Climate-driven expansion of northern agriculture must consider permafrost

Northern expansion is often seen as a solution to climate-driven agricultural challenges in lower latitudes, yet little is known about cultivation–permafrost interactions. We outline four science-based adaptations, informed by farmer knowledge, that reduce risk and inform decisions to sustainably manage and develop permafrost-agroecosystems.

Melissa K. Ward Jones, Tobias Schwoerer, Glenna M. Gannon, Benjamin M. Jones, Mikhail Z. Kanevskiy, Iris Sutton, Brad St. Pierre, Christine St. Pierre, Jill Russell and David Russell

Increasing temperatures and changing precipitation are projected to negatively affect agricultural outputs in many critical food-producing regions. Globally, it is estimated that major crop yields will decrease by up to 10% with every 1 °C of warming, with the exception of high-latitude countries[1]. In the absence of adaptation, changing climate patterns may also alter the spatial distribution of food production globally[2]. This geographical shift may already be occurring, as demonstrated by the 3.2% decline in the number of farms between 2012 and 2017 in the contiguous United States, and a concurrent 30% increase in Alaska (https://www.nass.usda.gov/).

Recent studies modelling potential agricultural expansion[3,4] found that increasing temperatures will benefit new climate-driven agricultural 'frontiers' in the circumpolar north[4]. Climate-driven benefits include warmer air and soil temperatures, and longer growing seasons compared with previous time periods[5], shifting warm-season crops northwards, including globally important crops like maize. The improved climate suitability for important food crops (Fig. 1) and availability of large tracts of undeveloped land in northern latitudes may contribute to the northern shift of food production systems[4]. Recent literature suggests such shifts could alleviate concerns about local food security in the north and further diversify the global food system[6]. However, the climate opportunism projected in agricultural climate models often lacks key observations from northern producers, notably the presence of permafrost itself and its associated potential challenges.

Permafrost is ground material that remains at or below 0 °C for two or more consecutive years[7]. It underlies a seasonally thawed layer of soil, and its mean ground temperature can range from just below freezing in the boreal forest to as cold as −20 °C in the high Arctic[8].

Fig. 1 | Sweetcorn grown as part of the University of Alaska Fairbanks' vegetable trials in 2021[19]. Cultivar, or 'variety', trials evaluate newly released and standard cultivars for yield and multiple subjective ratings (for example, pest resistance, bolt hardiness and taste), to determine suitability of cultivars for the local growing conditions. Trials are conducted to assist small market farms and home gardeners in making climate-smart decisions about which cultivars to select. The climate in interior Alaska, which was too cold to grow corn a few decades ago, demonstrates a climate-driven opportunity for northern agriculture.

The permafrost region covers 24% of the Northern Hemisphere terrestrial landscape[9] and is the literal foundation for northern social–ecological systems[10]. Permafrost is characterized into four zones that describe the lateral continuity of permafrost regions: continuous, discontinuous, sporadic and isolated[9]. Globally, about 90% of the 5 million people inhabiting permafrost areas live on discontinuous permafrost (Fig. 2a)[11]. Land with discontinuous permafrost is expected to provide the largest land area gains suitable for the cultivation of globally important food crops[4]. One of the challenges of converting boreal forest ecosystems to farmland will be the juxtaposition of human land-use change and climate-driven permafrost thaw[12].

Thawing permafrost is known to trigger various natural hazards that affect people and infrastructure differently across the circumpolar north[11]. One of the difficulties of farming on permafrost is that ground-ice content and its distribution is highly variable. As such, understanding the different types of permafrost is critical for sustainable agricultural systems located on arable permafrost-affected soils (permafrost-agroecosystems). For example, arable lands in Siberia, Alaska and Canada may contain ice-rich permafrost, where thawing leads to subsidence and lowering of the land surface due to ground-ice melt (Fig. 2b,c and Types 3 and 4 in Fig. 3). Subsidence on northern farms has led to problems with equipment, soil

