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LETTER

The costs of Arctic infrastructure damages due to permafrost degradation

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Abstract

Climate change has adverse impacts on Arctic natural ecosystems and threatens northern communities by disrupting subsistence practices, limiting accessibility, and putting built infrastructure at risk. In this paper, we analyze spatial patterns of permafrost degradation and associated risks to built infrastructure due to loss of bearing capacity and thaw subsidence in permafrost regions of the Arctic. Using a subset of three Coupled Model Intercomparison Project 6 models under SSP245 and 585 scenarios we estimated changes in permafrost bearing capacity and ground subsidence between two reference decades: 2015–2024 and 2055–2064. Using publicly available infrastructure databases we identified roads, railways, airport runways, and buildings at risk of permafrost degradation and estimated country-specific costs associated with damage to infrastructure. The results show that under the SSP245 scenario 29% of roads, 23% of railroads, and 11% of buildings will be affected by permafrost degradation, costing $182 billion to the Arctic states by mid-century. Under the SSP585 scenario, 44% of roads, 34% of railroads, and 17% of buildings will be affected with estimated cost of $276 billion, with airport runways adding an additional $0.5 billion. Russia is expected to have the highest burden of costs, ranging from $115 to $169 billion depending on the scenario. Limiting global greenhouse gas emissions has the potential to significantly decrease the costs of projected damages in Arctic countries, especially in Russia. The approach presented in this study underscores the substantial impacts of climate change on infrastructure and can assist to develop adaptation and mitigation strategies in Arctic states.

1. Introduction

The Arctic climate is warming more than two times faster than the global average, promoting significant environmental changes (Meredith *et al* 2019). These changes are further exacerbated in areas of concentrated human and industrial activities, including resource extraction, industrial centers, and urban environments (Grebenets *et al* 2012) with direct, immediate implications for the Arctic economy (Glomsrød *et al* 2021).

Although some aspects of climatic changes can be economically beneficial, such as decreases in climate severity and associated heating costs, decreases in sea ice subsequent lengthening of navigation season (Stephenson *et al* 2011), more favorable agriculture conditions (Ward Jones *et al* 2022), other changes such as decreases in terrestrial accessibility in winter can be detrimental to the socio-economic conditions of the region (Gädeke *et al* 2021). One of the most critical climate change issues is associated with the perennially frozen ground or permafrost, which occupies over 60% of Russia, 50% of Canada, and 80% of Alaska. Warming and degradation of permafrost have a pronounced direct impact on Arctic communities through their effects on infrastructure (Streletskiy *et al* 2015), food security (Nyland *et al* 2017, Maslakov *et al* 2020), and public health (Schaefer *et al* 2020, Puchkov *et al* 2021, Revich *et al* 2022).

The infrastructure built on permafrost relies on the mechanical strength of the frozen soils which is dependent on the ground thermal regime (Instanes and Anisimov 2008, Khrustalev *et al* 2011). However, in most Arctic regions, permafrost undergoes significant climate-induced changes manifested in the increase in its temperature and the thickening of the layer just above permafrost that undergoes seasonal freezing and thawing cycles (active layer) (Biskaborn *et al* 2019, Vasiliev *et al* 2020, Nyland *et al* 2021, Smith *et al* 2022). Such changes decrease the ability of the frozen ground to support the infrastructure causing its damage and/or collapse. A recent study by Hjort *et al* (2022) estimated that as much as 30%–50% of crucial circumpolar infrastructure on permafrost is at risk under projected climatic warming.

To date, most assessments of economic costs associated with damage to permafrost infrastructure were provided for individual countries primarily focused on the Russian Arctic and Alaska (Melvin *et al* 2017, Streletskiy *et al* 2019, Badina 2020, Melnikov *et al* 2022), or specific types of infrastructure such as roads (Porfiriev *et al* 2019), housing (Porfiriev *et al* 2021b), and healthcare facilities (Porfiriev *et al* 2021a). One study conducted at a circumpolar scale found that the total cost of Arctic infrastructure damages due to permafrost degradation is expected to exceed 20 billion USD (Suter *et al* 2019). However, the authors argued that their study was based on very limited infrastructure inventory resulting in a potential significant underestimation of costs, especially in case of Russia.

In this paper, we provide a circumpolar assessment of the potential economic impacts of infrastructure damage due to permafrost degradation for the mid-21st century. This study builds on previous assessments (Streletskiy *et al* 2019, Suter *et al* 2019) while utilizing the latest generation of climatic projections used by the Intergovernmental Panel on Climate Change (IPCC), a homogenized infrastructure database based on open source OpenStreetMap (OSM) and economic costs developed by assimilating a wide range of construction statistics, and associated regional costs for the Arctic states. An application of the uniform methodology and coherent data over circumpolar permafrost regions provides consistent estimates which allow a comparative analysis of potential costs of climate-induced damage to permafrost infrastructure across Arctic countries.

2. Methods

2.1. Study area

The study area represents the territories of Arctic countries or states where permafrost is present (figure 1). Permafrost patterns within the study area vary and can be characterized by a traditional zonal approach which classifies permafrost based on areal continuity, or extent into continuous, discontinuous, sporadic, and isolated zones. (Zhang *et al* 2008). The continuous zone indicates that 90%–100% of the area is underlain by permafrost and only ground under large water bodies remains unfrozen. In the discontinuous zone, 50%–90% of the areas are underlain by permafrost. In zones of sporadic and isolated permafrost, certain environmental conditions (e.g. thick organic layer, thin snow cover, microclimate) favor the presence of patches of perennially frozen ground under 10%–50% and 0%–10% of the territory. One of the most important engineering characteristics of permafrost is the ground ice content which ranges within the study area from high (20% or more ice by volume) to medium (10%–20%) and low ice content (less than 10% of ground ice by volume) (Brown *et al* 2002).

2.2. Climate input

A subset of three models from the Coupled Model Intercomparison Project 6 (CMIP6) (Eyring *et al* 2016) available through the Earth System Grid Federation (https://esgf-node.llnl.gov/projects/cmip6/) was used to provide climatological variables for this study. The models were chosen to represent a range of magnitudes of projected warming in Arctic regions by constructing temperature histograms and examining the spatial pattern of temperature change produced by each CMIP6 model. As a result, the Alfred Wegener Institute—Climate Model—Medium Resolution (AWI-CM-1-1-MR), Max Planck Institute Earth Systems Model—High Resolution (MPI-ESM1-2-HR), and Norwegian Earth System Model—Medium Resolution Model (NorESM2-MM) were selected to represent relatively 'warm', 'moderate', 'cold' climatic projections respectively.

