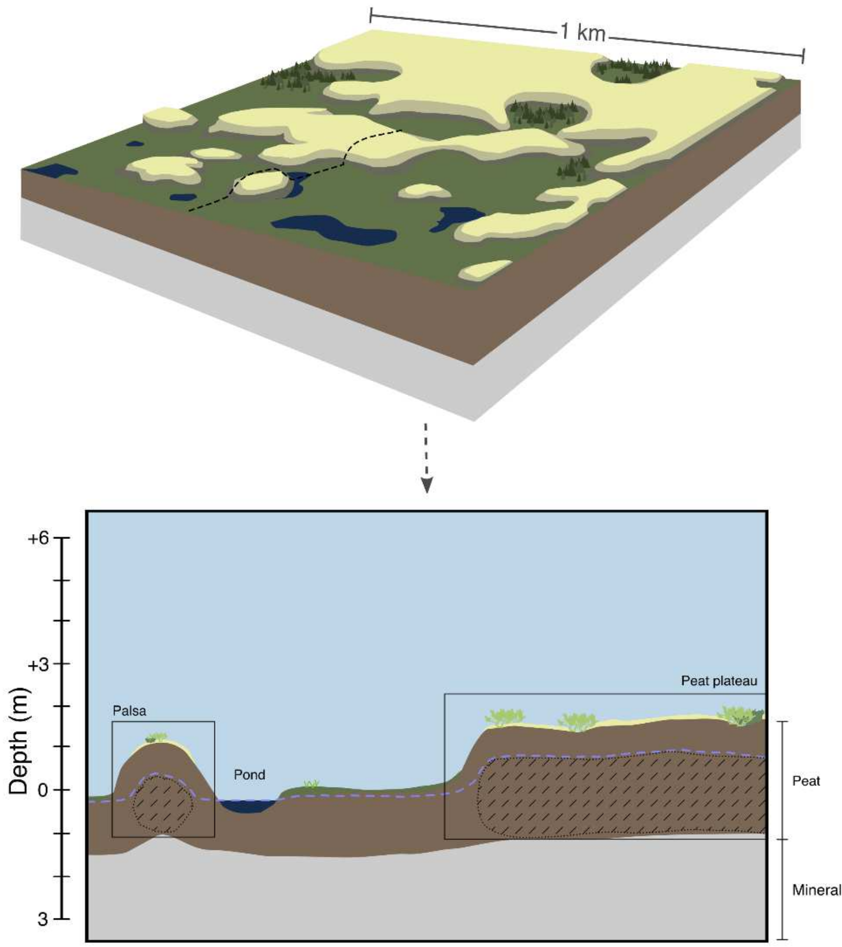
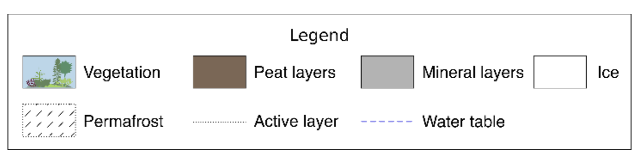


Fig. S8. Schematic representation of palsa and peat plateau peatlands.



State shift from *Mosaic of palsa and peat plateau peatlands* to *Non-permafrost peatlands* under a T+5°C scenario.

Response time: 10-100 years

Justification of response time: The transition to non-permafrost peatlands is linked to the local degradation of permafrost. Segregation ice thaw causes the ground to subside. As ground ice is heterogeneously distributed, it creates a patchwork of flat areas, slopes and depressions. Wet conditions generated by ice melting allow peat accumulation and lateral expansion through paludification. The saturated conditions surrounding ponds subsequently trigger colonization of plant species which, in turn, allows peat accumulation through terrestrialization (Payette et al. 2004, Fillion et al. 2014). This transition to a new state also corresponds to a state shift from extensive discontinuous permafrost to sporadic discontinuous permafrost. Response time is thus mainly determined by this state shift. Any residual permafrost patches (e.g., in fine sediments) in a landscape characterized by non-permafrost peatlands does not affect the characteristics of this resulting peatland type.

4. Non-permafrost peatlands

Non-permafrost peatlands form a patchwork covering relatively flat areas of permafrost-free terrain, sometimes interspersed with ponds. Peat accumulates through terrestrialization and paludification processes. There is no perennially frozen peat in this peatland type. Depending on local conditions (microtopography, soil properties, precipitation, etc.), the water table is usually at or near the surface and subsequently influences the plant cover. Wet areas are colonized by sedges (e.g., *Carex canescens*, *Carex aquatilis*, *Eriophorum vaginatum* subsp. *spissum*, *Eriophorum russeolum*) and mosses (e.g. *Sphagnum fallax*, *Sphagnum riparium*). Drier areas are colonized by ericaceous shrubs, dwarf shrubs (e.g., *Empetrum nigrum, Betula glandulosa*) and small trees (*Picea mariana*, *Larix laricina*).

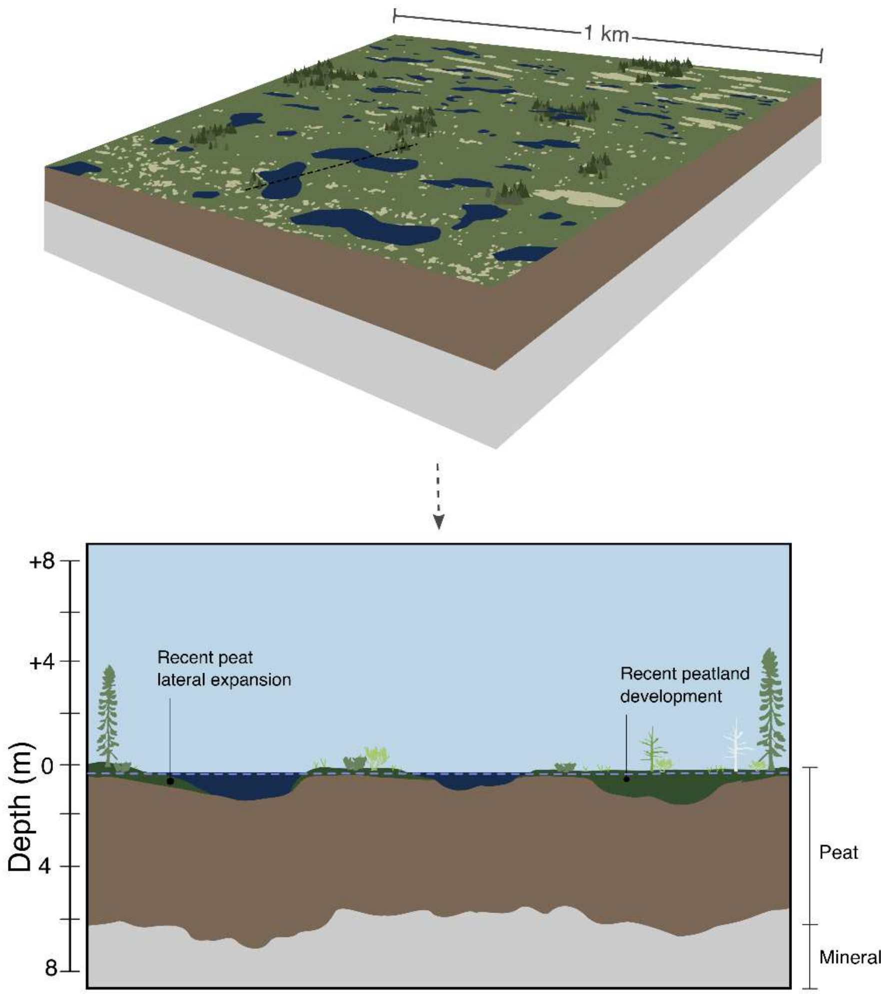
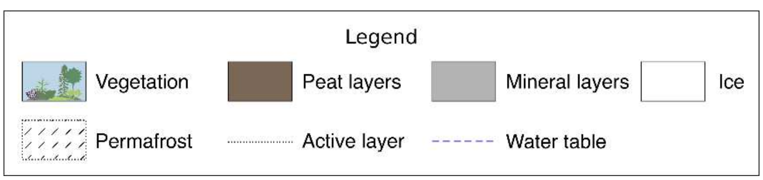


Fig. S9. Schematic representation of non-permafrost peatlands.



Glossary

Definitions come from the International Peatland Society (www.peatlands.org), the Canadian Wetland Classification system (https://publications.gc.ca/site/eng/9.867506/publication.html) and the National Snow and Ice Data Center's cryosphere glossary (https://nsidc.org/learn/cryosphere-glossary).

Active layer: Surface layer of earth material within the permafrost that thaws and refreezes each year.

Ice wedge: A massive, generally wedge-shaped ice body with its apex pointing downward, composed of foliated or vertically banded, commonly white, ice.

Ice-wedge polygon: A polygon outlined by ice wedges underlying its boundaries.

Palsa: Permafrost mounds covered by peat.

Paludification: Lateral spread of peatlands from depressions into bordering uplands.

Peat: Peat is the surface organic layer of a soil that consists of partially decomposed organic matter, derived mostly from plant material, which has accumulated under waterlogged conditions, oxygen deficiency, high acidity or nutrient deficiency.

Peat plateau: Perennially frozen flat-topped expanse of peat, uplifted above the peatland water table by frost heave.

Peatland: "Peatlands are terrestrial wetland ecosystems in which waterlogged conditions prevent plant material from fully decomposing. Consequently, the production of organic matter exceeds its decomposition, which results in a net accumulation of peat"

Patterned Ground: a general term for any ground surface exhibiting a discernibly ordered, more or less symmetrical, morphological pattern of ground and, where present, vegetation (ex. a polygonal pattern).

Permafrost: Rock or soil that remains below 0°C for at least two consecutive years.

Permafrost degradation: A naturally or artificially caused decrease in the thickness and/or areal extent of permafrost.

Polygon: literally means many angled; polygons are closed, multi-sided, roughly equidimensional shapes, bounded by more or less straight sides; some of the sides may be irregular; in cryospheric science, it refers to patterned ground formations.

Polygonal Pattern: a pattern consisting of numerous multi-sided, roughly equidimensional figures bounded by more or less straight sides.

Terrestrialization: Filling-in of lakes ("hydroseral succession") leading to the formation of peatlands.

Thermokarst: The process by which characteristic landforms (depressions, lakes, irregular topography, etc.) result from the thawing of ice-rich permafrost or the melting of massive ice.

Trough (polygon trough): the narrow depression surrounding a high-centre polygon.

Wetland: A wetland is defined as: land that is saturated with water long enough to promote wetland or aquatic processes as indicated by poorly drained soils, hydrophytic vegetation and various kinds of biological activity which are adapted to a wet environment.

References

Bhiry, N., Payette, S. & Robert, É. C. Peatland development at the Arctic tree line (Québec, Canada) influenced by flooding and permafrost. *Quaternary Research*, **67**, 426-437, (20070.

Charman, D. Peatlands and environmental change. (John Wiley & Sons Ltd 2002).

Couillard, L. & Payette, S. Évolution holocène d'une tourbière à pergélisol (Québec nordique). *Canadian Journal of Botany*, **63**, 1104-1121, (1985).

Daba, M. H., & Dejene, S. W. The role of biodiversity and ecosystem services in carbon sequestration and its implication for climate change mitigation. *International Journal of Environmental Sciences and Natural Resources*, **11**(2), 1-10, (2018).

Fillion, M.E, Bhiry, N. & Touazi, M. Differential Development of Two Palsa Fields in a Peatland Located near Whapmagoostui-Kuujjuarapik, Northern Québec, Canada. *Arctic, Antarctic, and Alpine Research*, **46**, 40–54, (2014).

Gagnon, S. & Allard, M. Changes in ice-wedge activity over 25 years of climate change near Salluit, Nunavik (northern Québec, Canada). *Permafrost and Periglacial Processes*, **31**, 69-84, (2020).

Gallego-Sala, A. V., Charman, D. J., Brewer, S., Page, S. E., Prentice, I. C., Friedlingstein, P., ... & Zhao, Y. Latitudinal limits to the predicted increase of the peatland carbon sink with warming. *Nature climate change*, **8**(10), 907-913, (2018).

Kanevskiy, M., Shur, Y., Walker, D. A., Jorgenson, T., Raynolds, M. K., Peirce, J. L., ... & Watson-Cook, E. The shifting mosaic of ice-wedge degradation and stabilization in response to infrastructure and climate change, Prudhoe Bay Oilfield, Alaska, USA. Arctic Science, **8**(2), 498-530, (2022).

Koven, C. D., Lawrence, D. M., & Riley, W. J. Permafrost carbon− climate feedback is sensitive to deep soil carbon decomposability but not deep soil nitrogen dynamics. *Proceedings of the National Academy of Sciences*, **112**(12), 3752-3757, (2015).

Langlais, K., Bhiry, N., & Lavoie, M. Holocene dynamics of an inland palsa peatland at Wiyâshâkimî Lake (Nunavik, Canada). *Écoscience*, **28**(3-4), 269-282, (2021).

Lantz, T. C. Vegetation succession and environmental conditions following catastrophic lake drainage in Old Crow Flats, Yukon. *Arctic*, 177-189, (2017).

Lawrence, D. M., & Slater, A. G. A projection of severe near-surface permafrost degradation during the 21st century. *Geophysical Research Letters*, **32**(24), L24401, (2005).

Liljedahl, A. K., Boike, J., Daanen, R. P., Fedorov, A. N., Frost, G. V., Grosse, G., ... & Zona, D. Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology. *Nature Geoscience*, ***9***(4), 312-318, (2016).

Loisel, J., Gallego-Sala, A. V., Amesbury, M. J., Magnan, G., Anshari, G., Beilman, D. W., ... & Wu, J. Expert assessment of future vulnerability of the global peatland carbon sink. *Nature climate change*, **11**(1), 70-77, (2021).

Minayeva, T., Sirin, A., Kershaw, P., & Bragg, O. Arctic peatlands. in *The Wetland Book*. (eds Finlayson, C. M., Milton, G. R., Prentice, R. C., Davidson, N.C.,) 1-15 (Springer Science+Business Media B.V. 2010).

Ouzilleau Samson, D., Bhiry, N., & Lavoie, M. Late-Holocene palaeoecology of a polygonal peatland on the south shore of Hudson Strait, northern Québec, Canada. *The Holocene*, **20**(4), 525-536, (2010).

Payette, S., & Rochefort, L. Écologie des tourbières du Québec-Labrador. (Presses de l'Université Laval, 2001).

Payette, S., Delwaide, A., Caccianiga, M., & Beauchemin, M. Accelerated thawing of subarctic peatland permafrost over the last 50 years. *Geophysical research letters*, ***31***(18), (2004).

Price, J. S. Role and character of seasonal peat soil deformation on the hydrology of undisturbed and cutover peatlands. *Water Resources Research*, **39**(9), (2003).

Sannel, A.B.K., & Kuhry, P. Warming-induced destabilization of peat plateau/thermokarst lake complexes. *Journal of Geophysical Research: Biogeosciences*, **116**(G3), (2011).

Seppälä, M. Depth of snow and frost on a palsa mire, Finnish Lapland. *Geografiska Annaler: Series A, Physical Geography,* ***72***(2), 191-201, (1990).

Schuur, E. A., Bockheim, J., Canadell, J. G., Euskirchen, E., Field, C. B., Goryachkin, S. V., ... & Zimov, S. A. Vulnerability of permafrost carbon to climate change: Implications for the global carbon cycle. *BioScience,* ***58***(8), 701-714, (2008).

Tarnocai, C., & Zoltai, S. C. Wetlands of arctic Canada. *Wetlands of Canada*, ***24***, 29-53, (1988).

Vardy, S. R., Warner, B. G., & Asada, T. Holocene environmental change in two polygonal peatlands, south-central Nunavut, Canada. *Boreas*, **34**(3), 324-334, (2005).

Lakes

Freshwater lakes range from perennially frozen clear lakes at the northern tip of the transect to lakes with seasonal ice cover and high dissolved organic matter content at the southern end of the transect.

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Introduction

Lakes are a ubiquitous feature of northern landscapes (Verpoorter et al. 2014) and are an important component of regional climate, namely through their role in surface energy balance. They play a significant role in the carbon budget (as sinks – see Heathcote et al. 2015) and are a source of greenhouse gases (especially methane – see Wik et al. 2016). Lake margins can be rich in vegetation and their ice-covered surface can affect snow accumulation in their catchments. Lakes have diverse microbiomes and serve as habitat for invertebrates, fish, mammals and birds, as well as provide drinking water for animals and humans.

The morphometry of lakes varies greatly and influences how they react to environmental changes (Rouse et al. 2005). In order to characterize the states of northern lakes and assess their relative sensitivity to warming, we needed to define a "typical lake" that would represent a vast proportion of those found throughout our latitudinal gradient. According to Wik et al. (2016), the most abundant lakes located North of 50°N are lakes of glacial/post-glacial origin. They represent 1.45 x 10^6 km^2 out of a total lake surface of 1.84 x 10^6 km^2 throughout the circumarctic region (based on the GLOWABO database that includes lakes larger than 0.002 km^2 - or 0.2 ha - and excludes lakes larger than 5000 km^2). The typical lake established for the present exercise is based on a study by Bélanger et al. (2020) conducted in Nunavik, where the authors determined seven classes of lakes, including three major classes representing 91% of lakes, which had an average area of 0.24 km^2 (24 ha) and a mean depth of 4.0 m. The following definitions of the different lake states encountered along the latitudinal gradient were based on this "typical lake".

Lake contrasting states are defined by the extent of ice cover, the stratification of the water column and the mixing regime, the oxygen and light availability, as well as the dissolved organic matter content (given as dissolved organic carbon, or DOC). The following five contrasting states are currently encountered from North to South along the latitudinal gradient covered by our study: 1. perennial ice-cover lake, 2. intermittent ice-cover lake, 3. seasonal ice-cover/clear lake, 4. seasonal ice-cover/low-colour lake, and 5. seasonal ice-cover/high-colour lake (see descriptions below). We defined the southern limit of a lake state as the southernmost modern-day position along the latitudinal gradient where typical lakes found in the landscape are dominated by a given state. The southern limit of seasonal ice cover/high colour lakes is not encompassed by our gradient. Southern limits identified along the transect were considered critical thresholds.

At each critical threshold, we determined the sensitivity of the lake state to a hypothetical warming scenario. We qualified sensitivity using the estimated time required (the response time, in years) for an initial lake state to shift to another existing state if exposed to a sudden and persistent 5°C increase in mean annual temperature. We considered that a state shift is reached when the resulting state becomes the dominant lake type at the landscape scale (30 km by 30 km).

Lake state shifts at critical thresholds are expected to be mainly driven by the direct effect of air temperature on lake water temperature and lake ice cover, as well as its effect on permafrost degradation and vegetation characteristics in the lake catchment (Arp et al. 2016, Solomon et al. 2015, Wauthy et al. 2018). Local conditions such as exposure to solar radiation and wind, as well as catchment soil characteristics and hydrological conditions can modulate response times of state shifts (increase or decrease the response time within the assessed time interval).

