Influence of permafrost characteristics on vegetation change in Yukon and Northwest Territories, Canada

by

Nina Vogt

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in
Wildlife Ecology and Management

Department of Renewable Resources
University of Alberta

Abstract

Permafrost thaw is a significant contributor to landscape change and ecosystem disruption in northern systems. While previous studies have examined the impact of permafrost on vegetation change, few have investigated the connection of permafrost characteristics to the type and extent of vegetation change. Additionally, much of the literature investigating vegetation change due to permafrost thaw has been restricted to peatlands. This thesis investigates the impacts of permafrost thaw on vegetation characteristics and how permafrost characteristics may influence the type and severity of ecosystem change in the peatlands of Jean Marie River, Northwest Territories, and lowland boreal forests of the Whitehorse and Kluane regions of Southern Yukon, Canada.

Ecological and geophysical field investigations were incorporated to examine how vegetation characteristics differ with permafrost thaw, how vegetation differences may indicate permafrost thaw, and what this may tell us about landscape transition and the availability of habitat for characteristic boreal species post-thaw. I hypothesized that post-thaw vegetation would shift to species supported by moister conditions and that permafrost characteristics would be linked to the type and extent of vegetation change. I further hypothesized that such changes could result in qualitative differences in the amount and distribution of future habitat available to woodland caribou (*Rangifer tarandus tarandus*) in these regions.

Ecosystems and permafrost conditions varied considerably across the three study areas in Jean Marie River, Greater Whitehorse, and Kluane. However, with permafrost degradation, vegetation across all study sites shifted from species supported by drier, intact permafrost conditions to those supported in wetter environments. In general, there was a loss of characteristic boreal

forest species, including lichens (*Cladina, Cladonia, Cetraria*), berries (*Vaccinium vitis-idaea, Empetrum nigrum, Shepherdia canadensis*), and forbs (*Lupinus arcticus, Galium boreale*), as well as loss of forest cover. Both permafrost characteristics and surrounding ecosystems influenced the shift of species. Type and severity of vegetation and ecosystem change appear to be linked to permafrost characteristics. Qualitative assessment suggests substantive implications from permafrost thaw for the amount and distribution of important seasonal habitats for woodland caribou in these systems, with related considerations of landscape connectivity for both boreal and northern mountain populations.

This research fills a critical knowledge gap in how ecosystems in northwestern Canada may transition with permafrost thaw and helps reduce uncertainties concerning potential landscape change associated with climate change.

Preface

This thesis is directly connected to a larger corpus of projects led by the Permafrost and Geoscience team at Yukon University, that focus on evaluating the impact of permafrost thaw on communities. The team is characterizing permafrost and mapping its vulnerability through a multi-disciplinary approach involving coring permafrost, measuring ground temperature, and generating profiles of permafrost through Electric Resistivity Tomography. I interpreted the influence of permafrost characterizations produced by this study on vegetation difference at the study sites included in this thesis, with the assistance of Dr. Fabrice Calmels. ERT figures were generated by the Permafrost and Geoscience team.

The extended methodology section located in section 0 of the appendix was developed by the Permafrost and Geoscience team. Extended methodology for imagery processing located in section 0 of the appendix was developed by Cyrielle Laurent. All other text in this thesis is original.

The vegetation surveys and related data analysis are my original work. However, vegetation survey methodology was adapted from Degré-Timmons et al. (2018) to fit the research questions addressed in this thesis. This was done with the assistance of Dr. Fiona Schmiegelow.

Acknowledgments

I would like to thank the Yukon University Research Centre, the Northern Scientific Training Program, the University of Alberta North, and the W. Garfield Weston Foundation for their generous financial support of this research.

Thank you to my supervisor Dr. Fiona Schmiegelow for supporting my project and sharing your advice and expertise in its development and execution.

Thank you to the Climate Change Research and Permafrost and Geoscience teams (formerly Norther Climate ExChange), who have been a great support network. Special thanks to my co-supervisor, Dr. Fabrice Calmels, for sharing your expertise and guidance and always taking the time to ensure I had all the information and tools I needed to be successful. And to Cyrielle Laurent, who encouraged me to pursue graduate school and opened the door to developing this project. The support, guidance, and opportunities you have provided me have been instrumental to my success.

Thank you to my family for your unconditional support and for always encouraging me to pursue my goals.

To Meghan and Hayley, your friendship and support have kept me going on many occasions, and I thank you for all that you do to brighten my life.

Finally, to my husband Michael, thank you for being in my corner throughout this journey, providing endless support, and pushing me to believe in my capabilities. I am so grateful for you.

Contents

List of Tables

List of Figures

1. Chapter 1: Introduction

1.1. Introduction

Climate change impacts in Canada's north are an issue of growing concern, as global temperatures have already increased by approximately 1 degree Celsius above pre-industrial conditions (Allen et al. 2018). This increase is exacerbated in the north, with climate warming at two to three times the average global rate of change (Environment and Climate Change Canada 2019). Temperatures are thought to have reached up to 2 degrees above pre-industrial conditions in some areas (Streicker 2015; Allen et al. 2018). This surpasses the critical 1.5-degree mark, stipulated by the Intergovernmental Panel on Climate change, to cause "long-lasting or irreversible damage" (Allen et al. 2018). Areas with mean annual temperatures around 0 degrees Celsius are at higher risk for drastic environmental change triggered by an increase in air temperature (Christensen 2004). Discontinuous permafrost in subarctic regions are within these parameters and are already experiencing climate change-triggered degradation, leading to the reshaping of ecosystems (Christensen 2004; Vitt et al. 2010).

Permafrost is defined as perennially frozen ground that remains at or below a temperature of 0^{o}C for at least two consecutive years and may or may not contain ice (French 2007). It is classified into zones of continuous permafrost, extensive discontinuous permafrost, sporadic discontinuous permafrost, and isolated patches of permafrost (Figure 1.1-1) based on permafrost extent or percent of the land area expected to be underlain by permafrost (Heginbottom et al. 1995). Approximately 50 – 60% of Canada is underlain by these classes of permafrost (Harris 2015). Distribution and thickness of permafrost depend on many factors, including surficial geology, topography, aspect, and vegetation. As well, the balance of geothermal heat gain and loss is critical to the formation and thickness of permafrost, which is heavily influenced by climatic conditions (French 2007). Permafrost thickness in Canada ranges from over 1,000 m to less than 10 cm (Harris 2015). The area above permafrost that seasonally freezes and thaws is the active layer (Murton 2019).

This thesis concerns the influence of permafrost characteristics on vegetation and thaw-related transition of landscapes in Jean Marie River, Northwest Territories, and two locations in Southern Yukon, Canada (Greater Whitehorse and Kluane). The Traditional Territory of Jean Marie River First Nation (JMRFN) is located in the Great Slave Plain Mid-Boreal ecoregion. Extensive lakebed plains left behind by glacial Lake McConnel heavily influenced the post-glacial ecological and permafrost characteristics in the area (Ecosystem Classification Group 2009; Calmels, Laurent, et al. 2015). JMRFN traditional territory spans the boundary of the sporadic discontinuous permafrost zone and the extensive discontinuous permafrost zone. Permafrost conditions are highly variable as a result, and between 10% and 90% of the landscape is expected to be underlain by permafrost (Heginbottom et al. 1995; Calmels, Laurent, et al. 2015). Permafrost in the area is characterized by thaw-sensitive peat plateaus surrounded by peatlands. With a thickness of <10m and a temperature close to 0^{o} C, this permafrost is very vulnerable to thaw (Smith and Burgess 2000; Calmels, Laurent, et al. 2015). See section 3.1 of **Chapter 3**: Transition of a permafrost landscape in a changing climate for a more extensive overview of ecological context, geological history, and permafrost conditions in Jean Marie River.

The Greater Whitehorse area is located on the traditional territory of Kwanlin Dün First Nation and Ta'an Kwäch'än Council and falls in the Southern Lakes Boreal Low Zone (Environment Yukon 2017). Sites in the Greater Whitehorse area are located within the sporadic discontinuous permafrost zone, with between 10% and 50% of the area expected to be underlain by permafrost. The Kluane study area is located in the traditional territory of The White River, Kluane, and Champagne Aishihik First Nations within the Ruby Range Boreal Low Zone (McKenna and Flynn 2017). Similar to JMR, sites in the Kluane area are located on the boundary of the sporadic discontinuous permafrost zone and the extensive discontinuous permafrost zone (Heginbottom et al. 1995). Permafrost surveyed in this region is characterized by thaw sensitive frost heave mounds, or lithalsas (French 2007). The Geological features in both southern Yukon study areas are largely influenced by the most recent McConnell glaciation (Kotler 2003; Bond 2004). See section 3.1.2 and 3.1.3 of **Chapter 3**: Transition of a permafrost landscape in a changing climate for a more extensive overview of ecological context, geological history, and permafrost conditions in the Greater Whitehorse and Kluane study areas.

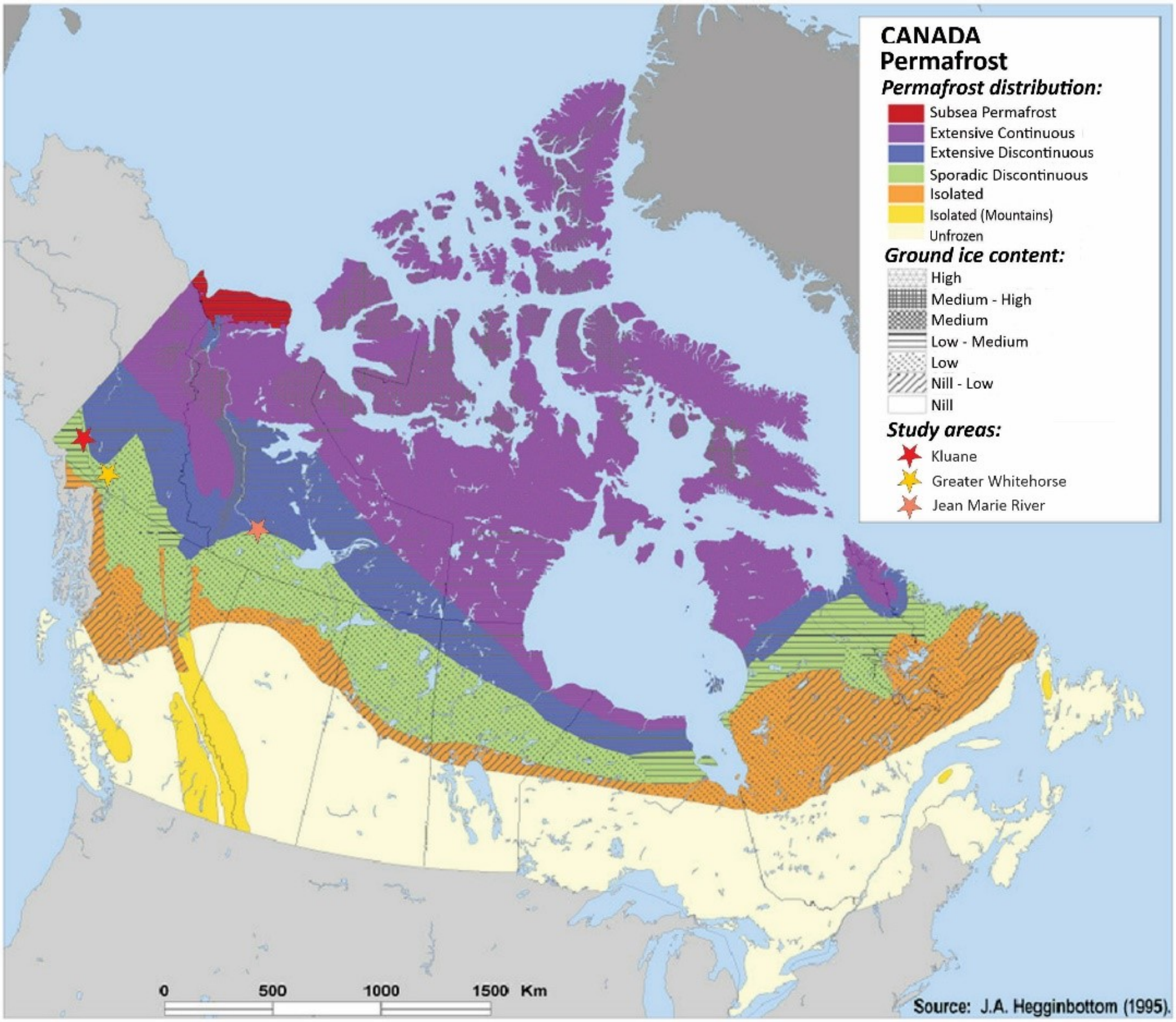


Figure 1.1-1. Adapted from Heginbottom (1995), showing distribution of permafrost zones in Canada based on the percent of land area expected to be underlain by permafrost, and level of ground ice content expected in permafrost areas. Study areas in Yukon and Northwest Territories are shown as stars on the map.

All of the study regions are vulnerable to landscape change in the face of changing climates, which raises concerns about the sustainability of northern ecosystems. These ecosystems support habitat for many species, including those relied upon by indigenous people for subsistence and cultural values. Degradation of permafrost alters surface topography (Lawson 1986) and causes changes in moisture levels and nutrient availability to plants (Camill et al. 2001; Baltzer et al. 2014). This may reduce habitat quality for boreal species, including those traditionally relied upon as country food.

1.2. Research goals and objectives

This thesis aims to understand and quantify the relationship between permafrost thaw and vegetation composition and how this relates to landscape transition and potential changes in habitat for woodland caribou. This involves three main research objectives:

1. Quantify vegetation characteristics associated with intact, transitional, and degraded permafrost conditions, and identify species that may be potential indicators of permafrost thaw (Chapter 2).
2. Evaluate the permafrost characteristics at sites using electrical resistivity tomography (ERT) surveys, permafrost coring, and temperature loggers, and understand how these characteristics may relate to vegetation differences between sites (Chapter 2).
3. Explore qualitatively how landscapes may change in a thawing environment and the impacts of these potential transitions on woodland caribou (Rangifer tarandus) habitat (Chapter 3).