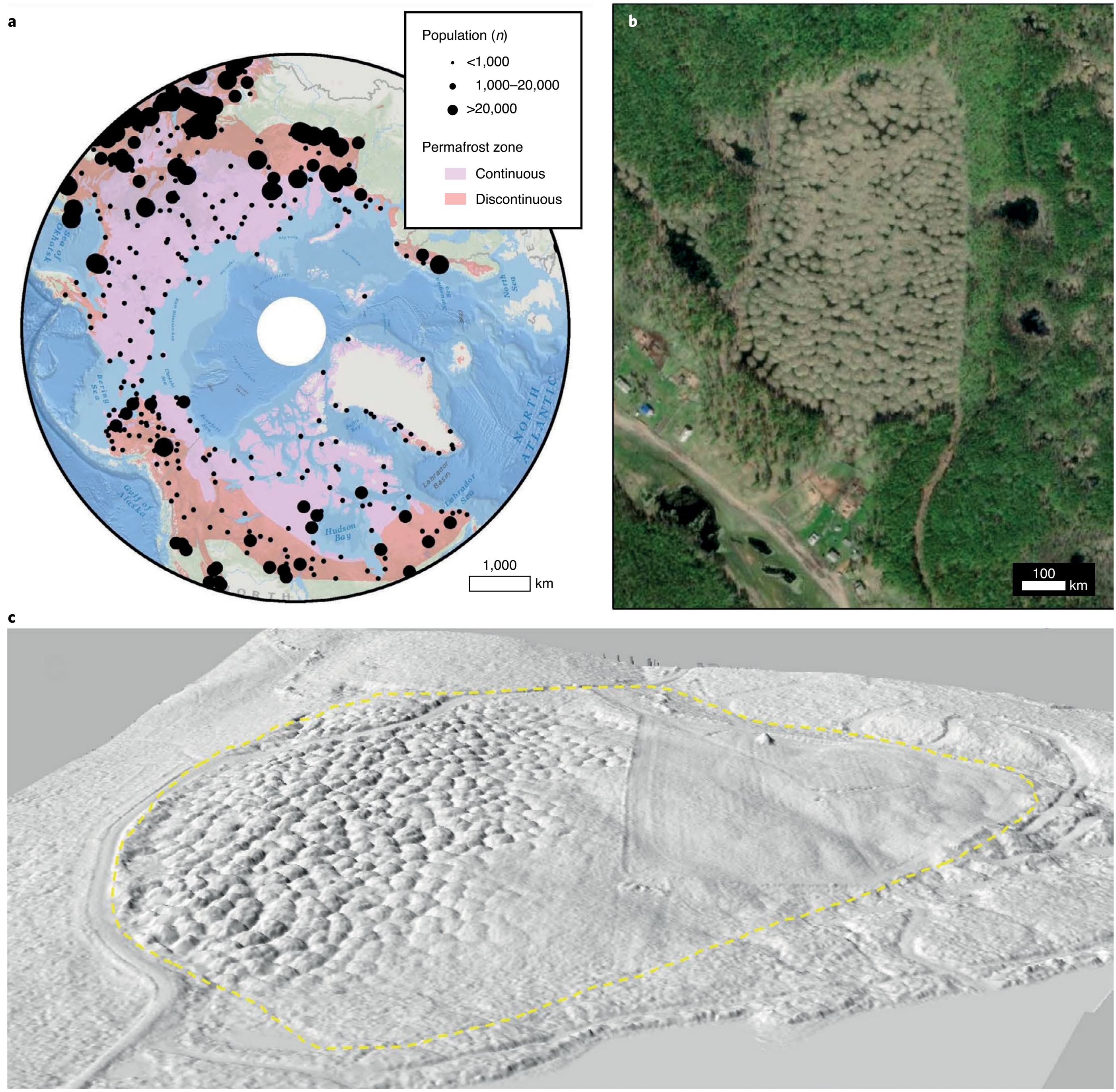

Fig. 2 | Interactions between permafrost thaw and land cultivation are becoming increasingly evident because of ongoing climate and land-use changes in northern regions. a, Five million people live in northern permafrost regions, a region that encompasses 24% of the Northern Hemisphere. Ice-wedge (a most common type of massive ground ice) degradation and development of micro-topographic relief (thermokarst) that hinders agricultural production is one major consequence of farming on soils with ice-rich permafrost in a warming climate. **b**,**c**, Two such examples portraying thermokarst development are shown in a high-resolution commercial satellite image for an area of agricultural production near Emissy, Sakha Republic, Russia (**b**) and a LiDAR-derived digital terrain model for a location on the University of Alaska Fairbanks Farm (outlined in dashed yellow) in Fairbanks, Alaska (**c**). The micro-topographic relief shown in **c** is of the order of 1–2 m. For **a**, the population data are from https://www.naturalearthdata.com/downloads/10m-cultural-vectors/10m-populated-places/, and the permafrost data are from ref. [9]. For **c**, data are from ref. [20]. Credit for maps in **a** and **b**: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community. Publ. note: Springer Nature is neutral about jurisdictional claims in maps.

water-logging, infrastructure damage, loss of topsoil and soil fertility that can be detrimental to crop production and eventually lead to field abandonment[12,13]. In contrast, permafrost in northern Europe is mostly underlain by thaw-stable ice-poor sporadic permafrost, which when thawed from land-use changes, will result in less severe consequences[11]. Thawing ice-poor

