Rapid and Gradual Permafrost Thaw: A Tale of Two Sites

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Abstract Warming temperatures and increasing disturbance by wildfire and extreme weather events is driving permafrost change across northern latitudes. The state of permafrost varies widely in space and time, depending on landscape, climate, hydrologic, and ecological factors. Despite its importance, few approaches commonly measure and monitor the changes in deep (>1 m) permafrost conditions with high spatial resolution. Here, we use electrical resistivity tomography surveys along two transects in interior Alaska previously disturbed by wildfire and more recently by warming temperatures and extreme precipitation. Long-term point observations of permafrost depth, temperature, and water content inform geophysical measurements which, in turn, are used to extrapolate interpretations over larger areas and with high spatial fidelity. We contrast gradual loss of recently formed permafrost driven by warmer temperatures and increased snowfall, with rapid permafrost loss driven by changes in air temperature, snow depth, and extreme summer precipitation in 2014.

Plain Language Summary Permafrost, or ground that remains perennially frozen, is thawing across Arctic and sub-Arctic regions, driven in part by climate warming, wildfire, and changes in the amount and timing of rain and snow. When permafrost thaws, previously frozen carbon can be released to the atmosphere as greenhouse gases, water flow and storage is altered, and community land use and access are impacted. Permafrost landscapes can be mapped over large areas from satellites or airborne remote sensing methods, but only at the surface with limited information obtained at depth. Measurements of deeper permafrost properties are often limited to point observations. We use geophysical measurements to indirectly map and monitor high spatial resolution changes in permafrost characteristics within the ground. Combined with point observations of soil temperature and moisture content, and thaw depths, geophysical measurements help to extend our ability to measure changing permafrost conditions over time. At two nearby transects in interior Alaska, we document the long-term trajectory of permafrost thaw following wildfire. Our results show similar yet distinct responses in shallow permafrost recovery and more recent degradation, both gradual and rapid, caused by warming temperatures, increased snowfall, and extreme summer rainfall events.

1. Introduction

Northern latitudes are transforming, with widespread thawing and degradation of permafrost—which underlies nearly one quarter of the northern hemisphere land mass—altering the structure and function of these critical landscapes. Permafrost is warming in Arctic and sub-Arctic regions (Smith et al., 2022), and permafrost loss is expected to continue throughout the 21st century (Fox-Kemper et al., 2021; Lawrence et al., 2012; Pastick et al., 2015). A vast amount of carbon is stored in the permafrost zone, a significant portion of which is vulnerable to degradation and release to the atmosphere as greenhouse gases when permafrost thaws (Miner et al., 2022; Natali et al., 2021; Schuur et al., 2015; Turetsky et al., 2020; Waldrop et al., 2021; Walter Anthony et al., 2018). Thawing of permafrost also impacts hydrologic systems (Walvoord & Kurylyk, 2016), including mobilization of organic matter and other dissolved constituents into surface water systems (Vonk et al., 2019). Societal impacts of thawing permafrost include risk to infrastructure (Hjort et al., 2022; Melvin et al., 2017) as well as direct and indirect impacts to northern communities (Gibson et al., 2021).

Many factors influence the trajectory of permafrost stability, including air temperature, snow depth, topography, vegetation cover, organic layer thickness (OLT), soil texture and moisture content, surface water extent, precipitation, and disturbance such as wildfire or land-use change (Jorgenson et al., 2010). While systematic climate
warming can lead to gradual top-down permafrost thaw, extreme or episodic events such as wildfire (Brown et al., 2015; Jafarov et al., 2013; Turetsky et al., 2020), precipitation (Douglas et al., 2020; Neumann et al., 2019), and surface water inundation (Walvoord & Kurylyk, 2016) can cause spatially and temporally variable abrupt thaw. Significant thaw can generate thermokarst features, typically in ice-rich permafrost environments, where melting of ground ice causes subsidence that impounds surface water in a positive feedback that promotes further permafrost degradation (Olefeldt et al., 2016). Conversely, permafrost can re-form after thaw when climatic and ecosystem conditions are favorable; for example, when vegetation and organic material recovers after wildfire (Brown et al., 2015; Gibson et al., 2018; Jafarov et al., 2013), or within the margins of recently receded lakes where ecological succession supports vegetation that fosters growth of new permafrost (Briggs et al., 2014). Near-surface permafrost in many areas of interior Alaska, including recently formed permafrost, is already close to 0°C, making these locations increasingly vulnerable to future thawing (Smith et al., 2022).