1.3.Background

1.3.1. Palsas and lithalsas

Palsas are low, peat-covered mounds caused by the buildup of ground ice (Washburn 1983a). Where peat layers are very thin or absent, the term mineral palsa or lithalsa is used (Washburn 1983a; Gurney 2001; Pissart 2002; French 2007). These mounds are circular or oval and up to 10m high (Gurney 2001). They vary in size and can be present individually or in large complexes (Seppala 1982a). In peatlands, palsas are generally in the range of 0.5 to 1.5 m high (Baltzer et al. 2014). Permafrost mounds most often occur in sporadic and discontinuous permafrost areas but may also occur in areas of continuous permafrost (Railton and Sparling 1973; Zoltai and Tarnocai 1975; Washburn 1983b; Gurney 2001; Pissart 2002). Palsas require a mean annual air temperature (MATT) below 0ºC, while lithalsas generally occur in areas with a MAAT of -4ºC or lower. There are exceptions to this, and lithalsas may form in warmer temperatures given the presence of very fine-grained materials like clay and silt (Pissart 2002). Morphology and genesis of palsas can differ, resulting in variable thicknesses of ice and peat. However, within a field of palsas, formation is generally analogous.

1.3.2. Drivers of permafrost mound formation and degradation

Permafrost mound formation is driven by several factors, including topography, snow depth, vegetation cover, and soil type (Gurney 2001; Riseborough 2002). Due to wind action, snow flattens over topography, causing raised areas to have shallower snow depth than depressions (Railton and Sparling 1973; Seppala 1982b; Seppala 1990; Gurney 2001). Thinner snow cover allows for deeper cold penetration, increasing the likelihood frost survives the summer (Seppala 1982b; Seppala 1990; Gurney 2001; Pissart 2002). Frost heaving caused by deeper frost penetration and expansion of freezing water increases topographic relief, leading to a positive feedback cycle as the mound becomes larger (Zoltai and Tarnocai 1975; Gurney 2001; Pissart 2002). Snow drifts on the margins of the mound while the center remains more exposed, creating a colder center and warmer edges. This causes the center of the mound to accumulate more ground ice, therefore rising slightly higher than the border. The snow cover occurring on the mound periphery also functions as a protective layer for vegetation (Calmels et al. 2008).

Vegetation cover influences permafrost mound formation through insulative value and change in surface albedo (Zoltai 1975; Pissart 2002). Organic cover shields frost from seasonal thaw (Zoltai 1975), which is exacerbated as the soil drains and moss cover dries, increasing its insulative value (Pissart 2002). As palsas form in peatlands, a change in dominant ground cover from *Sphagnum spp*. to *Cladonia spp.* occurs, lightening the color of ground covering vegetation. This increases surface albedo, further protecting frost from seasonal thaw (Railton and Sparling 1973; Worsley et al. 1995; Gurney 2001).

The establishment of palsas and lithalsas is heavily dependent on soil type. The dominant process of development is cryosuction, i.e., the migration of soil water into the freezing zone (French 2007). Segregated ice, i.e., layers of ice within surrounding material, are formed, raising the permafrost mound (French 2007). Fine-grained mineral sediments like silt and clay are most susceptible to cryosuction and segregated ice formation; however, it may also occur in peat (Allard and Rousseau 1999; Pissart 2002). In peatlands, palsas may occur only in peat or extend into the mineral sediment below peat at the base of the wetland. In the latter case, more extensive segregation ice forms in the mineral sediment than in the peat layer (Gurney 2001). Thicker ice lenses may also form at the permafrost table and in the lower portion of the permafrost profile. The former is caused by the repetitive freezing and thawing of surface water infiltrating from the active layer, while the latter is caused by a diminished thermal gradient as permafrost penetrates successively deeper (Calmels et al. 2008). These processes frequently cause the amount of ice present in permafrost to exceed the content that could be present in its thawed state (French 2007). This is termed excess ice (Harris et al. 1988; French 2007). Conversely, coarse, well-draining sediments like gravel generally exhibit low ice content (Jorgenson and Osterkamp 2005; French 2007).

The same factors that drive permafrost formation play a role in its degradation. Increases in air temperature warm permafrost and trigger thaw (Osterkamp 2007; Calmels et al. 2008). As degradation occurs, ground subsidence leads to greater snow accumulation, thereby increasing the ground's insulation and exacerbating thaw (Zhang 2005; Calmels et al. 2008; Jorgenson et al. 2010). Often, ponding is caused by the thaw of excess ice. The combination of latent heat carried by the groundwater and insulated by snow create a positive feedback loop for permafrost degradation (Calmels et al. 2008). Vegetation shifts that occur with permafrost can also drive degradation. Shrubification of degraded areas creates greater insulation combined with snowfall reducing frost penetration (Zuidhoff and Kolstrup 2005). In this way, increased snowfall and prevalence of shrubs due to climate change (Streicker 2015; IPCC 2018) may be a driver of permafrost thaw (Payette et al. 2004).

1.4. Thesis Structure

This thesis consists of four chapters. Chapter (1) outlines the context and thesis objectives. The second chapter investigates how vegetation differs between intact, transitional, and degrading permafrost conditions at surveyed locations and the permafrost characteristics of each of these sites. Using a combination of field and statistical analysis, it provides an interpretation of inter-site differences in vegetation and permafrost characteristics. Chapter 3 explores how landscape may change based on the observations in Chapter 2 and how this may impact woodland caribou habitat. Chapter 4 contains concluding statements, a discussion of the research limitations, and recommendations for future studies.

2. **Chapter 2:** Characterizing the relationship between vegetation and permafrost

2.1. Abstract

The effects of permafrost thaw on vegetation were evaluated in intact, transitional, and degraded permafrost conditions. Vegetation at sites was compared to permafrost conditions from geophysical surveys to evaluate relationships between permafrost characteristics and vegetation composition. Four peatland permafrost sites were analyzed in Jean Marie River, NT, and seven permafrost sites were evaluated in the greater Whitehorse and Kluane regions of Southern Yukon. NMDS ordination and ANOSIM tests showed a significant difference in vegetation composition between intact, transitional, and degraded areas at each site ($p < 0.05$). SIMPER analysis determined that this difference was primarily due to the introduction of *Sphagnum spp.* and the loss or reduction of *Cladina spp., Vaccinium vitis-idaea,* and *Rhododendron groenlandicum* in degraded areas of peatland permafrost sites. In Southern Yukon, an increase in *Carex and Eriophorum spp*. and a reduction in *Hylocomium/Pleurozium* mosses in degraded areas was largely responsible for the difference between plant communities present in intact and degrading permafrost areas.

Vegetation differences appear to have a direct link to permafrost conditions. Greater differences in functional characteristics between species present in intact and degraded permafrost were found at sites where the topography was more extreme, excess ice content was high, and surficial material did not support drainage (silt, clay, sand). These characteristics influenced the degree of vegetation difference and forest loss associated with degrading permafrost conditions.

2.2. Introduction

A large portion of Canada's boreal forest overlaps with discontinuous permafrost (Baltzer et al. 2014), making permafrost thaw one of the most substantial disturbances to this region (Jorgenson and Osterkamp 2005). Where permafrost is present, changes in soil foundation, surface topography, nutrient levels, and hydrology create microenvironmental conditions different from those on unfrozen ground (Seppala 1982a; Jorgenson et al. 2001; Christensen 2004; Jorgenson and Osterkamp 2005). Upward aggregation of permafrost mounds can cause the soil surface to rise above the water table (Vitt et al. 1994). In peatlands, this is observed in *Picea mariana* forested mounds with lichen-dominated ground cover surrounded by *Sphagnum*-dominated wetlands with few to no trees (Railton and Sparling 1973; Baltzer et al. 2014). Full forest species assemblages may be supported by these mounds (Worsley et al. 1995). Outside of peatlands, boreal forest can occur on permafrost mounds which more consistently resemble permafrost-free areas. This can include *Picea mariana* and *Picea glauca* forests and deciduous mixed forest cover (Jorgenson and Osterkamp 2005; Gaanderse et al. 2018).

When permafrost thaws, physical support of ecosystems is lost (Osterkamp et al. 2000). Frozen water becomes liquid, thermokarst depressions or ponds result (Camill et al. 2001; Schuur et al. 2007; Rydin and Jeglum 2013a). Surface moisture increases, drastically impacting vegetation composition (Camill 1999; Camill 2005; Schuur et al. 2007). The amount and characteristics of settlement are directly influenced by surficial geology, ice content of permafrost, landscape relief, and permafrost's size and distribution (Lawson 1986). Dependent on these conditions, thermokarst ponds may form (Osterkamp et al. 2000). Aquatic vegetation commonly to occurs in thermokarst ponds, which can eventually drain through stream channels, palduify with bog vegetation, or drain through subsurface sediments (Jorgenson and Osterkamp 2005). Areas of permafrost collapse can also be identified by species not typically found in moist conditions, most notably dead trees and woody debris (Zoltai 1975; Vitt et al. 1994; Worsley et al. 1995). Areas where active thaw is occurring can be identified by pooling of water and leaning or curved trees (Zoltai 1975; Rydin and Jeglum 2013a).

This study examines vegetation characteristics in intact, transitional, and degraded permafrost conditions in conjunction with the characteristics of permafrost at each site. It was hypothesized that, with loss of permafrost, vegetation would shift to species supported in moister habitats, and these differences would be influenced by permafrost characteristics. This research was conducted at study sites in Jean Marie, River, Northwest Territories, Greater Whitehorse, Yukon, and Kluane, Yukon. It compares permafrost conditions to the differences in vegetation between these conditions at each site, as well as the permafrost characteristics at each site.

2.3. Study region and sites

Study sites were located in discontinuous permafrost or on the boundary of discontinuous and continuous permafrost zones (Heginbottom et al. 1995) in Yukon and Northwest Territories, Canada. With mean annual air temperatures of close to 0° C, these zones are especially vulnerable to environmental change triggered by a warming climate (Christensen 2004). Mean annual air temperature at studied areas has increased between 1° C and 1.2° C since 1981 (Environment and Climate Change Canada 2020), triggering large scale permafrost degradation (Calmels, Laurent, et al. 2015; Calmels, Roy, et al. 2015; Yukon Research Centre Permafrost and Geoscience 2020a; Yukon Research Centre Permafrost and Geoscience 2020b).

Four study sites were located in the traditional territory of the Jean Marie River First Nation (JMRFN), Jean Marie River, Northwest Territories (61.5329° N, 120.6347° W), located at the Jean Marie and Mackenzie Rivers' confluence (Figure 2.3-1 A). The mean annual air temperature in nearby Fort Simpson (approximately 50 km SE of JMR, 61.8628° N, 121.3530° W) is -2.8° C (1981-2010), which has risen from an average of -3.8° C (1951-1980). The mean annual precipitation is 387.6 mm, consisting of 238.6 mm of rainfall and 187.0 cm of snowfall (1981-2010). On average, there are 97 frost-free days per year (1981-2010) (Environment and Climate Change Canada 2020). According to the Permafrost Map of Canada (Heginbottom et al. 1995), Jean Marie River is located at the boundary of the sporadic discontinuous permafrost zone and the extensive discontinuous permafrost zone. This means between 10 and 90% of JMRFNs traditional territory is expected to be underlain by permafrost. Permafrost in the area is characterized by thaw-sensitive palsas, surrounded by peatlands (Calmels, Laurent, et al. 2015). Palsas are forested with *Picea mariana* and have a ground cover of lichens and moss (*Hylocomium/Pleurozium*).

Seven sites were located in Yukon, Canada, in the traditional territory of the Kwanlin Dun First Nation, the Ta'an Kwach'an Council, the Kluane First Nation, the White River Frist the Champagne and Aishihik First Nation. According to the Permafrost Map of Canada (Heginbottom et al. 1995) these sites occur within zones of sporadic and discontinuous permafrost, meaning 10 to 90% of the surrounding area is underlain by permafrost.

Three of seven of Yukon sites were located in the Kluane area (Figure 2.3 1 B). YT 7 and YT 6 are located 20 and 40 km north of Burwash Landing (61.3542° N, 138.9944° W) on the Alaska Highway, respectively. YT 5 is located approximately 95 km south of Burwash Landing on the Alaska Highway. The mean annual air temperature of Burwash Landing is -3.4° C (1981-2010), which has risen from an average of -4.6° C (1951-1980). The mean annual precipitation is 274.7 mm, consisting of 196.2 mm of rainfall and 105.5 cm of snowfall (1981-2010). On average, there are 42 frost-free days per year (1981-2010) (Environment and Climate Change Canada 2020). Permafrost at these sites is characterized by thaw sensitive palsas and lithalsas (Calmels, Roy, et al. 2015) forested with *Picea glauca*.

Four of seven Yukon sites were located within the Greater Whitehorse area (60.7212° N, 135.0568° W: Figure 2.3-1 C). YT 2 is located close to the city center, while YT 1 is located approximately 20 km south of Whitehorse. YT 4 is located approximately 40 km north of Whitehorse, and YT 3 is located about 12 km west of Whitehorse city center on Fish Lake Road. Whitehorse's mean annual air temperature is -0.5 C (1981-2010), which has risen from an average of -1.5° C (1951-1980). The mean annual precipitation is 262.3 mm, consisting of 160.9 mm of rainfall and 141.8 cm of snowfall (1981-2010). On average, there are 80 frost-free days per year (1981-2010) (Environment and Climate Change Canada 2020). Permafrost at these sites is characterized by thaw sensitive palsas and lithalsas (Yukon Research Centre Permafrost and Geoscience 2020b; Yukon Research Centre Permafrost and Geoscience 2020a), except YT 4, which is likely relict permafrost, or permafrost that formed under past climactic conditions and exists in an area where it can not form under present conditions, and is therefore disconnected with surface features (F. Calmels, personal communication, September 14, 2020). YT 1 and 2 are forested with *Picea glauca*, while YT 4 is forested with deciduous mixed forest. YT 3 is unforested and dominated by *Betula glandulosa*, lichens, and moss (*Hylocomium/Pleurozium*).

