

Supplementary information for *Permafrost thaw-related infrastructure damage costs in Alaska are projected to double under low and medium emission scenarios*

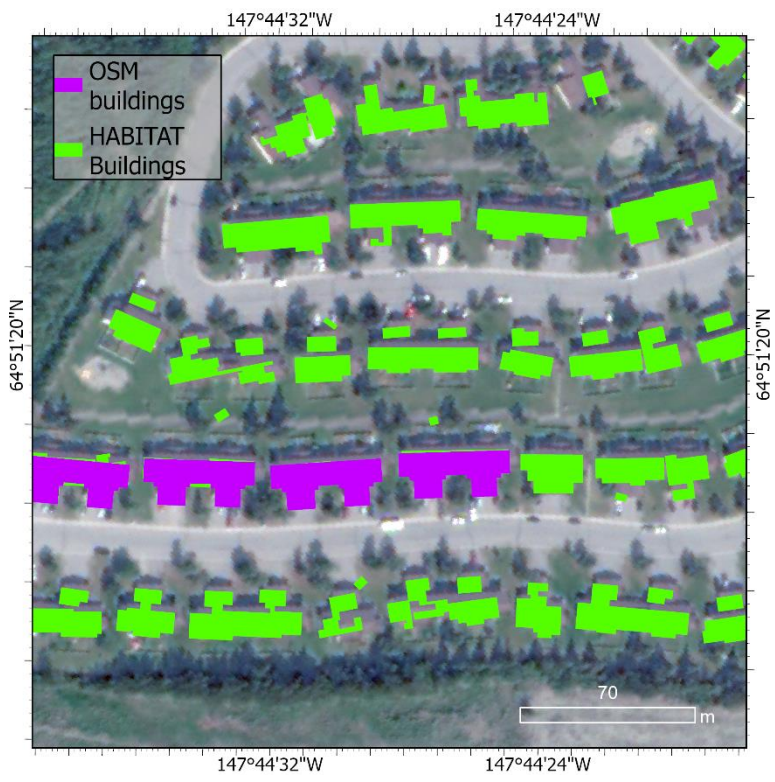
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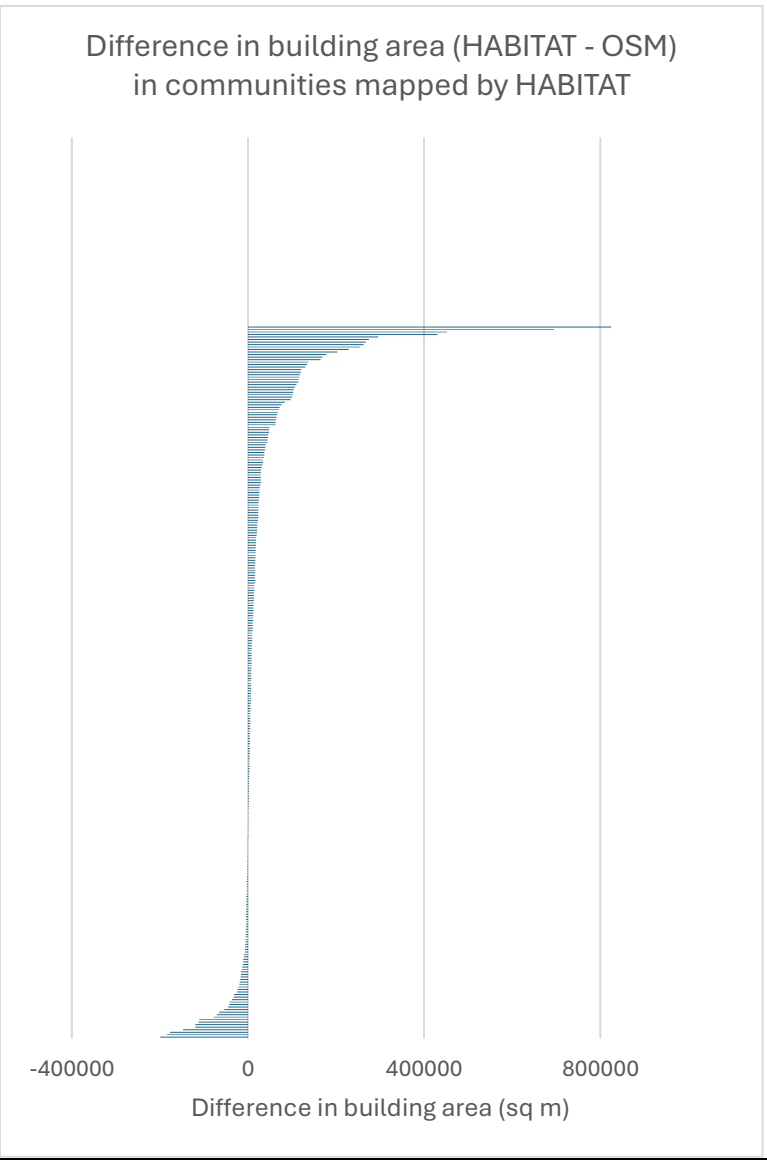
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a)



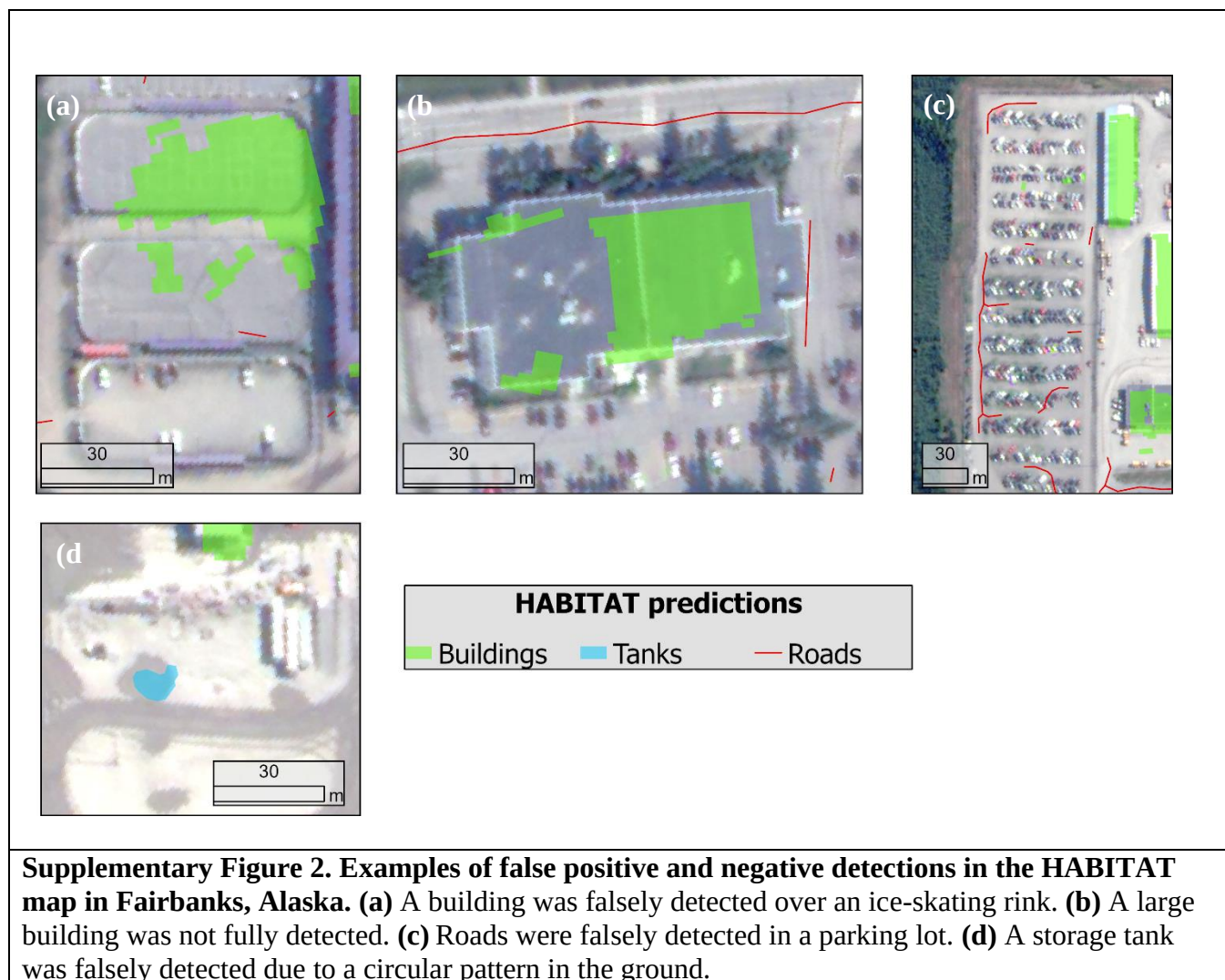
b)



Supplementary Figure 1. Comparison of buildings mapped by HABITAT and OpenStreetMap. (a) Zoomed-in example (located in Fairbanks, Alaska) of HABITAT including more buildings than OSM. Building footprints from the OSM dataset for the state of Alaska (downloaded in June 2024 from <https://download.geofabrik.de/>) are overlaid on building footprints from the HABITAT dataset. **(b)** Difference in building area across the 285 communities mapped by HABITAT when subtracting OSM area from HABITAT area. Bars extending to the right (positive difference) indicate that HABITAT includes more buildings, whereas bars extending to the left (negative difference) indicate that OSM includes more buildings. In 204 communities, HABITAT contains a larger building footprint. Badger CDP has a difference of -7,965,782 sq. m but is an extreme outlier and thus not plotted in the graph. *Imagery © Maxar, Inc.*

