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Permafrost and Road Degradation in Alaska

Juliana M. McMillan-Wilhoit, Heidi R. Howard, and Kate A. Morozova

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Permafrost and Road Degradation in Alaska

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Permafrost Thaw”

Abstract

Permafrost is rock, soil, or sediment that stays below 0 C for at least 2 consecutive years. About a quarter of the northern hemisphere's land mass is permafrost, and Alaska may be 85% permafrost. Permafrost is degrading. Uneven thaw is expected to significantly add to the current costs of road, pipeline, and airport maintenance over the next 20 years in Alaska. In the Arctic, permafrost degradation may impact training activities and increase operations and maintenance costs annually at U.S. Army installations. This work outlines a methodology to predict the probability that local infrastructure will incur damage (i.e., if a road will crack) based on the probability that the infrastructure was built on a permafrost location.

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Preface

This study was conducted for Office of the Assistant Secretary of the Army for Acquisition, Logistics, and Technology, ASA(ALT) under Program Element 622720896, “Base Facility Environmental Quality,” Work Package “Infrastructure Planning in an Arctic Domain: Mitigating the Effects of Permafrost Thaw.” The technical monitor was Alan B. Anderson, CEERD-CZT.

The work was performed by the Energy Branch (CFE) and the Ecological Processes Branch (CNN) of the Installations Division (CN), Construction Engineering Research Laboratory (ERDC-CERL). At the time of publication, Giselle Rodriguez was Chief, CEERD-CFE and Dr. Chris Rewerts was Chief, CEERD-CNN; Donald Hicks was Chief, CEERD-CN and CEERD-CF; and Alan Anderson was Technical Director, CEERD-CZT. The Interim Deputy Director of ERDC-CERL was Michelle Hanson and the Interim Director was Dr. Kirankumar V. Topudurti.

COL Bryan S. Green was Commander of ERDC, and Dr. David W. Pittman was the Director.

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1 Introduction

1.1 Background

Permafrost is rock, soil, or sediment that stays below 0 °C for at least 2 consecutive years. About a quarter of the northern hemisphere's land mass is permafrost, and Alaska may be 85% permafrost. However, due to many factors, permafrost is degrading. In areas near Alaska's coast, for example, permafrost has warmed 6 to 8 °F at a 3.3-ft depth since the mid-1980s (Romanovsky et al. 2008).

Degradation of permafrost represents a significant concern for the U.S. Army because permafrost thaw results in substantial changes in the geo-ecological system. To maintain an active fighting force into the future, the U.S. Army depends on its ability to train soldiers across a variety of environments, including areas characterized by permafrost. At installations in the Arctic, permafrost degradation may compromise training activities and increase annual operations and maintenance (O&M) costs. For example, the National Climate Assessment (NCADAC 2014) estimates that uneven thaw over the next 20 years in Alaska will add \$3.6 to \$6.1 billion (10-20%) to the current costs of road, pipeline, and airport maintenance (Larsen et al. 2008). The melting of ground ice can cause the development of thermokarst lakes, which can lead to subsidence (Figure 1). Even some routine activities can further contribute to irreparable damage to permafrost. Figure 2 shows an area in Storkerson Point, AK where a driven vehicle compacted soil (left) such that 5 years later (right), the resulting thermokarst depression disturbed the tundra so that water now collects in the ruts (Dublin et al. 2001, p 25).

Because permafrost is a subsurface phenomenon, it is difficult to know where permafrost is located, and whether its degradation will impact infrastructure built on a given location. Moreover, as temperature increases continue to degrade permafrost, the ability to estimate the location of permafrost and its impacts on infrastructure will become increasingly important to avoid future increases in O&M costs associated with permafrost degradation. This work was undertaken to outline a methodology to predict the probability that damage will occur to local infrastructure based on the probability that the infrastructure was built on permafrost.

Figure 1. A graphic from the 2014 National Climate Assessment illustrates some of the expenses resulting from permafrost thaw as well as the hazards from thawing permafrost.

Figure 2. Graphic demonstrating road marks left on permafrost and the degradation at Storkerson Point, AK.

Source: Dublin et al. 2001, 25

1.2 Objective

The objective of this work was to outline a methodology to predict the probability that local infrastructure will incur damage (i.e., if a road will crack) based on the probability that the infrastructure was built on a permafrost location.

1.3 Scope

This assessment was based on data pertaining to a study area that includes most of Alaska, including the cities of Fairbanks, Nome, Barrow, and Kotzebue; and the following U.S. Department of Defense (DoD) installations: Fort Wainwright, Eielson Air Force Base, and Donnelley Training Area (Figure 3). It is anticipated that the methodology outlined in this report may be expanded and adapted to other areas where permafrost occurs.

Figure 3. Study area. Data had to cover the entirety of the study area to be included.

2 Permafrost

Permafrost is rock or soil that stays below 2 °C for 2 or more years. Permafrost often does not exist in areas with ground ice, but instead exists under a top soil layer that freezes and thaws annually called the “active layer.” The active layer thickness (ALT) varies by season, longitude, and moisture content. It can be less than 1 ft in wet, organic sediment to several feet in well-drained soil (Péwé 2018). Interspersed and below the permafrost layer are pockets of unfrozen soil called “taliks” (the bottom brown layer shown in Figure 4). Because the active layer insulates the permafrost, the ALT impacts the preservation of permafrost. Factors that cause the ALT to deepen often result in permafrost degradation.

Figure 4. Diagram of permafrost.

Source: Weather Underground (2018).

2.1 Challenges with permafrost Identification

Permafrost can be classified by its lateral continuity into two broad categories: continuous and discontinuous. In the continuous areas of the Arctic and northwest Alaska, permafrost is ubiquitous. It covers almost all the landscape except for under lakes and rivers that do not freeze solid in the winter. Discontinuous permafrost, on the other hand, includes patches of frost-free area that gradually increase in size as one travels south until near the per-

mafrost southern boundary, there are only small patches of permafrost. Figure 5 shows the distribution of continuous and discontinuous permafrost in the northern hemisphere. Note the change from continuous permafrost to discontinuous permafrost as one moves south. In areas with discontinuous permafrost, it can be challenging to identify permafrost locations.

Figure 5. Distribution of continuous and discontinuous permafrost in the northern hemisphere.

On this map, darker shades of purple indicate larger percentages of permanently frozen ground. Lighter purples, and the terms isolated and sporadic, refer to lower percentages of frozen ground.

Source: Map by Philippe Rekacewicz, UNEP/GRID-Arendal; data from International Permafrost Association, 1998. Circumpolar Active-Layer Permafrost System (CAPS), version 1.0.*

There are few landscape-scale assessments of permafrost locations in large part because permafrost is a subsurface condition. Most recent studies have focused on estimations and probabilistic modeling of permafrost location. For example the National Snow and Ice Data Center estimates discontinuous, sporadic, or isolated permafrost boundaries (Figure 5) (Brown et al. 2001).

There is a lack of more extensive maps because field research on permafrost is currently an expensive undertaking. Permafrost occurs in remote regions characterized by harsh climates, where research entails expensive logistics requiring air support. Moreover, there are currently few continuous datasets to support permafrost research (Groose 2015).

* United Nations Environment Programme (UNEP); Global Resource Information Database (GRID)

However, increases in computing ability have enabled scientists to apply machine learning techniques to estimate the locations of permafrost. Pastick (2015) provided a 30m resolution estimation of “near-surface” permafrost (those areas where it is within 1m of the surface), and an accompanying dataset. The dataset was developed through decision and regression tree approaches that statistically and spatially extend field observations using remotely sensed imagery, climatic data, and thematic maps of a wide range of surface and subsurface biophysical characteristics. The resultant data have global accuracy of 85% with lower accuracy at smaller scales. This dataset provides a fundamental starting point for future estimations of permafrost locations.