These projections were then analyzed via two shared socioeconomic pathways (SSPs) to represent varying scenarios of global socioeconomic development. SSP245 is a 'middle-of-the-road' pathway that was chosen to represent the realistically attainable lower bound of mid-century climate change. As a realistic warming scenario, SSP245 assumes moderate challenges to adaptation and mitigation implying lower capital but higher operational expenditures on Arctic infrastructure. Alternatively, SSP585 assumes a high concentration of greenhouse gasses and accelerated warming resulting in significant challenges to mitigation, but low challenges to adaptation. This scenario was selected to represent the most pronounced climatic changes which translate to higher capital investment, but lower operational expenditures.

Daily values of surface air temperature and precipitation produced by the three models under SSP245 and SSP585 scenarios were used to calculate decadal climatologies of daily values for the 2015–2024 (baseline) and the 2055–2064 (future) periods. The future period was limited by the 2055–2064 decade to represent a typical lifespan of Arctic infrastructure and planning horizon for long-term development projects. All models were re-gridded from

Figure 1. Map showing the location of the Arctic countries and states with the contemporary presence of permafrost used in this study. These include: (1) in North America: parts of Alaska in the USA and Canadian provinces of the Northwest Territories, Nunavut, and Yukon; (2) in western Europe: Iceland; Lapland, Northern Ostrobothnia, and Kainuu (Finland); Finnmark, Nordland, and Troms (Norway); Norrbotten and Västerbotten (Sweden); (3) in Russian Federation: Murmansk Oblast', Northeast of Republic of Komi, Nenets AO, Yamal-Nenets AO (YNAO), north of Khanty-Mansi AO (KMAO), north of Krasnoyarsk Krai, Republic of Sakha, Chukotka AO, Magadan Oblast. Greenland was not considered due to a lack of substantial permafrost infrastructure.

native resolution to a standard 0.25 × 0.25 spherical degree grid using linear interpolation. Due to the study area's large extent and high altitudes, the projected grid areas range between 250 and 600 km^2 moving from the southern permafrost regions to the arctic coast.

2.3. Permafrost-geotechnical model

To provide a quantitative assessment of the effect of climate changes on the stability of Arctic infrastructure built on permafrost we have applied a permafrost-geotechnical model (Streletskiy *et al* 2012a), which utilizes the bearing capacity (ability to carry a structural load) of frozen soil and the relative subsidence of the ground surface as primary variables for engineering assessments of permafrost-affected territory. A detailed description of model parameterization is given in appendix section *Permafrost-geotechnical model*. The permafrost model was forced by baseline (2015–2024) and future (2055–2064) daily air surface temperature climatologies from the three CMIP6 models and the two SSP scenarios described above.

The changes in bearing capacity and ground subsidence were then used to determine infrastructure at risk within ArcPro. A description of infrastructure database is given in appendix section *Infrastructure database*. For buildings the loss of bearing capacity of >30% was considered high risk; 15%–30% moderate risk; and <15% low risk based on (Melnikov *et al* 2022). For linear infrastructure (e.g. roads, railroads, airstrips) the ground surface subsidence of

>0.2 m was considered high risk, 0.1–0.2 m moderate risk, and <0.1 m as low risk based on (Streletskiy *et al* 2019). The infrastructure database was used to estimate the amount (e.g. number of buildings/structures/airstrips, length of roads/railroads) of infrastructure within each risk zone and associated with their respective per-unit cost. The country- and region-specific costs were summarized to provide a total potential economic impact of climate-induced permafrost degradation on infrastructure in the Arctic. A detailed description is given in appendix section Construction costs.

3. Results

3.1. Climate change

Under SSP245, the mean annual temperature over the study area is projected to increase by 1.04 °C–1.41 °C depending on global climate model (GCM) used. Under the higher warming scenario (SSP585), the mean annual temperature across the study area is projected to increase by 1.91 °C–2.32 °C over the same period (table 1). Both climate scenarios project more pronounced warming in high-latitude areas underlain by continuous permafrost than in subarctic regions with discontinuous and sporadic permafrost (figure 2). While there is substantial spatial variability within each model, across the study area the least pronounced temperature changes will be based on climate from the MPI model under the SSP245 scenario, while the highest changes will be based on the AWI model under the SSP585 scenario (table 1). AWI produces considerably warmer temperatures relative to the other two climate models, especially over the North American Arctic and central Siberia. MPI produces a colder Atlantic sector compared to NorESM which is colder in the Alaskan Arctic compared to the other two climate models (figure 2).

Overall, the air temperature fields produced by three climate models demonstrate a large uncertainty in climatic projections even within the single SSP scenario. To address this problem, the economic estimates related to permafrost changes calculated using each of three SSP-specific, GCM-produced climates were averaged to represent a model ensemble mean. Minimums and maximums in economic estimates were used to quantify the effect of uncertainty in climate projections.

3.2. Transport infrastructure at risk of ground subsidence

3.2.1. Roads

According to OSM data, over the entire study area, a total of 358 000 km of roads are located in permafrost-affected regions with almost 50% or 175 000 km being in Russia's permafrost regions (table 2). We estimate that under the three models' average climate projections and the SSP245 climate scenario, 29% (or 105 500 km) of these roads are at moderate and high potential risks of damage due to ground subsidence by the 2055–2064 period (table 2). According to country-specific estimates, 49% (86 600 km) of all Russian, 17% (or 7200 km) Canadian, and 25% (or 6100 km) Alaskan roads on permafrost are at risk of significant damage due to climate-induced thaw subsidence. Note that the larger road network in Canada results in a smaller percentage of at-risk roads compared to Alaska (figure 3). Unlike Russia, where most impacts on roads are projected for the continuous permafrost zone, both Alaska and Canada had a higher percentage of at-risk roads on discontinuous permafrost. With the exception of Svalbard, Scandinavian countries do not have roads in the continuous permafrost zone but have dense road networks in the discontinuous and especially sporadic permafrost zone. Out of all roads in permafrost regions, 13% of roads in Finland and 20% in Norway were estimated to be at risk from ground subsidence with a total length of 759 and 3850 km, respectively. The total cost of replacing damaged sections of roads was estimated at $99.8 billion, including $56.6 billion in Russia, $10.0 billion in Alaska, and $11.9 billion in Canada. In European countries, the economic impact of permafrost-related road damage is estimated at 0.15 billion for Iceland, $0.8 billion for Finland, $1.0 billion for Sweden, and $18 billion for Norway. The high estimate for Norway is likely due to higher construction costs and the inability to adequately represent permafrost locations at the spatial scale and resolution adopted for this study due to the highly complex topography and the discontinuous nature of permafrost in Northern Norway.