We present new repeat geophysical measurements together with long-term observations of permafrost depth, temperature, and soil moisture at two transects within and across the boundary of the 1983 Rosie Creek fire, which burned a lowland black spruce forest in the Bonanza Creek Long Term Ecological Research (LTER) site near Fairbanks, Alaska (Figure 1a). This site is within an abandoned floodplain of the Tanana river, which is presently about 2 km to the southeast. Soils are primarily silty loams with shallow organic material and some sandy horizons (Van Cleve et al., 1996). Depth to permafrost is typically less than 50 cm in undisturbed areas, and total permafrost depth exceeds 25–45 m at two nearby boreholes. The climate is characteristic of continental sub-Arctic regions, with mean average air temperature of −3.3°C and mean annual precipitation is 280 mm water equivalent (Douglas et al., 2020).

Long-term monitoring (Viereck et al., 2021) and numerical modeling of post-fire permafrost thaw, recovery, and gradual degradation under a warming climate (Brown et al., 2015) provided motivation for initial geophysical measurements in 2014 to characterize deep subsurface permafrost characteristics not readily measured with surface or remote sensing observations, and with high spatial resolution across the burned-unburned transition (Minsley et al., 2016). Electrical resistivity tomography (ERT) measurements have proven useful in characterizing permafrost distributions (Briggs et al., 2014; Douglas et al., 2016; Lewkowicz et al., 2011), particularly when combined with downhole nuclear magnetic resonance (NMR) measurements that estimate in situ volumetric water content with depth (James et al., 2021; Kass et al., 2017; Minsley et al., 2016). Furthermore, repeat ERT measurements can detect changes in subsurface unfrozen water over time (Uhlemann et al., 2021). Warming temperatures and changes in the type, amount, and timing of precipitation observed here (Figures 1b and 1c) and elsewhere across northern latitudes are causing spatially and temporally variable thaw trajectories (Douglas et al., 2020; Farquharson et al., 2022). This study demonstrates how geophysical observations, coupled with more traditional physical measurements of permafrost, can quantify changes in permafrost distribution and liquid water content that elucidate how permafrost landscapes recover and evolve following disturbance.

2. Data and Methods

ERT data were acquired along two transects labeled LTER and KENJ (Figure 1a). Geophysical data collection at the LTER transect was repeated in 2014, 2015, 2016, 2019, and 2021, while the KENJ transect was surveyed once in 2015 (James et al., 2020; Kass et al., 2018; Minsley et al., 2015, 2016, 2018, 2022). Data sets were acquired between late August and early September to occur near the time of maximum seasonal thaw depth. ERT data were acquired with a SuperSting R8 instrument (Advanced Geosciences, Inc., Austin, Texas) using a dipole-dipole array geometry (Telford et al., 1990). The 2014 LTER survey was 111 m-long, with 112 electrode locations separated by 1 m. All subsequent LTER surveys started from the same position, but were extended to 124.5 m-length by using 84 electrodes separated by 1.5 m. The 2015 KENJ transect was 166.5 m long, with 112 electrodes and 1.5 m electrode spacing.