Olefeldt et al. (2016) performed another large scale estimation of permafrost location in northern circumpolar zones containing wetland, lakes, and thermokarst landscapes. The resulting dataset provides an areal estimate of permafrost locations in 2015. However, one of the limitations of the data is that they do not have consistent resolutions and they do not include all features. Similarly, Pastick et al. (2013) and Mishra and Riley (2012), respectively, applied machine learning to the estimation of active layer thickness for central Alaska, and to the organic-layer thickness across Alaska.

There is currently a push within the Arctic Community to better understand the co-dependent ecological characteristics that can assist with the identification of permafrost. A 2014 National Research Council focused on the remote assessment of permafrost. Their report states that “there are considerably more permafrost related ecological properties that can be observed with remote sensing methods than permafrost processes and properties” (NRC 2015, p 12). Through the course of their meeting they identified over 60 ecological features associated with permafrost. Many of these characteristics are difficult to map at the scale necessary for this project with the tools available. Below is a list of identified features:

- Active layer thickness
- Ground ice (volume and morphology)
- Snow characteristics (extent, water equivalent, depth, density, conductivity)
- Surface topography (static, macro-, and micro-)
- Longer-term surface subsidence
- Thermokarst distribution
- Surface water bodies (including dynamics, redistribution)

- Surficial geology-terrain units (including lithology, bedrock)
- Soil organic layer (thickness, moisture, conductivity)
- Land cover (including spectral vegetation indices)
- Vegetation structure and composition
- Methane (flux or concentration)
- Water vapor flux
- Carbon dioxide (flux or concentration)
- Land surface (skin) temperature
- Subsurface soil temperature
- Seasonal heave/subsidence
- Soil moisture
- Biomass (above ground).

These studies do not model ecological characteristics that exist alongside permafrost in nature, and that signal its potential degradation. For the purposes of the U.S. Army (infrastructure placement and planning), it is crucial to identify factors that lead to permafrost degradation and locations that are more likely to degrade. This research is working to fill that void by producing a scientific product that U.S. Army Range managers can use to identify areas that are more likely to degrade. To that end, this work further focused its literature review to answer three questions:

1. What are the landscape characteristics that are often indicators of the existence of permafrost?
2. What methods are used to measure those permafrost characteristics?
3. What are the characteristics that lead permafrost to change state?

2.2 Soil

Soil characteristics are strongly correlated with permafrost. Factors that are related to the soil organic layer (a layer of plant residues in relatively undecomposed form) and that are important to characterizing permafrost, are: thickness, moisture content, density, and texture. These factors relate to permafrost heave, thaw segmentation, and to its moisture-holding abilities (Farouki 1981).

The composition of the soil type can affect the ALT, which can range from less than 1 ft in wet organic sediment to several feet in well-drained soil (Péwé 2018). However, there is currently a research gap on how deepening of the active layer will occur on the landscape scale (NRC 2015).

Soil moisture is a significant factor in the surface energy balance, and a major factor in permafrost aggradation and degradation because of the thermal properties of water and ice (NRC 2015). Permafrost exerts a strong control on soil hydrologic conditions, since it acts as a barrier to vertical water flow and thereby supports perched water tables and saturated or near-saturated soils in the active layer. Isolated studies (Walvoord and Striegl 2007, Muskett and Romanovsky 2009) have demonstrated that increases in groundwater contributions to river base-flow have been attributed to permafrost. Precipitation has been demonstrated to be one of the key drivers in permafrost degradation (Lawrence et al. 2015). Conversely, reductions in soil moisture can increase precipitation as moisture transfers to the atmosphere. Additionally, soil moisture information is required to estimate the thermal properties of the ground required for permafrost modeling.

However, measuring soil moisture remotely requires sophisticated equipment. Synthetic Aperture Radar (SAR) instruments at the L-band and higher are suited for the estimation of soil and surface moisture to about 5 cm. SAR operating at the P-bands and below can penetrate to the 10s of centimeters to a meter. However, there are currently no P-band SAR in space, and the higher band SARs have only been used infrequently for soil moisture retrieval. This is a data acquisition issue. The National Aeronautics and Space Administration's (NASA's) Soil Moisture Active/ Passive (SMAP), which was launched at the end of 2015, is a combined radar-radiometer instrument with the goal of mapping soil moisture, including permafrost. The lowest resolution for SMAP products is 3 km (NSIDC 2017).

2.3 Climate

Climate is a key driver for the evolution of frozen landscapes. In the past, changes in climate have led to the creation of permafrost. More recently, changes are leading to its degradation.

2.3.1 Precipitation

While rates of precipitation on the Alaskan tundra is similar to that of deserts, precipitation is a source of moisture that is a driver for the evolution of permafrost and ground ice. Since water cannot penetrate permafrost, the active layer becomes saturated with water, resulting in wetlands or landscape features like pingos (Figure 6). Additional precipitation can damage the landscape. Flood events can wash away the top active layer,

thereby reducing the distance to the permafrost. Rainfall can cause this active layer to degrade or melt, which then affects the permafrost (Oht 2003). Moreover, the addition of liquid water when soil temperatures are between -6 and 0 °C significantly impacts soil temperatures as latent heat is released. Kokelj et al. (2015) analyzed LandSat Images from 1985-2011 in the Northwest Territory of Canada and found an increase in thaw slumps, which are slope failures resulting from thawing of ice-rich permafrost resulting from higher rainfall. They found that higher rainfall could intensify the slump activity and increase the slope-sediment cascade.

Figure 6. Photograph from 1985 of pingos, which are formed by water that is pushed upwards from the pressure of ice.

Source: Miller and Whitehead (1999).

There are a variety of ways to measure precipitation. Research summarized by the National Research Council (2014) found that there is a preference towards Quantitative Perception Estimates (QPEs). QPEs, which are generated by meteorological satellites, measure how much precipitation falls. QPE measurements work best for the contiguous United States and areas with precipitation that is solid or mixed. The newly (2014) launched Global Precipitation Mission by NASA is collecting precipitation data globally, including arctic areas. Currently precipitation estimates are available for 5 km grids (NASA 2017).

2.3.2 Snow

Another important characteristic for the evolution of permafrost is snow because of its insulating properties—however these properties can have varying results on the formation and survival of permafrost. As the winter

progresses and air temperature decreases while snow thicknesses increase with additional accumulation, snow begins to act as an insulator (Zhang 2005). In areas of continuous permafrost, seasonal snow cover can increase the mean annual ground and permafrost temperatures by several degrees (Zhang 2005). Autumn snowfall, because of its high albedo and solar elevation, has a cooling effect on the ground when the snow cover is relatively thin and air temperatures are around 0 °C. In particular, when snow depth increased in autumn rather than winter permafrost was more likely to degrade than if the snow fall occurred later. This is because the soil was not able to release as much heat before being insulated by the snow (Park et al. 2015). However, other research has found that in areas of discontinuous or sporadic permafrost, the absence of snow cover can contribute to permafrost formation (Tingjun Zhang 2005).

Studies in northern Quebec, Canada since the late 1950s have demonstrated a link between snow-fall and permafrost development (Zhang 2005). They found that deep snow cover prevents the development of permafrost even if the mean annual temperature is -4 °C. Other studies have demonstrated that discontinuous permafrost may develop if the snow depth is under 70 to 75 cm. For northern regions, researchers have had to rely on mapping snow-cover. Sensors with optical bands (like MODIS [Moderate Resolution Imaging Spectroradiometer]) can successfully map snow-covered areas at the 500-m pixel particularly in tree-less areas (Hall and Riggs 2007). However, because of the lack of landscape scale information on snow-depth is lacking. Seasonal totals on snow depth, density, data of first snow, and other factors are available for 1979-2012 as part of the SnowData project (LCC 2017). The SnowData project is the result of simulation modeling.