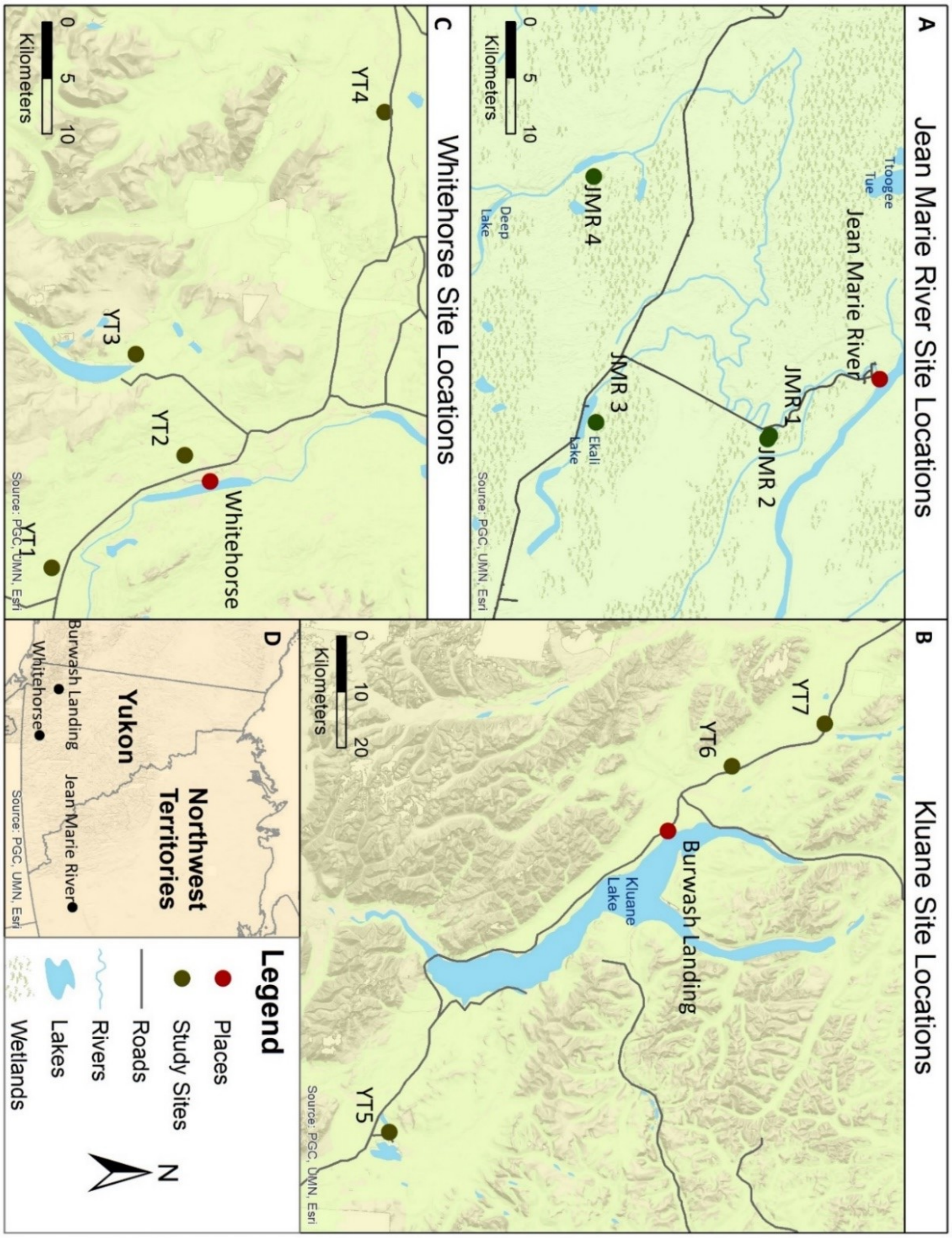


Figure 2.3-1. Map of the locations of study sites in A) Jean Marie River, Northwest Territories 2018 (JMR sites 1, 2, 3 and 4) B) Kluane Region, Yukon 2019 (YT sites 5, 6, and 7), and C) Whitehorse Region, Yukon 2019 (YT sites 1, 2, 3, and 4). D) shows sites in broader study region. Permafrost monitoring stations are located at sites JMR 1, 3, and 4, and YT 1 through 7. ERT surveys were conducted at JMR 1 and 3, and YT 1-6. Vegetation surveys were conducted at all sites.

2.4. Methods

2.4.1. Vegetation Survey

Vegetation transects were placed in three categories at each site, along a gradient of thawing permafrost: in intact areas (on permafrost plateaus), in transitioning areas (along the plateaus where permafrost was thawing), and in degraded areas (where permafrost had thawed). These areas were selected through visual differentiation of intact permafrost plateaus, including increased ponding and slumping of ground. Permafrost condition was verified by probing for permafrost and the location boreholes and permafrost monitoring stations. In each category, 2x30-meter banded transects were set as parallel to each other as possible, based on plateau configuration, as topography sometimes limited transect placement. In scenarios where a parallel configuration was not possible, transects were placed as close to parallel as possible and in the nearest possible location, ensuring the degraded area was associated with the intact permafrost (e.g., Figure 2.4.4-2 C). Vegetation sampling methodology was modified from protocol developed by Degré-Timmons et al. (2018). Systematic sampling of vegetation was undertaken by choosing a starting location centered on the permafrost plateau and extending out 15 m in each ordinal direction. In the case of transitional transects, the border of the thawing permafrost mound was followed. Five 1x1 meter vegetation plots were set every 6 meters facing the permafrost plateau, at 0m, 6m, 12m, 18m, and 24m. Figure 2.4.1-1 illustrates a schematic of the site layout. In each vegetation plot, ground cover, species type, and percent cover were recorded. Photos were taken of each plot for reference. GPS points were taken at each plot and the start and end of the transect. Within the banded transect, trees were assessed for condition (snag, cones, leaning) and size (DBH).

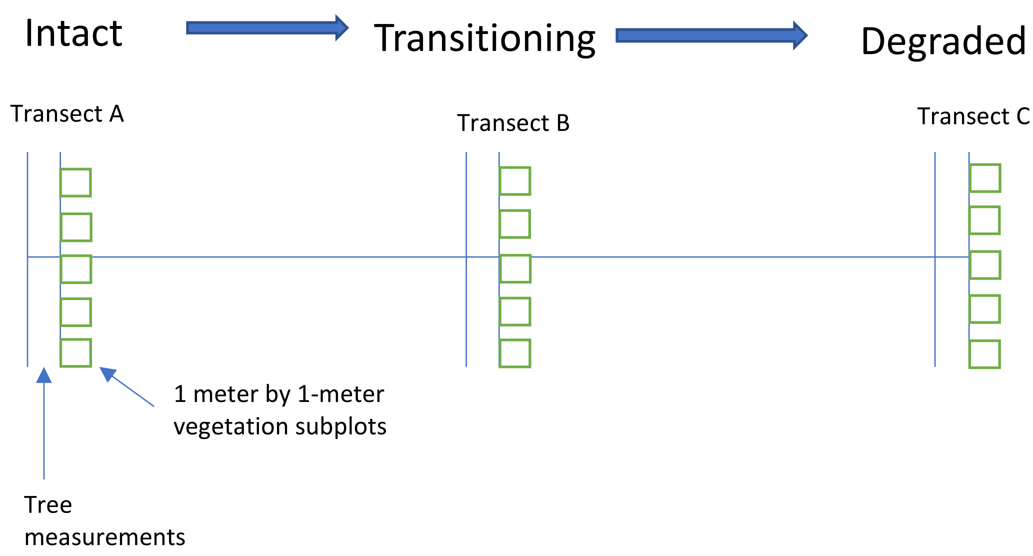


Figure 2.4.1-1. Schematic of vegetation sampling layout at study sites in Jean Marie River NT, Greater Whitehorse YT, and Kluane YT. Orientation of transects is based on permafrost condition (intact, transitional, degraded). Tree measurements for health, size, and number of trees were taken within each banded transect. Vegetation subplots were surveyed for species and percent cover.

2.4.2. Identification of Permafrost Characteristics

Permafrost characteristics were determined through examination of ERT profiles, permafrost cores, data from permafrost temperature monitoring stations, and observed characteristics of permafrost plateaus (height, aspect, etc.). ERT profiles were studied to determine the resistivity of ground and thickness of permafrost based on whether ground was more (indicates permafrost) or less resistive. This was validated by examining ice content, grain size, and permafrost depth obtained from borehole data. Permafrost temperature was obtained from temperature loggers installed in boreholes. For more detailed methodology on the collection of permafrost data, see section 0 of Appendix.

2.4.3. Appendix Data Analysis

Non-metric multidimensional scaling ordination (NMDS) using the Bray-Curtis dissimilarity calculation was run on each site's plots to identify and evaluate differences in plant species composition and structure in intact, transitional, and degraded permafrost conditions. NMDS was chosen because the species data contained many 0s, and the goal was to assess differences across an environmental gradient. Additionally, NMDS does not assume a linear relationship between variables. NMDS was run using the metaMDS function from the vegan package in RStudio (Oksanen et al. 2020). Species present at each site were displayed as variables on ordinations to evaluate species associations with permafrost conditions. Stress values were calculated to assess the goodness of fit of each ordination to the data. ANOSIM tests were run on each site to determine the statistical significance of differences between permafrost conditions, with a significance level of $p > 0.05$, and to determine the degree of difference between intact and degraded transects. SIMPER tests were used to identify the species most strongly contributing to observed differences between sites. SIMPER and ANOSIM functions were run in RStudio with the package vegan (Oksanen et al. 2020).

Dominant species at each site were determined by calculating proportional representation based on percent cover. Because of low species abundance, any species that contributed 20% or more were considered dominant species.

2.4.4. Imagery and Mapping

All Yukon sites, except for YT 2 (located within Whitehorse Airport airspace), were surveyed by drone to provide high-quality imagery. The imagery was processed with Agisoft Metashape to provide Digital Surface Models (DSM) and Orthoimages for each site. For more detailed information on the processing of imagery, see section 0 of Appendix.

Imagery for Hamilton Boulevard was obtained from the GeoYukon aerial photo database (https://mapservices.gov.yk.ca/GeoYukon/Index.html?layerTheme=Air%20Photo%20Library). A drone survey was not available for Jean Marie River Sites. Imagery quality was too low for mapping purposes, so permafrost condition was modeled based on elevation and vegetation characteristics to provide a reference for mapping sites. Sites were mapped in ArcMap based on GPS points taken during the survey.

Table 2.4.4-1. Summary of site location, survey, and analysis performed at sites surveyed in Jean Marie River in 2018 (JMR 1-4) and Southern Yukon in 2019 (YT 1-7). Analysis performed include electric resistivity tomography (ERT), temperature data from boreholes, geotechnical analysis of permafrost cores collected when drilling boreholes, surveys of vegetation on intact, transitional, and degraded permafrost conditions, and drone surveys. Checkmarks represent which surveys were conducted at which sites.

Site	Location	ERT	Borehole	Geotechnical Analysis	Vegetation Survey	Drone Survey
JMR 1	61.43411°N, 120.5477 °W	✓	✓	✓	✓	
JMR 2	61.43393°N, 120.548379 °W				✓	
JMR 3	61.295654°N, 120.580582 °W	✓	✓	✓	✓	
JMR 4	61.301982°N, 120.991043°W		✓	✓	✓	
YT 1	60.592443°N, 134.904312°W	✓	✓	✓	✓	✓
YT 2	60.69585°N, 135.016418°W	✓	✓	✓	✓	
YT 3	60.65369°N, 135.25941°W	✓	✓	✓	✓	✓
YT 4	60.844256°N, 135.672945°W	✓	✓	✓	✓	✓
YT 5	60.956234°N, 137.915524 °W	✓	✓	✓	✓	✓
YT 6	61.448118°N, 139.236232°W	✓	✓	✓	✓	✓
YT 7	61.58912°N, 139.411664°W		✓	✓	✓	✓

Figure 2.4.4-1. Maps of study sites JMR 1-4 surveyed in Jean Marie River in 2018. Maps show site layout and percent cover of functional group types. A) JMR 1, vegetation surveyed next to JMR permafrost station 1 along ERT transect, B) JMR 2, vegetation surveyed on a second palsa southwest of JMR permafrost station 1 (proximity shown in top right corner of inset), C) JMR 3, vegetation surveyed on a larger palsa northeast of JMR permafrost station 3, intersecting ERT transect. D) JMR 4, vegetation surveyed next to JRM permafrost station 4.