Under the SSP585 scenario, the length of roads at risk is estimated to increase to 156 000 km or 44% (table 2) with more pronounced impacts in Yamal-Nenets Autonomous Okrug (YNAO), Northern Alaska, and Sakha-Yakutia. In Russia, 121 700 km or 69% of roads in permafrost regions were estimated at risk. In Canada, the impacted roads increased to 14 200 km or 33% of roads, while in Alaska 11 600 km or 48% of all roads on permafrost are at risk of damage. Substantial increases are evident in Scandinavian countries. The average projected cost of mitigating potential road damage under the SSP585 scenario is $156.1 billion for the Arctic, including $71.2 billion in Russia.

3.2.2. Railroads

Based on OSM data, 27 500 km of railroads are located in the permafrost regions considered for this study (table 3). Most of the railroads (19 600 km) are located in Russian permafrost regions. Other countries combined contribute less than 30% of the total railroad network on permafrost. According to OSM, only Russia and Canada had railroads in continuous permafrost (figure 3). On average under the SSP245 scenario, 23% of Arctic railroads in permafrost regions are projected to be subjected to

Table 1. Summary statistics for a mean annual air temperature difference of future conditions (2055–2064) and current conditions (2015–2024) for three CMIP6 models across the study area under the SSP245 and SSP585 climate scenarios. Units reported in °C.

	SSP245				SSP585			
Model	Mean	Min	Max	SDEV	Mean	Min	Max	SDEV
Alfred Wegner Institute (AWI)	1.41	0.08	3.78	0.58	2.32	−0.65	6.00	0.96
Norwegian Earth System Model 2 (NorESM2)	1.28	−0.65	3.45	0.50	1.95	−0.74	4.50	0.61
Max Plank Institute (MPI)	1.04	0.50	2.72	0.41	1.91	−1.10	4.61	0.69

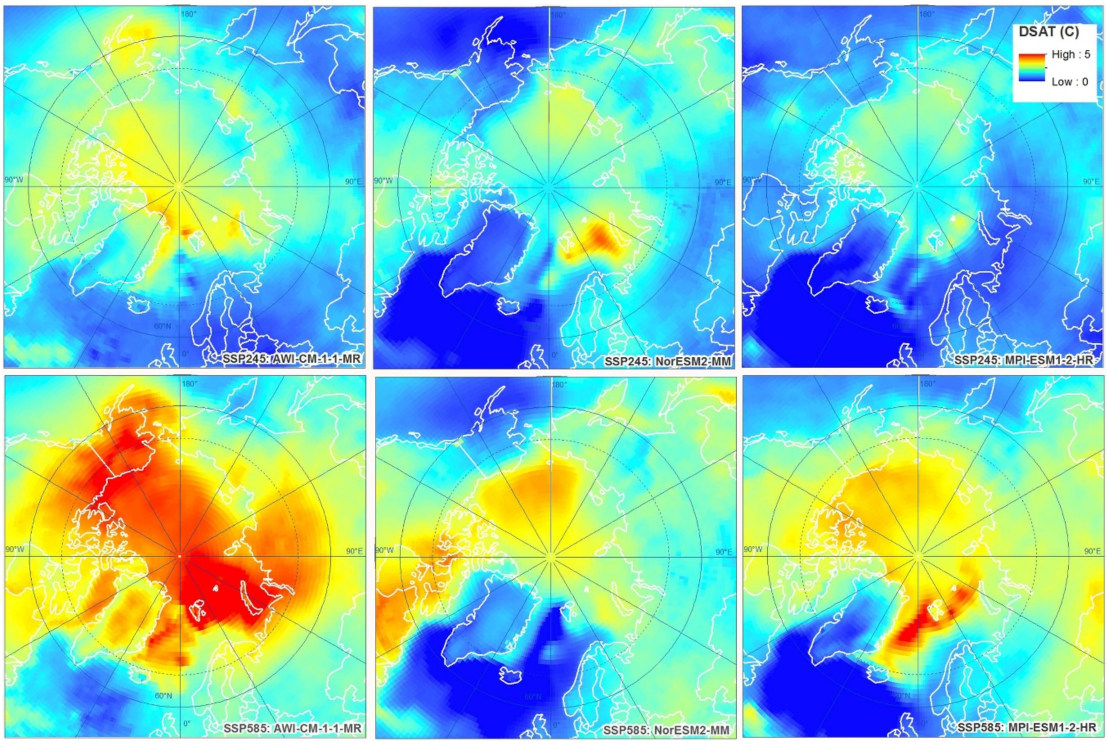

Figure 2. Mean annual surface air temperature difference (dSAT, °C) of future conditions (2055–2064) and current conditions (2015–2024) for AWI (left), NorESM2-MM (center), and MPI-ESM1-2-HR models (right) under the SSP245 (top panel) and SSP585 climate scenarios (bottom panel). Units reported in °C.

Table 2. Projected average, minimum and maximum percentages and replacement costs of roads in permafrost regions at risk of ground subsidence under the SSP245 and 585 scenarios for study area countries.

		SSP245						SSP585					
		Percent at risk (%)			Cost of replacement (mil USD)			Percent at risk (%)			Cost of replacement (mil USD)		
Country	Total length (km)	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
USA (Alaska)	24 280.4	25%	11%	36%	$10 057	$4598	$14 495	48%	38%	53%	$19 113	$15 182	$21 332
Canada	43 124.6	17%	9%	24%	$11 914	$6767	$16 937	33%	32%	35%	$23 496	$22 634	$25 015
Russia	175 724.5	49%	40%	57%	$50 645	$41 509	$58 794	69%	62%	79%	$71 177	$63 292	$80 927
Iceland	15 871.2	0%	0%	0%	$13	$0	$23	0%	0%	0%	$13	$0	$23
Sweden	35 255.9	3%	1%	4%	$5046	$1666	$7300	3%	0%	5%	$5543	$0	$8328
Finland	24 381.9	3%	0%	8%	$3645	$0	$9066	6%	0%	9%	$6941	$298	$10 272
Norway	39 352.4	10%	4%	21%	$18 496	$8069	$38 865	16%	5%	21%	$29 835	$8729	$40 393
Total Arctic	357 990.7	29%	25%	34%	$99 815	$84 968	$108 120	44%	40%	50%	$156 118	$116 155	$186 269

damaging ground subsidence with an estimated total cost to mitigate railroad damage of 18.0 billion. Russia, Alaska, and Canada are projected to have 28%, 18%, and 12% respectively. Despite relatively high percentages of at-risk railroads in Canada and Alaska, a small network of railroads on permafrost translates to considerably lower costs for all regions outside Russia. Under the SSP245 scenario, we estimate $11.6 billion in damages to railroads for Russia, while the rest of the Arctic countries with railroads on permafrost