2.3.3 Air temperature

Air temperature and snow pack have been demonstrated in multiple studies to be the greatest climatic factors with an impact on permafrost thaw. Air temperature and warming trends have an impact on permafrost by causing soil temperatures to rise, resulting in an increase in the active layer thickness (Zhang and Stamnes 1998). The greatest initial impact of air temperature increases is on discontinuous permafrost. Discontinuous permafrost has a mean annual surface temperature that is typically warmer than -5 °C; in some parts of the Seward Peninsula this is -2 °C. Be-

cause of this higher temperature, discontinuous permafrost is more vulnerable to warming (Osterkamp 2005). Zhang and Stamnes (1998) demonstrated that changes in air temperature in Barrow, AK have a greater impact on permafrost temperature than seasonal snow cover.

2.3.4 Water temperature

Temperatures of water in lakes influences the development of taliks, thermal erosion, and can lead to surface permafrost degradation (Arp et al. 2010). New research is additionally showing how increases in water temperatures can increase the soil temperature surrounding the lake leading to permafrost thaw (Lawrence et al. 2015). Thermal sensors record the surface temperature for water features. Satellites like MODIS and AVHRR capture only the surface temperatures of the largest features, as they have a spatial resolution of ~1km, but capture data twice or more a day. While Landsat and ASTER have a better resolution of ~100, they have reduced sampling to about once a week. Assessing seasonal changes in water temperatures. The changes in the temperature of the water can result in the surface permafrost melting.

Table 1. Summary of climate factors and their impact on permafrost development.

Factor	Negative Impact on Permafrost	Positive Impact on Permafrost
Snow	Early HEAVY snow pack (Park et al. 2015) Deep snow-cover insulates the ground too much (over 75 cm)	Light Autumn Snowfall (allows the ground to cool)
Precipitation	Higher rainfall levels can result in permafrost thaw (particularly if it is on slopes) (Kokelj et al. 2015). Melts/ degrades the active layer (Oht 2003)	
Air Temperature	causing soil temperatures to rise, resulting in an increase in the active layer thickness (Zhang and Stamnes 1998)	
Water Temperature	Increased temperature leads to increased soil temperature and permafrost thaw (Lawrence et al. 2015).	

2.4 Vegetation

Almost all of the soils biological activity takes place in the active layer during the summer (Kelley, Epstein, and Walker 2004). While any factors (precipitation, soil type, temperature) impact the depth of the active layer

thaw, vegetation does have a strong impact. The surface vegetation can intercept incoming solar radiation and thereby insulate the soil. A latitudinal temperature gradient study in Alaska and Canada found that there is an interaction between temperature and vegetation to control the active layer thickness thaw. Using the Normalized Difference Vegetation Index (NDVI) as an indicator of vegetation, the researchers combined variables of temperature, active layer depth, and NDVI (vegetation). Their study found shallow thaw depths in areas two areas: (1) warmer temperatures but higher vegetation levels, and (2) colder areas with lower vegetation levels. The latter is because bare ground has less insulation abilities. The greatest thaw depth was seen in areas with moderate air temperature and moderate vegetation (Kelley, Epstein, and Walker 2004).

Researchers studying permafrost degradation in Northeast China used multiple years of LandSat imagery to map vegetation. The study found reductions in “greenness” (vegetation) to be linked to permafrost degradation (Guo et al. 2017). An additional study connected in boreal forests of Northwest Canada found a relationship between leaf area thickens and shallower ALT. While the reasons behind this are not fully known, the limited thaw is believed to be a result of the protection provided by the canopy (Fischer 2014).

Additionally, there are relationships between the necessary soil characteristics for vegetation to thrive and permafrost. White spruce, cottonwood, birch, and certain willows will live where there is approximately 4 ft of soil above the permafrost (Lawrence et al. 2015). Through an Ecological Land Survey approach, researches characterized the Donnelley Training Area and found some relationships between vegetation and permafrost (Jorgenson et al. 2001):

- White Spruce occurred on well-drained upland sites that lack permafrost. The white spruce was also present on waterlogged and dry, sunny slopes.
- Paperbirch grows best in soil free from shallow permafrost (Safford and Bjorkbom 1975). However, paperbirch saplings have been found to be in areas underlain with discontinuous permafrost and shallow thaw permafrost.
- The Black Spruce dominated areas in the study where there was near surface permafrost. Black spruce tend to have a permafrost thaw depth of 8-35 inches (Fryer 2014).

Table 2. Summary of vegetation factors and their impacts on permafrost

Factor	Negative Impact on Permafrost	Positive Impact on Permafrost
NDVI	The greatest thaw depth was seen in areas with moderate air temperature and moderate vegetation (Kelley, Epstein, and Walker 2004). Reduction in vegetation (greenness) linked to permafrost degradation (Guo et al. 2017)	Their study found shallow thaw depths in areas two areas—1) warmer temperatures but higher vegetation levels 2) colder areas with lower vegetation levels (Kelley, Epstein, and Walker 2004).
Leaf Area Thickness		Shallower ALT (thereby limiting thaw) linked to higher leaf area index (Fischer 2014).
Trees	White Spruce: White spruce occurs in well	Commonly, landscapes underlain by permafrost support open dwarf spruce forest or woodland and the trees are tipped in various directions as a result of frost heave.

2.5 Landscape characteristics

Surface topography affects permafrost (Table 3). South-facing slopes receive more incoming solar radiation than other slopes (particularly northern). As a result, the permafrost is generally thinner on south-facing slopes in areas with continuous permafrost and absent in discontinuous zones (Cote 2002). With high resolution historic surface elevation data, one can identify elevation changes that may signify areas where active thermokarst is occurring (Jones et al. 2012). Light Detection and Ranging (LiDAR) provides data on elevation in addition to information on vegetation canopies. The high resolution of the produced datasets can be used in change detection.

Table 3. Surface topography effects on permafrost.

Factor	Negative Impact on Permafrost	Positive Impact on Permafrost
North-facing slopes		Permafrost is more likely to occur on a north-facing slope. (Viereck, Van Cleve, and Dyrness 1986; Williams 1970).
Valley Bottoms		Permafrost is more likely to occur on valley bottoms (Viereck, Van Cleve, and Dyrness 1986; Williams 1970).

2.5.1 Ice wedges

Remote Sensing using non-earth based sensors is one mechanism to assess the presence/ absence of permafrost based on surface characteristics. Remote sensing alone cannot identify the extents of permafrost as it is a

subsurface temperature phenomenon, so it may not be reflected on the surface. Ice-wedges can often be observed visually. Ice-wedges are formed over the timescale of centuries to millennia and are formed through snow-melt creating cracks in the ground through freeze-thaw cycles. These ice-wedges are generally 3-4 m wide and several meters deep (Liljedahl et al. 2016) and produce a surface of low-centered polygons (Figure 7). Ice-wedges have tremendous differential thaw potential as they account for about 20% of the uppermost permafrost volume (Kanevskiy et al. 2013).

Figure 7. Ice wedges.

Source: Canadian Soil Information Service, in Wooster Geologists (2016).

2.5.2 Surface lakes

Thermokarst lakes and ponds, which form through the degradation of permafrost, are indicators of permafrost. Grosse (2015) indicates that these lakes have an impact on the hydrology, geomorphology, and chemical cycling in the permafrost lowlands. LandSat imagery (~15-80 m) have been used to identify changes in thermokarst features; however due to the scale of the pixel cells this is not suitable for shore erosion studies. High-resolution satellite imagery (WorldView, QuickBird etc.) are commonly used for assessing local and regional changes in thermokarst lakes including appearance and disappearance. The Surface Water Ocean Topography

(SWOT) satellite to be launched in 2020 will be able to identify lakes as small as 250m² and get water elevation with an accuracy of 10cm.