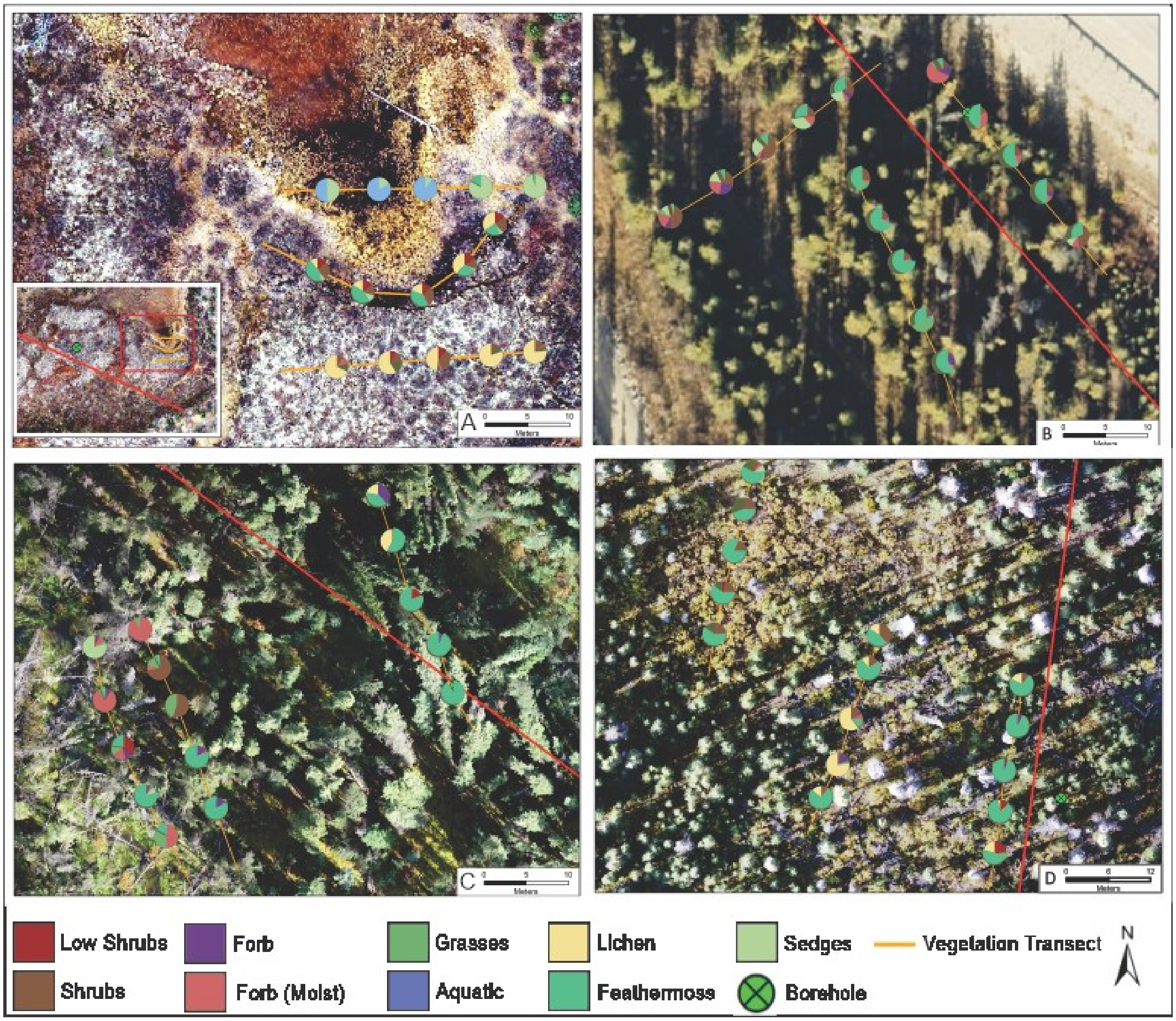


Figure 2.4.4-2. Maps of study sites YT 1-4 surveyed in Southern Yukon in 2019. Maps show site layout and percent cover of functional group types. Orthoimages developed from drone imagery, except for B) sourced from aerial photos. A) YT 1, vegetation surveyed next to Cowley Creek borehole along ERT transect, B) YT 2, vegetation surveyed next to Hamilton Boulevard borehole along ERT, C) YT 3, vegetation surveyed close to ERT, Fish Lake. Borehole later installed on palsa to the west of survey, D) YT 4, vegetation surveyed next to Ibex Valley borehole and ERT line.

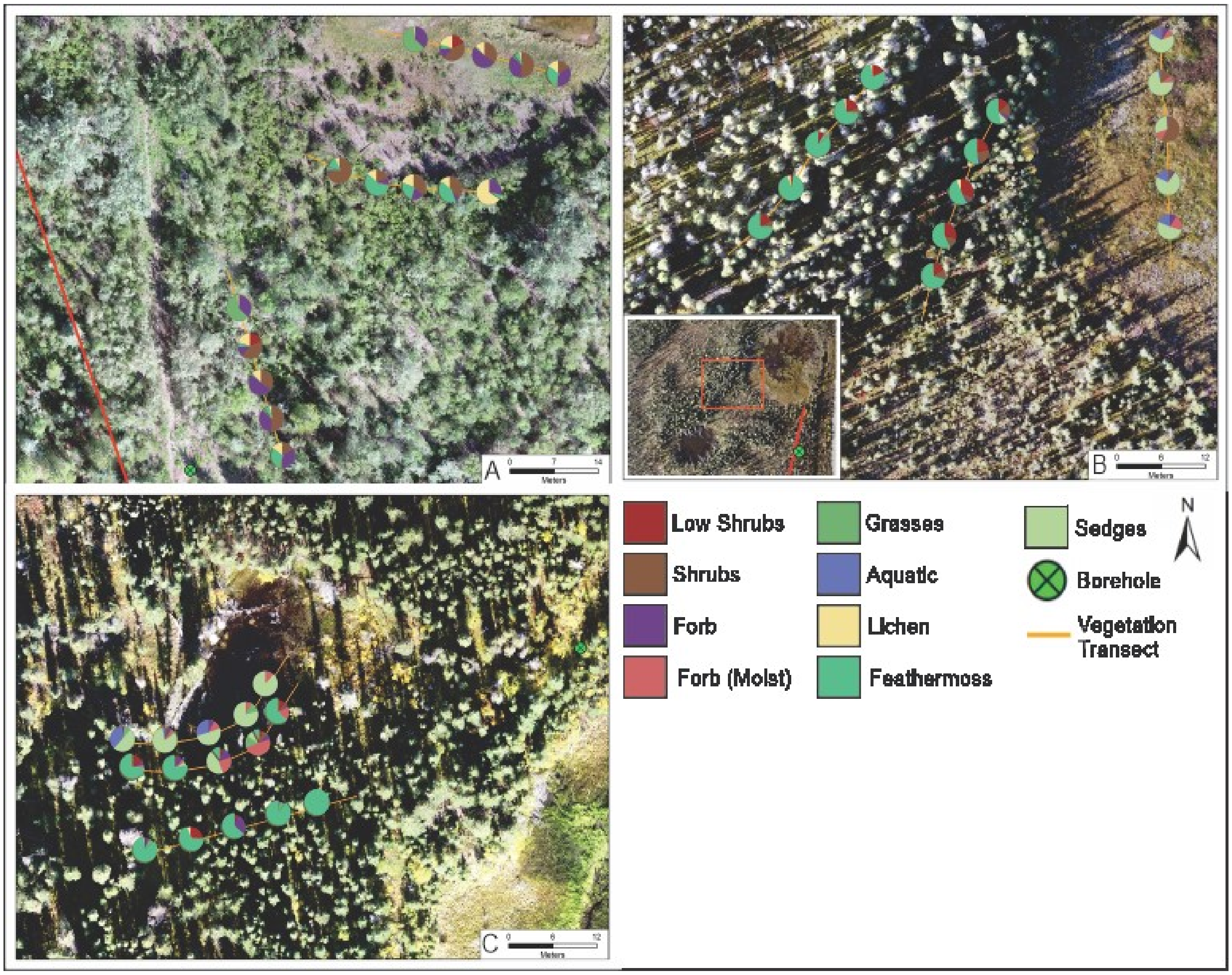


Figure 2.4.4-3. Maps of study sites YT 5-7 surveyed in Southern Yukon in 2019. Maps show site layout and percent cover of functional group types. Orthoimages developed from drone imagery, A) YT 5, vegetation surveyed next to borehole and ERT line, B) YT 6, vegetation surveyed near borehole and ERT line (inset shows proximity to borehole), C) YT 7, vegetation surveyed near borehole.

For full-page versions of site maps shown in Figure 2.4.4-1Figure 2.4.4-3, see sections 0 to 0 of Appendix

2.5. Results

2.5.1. Vegetation Characteristics

Dominant species varied between sites and permafrost conditions (see Table 2.5.1-1). At sites surveyed in Jean Marie River, lichens and shrubs dominated intact areas at all sites, while forbs also dominated JMR 3 and JMR 4. Degraded areas showed more variability in dominating species, with the commonality that all degraded sites were dominated by *Sphagnum* moss. Additional dominating species included sedges and ericaceous shrubs. Sites surveyed in southern Yukon had considerably more variation in dominating species (Table 2.5.1-1). In intact permafrost areas, moss (*Hylocomium/Pleurozium*) and shrubs were the dominant ground cover at most sites. Lichens and forbs were a dominant vegetation cover at only two and three out of seven sites, respectively. Only one site had grasses as a dominant species cover. In degraded permafrost areas, moss (*Hylocomium/Pleurozium*) was a dominating ground cover at three sites but at lower percentages than intact areas at the same sites. Sedges dominated four out of seven degraded sites, while forbs dominated two.

Table 2.5.1-1 Summary of dominant species present at each site surveyed in Jean Marie River, NT in 2018 and Southern Yukon in 2019 in areas of intact and degraded permafrost. Sites include Jean Marie River Sites (JMR) 1-4, and Yukon Sites (YT) 1-7. Because of low species abundance, any species that contributed 20% or more were considered dominant species.

Intact permafrost Dominating Species	Site(s)	Degraded permafrost Dominating Species	Site(s)
Lichens *(Cladina, Cladonia, Cetraria spp)*	JMR 1, 2, 3, 4 YT 3, 5	Sedges *(Carex, Eriophorum spp.)*	JMR 1, 2, 4 YT 1, 3, 5, 6, 7
Moss *(Hylocomnium, Pleurozium)*	YT 1, 2, 5, 6, 7	Moss (*Sphagnum spp.)*	JMR 1, 2, 3, 4
Rhododendron groenlandicum	JMR 1, 2, 3, 4	*Chamaedaphne calyculata*	JMR 1, 4
Vaccinium vitis-idaea	JMR 1, 2, 3, 4 YT 3, 6, 7	*Rhododendron groenlandicum*	JMR 3
Rubus chamaemorus	JMR 3, 4	Moss *(Hylocomnium, Pleurozium)*	YT 1, 2, 5
Betula glandulosa	YT 3	*Salix spp.*	YT 2, 5
Grasses	YT 5	*Equisetum arvense*	YT 1
Salix spp.	YT 2, 4	*Potentilla anserina*	YT 4
Lupinus arcticus	YT 8	Grasses	YT 4
Arctous rubra	YT 1		
Galium boreale	YT 1		
Hedysarum alpinum	YT 4		

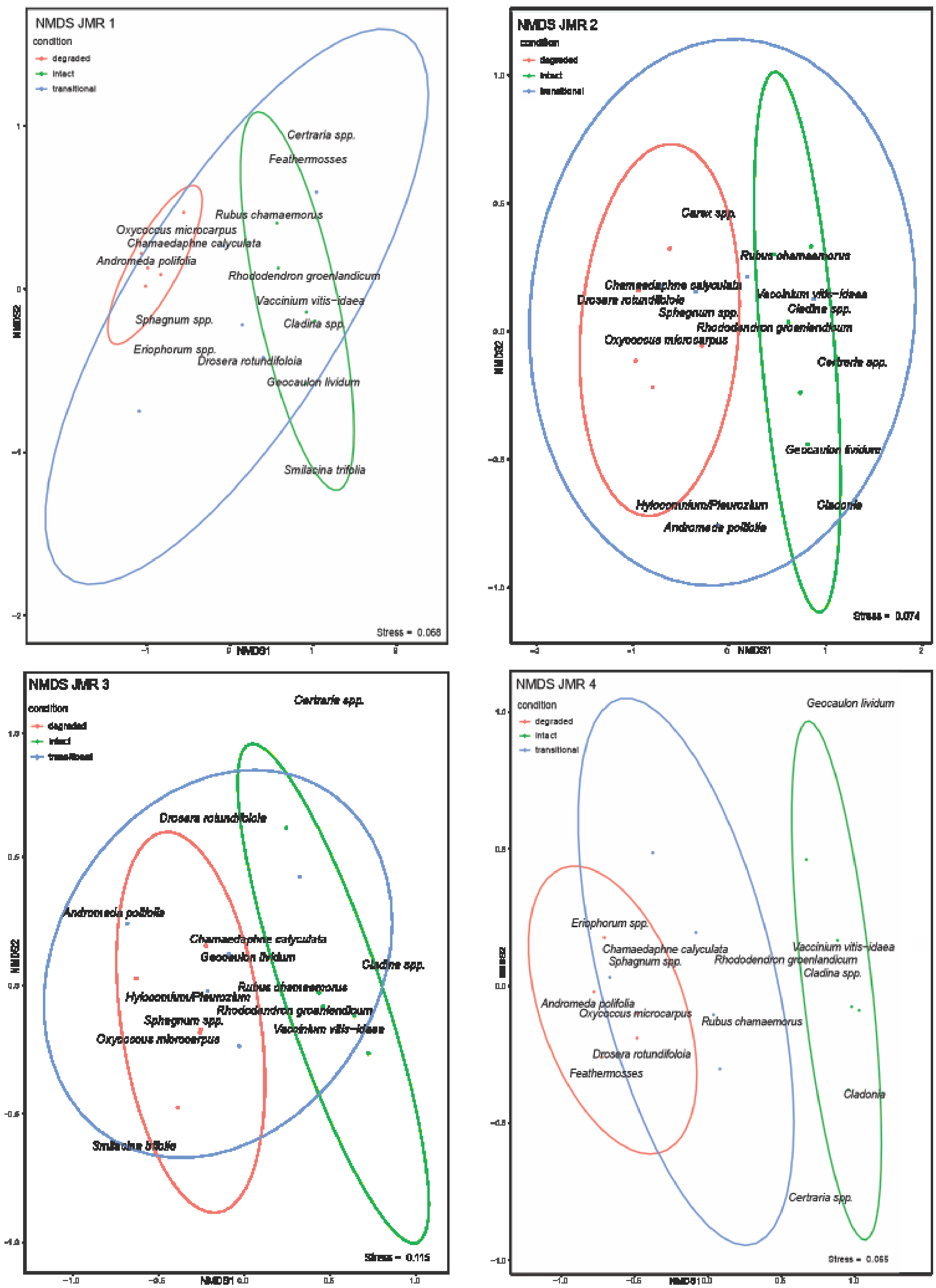


Figure 2.5.1-1. Non-metric multidimensional scaling (NMDS) plots of sites JMR 1-4 surveyed in Jean Marie River in 2018 for species and percent cover. Variables are percent cover of species present at each site. Ellipses represent communities of intact, transitional, and degraded permafrost.