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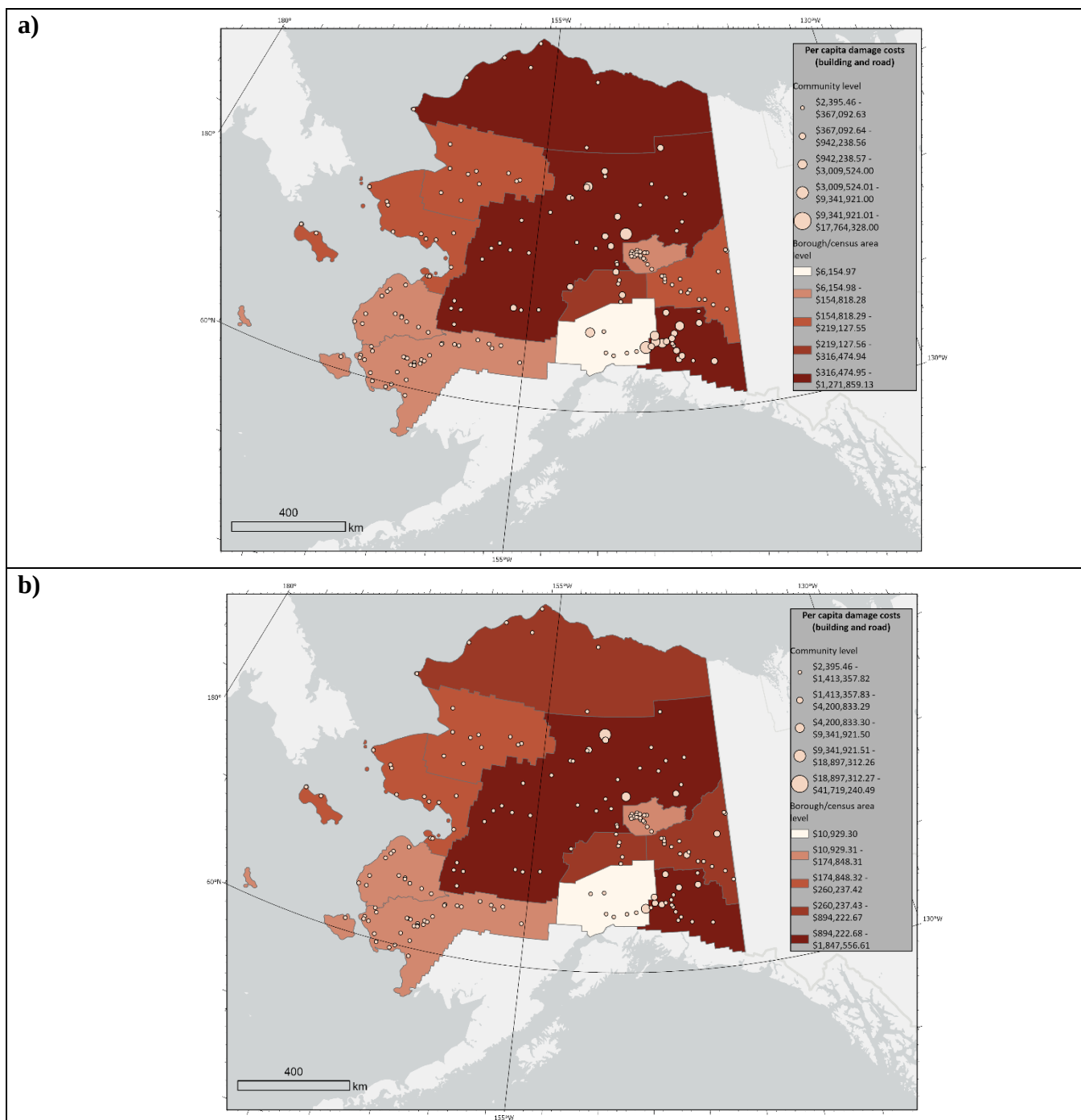
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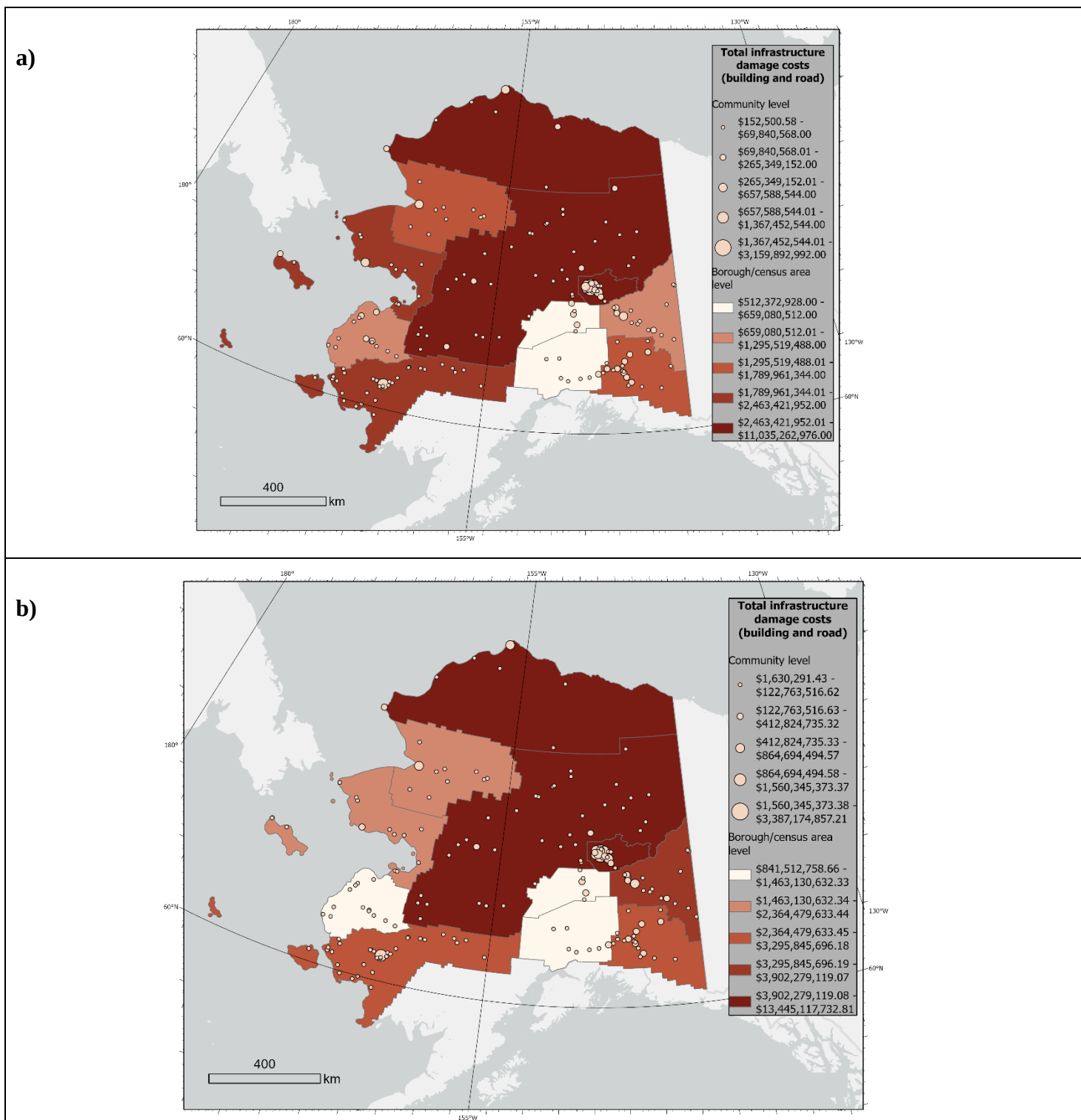
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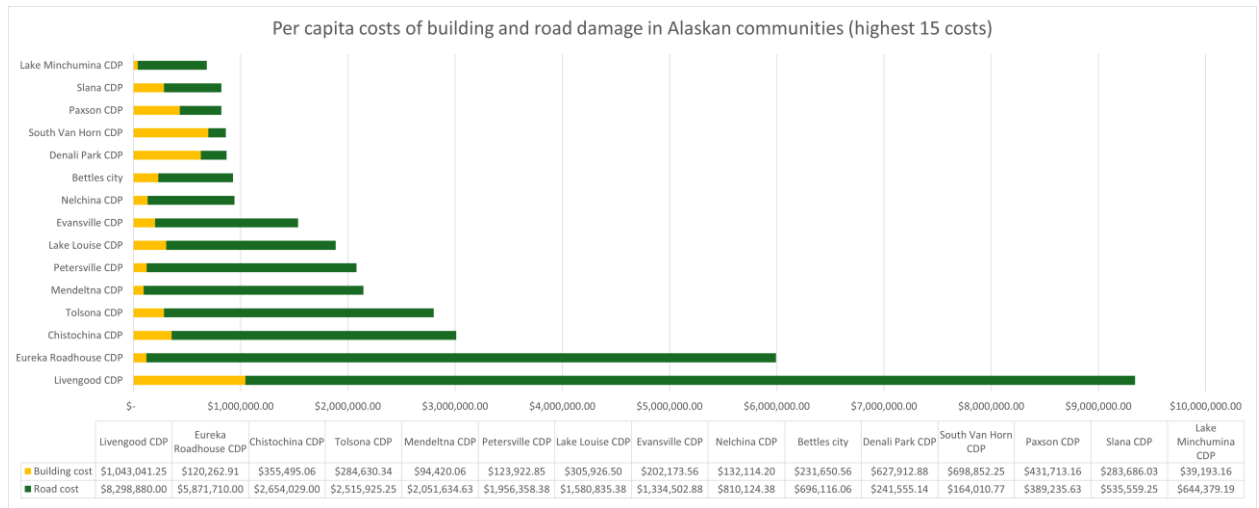


Supplementary Figure 3. Maps of per capita building and road damage costs (USD 2024). Maps show damage costs in Alaskan communities and boroughs/census areas caused by bearing capacity loss and ground subsidence projected by 2055-2064 under the **(a)** SSP245 and **(b)** SSP585 scenario. Red Dog Mine, Nabesna, and Prudhoe Bay, which are CDPs, were among these places with the highest per capita damage costs. However, these locations are primarily industrial installations (mining and oil) and were excluded from the results in order to give emphasis to permanent communities whose primary purpose is not economic.