2.6 Fire

Fire presents a significant disturbance on the permafrost landscape, as it affects the recovery patterns and the depth of the organic layers. In a study of permafrost in central Alaska, researchers found that fires caused a five-fold decrease in the mean surface organic thickness, a doubling of water storage in the active layer, a doubling of thaw depth, and an increase in soil temperature at the surface. Fires led to degradation of the upper permafrost layers at all burn sites, but the soil textures at some sites allowed lower permafrost to persist (Nossov et al. 2013). Devastating arctic fires caused by lightning are increasing, rising about 2-5% annually for the past four decades. These lightning induced fires are a result of increasing thunderstorm frequency, which is encouraged by warmer temperatures (Veraverbeke et al. 2017). Furthermore a study of lightning Continental United States (CONUS) estimates that with each degree of Celsius that global temperatures rise, CONUS lightning strikes are predicted to increase $12 \pm 5\%$ (Romps et al. 2014). As tree cover moves northward the damage from the trend and impact on permafrost could continue (Waldman 2017). Landsat 8 provides the necessary resolution, coverage, and frequency to assess the relationships between permafrost stability and fire disturbances. For known fires, the Bureau of Land Management (BLM) provides polygons of the fire perimeters (AICC 2016b).

3 Data Collection

Using the literature review as a basis for future work, the process of collecting spatially explicit data for the factors outlined above was begun. This process was used to develop a list data sources and factors that relate to permafrost degradation (included in Appendix A). Not all of the identified factors could be used in the analysis outlined in this report. To narrow down the factors, the following criteria were applied:

1. Data must be at a resolution of at least 2 km, but preferably at a lower resolution.
2. Data must be produced by a government agency as an authoritative dataset, or have a strong peer-review backing.
3. Data must be easily downloaded using a web interface or via file transfer protocol (FTP).
4. Data must be available in a format that could easily be imported into ArcMap Geographic Information System (GIS) software.
5. Data must have been taken within the study area (Figure 3, p 3), which was selected because it represented an area with exceptional data coverage, was large enough to provide a meaningful statistical analysis, and included areas of both continuous and discontinuous permafrost.

3.1 Permafrost characteristic data

The literature review confirmed that it is nearly impossible to identify permafrost from remote data. Consequently, data were collected from a variety of locations that can be indicators of the presence of permafrost, or that are signals of possible permafrost degradation.

Elevation: The National Geospatial Intelligence Agency's (NGA's) Digital Terrain Elevation Data (DTED) product, which is a 30m digital elevation model (DEM), was used to produce three further products using the desktop GIS software ArcGIS: hillshade, slope, and aspect (NGA 2012).

- **Geology:**

- Soil albedo data were provided through the ArcGIS Online platform. These data were derived using the Natural Resources Conservation Service data by taking the component table field "Albedo Dry - Representative Value (albedodry_r)." (NRCS 2017).

- As discussed in the literature review, locations of thermokarst sites are difficult to identify remotely. A 2014 Thermokarst estimation map produced by the U.S. Geological Survey (USGS) was used as a starting estimation point for thermokarst locations (Szukalski 2014).
- A permafrost probability map developed by the USGS was used as a mechanism of roughly estimating the location of permafrost (Pastick et al. 2015).
- Wetlands data from the National Wetlands Inventory were used to identify wetland areas and thus areas that may have thermokarst development (USFWS 2016).
- To better assess the impacts of lightning and fire on permafrost, data were obtained from the Alaska Interagency Coordination Center lightning (AICC) (1986) and from fire polygons (AICC 2016).
- Landcover data were obtained the National Land Cover database land cover classifications for the state of Alaska (MRLC 2014).
- **Climate:** Data produced by SnowData were used for the climate characteristics. Snowdata is a simulation of climate and snow information based on historical weather and climate information. It includes 21 data variables for each year between 1979 and 2012. Some of the variables measure similar characteristics. For example, the dataset includes “First Snow” calculated as the “day of the year” and “day of simulation.” For ease within the statistical model, the day of simulation (dos) variables were used. Since data were available over many years, the values for the years 2008-2012 were selected and averaged so that possible anomalies in any one year would not overly impact the results of the study. SnowData (LCC 2017) provided the following variables: Air Temperature, Last Snow Day, Number of days with rain on snow, First Snow Day, Snow-free days, and Snow up to date.
- **Human Impact:** A factor that was not highlighted in the literature review, but that was deemed important for this study, was human impact. Because the objective of this work was to examine the probability of roads cracking, it seemed probable that areas with higher usage might be more likely to crack. Because road count data were unavailable, urban area outlines from the U.S. Census Bureau were used as a rough estimate of population centers and areas with higher populations (U.S. Census Bureau 2016).

3.2 Data exclusions

Note that some factors that were identified in the literature review as being important characteristics were not included in the preceding list. There are many reasons for their exclusion, most commonly because of the difficulty in obtaining data. Factors excluded from this analysis were soils, soil moisture, and vegetation.

3.3 Pavement crack data

A model of the probability map of the likelihood that a road would crack was developed using existing road crack data from the Alaskan Department of Transportation (AKDOT). Using road cracking probability was a way to roughly estimate the impact of permafrost, even though these cracks can result from frost heave, expansion, and road use. The AKDOT (2016) dataset is produced annually for the Highway Performance Monitoring System (HPMS) and includes location, size of the crack, and roughness of the road. Data for the years 2005-2015 at various scales ranging from 1/100 mile to 1 mile were obtained from AKDOT officials. For simplicity, this analysis dealt only with the 2015 data, which was at the 1/10th mile. These data were selected because they were temporally the newest, they had few missing values, and they conveyed data at a small scale. It was decided not to combine data from multiple years because it was not possible to know if there had been any road maintenance on a segment that could account for a cracks absence in later years. Furthermore, the road segments differed slightly from year to year in length and there was no clear identifier field that persisted through multiple years of data.

The 2015 dataset contained 32,607 road segments and attributes for each segment, including the length of road that was cracked and the percentage of the road segment that was cracked. This analysis used the attribute “HPMS_Cracking_Per,” which is the percent of a segment that is cracked. This is a percentage of the wheelpath that has alligator/fatigue cracking in it. It is calculated by taking the square feet from the pattern cracking zones 2 and 5 and dividing it by the entire section area.* Using the percentage of a segment that was cracked made it possible to account for differences in the road segment lengths, as road segment lengths ranged from 6 ft to just over

* Pavey, Andrew. 2017. Letter to Juliana Wilhoit. Subject: Overall Pavement Data as Feature Layer? July 18, 2017. Champaign, IL: Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL).

the designated road length at 0.11 miles. The average road length was 0.98 miles, which was slightly shorter than the designated road length. In addition to all of the possible attributes for road cracks, this characteristic had the fewest null values, which gave it the greatest use in this analysis. Figure 8 shows the distribution of crack lengths in the 2015 pavement dataset.

Figure 8. The distribution of crack lengths in the 2015 pavement dataset.

For the analysis of probability of roads cracking, the dependent variable was a binary coding of crack presence/absence. Segments were marked as having an absence of a crack if the crack coverage was less than 2%. This value was a rough estimate used in an effort to exclude small cracks and to focus on larger cracks.

3.4 Processing data

The data sources collected (see Section 2.1, “Challenges with permafrost Identification,” p. 4) were then opened in the desktop GIS software ArcGIS Pro. Each data layer was processed to summarize the particular input data to each road segment so that each segment would have a value as it related to each factor. Given the differences in spatial scale, the element that each factor was measuring, and the uniqueness of the data, the data were not summarized uniformly. Table 4 summarizes the completed processing. In general, the zonal statistics tool was used for continuous data while the

near tool was used for feature data that were only present in certain locations. The processing relied on two tools within the ArcGIS software:

- **Zonal Statistics:** Zonal statistics provide a summary of the data that intersect or are contained within another layer (Esri 2014). For example, if one had parcel data for multiple neighborhoods within a city, it would be possible to use the zonal statistics tool to get a summary for the parcels within a neighborhood.
- **Near:** the Near tool provides a summary of the distance between one feature and another. For this research, the Near tool was used to determine the distance between each road segment and the applicable factor (Esri 2017).

Table 4. Summary of processing done in ArcGIS.