NMDS ordinations of species distribution in JMR showed distinct plant communities between intact and degraded permafrost conditions (Figure 2.5.1-1). Transitional communities overlapped with intact and degraded plots, apart from JMR 4, where the intact community was entirely distinct from degraded and transitional plots (Figure 2.5.1-1). The greatest distinction between intact and degraded communities was observed at JMR 1, with reduced separation in communities at sites 4, 2, and 3, respectively. This pattern differs in NMDS ordinations of sites surveyed in southern Yukon, although distinct plant communities between permafrost conditions were still observed (Figure 2.5.1-2 and Figure 2.5.1-3). However, the amount of overlap between these communities was more variable. At YT 3 and 6, there was a clear distinction between intact and degraded permafrost conditions. At all other sites, all three permafrost conditions had some degree of overlap with each other. YT 1, 7, and 4 showed moderate overlap. The distinction of intact and degraded communities further increased with YT 2 and YT 5.

An ANOSIM test confirms that all sites showed significant dissimilarities based on permafrost condition (intact, degraded) (p-value < 0.05; Table 2.5.1-2), although there was variability in the degree of dissimilarity among sites.

Table 2.5.1-2. ANOSIM results derived from percent cover of vegetation at all sites surveyed in Jean Marie River, NT in 2018 and Southern Yukon in 2019 in areas of intact and degraded permafrost. Sites include Jean Marie River Sites (JMR) 1-4, and Yukon Sites (YT) 1-7, H_0 = there is no difference between permafrost conditions at each site (p=0.05).

Site	ANOSIM statistic	p-value
JMR 1	0.6493	0.0002
JMR 2	0.4951	0.0035
JMR 3	0.5804	0.0004
JMR 4	0.6458	0.0001
YT 1	0.6100	0.0070
YT 2	0.7160	0.0120
YT 3	0.9556	0.0150
YT 4	0.4600	0.0012
YT 5	0.2960	0.0014
YT 6	0.6689	0.0006
YT 7	0.6314	0.0001

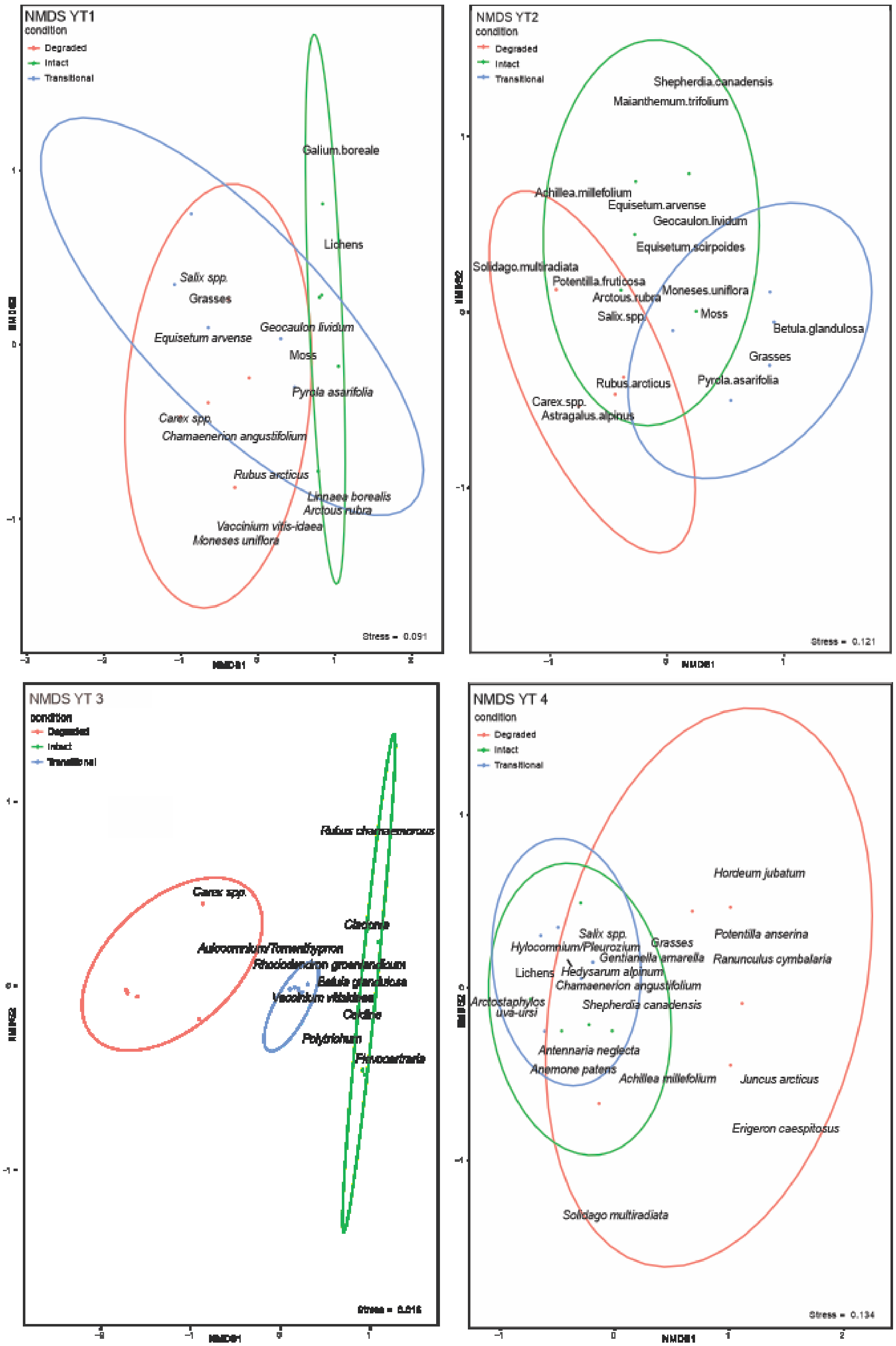


Figure 2.5.1-2. Non-metric multidimensional scaling (NMDS) plots of sites YT 1-4 surveyed in Southern Yukon in 2019 for species and percent cover. Variables are percent cover of species present at each site. Ellipses represent communities of intact, transitional, and degraded permafrost.

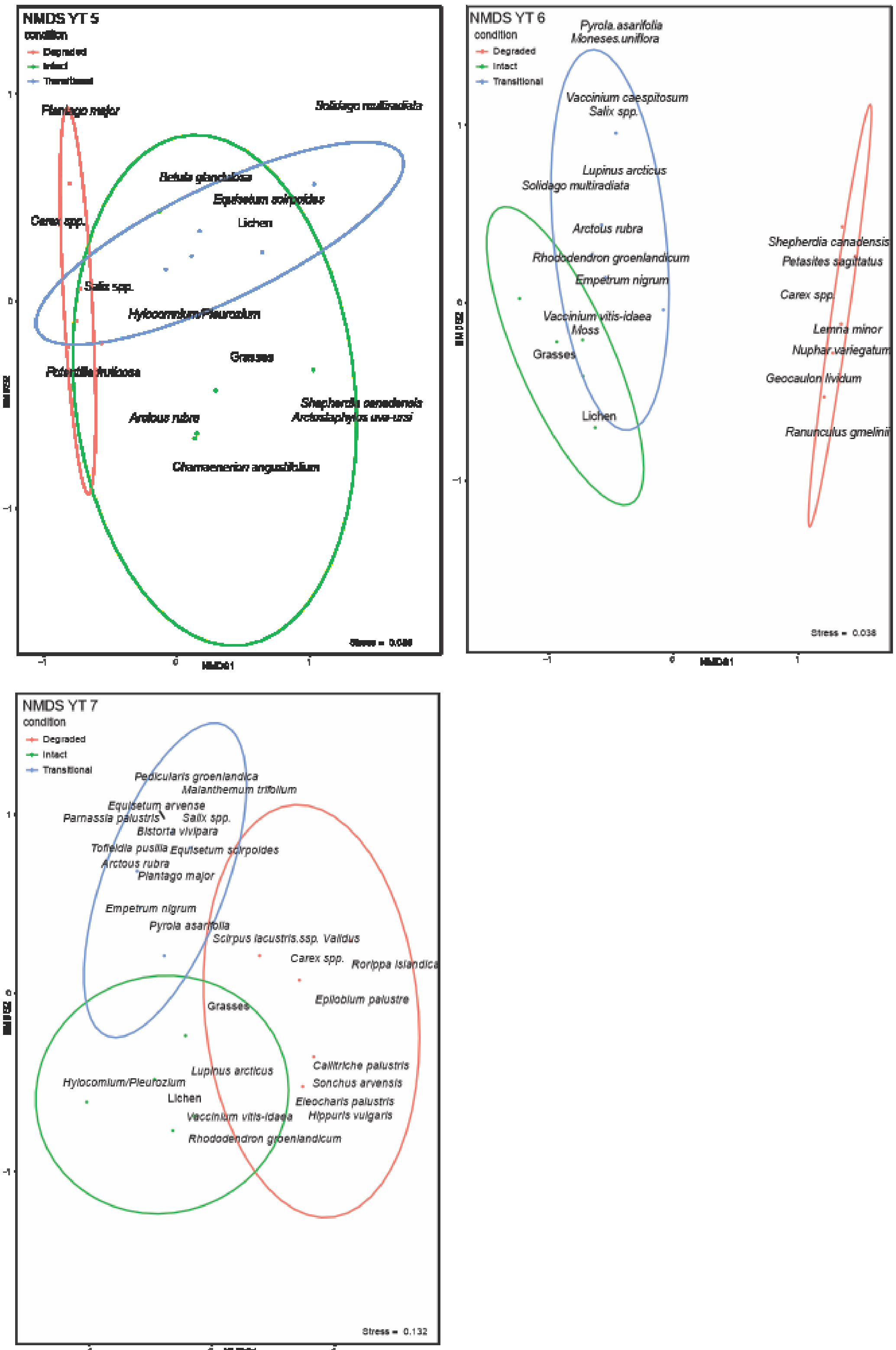


Figure 2.5.1-3. Non-metric multidimensional scaling (NMDS) plots of sites YT 5-7 surveyed in Southern Yukon in 2019 for species and percent cover. Variables are percent cover of species present at each site. Ellipses represent communities of intact, transitional, and degraded permafrost.

SIMPER analysis determined that in permafrost peatlands (JMR), differences between intact and degraded transects (Table 2.5.1-3) were primarily accounted for by the increase of *Sphagnum spp.* and the decrease/absence of *Cladina spp.,* in degraded transects. A decrease in shrubs in degraded transects contributed to minor differences in JMR 3 and 4. Similarly, the difference between intact and transitional transects (Table 2.5.1-4) was influenced mainly by the increase of *Sphagnum spp.* and the decrease of *Cladina spp.* in transitional transects. A decrease in shrubs contributed to minor differences in JMR 2.

Table 2.5.1-3. SIMPER results for sites JMR 1-4 surveyed in Jean Marie River in 2018, showing % contribution of largest contributing species to dissimilarity between intact and degraded transects, and total percent contribution to dissimilarity accounted for by all species. Vegetation was surveyed for species and percent cover in areas of intact, transitional, and degraded permafrost.

Condition	Site	Total %	Species	% contribution
Degraded vs. Intact	JMR 1	78%	*Sphagnum spp.*	45%
			Cladina spp.	28%
	JMR 2	75%	*Sphagnum spp.*	47%
			Cladina spp.	18%
			Vaccinium vitis-idaea	10%
	JMR 3	80%	*Sphagnum spp.*	55%
			Cladina spp.	25%
	JMR 4	76%	*Sphagnum spp.*	52%
			Cladina spp.	18%
			Rhododendron groenlandicum	6%

Table 2.5.1-4. SIMPER results for sites JMR 1-4 surveyed in Jean Marie River in 2018, showing % contribution of largest contributing species to dissimilarity between intact and transitional transects, and total percent contribution to dissimilarity accounted for by all species. Vegetation was surveyed for species and percent cover in areas of intact, transitional, and degraded permafrost.

Condition	Site	Total %	Species	% contribution
Intact vs. Transitional	JMR 1	77%	*Cladina spp.*	40%
			Sphagnum spp.	37%
	JMR 2	78%	*Sphagnum spp.*	33%
			Cladina spp.	57%
			Vaccinium vitis-idaea	11%
			Rhododendron groenlandicum	10%
	JMR 3	73%	*Sphagnum spp.*	48%
			Cladina spp.	25%
	JMR 4	75%	*Sphagnum spp.*	57%
			Cladina spp.	18%

Table 2.5.1-5 SIMPER results for sites JMR 1-4 surveyed in Jean Marie River in 2018, showing % contribution of largest contributing species to dissimilarity between degraded and transitional transects, and total percent contribution to dissimilarity accounted for by all species. Vegetation was surveyed for species and percent cover in areas of intact, transitional, and degraded permafrost.