Supplementary Figure 4. Total (not normalized by population) building and road damage costs (USD 2024). Maps show costs in both Alaskan communities and boroughs/census areas caused by bearing capacity loss and ground subsidence projected by 2055-2064 under the (a) SSP245 and (b) SSP585 scenario.

a)

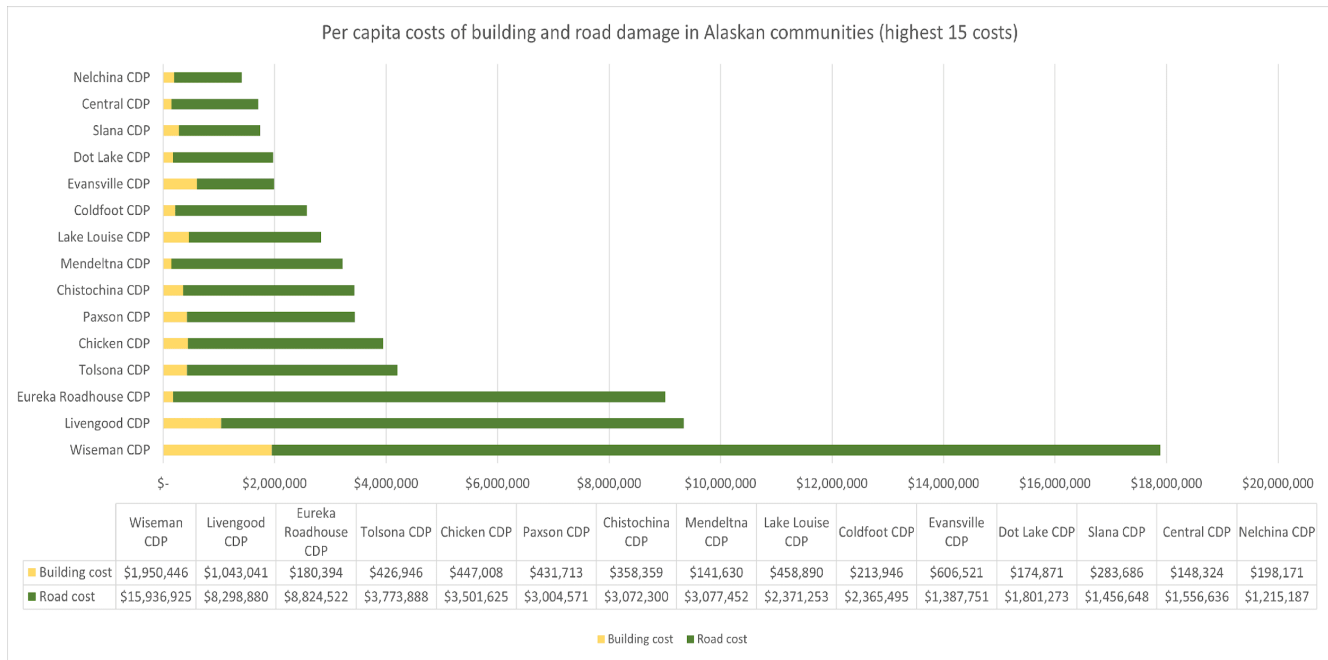


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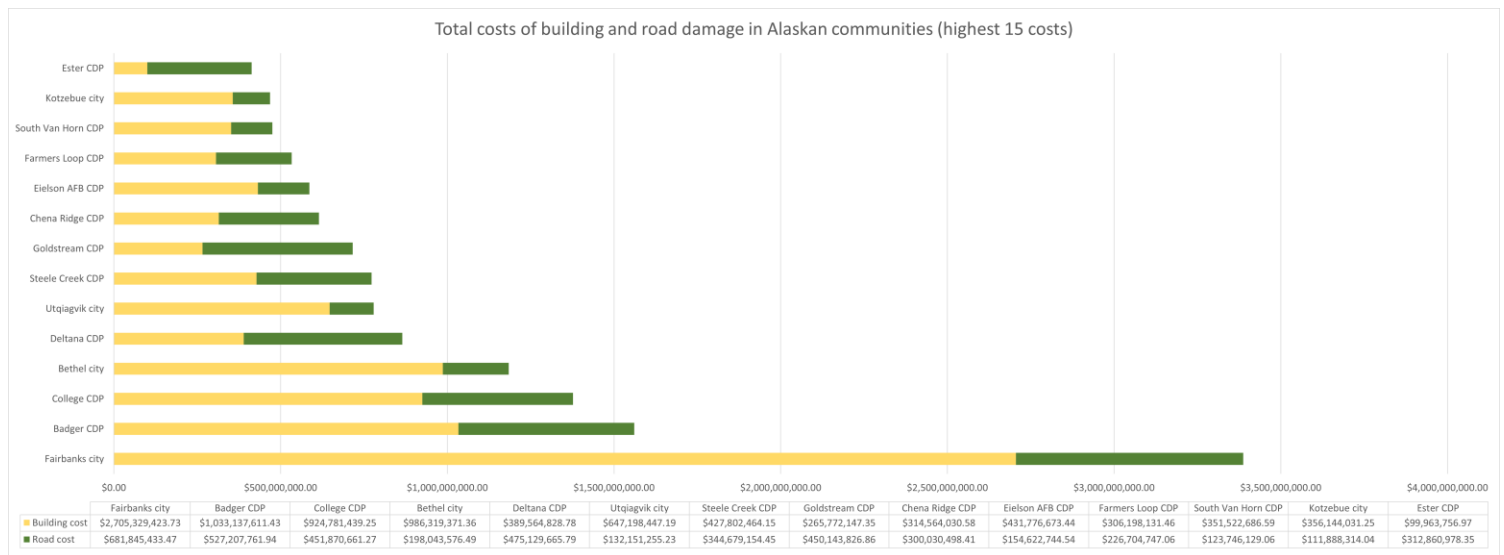


Supplementary Figure 5. Combined per capita damage costs (USD 2024) under the SSP245 scenario. (a) Highest fifteen damage costs for communities and **(b)** all costs for Alaskan boroughs/census areas underlain by continuous and discontinuous permafrost caused by bearing capacity loss and ground subsidence projected under the SSP245 scenario. Breakdowns of the costs into building and road costs are provided. As shown in **(a)**, the highest estimated damage costs among Alaskan communities are located in Livengood CDP, which amount to ~\$9M, followed by Eureka Roadhouse CDP at ~\$6M and Chistochina CDP at ~\$3M. As shown in **(b)**, the highest estimated damage costs among Alaskan boroughs/census areas are located in the Yukon-Koyukuk Census Area, which amount to ~\$1.2M, followed by the North Slope Borough and Copper River Census Area at ~\$0.7M.

a)

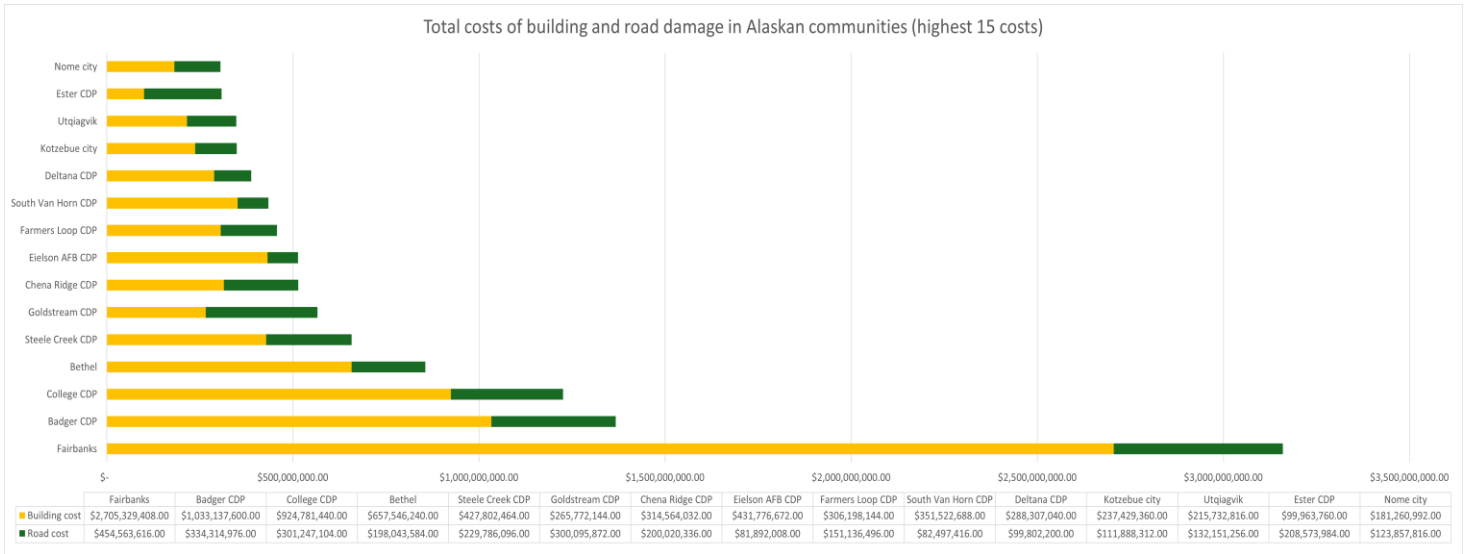


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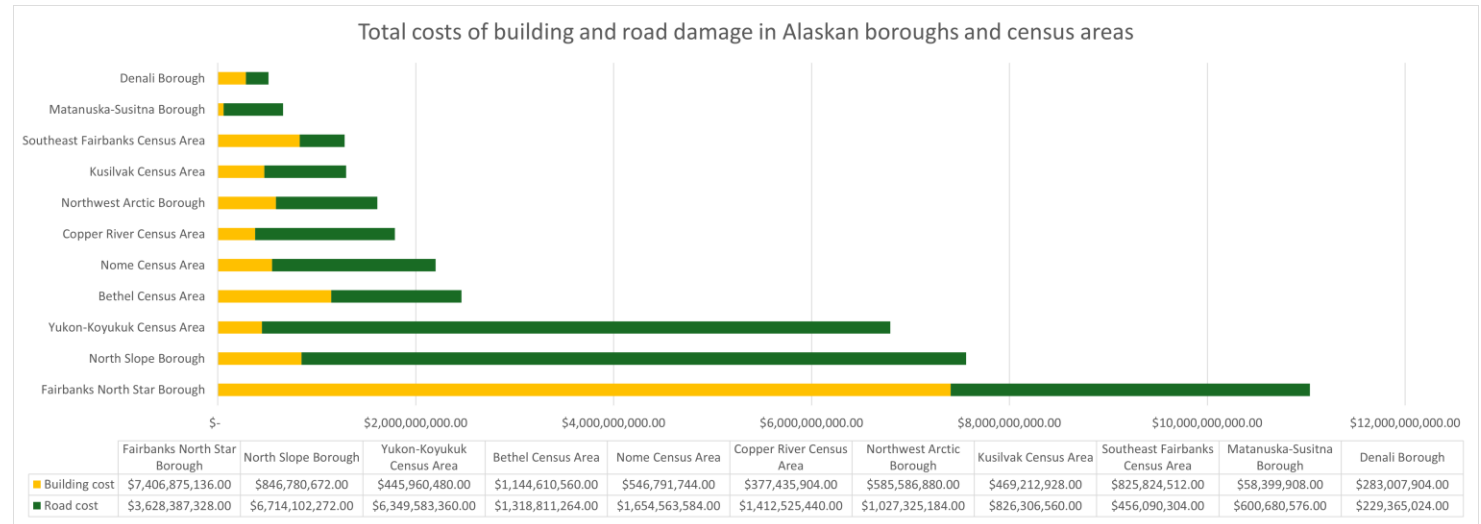


Supplementary Figure 6. Estimated per capita and total damage costs under the SSP585 scenario per community. (a) Highest fifteen per capita costs for communities on discontinuous and continuous permafrost. **(b)** Highest total costs. Breakdowns of the costs into building and road costs are provided. The highest estimated damage costs per capita are represented by Wiseman CDP, which amount to ~\$18M, followed by Livengood CDP at ~\$9.3M and Eureka Roadhouse CDP at ~\$9M. The highest total estimated damage costs among Alaskan communities are located in Fairbanks, which amount to ~\$3.4B, followed by Badger CDP at ~\$1.6B and College CDP at ~\$1.4B.