Data	Notes
Lightning	The NEAR tool was used to calculate the distance to the nearest lightning strike from 2008-2015. The near tool was used because there were only three instances of reported lightning strikes on a roadway in Alaska, and because it was determined that spatial fidelity of the data for its precession in marking road strikes was not trustworthy.
Wetlands	Using the NEAR tool calculated the distance from each road segment to wetlands. The near tool was used because it was known that permafrost can degrade around the edges of water features as the temperatures increase.
Soil Albedo	Used Zonal Statistics to summarize the average soil albedo per road segment. Because the soil albedo was a layer that was present for the entirety of the study area, It was possible to simply do the zonal statistics to get a summary of albedo for the road segment. The average of the albedo was taken over the segment.
Fire	The NEAR tool was used to calculate the distance to a fire from 2008-2015. Since fire is much like lightning, and because the spatial data was considered untrustworthy, there was a desire to see the distance from the road to a fire. It was assumed that areas that were close to a fire area may have received some level of damage to both infrastructure and permafrost.
Land Cover	The Landcover data are a continuous dataset for Alaska. However, because of the manner that land cover data are processed, road segments are often categorized as “developed.” It was assumed that the landcover surrounding the roads is indicative of the original landscape state and that properties associated with landcover (e.g., soil type) would be similar beneath the roads. To get an estimation of the surrounding land cover for an area, a 120-ft buffer was added to the roads and MAJORITY was used to get the most common land cover.

Data	Notes
Thermokarst	The NEAR tool was used to calculate the distance from each road segment to USGS identified thermokarst. The near tool was used here to assess proximity to thermokarst. Locations that were closer were presumed to being at a higher risk of degradation.
Permafrost estimated depth	These data were summarized using zonal statistics to obtain the mean estimated depth to permafrost.
Probability of Permafrost Presence Map	These data were summarized using zonal statistics to obtain the mean probability of the presence of permafrost. The original data had values of probability from 5-105. Efforts were made to contact the studies' authors for confirmation on the data, they did not respond. As a result the values over 100 were resampled to be the values 1-5%.
slope	Using an input DEM the slope was calculated in degrees. Then the average slope for each road segment was calculated using zonal statistics.
Aspect	The aspect was calculated in degrees using an input DEM. The aspect is the direction of the slope. Then the average aspect for each road segment was calculated using zonal statistics.
Hillshade	The hillshade was calculated using an input DEM. Hillshade is the illumination of a surface. Areas with the greatest shadow have a value of 255 while areas with no shadow are coded as 0. The average hillshade for each road segment was then calculated using zonal statistics.
Snow data	SnowData contains simulated information on various snow related factors for a number of years. Since there were no data for 2015 (when the roads in this study were from) a 5-year average, 2008-2012, was taken. Zonal statistics were then applied to the 5-year average product.
Urban Areas	To estimate the human impact on roads, the distance from each road segment to the nearest urban area was calculated. If the road was located within the Census defined urban area, the distance was 0.

4 Modeling Pavement Cracks

The acquired, formatted data were used to elicit a more thorough investigation of infrastructure in Alaska and of the potential impact of permafrost thaw on road cracks, specifically, by answering the following questions:

1. **What landscape features are related to pavement cracks in Alaska?** (Answers to this question could help to more fundamentally determine the relationships between landscape characteristics and road cracks.)
2. **What is the probability of the road at any given location cracking?**

4.1 Data down Selection

Using ArcGIS (as previously discussed) each landscape characteristic was summarized to each road segment. A table containing all of this information was then exported to Microsoft Excel where the data were manually examined and filtered through a Quality Assurance/Quality Control (QA/QC) process, in which any road segments that had missing data were removed so as to not confuse the statistical analysis. The newly cleaned table was then imported into the IBM SPSS Statistics statistical programming software.*

All of the variables were first evaluated for their variance inflation factor (VIF). The VIF is a measure of multi-collinearity, which indicates that two or more variables are highly correlated. If there is multi-collinearity then one variable may be over-predicting. An example of collinearity in this model were snow days and snow free days since both variables measure a similar characteristic. In fact, snow free days = 365 – snow days. Table 5 summarizes the VIF. Before proceeding to the regression, variables with VIFs greater than 10 were removed to reduce multi-collinearity. Removing the VIFs was important to do before starting a regression analysis so that variables did not over-influence the model results. Note that the VIF was only able to assess variables that were of a continuous data type. Land cover data were excluded from the VIF because it was discreet—being broken into a dozen land cover types.

* International Business Machines (IBM).

Table 5. Coefficients and VIFs for factors.

Coefficients ^a							
	Unstandardized Coefficients		Standardized Coefficients	T	Sig.	Collinearity Statistics	
	B	Std. Error	Beta			Tolerance	VIF
(Constant)	0.246	0.648		0.38	0.704		
air_temp	-0.033	0.004	-0.109	-8.951	0	0.333	3.002
last_s_d	0.012	0.003	0.246	3.513	0	0.01	99.607
Rain_on_	-0.015	0.004	-0.038	-3.507	0	0.411	2.434
s_1_doy	0.002	0.001	0.045	2.484	0.013	0.15	6.676
s_days	0.002	0.002	0.096	1.465	0.143	0.011	88.004
s_free_d	-0.015	0.003	-0.303	-4.244	0	0.01	103.416
s_up_doy	-0.005	0.001	-0.12	-3.793	0	0.049	20.238
t_s_days	-0.004	0.001	-0.167	-2.717	0.007	0.013	76.255
Thermok	-1.71E-06	0	-0.087	-8.242	0	0.447	2.236
AK_Wetl	3.84E-06	0	0.043	5.407	0	0.794	1.259
ALBEDO	-0.003	0	-0.075	-6.97	0	0.428	2.339
PermProb	4.01E-05	0	0.002	0.257	0.797	0.982	1.018
HILLSHADE	0.002	0.001	0.026	2.941	0.003	0.633	1.58
SLOPE_D	0.007	0.003	0.023	2.76	0.006	0.688	1.453
ASPECT_	0	0	-0.02	-2.667	0.008	0.852	1.174
Urban	-5.91E-07	0	-0.125	-9.891	0	0.308	3.247
FireAre	4.95E-06	0	0.127	12.351	0	0.47	2.129
^a Dependent Variable: Crack_Presence							

4.2 Logistic regression modeling

A logistic regression was conducted to determine the probability of roads cracking, where probability of a binary outcome is determined based on various predictor values. The dependent variable was a coded binary—if a road was cracked (1) or not cracked (0). Roads were determined to be cracked if more than 2% of the segments length was cracked (for more information see Section 3.3, p 18). This is then tested against a set of independent variables that were downselected from a larger list using VIF (see Section 4.1, p. 22). The list of variables used in the logistic regression were:

- Air Temperature (Air_Temp)
- Rain on snow (Rain_on_)
- Date of the first day of snow (s_1_dos)
- Distance to thermokarst features (Thermok)
- Distance to wetlands (AK_Wetl)
- Distance to fire (FireAre)
- Soil albedo (ALBEDO)

- Probability of the presence of permafrost (PermProb)
- Hillshade (HILLSHADE)
- Slope (SLOPE_D)
- Aspect (ASPECT_)
- Distance to urban areas (Urban)
- Land cover.

A Binomial Logistic Regression was run using IBM SPSS Statistics software (IBM 2017a). Of the variables used, only one was a categorical variable (Land Cover Type) that required a special classification. The Land Cover data were broken into eight categories. In the “Define Categorical Variables” option within SPSS, “Indicator” was selected as the change contrast (IBM 2017a). The default probability threshold was accepted, so if the likelihood of a crack forming is > 0.5 , it is assumed to be cracked; if it is < 0.5 , it is assumed to be not cracked.

Table 6. Results of logistic regression.