ERT data were inverted to recover resistivity models using the ResIPy software (Blanchy et al., 2020) that is based on the R2 inversion algorithm (http://www.es.lancs.ac.uk/people/amb/Freeware/Freeware.htm). The 2014 LTER data set was inverted independently because of its different transect length and electrode spacing compared with later years, while the 2015–2021 data were processed using a time-lapse difference inversion. The difference inversion uses the recovered resistivity from the first (2015) data set as a reference model for the inversion of subsequent data sets. A single borehole NMR log was also collected at LTER in 2015 to estimate volumetric water content in the upper 1 m (see Methods section in Minsley et al. [2016]).
Figure 1. Study area map, soil temperature, and precipitation trends. (a) Electrical resistivity tomography (ERT) transect locations (KENJ and LTER) within the Bonanza Creek LTER in interior Alaska cover both burned and unburned areas of the 1983 Rosie Creek fire (red hatched area). Green shaded areas in the state inset map show other areas with silty fluvial sediments in the discontinuous permafrost zone with mean annual air temperature between −5 and −1°C (Jorgenson et al., 2008). (b) Soil temperature (Farquharson et al., 2022) and (c) precipitation and snow depth data from a nearby undisturbed site show decadal warming of shallow soils and variable precipitation (Bonanza Creek LTER - University of Alaska Fairbanks [http://www.lter.uaf.edu], 2021).
Thaw depth was measured along each transect at the time of each ERT survey using a permafrost probe; OLT was measured in 2014, 2015, and 2021; and plant species cover was visually estimated in 2014 and 2015 (James et al., 2020; Kass et al., 2018; Minsley et al., 2015, 2016, 2018, 2022). At LTER, we also incorporate the long-term record of annual depth-to-permafrost measurements along portions of the LTER profile since 1984 (Viereck et al., 2021). At KENJ, annual temperature measurements are available in a nearby 24-m-deep borehole (Yoshikawa et al., 2002, https://permafrost.gi.alaska.edu/site/bz2) as well as hourly temperature and volumetric water content measurements at depths from 0.19 to 4.5 m in a separate downhole sensor array (http://lapland.gi.alaska.edu/vdv/vdv.php/historical/54).

### 3. Results

Elevation decreases about 1 m from north to south along the LTER transect, which begins in the Rosie Creek burn area, crosses a fireline, and ends in an unburned area (Figure 2a). Primary vegetation in the burned and unburned parts of the transect is black spruce, shrub, and moss; re-growth in the burned area has lower density spruce trees and a greater abundance of deciduous shrubs compared with the unburned area. The fireline, a relative topographic low occasionally accumulating standing surface water, has fewer black spruce and shrubs, with Sphagnum and other mosses being dominant. OLT was similar in the burned and fireline areas, both significantly thinner than in the unburned part of the transect (Table S1 in Supporting Information S1). There was not a discernible change in OLT between 2015 and 2021.

Depth to frozen ground measured along the transect during each ERT survey was consistent from 2014 to 2021 with slightly deeper measurements at several locations in more recent years. Frozen ground was around 70–100 cm in the burned area, greater than 250 cm in the middle of the fireline, and 50–75 cm in the unburned area (Figure 2a). Long-term permafrost depth measurements made annually since 1984 (Viereck et al., 2021) are...
summarized as box-and-whisker plots for 10 staked locations in the burned area (Figure 2b), 20 locations in the fireline (Figure 2c), and 10 locations in the unburned control (Figure 2d).

Resistivity models are shown for the independent inversion of the 2014 ERT data (Figure 2e) as well as time-lapse difference inversions of the 2015–2021 data sets (Figures 2f–2i). Resistivity values were consistently lowest beneath the fireline (<100 Ω·m), with variable patches of low and intermediate resistivity (100–1,000 Ω·m) beneath the burned portion of the transect, and high resistivity values (>1,000 Ω·m) observed beneath the unburned portion and at depths >7–12 m. The percentage change of the 2016, 2019, and 2021 resistivity models relative to the 2015 reference resistivity model are shown in Figures 2j–2l. Downhole NMR measurements made in 2015 near the 35 m mark (Kass et al., 2018) indicated decreasing volumetric water content with depth in the active layer (Figure 2f2). The probed depth to permafrost near this location was 101–116 cm.

The KENJ transect is about 300 m northeast of LTER (Figure 1), and rises about 2.5 m in elevation from west-to-east over its 166.5 m length (Figure 3a). KENJ is entirely within the burn area, and the 2015 measured OLT was similar to the LTER burned area (Table S1 in Supporting Information S1). Plant species cover was also similar to the LTER burned area, though with somewhat lower density of black spruce, less moss, and more lichen. Measured thaw depth was highly variable, from 60 to 120 cm where permafrost was detected but greater than the 245 cm probe length at a number of locations along the transect.