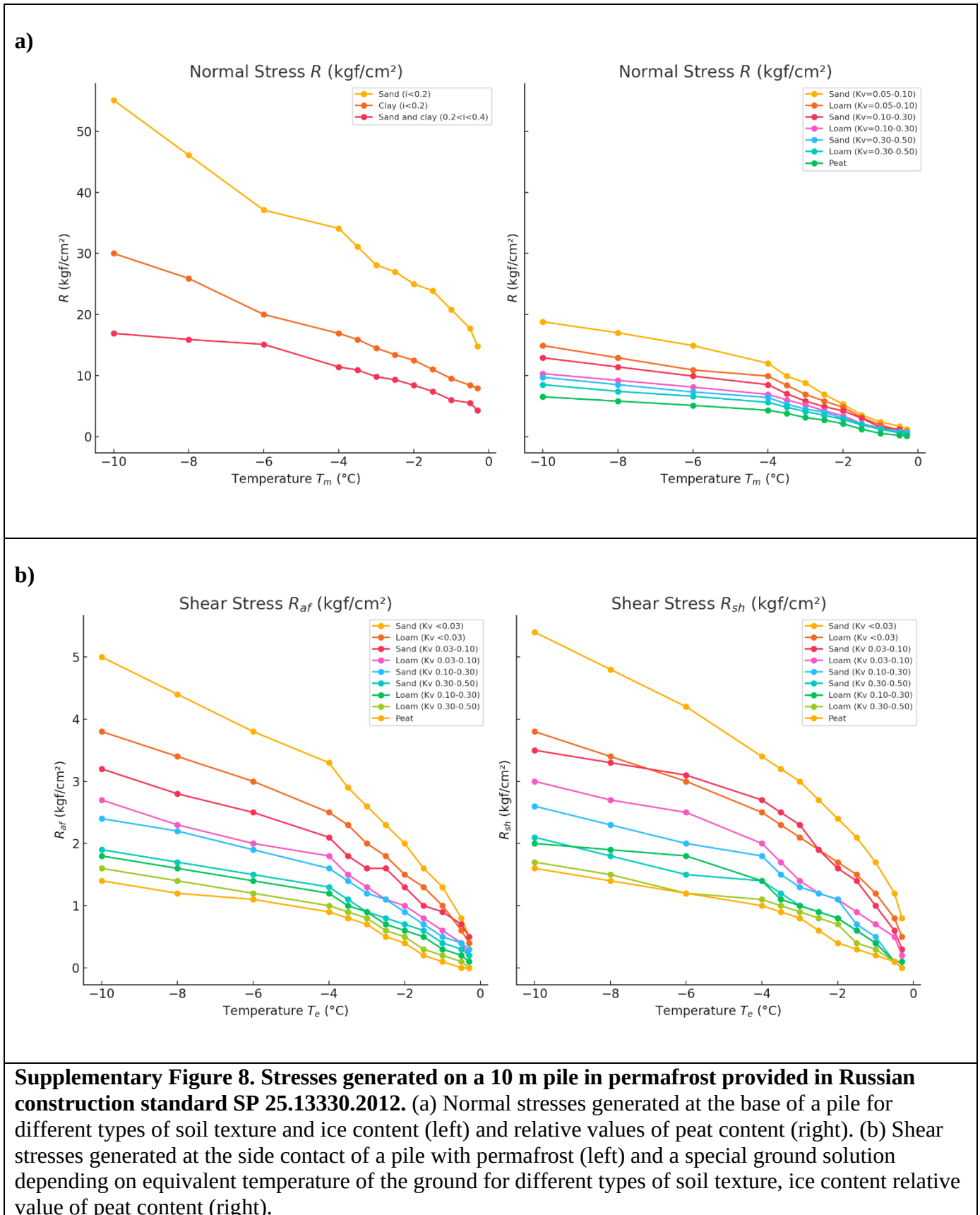
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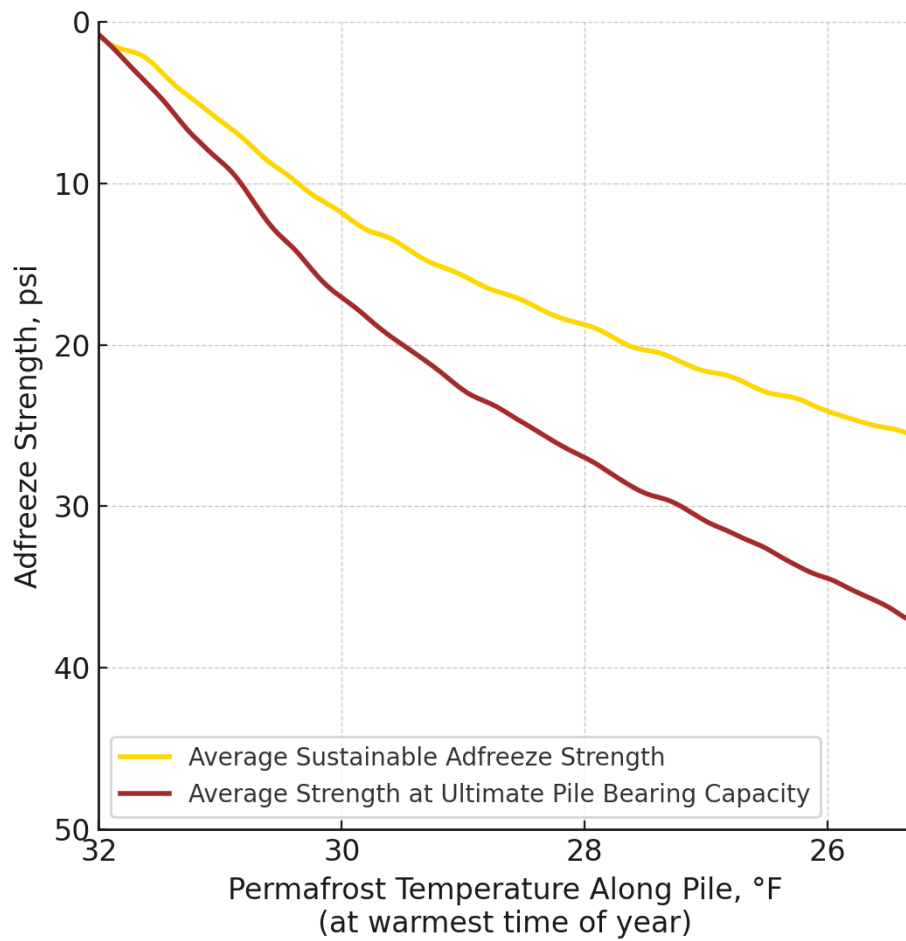


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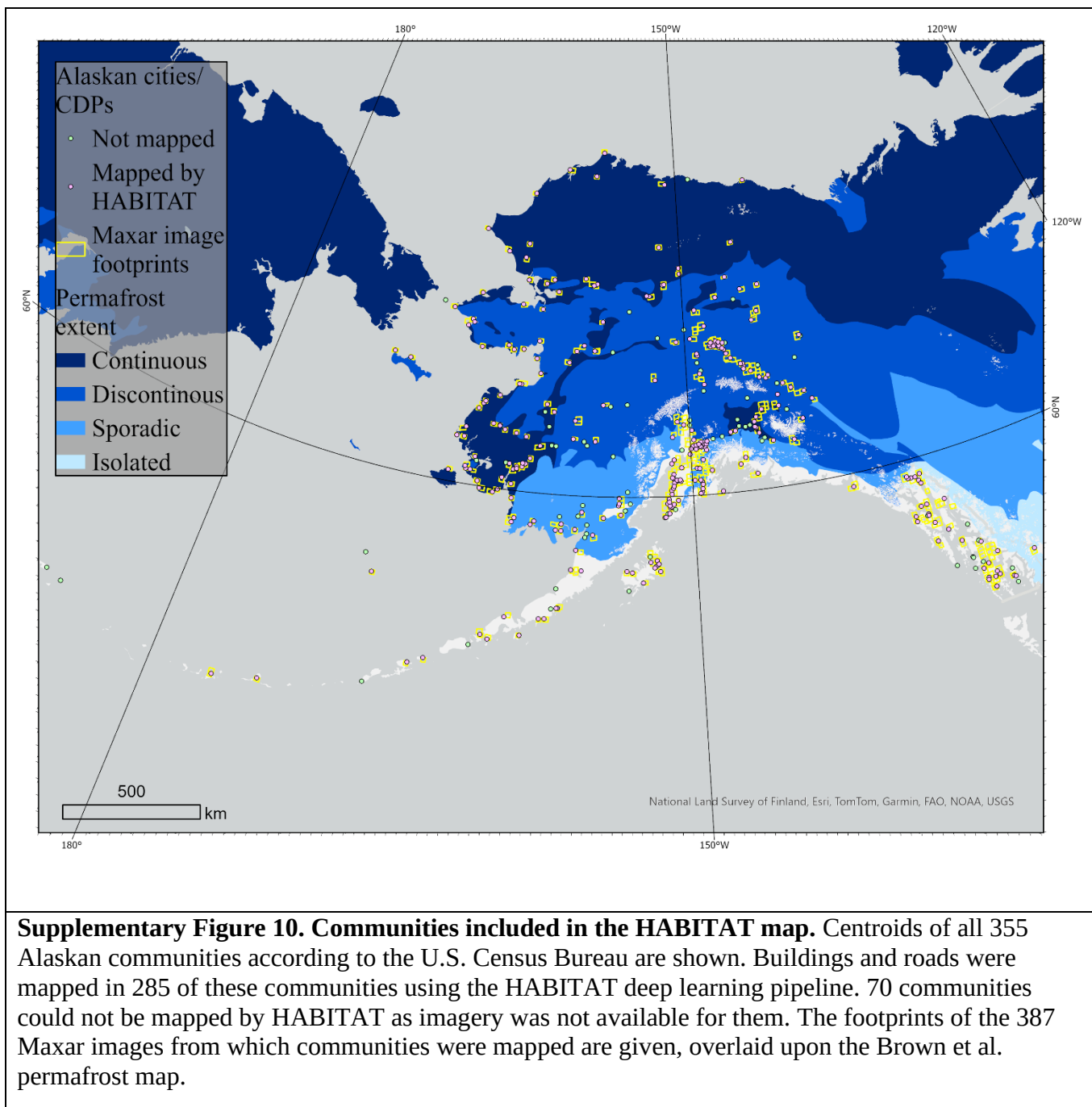


Supplementary Figure 7. Total damage costs (USD 2024) under the SSP245 scenario. (a) Highest fifteen damage costs for communities and **(b)** all costs for Alaskan boroughs/census areas caused by bearing capacity loss and ground subsidence projected by 2055-2064 under the SSP245 scenario. Breakdowns of the costs into building and road costs are provided. As shown in **(a)**, the highest total estimated damage costs among Alaskan communities are located in Fairbanks, which amount to ~\$3.2B, followed by Badger CDP at ~\$1.4B and College CDP at ~\$1.2B. As shown in **(b)**, the highest total estimated damage costs among Alaskan boroughs/census areas are located in the Fairbanks North Star Borough, which amount to ~\$11B, followed by North Slope Borough at ~\$7.6B and Yukon-Koyukuk Census Area at ~\$6.8B.