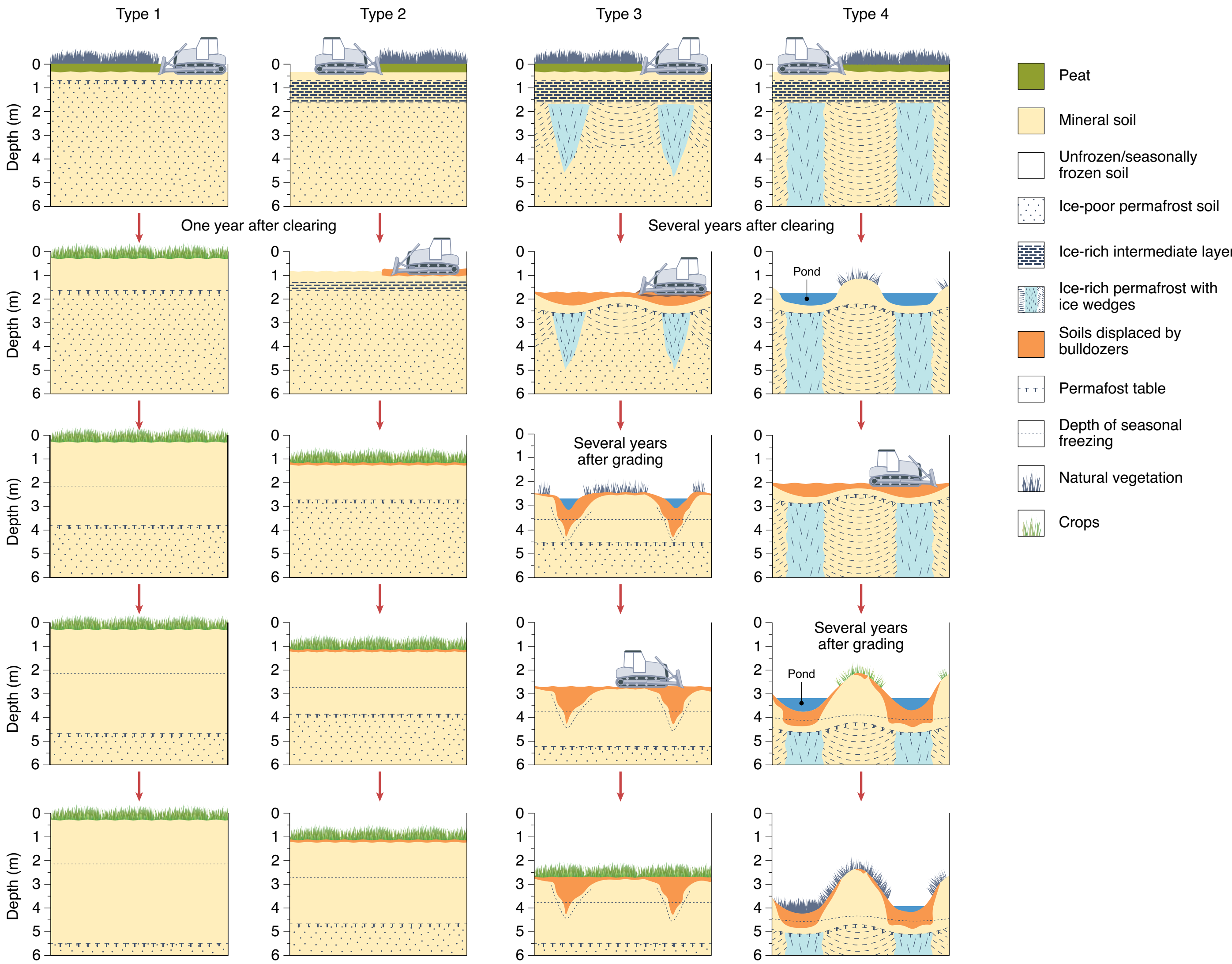

Fig. 3 | Permafrost degradation scenarios in agricultural fields based on ground-ice content and the common practice of surface grading to manage subsidence. Type 1 represents ice-poor permafrost where thaw does not lead to substantial land surface subsidence. Type 2 represents an ice-rich intermediate layer of the upper permafrost with thick ice lenses overlaying ice-poor permafrost, where thaw leads to some subsidence that will stop once all the ice lenses have melted; cleared lands do not require substantial grading after termination of thaw settlement. Type 3 and Type 4 represent ice-rich soils with ice wedges of varying vertical extents immediately below an ice-rich intermediate layer; thaw results in the micro-topography shown in Fig. 2b,c. Such land is suitable for farming after complete degradation of ice wedges, and lands may be arable after several cycles of grading (Type 3). Continued surface subsidence caused by thawing of deep ice wedges (Type 4) is the most unfavourable for farming because agricultural fields are not navigable, and land surface changes become disruptive to farming activities. Attempts at cultivation of this permafrost type commonly result in abandonment, and additional mitigation techniques need to be developed to cultivate on ice-rich permafrost soils.

permafrost will not produce substantial surface subsidence but will rather increase overall soil temperature and probably benefit yields (Types 1 and 2 in Fig. 3).

Challenges related to cultivating on permafrost-laden soils are affecting both new and experienced farmers alike. In North America, farmers trained in southern latitudes and moving northwards for new opportunities[14] are encountering permafrost for the first time. In the Sakha Republic, Russia, local Indigenous people have for centuries successfully used