Condition	Site	Total %	Species	% contribution
Degraded vs. Transitional	JMR 1	74%	*Sphagnum spp.*	51%
			Rhododendron groenlandicum	14%
			Eriophorum spp.	9%
	JMR 2	72%	*Sphagnum spp.*	48%
			Cladina spp.	14%
			Chamaedaphne calyculata	10%
	JMR 3	73%	*Sphagnum spp.*	40%
			Rhododendron groenlandicum	20%
			Cladina spp.	13%
	JMR 4	66%	*Sphagnum spp.*	23%
			Cladina spp.	17%
			Rubus chamaemorus	16%
			Rhododendron groenlandicum	10%

The difference between transitional and degraded transects (Table 2.5.1-5) was primarily accounted for by the invasion of *Sphagnum spp.* in degraded transects across all JMR sites. *Rhododendron groenlandicum* and *Cladina spp.* decreased or were lost in degraded transects at most sites. The presence of sedges at JMR 1, *Chamaedaphne calyculata* at JMR 2 was also responsible for the difference in vegetation characteristics between transects. At JMR 4, a decrease in *Rubus chamaemorus* also contributed.

Table 2.5.1-6. SIMPER results for sites YT 1-7 surveyed in southern Yukon in 2019, showing % contribution of largest contributing species to dissimilarity between degraded and intact transects, and total percent contribution to dissimilarity accounted for by all species. Vegetation was surveyed for species and percent cover in areas of intact, transitional, and degraded permafrost.

Condition	Site	Total %	Species	% contribution
Degraded vs. Intact	YT 1	71%	*Hylocomium/Pleurozium*	38%
			Equisetum spp.	19%
			Carex spp.	14%
	YT 2	75%	*Hylocomium/Pleurozium*	27%
			Carex spp.	14%
			Salix spp.	13%
			Equisetum spp.	21%
	YT 3	75%	*Cladina spp.*	35%
			Carex spp.	28%
			Betula glandulosa	12%
	YT 4	77%	*Potentilla ansernia*	20%
			Grasses	18%
			Hedysarum alpinum	17%
			Salix spp.	14%
			Shepherdia canadensis	8%
	YT 5	79%	*Salix spp.*	37%
			Hylocomium/Pleurozium	33%
			Carex spp.	9%
	YT 6	77%	*Hylocomium/Pleurozium.*	46%
			Carex spp.	24%
			Salix spp.	7%
	YT 7	71%	*Hylocomium/Pleurozium*	48%
			Carex spp.	23%

On palsas and lithalsas surveyed in southern Yukon, the presence of *Carex spp*. and decrease or absence of *Hylocomium/Pleurozium* moss in degraded transects heavily influenced the difference in vegetation characteristics between intact and degraded permafrost conditions at most sites surveyed (Table 2.5.1-6). *Salix spp.* increased in degraded transects at all sites but YT 4 (decreased). An increase in *Equisetum spp.* in degraded transects at YT 1 and 2 contributed moderately. At YT 4, an increase in grasses and *Potentilla ansernia and decreased shrubs and Hedysarum alpinum* contributed to differences in vegetation characteristics. A decrease in *Cladina spp.* in degraded transects only affected YT 3.

Table 2.5.1-7. SIMPER results for sites YT 1-7 surveyed in southern Yukon in 2019, showing % contribution of largest contributing species to dissimilarity between intact and transitional transects, and total percent contribution to dissimilarity accounted for by all species. Vegetation was surveyed for species and percent cover in areas of intact, transitional, and degraded permafrost.

Condition	Site	Total %	Species	% contribution
Intact vs. Transitional	YT 1	73%	*Hylocomium/Pleurozium*	50%
			Salix spp.	13%
			Equisetum spp.	10%
	YT 2	77%	*Hylocomium/Pleurozium*	27%
			Salix spp.	14%
			Grasses	14%
			Equisetum spp.	20%
	YT 3	75%	*Cladina spp.*	26%
			Hylocomium/Pleurozium	19%
			Betula glandulosa	11%
			Flavocertraria	10%
			Vaccinium vitis-idaea	9%
	YT 4	74%	*Salix spp.*	36%
			Hedysarum alpinum	22%
			Grasses	16%
	YT 5	71%	*Hylocomium/Pleurozium*	47%
			Cladina spp.	24%
	YT 6	71%	*Rhododendron groenlandicum*	21%
			Empetrum nigrum	20%
			Hylocomium/Pleurozium	11%
			Vaccinium vitis-idaea	10%
			Arctous rubra	9%
	YT 7	71%	*Hylocomium/Pleurozium*	37%
			Carex spp.	10%
			Lupinus arcticus	9%
			Equisetum spp.	15%

A decrease in moss (*Hylocomium/Pleurozium*) was primarily responsible for the difference in vegetation characteristics between intact and transitional permafrost conditions at most sites (Table 2.5.1-7). *Carex spp.* appeared in transitional transects at YT 7. At all sites but YT 1 (decreased), *Salix spp.* increased from intact to transitional permafrost. At YT 1 and 2, *Equisetum spp.* increased in transitional areas. A decline in shrubs in transitional transects contributed to the difference in vegetation characteristics at YT 3 and 6, while a decrease in *Lupinus arcticus* influenced YT 7. A reduction of lichen species from intact to degraded conditions influenced the difference in vegetation at YT 3, while an increase in grasses influenced YT 2 and 4.

Table 2.5.1-8. SIMPER results for sites YT 1-7 surveyed in southern Yukon in 2019, showing % contribution of largest contributing species to dissimilarity between transitional and degraded transects, and total percent contribution to dissimilarity accounted for by all species. Vegetation was surveyed for species and percent cover in areas of intact, transitional, and degraded permafrost.

Condition	Site	Total %	Species	% contribution
Degraded vs. Transitional	YT 1	79%	*Hylocomium/Pleurozium*	33%
			Equisetum spp.	21%
			Carex spp.	15%
			Salix spp.	10%
	YT 2	75%	*Hylocomium/Pleurozium*	34%
			Carex spp.	14%
			Salix spp.	13%
			Grasses	12%
	YT 3	77%	*Carex spp.*	18%
			Cladina spp.	17%
			Hylocomium/Pleurozium	18%
			Betula glandulosa	14%
	YT 4	72%	*Salix spp.*	26%
			Potentilla ansernia	23%
			Grasses	22%
	YT 5	85%	*Hylocomium/Pleurozium*	38%
			Cladina spp.	25%
			Salix spp.	22%
	YT 6	71%	*Hylocomium/Pleurozium*	38%
			Carex spp.	19%
			Rhododendron groenlandicum	8%
			Empetrum nigrum	6%
	YT 7	72%	*Hylocomium/Pleurozium*	31%
			Carex spp.	20%
			Eriophorum spp.	11%
			Lupinus arcticus	5%
			Eleocharis palustris	5%

At most sites, the difference in vegetation characteristics between degraded and transitional sites was heavily influenced by the decrease of moss (*Hylocomium/Pleurozium*) and an increase in sedges in degraded transects (Table 2.5.1-8). An increase of *Salix spp.* in degraded transects also contributed to multiple sites. A reduction in other shrubs in degraded transects impacted YT 1, 3, and 6. At YT 2 and 4, vegetation characteristics were influenced by an increase in grasses in degraded transects. Both YT 3 and 5 were influenced by a decrease of *Cladina spp.* in degraded transects. Forbs increased or decreased in degraded transects, dependent on species characteristics.

2.5.2. Permafrost Characteristics

Dipole-Dipole ERT surveys are presented for interpretation due to their deeper and more accurate representation of permafrost features over Wenner surveys (Figure 2.5.2-1)**Error! Reference source not found.**

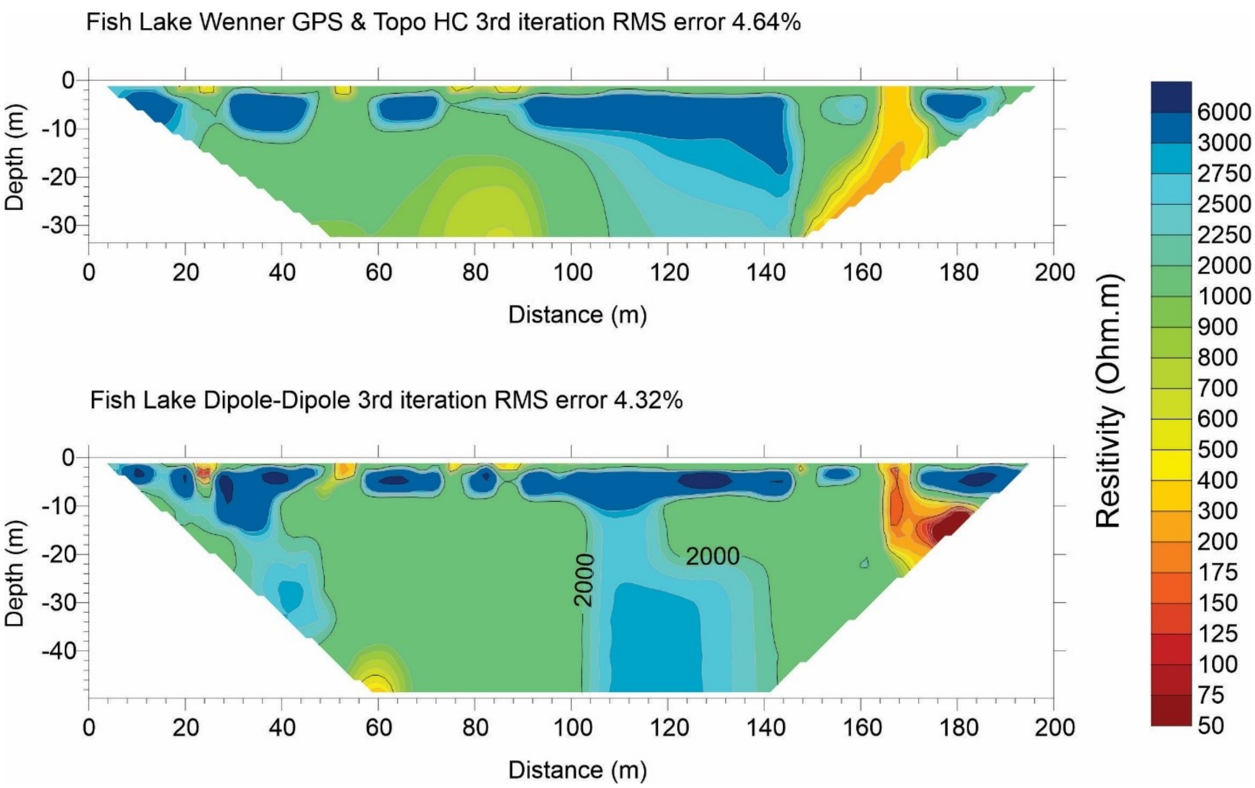


Figure 2.5.2-1. Comparison of Wenner (Top) and Dipole-Dipole (Bottom) ERT profiles from YT 3 (Fish Lake). Dipole-Dipole surveys are shown to have deeper and more accurate representation of permafrost features over Wenner surveys and were therefore chosen for interpretation. RMS value represents how well the figure fits the ERT data used to develop it.

The ERT transect from JMR 1 (Figure 2.5.2-2) showed high resistivity ground with permafrost presence along the entire transect, except between 90 and 105 meters. Permafrost appeared to be between 5 and 7 meters thick. Coring at JRM 1 showed that permafrost was at least 2.9 m thick, consisting of 1.3 m of ice-rich frozen peat and 1.7 m of ice-rich lacustrine clay. Drilling did not reach the base of permafrost due to high water content in the clay. Excess ice content in cores ranged between 40% and 60%. Probing at transects at each permafrost condition identified an average active layer depth of 52.4 cm in intact areas, which increased to 65.6 cm in transitional areas. The organic layer at JMR 1 was 1.7 m deep. Borehole loggers showed permafrost temperatures close to 0° C, indicating that permafrost at this site was very warm. Some pooling of water was observed at the boundaries of the palsa.

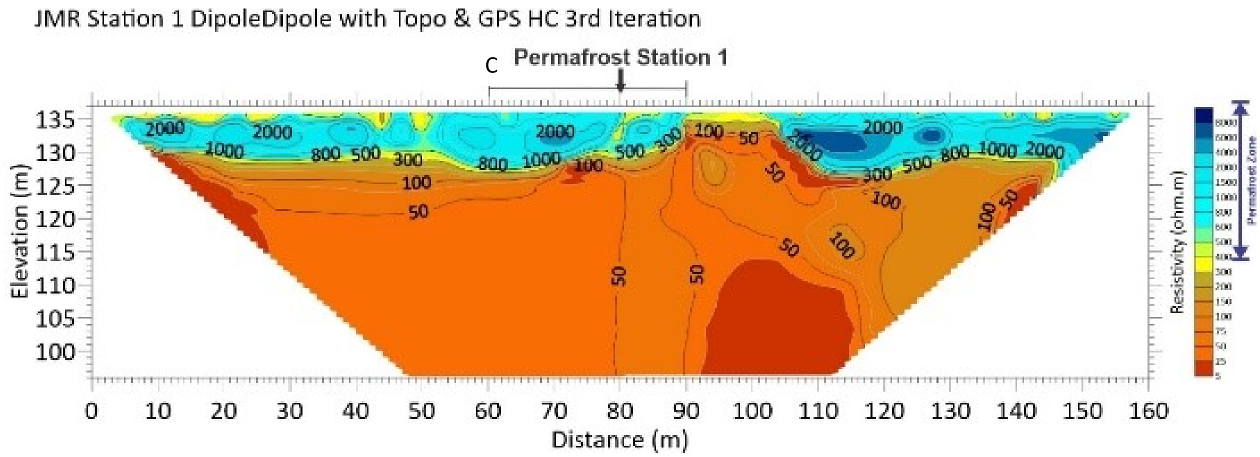


Figure 2.5.2-2. Dipole-Dipole ERT surveyed at JMR 1 during the 2018 field season in Jean Marie River, NT showing the location of borehole and vegetation transect C (intact). Transects A and B were positioned parallel to transect C. Low resistivity permafrost is shown in light green, with darker blue indicating higher resistivity permafrost. Orange to red indicates unfrozen ground.