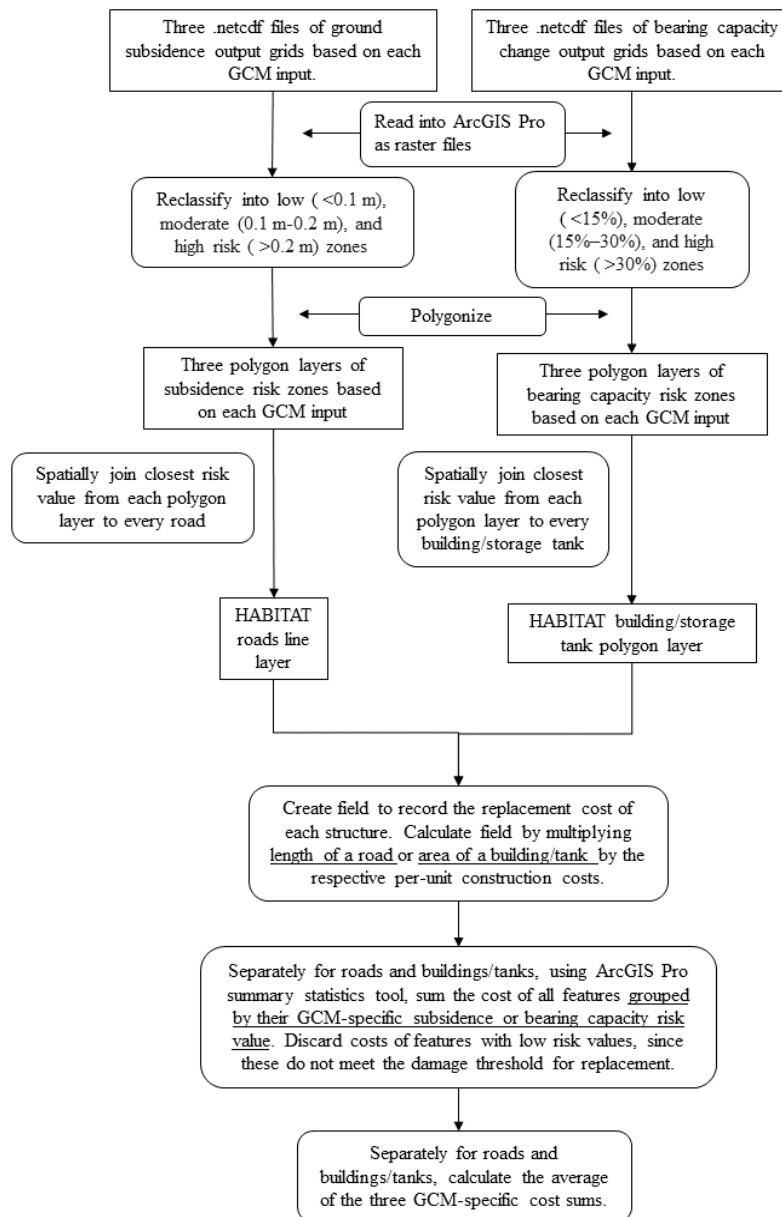
Supplementary Figure 9. Experimental shear stress values (psi) on a steel pile in silt from U.S. construction standard TM 5-852-4/AFM 88-19. These values can be compared to those prescribed in Russian standard SP 25.13330.2012 (in which a reduction factor of 0.7 is provided if a steel piling is used as opposed to cement) based on the curves in Supplementary Figure 8. The shear stress values given for low-organic clay/loam in SP 25.13330.2012 would theoretically be the closest to low-organic silt: At 25°F (-3.9°C), TM-5-852-4/AFM 88-19 prescribes a shear stress value of ~40 PSI (or ~2.8 kgf/cm²). In comparison, SP 25.13330.2012 prescribes a shear stress value of ~1.8 kgf/cm² for low-organic clay/loam (based on the 0.7 conversion factor for a steel piling). At 28°F (-2.2°C), TM-5-852-4/AFM 88-19 prescribes ~1.96 kgf/cm² and SP 25.13330.2012 prescribes ~1.26 kgf/cm². Furthermore, for a steel pile in sand, as opposed to silt, at -3.9°C, TM-5-852-4/AFM 88-19 prescribes ~4.2 kgf/cm² (using a conversion factor of 1.5 provided by TM 5-852-4/AFM 88-19) and SP 25.13330.2012 prescribes ~2.5 kgf/cm². At 28°F (-2.2°C), TM-5-852-4/AFM 88-19 prescribes ~2.9 kgf/cm² and SP 25.13330.2012 prescribes ~1.8 kgf/cm².



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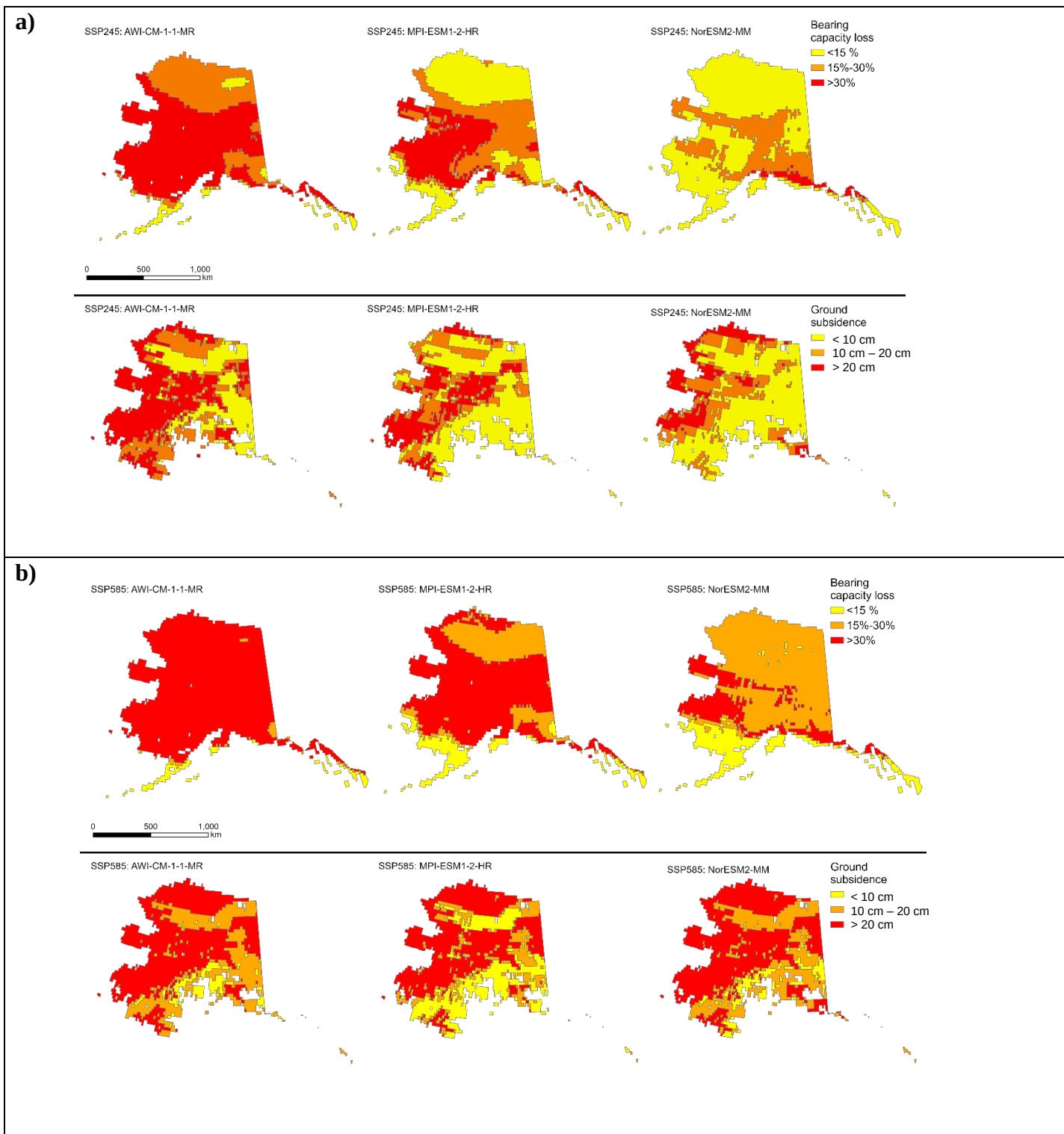
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Supplementary Figure 11. GIS workflow for infrastructure damage cost estimation. The following workflow was performed in the ArcGIS Pro software to estimate the costs associated with building and road damages from bearing capacity loss and ground subsidence.