Inverted resistivity values from the single 2015 ERT data set were low across the entire profile (Figure 3b), with exception of a few patches of elevated shallow resistivity (e.g., 110–125 m profile distance). Annual temperature was recorded in the 24 m-deep borehole (Yoshikawa et al., 2002) near the middle of the transect (Figure 3c) and a shallower array of temperature and volumetric water content probes recorded hourly data (http://lapland.gi.alaska.edu/vdv/vdv.php/historical/54) at six discrete depths between 0.19 and 4.50 m (Figures 3d–3g).

Annual deep borehole temperature measurements reveal warm permafrost (≥−0.2°C) that has remained stable beneath 6 m over the 2007–2021 time interval (Figure 3c), with deepening of the permafrost table from 2.5 m in 2007 to 5 m after 2016. Hourly soil temperature measured nearby at 0.19 m, 0.51 m, and 1.2 m depths indicate annual freezing and thawing, though the 1.2 m values shifted from a maximum annual temperature of 0.5–1.7°C
and minimum temperature of −1.5—−0.2°C before 2014 to maximum temperature ranging between 1.7 and 4.7°C and minimum temperature that remained above 0°C after 2014. At 2 and 3 m depth, temperatures remained near 0°C before 2014, after which they began to vary annually, reaching a maximum of 2–3°C in 2019. Temperature at 4.5 m depth was always above 0°C; however little-to-no annual variability was observed before 2014 with values remaining near ~0.6°C, whereas temperature began to vary annually between 0.6 and 1.7°C after 2014.

Soil moisture data also show a shift in trends beginning in 2014 (Figure 3e). Before 2014, water content above 1.2 m depth varied seasonally during annual freeze-thaw, though the magnitude of unfrozen water variation was muted at 1.2 m depth compared with 0.19 and 0.51 m. Water content at 2 and 3 m depth was near zero and <0.1, respectively, and had no annual cycle. At 4.5 m depth, water content varied from <0.1 to >0.6 annually. After 2014, water content trends below 1.2 m changed significantly, with most depths exhibiting annual variability from <0.1 to >0.6. At 4.5 m, annual variability ceased after 2014 and water content remained above 0.6. Temperature and water content data are also shown with more detail during a portion of 2014 (Figures 3f and 3g) and discussed below.

4. Discussion

4.1. Post-Fire Thaw

Thaw depth increased steadily for 16 years after the 1983 Rosie Creek fire in both the burned and fireline parts of the LTER transect at a rate of about 7–14 cm/year, while depth to the permafrost table remained unchanged in the unburned control (Figures 2b–2d). This thawing is consistent with removal of vegetation and organic material caused by wildfire, and by mechanical disturbance along the fireline, the southern half of which was scraped to mineral soil (Viereck et al., 2021). Deep thaw was observed beneath the burned part of the ERT transect (Figures 2e–2i), with low resistivity measured to depths of about 7–12 m. Significant thaw is also observed beneath the fireline; while not as deep as beneath the burned section of the transect, thaw was deepest to the south where the fireline disturbance was greatest. Resistivity in the fireline was notably lower than other unfrozen areas, which we interpret as higher liquid water content, consistent with the low topography and vegetation cover. While the KENJ site does not have a similar record of thaw depth measurement after fire, borehole temperature measurements suggest that it also experienced deep post-fire thawing given its position within the fire perimeter (Yoshikawa et al., 2002). This is supported by the ERT data (Figure 3b) that also shows low resistivity to similar depth as at LTER.

Our results show deep thaw occurred in both the burned area and fireline; however, land surface elevation within the fireline decreased by ~40–50 cm relative to the unburned side while the burned surface had negligible decreases. Therefore, we presume soils at this site were not ice-rich, and the topographic decrease observed in the fireline was caused by mechanical disturbance rather than thaw settlement.

4.2. Shallow Permafrost Recovery

In 1999, a shallow permafrost layer began to reform at about 1 m depth in the burned area of the LTER transect and has persisted ever since (Figure 2b). Favorable conditions for reforming shallow permafrost in the burned part of the transect are attributable to below-average temperature and snow depth that year (Bonanza Creek LTER - University of Alaska Fairbanks [http://www.lter.uaf.edu], 2021), along with gradual recovery of vegetation and organic material.