No permafrost data exists for JMR 2, but it was close to permafrost station 1 and likely has similar characteristics. Some pooling of water was observed at the boundaries of the palsa. The ERT transect from JMR 3 (Figure 2.5.2-3) showed mostly low resistivity ground with very little permafrost. Permafrost appeared to be very sporadic and thin. This was corroborated by cores taken at station 3, showing 2.6 m of ice-rich frozen peat. Probing at transects in each permafrost condition identified an active layer depth of 56.2 cm in intact areas, which increased to 64.5 cm in transitional areas. Drilling showed that the organic layer thickness at this site was at least 2.6 m, but ERT indicates it may have been closer to 4 m. Borehole loggers showed permafrost temperatures of close to 0° C, indicating that permafrost at this site was very warm. When boreholes were drilled in 2013, this site was observed to be undergoing substantial degradation with ponding. In 2018, the site was found to be much drier.

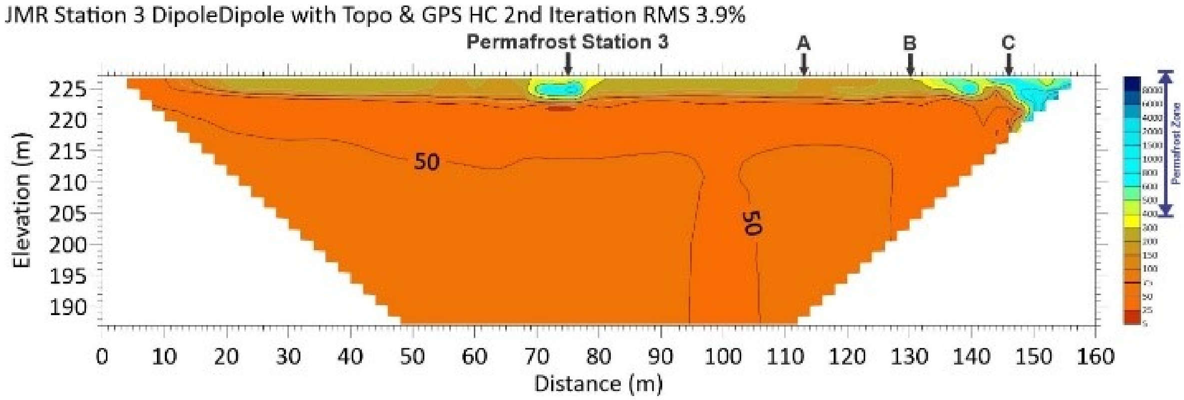


Figure 2.5.2-3. Dipole-Dipole ERT surveyed at JMR 3 during the 2018 field season in Jean Marie River, NT showing location of borehole and vegetation transects. Transects located at A = degraded, B = transitional, and C = intact. Low resistivity permafrost is shown in light green, with darker blue indicating higher resistivity permafrost. Orange to red indicates unfrozen ground. RMS value represents how well the figure fits the ERT data used to develop it. Iteration represents the number of times the program ran the data before the figure was developed.

ERT data was not available for JMR 4, but borehole data showed that permafrost consisted of ice-rich peat and sediment. Coring was limited to 3.5m by water table depth. Excess ice content in cores ranged between 37% and 62%. Probing at transects in each permafrost condition identified an average active layer depth of 53.2 cm in intact areas, which increased to 60.4 cm in transitional areas. The organic layer thickness was at least the depth of the permafrost core (3.5m). Borehole loggers showed permafrost temperatures of close to 0° C, indicating that permafrost at this site was very warm.

The ERT transect from YT 1 (Figure 2.5.2-4) showed high resistivity ground along the entire transect and permafrost presence to a depth of 2 - 18 m. Some pockets of low resistivity were present near the surface, likely due to ponding. Coring showed that permafrost was at least 3.9 m thick and contained ice-rich sand, silt, and clay. Excess ice content ranged from 4% (at the base of the borehole) to 71%. Probing at transects showed an average active layer depth of 55 cm on intact permafrost, which increased to 70 cm in the transitional area. The organic layer consisted of a 5 cm thick moss (*Hylocomium/Pleurozium*) layer. Borehole loggers showed permafrost temperatures of close to 0° C, indicating that permafrost at this site was very warm.

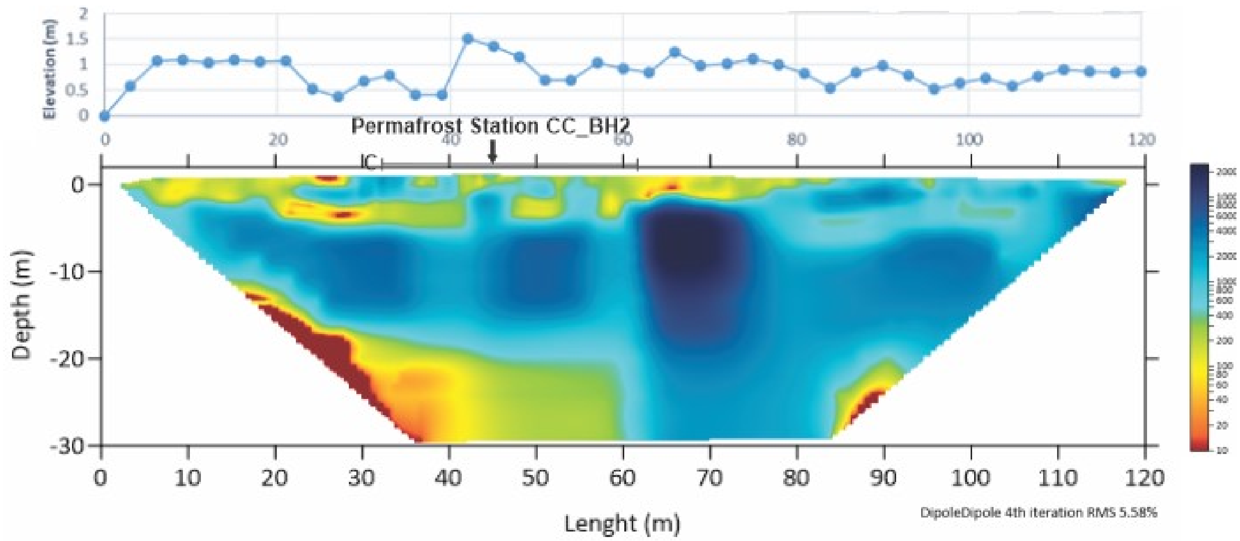


Figure 2.5.2-4. Dipole-Dipole ERT surveyed at YT 1 in southern Yukon during the 2018 field season showing the location of borehole and vegetation transect C (intact), and DGPS elevation data on the ground surface for the survey line. Low resistivity permafrost is shown in light green, with darker blue indicating higher resistivity permafrost. Orange to red indicates unfrozen ground. RMS value represents how well the figure fits the ERT data used to develop it. Iteration represents the number of times the program ran the data before the figure was developed.

The ERT survey at YT 2 (Figure 2.5.2-5) showed low resistivity ground with a thin layer of moderate to high resistivity along the transect surface, indicating a thin layer of permafrost. There was a pocket of high resistivity ground at 125 m, representing a permafrost mound where the monitoring station was located. Coring showed that permafrost was 1.8 m thick and contained a 0.2 m layer of ice-rich organic material followed by a 0.6m ice-poor cobble layer. The remainder of the permafrost was ice-rich sand, silt, and clay, interspersed with cobble and gravel. Excess ice content ranged from 0% (in the cobble layer) to 53%. Probing at transects showed an average active layer depth of 40 cm on intact permafrost, which increased to 70 cm in the transitional area. The organic thickness was 60 cm. Borehole loggers showed permafrost temperatures of close to 0° C, indicating that permafrost at this site was very warm.

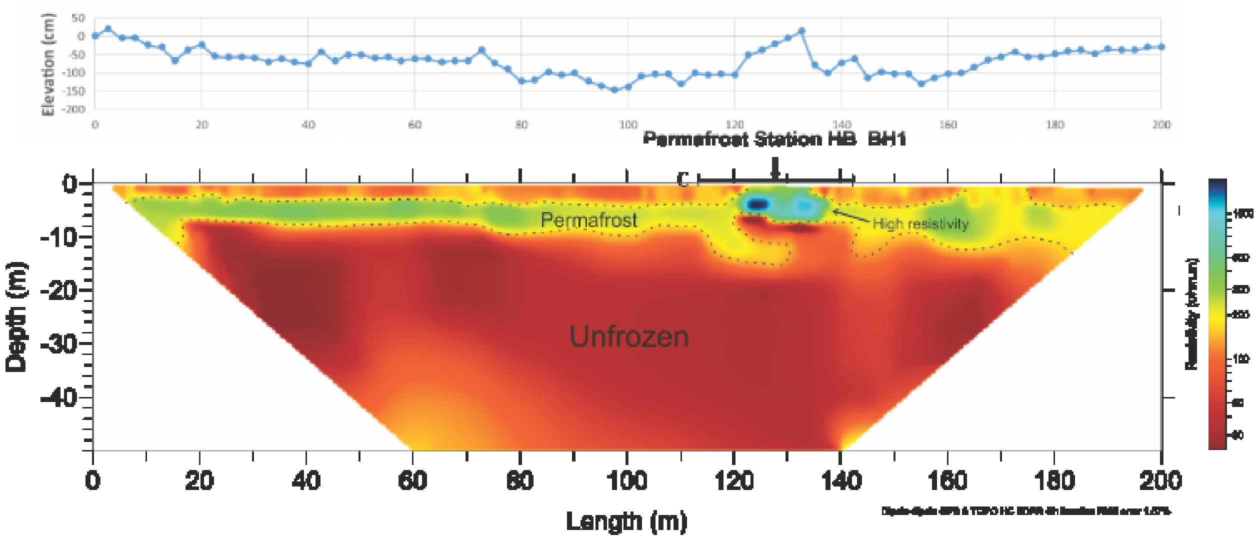


Figure 2.5.2-5. Dipole-Dipole surveyed at YT 2 in southern Yukon during the 2018 field season showing the location of borehole and vegetation transect C (intact), and DGPS elevation data for the survey line. Low resistivity permafrost is shown in light green, with darker blue indicating higher resistivity permafrost. Orange to red indicates unfrozen ground. RMS value represents how well the figure fits the ERT data used to develop it. Iteration represents the number of times the program ran the data before the figure was developed.

The ERT transect from YT 3 (Figure 2.5.2-6) showed high resistivity ground with permafrost segments along most of the transect. This was interspersed with unfrozen ground and low resistivity areas likely associated with thermokarst ponds. Higher resistivity areas corresponded with higher elevation (mound) topography, while lower resistivity areas corresponded with lower elevation (ponds) at the surface. A lower resistivity area at 170 – 190 m may have been associated with groundwater. ERT showed that permafrost was between 10 and 15 meters thick and drilling confirmed permafrost to 4.1m. Coring was stopped when a mixture of clay and cobble was reached, preventing further drilling. Permafrost consisted of frozen peat to approximately 3.6 m, transitioning to clay and cobble beyond this point. It is unclear what caused a deep high resistivity pocket at 100 – 140 m. It may have been associated with the presence of bedrock or an issue with inversion during ERT processing. Probing at transects in each permafrost condition identified an active layer depth of 52 cm in intact areas, which increased to 75 cm in transitional areas. The organic layer was approximately 360 cm deep.

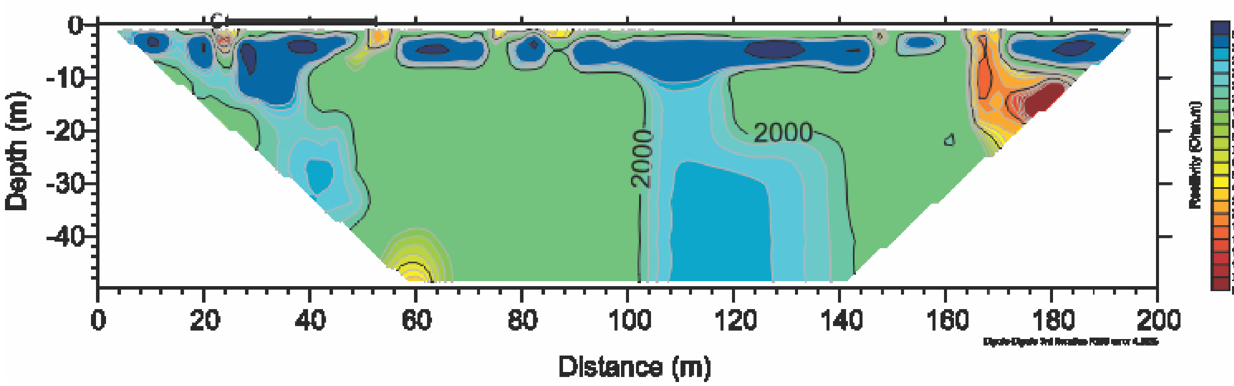


Figure 2.5.2-6. Dipole-Dipole ERT surveyed at YT 3 in southern Yukon during the 2019 field season showing location of borehole and vegetation transect C (intact), and DGPS elevation data for the survey line. Low resistivity permafrost is shown in light blue, with darker blue indicating higher resistivity permafrost. Orange to red indicates unfrozen ground. RMS value represents how well the figure fits the ERT data used to develop it. Iteration represents the number of times the program ran the data before the figure was developed.

The ERT transect from YT 4 (Figure 2.5.2-6) showed mostly high resistivity ground and permafrost presence to a depth of 25 m. Very high resistivity was present below the borehole, with lower resistivity permafrost extending to 25 m. Depth was corroborated by a core that showed permafrost to be at least 20 m thick and made up of ice-rich fine-grained material, with some coarser sand levels. Deep low resistivity pockets existed at 10 – 30 m and 80 – 90 m, potentially associated with groundwater. Excess ice content ranged from 23% to 97%. Probing was not possible at this site as the active layer depth exceeded the probe's length (>2 m), but the borehole showed an active layer depth of 4.9 m in the intact area. Organic cover at this site was minimal, and mineral soil was exposed in many places. Borehole loggers showed permafrost temperatures of close to 0° C, indicating that permafrost at this site was very warm.