	B	S.E.	Wald	Sig.	Exp(B)
air_temp	-0.263	0.016	262.151	0	0.769
Rain_on_	-0.138	0.02	48.233	0	0.871
s_1_dos	0.002	0.002	0.584	0.445	1.002
Thermok	0	0	170.722	0	1
AK_Wetl	0	0	26.306	0	1
FireAre	0	0	267.569	0	1
ALBEDO	-0.026	0.002	138.21	0	0.975
PermProb	0.002	0.001	5.819	0.016	1.002
HILLSHADE	0.014	0.004	9.952	0.002	1.014
SLOPE_D	0.035	0.014	6.496	0.011	1.036
ASPECT_	-0.001	0	9.13	0.003	0.999
Urban	0	0	254.893	0	1
NLCD_Group*			46.005	0	
NLCD_Group (1)	0.715	0.802	0.795	0.373	2.045
NLCD_Group (2)	0.193	0.155	1.546	0.214	1.213
NLCD_Group (3)	0.002	0.081	0.001	0.98	1.002
NLCD_Group (4)	0.148	0.088	2.806	0.094	1.159
NLCD_Group (5)	0.546	0.545	1.004	0.316	1.726
NLCD_Group (6)	-0.842	0.315	7.146	0.008	0.431
NLCD_Group (7)	-0.312	0.105	8.892	0.003	0.732
NLCD_Group (8)	0.253	0.284	0.791	0.374	1.288
Constant (a)	-1.835	0.805	5.194	0.023	0.16
*National Land Cover Database (NLCD)					

4.3 Map production

The results of the logistic regression were then applied back onto the input variable data. For variables in the final model that were calculated using the near tool (thermokarst, wetlands, fire, and urban area), a surface raster was first generated to calculate the distance from each feature to every cell on the map as a means of creating an equivalent dataset. Figure 9 shows the newly created distance raster for urban areas. Areas that are darker are closer to/within an urban area while white areas are farther away.

The next step was to multiply each raster by the constant value (B) produced in IBM SPSS Statistics. As the analysis was conducted, however, it was found that there were issues with extents, cell size, and projection of the data. These issues resulted in analysis outputs that had no associated error message, but were clearly displaying incorrect results.

Figure 9. New raster created by calculating the distance from urban areas.

After much trial and error within the data, a script was finally developed using ArcGIS Model Builder that would process the data appropriately (Figure 10). A “master raster” that had the projection, appropriate cell size, and extent for the analysis was developed. This raster (Masked_Area) was then used as a template for the rest of the rasters. Each value raster was first projected to be in “NAD_1927_Albers,”* a projected coordinate system measured in feet, in which the projection and the extent were set to the template raster. In other words, that the output raster would have the NAD_1927_Albers projection and its extent would match the template. The data were then resampled to a new cell size of 2000 x 2000 ft. This size was selected because of computational issues that required data to be processed at a smaller cell size. Finally, a python script was used to identify the correct constant (B) value for the raster, and then each raster cell was multiplied by that value.

Figure 10. Screen shot of the final data processing tool developed using ArcGIS pro. This tool enabled the rapid processing of input variable data.

The result was a series of raster files such as the one shown in Figure 11, which demonstrates the output generated when the input raster (slope) was multiplied by the constant value from the logistic regression (-0.038022114420544) to produce an output raster with values ranging from -1.6 – 0. This stands in contrast to the input slope dataset, which had values ranging from 0 – 45.

* Note: NAD = “North American Datum”

Figure 11. Illustration of the output of multiplying slope by the variable coefficient from the statistical analysis.

The probability of roads cracking using the logistic regression formula was calculated using the raster calculator function in ArcGIS:

$$p = \frac{e^{a+b_1x_1+b_2x_2+\dots}}{1 + e^{a+b_1x_1+b_2x_2+\dots}} \quad (1)$$

where:

- P = Probability of “1” (roads cracking)
- A = constant (from “B” column of “Variables in the Equation” table); b_i = coefficients (from “B” column of “Variables in the Equation” table)
- X_i = variable values.

5 Results

5.1 Limitations

1. **Cell size:** The probability map produced through this analysis was done using generalized cell sizes of 2000 x 2000 ft. In other words, data were taken from its original resolution (generally between 30-90 m) and aggregated so that each cell was 2000 x 2000 ft. The resampling process was used to gain computational processing speed, which was required because of limitations on the computer being used. The trade-off, however, was that nuances in the landscape and data were lost.
2. **Lack of key variables:**
 - a. One of the key missing factors from this analysis were any soil related characteristics. The initial model setup did include data from Soil Survey Geographic (SSURGO) database from the National Cooperative Soil Survey (USDA 2017). Unfortunately, the breadth of values presented in that dataset resulted in a truncated data output and the SSURGO data had to be removed. Soil moisture was excluded from the analysis because it was not possible to obtain a dataset at a fine enough resolution. Since the conclusion of the analysis, an improved dataset has been acquired.
 - b. Also missing from this analysis were vegetation data via leaf-area index, tree-line, or normalized difference vegetation index (NDVI). The NDVI is available from the USGS and is cumbersome to download and process. The data are provided as individual tiles that are individually downloaded, and then need to be combined. Given time constraints of this research, the NDVI had to be excluded.
3. **Exclusions:** One way to produce a more explanatory graphic and analysis is to exclude areas that are known to be unsuitable for development from the final mapping portion. The analysis presumes that all land in Alaska is suitable for road construction and does not exclude areas that are known to be non-conducive to road construction—such as areas having a high slope or bodies of water.

5.2 Results discussion

The logistic regression model developed provides an initial estimate of locations in Northern Alaska where roads may crack. The data in Table 7 summarize the model output. The logistic regression model correctly predicted the presence of cracks 63.7% of the time. The model results are

skewed, in that they only correctly predict the lack of a crack 31.6% of the time while they correctly predict cracks 86.5% of the time. While a higher fit is desirable, a correct classification of over 50% demonstrates a strong model. For this analysis, the cut percentage was 50%. In other words, if it had a value of 50% or greater, it was coded as cracked; if it had a value under 50%, it was coded as not cracked.

Table 7. Classification resulting from the logistic regression.

Observed		Predicted		
		Crack_Presence		Percentage Correct
		No (0)	Yes (1)	
Crack_Presence	No (0)	1793	3875	31.6
	Yes (1)	1067	6866	86.5
Overall Percentage				63.7

The mapped results shown in Figure 12 show that many areas in Alaska have a low probability of roads cracking while a few concentrated areas demonstrate a high probability.

- **Lower probability of roads cracking in northern Alaska.** This is likely due to several factors: the sparse population (high distance from an urban area), presence of continuous permafrost, and minimal precipitation. In the original data from the Alaskan department of transportation, there were fewer large road cracks in the north compared to the south.
- **Air Temperature.** In the model, air temperature, which was estimated from SNOWDATA, had a tremendous impact on the final results. The map shown in Figure 13 shows areas with higher temperatures in darker blue. The purple boxes on the map, which indicate areas with a higher probability of cracking, also all had higher temperatures, indicating a link between temperature and probability of road cracking.
- **Minimal effect urban areas.** One expected result from this research was that there would be more road cracking around urban areas. This was tied to the likely assumption that many of the road cracks were a result of driving and road wear that come from heavy use. However, urban areas in Alaska are not very large. U.S. Census figures show that Fairbanks has a population of about 64,000, and the Nome area has a population of about 3,300. A way to improve the counting of road use from human use would be to use population estimates.

Figure 12. Mapped results of the probability of roads cracking in Alaska.

Figure 13. Map illustrating air temperature data from SnowData mapped in relationship to the areas of high probability of cracking (purple boxes).