1. Perennial ice cover lake

Amictic lake for which ice cover persists throughout summer (but with presence of a peripheral moat; Bégin et al. 2020), water column is inversely stratified (i.e., warmer at the bottom) but internal convective mixing occurs in summer; DOC content is low (≤ 1 mg L^{-1}); light availability is low but enough for photosynthesis in summer, prolonged heterotrophy with summer mixotrophy and phototrophy, the latter dominated by benthic communities (cyanobacterial mats, biofilms and aquatic mosses, Mohit et al. 2017); simple food webs with limited plankton diversity. With crustacean plankton and fish absent, the rotifers form the highest food web level (Culley et al. 2022). Overall, very low productivity and diversity, low-oxygen environment in bottom waters during winter, and oxygen supersaturation in summer because ice cover prevents wind-induced mixing and gas exchange with the atmosphere (e.g., Bégin et al. 2021). Ice can sometimes extend to the lake bottom in winter. Perennial ice cover lakes likely no longer exist in our transect (since ~2011: W.F. Vincent, pers. obs., Paquette et al. 2015).

Modern day southern limit: 83 ± 2.5 °N

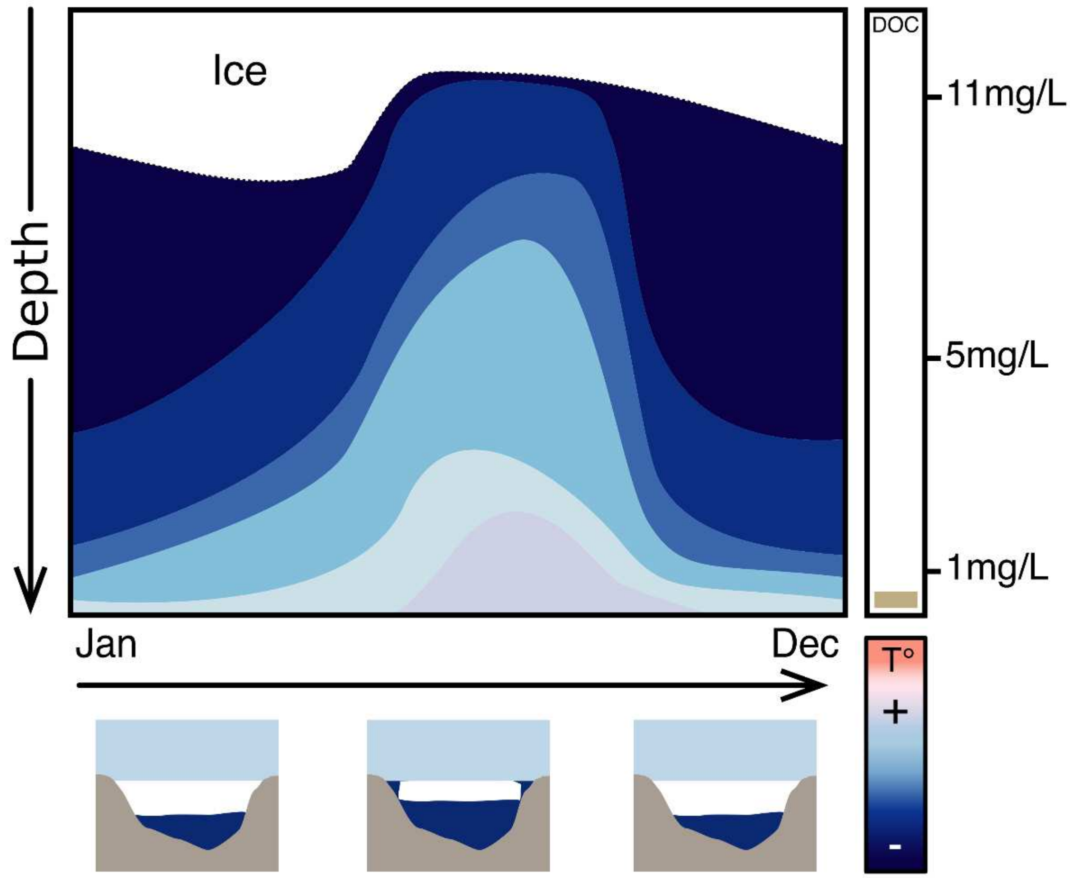

Fig. S10. Schematic representation of perennial ice cover lakes

State shift from <u>Perennial ice cover lake</u> to <u>Intermittent ice-cover lake</u> under a T+5°C scenario

Response time: 1-10 years

Justification of response time: State shift involves faster ice thaw during summer, inducing formation of a moat (the extent of which varies according to temperature), leading to warmer lake water temperature. These factors are directly affected by air temperature and are expected to respond very quickly to air temperature changes (Brown & Duguay 2011, Lehnherr et al. 2018). The reduction in ice cover leading to intermittent (varying from year to year) open-water periods will increase light availability and facilitate reoxygenation in summer (Mueller et al. 2009).

2. Intermittent ice-cover lake

Intermittently ice-free during summer, varying from year to year depending on temperature, fluctuating between multiyear ice cover and short, open water periods (during warmer summers); cold monomictic lake, direct light availability, reoxygenation in summer and lower average water temperature than perennially ice cover lakes (due to loss of accumulated under-ice heat to the atmosphere); DOC content is low (≤ 1 mg L^{-1}); simple food webs but with higher primary productivity and biodiversity than in perennial ice cover lakes leading to more complexity; low concentrations of copepods and cladocerans, suitable habitat for fish, overall very low productivity and diversity (Rigler et al. 1974).

Modern day southern limit: 74 ± 2.5 °N

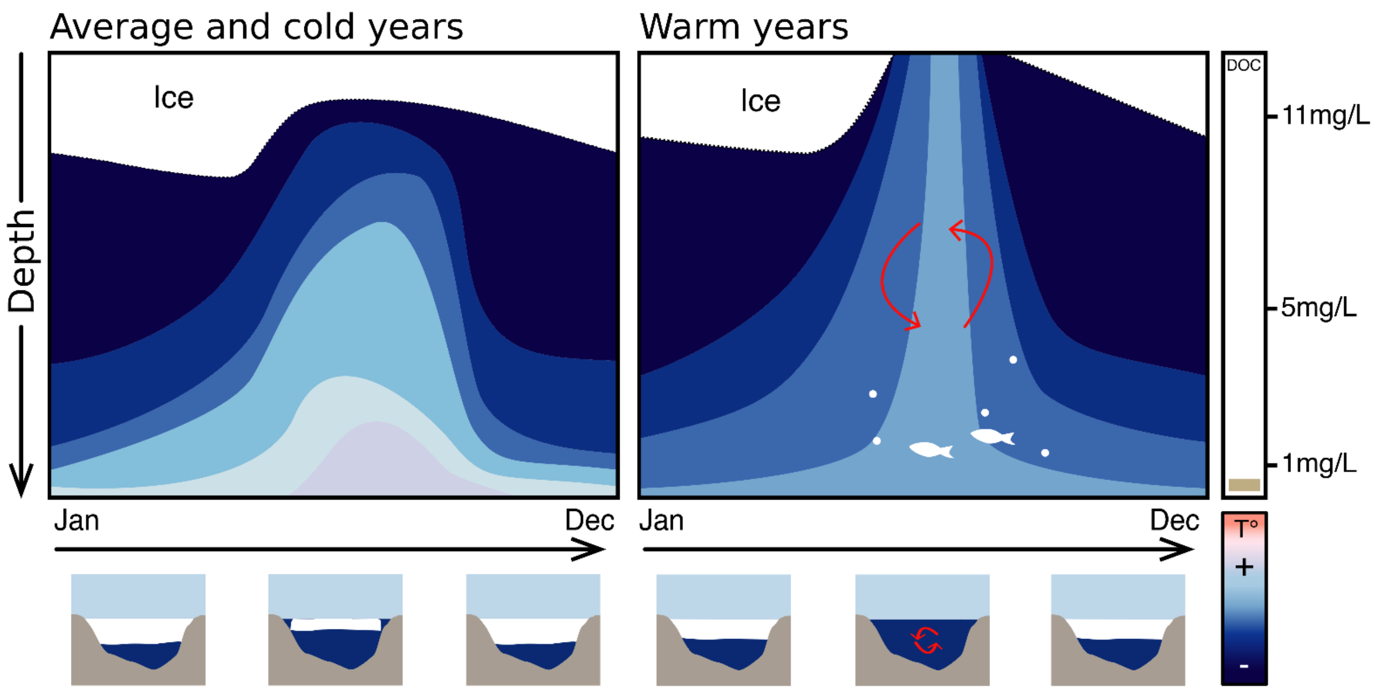

Fig. S11. Schematic representation of intermittent ice-cover lakes

State shift from *__Intermittent ice-cover lake__* *to* *__Seasonal ice cover/clear lake__* *under a T+5°C scenario*

Response time: 1-10 years

Justification of response time: State shift involves a decrease in seasonal lake ice cover duration and warmer water temperatures. These factors are expected to respond very quickly to air temperature changes (Brown & Duguay 2011, Lehnherr et al. 2018, Mueller et al. 2009). Reduction in ice cover resulting in yearly open-water periods will increase direct light availability and reoxygenation.

3. Seasonal ice cover/clear lake

Seasonal ice cover/clear water (< 5 mg L^{-1} DOC); always ice-free in summer; continuous cold polymictic during the ice-free season (well-mixed), saturated in oxygen (summer); light penetrates to the bottom; benthic autotrophic production still dominates (due to low nutrient content of the water column); diverse zooplankton are present; suitable habitat for fish, low productivity and diversity.

Modern day southern limit: 58 ± 2.5 °N

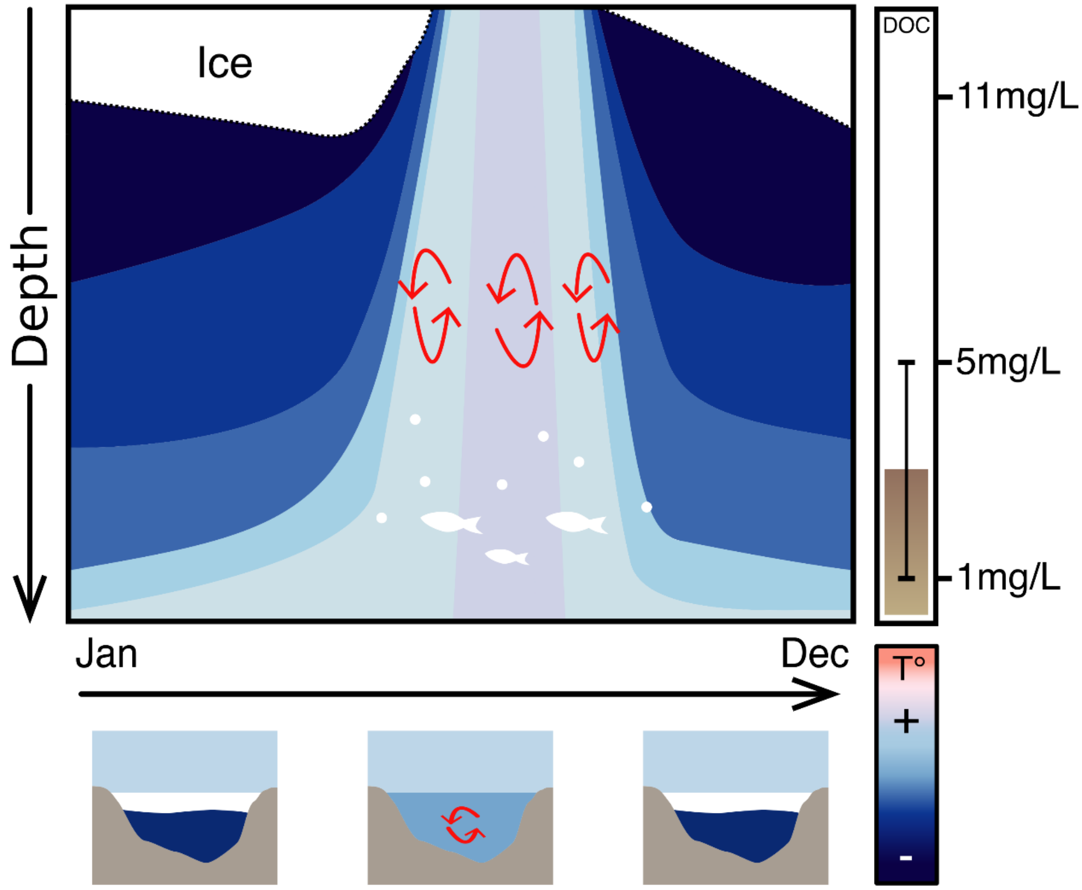

Fig. S12. Schematic representation of seasonal ice cover/clear lakes

State shift from <u>Seasonal ice cover/clear lake</u> to <u>Seasonal ice cover/low colour lake</u> under a T+5°C scenario

Response time: 10-100

Justification of response time: State shift involves warmer lake temperatures and an increase in the length of the ice-free season. These factors are expected to respond very quickly to air temperature changes, but since the transition also involves slower changes including browning (rising DOC content), it rather depends on changes in catchment vegetation (densification or "greening", change in vegetation assemblages) and permafrost degradation (Saulnier-Talbot et al. 2020). These changes induce alterations in the mixing regime and light availability at the bottom.

4. Seasonal ice cover/low colour lake

Seasonal ice cover/low colour (5-11 mg L^{-1} DOC); always ice-free in summer; dimictic; stratified for part of the summer, potentially leading to a slight decline of oxygen at depth; decreased light availability at the bottom compared to clearer lakes; peak primary production (benthic + planktonic) linked to a good balance between nutrient inputs and light availability (Creed et al. 2018); zooplankton diversity and abundance increase, fish abundance increases but diversity remains limited.

Modern day southern limit: 52 ± 2.5 °N

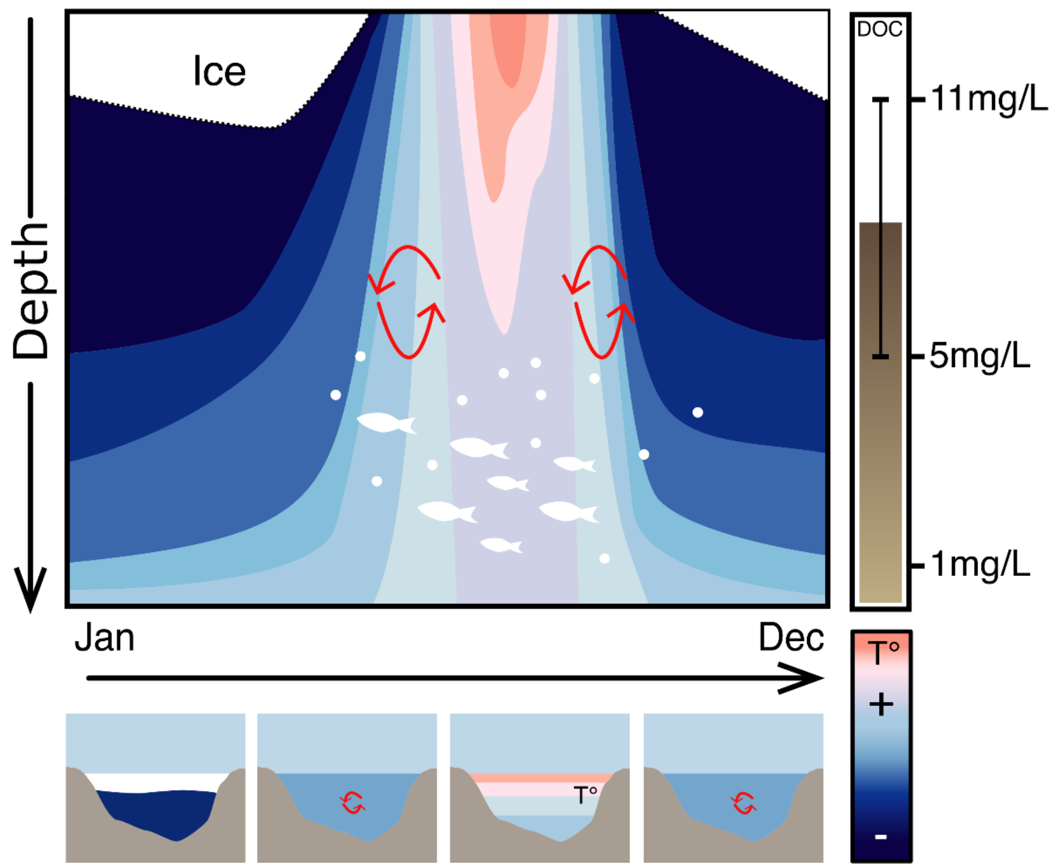

Fig. S13. Schematic representation of seasonal ice cover/low colour lakes

State shift from <u>*Seasonal ice cover/low colour lake*</u> *to* <u>*Seasonal ice cover/high colour lake*</u> *under a T+5°C scenario*

Response time: 10-100 years

Justification of response time: State shift involves warmer lake temperatures and an increase in the length of the ice-free season. These factors are expected to respond very quickly to air temperature changes, but since the transition also involves slower changes including browning (rising DOC content), it rather depends on changes in catchment vegetation (densification or "greening", change in vegetation assemblages) and permafrost degradation (Saulnier-Talbot et al. 2020). These changes induce alterations in the mixing regime, light availability at depth, and nutrient content.

5. Seasonal ice cover/high colour lake

Seasonal ice cover/high colour (>11 mg L^{-1} DOC); always ice-free in summer; dimictic; stratified for part of the warm season, leading to a decline of oxygen at the bottom; decreased light availability and colder water at the bottom compared to clearer lakes (Bartosiewicz et al. 2019); reduced planktonic primary production, and benthic production limited to shallows; zooplankton and fish diversity and abundance can be high but relying more on allochthonous carbon (Wauthy and Rautio 2020); fish habitat compromised by hypoxia.