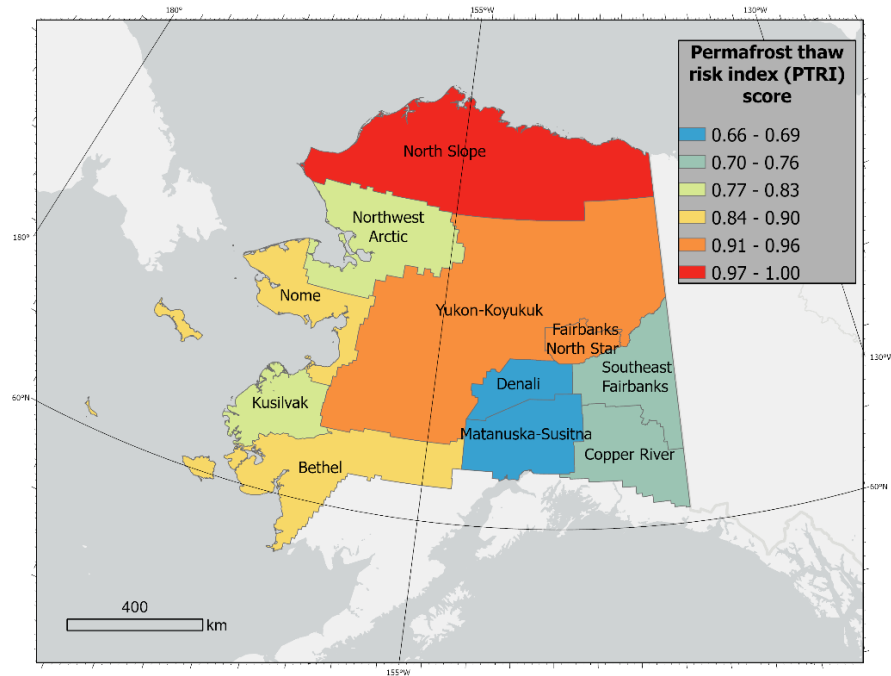
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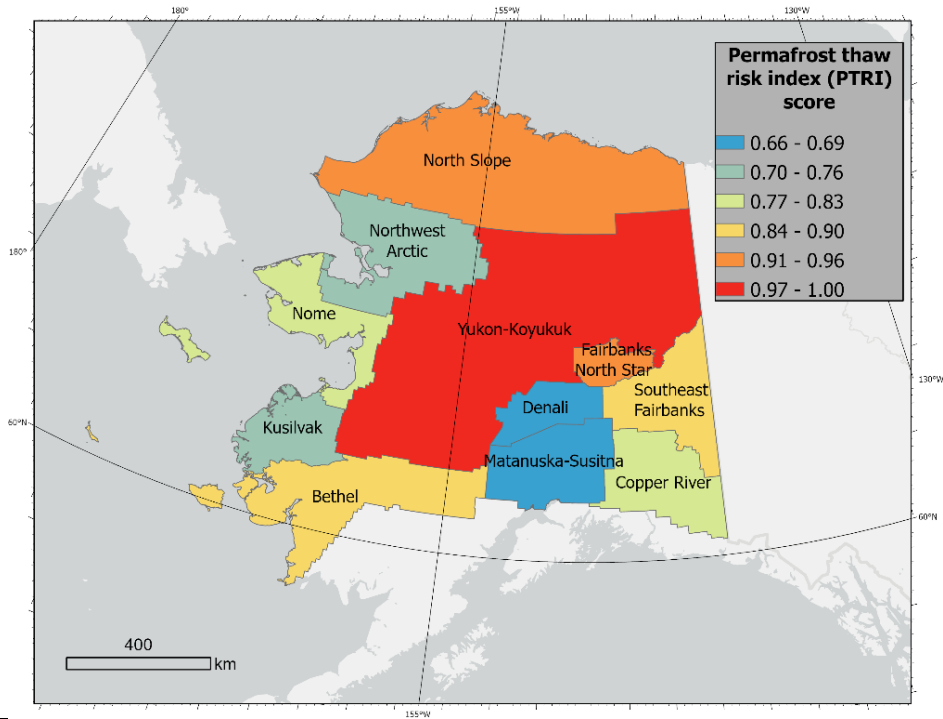


Supplementary Figure 12. Bearing capacity loss and ground subsidence mapped by the permafrost geotechnical model. Maps show bearing capacity loss and ground subsidence grouped in low (yellow), moderate (orange), and high risk (red) classes based on the **(a)** SSP245 and **(b)** SSP585 scenarios. If buildings and roads fall within moderate-high risk zones, they are considered to be damaged beyond repair and require replacement.

a)

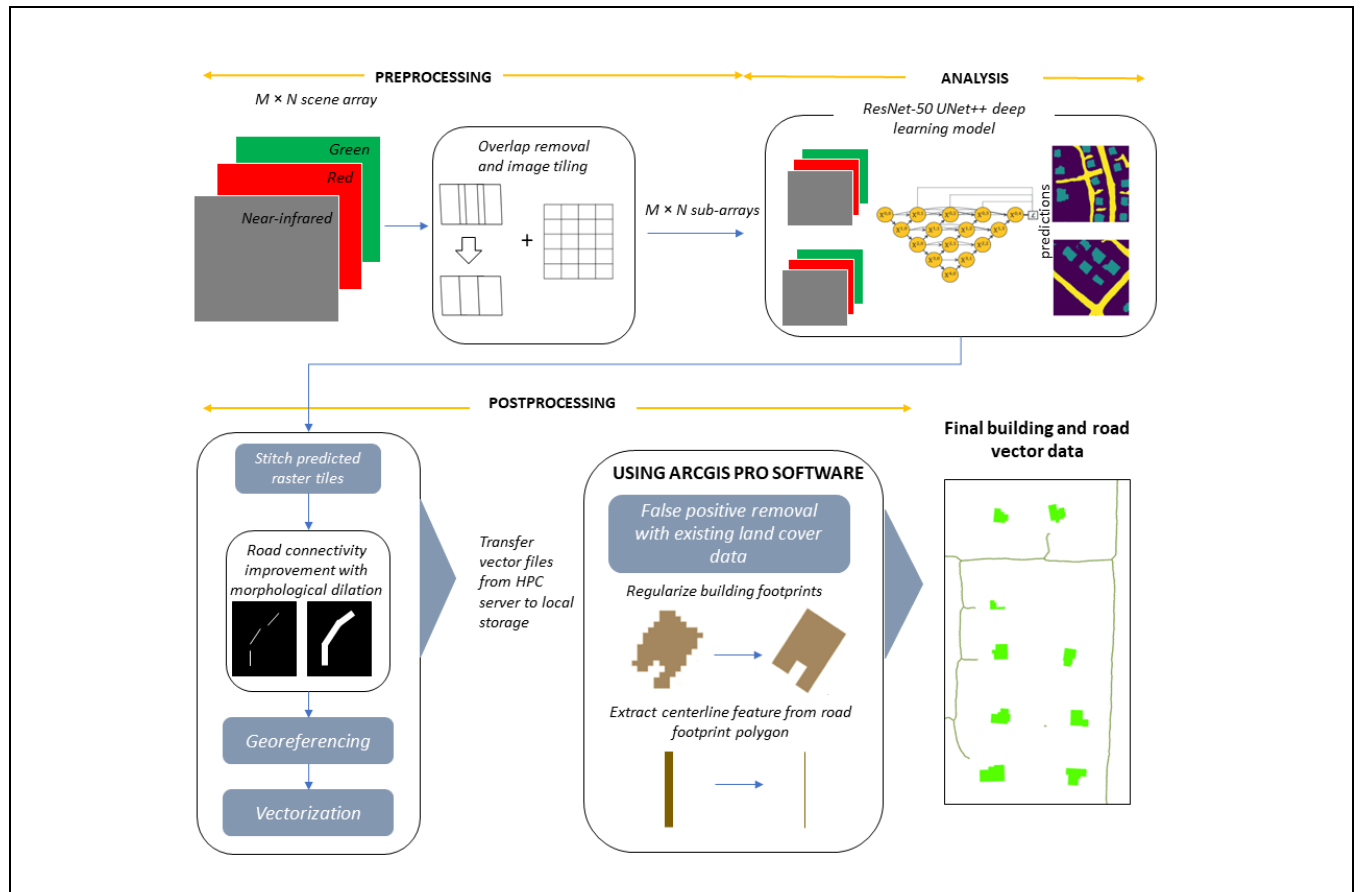


b)



Supplementary Figure 13. Permafrost thaw risk index (PTRI) scores. PTRI scores are given for the (a) SSP245 and (b) SSP585 climate scenarios. PTRI scores are computed for each county under each scenario by multiplying expected cumulative building and road damage costs between 2015-2064 by a county's community risk factor. This score is a state percentile ranking for a given county in comparison to all other counties. Under SSP245, North Slope Borough has the highest PTRI score, having higher risk to permafrost thaw than all other counties. Under SSP585, Yukon-Koyukuk Census Area has the highest PTRI score.

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Supplementary Figure 14. Diagram of the full HABITAT workflow. This consists of a pre-processing stage in which satellite images are cropped to remove overlapping areas and split into smaller tiles that are input to the CNN model. In the analysis stage, the model outputs predicted masks containing detected infrastructure. In the post-processing stage, these predicted mask tiles are stitched into a larger image mask with the same dimensions as the input satellite image scene. The image mask is then vectorized to produce shapefiles containing polygon footprints of detected features. These shapefiles undergo further post-processing in the ArcGIS Pro software to remove false positives, regularize building footprints, and extract road centerlines.

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Supplementary Table 1. Peer-reviewed studies that have estimated monetary losses of infrastructure damage caused by projected permafrost thaw hazards in Alaska.

Reference	Study area	Infrastructure focus	Geospatial infrastructure inventory	Findings (costs adjusted for inflation to USD 2024)
Larsen et al. ¹⁴	Alaska	Public infrastructure (e.g., airports, bridges, defense facilities, emergency services, energy, healthcare, railroads, roads)	Publicly owned structures and their costs (USD 2006) were compiled from public sources (e.g., the Alaska State Office of Risk Management, Denali Commission).	Climate change (including other hazards besides permafrost thaw) could add \$5.6–\$9.5B (+10% to +20% above normal wear and tear) to future costs for public infrastructure from now to 2030 and \$8.7–\$11.8B (+10% to +12%) from now to 2080.
Melvin et al. ¹⁵	Alaska	Publicly owned roads, airports, buildings, railroads, and pipelines	Publicly owned structures and their costs (USD 2015) were compiled from numerous public sources including State of Alaska and national geospatial datasets	Cost of permafrost thaw damage to infrastructure without adaptation measures from 2015 to 2099 will total \$2.1B for RCP4.5 and \$2.8B for RCP8.5.
Suter et al. ¹⁶	Pan-Arctic	Roads, railroads, pipelines, airports/ports, buildings	Public sources of governmental geodata were used to compile a pan-Arctic infrastructure inventory. Costs were based on (Larsen et al., 2008) and adjusted to USD 2017. Only publicly owned Alaskan infrastructure is considered.	Cost of damaged infrastructure across the entire Arctic is \$27.7B by 2059 under RCP8.5. An estimated 22% of total assets will be affected in Alaska. Damages in Alaska amount to \$4.5B.