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Acronyms and Abbreviations

Term	Definition
AHAP	AK High Altitude Photography
AKDOT	Alaska Department of Transportation
AKOATS	Alaska Online Aquatic Temperature Site
AICC	Alaska Interagency Coordination Center
ALT	Active Layer Thickness
BLM	Bureau of Land Management
CAPS	Circumpolar Active-Layer Permafrost System
CEMML	Center for the Environmental Management of Military Lands
CERL	Construction Engineering Research Laboratory
CONUS	Continental United States
CRREL	Cold Regions Research and Engineering Laboratory
DAAC	Distributed Active Archive Center
DEM	Digital Elevation Model
DGGS	Division of Geological & Geophysical Surveys
DoD	U.S. Department of Defense
DOT	Department of Transportation
DTA	Differential Thermal Analysis
DTED	Digital Terrain Elevation Data
ERDC	U.S. Army Engineer Research and Development Center
ERDC-CERL	Engineer Research and Development Center, Construction Engineering Research Laboratory
FEIS	Fire Effects Information System
FTP	File Transfer Protocol
GINA	Geographical Information Network of Alaska
GIPL	Geophysical Institute Permafrost Laboratory
GIS	Geographic Information System
GPM	Global Precipitation Measurement
GPP	Gross Primary Productivity
GRID	Global Resource Information Database
HPMS	Highway Performance Monitoring System
IBM	International Business Machines (Corp.)
IfSAR	Interferometric Synthetic Aperture Radar
JAWRA	Journal of American Water Resources Association
LAI	Leaf Area Index
LCC	(Arctic) Landscape Conservation Cooperative
LiDAR	Light Detection and Ranging
MODIS	Moderate Resolution Imaging Spectroradiometer

Term	Definition
MRLC	Multi-Resolution Land Characteristics Consortium
NAD	North American Datum
NASA	National Aeronautics and Space Administration
NCADAC	(Federal) National Climate Assessment and Development Advisory Committee
NDVI	Normalized Difference Vegetation Index
NGA	National Geospatial Intelligence Agency
NLCD	National Land Cover Datanase
NPP	Net Primary Productivity
NRC	National Research Council
NRCS	Natural Resources Conservation Service
NSIDC	National Snow and Ice Data Center
NSSI	North Slope Science Initiative
O&M	Operations and Maintenance
PGC	Polar Geospatial Center
QA/QC	Quality Assurance/Quality Control
QC	Quality Control
QPE	Quantitative Perception Estimates
SAR	Synthetic Aperture Radar
SMAP	Soil Moisture Active/Passive
SNAP	Scenarios Network for Alaska + Arctic Planning
SSURGO	Soil Survey Geographic
SWOT	Surface Water Ocean Topography
TR	Technical Report
TWC	The Weather Channel
UAA	University of Alaska Anchorage
UAF	University of Alaska at Fairbanks
UNEP	United Nations Environment Programme
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USDOI	U.S. Department of the Interior
USFS	U.S. Forest Service
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
VIF	Variance Inflation Factor
WU	Weather Underground

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Appendix A: Data Sources

Table A-1. Summary of data sources identified through research process.

Name	Resolution	Date	Published	Source/Agency	Link
Digital Elevation Models (DEMs)					
3DEP (2-Arc Second)	60m			USGS, 3D Elevation Program	https://nationalmap.gov/3DEP/
3DEP (1-Arc Second)	30,			USGS, 3D Elevation Program	https://nationalmap.gov/3DEP/
3DEP (1/3 Arc Second DEM)	7	2007-2014	2016	USGS, 3D Elevation Program	https://nationalmap.gov/3DEP/
3DEP Interferometric Synthetic Aperture Radar (IFSAR)	5	6/11-21/2010	2016	USGS, 3D Elevation Program	https://nationalmap.gov/3DEP/
ArcticDEMs project	2 and 5 m	Oct-16	2016	NGA, Polar Geospatial Center (PGC)	http://nga.maps.arcgis.com/home/item.html?id=b0ba5bb085eb438e95001b528384d4db
DTED (1-Arc Second)	30 m	Jul-05		NGA	https://agcwfs.agc.army.mil/CMB_Online/default.aspx
LIDAR Data					
G-LIHT (NASA/U.S. Forest Service [USFS])	0.24 m spacing	Jul-14	2014	NASA/USFS	http://gliht.gsfc.nasa.gov/
Infrastructure Corridor	<1m spacing	5/17/2011-7/22/2011	2013	Alaska Division of Geological & Geophysical Surveys (DGGs)	http://maps.dggs.alaska.gov/elevationdata/#-16000000:9338001:4
U.S. Army Corps of Engineers (USACE)	0.82 m spacing	4-6 May 2010		USACE	https://nationalmap.gov/3DEP/
Ft. Greely Lidar data	5 m raster	2012?		Center for the Environmental Management of Military Lands, Fort Wainwright	Not high quality

Name	Resolution	Date	Published	Source/Agency	Link
Permafrost					
2008 Permafrost Characteristics of Alaska	10-20 km	Dec. 2008		North Slope Science Initiative (NSSI)	http://catalog.northslope.org/catalog/entries/3587-permafrost-characteristics-of-alaska-2008-sha
Circum-arctic map of permafrost and ground ice conditions	>10km	1998		National Snow and Ice Data Center (NSIDC)	https://nsidc.org/data/docs/fgdc/ggd318_map_circum_arctic/
Permafrost Map produced by Torre Jorgensen	~30 m	1998		Torre Jorgensen	http://ine.uaf.edu/werc/projects/cpcrw/map/paper/jor88.pdf
Distribution of Near-Surface (within 1m) Permafrost in Alaska	30 m	2015	2015	Pastick et al. 2015	https://www.sciencebase.gov/catalog/item/5602ab5ae4b03bc34f5448b4
Distribution of boreal and arctic thermokarst landscapes	<1ha polygons	2015		Olefelt et al. 2016	https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1332
Depth to Permafrost	1:500000	2012	2012	LandCarbon Project	http://ckan.snap.uaf.edu/dataset/depth-to-permafrost-alaska-landcarbon-project
Landscape scale permafrost model output (GIPL)	1 km	1901-2100		GIPL Team, Permafrost Lab, University of Alaska at Fairbanks (UAF)	http://ckan.snap.uaf.edu/dataset/gipl-model-outputs-linear-coupled-annual
Thermokarst Extent Model (downscaled)	1km	2014			http://ckan.snap.uaf.edu/dataset/thermokarst-formation
Near Surface permafrost					http://www.sciencedirect.com/science/article/pii/S0034425715300778
LandCarbon					http://data.snap.uaf.edu/data/Base/Other/LandCarbon/TEM_Active_Layer_Depth/
Karst in the U.S. (Thermokarst)	unknown, polygon		2014	USGS	https://pubs.usgs.gov/of/2014/1156/pdf/of2014-1156.pdf

Name	Resolution	Date	Published	Source/Agency	Link
Geology					
Geologic Map of Alaska	1:250000	2015	2015	USGS, Wilson et al. 2015	https://pubs.er.usgs.gov/publication/sim3340
Surface Lakes			2014	Alaska Online Aquatic Temperature Site (AKOATS).	http://www.arcgis.com/home/item.html?id=732d41cef68d4a5292c986dc0c9f262c
Bedrock_Geology	1:2,500,000		2013	minerals.usgs.gov	
Soils					
Relative Soil Moisture DASSP	30-90 m				https://mobility.crearecomputing.com/
Volumetric Soil Moisture (DASSP)	30-90 m				https://mobility.crearecomputing.com/
USA Soils Albedo	30 m			Esri	http://www.arcgis.com/home/item.html?id=e89fdc8e8b13417daa5ad232312f58cf
USA Soils Available Water Storage	30		2014	Esri processed the Soil Survey Geographic Database (SSURGO) dataset that is produced by the Natural Resources Conservation Service (NRCS)	https://www.arcgis.com/home/item.html?id=9cf1a71ea80417972d9a41cf0ca9cd
Soil Carbon Content 100cm			2014	Hugelius et al. 2013)	http://www.arcgis.com/home/item.html?id=d4226bfe0c5044edacb4e214d6f3ce2a
Hydrology					
Surface Water (Streams, Lakes, Ice)	HUC8	Mar-17		National Hydrography Dataset	https://viewer.nationalmap.gov/basic/?howTo=true#productSearch