ERT data also detected the reformed shallow permafrost layer, augmenting the thaw-depth measurements (Figures 2e–2i). Furthermore, the ERT results mapped its thickness (~1–2 m) and imaged with high spatial resolution an intra-permafrost talik between the shallow reformed permafrost layer and deeper undisturbed permafrost. Mapping beneath the permafrost layer is not feasible with typical thaw-depth measurements without drilling, highlighting the value of remotely sensed geophysical observations in this setting. Resistivity within the reformed permafrost layer was notably lower than the undisturbed shallow permafrost beneath the unburned part of the transect, likely indicating the reformed permafrost is warmer and contains a greater fraction of liquid water.
4.3. Gradual Warming and Permafrost Degradation

Probed depths to the newly formed permafrost layer in the LTER transect began to increase around 2014, with an average depth of 106.7 cm from 1999 to 2013 and 133.4 cm from 2014 to 2021 (Figure 2b). Slight deepening of the active layer was also observed after 2014 in the unburned part of the transect (67.4 cm on average before 2014 vs. 76.3 after). Repeat ERT survey results (Figures 2e–2i) corroborate and extend observations of depth to permafrost, indicating both top-down and lateral changes in permafrost. Time-lapse changes (Figures 2j–2l) indicate decreasing resistivity in both the burned and unburned parts of the transect, consistent with top-down thawing. Large decreases in resistivity are also observed at the margins of the fireline, indicating lateral thaw. Within the fully thawed fireline, minimal changes in resistivity are observed, likely due to changes in liquid water saturation over time.

Several factors may contribute to the degradation of shallow permafrost after 2014. In addition to overall climate warming, increases in rainfall have been observed to stimulate permafrost thaw in boreal ecosystems, and this timeframe has seen the wettest (2014) and third-wettest (2016) summers over a 91-year record (Douglas et al., 2020). In addition, the winter of 2017–2018 saw early and deep snowfall that has been attributed to widespread increases in talik formation, including a nearby site within the Bonanza Creek LTER (Farquharson et al., 2022). Numerical simulations driven by local air temperature and snow depth data also support the trajectory of deep talik formation after fire, followed by a reforming shallow permafrost layer that ultimately degrades and thaws completely (Brown et al., 2015, Figure 11c).

4.4. Rapid Permafrost Loss

Rapid loss of permafrost at KENJ occurred over a short period between July and September 2014 (Figures 3f and 3g). Pre-2014 temperature and water content observations were consistent with the shallow permafrost layer discussed previously in the burned portion of the LTER transect (Figures 2e–2i). About 230 mm of rainfall occurred during June–July 2014, including 66.5 mm over July 1–2, two of the 10 wettest days on record since 1929. Shallow soil moisture at 0.19 and 0.51 m followed patterns consistent with earlier years, rapidly increasing in the spring to peak values around mid-May to mid-June (Figure 3d). However, at 4.5 m depth an annual pulse of increased water content was observed earlier in 2014 (mid-July, Figure 3g) than the previous 4 years (late August–November), indicating earlier recharge of this deeper unfrozen layer (Figures 3d and 3e).

Shortly after the rapid increase at 4.5 m depth, water content rose quickly at 3.0 m, exceeding maximum values over the previous 4 years and reaching a maximum of 0.43 by August 3, along with increase in temperature to about 0.1°C (Figures 3f and 3g). Concurrently, shallow water content at 1.2 m depth rose quickly from near 0 to about 0.09, also higher than recent-year maxima. These trends suggest both increasing water levels at depth, likely from nearby lateral transport, as well as recharge from above. Very suddenly starting late on September 1 and into early September 2, water content at 2.0 m depth spiked from 0 to 0.7, decaying slowly to a level of about 0.53 by the end of September (Figures 3f and 3g). Just a few hours after the spike at 2.0 m depth, water content at 1.2 m depth rose from its previous level of 0.09 to about 0.4 over a period of several hours on September 2. Ever since this 2014 event, water content at all depths shows significant annual variability, peaking around 0.25–0.5, except for the deepest sensor at 4.5 m that has remained >0.5 (Figure 3e). Temperature trends also shifted after 2014, with significant seasonal increases at 2.0–3.0 m depth which had previously remained around 0°C (Figure 3d).