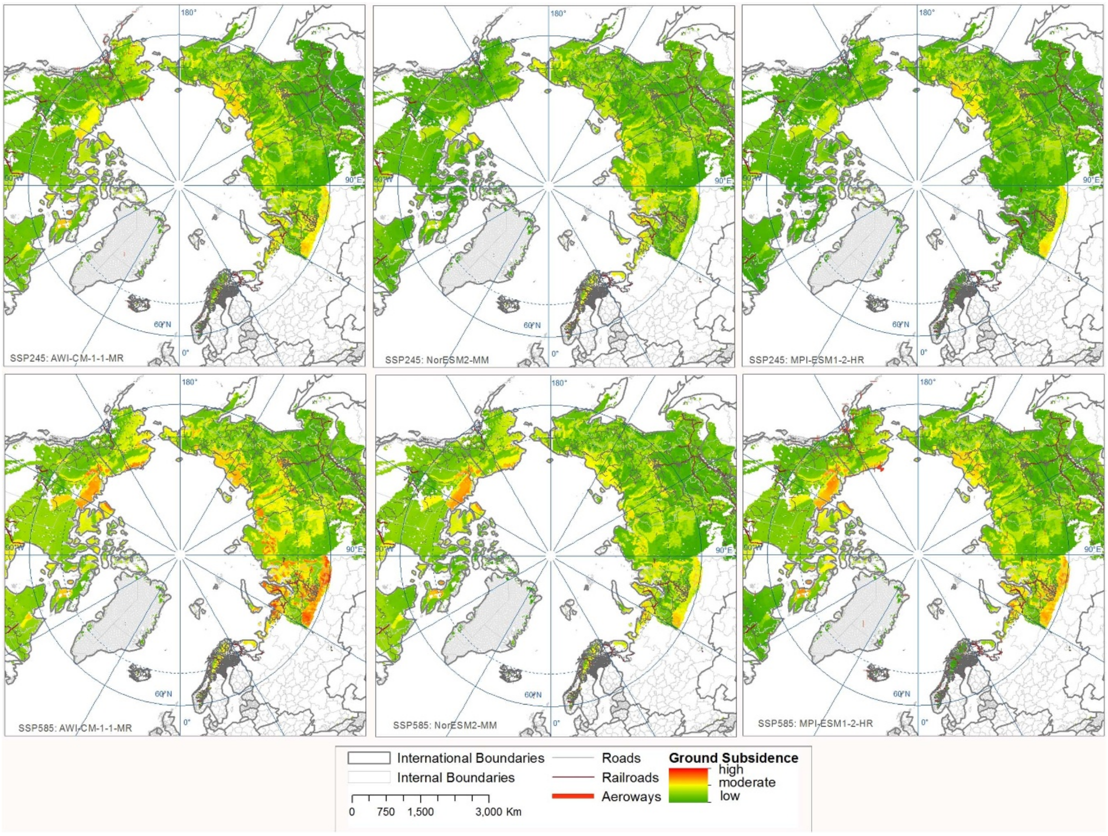

Figure 3. Roads, railroads, and airport runways and at risk of ground subsidence (cm) using AWI (left), NorESM2-MM (center), and MPI-ESM1-2-HR (right) climate models under the SSP245 (top panel) and SSP585 (bottom panel) climate scenarios. The areas in green are considered low risk, yellow/orange are moderate risk and red are high risk of ground subsidence.

Table 3. Projected average, minimum and maximum percentages and replacement costs of railroads in permafrost regions at risk of ground subsidence under the SSP245 and 585 scenarios for study area countries.

		SSP245						SSP585					
		Percent at risk (%)			Cost of replacement (mil USD)			Percent at risk (%)			Cost of replacement (mil USD)		
Country	Total length (km)	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
USA (Alaska)	1136.7	18%	0%	34%	$1075	$0	$2063	33%	19%	44%	$2039	$1157	$2712
Canada	2989.4	12%	11%	12%	$2301	$2245	$2384	13%	13%	13%	$2646	$2621	$2668
Russia	19 617.3	28%	14%	38%	$11 573	$5847	$15 979	41%	37%	44%	$17 403	$15 571	$18 506
Iceland	0.0	0%	0%	0%	$0	$0	$0	0%	0%	0%	$0	$0	$0
Sweden	1876.2	7%	2%	9%	$1523	$502	$2034	9%	0%	14%	$2091	$0	$3136
Finland	513.4	0%	0%	0%	$0	$0	$0	0%	0%	0%	$0	$0	$0
Norway	1358.2	12%	3%	29%	$1562	$423	$3636	21%	6%	29%	$2672	$744	$3636
Total	27 491.2	23%	12%	30%	$18 034	$10 382	$24 033	34%	32%	36%	$26 850	$23 028	$29 819

will encounter costs between $1 and $2 billion per country. Under the SSP585 scenario, 34% of Arctic railroads on permafrost will be affected with a total cost of $26.9 billion (table 3). In Alaska, 33% of railroads will be affected, while 13% in Canada and 41% in Russia. While there is a wider range of estimates in Scandinavian countries, there is a considerable increase in impacts of subsidence on railroads under the SSP585 scenario relative to the SSP245 scenario.

3.2.3. Airport runways at risk of ground subsidence

More than 1000 airstrips are located in permafrost regions according to OSM, with a total length of 1082 km (table 4). By count, Alaska has 39%, Canada 34%, and Russia 22% of runways in permafrost regions amounting to 95% of all runways within the study area. By length Alaska has 34%, Canada 29%, and Russia 33%, indicating that Alaska and Canada have higher absolute numbers but smaller-sized runways compared to Russia. Out of 401 runways, 134 were found in continuous permafrost regions of Alaska, including 34 in regions of ice-rich permafrost. Out of 349 runways in Canadian permafrost regions, 160 were found in the continuous permafrost zone, including 47 on ice-rich permafrost. In Russia, 229 airways are located in permafrost regions with 128

Table 4. Projected average, minimum and maximum percentages and replacement costs of runways in permafrost regions at risk of ground subsidence under the SSP585 scenario for study area countries.

Country	Total length (km)	Count by permafrost zone			Percent at risk by count (%)			Percent at risk by length (%)			Cost of replacement (mil USD)		
		Continuous	Discontinuous	Sporadic	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
USA (Alaska)	374.2	134	203	64	4%	2%	7%	6%	3%	9%	$220	$119	$345
Canada	312.5	160	80	103	5%	5%	6%	3%	3%	3%	$101	$97	$104
Russia	356.0	128	41	60	5%	0%	10%	5%	0%	10%	$171	$12	$365
Iceland	0.0	0	0	6	0%	0%	0%	0%	0%	0%	$0	$0	$0
Sweden	9.7	0	0	11	0%	0%	0%	0%	0%	0%	$0	$0	$0
Finland	6.0	0	1	5	0%	0%	0%	0%	0%	0%	$0	$0	$0
Norway	23.4	4	4	16	16%	16%	17%	18%	18%	18%	$42	$42	$42
Total	1081.8	426	329	265	5%	4%	7%	5%	3%	8%	$506	$356	$765

Table 5. Projected average, minimum and maximum percentages and replacement costs of buildings in permafrost regions at risk of bearing capacity loss under the SSP245 and 585 scenarios for study area countries.