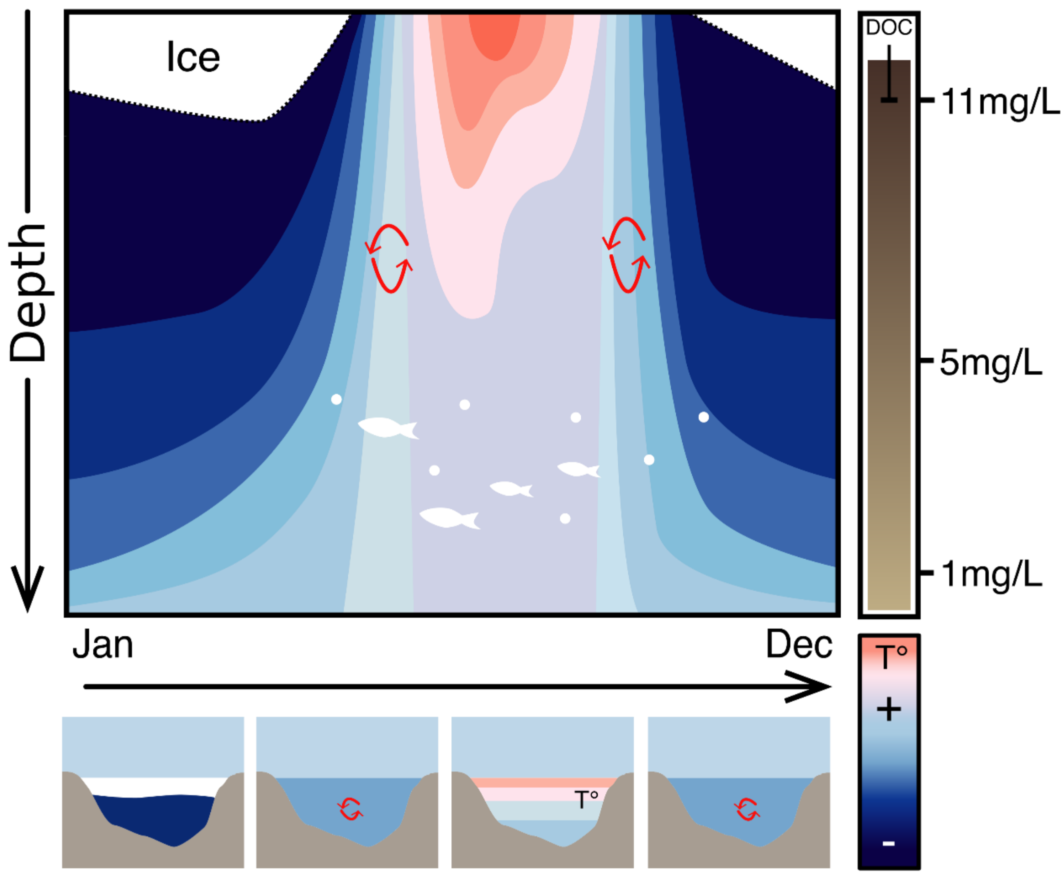

Fig. S14. Schematic representation of seasonal ice cover/high colour lakes

Glossary

Allochthonous carbon: Materials (e.g., organic matter and sediment) which enter a lake from the atmosphere or drainage basin. (https://www.nalms.org/water-words-glossary/)

Amictic lake: A lake that is always ice-covered (Lewis, 1983) and which does not experience vertical mixing (Likens, 2010).

Autotrophy: Process by which organisms obtains energy from carbon dioxide or carbonates and inorganic substances.

Catchment area: The land (and including the streams, rivers, wetlands and lakes) from which water runs off to supply a particular location in a freshwater system. (https://www.nalms.org/water-words-glossary/)

Cold monomictic lake: A lake covered by ice for most of the year, but with sufficient warming for the ice cover to thaw during a brief period; the water column warms but does not exceed 4°C (Lewis, 1983); experiences one period of mixing in summer (Likens, 2010).

Dimictic lake: A lake that is ice-covered part of the year, stably stratified part of the year, and mixing in spring and fall (Lewis, 1983)

Dissolved organic carbon (DOC): A measure of the organic compounds that are dissolved in water. In the analytical test for DOC, a water sample is first filtered to remove particulate material, and the organic compounds that pass through the filter are chemically converted to carbon dioxide, which is then measured to compute the amount of organic material dissolved in the water.

Heterotrophy: Process by which organisms use organic compounds for their metabolic synthesis.

Hypoxia: A condition in which natural waters have a low concentration of dissolved oxygen (about 2 milligrams per liter as compared with a normal level of 8 to 10 milligrams per liter). (https://www.nalms.org/water-words-glossary/)

Mixotrophy: Process by which organisms can perform heterotrophy and phototrophy depending on local environmental conditions.

Permafrost degradation: A naturally or artificially caused decrease in the thickness and/or areal extent of permafrost.

Phototrophy: Process by which organisms use sun light to produce chemical energy.

Polymictic lake: A lake that experiences several episodes of mixing per year (during the ice-free season) (Lewis, 1983, Likens, 2010)

Stratification: The arrangement of a body of water, such as a lake, into two or more horizontal layers of differing characteristics, such as temperature, density, etc. (https://www.nalms.org/water-words-glossary/)

References

Arp, C. D., Jones, B. M., Grosse, G., Bondurant, A. C., Romanovsky, V. E., Hinkel, K. M., & Parsekian, A. D. Threshold sensitivity of shallow Arctic lakes and sublake permafrost to changing winter climate. *Geophysical Research Letters*, ***43***(12), 6358-6365, (2016).

Bartosiewicz, M., Przytulska, A., Lapierre, J. F., Laurion, I., Lehmann, M. F., & Maranger, R. Hot tops, cold bottoms: Synergistic climate warming and shielding effects increase carbon burial in lakes. *Limnology and Oceanography Letters*, ***4***(5), 132-144, (2019).

Bégin, P. N., Rautio, M., Tanabe, Y., Uchida, M., Culley, A. I., & Vincent, W. F. The littoral zone of polar lakes: inshore–offshore contrasts in an ice-covered High Arctic lake. *Arctic Science*, ***7***(1), 158-181, (2020).

Bégin, P. N., Tanabe, Y., Rautio, M., Wauthy, M., Laurion, I., Uchida, M., ... & Vincent, W. F. Water column gradients beneath the summer ice of a High Arctic freshwater lake as indicators of sensitivity to climate change. *Scientific reports*, ***11***(1), 1-12, (2021).

Bélanger, C., Gratton, Y., St-Hilaire, A., Ouellet, V., Duchesne, V., Dubos, V., Logan, T., Laurion, I., & Pienitz, R. Impacts des changements climatiques sur les habitats thermiques du touladi (*Salvelinus namaycush*) et de l'omble chevalier (*Salvelinus alpinus*) dans les lacs du Nunavik. Rapport R1953, INRS-Eau, terre et environnement, Québec, Qc, xxxiii + 185 p. (2020).

Brown, L. C., & Duguay, C. R. The fate of lake ice in the North American Arctic. *The Cryosphere*, ***5***(4), 869-892, (2011).

Creed, I. F. et al. Global change-driven effects on dissolved organic matter composition: Implications for food webs of northern lakes. *Global Change Biology,* **24,** 3692–3714, (2018).

Culley, A. I., Thaler, M., Kochtitzky, W., Iqaluk, P., Rapp, J. Z., Rautio, M., ... & Girard, C. The Thores Lake proglacial system: remnant stability in the rapidly changing Canadian High Arctic. *Arctic Science*, e-First https://doi.org/10.1139/as-2022-0023 (2022).

Heathcote, A. J., Anderson, N. J., Prairie, Y. T., Engstrom, D. R., & Del Giorgio, P. A. Large increases in carbon burial in northern lakes during the Anthropocene. *Nature Communications*, ***6***(1), 1-6, (2015).

Lehnherr, I., St Louis, V. L., Sharp, M., Gardner, A. S., Smol, J. P., Schiff, S. L., ... & Talbot, C. H. The world's largest High Arctic lake responds rapidly to climate warming. *Nature Communications*, ***9***(1), 1-9, (2018).

Likens, G. E. Lake Ecosystem Ecology: A Global Perspective (Academic Press, 2010).

Mohit, V., Culley, A., Lovejoy, C., Bouchard, F., & Vincent, W. F. Hidden biofilms in a far northern lake and implications for the changing Arctic. *npj Biofilms and Microbiomes*, ***3***(1), 1-4, (2017).

Mueller, D. R., Van Hove, P., Antoniades, D., Jeffries, M. O., & Vincent, W. F. High Arctic lakes as sentinel ecosystems: Cascading regime shifts in climate, ice cover, and mixing. *Limnology and Oceanography*, *54*(6part2), 2371-2385, (2009).

Paquette, M., Fortier, D., Mueller, D. R., Sarrazin, D., & Vincent, W. F. Rapid disappearance of perennial ice on Canada's most northern lake. *Geophysical Research Letters*, ***42***(5), 1433-1440, (2015).

Rigler, F. H., MacCallum, M. E., & Roff, J. C. Production of zooplankton in Char Lake. *Journal of the Fisheries Board of Canada*, ***31***(5), 637-646, (1974).

Rouse, W. R., Oswald, C. J., Binyamin, J., Spence, C., Schertzer, W. M., Blanken, P. D., ... & Duguay, C. R. The role of northern lakes in a regional energy balance. *Journal of Hydrometeorology*, ***6***(3), 291-305, (2005).

Solomon, C. T., Jones, S. E., Weidel, B. C., Buffam, I., Fork, M. L., Karlsson, J., ... & Saros, J. E. Ecosystem consequences of changing inputs of terrestrial dissolved organic matter to lakes: current knowledge and future challenges. *Ecosystems*, ***18***(3), 376-389, (2015).

Saulnier-Talbot, É., Antoniades, D., & Pienitz, R. Hotspots of biotic compositional change in lakes along vast latitudinal transects in northern Canada. *Global Change Biology*, ***26***(4), 2270-2279, (2020).

Verpoorter, C., Kutser, T., Seekell, D. A., & Tranvik, L. J. A global inventory of lakes based on high-resolution satellite imagery. *Geophysical Research Letters*, ***41***(18), 6396-6402, (2014).

Wauthy, M., & Rautio, M. Permafrost thaw stimulates primary producers but has a moderate effect on primary consumers in subarctic ponds. *Ecosphere*, ***11***(6), e03099, (2020).

Wauthy, M., Rautio, M., Christoffersen, K. S., Forsström, L., Laurion, I., Mariash, H. L., ... & Vincent, W. F. Increasing dominance of terrigenous organic matter in circumpolar freshwaters due to permafrost thaw. *Limnology and Oceanography Letters*, ***3***(3), 186-198, (2018).

Wik, M., Varner, R. K., Anthony, K. W., MacIntyre, S., & Bastviken, D. Climate-sensitive northern lakes and ponds are critical components of methane release. *Nature Geoscience*, ***9***(2), 99-105, (2016).

Snowpack

*Winter snowpack covers the study region for 6 to 10 months of the year.
Along the transect, it ranges from a two-layer poorly insulating, thin, hard and dense polar desert snowpack to a multi-layer, very thick and insulating boreal forest snowpack.*

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Introduction

Snow covers northern lands from six to ten months of the year with major impacts on the ecosystems. Snow cools the surface because of its high **albedo** and its impact on the atmospheric **lapse rate**, since it favors a cold atmospheric surface layer (Pithan & Mauritsen, 2014). The thermal insulation capacity of the snow cover also affects the **thermal regime of the ground** by limiting its winter cooling (Domine et al. 2016a, Sturm et al. 2001). Insulating properties of the snow cover can also favor vegetation growth, through processes including enhanced nutrient cycling (Saccone et al. 2013, Ping et al. 2015, Pelletier et al. 2018). Vertebrate species such as small rodents and large mammals are also affected by snowpack characteristics. The case of lemmings, who live under the snow for up to 9 months of the year has been well documented. Years where a soft **depth hoar** layer formed at the base of the snowpack was found to coincide with summer peaks in lemming populations as soft snow facilitates locomotion and access to food and mating partners (Domine et al. 2018b). Another example is the formation of a hard **melt-freeze layer** caused by winter rain that can lead to caribou die offs because of its restricting access to food (Dolant et al. 2018b, Langlois et al. 2017).

The snowpack is comprised of several distinct layers. After deposition, snow physical properties are modified by changing thermodynamic conditions. When snow temperature remains below freezing, temperature gradients in the snowpack produce a water vapor pressure gradient that generates sublimation and condensation processes. This leads to changes in snow crystals sizes and shapes, and to various bond strengths between snow crystals. Snow physical properties such as density, thermal conductivity, hardness and albedo are then modified (Carmagnola et al. 2013, Domine et al. 2015). These physical transformations are grouped under the term “snow **metamorphism**” (Colbeck 1982). Wind is also an important factor affecting snow metamorphism. Wind-induced snow drifting leads to the sublimation of snow crystals and to their compaction into hard wind slabs (Domine et al. 2018a). On the other hand, non-drifted snow can undergo **temperature-gradient metamorphism**. Temperature gradients are largest during fall when the snowpack is thin and the ground still warm. Snow can then transform into **depth hoar** (Marbouty 1980, Akitaya 1967), composed of large **faceted** hollow and non-cohesive snow crystals (Figure S15). Depth hoar crystals are thus mostly found at the base of Arctic snowpacks and this is where lemmings move under the snow (Poirier et al. 2019). Regarding snow thermal properties, depth hoar layers have a low thermal conductivity and are the main contributor to snowpack insulating properties, thereby reducing ground cooling during winter (Zhang et al. 2005, Domine et al. 2016b). Vegetation cover and height can increase soil moisture and provide wind protection, and thus can greatly affect snowpack properties.

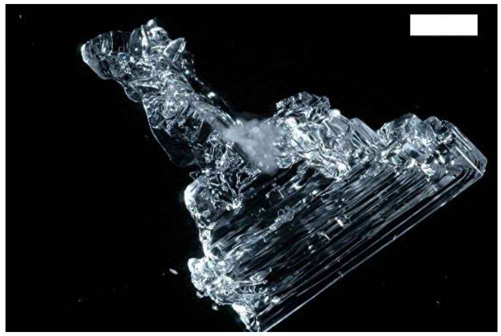


Fig. S15. A Depth hoar crystal. Scale bar: 1 mm.

Snowpack contrasting states are described based on the depth of snow an**d snowpack stratigraphy** (Fierz et al. 2009), describing ice crystal type, grain size and hardness of the different snow layers (Sturm et al. 1995, Royer et al. 2021). Snow vertical density profiles are also often considered when describing snowpack states. The following four snowpack contrasting states are currently encountered from North to South along the latitudinal gradient covered by our study: 1. polar desert, 2. polar tundra, 3. shrub tundra and 4. boreal forest snowpacks. We defined the southern limit of a snowpack contrasting state as the southernmost modern-day position of a landscape (30 km X 30 km) where a flat terrain with mesic conditions is dominated by a given state along the latitudinal gradient. The southern limit of boreal forest snowpack is not encompassed by the transect. Southern limits identified along our transect were considered critical thresholds. Local snowpack features, such as the presence of snowbeds, can have important impacts on local hydrology and biodiversity, especially in the northern part of the transect (Woo & Young 2014). However, they are not considered in the states definitions as they are scattered across the landscape, and thus not a dominant snowpack feature at the landscape scale. Even though snow cover length is another important factor, it is not used to characterize the contrasting states as it varies very gradually along the transect and is fluctuating greatly from year to year.

At each critical threshold, we determined the sensitivity of the snowpack state to a hypothetical warming scenario. We assessed the sensitivity using the estimated time required (the response time, in years) for an initial snowpack state to shift to another existing state if exposed to a sudden and persistent 5°C increase in mean annual temperature. We considered that a state shift is reached when more than 50% of the landscape (flat terrain with mesic conditions) is covered by the resulting state.

A change in air temperature is expected to have a significant impact on snowpack thickness, stratigraphy (via changes in precipitation amounts and phase or the occurrence of melt-freeze events) and snow cover duration. However, snowpack state shifts at critical thresholds are expected to be mainly driven by changes in vegetation structure that affects snow accumulation and compaction, ground moisture as well as wind protection (Sturm et al. 2001, Domine et al. 2016a, Domine et al. 2018a, Sturm et al. 1995, Grünberg et al. 2020). As snowpack properties are directly linked to contrasting vegetation types along our latitudinal gradient, snowpack state shifts at critical threshold are expected to follow vegetation state shifts. Local conditions such as topography, wind exposure, precipitation and soil characteristics may modulate the response time (increase or decrease response time within the assessed time interval).

1. Polar desert snowpack

(10-50 cm thick, typically 25 cm)

The polar desert snowpack is usually composed of a thin **depth hoar** layer (< 10 cm) of low to moderate density, typically 260 kg m^{-3}, topped by a hard and often thicker wind slab of higher density, typically 380 kg m^{-3} (Domine et al. 2002, Domine et al. 2018a, Davesne et al. 2022). Low soil moisture leading to rapid soil freezing and high wind exposure causing snow hardening that impedes water vapor fluxes can prevent depth hoar formation (Domine et al. 2018a). The hard and dense wind slab is composed of wind-drifted snow grains 0.2 to 0.3 mm in size with a rather rounded shape that often get compacted into dune-looking surface structures called **sastrugi** (Domine et al. 2002). Given the limited thickness of this snowpack type, its thin or absent depth hoar layer, and its relatively important and dense wind slab, the polar desert snowpack has poor thermal insulation properties.

Modern day southern limit: 74 ± 2.5 °N

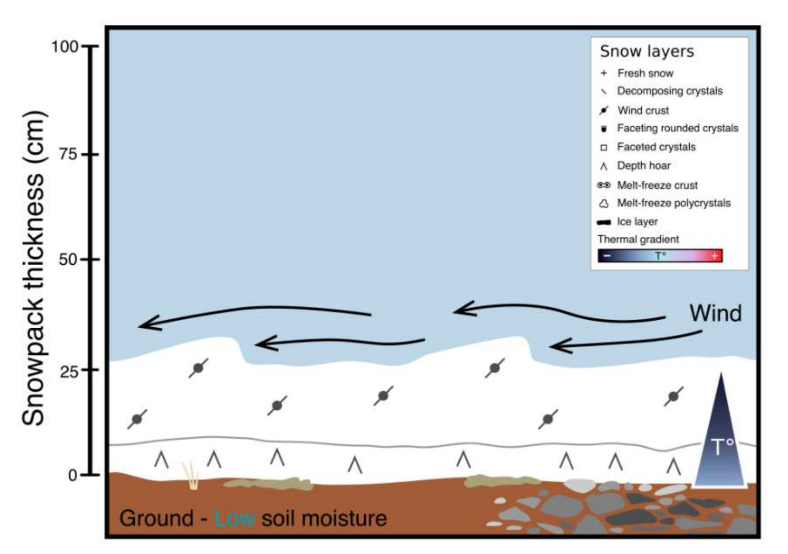


Fig. S16. Schematic representation of typical polar desert snowpack. The photograph shows a fairly thick polar desert snowpack comprised of essentially hard dense wind slabs, with very little depth hoar.