permafrost landscapes known as alases (thaw-lake basins) to produce hay[15]. However, these features are now rapidly changing as a result of climate-driven thaw leading to field abandonment, despite long-established permafrost-agroecosystems that sustained generations of northern farmers[15].

The following four science-based adaptations will reduce risk and inform decisions for northern permafrost-agroecosystems.

Transdisciplinary research

Traditionally, permafrost and agriculture research have remained within their disciplinary silos; however, to adequately study permafrost-agroecosystems, a transdisciplinary approach is required to understand the agricultural, natural, economic, social and engineering aspects of these systems within the context of climate change. Moreover, it is essential that funding agencies provide long-term opportunities to fund transdisciplinary projects that converge between the physical and social sciences to adequately study these systems.

Agricultural practices

Northern agriculture fundamentally differs from agricultural practices conducted at lower latitudes. Already, agricultural techniques have been developed to address northern-specific challenges such as long photo periods during the growing season; however, techniques must also be developed to proactively manage and mitigate permafrost thaw. Permafrost not only affects crop physiology directly but also impacts surface hydrology, groundwater availability and biogeochemical cycling. Expansion of northern agriculture should adopt techniques specifically adapted for permafrost-affected soils rather than simply transposing techniques developed farther south. Lessons learned from failed northern infrastructure development using engineering techniques suited to lower latitudes should be proof that the same will not work for burgeoning northern agriculture[16].