Streletskiy et al. ¹⁷	Pan-Arctic	Roads, railroads, runways, buildings	OpenStreetMap data was used to compile a pan-Arctic inventory. Country-specific costs (USD 2020) for each infrastructure type were calculated by averaging several sources.	Under SSP245, 29% of roads, 23% of railroads, and 11% of buildings will be affected, costing \$221B by 2055-2064. Under SSP585, 44% of roads, 34% of railroads, and 17% of buildings will be affected with estimated cost of \$335B. Damages in Alaska amount to \$17.2B under SSP245 and \$29.7B under SSP585 by 2055-2064.
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Supplementary Table 2. Literature survey on satellite-based Arctic built infrastructure mapping efforts.					
Reference	Study Area	Data	Spatial Resolution (in Order of Listed Data, “Field Survey” Omitted)	Method	Feature(s) of Interest
Kumpula et al. (2006) ⁵	Bovanenkovo gas field, Yamal Peninsula (West Siberia)	Field survey, QuickBird-2 (panchromatic, multispectral), ASTER VNIR, Landsat (TM, MSS)	0.61 m, 2.5 m, 15 m, 30 m, 80 m	Manual digitization	Quarries, power lines, roads, winter roads, drill towers, barracks
Kumpula et al. (2010) ⁶	Bovanenkovo gas field, Yamal Peninsula (West Siberia)	Field survey, QuickBird-2 (pan, multi), ASTER VNIR, SPOT (pan, multi), Landsat (ETM7, TM, MSS)	0.63 m, 2.4 m, 15 m, 10 m, 20 m, 30 m, 30 m, 80 m	Manual digitization	Roads, impervious cover, barracks, winter roads, settlements, quarries
Kumpula et al. (2011) ⁷	Bovanenkovo gas field and Toravei oil	Field survey, QuickBird-2 (pan, multi), ASTER VNIR, SPOT	0.63 m, 2.4 m, 15 m, 10 m, 20 m, 30 m, 30 m	Manual digitization	Buildings, roads, sand quarries, pipelines

	field, Yamal Peninsula (West Siberia)	(multi), Landsat (ETM7, TM, MSS)			
Kumpula et al. (2012) ⁸	Bovanenkovo gas field, Yamal Peninsula (West Siberia)	Field survey, QuickBird-2 (pan, multi), GeoEye, ASTER VNIR, SPOT (multi), Landsat (ETM7, TM, MSS)	0.63 m, 2.4 m, 1.65 m, 15 m, 20 m, 30 m, 30 m, 70 m	Manual digitization	Pipelines, powerlines, drilling towers, roads, impervious cover, barracks, settlements, quarries
Raynolds et al. (2014) ⁹	Prudhoe Bay Oilfield, Alaska	Aerial photography (B&W, color, color infrared)	1 ft resolution for two images. Map scale was then used to describe the rest of the imagery. Scales are as follows: 1:3000, 1:6000, 1:12,000, 1:18,000, 1:24,000, 1:60,000, 1:68,000, 1:120,000	Manual digitization	Roads, gravel pads, excavations, pipelines, powerlines, fences, canals, gravel and construction debris
Gadal and Ouerghemmi (2019) ¹⁰	Yakutsk, Russia	SPOT-6 (pan, multi), Sentinel-2 (multi)	1.5 m, 6 m, 10 m	Semi-automated (object-based image analysis)	Houses, other structures
Ourng et al. (2019) ¹¹	Surgut, Russia	Sentinel-1 (SAR), Sentinel-2 (multi), Landsat (TM, MSS)	10 m, 10 m, 30 m, 60 m	Automated (machine learning)	Built-up area
Bartsch et al. (2020) ¹²	Pan-Arctic, within 100	Sentinel-1 (SAR) and Sentinel-2 (multi)	10 m, 10 m	Automated (machine learning and	Buildings, roads, other human-

	km of the Arctic coast			deep learning)	impacted areas
Ardelean et al. (2020) ¹³	Bovanenkovo gas field, Yamal Peninsula (West Siberia)	QuickBird-2 (pan, multi), GeoEye-1 (pan, multi)	0.6 m, 2.4 m, 0.4 m, 1.8 m	Manual digitization	Buildings, roads
Manos et al. (2022) ¹⁴	North Slope of Alaska	WorldView-2, QuickBird-2	0.5 m – 0.87 m	Automated (deep learning)	Buildings (public, commercial, residential, industrial, roads)

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Supplementary Table 3. Projected average, minimum, and maximum area/length and damage costs of buildings and roads in Alaskan discontinuous and continuous permafrost regions at risk of bearing capacity loss and ground subsidence between the decades 2015-2024 and 2055-2064. Calculations are based on the AWI-CM-1-1-MR, MPI-ESM1-2-HR, and NorESM2-MM global climate models analyzed under the SSP245 and SSP585 scenarios.									
	Total infrastructure			Area/length at risk			Cost of replacement (billion USD 2024)		
	Statewide	Within discontinuous/continuous permafrost		Mean	Min	Max	Mean	Min	Max
Buildings	53M m ²	13M m ²							
			SSP 245	10.36M m ²	8.08M m ²	12.31M m ²	12.99	9.23	16.37
			SSP 585	12.15M m ²	12.05M m ²	12.31M m ²	16.06	15.88	16.37
Roads	50,477 km	32,628 km							

			SSP 245	18,397 km	13,244 km	23,981 km	24.22	22.96	30.34
			SSP 585	28,499 km	25,666 km	30,083 km	35.30	32.15	36.99
					Total costs	SSP245	37.21	32.19	46.71
						SSP585	51.36	48.03	53.36

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Supplementary Table 4. Normal stress (R) at the bottom of the pile as a function of soil texture, peat presence, and temperature at pile depth.		
Soil texture	Organic matter coef. (K_v)	Normal stress at the base of pile (R , kgf/cm ²)
Sand	0.00-0.03	$R = -0.046T_m^2 - 4.217T_m + 16.18$ (1)
Sand	0.03-0.10	$R = -0.156T_m^2 - 3.48T_m - 0.37$ (2)
Sand	0.10-0.30	$R = -0.110T_m^2 - 2.39T_m - 0.08$ (3)
Sand	0.30-0.50	$R = -0.090T_m^2 - 1.85T_m - 0.12$ (4)
Loam and Clay	0.00-0.05	$R = -0.012T_m^2 - 2.373T_m + 7.44$ (5)
Loam and Clay	0.05-0.10	$R = -0.132T_m^2 - 2.80T_m - 0.23$ (6)
Loam and Clay	0.10-0.30	$R = -0.105T_m^2 - 2.09T_m - 0.17$ (7)
Loam and Clay	0.30-0.50	$R = -0.089T_m^2 - 1.74T_m - 0.31$ (8)
Peat	>0.50	$R = -0.071T_m^2 - 1.40T_m - 0.39$ (9)

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Supplementary Table 5. Shear stress (R_{af}) at the middle of the pile in permafrost with low ice content (<20%) as a function of soil texture, peat presence and equivalent temperature.		
Soil texture	Organic matter coef. (K_v)	Shear stress at a side contact of pile with frozen ground with low ice content (R_{af} , kgf/cm ²)
Sand	0.00-0.03	$R_{af} = -0.039T_e^2 - 0.828T_e + 0.43$
Sand	0.03-0.10	$R_{af} = -0.020T_e^2 - 0.470T_e + 0.43$ (2)
Sand	0.10-0.30	$R_{af} = -0.019T_e^2 - 0.412T_e + 0.16$ (3)
Sand	0.30-0.50	$R_{af} = -0.015T_e^2 - 0.326T_e + 0.12$ (4)

Loam and Clay	0.00-0.05	$R_{af} = -0.032T_e^2 - 0.655T_e + 0.32$ (5)
Loam and Clay	0.05-0.10	$R_{af} = -0.020T_e^2 - 0.443T_e + 0.16$ (6)
Loam and Clay	0.10-0.30	$R_{af} = -0.016T_e^2 - 0.334T_e + 0.02$ (7)
Loam and Clay	0.30-0.50	$R_{af} = -0.015T_e^2 - 0.310T_e - 0.06$ (8)
Peat	>0.50	$R_{af} = -0.015T_e^2 - 0.300T_e - 0.11$ (9)

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Supplementary Table 6. Shear stress (R_{sh}) at the middle of the pile with cement solution in permafrost with high ice content (>20%) as a function of soil texture, peat presence and equivalent temperature.		
Soil texture	Organic matter coef. (K_v)	Shear stress at a side contact of pile with frozen ground with high ice content (R_{sh} , kgf/cm ²)
Sand	0.00-0.03	$R_{sh} = -0.035T_e^2 - 0.793T_e + 0.85$
Sand	0.03-0.10	$R_{sh} = -0.048T_e^2 - 0.791T_e + 0.23$
Sand	0.10-0.30	$R_{sh} = -0.026T_e^2 - 0.505T_e + 0.05$
Sand	0.30-0.50	$R_{sh} = -0.018T_e^2 - 0.377T_e + 0.05$
Loam and Clay	0.00-0.05	$R_{sh} = -0.028T_e^2 - 0.599T_e + 0.54$
Loam and Clay	0.05-0.10	$R_{sh} = -0.025T_e^2 - 0.531T_e + 0.14$
Loam and Clay	0.10-0.30	$R_{sh} = -0.020T_e^2 - 0.404T_e - 0.02$
Peat	>0.50	$R_{sh} = -0.015T_e^2 - 0.314T_e - 0.08$
Ice	-	$R_{sh} = 0.324\ln(-T_e) + 0.17$

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Supplementary Table 7. Per unit infrastructure construction costs (USD 2024) averaged from government, public, commercial, and local information across the Arctic from Streletskiy et al.	
Infrastructure type (measurement unit)	Cost per unit (\$)
Buildings/tanks (m ²)	2,107
Roads (km)	1,998,617

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Supplementary Results

Permafrost thaw risk index

Considering the five highest PTRI scores under the SSP245 scenario, North Slope Borough has a PTRI score of 1, indicating that its communities have higher risk to permafrost thaw hazards than those in all other boroughs or census areas, followed by Fairbanks North Star Borough with 0.96, Yukon-Koyukuk Census Area with 0.93, Bethel Census Area with 0.90, and Nome Census Area with 0.86 (Supplementary Fig. 13a). Considering the five highest PTRI scores under the SSP585 scenario, Yukon-Koyukuk Census Area has a PTRI score of 1, followed by North Slope Borough with 0.96, Fairbanks North Star with 0.93, Southeast Fairbanks Census Area with 0.90, and Bethel Census Area with 0.86 (Supplementary Fig. 13b). For both climate scenarios, Matanuska-Susitna Borough and Denali Borough have the lowest PTRI scores out of those counties that are subject to permafrost thaw hazards between 2015-2064, receiving 0.69 and 0.65 respectively. For details regarding the PTRI calculation, see *Permafrost thaw risk index*.