State shift from Polar desert snowpack to Polar tundra snowpack under a T+5°C scenario

Response time: 10-100 years

Justification of response time:

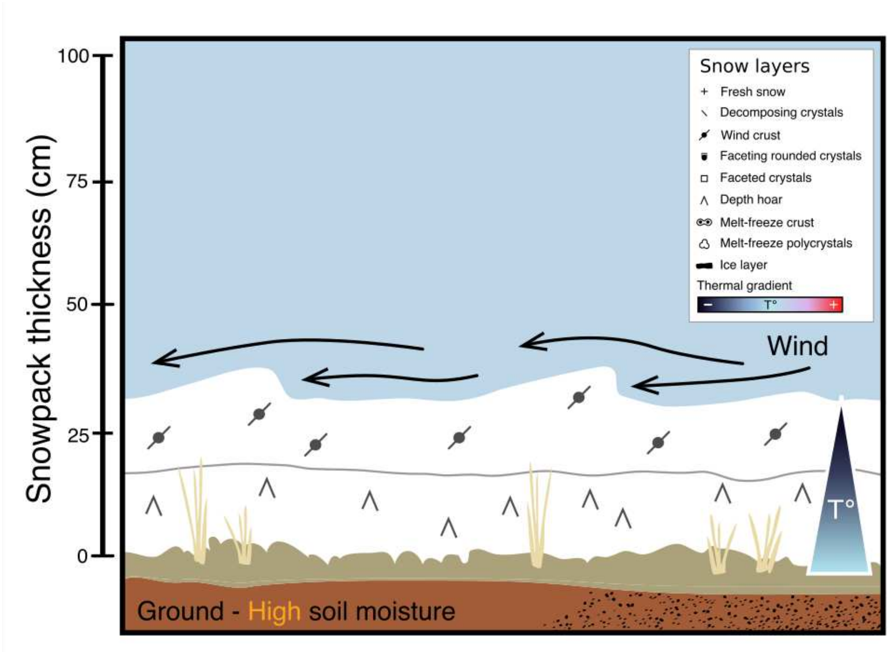
State shift is mostly triggered by a change in horizontal and vertical vegetation cover that increase soil moisture and slightly decrease wind exposure. Such changes directly affect the depth hoar layer that will reach a thickness providing good thermal insulation even in windy conditions. The snowpack state shift thus follows a state shift from polar desert vegetation to polar tundra vegetation.

2. Polar tundra snowpack

(10-60 cm thick, typically 30 cm)

The polar tundra snowpack is characterized by the presence of basal **depth hoar** even in windy conditions due to the increased amount of soil moisture (Domine et al. 2012, Derksen et al. 2014). Higher soil moisture delays soil freezing, creating a stronger temperature gradient in the snowpack that can be maintained for several weeks to months (Domine et al. 2016b). It results in a thicker depth hoar layer (typically 10 cm or more, with typical density of 230 kg m^{-3}) than in polar desert which provides better thermal insulation. As for the polar desert snowpack, the depth hoar layer is topped by a hard and dense wind slab with **sastrugi** at its surface (Filhol & Sturm 2015). However, this layer is proportionally thinner and slightly less dense (typically 360 kg m^{-3}) than in polar desert snowpacks. Given the greater thickness of the depth hoar layer, as well as the thinner wind slab, the polar tundra snowpack has increased thermal insulation properties compared to the polar desert snowpack.

Modern day southern limit: 61 ± 2.5 °N



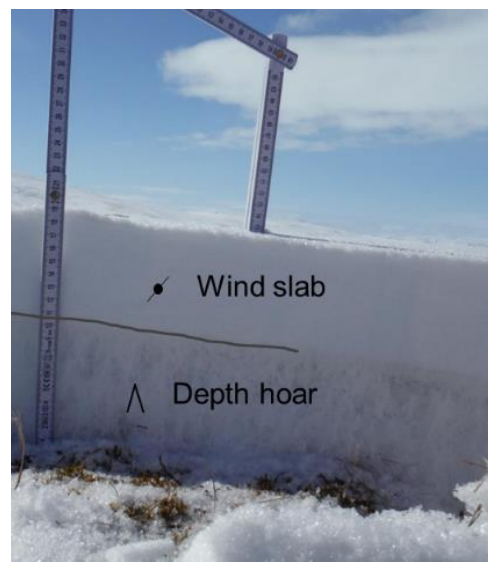


Fig. S17. Schematic representation of typical polar tundra snowpack. The photograph shows a fairly thin polar desert snowpack with a simple but typical stratigraphy featuring a thick depth hoar layer, here extending over >50% of the snowpack height, The top of the snowpack is a wind slab.

State shift from <u>Polar tundra snowpack</u> to <u>Shrub tundra snowpack</u> under a T+5°C scenario

Response time: 10-100 years

Justification of response time: State shift is mostly linked to an increased snowpack thickness, especially of the depth hoar layer, and a decreased wind crust layer thickness. These changes are mostly triggered by the presence of higher stature vegetation (shrubs) that increase soil moisture, provide wind protection and allow greater snow accumulation

(Domine et al. 2016a, Grünberg et al. 2020). The snowpack is thus expected to adjust continuously to the changing vegetation. Its response time is therefore the same as that for a state shift from polar tundra vegetation to shrub tundra vegetation.

3. Shrub tundra snowpack

(30-70 cm thick, typically 50 cm)

The shrub tundra snowpack is characterized by a very thick **depth hoar** basal layer (> 20 cm). Depth hoar can form up to the top of the shrubs due to a combination of high soil humidity and wind protection by shrub branches, and because of positive feedback where increased depth hoar formation maintains a warm ground and therefore a high temperature gradient in the snowpack (Domine et al. 2016a). This thick depth hoar layer is often composed of large crystals (that can exceed 10 mm in size) and provides excellent thermal insulation for the ground (Sturm et al. 2001, Domine et al. 2016a). The depth hoar layer, with a density ranging from 200 kg m^{-3} to 300 kg m^{-3}, with the higher values caused by melting events and water percolation, is usually topped by a thinner layer of **faceted crystals**. These crystals represent an initial stage of depth hoar formation. These upper layers form later during the season, when the temperature gradient has decreased too much for the depth hoar stage to be reached. Further up, yet an earlier stage of development is often observed in the form of faceted rounded crystals, which is the first stage of evolution of **rounded crystals** into faceted ones. If the snow cover reaches or exceeds shrub height, a wind slab can form on top of the snowpack. It often reaches or exceeds 400 kg m^{-3} when large amounts of precipitation allow the snowpack to extend well above the shrub top. A **fresh snow** layer can sometimes be seen on top of wind crusts. Furthermore, warm spells or rain-on snow events during winter can occasionally lead to the formation of **melt-freeze layers**, as well as percolation structures in the snowpack (Dolant et al. 2018a, Barrere et al. 2018). As the shrub tundra snowpack is usually mainly composed of low-density layers, it has increased thermal insulation properties compared to the polar tundra snowpack (Sturm et al. 2001, Domine et al. 2016a).

Modern day southern limit: 58 ± 2.5 °N

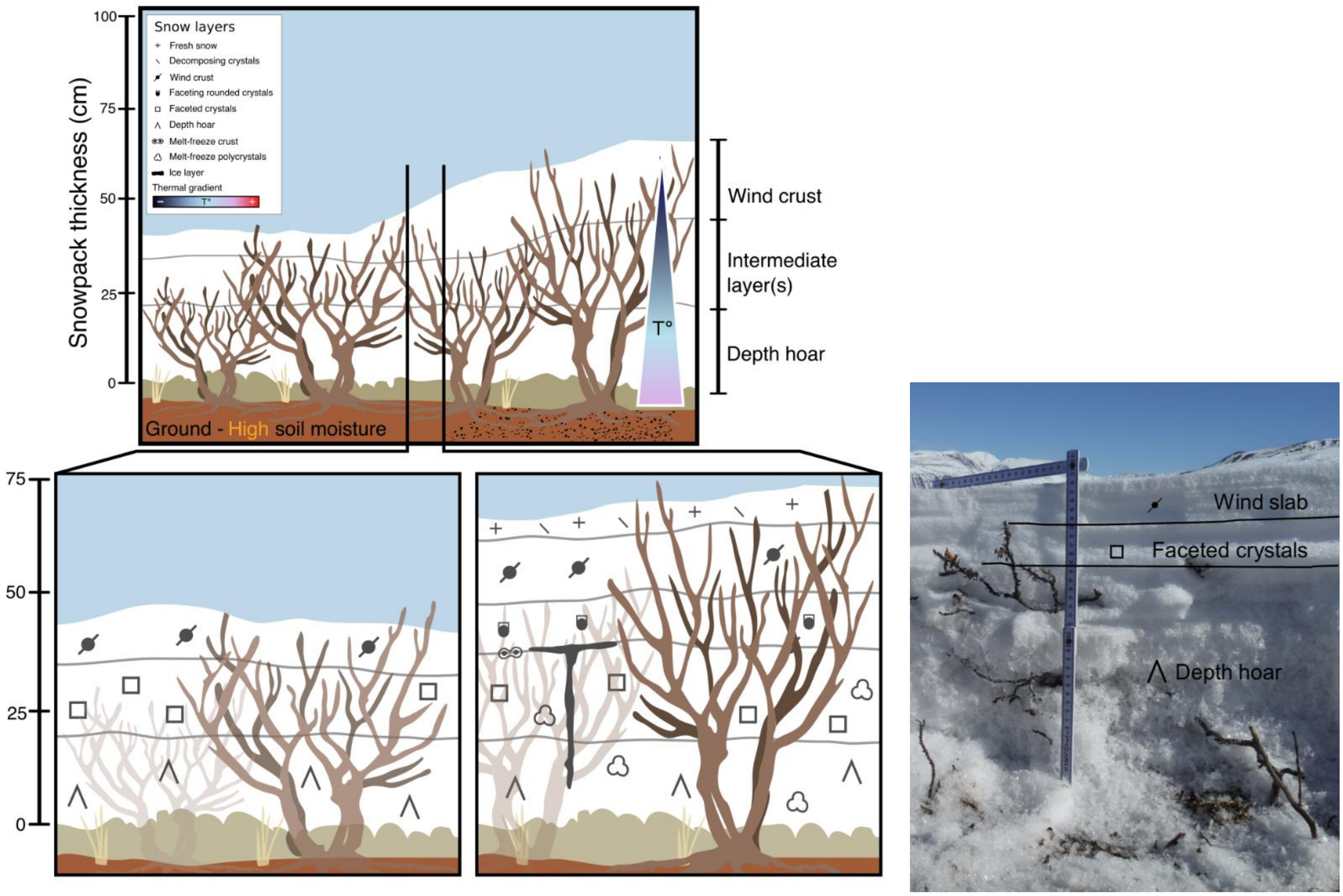


Fig. S18. Schematic representation of typical shrub tundra snowpack. The photograph shows an example of shrub tundra snowpack with a very thick depth hoar layer (28 cm), a thinner faceted crystals layer and a wind slab.

State shift from <u>Shrub tundra snowpack</u> to <u>Boreal forest snowpack</u> under a T+5°C scenario

Response time: >100 years

Justification of response time: State shift is mostly linked to an increase in snowpack and basal depth hoar layer thickness, the absence of a wind slab and the apparition of a more complex layer structure in the snowpack. These changes are triggered by the presence of trees that greatly reduce wind exposure and allow greater snow accumulation. The snowpack is thus expected to quickly follow a state shift from shrub tundra vegetation to forest vegetation.

4. Boreal forest snowpack

(70-180 cm thick, typically 100 cm)

The boreal forest snowpack is characterized by a **depth hoar** layer that can be very thick (30-60cm) but in which crystals are less well-formed, with a size rarely exceeding 5 mm and usually in the 2 to 3 mm range. Because of compaction by upper layers and the occurrence of melting events, this depth hoar layer has a typical density of 300 kg m^{-3}, often higher. However, layers of small depth hoar or **faceted crystals** can form over tens of cm above the basal depth hoar layer (Sturm 1992). Warm spells often lead to the formation of **melt-freeze layers** and percolation structures in the snowpack. The top layer is rarely a wind slab because of low wind speed in the forest and is often comprised of moderately consolidated fine-grained snow or **faceting rounded crystals**. Overall, the very thick snowpack, typically 100 cm, is highly insulating so that the ground, if it freezes, cools down by just a few degrees below zero (Kropp et al. 2020).

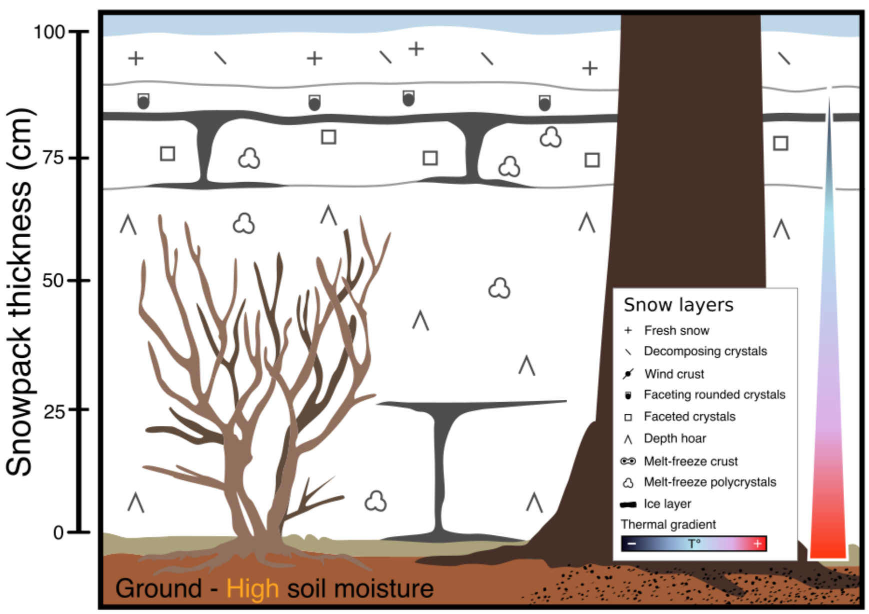


Fig. S19. Schematic representation of typical boreal forest snowpack. The photograph shows a typical boreal forest snowpack with numerous snow layers and a shrub understory.

Glossary

Definitions come from the cryosphere glossary of the National Snow & Ice Data Center https://nsidc.org/cryosphere/glossary and (Domine et al. 2008)

Albedo: A measure of how well a surface reflects solar energy; ranges from 0 - 1; a value of 0 means the surface is a perfect absorber, where all incoming energy is absorbed, a value of 1 means the surface is a perfect reflector, where all incoming energy is reflected and none is absorbed.

Depth hoar: Depth hoar crystals in seasonal snow usually result from the **metamorphism** of snow with low to moderate density under high temperature gradient that generate strong water vapor fluxes and rapid growth, resulting in hollow faceted crystals with sharp angles. Their sizes range from 2 to 20 mm. The connectivity between crystals is usually very weak, producing very uncohesive snow (Domine et al. 2008).

Faceted crystals: ice crystals with flat faces and sharp angles, that are usually 0.5 to 2 mm in size. They are produced in the early stages of depth hoar formation (Sturm and Benson, 1997), or under conditions of moderate temperature gradient. They are poorly interconnected, and layers of such crystals are as uncohesive as depth hoar layers. (Domine et al. 2008)

Faceting rounded crystals: Crystals displaying both flat faces and rounded shapes. Their size is often in the range 0.3 to 1 mm. They can be formed under low to moderate temperature gradients, or by the rounding of small **faceted crystals** following a decrease in the temperature gradient. (Domine et al. 2008)

Fresh snow crystals: Freshly precipitated snow crystals have varied shapes depending mostly on the temperature and supersaturation in the cloud where they formed (Nakaya 1954). Common shapes include plates, dendritic crystals, graupel, columns and needles, as abundantly illustrated by Wergin et al. (1995 and 1996) and Domine et al. (2003). (Domine et al. 2008)

Lapse rate: The rate of change of any meteorological element with height.

Melt-freeze crusts and layers: Melt-freeze layers are formed by the thermal cycling of snow layers, usually with diurnal melting and nocturnal freezing (Colbeck 1982). Grains grow with each cycle and are often observed to have a size in the range 0.5 to 2 mm (Raymond and Tusima, 1979). The melting of low-density snow allows facile percolation and **forms melt freeze layers of low density (down to 0.1 g/cm), and of moderate cohesiveness when frozen.** Melting in denser layers results in dense melt-freeze crusts that have a strong cohesiveness when frozen (Domine et al. 2008). A melt freeze crust is a thin melt-freeze layer that has usually been subjected to a single melting event.

Metamorphism: changes in the structure and texture of snow grains which result from the effect of wind, variations in temperature, migration of liquid water and water vapor within the snow cover.

Rounded crystals: Rounded grains are produced by low-temperature gradient **metamorphism** of precipitated snow, and layers of such crystals have densities between 200 and 350 kg/m3 (Albert & Shultz 2002, Domine et al. 2003). Crystal size range from 0.1 mm to almost 1 mm at the end of the season. Rounded grains can also be produced by hard-packed wind-blown snow crystals, in which case their density can reach 500 kg m^{-3} (Domine et al. 2002). Crystals in hard windpacks seldom exceed 0.4 mm in size. The interconnectivity between rounded grains is strong: these layers are cohesive and their cohesiveness increases with density (Domine et al. 2008).

Sastrugi: snow structures formed by wind. These structures are elongated along the wind direction and have a steep erosion face facing the wind.

Snow: (1) precipitating snow is ice crystals formed by condensation of water vapor into ice in the atmosphere or by the freezing of supercooled water droplets, or more frequently by a combination of both processes; (2) snow on the ground is precipitated snow that has evolved following **metamorphism**, to form the snowpack. Part of the snowpack can be formed by the direct condensation of water vapor or by the freezing of supercooled water droplets onto its surface.

Snowpack stratigraphy: The vertical succession of distinct snow layers.

Temperature-gradient metamorphism: snow **metamorphism** that occurs when there are strong differences in temperature between the bottom and the top of a snow layer.

Thermal regime of the ground: a general term encompassing the temperature distribution and heat flows in the ground and their time-dependence.

References

Akitaya, E. Some experiments on the growth of depth hoar. *Physics of Snow and Ice: proceedings*, ***1***(2), 713-723, (1967).

Albert, M. R., & Shultz, E. F. Snow and firn properties and air–snow transport processes at Summit, Greenland. *Atmospheric Environment*, ***36***(15-16), 2789-2797, (2002).

Barrere, M., Domine, F., Belke-Brea, M., & Sarrazin, D. Snowmelt events in autumn can reduce or cancel the soil warming effect of snow–vegetation interactions in the Arctic. *Journal of Climate*, **31**(23), 9507-9518, (2018).

Carmagnola, C. M., Domine, F., Dumont, M., Wright, P., Strellis, B., Bergin, M., ... & Morin, S. Snow spectral albedo at Summit, Greenland: measurements and numerical simulations based on physical and chemical properties of the snowpack. *The Cryosphere, **7***(4), 1139-1160, (2013).

Colbeck, S. C. An overview of seasonal snow metamorphism. *Reviews of Geophysics*, ***20***(1), 45-61, (1982).

Davesne, G., Domine, F., & Fortier, D. Effects of meteorology and soil moisture on the spatio-temporal evolution of the depth hoar layer in the polar desert snowpack. *Journal of Glaciology*, ***68***(269), 457-472, (2022).

Derksen, C., Lemmetyinen, J., Toose, P., Silis, A., Pulliainen, J., & Sturm, M. Physical properties of Arctic versus subarctic snow: Implications for high latitude passive microwave snow water equivalent retrievals. *Journal of Geophysical Research: Atmospheres*, ***119***(12), 7254-7270, (2014).

Dolant, C., Langlois, A., Brucker, L., Royer, A., Roy, A., & Montpetit, B. Meteorological inventory of rain-on-snow events in the Canadian Arctic Archipelago and satellite detection assessment using passive microwave data. *Physical Geography*, ***39***(5), 428-444, (2018a).