Country	Total area (million sq m)	SSP245						SSP585					
		Percent at risk (%)			Cost of replacement (mil USD)			Percent at risk (%)			Cost of replacement (mil USD)		
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
USA (Alaska)	27.6	6%	5%	8%	$3029	$2175	$3883	7%	7%	8%	$3394	$3137	$3616
Canada	10.5	13%	11%	15%	$2000	$1740	$2209	15%	14%	16%	$2359	$2106	$2520
Russia	142.8	18%	14%	25%	$53 000	$42 152	$7 937	28%	23%	30%	$80 477	$66 738	$87 604
Iceland	21.3	0%	0%	0%	$2	$0	$6	0%	0%	0%	$5	$0	$8
Sweden	25.2	1%	0%	1%	$1089	$536	$1579	1%	1%	2%	$1498	$1194	$1721
Finland	15.6	2%	0%	4%	$1487	$226	$2213	3%	1%	4%	$1854	$631	$2468
Norway	26.6	4%	0%	9%	$3502	$312	$7416	4%	1%	8%	$3367	$836	$6792
Total	269.7	11%	10%	15%	$64 110	$54 402	$80 720	17%	14%	18%	$92 955	$76 864	$104 145

in continuous permafrost including 55 on ice-rich permafrost. Iceland had six and Sweden had 11 runways in sporadic permafrost regions, but none were built directly on permafrost. The absolute majority of the runways with unpaved surfaces are commonly composed of gravel or dirt without terminals or with small structures next to them, however larger settlements and industrial centers had asphalt or concrete runways.

According to modeling results, no runways are determined under the threat of thaw subsidence under the SSP245 scenario in Alaska. However, under the SSP585 scenario on average 17 runways (or 4%) with a total length of 22.0 km (6% of total length) are projected to be negatively affected with an estimated cost of 220 mil. In Canada, only two airstrips are affected under SSP245, while 17 airstrips (5%) with a total length of 10 km (3%) and at a cost of 100.5 million under the SSP585 scenario. In both Alaska and Canada, all affected airstrips are located in ice-rich continuous permafrost zones. In Russia, out of 229 runways in permafrost regions, no effects were evident under SSP245, while 14 runways with a total length of 18.1 km (5%) were affected under SSP585 at an estimated cost of $171 million. Finland has one airway in discontinuous permafrost but with low ice content and five in the sporadic permafrost zone. While no runways on continuous permafrost were detected in continental Norway, several runways with a total of 4.2 km in Svalbard are located on continuous permafrost with medium ice content and can potentially sustain damage at an estimated cost of $42 million. Overall, while almost 32% of runways in the study area were located in regions with ice-rich continuous permafrost that is most vulnerable to thaw subsidence, only 50 (or 5%) runways in the study area were determined to be at risk beyond the safety thresholds. Under the SSP585 scenario, we estimate an average cost of $506 million, with the highest costs projected for Alaska (table 4).

3.3. Buildings at risk of bearing capacity loss

According to OSM data, the study area's total footprint of buildings erected on permafrost is 269.7 million sq m with 142.8 million sq m in Russian permafrost regions (table 5). Under the SSP245 scenario, we estimate that 11% of buildings or 30.9 million sq m will be affected by moderate to high loss of bearing capacity and will need to be rebuilt. The highest projected impact is expected in Russia, where 18% or 26.0 million sq m of buildings on permafrost will be at risk of permafrost bearing capacity loss beyond the safety thresholds (figure 4). Canada is projected to have 13% of buildings or 1.4 million sq m and Alaska 6% or 1.7 million sq m of buildings affected by the loss of permafrost bearing capacity. No impacts on buildings are expected in Iceland and small impacts are projected Scandinavia, which is likely to be overestimated, as a substantial amount of building footprint is attributed to

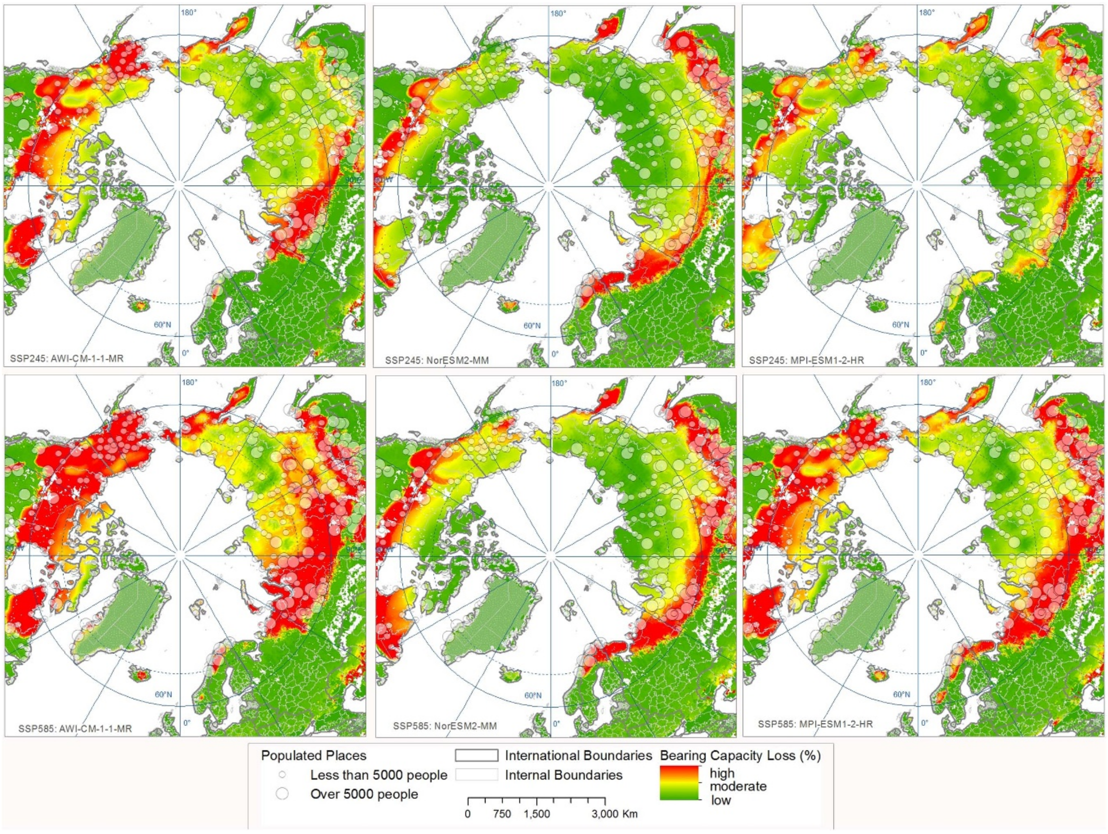

Figure 4. Buildings and at risk of damage due to permafrost bearing capacity loss using AWI (left), NorESM2-MM (center), and MPI-ESM1-2-HR climate models (right) under the SSP245 (top panel) and SSP585 climate scenarios (bottom panel). The areas in green are considered low risk, yellow/orange—moderate risk, and red—high risk of ground subsidence. Due to high volume and small size of buildings, populated places are shown on the maps instead.