A strategy commonly employed to manage permafrost in agricultural fields is to clear and grade land to allow soil to pre-emptively thaw and dry (Fig. 3); however, this strategy jeopardizes soil fertility as topsoil is removed and land subsidence can occur in ice-rich terrain. Additional strategies for production methods on permafrost must be developed and tested. For example, common season-extension techniques used in northern cultivation, such as the use of plastics to warm the soil, may not be appropriate in the presence of permafrost and need to be evaluated to determine if they are contributing to permafrost degradation. Similarly, other materials used for extending the growing season, such as white-coloured frost protection fabrics, potentially have insulative qualities that may mitigate permafrost thaw and should be tested further. Finally, variety trials evaluating a range of crops grown in various permafrost conditions will create guidelines for pairing crop and permafrost types.

Co-generate science with farmers

Farmers are inherently innovative and adaptive. Research needs to include farmer knowledge to identify problems and create relevant solutions. Farmers can also identify knowledge gaps in how to address and mitigate challenges related to permafrost. Therefore, research should have strong outreach components and dedicated communication programmes to pass knowledge from researchers to producers and from producers to researchers.

Co-production of knowledge approaches between researchers and farmers[17] are promising for knowledge sharing and innovation. Recruiting farmer participation in research projects should occur prior to or during proposal development. Farmers should be given the opportunity to provide input to project research questions and be compensated for their time and role in the research.

Government policies

To better support farmers and future northern agricultural expansion, government policies at multiple scales must be developed with permafrost and its heterogeneity across northern regions in mind (Fig. 3). The following three points are critical topics for permafrost-conscious policy.

First, local governments may vary in the way they perceive permafrost. For example, one view recognizes permafrost as the literal foundation and an asset worth protecting, while another view categorizes permafrost as primarily a hazard. Recognizing this dichotomy is important for policy design and effective long-term adaptation.

Second, policymakers must also be mindful of the social and economic demographics of the agricultural sector and account for the unique role early adopters of northern agriculture play in advancing a growing agricultural sector. For example, small-scale farms (<13 acres) are mostly owned and operated by individuals or families, and comprise most of Alaska's high-latitude agriculture (https://www.nass.usda.gov/). Commonly, small-scale farmers are unable to leave fields to thaw for extended periods of time before cultivation like larger-scale farmers can do. Furthermore, permafrost lands are often the least expensive and the only economically feasible option for beginning farmers to develop. The presence of permafrost is rarely explicitly indicated in agency-derived soil classifications[18] and its presence should be well communicated to potential buyers in land-lease sales.

Finally, policies designed in support of developing northern agriculture must be mindful of the fact that development is taking place in and around Indigenous lands, and this context cannot be ignored. Future agricultural development in the north must take into consideration the traditional hunting, fishing and gathering activities of those Indigenous populations that depend on them, and tribal consultation should be prioritized.

Now is the time to invest in permafrost-agroecosystem research and to develop permafrost-conscious government policies prior to substantial agricultural development. Globally, boreal regions are estimated to gain over 8.5 million km^2 in land with suitable climate to grow globally important crops by 2060–2080 under Representative Concentration Pathway 8.5[4]. Given these projections, we must be proactive and prepare for appropriately scaled and scientifically informed decision-making, in collaboration with northern farmers and Indigenous populations, to ensure sustainable permafrost region agriculture in the future. ❐

Melissa K. Ward Jones[1]✉, Tobias Schwoerer[2], Glenna M. Gannon[3], Benjamin M. Jones[1], Mikhail Z. Kanevskiy[1], Iris Sutton[4], Brad St. Pierre[5], Christine St. Pierre[5], Jill Russell[6,7] and David Russell[6,7]