Dolant, C., Montpetit, B., Langlois, A., Brucker, L., Zolina, O., Johnson, C. A., ... & Smith, P. Assessment of the Barren Ground Caribou Die-off During Winter 2015–2016 Using Passive Microwave Observations. *Geophysical Research Letters*, ***45***(10), 4908-4916, (2018b).

Domine, F., Albert, M., Huthwelker, T., Jacobi, H. W., Kokhanovsky, A. A., Lehning, M., ... & Simpson, W. R. Snow physics as relevant to snow photochemistry. *Atmospheric chemistry and physics*, ***8***(2), 171-208, (2008).

Domine, F., Barrere, M., & Morin, S. The growth of shrubs on high Arctic tundra at Bylot Island: impact on snow physical properties and permafrost thermal regime. *Biogeosciences*, ***13***(23), 6471-6486, (2016a).

Domine, F., Barrere, M., & Sarrazin, D. Seasonal evolution of the effective thermal conductivity of the snow and the soil in high Arctic herb tundra at Bylot Island, Canada. *The Cryosphere*, ***10***(6), 2573-2588, (2016b).

Domine, F., Barrere, M., Sarrazin, D., Morin, S., & Arnaud, L. Automatic monitoring of the effective thermal conductivity of snow in a low-Arctic shrub tundra. *The Cryosphere*, ***9***(3), 1265-1276, (2015).

Domine, F., Belke-Brea, M., Sarrazin, D., Arnaud, L., Barrere, M., & Poirier, M. Soil moisture, wind speed and depth hoar formation in the Arctic snowpack. *Journal of Glaciology*, ***64***(248), 990-1002, (2018a).

Domine, F., Cabanes, A., & Legagneux, L. Structure, microphysics, and surface area of the Arctic snowpack near Alert during the ALERT 2000 campaign. *Atmospheric Environment*, ***36***(15-16), 2753-2765, (2002).

Domine, F., Gauthier, G., Vionnet, V., Fauteux, D., Dumont, M., & Barrere, M. Snow physical properties may be a significant determinant of lemming population dynamics in the high Arctic. *Arctic Science*, ***4***(4), 813-826, (2018b).

Domine, F., Gallet, J. C., Bock, J., & Morin, S. Structure, specific surface area and thermal conductivity of the snowpack around Barrow, Alaska. *Journal of Geophysical Research: Atmospheres*, ***117***(D14), (2012).

Domine, F., Lauzier, T., Cabanes, A., Legagneux, L., Kuhs, W. F., Techmer, K., & Heinrichs, T. Snow metamorphism as revealed by scanning electron microscopy. *Microscopy research and technique*, ***62***(1), 33-48, (2003).

Fierz, C., Armstrong, R. L., Durand, Y., Etchevers, P., Greene, E., McClung, D. M., Nishimura, K., Satyawali, P. K., & Sokratov, S. A. The International classification for seasonal snow on the ground UNESCO-IHP, ParisIACS Contribution N°1, 80, (2009).

Filhol, S., & Sturm, M. Snow bedforms: A review, new data, and a formation model. *Journal of Geophysical Research: Earth Surface*, ***120***(9), 1645-1669, (2015).

Grünberg, I., Wilcox, E. J., Zwieback, S., Marsh, P., & Boike, J. Linking tundra vegetation, snow, soil temperature, and permafrost, *Biogeosciences*, **17**, 4261-4279, (2020).

Kropp, H., Loranty, M. M., Natali, S. M., Kholodov, A. L., Rocha, A. V., Myers-Smith, I., ... & Lund, M. Shallow soils are warmer under trees and tall shrubs across Arctic and Boreal ecosystems. *Environmental research letters*, ***16***(1), 015001, (2020).

Langlois, A., Johnson, C. A., Montpetit, B., Royer, A., Blukacz-Richards, E. A., Neave, E., ... & Brucker, L. Detection of rain-on-snow (ROS) events and ice layer formation using passive microwave radiometry: A context for Peary caribou habitat in the Canadian Arctic. *Remote Sensing of Environment*, ***189***, 84-95, (2017).

Marbouty, D. An experimental study of temperature-gradient metamorphism. *Journal of Glaciology*, ***26***(94), 303-312, (1980).

Nakaya, U. Snow crystals: natural and artificial. (Harvard university press, 1954).

Pelletier, M., Allard, M., & Levesque, E. Ecosystem changes across a gradient of permafrost degradation in subarctic Québec (Tasiapik Valley, Nunavik, Canada). *Arctic Science*, ***5***(1), 1-26, (2018).

Ping, C. L., Jastrow, J. D., Jorgenson, M. T., Michaelson, G. J., & Shur, Y. L. Permafrost soils and carbon cycling. *Soil*, ***1***(1), 147-171, (2015).

Pithan, F., & Mauritsen, T. Arctic amplification dominated by temperature feedbacks in contemporary climate models. *Nature geoscience*, ***7***(3), 181-184, (2014).

Poirier, M., Gauthier, G., & Domine, F. What guides lemmings movements through the snowpack? *Journal of Mammalogy*, **10**, 1416-1426, (2019).

Raymond, C. F., & Tusima, K. Grain coarsening of water-saturated snow. *Journal of Glaciology*, ***22***(86), 83-105, (1979).

Royer, A., Domine, F., Roy, A., Langlois, A., Marchand, N., & Davesne, G. New northern snowpack classification linked to vegetation cover on a latitudinal mega-transect across northeastern Canada, *Écoscience*, **28**, 225-242, (2021).

Sturm, M. Snow distribution and heat flow in the taiga. *Arctic and Alpine Research*, ***24***(2), 145-152, (1992).

Sturm, M., & Benson, C. S. Vapor transport, grain growth and depth-hoar development in the subarctic snow. *Journal of Glaciology*, ***43***(143), 42-59, (1997).

Sturm, M., Holmgren, J., & Liston, G. E. A seasonal snow cover classification system for local to global applications. *Journal of Climate*, ***8***(5), 1261-1283, (1995).

Sturm, M., Holmgren, J., McFadden, J. P., Liston, G. E., Chapin, F. S., & Racine, C. H. Snow–shrub interactions in Arctic tundra: a hypothesis with climatic implications. *Journal of Climate*, ***14***(3), 336-344, (2001).

Saccone, P., Morin, S., Baptist, F., Bonneville, J. M., Colace, M. P., Domine, F., ... & Clément, J. C. The effects of snowpack properties and plant strategies on litter decomposition during winter in subalpine meadows. *Plant and soil*, ***363***, 215-229, (2013).

Wergin, W. P., Rango, A., & Erbe, E. F. Observations of snow crystals using low-temperature scanning electron microscopy. *Scanning*, ***17***(1), 41-50, (1995).

Wergin, W. P., Rango, A., Erbe, E. F., & Murphy, C. A. Low temperature SEM of precipitated and metamorphosed snow crystals collected and transported from remote sites. Microscopy and Microanalysis, **2**(3), 99-112, (1996).

Woo, M. K., & Young, K. L. Disappearing semi-permanent snow in the High Arctic and its consequences. *Journal of Glaciology*, ***60***(219), 192-200, (2014).

Zhang, T. Influence of the seasonal snow cover on the ground thermal regime: An overview. *Reviews of Geophysics*, ***43***(4), (2005).

Vegetation

Vegetation ranges across our transect from very sparse and low polar desert vegetation to dense and tall, closed canopy boreal forest vegetation.

Contributing experts (alphabetical order):

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de Lafontaine, Guillaume
Lévesque, Esther
Simard, Martin
Payette, Serge

Introduction

Vegetation structures the landscape and can affect other ecosystem components through various direct and indirect mechanisms, including the radiation balance, through an alteration of the surface albedo, and by providing food and shelter to wildlife (Bruhwiler et al. 2021). For example, the vertical structure of vegetation traps snow in winter (Sturm et al. 2001) and creates breeding and foraging sites for vertebrates (Ims & Henden 2012). Vegetation also shields and insulates frozen grounds (Shur and Jorgenson, 2007), and greatly contributes to the carbon production, storage and exportation from northern ecosystems (Bruhwiler et al. 2021).

Vegetation contrasting states are defined by the dominant structural characteristics of vegetation cover, namely height and **growth form** (herbs, forbs, shrubs, coniferous and deciduous trees), as commonly used in the literature (Bliss & Matveyeva 1992, Walker et al. 2005, Leboeuf et al. 2018, Payette & Delwaide 2018). The vegetation along the latitudinal gradient covered by our study is a complex mosaic crafted by the regional timing of deglaciation, topography, arrival and success of colonizing species, regeneration, and forest cover degradation across the different climatic episodes (e.g., Hypsithermal, Neoglacial period, Medieval Climate Anomaly, Little Ice Age), as well as the nature, intensity, and frequency of disturbances such as fire and insect outbreaks (Payette 1993, Payette et al. 2001, Gajewski et al. 2021).

The following six vegetation contrasting states are currently encountered from North to South along the latitudinal gradient: 1. polar desert, 2. polar tundra, 3. shrub tundra, 4. open-crown coniferous forest, 5. closed-crown coniferous forest, and 6. mixed-wood boreal forest (currently found in isolated patches in the area covered by our transect but is expected to expand under warmer conditions). We defined the southern limit of a given vegetation state as the southernmost modern-day position of a landscape (30 km × 30 km) where a flat terrain with mesic conditions is dominated by a given vegetation state. The southern limit of mixed-wood boreal forest is not encompassed by our gradient. Southern limits identified along the transect were considered critical thresholds.

At each critical threshold, we assessed the sensitivity of the vegetation state to a hypothetical warming scenario. We quantified the sensitivity using the estimated time required (the response time, in years) for an initial vegetation state to shift to another existing state if exposed to a sudden and persistent 5°C increase in mean annual temperature. We considered that a state shift is reached when more than 50% of the landscape (flat terrain with mesic conditions) is covered by the resulting state.

State shifts in vegetation found along the latitudinal gradient are expected to be mainly driven by the effect of air temperature on plant growth, survival, and reproduction. Local conditions such as precipitation, frequency and intensity of disturbances (especially fire and insects), exposure to solar radiation and wind, species colonization rate, herbivory, as well as soil characteristics could modulate the response time (increase or decrease response time within the assessed time interval).

1. Polar desert

(traces to 40-60% cryptogamic **ground cover**, sparse vascular plant **ground cover**, < 5 cm tall)

Here the term polar desert is broadly used to encompass the vegetation types typical of cold, low precipitation zones of the Arctic corresponding to the polar desert and polar semi-desert vegetation of Bliss and Matveyeva (1992). The vegetation is sparse (vascular plant cover limited to less than 25%) and prostrate (generally < 5 cm tall). The cryptogamic cover (including lichens, mosses, liverworts and cyanobacteria) is variable from traces to 40-60% depending on local moisture availability. The dominant vascular plant species include forbs (*Saxifraga* spp., *Papaver* spp.), prostrate shrubs (*Salix arctica*, *Dryas integrifolia*) and graminoids (*Carex nardina*, *Phippsia algida*). This type of cover is commonly found in zones A and B of the Circumpolar Arctic vegetation map (CAVM 2003, Walker et al. 2005).

Modern day southern limit: 74 ± 2.5 °N

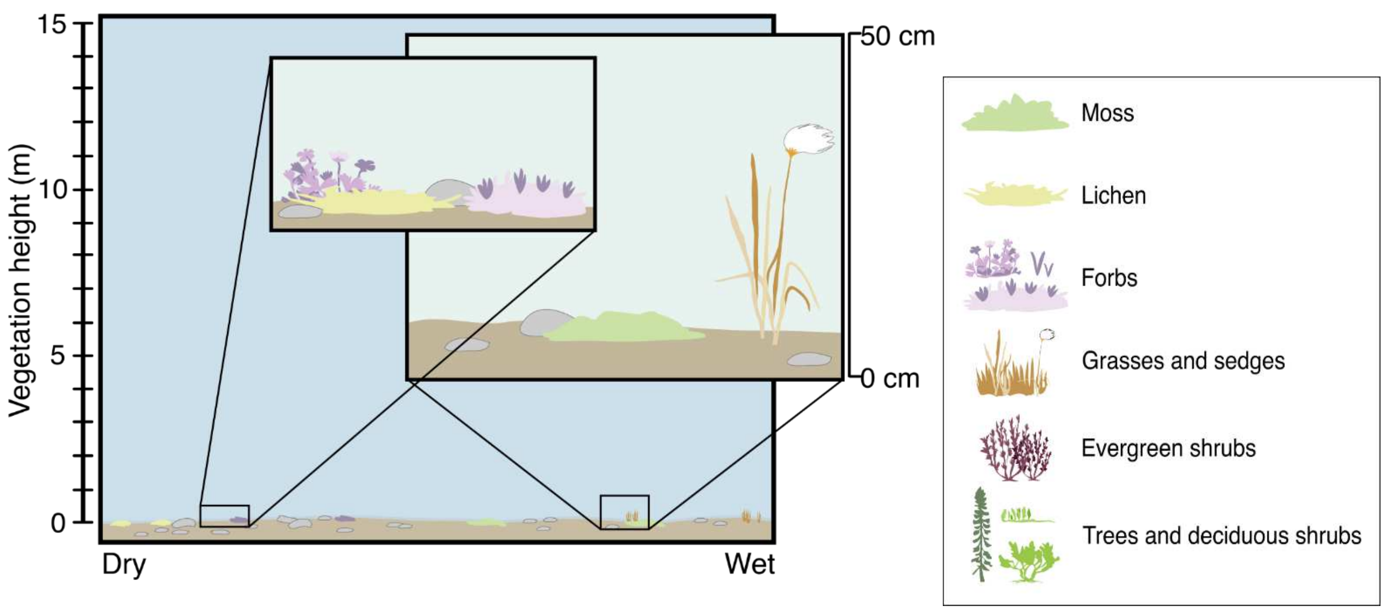

Fig. S20. Schematic representation of typical polar desert vegetation. Pictograms and colours represent plant functional groups and growth forms (see legend).

State shift from <u>*Polar desert*</u> *to* <u>*Polar tundra*</u> *under a T+5°C scenario*

Response time: 10-100 years

Justification of response time: State shift is mostly linked to an increase in vegetation horizontal cover that involves the lateral expansion of pre-established species and the colonisation of new low stature species. These changes are mostly driven by a direct effect of air temperature on plant species growth, survival and reproduction. The response time is expected to be relatively rapid, as some plant species are already present on site whereas others are present near the southern limit of the polar desert.

2. Polar tundra

(40 - 100% **plant ground cover**, < 25 cm tall)

Mesic and wet vegetation types with low vertical structure (height dependant on latitude and species diversity but generally < 25 cm), horizontal cover from 40 to 100% including a strong cryptogam cover varying with moisture and latitude up to 100%. Drier vegetation dominated by prostrate shrubs (*Dryas integrifolia*, *Salix arctica*), cushion forbs (*Saxifraga oppositifolia, Saxifraga tricuspidata*) and sedges (*Carex nardina, Carex myosuroid*es). Wet vegetation dominated by grasses (*Alopecurus, Dupontia and Poa* spp.), sedges (*Carex* and *Eriophorum* spp.) and rushes (*Luzula* spp.). This type of cover is generally found in zones C and D of the Circumpolar Arctic vegetation map (Walker et al. 2005).

Modern day southern limit: 61 ± 2.5 °N

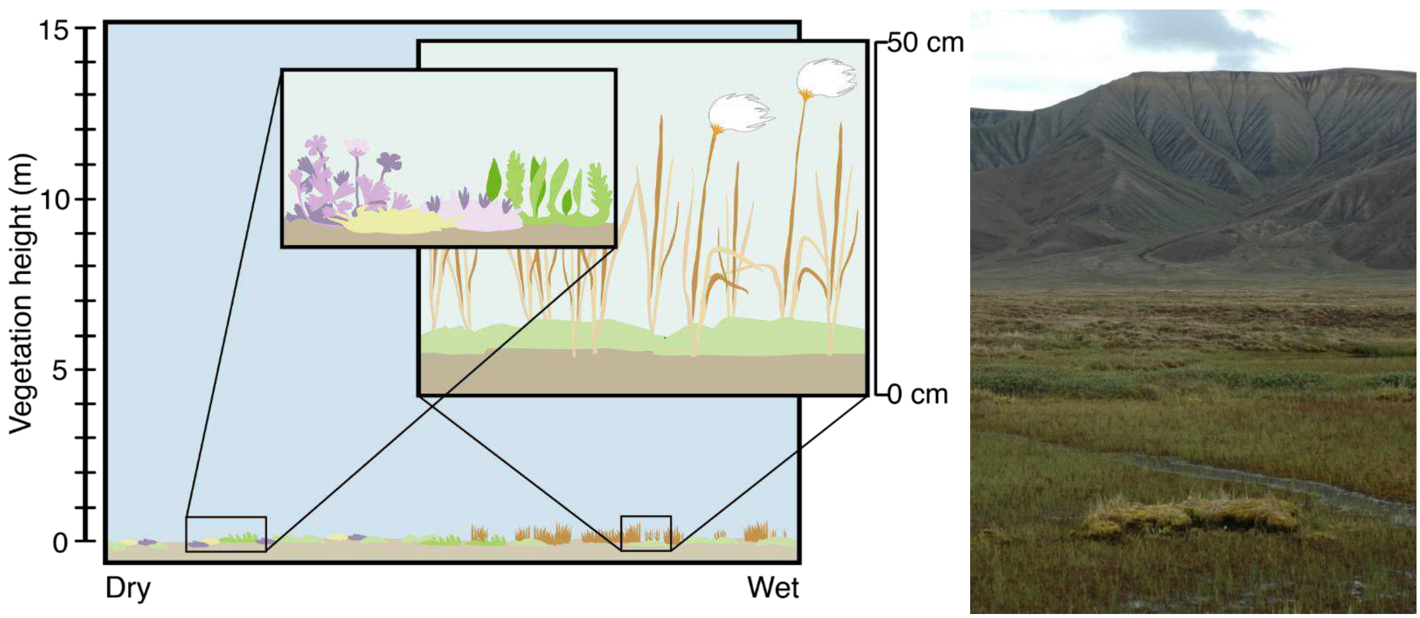

Fig. S21. Schematic representation of typical polar tundra vegetation. Pictograms and colours represent plant functional groups and growth forms (see legend).

State shift from *Polar tundra* *to* *Shrub tundra* *under a T+5°C scenario*

Response time: 10-100 years

Justification of response time: State shift is mostly linked to an increase in vegetation vertical cover linked to growth and the establishment of taller, mostly erect shrub, species. These changes are driven by a direct effect of air temperature on plant species growth, survival and reproduction. The response time is expected to be relatively rapid, as species are already present on site whereas others are present near the southern limit of the polar tundra.