permafrost-affected areas on sporadic permafrost and much higher construction costs in the region. The average total cost of damage due to loss of bearing capacity under the SSP245 scenario is \$64.1 billion for the circumpolar Arctic, with Russia accounting for over 80% of the total loss or \$53.0 billion. Russia has the absolute majority of building on permafrost and a substantial part of these buildings are within the continuous permafrost zone. In other Arctic countries, most of the infrastructure is discontinuous or sporadic permafrost zones.

Under the SSP585 scenario, the number of buildings affected by the loss of permafrost bearing capacity increases to 17%. The total cost of building damage to Arctic countries increases by \$28.8 billion relative to the SSP245 scenario and totals 93.0 billion, with most of the costs (\$80.5 billion) associated with building damages in Russia's permafrost regions (figure 4). Canada and Alaska are projected to have relatively low increases due to their small building footprint within the continuous permafrost zone. Cost from damages in Alaska will increase from \$3.0 to \$3.4 and in Canada from \$2.0 to \$2.4 billion (table 5). Even smaller increases are projected in Scandinavian countries where buildings' footprints on permafrost are mostly in the zone of sporadic permafrost and have a small impact from permafrost degradation as buildings are assumed to not be directly located on permafrost.

4. Discussion

4.1. North America

Except for a few relatively small cities and isolated industrial areas, the permafrost regions of North America are characterized by widely dispersed and sparsely populated rural communities. Such distribution promotes the development of a relatively dense road network and a high number of airport runways connecting the remote communities. The highest costs due to climatically driven damage to infrastructure on permafrost for the mid-century resulted from risks to the road network, which were significantly higher than the cost of impacted buildings and railroads. Only a small percentage of airport runways in Alaska and Canada were considered at risk and contributed very little to the overall expense.

In Canada, the regions most affected by roads at risk of ground subsidence include the territory of Yukon near the city of Whitehorse, as well as the Northwest Territories near Yellowknife and throughout the Mackenzie Valley. In Alaska, we estimate that the road networks in proximity to the communities of Utqiagvik (Barrow), Deadhorse, and Fairbanks can be subjected to moderate to high ground subsidence under projected climatic change.

The highest proportion of buildings at risk associated with bearing capacity loss is projected for the communities of Yellowknife, Norman Wells, and Inuvik in the Northwest Territories. Buildings in the towns of Faro and Mayo in Yukon and Fairbanks, Buckland, Bethel, and Tok in Alaska were also determined to be at risk.

For all infrastructure types in North America, the extent and costs of at-risk infrastructure are likely to increase when moving from the moderate warming scenario with baseline mitigation (SSP245) to the higher warming scenario following a business-as-usual trajectory (SSP585). Under the SSP245 scenario, combined costs for roads, railroads, and buildings in North America were estimated within the \$42.0 billion to \$17.5 billion range, with \$30.4 billion on average by the mid-21 century. Under the SSP585 scenario, the average projected cost was \$53.1 billion (+\$22.7), a maximum of \$57.9 billion (+\$15.9), with a minimum of \$46.9 billion (+\$29.4). Other study estimated the cost of replacing existing public infrastructure in Alaska to be \$32 billion by 2030 and \$56 billion by 2080, with roads and airports contributing the largest amounts to these totals (Melvin *et al* 2017). In comparison, the results of this study estimated costs for Alaska to reach approximately \$14.16–24.5 billion by mid-century depending on the climate scenario, although the study area was smaller and damage to pipelines was not included.

Overall, North America is facing challenges to infrastructure located mainly in low-lying coastal areas with ice-rich permafrost. These challenges have the potential to severely impact linear infrastructure, communities and industrial centers located there.

4.2. Scandinavia and Iceland

Scandinavia contains about 23 400 square kilometers of permafrost (Gisnås *et al* 2017), but with exception of Svalbard, most of this permafrost is discontinuous or sporadic and closely related to topography and/or localized edaphic conditions. As a result, the permafrost-affected areas can be avoided during infrastructure planning and construction. Our economic estimates of permafrost-related infrastructure damage in Scandinavia can be on the higher side, even considering the 0.1 and 0.5 weights applied to account for permafrost continuity in the discontinuous and sporadic zones. However, the infrastructure built in permafrost-free areas but under a climate susceptible to permafrost development can experience negative cryogenic processes (e.g. frost heave, cryogenic weathering) and have problems similar to those considered in this study. Moreover, permafrost warming and loss of bearing capacity may decrease the stability of slopes contributing to landslides and related infrastructure damage in mountain terrain.

In Norway, the regions most affected by roads at risk of ground subsidence include the mountainous areas of eastern Norland and southern Finnmark regions. Communities with roads in ground subsidence hazard zones in Finland included Ivalo, Inari, and Enontekiō. Sweden observed impacts in northern Norrbotten County, north of Kiruna, and around Abisco.

The highest proportion of building damage due to bearing capacity loss in Sweden was determined to be in northern Norrbotten. However, no large communities currently exist north of Kiruna which is located at the southern limit of permafrost extent. Bearing capacity loss in Finland primarily impacted Lapland, with the town of Inari having buildings potentially at risk. In Norway, Finnmark was most affected, with the town Karasjok at risk.

Iceland is dominated by permafrost above 800 m on mountain plateaus and around Hofsjökull, Langjökull, Vatnajökull. Above 600 m asl permafrost develops sporadically mostly in areas with thick organic layers (e.g. peat bogs and peat plateaus), especially in the Northern highlands (Czekirda *et al* 2019). While permafrost did not overlap with the OSM infrastructure, Iceland maintains a dense network of local roads and trails essential for tourism and, herding, as well as dams (ex: Kárahnjúkar) and power lines traversing permafrost-affected areas. Mountain permafrost degradation is likely to affect slope stability and promote landslides which may have negative effects on accessibility and transportation. Climate change effects on Icelandic infrastructure are therefore under-represented in this study. Increasing data resolution and including other types of infrastructure such as trails and powerlines would contribute to a more accurate assessment of permafrost degradation impacts in Iceland and Scandinavia.