[1]*Institute of Northern Engineering, University of Alaska Fairbanks, Fairbanks, AK, USA.* [2]*International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK, USA.* [3]*Institute of Agriculture, Natural Resources and Extension, University of Alaska Fairbanks, Fairbanks, AK, USA.* [4]*Ice Wedge Art and Farm, Fairbanks, AK, USA.* [5]*Goosefoot Farm LLC, Fairbanks, AK, USA.* [6]*Boreal Peonies, Two Rivers, AK, USA.* [7]*Miami University, Oxford, OH, USA.*

✉*e-mail:* mkwardjones@alaska.edu

Published online: 28 July 2022
https://doi.org/10.1038/s41558-022-01436-z

References

1. Lobell, D. B., Schlenker, W. & Costa-Roberts, J. *Science* **333**, 616–620 (2011).
2. Belyaeva, M. & Bokusheva, R. *Clim. Change* **149**, 205–217 (2018).
3. King, M. et al. *Sci. Rep.* **8**, 7904 (2018).
4. Hannah, L. et al. *PLoS ONE* **15**, e0228305 (2020).
5. Wendler, G. & Shulski, M. *Arctic* **62**, 295–300 (2009).
6. Unc, A. et al. *Front. Sustain. Food Syst.* **5**, 663448 (2021).
7. van Everdingen, R. O. (ed.) *Multi-Language Glossary of Permafrost and Related Ground-Ice Terms* Version 2.0 (Arctic Institute of North America, 1998).
8. Biskaborn, B. K. et al. *Nat. Commun.* **10**, 264 (2019).
9. Brown, J., Ferrians, O., Heginbottom, J. A. & Melnikov, E. *Circum-Arctic Map of Permafrost and Ground-Ice Conditions* Version 2 (National Snow and Ice Data Center, 2002); https://doi.org/10.7265/skbg-kf16
10. Vincent, W. F., Lemay, M. & Allard, M. *Arctic Sci.* https://doi.org/10.1139/as-2016-0027 (2017).
11. Ramage, J. et al. *Popul. Environ.* **43**, 22–38 (2021).
12. Pewe, T. L. *Effect of Permafrost on Cultivated Fields, Fairbanks Area, Alaska* (US Government Printing Office, 1954); https://pubs.usgs.gov/bul/0989f/report.pdf
13. Desyatkin, R., Filippov, N., Desyatkin, A., Konyushkov, D. & Goryachkin, S. *Front. Earth Sci.* **9**, 683730 (2021).
14. Poeplau, C., Schroeder, J., Gregorich, E. & Kurganova, I. *Land* **8**, 190 (2019).
15. Crate, S. et al. *Anthropocene* **18**, 89–104 (2017).
16. Johnston, G. H. *Permafrost: Engineering Design and Construction* (Wiley, 1981).
17. Norström, A. V. et al. *Nat. Sustain.* **3**, 182–190 (2020).
18. *Land Capability Class, by State, 1997* (NRCS, 1997); https://go.nature.com/3IgxrJA
19. Gannon, G. & Maijala, A. *Fairbanks Vegetable Variety Trials 2021* (Alaska Agricultural and Forestry Experiment Station, 2021).
20. Hubbard, T. D., Koehler, R. D. & Combellick, R. A. *High-Resolution Lidar Data for Alaska Infrastructure Corridors* Raw Data File 2011-3 (Alaska Division of Geological & Geophysical Surveys, 2011); https://doi.org/10.14509/22722

Acknowledgements
Our research takes place on the unceded homelands of the Lower Tanana Dene, the Nunamiut and the Central Yupik. We acknowledge that these peoples have been in relationship with the land on which we work and reside since time immemorial, and we are grateful for that stewardship and care. Funding for this research is from the US National Science Foundation's Navigating the New Arctic initiative under RISE award 2126965.

Author contributions
M.K.W.J. led the preparation of the manuscript and wrote the first draft. All authors contributed to the conceptualization, editing and reviewing of the manuscript. G.M.G. provided the photo for Fig. 1, B.M.J. produced Fig. 2 and M.Z.K. created Fig. 3.

Competing interests
The authors declare no competing interests.