The transition in temperature and water content at this point location is evidence of rapid permafrost thaw, likely of a similar shallow reformed permafrost layer as was found at LTER, due to higher air temperatures, deeper snow during two previous winters, and the extreme precipitation and increased saturation from both above and below the permafrost layer. The pre-2014 spatial extent of this shallow permafrost at KENJ is unknown, but we hypothesize that it may have been similar to conditions on the burned part of the LTER transect. By the 2015 ERT survey at KENJ, the entire transect appeared almost fully thawed in the uppermost ~5–10 m, also consistent with borehole temperature observations. Isolated pockets of elevated resistivity remained, for example, around 110–125 m distance on the profile which was ground-truthed by drilling as shallow permafrost (Figure 3b), that are similar in character to the shallow permafrost layer at LTER, suggesting most permafrost at this location may have been lost in 2014 as documented by the downhole temperature and water content observations. Given similar meteorological forcing at the two sites, differences in shallow permafrost thaw are attributed to local variability in soils, organic layer insulation, lateral groundwater transport, and recharge.
4.5. Estimating Changes in Belowground Water Content

The spatial and temporal changes in electrical resistivity described above are primarily controlled by changes in unfrozen water content. We developed an empirical relationship between resistivity and volumetric water content using 53 co-located ERT and NMR measurements extracted from 10 different silty lowland sites with similar soil characteristics (Kass et al., 2017; Minsley et al., 2016) to transform resistivity values along our transects into estimates of unfrozen water content (see Supporting Information S1). Resistivity values from the 2015 LTER transect (Figure 2f, Figure S1c in Supporting Information S1) were mapped using the power-law fit to predict unfrozen water content (Figure 4a, Figure S1a in Supporting Information S1). Because of the nonlinear fitting relationship, the significant portion of resistivity values above 1,000 Ω-m map to a small range of water content less than 0.1, whereas resistivity between 100 and 1,000 Ω-m translate to a wide range of water content. The bias toward low water content over a large range of resistivity is evident along the ERT cross-section (Figure 4a), with high water content beneath the fireline (∼60–80 m) and intermediate values in the burned area (0–60 m).

Finally, time-lapse changes in resistivity at LTER (Figures 2j–2l) were used to infer absolute changes in subsurface unfrozen water. Although the magnitude of change in resistivity is similar (∼20%–75%) in both the burned and unburned parts of the transect, the total change in unfrozen water is different in these areas because of their different starting conditions. This pattern of change in absolute water content is shown for the 2015–2021 timelapse ERT difference (Figure 4b). Mostly frozen and low water content in the unburned area results in smaller changes in water content for a given change in resistivity than partly frozen and intermediate-to-high water content in the burned area and at the fireline margins. Within the fireline, shallow decreases in water content may relate to drier conditions in 2021 compared to 2015, when standing water was present.

5. Conclusions

Multiple rates and stages of permafrost change are observed at two nearby transects: gradual thawing of permafrost initiated by the 1983 wildfire; reforming of a shallow frozen layer beginning around 1999, leaving a talik at depth; gradual deepening and degradation of the shallow permafrost layer since about 2014; and rapid loss of permafrost at one site over a period of just a few weeks in summer 2014. By combining repeat geophysical measurements and long-term observations of the state of permafrost at these sites, we were able to develop
an interpretive timeline of gradual and abrupt permafrost change, as well as an approach for assessing below-
ground water content dynamics. These multi-modal observations help to link long-term monitoring at point locations 
with high spatial-resolution information along geophysical transects, providing a more robust interpretive 
framework than either dataype alone.

Data Availability Statement

Geophysical data sets acquired as part of this study are published in the USGS ScienceBase repository (https://
www.sciencebase.gov/catalog/). Direct links to the data sets cited in the article text are: https://doi.org/10.5066/
F7959FM0 (2014 data), https://doi.org/10.5066/F7F18WT1 (2015 data), https://doi.org/10.5066/P99PTGP4 (2016–2017 data), https://doi.org/10.5066/P9H6UVQ (2019 data), and https://doi.org/10.5066/P9XEMDE1 (2021 data).

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