For all infrastructure types, the extent and cost of infrastructure at risk increased when moving from the moderate SSP245 scenario to the SSP585 scenario. Under the SSP245 for all infrastructure types in Scandinavia, the cost was an estimated \$36.4 billion on average of the three climate inputs, \$72.2 billion at the highest and \$11.7 billion at the lowest. These calculations all increased under the SSP585 scenario for an average of \$53.9 billion (+\$17.5), a maximum of \$76.8 billion (+\$4.6), and a minimum of \$12.4 billion (+\$0.7).

This region has a higher capacity to adapt to permafrost degradation as it generally has few areas of ice-rich, fine-grained soils, a small population living on permafrost, and a small amount of infrastructure at higher elevations affected by permafrost.

4.3. Russia

Unlike other Arctic countries, Russia is characterized by a more developed and dense infrastructure, built predominantly during Soviet Union time, and is near the end or beyond its lifespan (Khrustalev *et al* 2011). It is also the country where substantial new development of infrastructure recently occurred and is projected to continue (Bartsch *et al* 2021). A vast area of permafrost in Russia stretching across numerous bioclimatic zones, as well as the presence of large population and industrial centers on permafrost, makes Russian infrastructure especially vulnerable to permafrost degradation resulting in the highest overall costs of damage (Streletskiy *et al* 2019). Russia is the only Arctic country where buildings contribute a higher proportion of expected cost due to climatically driven permafrost infrastructure damage, while roads contribute significantly less. It is also the only country that has large cities in the continuous permafrost zone, where virtually all infrastructure depends on permafrost stability (Grebenets *et al* 2012).

The roads at high risk of ground subsidence were found in Yakutsk in Sakha (Yakutia); Salekhard, Nadym, and Noyabrsk in YNAO; Igrim and Beryozovo in Khanty-Mansi AO. Railroads at risk were Bovanekkovo-Obskaya Line in Yamal-Nenets AO, railroads near Vorkuta, around Noybrsk, Tarko-Sale, Nadym, and Norilsk. The highest proportion of building subjected to high bearing capacity loss is projected for the Sakha Republic, especially in Yakutsk and Mirniy. Other affected cities are Naryan-Mar (Nenets AO), Vorkuta (Komi Republic), Salekhard and Labitnangy (YNAO), Norilsk, and Dudinka (Krasnoyarsk Kray), Anadyr (Chukotka AO). Airstrips at risk were found in the Sakha Republic near Yakutsk and Mirniy as well as airports in Vorkuta (Komi), Amderma (NAO), Kharasavey (YNAO) Nadym, Alykel (Norilsk), and Novozapolyarniy.

For all infrastructure types, the extent and cost of infrastructure at risk increased under the SSP585 climate scenario compared to the SSP245. Under the SSP245 scenario for all types of infrastructure in Russia, the total cost was estimated at $121.9 billion considering the three-model ensemble mean climate, and $152.8 billion as the highest and $97.5 billion as the lowest estimate. These calculations all increased under the SSP585 scenario for an average of $169.3 billion (+$16.5), a maximum of $187.3 (+$34.5), and a minimum of $145.7 billion (+$48.2). This is higher than the $137 billion by Streletskiy *et al* (2019) and $132 billion by Melnikov *et al* (2022). However, these studies are not directly comparable due to differences in climatic input, methodologies, and time periods.

Russia faces unparallel impacts of permafrost degradation on infrastructure due to the unmatched scale of infrastructure. This region has a negative outlook considering aging large infrastructure and limited geotechnical monitoring in population centers. There is, however, substantial variability within the Russian Federation, as oil and gas-rich regions like YNAO, NAO and KMAO have higher capacity to address the impacts of permafrost degradation on infrastructure compared to regions that depend on federal transfers.

5. Conclusions

This study has demonstrated that under the SSP245 scenario, 29% of roads, 23% of railroads, and 11% of buildings will be affected by climatically-driven permafrost degradation. The resulting expense from this is estimated to be $182.1 billion. Under the SSP585 scenario, 44% of roads, 34% of railroads, and 17% of buildings will be impacted by climate change. As a result, the cost will increase to $276.1 billion, indicating that throughout the Circumpolar Arctic, approximately $100 billion can be potentially saved under a climate scenario where mitigation is prioritized with moderate warming versus a high emission scenario. These funds can support an adaptation of the existing infrastructure, development of new materials and construction designs, and permafrost monitoring and early warning permafrost systems capable of advanced notification of various actors and stakeholders on permafrost.

The role of non-climatic factors, such as aging infrastructure, inadequate land use and planning, lack of permafrost monitoring and construction standards on permafrost, and other socio-economic factors can exacerbate climate-induced costs. Investing in permafrost monitoring in natural and urban environments, developing automated monitoring, data sharing and distribution, and early warning systems will help to minimize the costs of infrastructure damage due to permafrost degradation in rapidly changing climatic conditions.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Appendix

Permafrost-geotechnical model

The bearing capacity of frozen soils was estimated as a function of permafrost temperature and maximum annual thaw propagation (or active-layer thickness (ALT)) using parameterizations developed for common types of infrastructure (Streletskiy, Shiklomanov, Nelson 2012a). The bearing capacity of a foundation is represented as the sum of normal stresses at the base of the pile, and shear stress at the pile sides in contact with permafrost, for permafrost with low ice content according to (equation (1)) and for high ice content according to (equation (2)):

$$F_u = \gamma_t \gamma_c \left(RA + \sum_{i=1}^{n} R_{af,i} A_{af,i} \right) \quad (1)$$

$$F_u = \gamma_t \gamma_c \left(RA + \sum_{i=j}^{n} \left(\left(1 - i_j\right) R_{sh,j} + i_j R_{sh,i,j} \right) A_{sh,j} \right) \quad (2)$$

where γ_t is a temperature coefficient accounting for potential changes in the ground thermal regime after construction ($\gamma_t = 1.0$ used in this study). γ_c is a production coefficient ($\gamma_c = 1.0$ used in this study); R represents normal stresses generated at the base of the pile (kPa); A is bottom area of the bearing post or pile at its contact with the ground (m^2); $R_{af,i}$ represents shear stresses generated along the pile at a contact with layer i (kPa); $A_{af,i}$ is the area of the side contact of a pile with frozen ground (m^2); n is the number of different layers of permafrost in contact with the pile. i_j is ice content of the jth layer; $R_{sh,j}$ and $R_{sh,i,j}$ are shear stresses on a pile with special cement solution at a side contact for the jth layer (kPa); and $A_{sh,j}$ is the area of side contact of pile with ground in layer j (m^2).