Supplementary Discussion

Permafrost Thaw Risk Index

In a January 2024 report outlining the needs of Alaskan native villages threatened by environmental hazards, the Alaska Native Tribal Health Consortium and the State of Alaska stated that few communities have completed or started site-specific erosion, flooding, or permafrost risk assessments needed to assess unmet funding needs for hazard adaptation and mitigation projects¹⁵. Community-specific risk assessments provide vital information needed to meet the requirements of many funding programs, such as FEMA's Hazard Mitigation Assistance programs. However, these assessments are costly to perform, and most existing risk

datasets or assessments developed for the contiguous U.S. (e.g., FEMA's National Risk Index) do not account for hazards specific to Alaskan communities, such as permafrost thaw¹⁵. These gaps are highlighted when comparing the results of the PTRI to the NRI scores for Alaska. For the entire state of Alaska, the NRI estimates expected annual building losses of \$157M due to various hazards not directly related to permafrost thaw¹⁶. This would amount to cumulative building losses of \$8B over fifty years (assuming the annual loss does not change), which is the period of time over which we estimated building losses in this study. Compared to this study's estimate of \$37B -\$51B of building losses due to permafrost thaw, it is clear that the NRI is largely underestimating disaster risk in Alaska by not including permafrost thaw hazards. Also, the NRI identifies Matanuska-Susitna Borough, Anchorage Municipality, and Kenai Peninsula Borough as having the highest risk scores out of all counties in Alaska¹⁶. This risk is mostly attributed to hazards such as earthquake, tsunami, avalanche, and wildfire. Comparatively, Matanuska-Susitna has a PTRI score of 0.69, and Anchorage and Kenai Peninsula are not even located on continuous or discontinuous permafrost. Ultimately, the lack of permafrost thaw hazard occurrence data likely makes including permafrost thaw hazards in the NRI currently unfeasible¹⁷.

Supplementary Methods

Permafrost geotechnical model

Spatial equilibrium permafrost model

To calculate potential bearing capacity loss and the amount of ground subsidence, PT (permafrost temperature) and ALT (active layer thickness) are first estimated by the spatial equilibrium permafrost model developed by Streletskiy et al. (2012)¹⁸, which is based on the Kudryavstev solution of Stephan's problem of heat conduction in a porous medium with phase transition. The model was validated by earlier publications at varying scales, including at the

landscape scale for sites representative of generalized landcover categories on the North Slope of Alaska¹⁹. The model is driven by daily climatic data (air temperature and precipitation), surface characteristics (vegetation and snow), and subsurface properties (organic and mineral soil). Daily surface air temperature and precipitation were calculated for the 2015-2024 (baseline) and the 2055–2064 (future) periods from a subset of three selected global climate models (GCMs) from the Coupled Model Intercomparison Project 6 (CMIP6). These time periods were selected in order to represent the typical lifespan of Arctic infrastructure. The chosen GCMs were 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). These GCMs represent ‘warm’, ‘moderate’, and ‘cold’ climatic projections, respectively, and are chosen due to their ability to reproduce historical temperature trends in the Arctic²⁰. Each GCM was analyzed via the shared socioeconomic pathway (SSP) 245 and 585 scenarios^{21,22}. SSP245 is a ‘middle-of-the-road’ pathway that represents the lower limit of climate change that can be realistically attained by mid-century. This includes moderate challenges to mitigation and adaptation. SSP585 involves a high greenhouse gas emissions scenario with accelerated warming, creating significant mitigation challenges but conversely lower adaptation challenges. Considering political trends, observed patterns of socioeconomic development and climate change, the SSP585 scenario is likely to occur²³.

Pile bearing capacity estimation

In the approach developed by Streletskiy et al. (2012)¹⁸, the capacity of permafrost-affected ground to bear square cement piling foundations ($0.35 \times 0.35 \times 10$ m) with vertically loaded friction piles is calculated as the sum of normal stresses at the base of the pile and shear stress at the pile sides in contact with permafrost. This calculation is a function of PT and ALT. The

model was previously used to calculate pile bearing capacity changes on the North Slope of Alaska and was shown to be effective at facilitating the general depiction of locations where changes in bearing capacity can create hazardous conditions¹⁸. To spatially assess the impact of pile bearing capacity changes across Alaskan permafrost, we have assumed that all buildings are constructed with this piling foundation (such was also assumed in various similar studies^{3,4,24,25}). Most buildings on the North Slope and northwest coast of Alaska, and many in southwestern Alaska and interior rural communities, are indeed constructed on pilings²⁶. This ‘passive principle of permafrost construction’ aims to maintain thermal stability of the underlying ground across the lifespan of the building by disconnecting the building from the ground²⁷. As defined in Russian standard SP 25.13330.2012, “Basements and Foundations on Permafrost”²⁸, equation 1 is used to calculate bearing capacity for vertically loaded friction piles in permafrost with low ice content and equation 2 for high ice content.

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

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

In both equations, 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); n is the number of different layers of permafrost in contact with the pile; i_j is ice content of the j th layer; 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). In equation 1, $R_{af,i}$ 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). In equation 2, $R_{sh,j}$ and $R_{sh,i,j}$ are shear

stresses on a pile with special cement solution at a side contact for the j th layer (kPa); and $A_{sh,j}$ is the area of side contact of pile with ground in layer j (m^2).

Experimental values of the normal (R) and shear stresses ($R_{af,i}$, $R_{sh,j}$, and $R_{sh,i,j}$) on a friction pile in varying soils (clay, loam, and sand with varying levels of organic content, as well as peat), ground temperatures (-10°C to 0°C), and ground ice content ($<20\%$ and $>20\%$) are prescribed in Russian standard SP 25.13330.2012²⁸. These are implemented as a series of polynomial equations, each for a specific soil composition and ground ice content, in which stress (given in kgf/cm^2) is calculated based on ground temperature (given in $^\circ\text{C}$). These equations and their outputs, as adopted from Streletskiy et al. (2012)¹⁸ and Streletskiy (2010)²⁹, are given in Supplementary Figures 8 and 9. The stress values used to calculate bearing capacity thus depend on PT, while $A_{af,i}$ and $A_{sh,j}$ depend on the ALT. The amount of stress on the piles will be highest when PT is low and ALT is low. If PT increases, the soil cohesion decreases, and the ground is less able to keep the pile in place. As ALT increases, the surface area where the pile can bond to the frozen soil decreases, also decreasing F_u .

The U.S. Army and Air Force Technical Manual TM 5-852-4/AFM 88-19, Chap. 4, “Arctic and Subarctic Construction, Foundations for Structures”³⁰ provides experimental values of stress for 5 to 6-meter-long steel pilings in low-organic silt, with conversion factors for sand, as well as other pile types (Supplementary Figure 9). The Russian standard suggests more conservative values of shear stress compared to the American standard, which in turn likely results in overly conservative bearing capacity estimates when applied to Alaskan construction. The American standard also emphasizes higher design factors of safety for geotechnical applications than those implemented in Russia, as suggested by Streletskiy et al. (2012)¹⁸, which could justify the more conservative values assigned for cohesion in Russian standards. Ideally, pile bearing capacity for

Alaskan buildings should be computed using stress values prescribed for piling foundations of American design. However, the values prescribed in Russian standard SP 25.13330.2012 cover a wider range of ground temperatures, ground ice content, and soil composition. For example, TM-5-852-4/AFM 88-19 only considers temperatures down to 25°F, or -3.9°C, which does not provide enough information to accurately calculate pile bearing capacity for regions such as the North Slope where temperatures can be lower³¹. It also does not consider variation in ground ice content, which varies considerably across Alaska³².

Ground subsidence estimation

In the approach of Streletskiy et al. (2012)¹⁸, the amount of ground subsidence is calculated with the settlement index³³, which is a function of changes in ALT (ΔALT) and ground ice content (V_{ice}).

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

Ground ice content was obtained from the Arctic Map of Permafrost and Ground-Ice Conditions: version 2³⁴. The permafrost map classifies ground ice as low, medium, or high. These zones are assigned quantitative ground ice volume values of 10%, 20%, and 40%, based on the ranges established by Brown et al.³⁴.

Model outputs

For each of the two SSP scenarios, three GCM-specific estimates of bearing capacity loss and ground subsidence between the baseline and future periods were produced using PT and ALT estimated from the permafrost model using each GCM. Therefore, there are a total of twelve bearing capacity loss and ground subsidence maps. NetCDF grids covering the circumpolar permafrost region were output by the model and clipped to the Alaska state boundary.

Permafrost thaw risk index

We extend the U.S. Federal Emergency Management Agency's National Risk Index (NRI) to the two permafrost thaw hazards considered in this study, that is, bearing capacity loss and ground subsidence. In this section, the NRI equation and each component is briefly described. For a detailed technical explanation, please see the technical documentation¹⁶ and the associated study which presents the methodology¹⁷. The NRI measures the risk of every U.S. census tract and county to 18 natural hazards (not including permafrost-related hazards) through the following equation:

$$Risk = Expected Annual Loss \times Community Risk \quad (4)$$

$$where Community Risk Factor = f\left(\frac{Social Vulnerability}{Community Resilience}\right)$$

The function $f(\cdot)$ is a transformation that maps the ratio of social vulnerability and community resilience to a triangular distribution which ensures that higher social vulnerability and lower community resilience, relative to all other counties or census tracts, result in higher NRI values for a given level of expected annual loss. The expected annual loss (EAL), quantified as a dollar amount, for each census tract or county is the average economic loss in dollars resulting from 18 natural hazards each year. EAL is computed for each hazard type and only quantifies loss for consequence types (i.e., buildings, population, or agriculture) relevant to a given hazard. This component determines the expected consequence of a given hazard. However, we replace the expected annual losses from the 18 considered hazard types with our estimated cumulative building and road damage costs due to bearing capacity loss and ground subsidence between 2015-2024 and 2055-2064. We name this modified version of the NRI the *permafrost thaw risk index* (PTRI).

The community risk factor (CRF) determines the degree to which the expected consequence will be enhanced or reduced, depending on the ratio of social vulnerability to community resilience. In the NRI, the social vulnerability score is a consequence-enhancing factor that represents the national percentile ranking of social vulnerability for a given county or census tract in comparison to all other counties or census tracts. A higher social vulnerability score results in a higher NRI score. This component uses the U.S. Center for Disease Control and Prevention's Social Vulnerability Index (CDC SVI), which utilizes 16 socioeconomic variables deemed to contribute to a community's reduced ability to prepare for, respond to, and recover from hazards³⁵. The community resilience score is a consequence-reducing factor that represents the relative level of community resilience within a county or census tract in comparison to all other counties or census tracts. A higher community resilience score results in a lower NRI score. This component uses the University of South Carolina Hazards Vulnerability & Resilience Institute's Baseline Resilience Indicators for Communities (HVRI BRIC)³⁶. The HVRI BRIC quantifies community resilience by identifying the ability of a community to prepare and plan for, absorb, recover from, and more successfully adapt to the impacts of natural hazards. It is based on a set of 49 indicators that represent six categories of resilience: social, economic, community capital, institutional capacity, housing/infrastructure, and environmental.

Based on the NRI equation, we compute the PTRI by multiplying estimated total (not normalized by population) building and road damage costs for all thirty Alaskan counties by their corresponding CRF as given by the NRI dataset. Then we compute the percentile rank of each county's raw PTRI value to produce the PTRI score. Therefore, the final PTRI score is a state percentile ranking for a given county in comparison to all other Alaskan counties. This is done for both SSP245 and SSP585-derived damage cost estimates.

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