3. Shrub tundra

(generally continuous **plant ground cover**, 25cm-5m tall)

Mostly continuous vegetation dominated by shrub cover generally with heights varying from 25 cm to a few meters (< 5 m), mostly deciduous (incl. *Betula glandulosa*, *Salix* spp. and *Vaccinium uliginosum*) but also evergreen (*Rhododendron* and *Empetrum* spp.) with a high lichen cover in dry conditions, a higher abundance of graminoids and mosses in wet conditions and taller hydrophilous shrub species (*Alnus* spp.) in protected riverine areas.

Modern day southern limit: 58 ± 2.5 °N

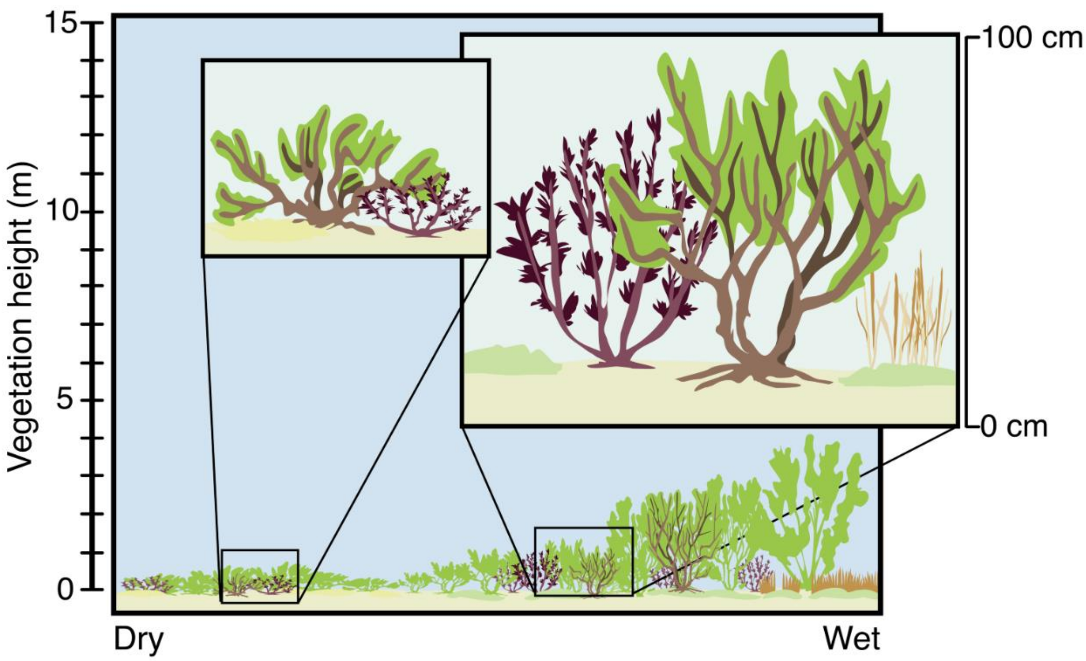

Fig. S22. Schematic representation of typical shrub tundra vegetation. Pictograms and colours represent pant functional groups and growth forms (see legend).

State shift from <u>Shrub tundra</u> to <u>Closed-crown coniferous forest or mixed wood boreal forest</u> under a T+5°C scenario

Response time: >100 years

Justification of response time: State shift (either to closed-crown or mixed wood boreal forest) is mostly linked to the colonization and growth of tree species that are not yet dominant in the landscape. These changes are driven by a direct effect of air temperature on plant species growth, survival and reproduction. Even if tree species are present near or at the southern limit of this state, colonization and expansion could be slowed down or even prevented by a relatively rapid expansion in height and cover of shrub species already present. In addition, successful tree colonization requires time to transform the vertical structure at the landscape scale.

N. B. The direct shift from shrub-tundra to a closed-crown or mixed wood boreal forest need not go through an open-crown forest. Although there might be a transient woodland at the expansion front during the very first stage of a northward colonization process, the rapid population densification following this initial establishment should readily lead to a closed-crown or mixed wood boreal forest state. By contrast, the steady open-crown coniferous forest state reveals the lingering impact of historical wildfires during periods of unfavourable climate, disrupting the regeneration process (see below).

4. Open-crown coniferous forest

(generally continuous plant **ground cover**, < 40% tree cover, 5 - 15 m tall)

Conifer forest dominated by black spruce *Picea mariana* with a tree cover less than 40%. This vegetation type comprises the forest-tundra, where stunted spruce trees may grow up to 5 m tall in clones of krummholz, and the lichen woodland, where sparse spruce trees show an arborescent **growth form** (up to 15 m tall). The understory is dominated by lichens as well as deciduous and evergreen shrubs (*Betula glandulosa*, as well as *Vaccinium, Empetrum, Kalmia and Rhododendron* spp.).

Modern day southern limit: 51 ± 2.5 °N

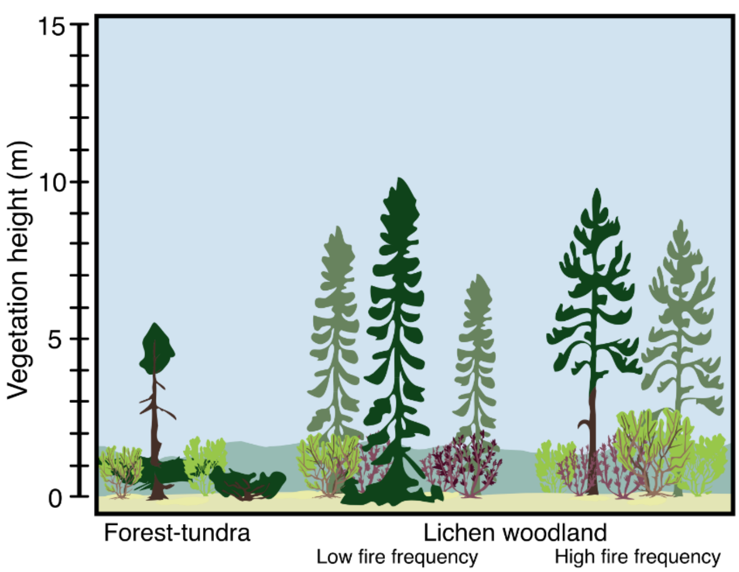

Fig. S23. Schematic representation of typical open-crown coniferous forest vegetation. Pictograms and colours represent pant functional groups and growth forms (see legend).

State shift from <u>Open-crown coniferous forest</u> to <u>Closed-crown coniferous forest or Mixed wood boreal forest</u> under a T+5°C scenario

Response time: >100 years

Justification of response time: State shift to either closed-crown coniferous forest or mixed wood boreal forest is mostly linked to the gradual colonization and/or densification of thermophilous species (balsam fir *Abies balsamea*, white birch *Betula papyrifera*) in wet conditions or a densification of fire-adapted species (Jack pine *Pinus banksiana*, trembling aspen *Populus tremuloides*) in dry conditions. These changes are driven by a direct effect of air temperature on plant species growth, survival and reproduction.

N. B. It is perhaps a common misinterpretation to conceive the state shift (transition) from open-crown forest to the closed-crown boreal forest in terms of a strict climatic gradient (i.e., increasing temperature). Under this view, one should expect that warming would systematically induce a rapid northward shift of the closed-crown coniferous forest as it tracks latitudinal change in its climatic envelope. In fact, despite a sustained warming since the Little Ice Age, it is a southward expansion of the open-crown forest into the closed-crown coniferous forest that is ongoing as a result of recurrent wildfires and poor regeneration (Payette & Gagnon 1985, Girard et al. 2009). Dry conditions imply temperature warming with no consequential increase in precipitation, fostering fire-prone environments whereas mesic conditions do not promote fire activity thus focusing on the prominent role of increasing temperature over fire disturbances.

5. Closed-crown coniferous forest

(Generally continuous plant **ground cover**, > 40% tree cover, 10 - 20 m tall,)

Closed-crown forest dominated by black spruce; secondary tree species include Jack pine *Pinus banksiana*, balsam fir, white birch and trembling aspen, trees frequently > 10 m tall. The understory is dominated by feathermosses and ericaceous shrubs (*Vaccinium* spp., *Kalmia* spp., *Rhododendron* spp.). This vegetation type is also called the spruce-feathermoss forest.

Modern day southern limit: 49 ± 2.5 °N

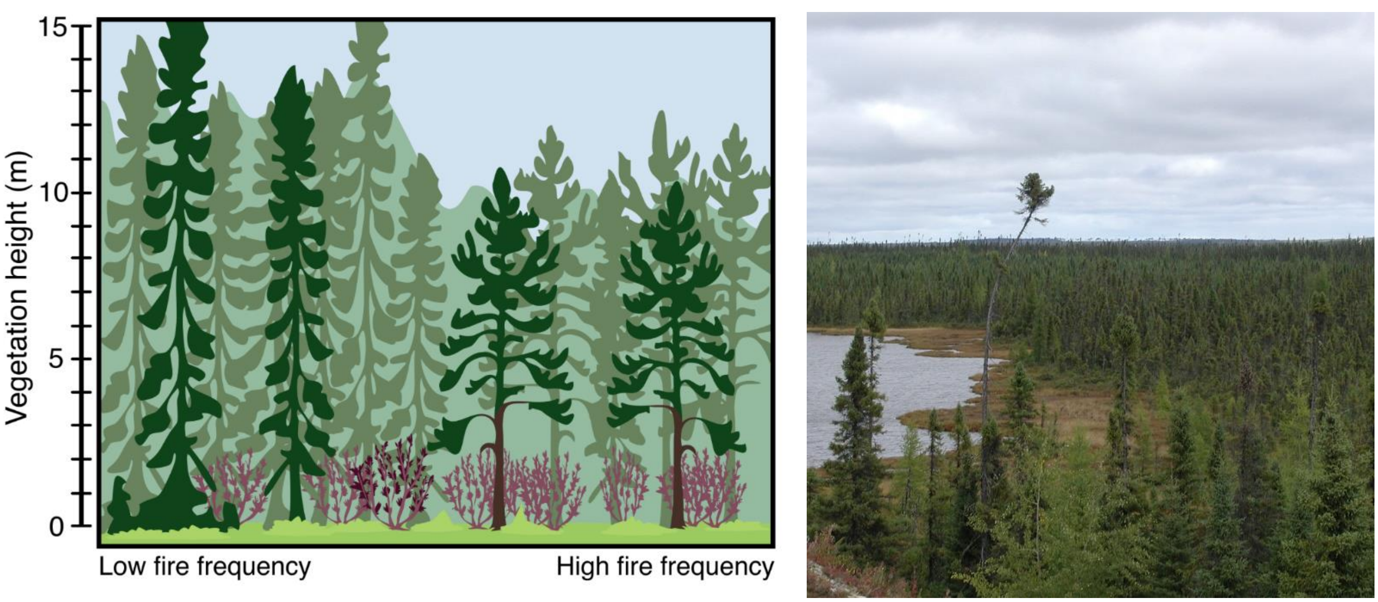

Fig. S24. Schematic representation of typical closed-crown coniferous forest vegetation. Pictograms and colours represent pant functional groups and growth forms (see legend).

State shift from <u>Closed-crown coniferous forest</u> to <u>Mixed wood boreal forest</u> under a T+5°C scenario

Response time: >100 years

Justification of response time: State shift to a mixed wood boreal forest is mostly linked to the gradual establishment, in humid conditions, of shade tolerant conifers (white spruce *Picea glauca* and balsam fir) favoured by a gradual densification of trees under a low fire frequency regime. However, dry conditions with a high fire frequency regime could favour other conifers like Jack pine and broadleaf species. These changes are mainly driven by a direct effect of air temperature on plant species growth, survival and reproduction.

6. Mixed wood boreal forest

(Generally continuous plant **ground cover**, generally continuous tree cover, > 15 m tall)

Closed crown boreal forest with varying abundance of conifer (spruce, Jack pine, *balsam fir*) and broadleaf trees (trembling aspen, white birch) and a diversified herbaceous understory. Dry conditions will have higher fire activity promoting fire-adapted species such as Jack pine, black spruce, and trembling aspen. Wet conditions will foster mesic tree species such as balsam fir, white spruce, white birch, and red maple *Acer rubrum.*

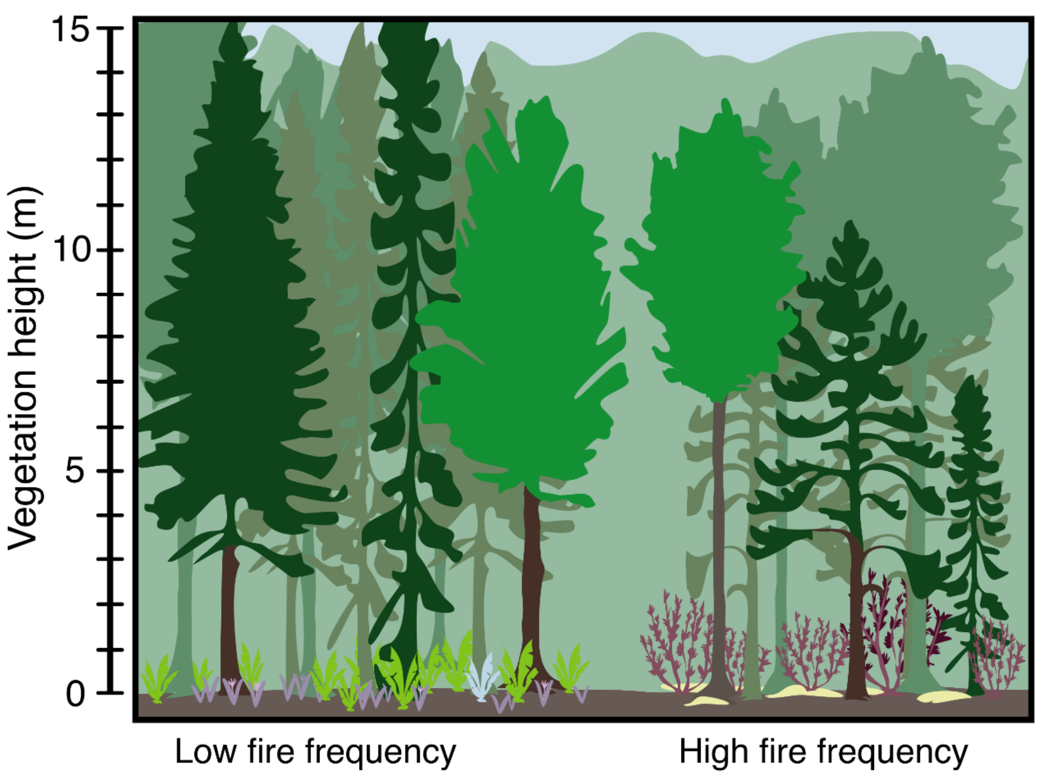

Fig. S25. Schematic representation of typical mixed wood boreal forest vegetation. Pictograms and colours represent pant functional groups and growth forms (see legend).

Glossary

Definitions come from the California native plant society glossary https://vegetation.cnps.org/glossary and University of Idaho Principles of Vegetation Measurement & Assessment and Ecological Monitoring & Analysis https://www.webpages.uidaho.edu/veg_measure/Modules/Lessons/Module%208(Cover)/8_1_What%20is%20Cover.htm

Growth form: The shape or appearance of a plant reflecting growing conditions and genetics. Growth form is usually consistent within a species but may vary under extremes of environment (Mueller-Dombois and Ellenberg1974). Growth forms determine the visible structure or physiognomy of plant communities (Whittaker 1973a).

Ground cover: Cover of the soil surface with plants, mosses, lichens and biotic soil crust.

References

Bliss, L.C., & Matveyeva N.V. Circumpolar arctic vegetation. in Arctic ecosystems in a changing climate: An ecophysiological perspective. San Diego, United States (eds Chapin III, F.S., Jefferies, R.L., Reynolds, J.F., Shaver G.R., Svoboda, J.) 59-89 (Academic Press Inc, 1992).

Bruhwiler, L., Parmentier, F. J. W., Crill, P., Leonard, M., & Palmer, P. I. The Arctic carbon cycle and its response to changing climate. *Current Climate Change Reports*, ***7***, 14-34, (2021).

CAVM Team. Circumpolar Arctic Vegetation Map. (1:7,500,000 scale), Conservation of Arctic Flora and Fauna (CAFF) Map No. 1. U.S. Fish and Wildlife Service, Anchorage, Alaska, (2003).

Gajewski, K., Grenier, A., & Payette, S. Climate, fire and vegetation history at treeline east of Hudson Bay, northern Quebec. *Quaternary Science Reviews, **254***, 106794, (2021).

Girard, F., Payette, S., & Gagnon, R. Origin of the lichen–spruce woodland in the closed-crown forest zone of eastern Canada. *Global Ecology and Biogeography*, ***18***(3), 291-303, (2009).

Ims, R. A., & Henden, J. A. Collapse of an arctic bird community resulting from ungulate-induced loss of erect shrubs. *Biological conservation*, ***149***(1), 2-5, (2012).

Leboeuf, A. *Ecological Mapping of the Vegetation of Northern Québec: Mapping Standard*. Ministere des Forets, de la Faune et des Parcs (2018).

Payette, S. The range limit of boreal tree species in Québec-Labrador: an ecological and palaeoecological interpretation. *Review of Palaeobotany and Palynology*, ***79***(1-2), 7-30, (1993).

Payette, S., & Delwaide, A. Tamm review: the North-American lichen woodland. *Forest Ecology and Management*, *417*, 167-183, (2018).

Payette, S., Fortin, M. J., & Gamache, I. The subarctic forest–tundra: the structure of a biome in a changing climate: the shifting of local subarctic tree lines throughout the forest–tundra biome, which is linked to ecological processes at different spatiotemporal scales, will reflect future global changes in climate. *BioScience*, ***51***(9), 709-718, (2001).

Payette, S., & Gagnon, R. Late Holocene deforestation and tree regeneration in the forest–tundra of Québec. *Nature*, ***313***(6003), 570-572, (1985).

Shur, Y.L., & Jorgenson, M.T. Patterns of Permafrost Formation and Degradation in Relation to Climate and Ecosystems. *Permafrost and Periglacial Processes*, ***18*,** 7–19, (2007).

Sturm, M., Holmgren, J., McFadden, J. P., Liston, G. E., Chapin, F. S., & Racine, C. H. Snow–shrub interactions in Arctic tundra: a hypothesis with climatic implications. *Journal of Climate*, ***14***(3), 336-344, (2001).

Walker, D. A., Raynolds, M. K., Daniëls, F. J., Einarsson, E., Elvebakk, A., Gould, W. A., ... & Yurtsev, B. A. The circumpolar Arctic vegetation map. *Journal of Vegetation Science*, ***16***(3), 267-282, (2005).

Endothermic terrestrial vertebrates (birds and mammals)

Endothermic terrestrial vertebrates are composed of various mammalian and avian functional groups. Along our transect, vertebrate communities range from an assemblage of few functional groups in the High-Arctic to the highly functionally diverse boreal vertebrate community.