Name	Resolution	Date	Published	Source/Agency	Link
Circumpolar Arctic Lake Cover	1:7,500,000	2003	2011	U.S. Fish and Wildlife Service, Anchorage, Alaska.	http://www.arcgis.com/home/item.html?id=cc300ca738364249b538cc7ae56d4029
Circumpolar Arctic Landscape (Data Basin Dataset)	1:7,500,000	2003	2011	U.S. Fish and Wildlife Service, Anchorage, Alaska.	http://www.arcgis.com/home/item.html?id=bdeef3498c82436fa46aacef1aee74a1
Wetlands					
National Wetlands Inventory	1:40,000	Mar-17		U.S. Fish and Wildlife Service	https://www.fws.gov/wetlands/Data/Mapper.html
Wetland Distribution Map - Alaska LandCarbon Project	30 m		2016	USGS LandCarbon Alaska assessment (Zhu and McGuire 2016)	http://ckan.snap.uaf.edu/dataset/wetland-distribution-map-alaska-landcarbon-project
Land Cover					
2001 NLCD data for Alaska	30 m	2008	Homer et al. 2007	USGS National Land Cover Data	https://www.mrlc.gov/nlcd01_data.php
2011 National Land Cover Data for Alaska	30 m	2016	Homer et al. 2015	USGS National Land Cover Data	https://www.mrlc.gov/nlcd11_data.php
Vegetation Map and Classification: Northern, Western, and Interior Alaska	30 m	2016	2016	Alaska Center for Conservation Science, University of Alaska Anchorage (UAA)	http://accs.uaa.alaska.edu/vegetation-ecology/landcover-mapping/
U.S. Army Alaska Habitat Map	polygon	Unknown		CEMML*, Fort Wainwright	

* Center for the Environmental Management of Military Lands (CEML)

Name	Resolution	Date	Published	Source/Agency	Link
Normalized Difference Vegetation Index (NDVI)					
AVHRR-Derived, GIMMS3g	8 km	1982-2015		NASA, Goddard Space Flight Center	https://nex.nasa.gov/nex/projects/1349/
eMODIS, March 2000-present	250 m	2000-2017		USGS, U Alaska Fairbanks	https://lta.cr.usgs.gov/emodis ; http://www.gina.alaska.edu/projects/modis-derived-ndvi-metrics ; http://alaska.portal.gina.alaska.edu/catalogs/9738-modis-derived-ndvi-metrics
MODIS NDVI	250 m	2000-2017		USGS	https://earthexplorer.usgs.gov/
Landsat NDVI (produced corrected)	30 m	1984-present		USGS	https://earthexplorer.usgs.gov/ ; https://landsat.usgs.gov/landsat-surface-reflectance-high-level-data-products
Leaf Area Index (LAI3g)					
AVHRR-Derived, 30 year product	8 km	July 1981 - Dec 2011		Myneni (2013), Boston University	http://cliveg.bu.edu/modismisr/lai3g-fpar3g.html
LEAF AREA INDEX (1 MONTH - TERRA/MODIS)	0.1 degree	2000-present		NASA Earth Observations	https://neo.sci.gsfc.nasa.gov/view.php?datasetId=MOD15A2_M_LAI
Forest Canopy					
Simard et al. Canopy height	1km	2011		Simard et al., 2011	http://webmap.ornl.gov/wcsdown/dataset.jsp?ds_id=10023
LandFire Data	30 km	2012			https://www.landfire.gov/NationalProductDescriptions5.php
Treeline, ALFRESCO Model Outputs - Linear Coupled	1 km				http://ckan.snap.uaf.edu/dataset/treeline-maps-alfresco-model-outputs-linear-coupled
NLCD Tree Canopy			2001 & 2011	Multi-Resolution Land Characteristics Consortium	https://www.mrlc.gov/nlcd01_data.php

Name	Resolution	Date	Published	Source/Agency	Link
Gross Primary Productivity (GPP)/ Net Primary Productivity (NPP)					
Eight Day GPP, Eight Day NPP, and Annual NPP	1 km	2000-2012			http://www.nts.gov/ntsg/umt.edu/project/mod17
High-Resolution Commercial Imagery & Historical Imagery					
Aerial Photography (1938-1990s)	1-5 m	1938,1949,1960s-1990s		Earth Explorer, USGS (not rectified)	https://earthexplorer.usgs.gov/
AK High Altitude Photography (AHAP)	1 m	summer 1986		Earth Explorer, USGS (not rectified)	https://earthexplorer.usgs.gov/
CEMML Image of Donnelly Training Area (contract work)	1 m	2002?		CEMML, Fort Wainwright	Entire differential thermal analysis (DTA) Image from 2002
Historical Images (generate surfaces from)	< 1m	1970-1990		USACE, Cold Regions Research and Engineering Laboratory (CRREL)	
Digital Globe- Enhanced View Web Hosting Service (for DoD)	<1 m	~2010-2016	2017	NGA/ Digital Globe	https://ewhhs.digitalglobe.com
Snow Depth, Snow Water Equivalent , and duration					
Pan-Arctic Snow Climatology	10 km	1979-2011	2011	Liston and Hiemstra, 2011, J of Clim.	I have these data; http://arcticcc.org/projects/geophysical/snowdata
SnowData	2 km	1979-2012	2015	Liston and Hiemstra 2008	http://arcticcc.org/products/spatial-data/show/snowdata-annual-summaries

Name	Resolution	Date	Published	Source/Agency	Link
MODIS-Derived Snow Metrics	500 m	2001-2016	Lindsay et al. 2015	Geographical Information Network of Alaska (GINA), U of Alaska Fairbanks	http://www.gina.alaska.edu/projects/modis-derived-snow-metrics
Drought Severity Indices					
Drought Severity Index	1 km	2001-2012			Stale; can find other drought indices http://www.ntsg.umd.edu/project/dsi#data-product
Drought Monitor					https://www.drought.gov/nadm/content/shape-files
Fire					
Alaska Fire Service Burned Areas Polygons	unknown	1946-2016		Alaska Fire Service	https://fire.ak.blm.gov/
Alaska Fire Service Lightning Detection	point data	1990-2016	2016	Alaska Fire Service	https://fire.ak.blm.gov/
Climate Data					
Scenarios Network for Alaska + Arctic Planning (SNAP) Climate History for Precipitation and Temperature	1km	1901-2009	Mar-17	University of Alaska Fairbanks	https://www.snap.uaf.edu/tools/data-downloads
SNAP Downscaled Climate Projections for Precipitation and Temperature	771 m	2006-2100	Mar-17	University of Alaska Fairbanks	https://www.snap.uaf.edu/tools/data-downloads
Quantitative Perception Estimates (QPE)	5km	Current, 15-minute product,	2017	NASA, Short-term Prediction Research and Transition Center	https://weather.msfc.nasa.gov/sport/qpe/

Name	Resolution	Date	Published	Source/Agency	Link
Transportation					
<u>Traffic Counts - Average Annual Daily Traffic</u>		2012-2013	2017	AKDOT	http://www.dot.state.ak.us/ArcGIS/rest/services/AADT_TrafficCounts/MapServer
2016 - 2017 Winter Road Maintenance Priority		2017	2017	AKDOT	http://www.arcgis.com/home/item.html?id=3311c052030044969b6fc3a819a79f0c
2014 & 2015 HPMS Pavement Data		2014-2015	2016	AKDOT	http://www.arcgis.com/home/item.html?id=731c7487046c4a5faa9841853e7a94e1
State Improvement Plan Sites			2016	AKDOT	http://www.arcgis.com/home/item.html?id=c01edacf6a364164a124fd4f82836214
Overall Pavement Data			2016	AKDOT	http://www.arcgis.com/home/item.html?id=b9315d5763064005af2198e6dd09ba8c
Open Street Map		2017	2017	Open Street Map Foundation	
Borehole					
CALM Sites 2012		2012	2013	Nikolay Shiklomanov and Dmitry Streletskiy	http://www.arcgis.com/home/item.html?id=b330b8d3ecd247eaa6d6ca6a4c992877
Borehole Temperature		2008	2013	Institute of Northern Engineering, University of Alaska	http://www.arcgis.com/home/item.html?id=2b058998ce694fdaf0dd85a738e06324
Global Terrestrial Network for Permafrost - United States/Alaska			2014	Alexandre Bevington/ Department of Geography/ University of Ottawa/ abevi061@uottawa.ca	http://www.arcgis.com/home/item.html?id=bf6f0a2af68e45998da74ed2549e6f5c

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