The simple 'settlement index', which depends on relative changes in ALT from present to future periods and ground ice content, was used to evaluate the potential for ground subsidence (Nelson et al 2001) as follows:

$$I_s = \Delta \text{ALT} * V_{ice}. \quad (3)$$

Ground subsidence (I_s), is the function of the change in ALT (ΔALT) and ground ice content (V_{ice}). ΔALT, is calculated using the change in ALT between future and present baseline periods based on spatial permafrost model described below. Ground ice content was obtained from Arctic Map of Permafrost and Ground-Ice Conditions: version 2 (Brown et al 2002; Accessed November 2022). The permafrost map classifies ground ice as low, medium, and high. These zones were assigned quantitative values of 10%, 20%, and 40%, based on the values provided in the NSIDC user guide (Brown et al 2002).

Permafrost temperature and the active layer thickness were provided by the spatial equilibrium permafrost model based on the Kudryavstev solution of Stephan's problem of heat conduction in a porous medium with phase transitions (Sazonova and Romanovsky 2003, Streletskiy et al 2012b). The model uses daily climate (temperature and precipitation) and accounts for soil characteristics, such as texture, soil moisture, ice content, and organic material to estimate the permafrost temperature and ALT. Details on the modeling approach are provided in (Streletskiy et al 2012). This methodology was previously used for geographic assessments of the stability of permafrost infrastructure under ongoing and projected climatic changes at various spatial and temporal scales (Streletskiy et al 2012, 2019, Shiklomanov et al 2017, Suter et al 2019, Faki et al 2022). Vegetation and soil parameters were assumed to be the same for baseline and future periods and were obtained from the following spatial databases standardized to a common spatial resolution: vegetation properties from Global Land Data Assimilation System GLDAS/Noah Land/Sea Mask Dataset. Parameterization for vegetation thermal diffusivity (thawed and frozen) and soil thermal conductivity (thawed and frozen) were manually assigned to GLDAS zones. Aggregated Soil Moisture 2005/2014 from Copernicus Climate Change Service; ground ice content from IPA Permafrost map; soil texture and parametrization of frozen and thawed thermal conductivity and heat capacity from GLDAS, topsoil bulk density from Harmonized World Soil Database. No snow accumulation was assumed under buildings and snow removal was assumed for roads, railroads, and runways.

Considering the geographic extent of this study and the lack of high-quality, high-resolution, and uniform spatial data, we assumed that the ratio of infrastructure built on permafrost corresponds to the lower bound of permafrost extent characteristic of each permafrost zone (Streletskiy et al 2019). Therefore, the relative proportion of at-risk roads, railroads, and buildings was weighted by the 0.1, 0.5, and 0.9 coefficients for sporadic (10%–50% of the area with permafrost), discontinuous (50%–90% of the area with permafrost), and continuous (>90% of the area with permafrost) zones, respectively. Runways were assumed to be built on permafrost only in the continuous permafrost zone. In other permafrost zones, we assumed that permafrost was avoided during the construction of runways. No infrastructure was assumed to be directly affected in the island permafrost zone.

Infrastructure database

OSM was used as a consistent, harmonized product to identify various types of infrastructure at risk, including transportation infrastructure such as roads, railways, and airstrips as well as residential and commercial infrastructure including buildings. A sample of OSM data representing several Arctic locations in Russia, Scandinavia, and North America was overlaid with Google Earth to ensure a reasonable representation of built infrastructure. The entire OSM datasets for each Arctic country were downloaded in 2021 from the official OSM repository and specific infrastructure layers were extracted using 'Osmosis' Java application for processing OSM data. A Geographic Information System 'QGIS' was used to select attributes and geometry from the OSM files and to save results as shapefiles and geodatabases representing roads, railroads, airports, and buildings. All shapefiles were reprojected using North Pole Lambert Azimuthal Equal Area and the resulting geodatabase was used to estimate the length (roads, railroads, airways) and areas (buildings) within ArcGIS Pro. In case the infrastructure object was not within the model output the nearest neighbor was used to assign the values of ground subsidence and bearing capacity to the object.

Construction costs

Publicly available sources on construction costs of major types of infrastructure were used to estimate the potential replacement for roads, railroads, and buildings. Governmental sources include but are not limited to: Alaska Department of Transportation, Alaska State Rail Plan, British Columbia Ministry of Transportation and Infrastructure, Government of Northwest Territories Infrastructure, Iceland Parliamentary Resolution on Transport Plan, Norwegian Ministry of Transport, Swedish Transport Administration, and the Finnish Transport Infrastructure Agency. Government sources of construction costs were prioritized and supplemented with public repositories such as the Wilson Center's Arctic Infrastructure Database, public records published by third-party private contractors, or official reports made by local news organizations. Specifically, we used data and information from Arctic Slope Regional Corporation Construction Holding Company, Hatch Ltd, Altus Group, GAMMA Capital Management Ltd, Skanska Group, and the Nordic Office of Architecture. Local news organizations used as sources include: Barents Observer, Forbes, The B1M, Alaska Public Media, Zillow, and Alaska Business. The costs of construction were used to produce the median cost of construction of one linear meter of roads and/or railroads) or square meter of buildings per country. In the case of Russia, the costs of road construction were estimated based on a specific type of road class, its length, and region-specific costs based on 'Average cost of roadwork in Russia in 2017' and 'Length of motor roads located in the permafrost zone in regions of the Russian North in 2018' (tables 3 and 6 in Porfiriev *et al* 2019). The building construction costs in Russia were based on a weighted average of construction costs available for administrative regions on permafrost (tables 3 and 4 in Porfiriev *et al* 2021b). The variability of lengths, widths, and surface (grass/dirt/concrete/asphalt) characteristics of runways even within small regions results in high variability of construction costs. To mitigate a lack of reliable sources we assume the uniform cost of $10 000 per 1 m of runway length within the entire study area.

The 2020 purchasing power parity (PPP) index from the Organization for Economic Co-operation and Development (OECD) was used to standardize the costs across the Arctic countries. It is important to mention that OECD PPP may be substantially different from exchange rates, so careful attention should be given when comparing the results of this study with studies based on specific exchange rates. The 2020 PPP exchange values among Arctic countries were assumed to be constant in the future. The resulting country-specific costs are summarized in table S1.

Table S1. Average per unit cost of construction for roads, railroads, buildings, and airports. Cost per unit is given values adjusted based on PPP USD 2020.

	Cost per unit ($)		
Country	Roads (km)	Railroads (km)	Buildings (m^2)
USA (Alaska)	1646 986	5386 368	1736
Canada	1654 780	6614 786	1442
Iceland	776 631	13 265 306	1524
Norway	4799 548	9228 610	3034
Sweden	4960 317	12 277 939	4377
Finland	4799 548	5701 582	3994
Russia	584 855	2143 470	2042

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