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Gravel, Dominique
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Introduction

Endothermic vertebrates require high amounts of energy to maintain their body temperature (Scholander et al. 1950). Whereas this affects the latitudinal distribution and behavior of mammals and birds, it also explains the strong role that vertebrates can play in regulating northern ecosystem processes such as nutrient cycling, plant succession, diseases, propagules and energy transport between distant or adjacent terrestrial, aquatic, coastal and marine ecosystems (Bauer & Hoye 2014, Davidson 1993, Fourment et al. 2017, Gauthier et al. 2011, Lewis et al. 2014, Speed et al. 2021). Endothermic vertebrates can interact with each other but also with other organisms that have similar or very different thermodynamic constraints across food webs. These interactions are essential to understand the structure and functioning of northern ecosystems (Bideault et al. 2021, Fryxell et al. 2022, Legagneux et al. 2014, Oksanen et al. 2020, Speed et al. 2019). Food web interactions are best described by grouping species within functional groups, that are sets of species showing similar responses to the environment or having similar effects on ecosystem processes (Barrio et al. 2016, Gravel et al. 2016, Speed et al. 2019, Speed et al. 2021).

Endothermic vertebrate contrasting states are defined using vertebrate functional groups (see Tables S1 and S2). In order to decipher critical changes in the functioning of ecosystems, we focused on functional traits known to affect species interaction strength, dynamics of vertebrate communities and ecosystem processes (Bauer & Hoye 2014, Beauchamp 2010, Brose 2010, Hanski et al. 1991, Legagneux et al. 2014, Makin et al. 2017, Martin & Li 1992, Schmidt & Whelan 1998, Woodward et al. 2005, see glossary for details on traits). We also considered whether functional groups were present (and active) throughout the annual cycle (i.e., resident or seasonal) and their relative abundance in the landscape (common or irregular).

The following four contrasting states of endothermic vertebrate communities are currently encountered from North to South along the latitudinal gradient covered by our study: 1. High-Arctic, 2. Arctic, 3. low Arctic and 4. boreal vertebrate communities. We defined the southern limit of an endothermic vertebrate state as the southernmost modern-day position where vertebrate communities in the landscape (at a scale, i.e., 100 km x 100 km, that encompasses summer home ranges of most taxa) are characterized by the functional groups of a given state. The southern limit of the boreal vertebrate community is not encompassed by our gradient. Southern limits of contrasting states identified along our transect were considered critical thresholds.

At each critical threshold, we determined the sensitivity of the endothermic vertebrate state to a hypothetical warming scenario. We assessed the sensitivity using the estimated time required (the response time, in years) for an initial vertebrate community to shift to another existing state if exposed to a sudden and persistent 5°C increase in mean annual temperature. We considered that a state shift is reached when >50% of the functional groups that differentiate the initial and resulting state either become establish in the landscape or disappear from the initial community.

At the critical thresholds, state shifts in endothermic vertebrate communities are expected to be mainly driven by the cascading effects of changes in habitat structure, food availability and abundance (Barrio et al. 2016, Boelman et al. 2015, Henden et al. 2013, Ims & Henden 2012), as well as on the direct effect of temperature on species energetic constraints for some species (Humphries et al. 2002, see also Speed et al. 2021). Along our gradient, several functional groups depend on i) the availability of specific habitat structure to breed or to hide (e.g., the presence of erect shrubs and trees, or ice-free lakes; presence of lateral covers for hares/ambush predators), and ii) the availability of specific food resources during part of their annual cycle (e.g., fungivores, granivores). Although some species and functional groups may respond more quickly than others to warmer conditions (Speed et al. 2021), a shift from one vertebrate state to a contrasting state along our latitudinal gradient is expected to be strongly affected by changes in vegetation and lake state (for aquatic functional groups) in the landscape. Local conditions, such as vertebrate species colonization rate and predation rate could modulate response time (increase or decrease response time within the selected time interval). At the critical thresholds identified along our latitudinal gradient, there are no geophysical barriers or important phylogeographic and historic constraints (glaciation and postglacial recolonization) that can prevent colonization or significatively slow response time (see below).

Common to all states – Endothermic terrestrial vertebrates

Six vertebrate functional groups are present in all four states found across the latitudinal gradient (three mammalian and three avian functional groups). Mammalian groups are small carnivores, meso cursorial carnivores (mustelids and canids) and small herbivores (rodents) (Table S1). Avian groups are small insectivores nesting in low-growing ground cover (shorebirds and some passerines), large seasonal and resident ground-nesting carnivores (falcons, gulls and ravens) and large seasonal and resident ground-nesting herbivores (including waterfowl, grouse and ptarmigans) (Table S2).

1. High-Arctic vertebrates

Mammals belonging to the three functional groups common to all states include collared lemmings (small herbivores), ermines (small carnivores) and arctic foxes (meso cursorial carnivores). Birds belonging to the common functional groups include *Charadriidae* and *Scolopacidae* shorebirds (small insectivores nesting in low-growing ground cover), gyrfalcons and ravens (large seasonal and resident ground-nesting carnivores), as well as rock ptarmigans and snow geese (large seasonal and resident ground-nesting herbivores).

Other functional groups that characterize this specific assemblage are as follow:

For mammals, meso gregarious herbivores (arctic hares), as well as large seasonal and resident gregarious herbivores (caribou and muskoxen) and carnivores (wolves) are present (see Table S1 for a list of functional groups). Birds include small insectivore-granivore nesting in low growing ground cover (*Calcariidae* and Fringilidae passerines (snow bunting, lapland longspur, hoary redpoll)) and large irregular ground nesting carnivores (snowy owl and long-tailed jaeger) (Table S2).

Modern day southern limit: 83 ± 2.5 °N

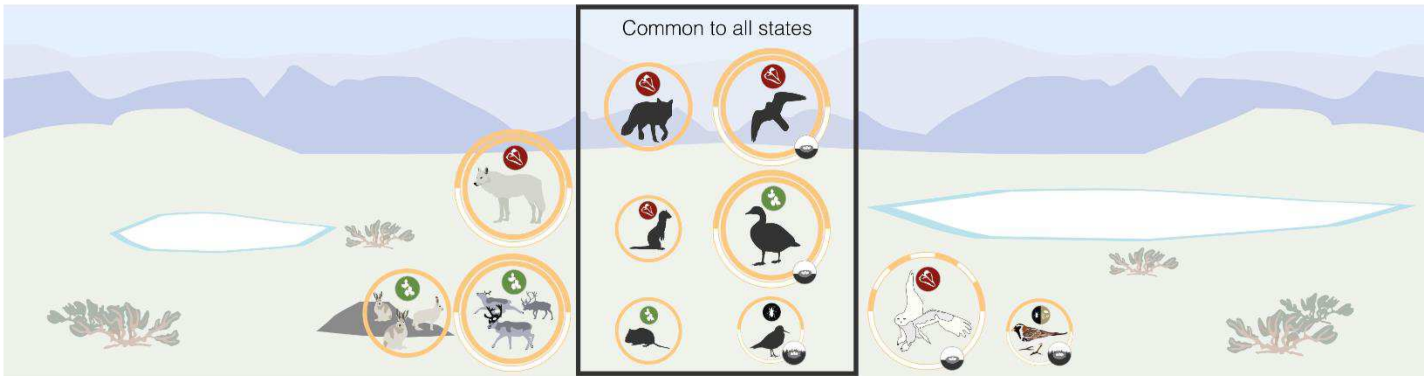

Fig. S26. Schematic representation of the High-Arctic vertebrates. Pictograms are used to represent vertebrate functional groups found in this contrasting state (see tables S1-S2 for details on functional groups)

State shift from High-Arctic vertebrates to Arctic vertebrates under a T+5°C scenario

Response time: 1-10, 10-100 years

Justification of response time: State shift mainly depends on the establishment of birds requiring aquatic habitats throughout their entire breeding season. Such change is triggered by the lengthening of the lake ice-free season that depends on changes in lake ice cover and subsequent lake state shift. Bird species are highly mobile and are expected to colonize the landscape shortly after aquatic habitat becomes available inland as they are already present relatively close to the southern limit of the contrasting state or are present in coastal areas of the High-Arctic. There are no important ecological barriers preventing colonization by birds currently found in the arctic vertebrate community.

2. Arctic vertebrates

Arctic mammals belonging to the three functional groups common to all states include voles and lemmings (small herbivores), ermines (small carnivores) and red and arctic foxes (meso cursorial carnivores). Birds belonging to the common functional groups include *Charadriidae* and *Scolopacidae* shorebirds as well as some passerines including Northern Wheatear and American Pipit. (small ground-nesting insectivores), gyrfalcons, peregrine falcons, parasitic jaegers and ravens (large seasonal and resident ground-nesting carnivores), as well as rock ptarmigans, snow geese, cackling geese and sandhill cranes (large seasonal and resident ground-nesting herbivores).

Other functional groups that characterize this specific assemblage are as follow:

For mammals, meso gregarious herbivores (arctic hares), as well as large seasonal and resident gregarious herbivores (caribou and muskoxen) and carnivores (wolves) are present (Table S1). Birds include small insectivore-granivore nesting in low growing ground cover (*C*alcariidae, Fringilidae and Alaudidae passerines (lapland longspurs and snow bunting, hoary redpoll and horned lark)) and large irregular ground nesting carnivores (snowy owl, rough-legged hawk and long-tailed jaeger). A main difference with the High-Arctic vertebrate assemblage is the presence of large ground nesting aquatic carnivores and insectivores dominated respectively by *Gaviidae* and *Anatidae* (red-throated loon, pacific loon, long-tailed duck, common eider, king eider) (Table S2).

Modern day southern limit: 61 ± 2.5 °N

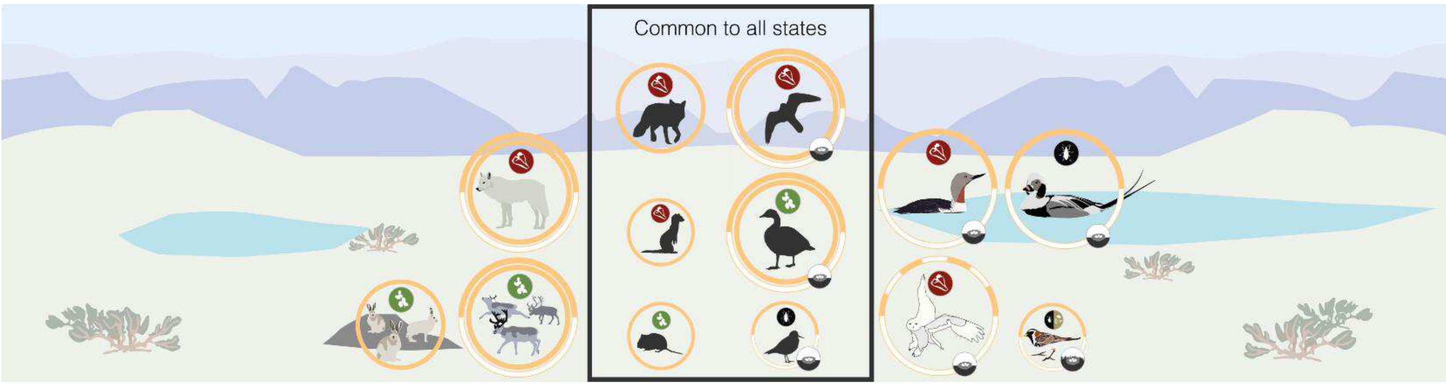

Fig. S27. Schematic representation of the Arctic vertebrates. Pictograms are used to represent vertebrate functional groups found in this contrasting state (see tables S1-S2 for details on functional groups)

State shift from <u>Arctic vertebrates</u> to <u>Low-Arctic vertebrates</u> under a T+5°C scenario

Response time: 10-100 years

Justification of response time: The transition to low Arctic vertebrate community largely depends on the establishment of mammals requiring a greater diversity or abundance of food resources, as well as birds that require the presence of shrubs to nest and feed. This change is expected to be mainly driven by direct and indirect effects of changes in vegetation vertical structure and primary production, and thus response time should be mainly determined by vegetation state shift from polar tundra to shrub tundra. An increase in shrub cover in the landscape creates new possible nest placements (Boelman et al. 2015). A higher primary productivity and longer growing season increase food resources (including plant and fungi biomass, arthropod abundance and availability, Clemmensen et al. 2006, Ims & Henden 2012, Boelman et al. 2015). Species expected to establish are highly mobile and should quickly colonize newly available habitats as they are already present relatively close to the southern limit of the contrasting state. There are no ecological barriers preventing colonization by birds and mammals currently found in the low-arctic vertebrate community.

3. Low Arctic vertebrates

Low Arctic mammals belonging to the three functional groups common to all states include lemmings and voles (small herbivores), ermines and least weasel (small carnivores), arctic and red foxes (meso cursorial carnivores). Birds belonging to the common functional groups include *Charadriidae* and *Scolopacidae* shorebirds, as well as some passerines including american pipit) (small ground-nesting insectivores), gyrfalcons, peregrine falcons and ravens (large seasonal and resident ground-nesting carnivores), as well as rock and willow ptarmigans, geese and tundra swan (large seasonal and resident ground-nesting herbivores).

Other functional groups that characterize this specific assemblage are as follow:

For mammals, small fungivores-herbivores (some voles), meso gregarious herbivores (arctic hares), large seasonal and resident gregarious herbivores (caribou and muskoxen) and carnivores (wolves) as well as large seasonal omnivores (black bears) are present (Table S1). Bird assemblages are composed of small insectivores-granivores nesting on the ground in low-growing ground cover and understory as well as nesting in trees or shrubs (*C*alcariidae, Passerellidae, Fringilidae and *Turdidae* passerines (lapland longspur, savannah sparrow, American tree sparrow, white-crowned sparrow, fox sparrow, common redpoll, gray-cheeked thrush and American robin)), and large irregular ground nesting carnivores (snowy owl, rough-legged hawk and long-tailed jaeger). It also includes large ground nesting aquatic carnivores and insectivores dominated respectively by *Gaviidae* and *Anatidae* (red-throated loon, pacific loon, common loon, long-tailed duck, eiders, red-breasted merganser, northern pintail) (Table S2).

Modern day southern limit: 58 ± 2.5 °N

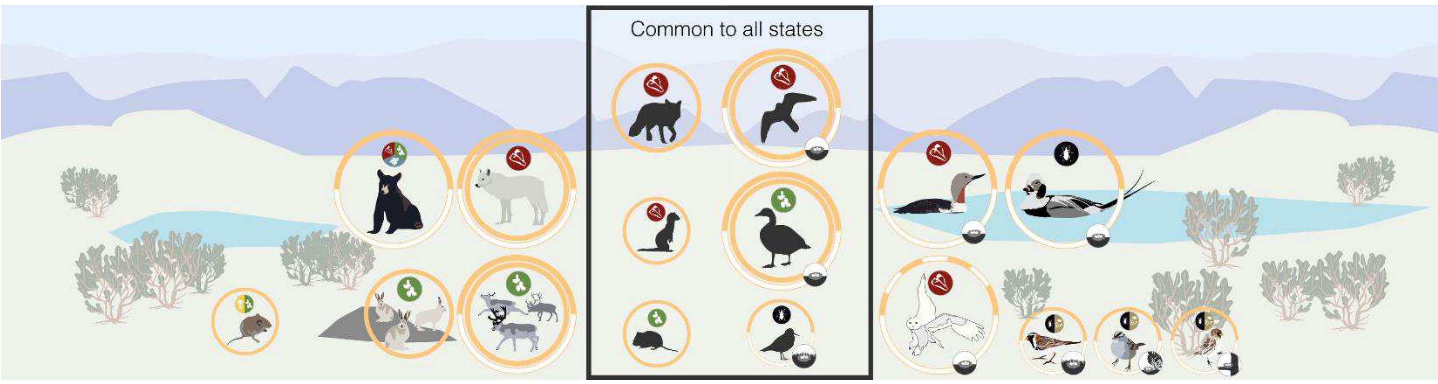

Fig. S28. Schematic representation of the low Arctic vertebrates. Pictograms are used to represent vertebrate functional groups found in this contrasting state (see tables S1-S2 for details on functional groups)

State shift from *<u>Low-Arctic vertebrates</u>* *to* *<u>Boreal vertebrates</u>* *under a T+5°C scenario*

Response time: >100 years

Justification of response time: Transition to boreal vertebrate community strongly depends on the establishment of functional groups that need the presence of trees in the landscape to breed, to feed or to shelter. It also depends on the loss of small birds nesting in low-growing ground cover vegetation. This change is expected to be mainly driven by direct and indirect effects of changes in vegetation structure and primary production. An increase in tree cover in the landscape creates new nest placement opportunities (in trees and tree cavities) and reduces suitable habitat availability for species that need low growing ground cover. A higher primary productivity and longer growing season increase food availability (including fruits, invertebrates, fungi). Such changes in the landscape are expected to be slow, as trees need to reach the various life cycle stages needed by the new vertebrate functional groups (e.g., tall trees with branches large enough to support bird nests and trunks that are large enough for cavities to be excavated or naturally formed, mature trees and shrubs producing seed and fruits for omnivores and granivores, etc.) and generate structures (dead wood, litter, etc.) needed by some species. However, species expected to establish are highly mobile and should quickly colonize newly available habitats as they are already established relatively close to the southern limit of the contrasting state. At the southern limit, there are no ecological barriers preventing colonization by birds and mammals currently found in the boreal vertebrate community.

4. Boreal vertebrates

Boreal mammals belonging to the three functional groups common to all states are voles and mice (small herbivores), ermines and weasels (small carnivores), red foxes, fishers and pine martens (meso cursorial carnivores). Birds belonging to the common functional groups include Scolopacidae shorebirds as well as some passerines (small insectivores nesting in low growing ground cover), peregrine falcon, raven and short-eared owl (large seasonal and resident ground-nesting carnivores), as well as ruffed grouse, spruce grouse, willow ptarmigan, and Canada geese (large seasonal and resident ground-nesting herbivores).

Other functional groups that characterize this specific assemblage are as follow:

Mammals are composed of small resident mammals including fungivores-herbivores (some voles), granivores (Sciuridae), fungivores (northern flying squirrel) and insectivores (*Soricidae* and *Talpidae*), as well as aquatic carnivores (american mink). Small seasonal insectivores and small seasonal granivores are also present (*Vespertilionidae* migratory and hibernating bats, and the hibernating meadow jumping mouse). Meso mammals are solitary herbivores (snowshoe hares and North american porcupines), aquatic herbivores (beavers and muskrats), aquatic carnivores (river otters) as well as ambush carnivores (Canada lynx). Large mammals are resident solitary herbivores (woodland caribou and moose) and carnivores (wolves), as well as seasonal omnivores (black bears) (Table S1). Bird assemblages are composed of a wide variety of seasonal and resident, terrestrial and aquatic small insectivores, granivores and carnivores nesting on the ground in low growing ground cover or understory, nesting in trees or shrubs, nesting in tree cavities and nesting in burrows. They include *Picidae*, *Passerellidae*, *Turdidae*, *Parulidae*, *Tyrannidae*, *Fringillidae*, *Vireonidae*, *Hirundinidae*, *Paridae*, *Laniidae* and *Alcedinidae* species. Large species include seasonal and resident carnivores nesting in trees and in tree cavities (*Strigidae and Accipitridae*) as well as seasonal aquatic insectivores and carnivores that nest on the ground, in trees and in tree cavities (*Anatidae, Gaviidae* waterfowl as well as osprey) (Table S2).

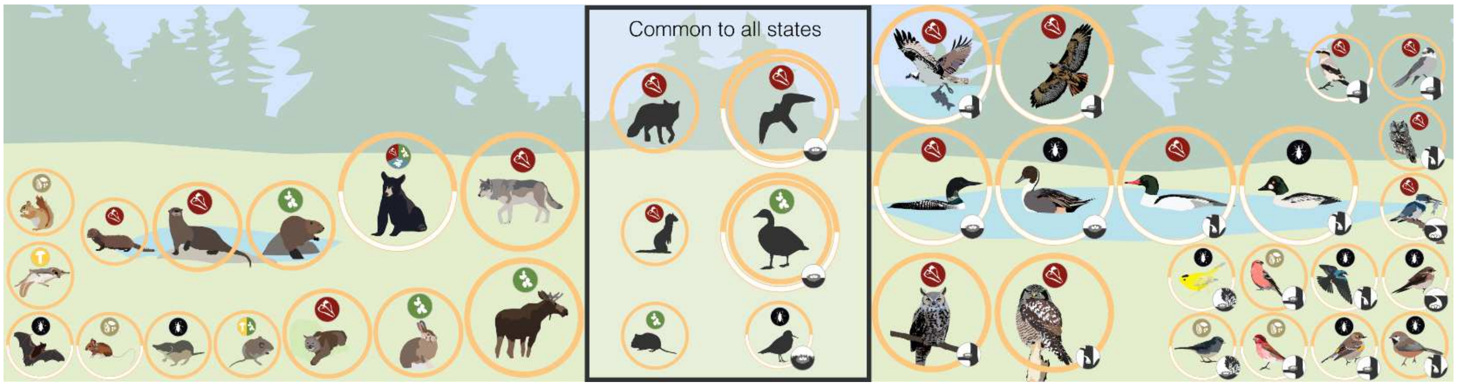

Fig. S29. Schematic representation of the boreal vertebrates. Pictograms are used to represent vertebrate functional groups found in this contrasting state (see tables S1-S2 for details on functional groups)

Glossary

Body mass categories (Legagneux et al. 2014, Pineda-Munoz et al. 2016)

Mammals:

- Small mammals: < 1kg
- Meso mammals: 1-30 kg
- Large mammals: > 30 kg

Birds:

- Small birds: <= 200 g
- Large birds: > 200g

Annual status is used to describe functional groups and characterize contrasting states. Only resident and seasonal species are used to describe the functional groups; species with other statuses (e.g., transient, visitor) are not considered characteristic of contrasting states. The communities are composed of species spending all or a significant portion of their annual cycle (minimally, the complete breeding cycle in the case of birds) in the landscape. It excludes species that are restricted to coastal areas. (Adapted from: Richards & Gaston 2018)

- **Resident**: Species that are present and active in the landscape year-round (for which breeding is confirmed in the case of birds), and which are not restricted to coastal areas. This excludes hibernating species.
- **Seasonal**: Species that are present and active in the landscape during a significant portion (but not year-round) of their annual cycle (for which breeding is confirmed in the case of birds), and which are not restricted to coastal areas. This includes migratory and hibernating species.

Some animal populations can be composed of a mix of resident and seasonal individuals. Functional groups were thus defined as resident and seasonal.

General occurrence describes the commonness of bird functional groups in the landscape. Only species that are common or irregular characterize the contrasting states. It is specified only for groups for which there is a contrast across the latitudinal gradient. (Adapted from: Birds of Nunavut UBC Press)

- **Common**: Species groups that are observed annually, on most days, in appropriate habitat, with a varying number of individuals.
- **Irregular**: Species groups that can vary among years from relatively common to absent depending on food supply.

Diet characterizes the main food source:

- **Herbivore**: Vertebrates for which the main diet component is plant material (including fruits).
- **Carnivore**: Vertebrates for which the main diet component is vertebrate tissue.
- **Granivore**: Vertebrates for which the main diet component is plant seeds.
- **Insectivore**: Vertebrates for which the main diet component is invertebrates.
- **Fungivore**: Vertebrates for which the main diet component is fungi.
- **Omnivore**: Vertebrates for which main diet components are both plant material (including fruits and seeds) and animal tissue.

Hunting mode characterizes how mammalian carnivores hunt for prey in the landscape. It is specified only for functional groups for which there is a contrast across the latitudinal gradient.

- **Cursorial carnivores**: « Predators roaming over large areas looking for prey, and then approaching prey rapidly and silently when found. » (Makin et al. 2017).
- **Ambush carnivores**: «Predators relying on places where the likelihood of meeting prey is high, relying on small-scale vegetation cover, rather than speed, to approach prey. » (Makin et al. 2017).

Sociality indicates if mammalian species live in groups or alone outside of reproductive periods. It is specified only for functional groups for which there is a contrast across the latitudinal gradient. (Adapted from Pérez-Barberia et al. (2007) classification)

- **Solitary**: Species spending most of their annual cycle alone (excluding mates and offspring).
- **Gregarious**: Species spending a significant part of their annual cycle in groups of several conspecifics (excluding mates and offspring).

Habitat is specified only for groups for which there is a contrast across the latitudinal gradient.

- **Aquatic**: Species groups strongly (or strictly, in the case of birds) associated with freshwater (i.e they need freshwater bodies either for foraging, breeding or as a shelter).
- **Terrestrial**: Species groups that are not strongly (or strictly, in the case of birds) associated with freshwater bodies.

Nest placement describes where nests of a given bird group are generally established. For birds nesting on the ground, the ground cover type (low-growing ground cover, or understory) is specified only for functional groups for which there is a contrast across the latitudinal gradient.

- **Ground, low-growing ground cover**: Ground nest located in low-growing ground cover (canopy-free areas). Some species nesting in low growing ground cover are intolerant to closed canopies, such as thickets and forests (Boelman et al. 2015). Type of ground cover is only mentioned when there is a contrast across the gradient. Ground nests include nests located on cliffs and islets.
- **Ground, understory**: Ground nest located under relatively high growing vegetation cover, such as shrubs, bushes or trees. Type of ground cover is only mentioned when there is a contrast across the gradient.
- **Tree or shrub**: Above-ground nest, located in a tree or a shrub.
- **Tree cavity**: Above-ground nest located in a tree cavity.
- **Burrow**: Nest excavated below-ground.

Table S1. Mammal functional groups identified in vertebrate communities along the latitudinal transect. To decipher critical changes in the functioning of ecosystems, we focused on functional traits known to affect species interaction strength, dynamics of vertebrate communities and ecosystem processes. We also considered the presence of functional groups throughout the annual cycle (i.e., resident or seasonal) and their relative abundance in the landscape (common or irregular). A total of 19 mammal functional groups were identified along the gradient. Symbols refer to those used in Figs S26-S29.

Mammal functional groups and criteria used to define them								
Body size	General status and abundance	Habitat	Sociality	Hunting mode	Diet	Functional group	Icon	Present in state
Small	Resident	Terrestrial	-	-	Herbivore	Small herbivore		1,2,3,4
			-	-	Carnivore	Small carnivore		1,2,3,4
			-	-	Granivore	Small granivore		4
			-	-	Insectivore	Small insectivore		4
			-	-	Fungivore	Small fungivore		4
			-	-	Fungivore-Herbivore	Small fungivore-herbivore		3,4
		Aquatic	-	-	Carnivore	Small aquatic carnivore		4
	Seasonal	Terrestrial	-	-	Insectivore	Small seasonal insectivore		4
			-	-	Granivore	Small seasonal granivore		4
Meso	Resident	Terrestrial	Solitary	-	Herbivore	Meso solitary herbivore		4
			Gregarious	-		Meso gregarious herbivore		1,2,3
			-	Cursorial	Carnivore	Meso cursorial carnivore		1,2,3,4
			-	Ambush		Meso ambush carnivore		4
		Aquatic	-	-	Herbivore	Meso aquatic herbivore		4
			-	-	Carnivore	Meso aquatic carnivore		4
Large	Resident	Terrestrial	Solitary	-	Herbivore	Large solitary resident herbivore		4
			-	-	Carnivore	Large resident carnivore		4
	Seasonal		-	-	Omnivore	Large seasonal omnivore		4
	Resident and seasonal		Gregarious	-	Herbivore	Large resident and seasonal gregarious herbivore		1,2,3
			-	-	Carnivore	Large resident and seasonal carnivore		1,2,3

Table S2. Bird functional groups identified in vertebrate communities along the latitudinal transect. To decipher critical changes in the functioning of ecosystems, we focused on functional traits known to affect species interaction strength, dynamics of vertebrate communities and ecosystem processes. We also considered the presence of functional groups throughout the annual cycle (i.e., resident or seasonal) and their relative abundance in the landscape (common or irregular). A total of 24 bird functional group were identified along the gradient. Symbols refer to those used in Figs. S26-S29.

Bird functional groups and criteria used to define them							
Body size	General status, abundance	Habitat	Diet	Nest placement	Functional group	Icon	Present in state
Small	Common, seasonal	Terrestrial	Carnivore	Tree/shrub	Small tree/shrub nesting carnivore		4
			Granivore	Ground, understory	Small understory nesting granivore		4
				Tree/shrub	Small tree/shrub nesting granivore		4
			Insectivore-granivore	Ground, low growing ground cover	Small insectivore-granivore nesting in low growing ground cover		1,2,3
				Ground, understory	Small understory nesting insectivore-granivore		3
				Tree/shrub	Small tree/shrub nesting insectivore-granivore		3
			Insectivore	Ground, low-growing ground cover	Small insectivore nesting in low growing ground cover		1,2,3,4
				Ground, understory	Small understory nesting insectivore		4
				Tree/shrub	Small tree/shrub nesting insectivore		4
				Burrow	Small burrow nesting insectivore		4
				Cavity	Small cavity nesting insectivore		4
		Aquatic	Carnivore	Burrow	Small burrow nesting aquatic carnivore		4
	Common, resident	Terrestrial	Insectivore	Cavity	Small resident cavity nesting insectivore		4
			Granivore	Tree/shrub	Small resident tree/shrub nesting granivore		4
			Carnivore	Cavity	Small resident cavity nesting carnivore		4
				Tree/shrub	Small resident tree/shrub nesting carnivore		4
Large	Common, seasonal	Terrestrial	Carnivore	Tree/shrub	Large tree/shrub nesting carnivore		4
	Common, resident and seasonal		Herbivore	Ground	Large resident/seasonal ground nesting herbivore		1,2,3,4
			Carnivore	Ground	Large resident/seasonal ground nesting carnivore		1,2,3,4
	Irregular, seasonal			Ground	Large irregular ground nesting carnivore		1,2,3
	Common, resident			Tree/shrub	Large resident tree/shrub nesting carnivore		4

				Cavity	Large resident cavity nesting carnivore		4
	Common, seasonal	Aquatic	Carnivore	Ground	Large ground nesting aquatic carnivore		2,3,4
				Tree/shrub	Large tree/shrub nesting aquatic carnivore		4
				Cavity	Large cavity nesting aquatic large carnivore		4
			Insectivore	Ground	Large ground nesting aquatic insectivore		2,3,4
				Cavity	Large cavity nesting aquatic insectivore		4

References

Pérez-Barbería, F. J., Shultz, S., & Dunbar, R. I. Evidence for coevolution of sociality and relative brain size in three orders of mammals. *Evolution*, ***61***(12), 2811-2821, (2007).

Barrio, I. C., Bueno, C. G., Gartzia, M., Soininen, E. M., Christie, K. S., Speed, J. D., ... & Hik, D. S. Biotic interactions mediate patterns of herbivore diversity in the Arctic. *Global Ecology and Biogeography*, ***25***(9), 1108-1118, (2016).

Bauer, S., & Hoye, B. J. Migratory animals couple biodiversity and ecosystem functioning worldwide. *Science*, ***344***(6179), 1242552, (2014).

Berteaux, D., Gauthier, G., Domine, F., Ims, R. A., Lamoureux, S. F., Lévesque, E., & Yoccoz, N. Effects of changing permafrost and snow conditions on tundra wildlife: critical places and times. *Arctic Science*, ***3***(2), 65-90, (2016).

Bideault, A., Galiana, N., Zelnik, Y. R., Gravel, D., Loreau, M., Barbier, M., & Sentis, A. Thermal mismatches in biological rates determine trophic control and biomass distribution under warming. *Global Change Biology*, ***27***(2), 257-269, (2021).

Beauchamp, G. Relaxed predation risk reduces but does not eliminate sociality in birds. *Biology Letters*, ***6***(4), 472-474, (2010).

Boelman, N. T., Gough, L., Wingfield, J., Goetz, S., Asmus, A., Chmura, H. E., ... & Guay, K. C. Greater shrub dominance alters breeding habitat and food resources for migratory songbirds in Alaskan arctic tundra. *Global Change Biology*, ***21***(4), 1508-1520, (2015).

Brose, U. Body-mass constraints on foraging behaviour determine population and food-web dynamics. *Functional Ecology*, *24*(1), 28-34, (2010).

Clemmensen, K. E., Michelsen, A., Jonasson, S., & Shaver, G. R. Increased ectomycorrhizal fungal abundance after long-term fertilization and warming of two arctic tundra ecosystems. *New phytologist*, ***171***(2), 391-404, (2006).

Davidson, D. W. The effects of herbivory and granivory on terrestrial plant succession. *Oikos*, 23-35, (1993).

Fourment, M., Darling, A. E., & Holmes, E. C. The impact of migratory flyways on the spread of avian influenza virus in North America. *BMC evolutionary biology*, ***17***, 1-12, (2017).

Fryxell, J. M., Mduma, S., Masoy, J., Sinclair, A. R., Hopcraft, G. J., & Packer, C. Stabilizing effects of group formation by Serengeti herbivores on predator-prey dynamics. *Frontiers in Ecology and Evolution*, ***10,*** (2022).

Gauthier, G., Berteaux, D., Bêty, J., Tarroux, A., Therrien, J. F., McKinnon, L., ... & Cadieux, M. C. The tundra food web of Bylot Island in a changing climate and the role of exchanges between ecosystems. *Ecoscience*, ***18***(3), 223-235, (2011).

Gravel, D., Albouy, C., & Thuiller, W. The meaning of functional trait composition of food webs for ecosystem functioning. *Philosophical Transactions of the Royal Society B: Biological Sciences*, ***371***(1694), 20150268, (2016).

Hanski, I., Hansson, L., & Henttonen, H. Specialist predators, generalist predators, and the microtine rodent cycle. *The Journal of Animal Ecology*, ***60***, 353-367, (1991).

Henden, J. A., Yoccoz, N. G., Ims, R. A., & Langeland, K. How spatial variation in areal extent and configuration of labile vegetation states affect the riparian bird community in Arctic tundra. *PLoS One*, ***8***(5), e63312, (2013).

Holt, R. D., & Lawton, J. H. The ecological consequences of shared natural enemies. *Annual review of Ecology and Systematics*, ***25***(1), 495-520, (1994).

Humphries, M. M., Thomas, D. W., & Speakman, J. R. Climate-mediated energetic constraints on the distribution of hibernating mammals. *Nature*, ***418***(6895), 313-316, (2002).

Ims, R. A., & Henden, J. A. Collapse of an arctic bird community resulting from ungulate-induced loss of erect shrubs. *Biological conservation*, ***149***(1), 2-5, (2012).

Legagneux, P., Gauthier, G., Lecomte, N., Schmidt, N. M., Reid, D., Cadieux, M., ... & Gravel, D. Arctic ecosystem structure and functioning shaped by climate and herbivore body size. *Nature Climate Change*, ***4***(5), 379-383, (2014).

Legagneux, P., Gauthier, G., Berteaux, D., Bêty, J., Cadieux, M. C., Bilodeau, F., ... & Krebs, C. J. Disentangling trophic relationships in a High Arctic tundra ecosystem through food web modeling. *Ecology*, ***93***(7), 1707-1716, (2012).

Lewis, L. R., Behling, E., Gousse, H., Qian, E., Elphick, C. S., Lamarre, J. F., ... & Goffinet, B. First evidence of bryophyte diaspores in the plumage of transequatorial migrant birds. *PeerJ*, ***2***, e424, (2014).

Makin, D. F., Chamaillé-Jammes, S., & Shrader, A. M. Herbivores employ a suite of antipredator behaviours to minimize risk from ambush and cursorial predators. *Animal Behaviour*, *127*, 225-231, (2017).

Mallory, M. L., & Forbes, M. R. Nest shelter predicts nesting success but not nesting phenology or parental behaviors in high arctic Northern Fulmars Fulmarus glacialis. *Journal of Ornithology*, ***152***, 119-126, (2011).

Martin, T. E., & Li, P. Life history traits of open-vs. cavity-nesting birds. *Ecology*, *73*(2), 579-592, (1992).

Oksanen, T., Oksanen, L., Vuorinen, K. E., Wolf, C., Mäkynen, A., Olofsson, J., ... & Utsi, T. A. The impact of thermal seasonality on terrestrial endotherm food web dynamics: a revision of the exploitation ecosystem hypothesis. *Ecography*, ***43***(12), 1859-1877, (2020).

Peters, R. H. *The ecological implications of body size* (Vol. 2). (Cambridge university press, 1986).

Pineda-Munoz, S., Evans, A. R., & Alroy, J. The relationship between diet and body mass in terrestrial mammals. *Paleobiology*, ***42***(4), 659-669, (2016).

Richards, J. M., & Gaston, A. J. (Eds.). *Birds of Nunavut*. (UBC Press, 2018).

Schmidt, K. A., & Whelan, C. J. Predator-mediated interactions between and within guilds of nesting songbirds: experimental and observational evidence. *The American Naturalist*, ***152***(3), 393-402, (1998).

Scholander, P. F., Hock, R., Walters, V., Johnson, F., & Irving, L. Heat regulation in some arctic and tropical mammals and birds. *The Biological Bulletin*, ***99***(2), 237-258, (1950).

Speed, J. D., Skjelbred, I. Å., Barrio, I. C., Martin, M. D., Berteaux, D., Bueno, C. G., ... & Soininen, E. M. Trophic interactions and abiotic factors drive functional and phylogenetic structure of vertebrate herbivore communities across the Arctic tundra biome. *Ecography*, ***42***(6), 1152-1163, (2019).

Speed, J. D., Chimal-Ballesteros, J. A., Martin, M. D., Barrio, I. C., Vuorinen, K. E., & Soininen, E. M. Will borealization of Arctic tundra herbivore communities be driven by climate warming or vegetation change? *Global Change Biology*, ***27***(24), 6568-6577, (2021).

Woodward, G., Ebenman, B., Emmerson, M., Montoya, J. M., Olesen, J. M., Valido, A., & Warren, P. H. Body size in ecological networks. *Trends in ecology & evolution*, ***20***(7), 402-409, (2005).