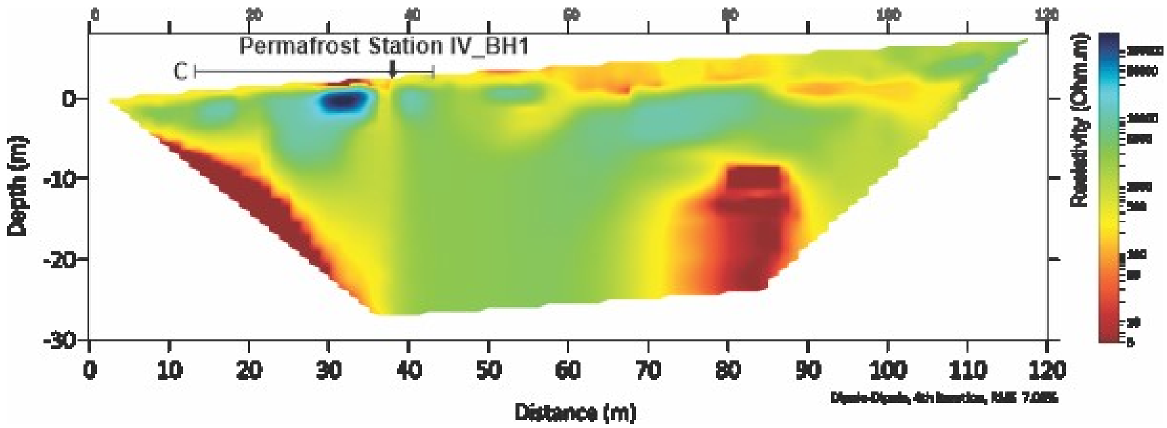


Figure 2.5.2-7. Dipole-Dipole ERT surveyed at YT 4 in southern Yukon during the 2019 field season showing the location of borehole and vegetation transect C (intact), and DGPS elevation data for the survey line. Low resistivity permafrost is shown in light blue, with darker blue indicating higher resistivity permafrost. Orange to red indicates unfrozen ground. RMS value represents how well the figure fits the ERT data used to develop it. Iteration represents the number of times the program ran the data before the figure was developed.

The ERT transect from YT 5 (Figure 2.5.2-8) showed high resistivity ground with permafrost along the entire transect. Permafrost appeared to be between 5 and 20 meters thick. Coring showed that permafrost was at least 1.4 m thick, including 20 cm of peat. Drilling did not reach the base of permafrost due to ice-poor gravel at 1.4 m. Probing at transects in each permafrost condition identified an active layer depth of 35 cm in intact areas, which increased to 65 cm in transitional areas. The organic layer was 30 cm deep.

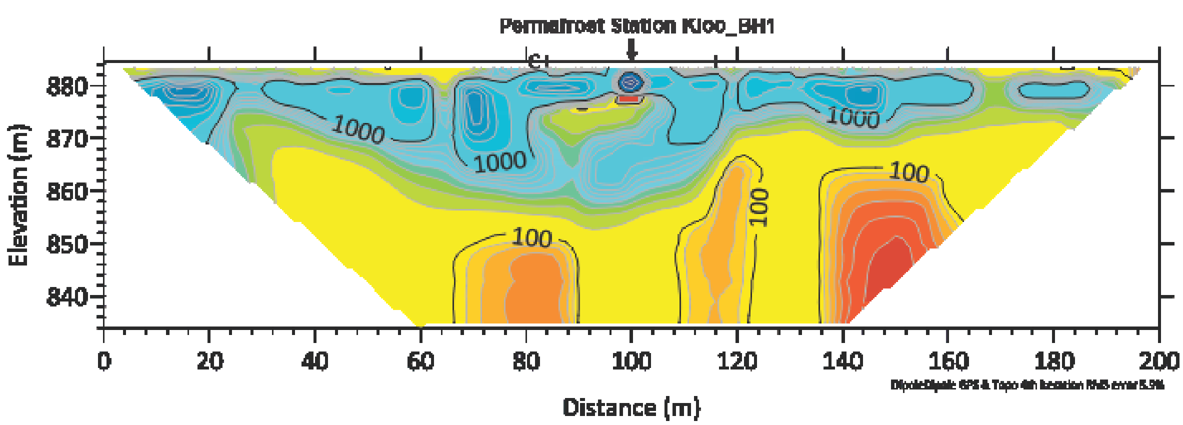


Figure 2.5.2-8. Dipole-Dipole ERT surveyed at YT 5 in southern Yukon during the 2019 field season showing the location of borehole and vegetation transect C (intact). Low resistivity permafrost is shown in light green, with darker blue indicating higher resistivity permafrost. Orange to red indicates unfrozen ground. RMS value represents how well the figure fits the ERT data used to develop it. Iteration represents the number of times the program ran the data before the figure was developed.

The ERT transect from YT 6 showed medium to high resistivity ground with a large section of high resistivity permafrost spanning 15 to 95 m along the transect (Figure 2.5.2-9). Permafrost extended to a depth of 15 - 17.5 m. Coring confirmed that permafrost was at least 3.89 m thick and contained ice-rich sand, silt, and clay, with minimal (<10%) coarser pebbles. Excess ice content ranged from 44% to 100%. Probing at transects showed an average active layer depth of 66.8 cm on intact permafrost, which increased to 110 cm in the transitional area. The organic layer consisted of a thick moss (*Hylocomium/Pleurozium*) layer (at least 12.5 cm). Borehole loggers showed permafrost temperatures of -1.5° C, indicating that permafrost at this site was warm but less so than other sites in the area (YT 7).

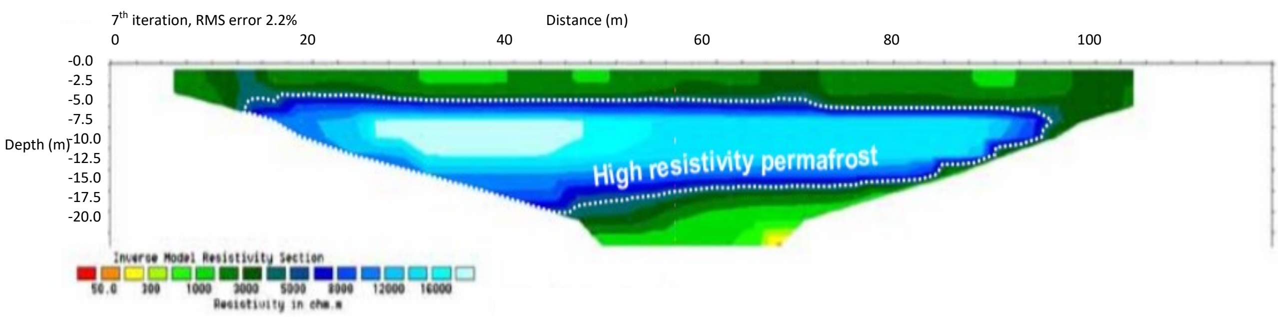


Figure 2.5.2-9. Dipole-Dipole ERT surveyed at YT 6 in southern Yukon during the 2013 field season showing the location of borehole permafrost conditions. Low resistivity permafrost is shown in dark green and blue, with lighter blue indicating higher resistivity permafrost. Light green to red indicates unfrozen ground. RMS value represents how well the figure fits the ERT data used to develop it. Iteration represents the number of times the program ran the data before the figure was developed.

There was no ERT transect for site YT 7. However, coring showed that permafrost was at least 3.6 m thick and contained ice-rich sand, silt, and clay, with some coarser pebbles and gravel (up to 50% in some layers). Excess ice content ranged from 4% to 45%. Probing at transects showed an average active layer depth of 51.6 cm on intact permafrost, which increased to 69 cm in the transitional area. The organic layer consisted of a thick moss (*Hylocomium/Pleurozium*) layer (at least 13 cm). Borehole loggers showed permafrost temperatures of close to 0° C, indicating that permafrost at this site was very warm.

2.5.3. Forest Response

Intact JMR sites were forested with *Picea mariana* with an average DBH of between 2.2 cm and 4.8 cm. All sites had the largest number of trees in the intact transect but JMR 4, which had the largest number in the transitional transect (Figure 2.5.3-1). JMR 3 was forested in the degraded transect and had a higher number of trees in this area than the transitional transect. All other sites were unforested in the degraded area. Intact permafrost at YT 3 was unforested, while YT 4 was forested with deciduous mixed (*Pinus contorta, Populus tremuloides, Picea glauca*) with an average DBH of 4.5 cm. Permafrost mounds at all other YT sites were forested with *Picea glauca* with an average DBH ranging from 8.4 cm to 14.4 cm (Table 2.5.3-1). YT 1, 4, and 6 had the highest number of trees per hectare in intact transects (Figure 2.5.3-1). In contrast, YT 1, 5, and 7 had the highest stems per hectare in transitional plots. However, at YT 7, DBH dropped substantially between intact and transitional plots. Only YT 1 and 5 were forested in degraded transects. DBH was consistent between transects, except where trees remained. In these scenarios, DBH increased in degraded transects.

Table 2.5.3-1. Average DBH for trees surveyed in southern Yukon in 2019 (sites YT 1 – 7), and in Jean Marie River, NT in 2018 (sites JMR 1-4). Trees were surveyed in 2x30m banded transects in intact, transitional, and degraded permafrost conditions.

Site	Forest type	Mean DBH intact (cm)	Mean DBH transitional (cm)	Mean DBH degraded (cm)
YT 1	Coniferous	11.9	17.7	14.8
YT 2	Coniferous	8.5	7.5	n/a
YT 3	Unforested	n/a	n/a	n/a
YT 4	Deciduous mixed	4.5	4.6	n/a
YT 5	Coniferous	6.6	5.5	1.4
YT 6	Coniferous	8.4	5.2	n/a
YT 7	Coniferous	14.4	3.9	n/a
JMR 1	Coniferous	4.8	4.4	n/a
JMR 2	Coniferous	2.2	2.9	n/a
JMR 3	Coniferous	4.2	4.4	5.1
JMR 4	Coniferous	3.4	3.2	n/a

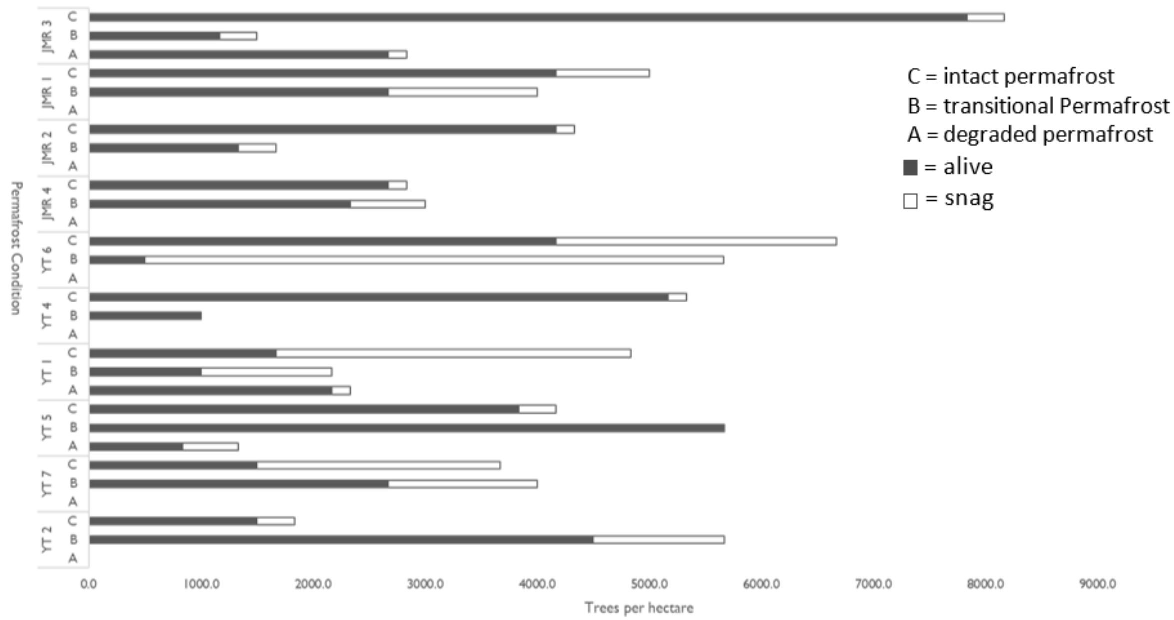


Figure 2.5.3-1. Tree densities in trees per hectare surveyed in intact, transitional, and degraded permafrost conditions at sites JMR 1-4 and YT 1-7. Trees were surveyed in 2x30 m banded transects in each permafrost condition. Proportion of alive trees shown in grey, and snags (dead standing trees) shown in white. Corresponding numeric values are shown in chart. (A = Degraded, B = Transitional, C = Intact)

2.6. Discussion

2.6.1. Thaw-induced difference in vegetation

All sites surveyed indicate a clear distinction between vegetation composition in intact and degraded areas. This is due to changes in surface stability, moisture level, and microtopography triggered by permafrost thaw (Jorgenson et al. 2001). It is evident that rapid permafrost thaw will significantly impact vegetation composition and subsequent structure and function of these ecosystems. At sites surveyed in Jean Marie River's peatlands, palsas support a drier ecosystem raised above the water table (Vitt et al. 1994; Christensen 2004). These palsas are vegetated with shrubs (*Rhododendron groenlandicum, Vaccinium vitis-idaea),* forbs (*Rubus chamaemorus)*, and Lichens *(Cladina, Cladonia, Cetraria spp.)*. In contrast, degraded areas are taken over by species thriving in moister conditions like *Sphagnum spp.* mosses, sedges *(Carex, Eriophorum spp.),* and ericaceous shrubs (*Chamaedaphne calyculata, Andromeda polifolia)*. As permafrost degrades, drier plateaus supporting important boreal species like lichens - a key winter food source for woodland caribou - are absorbed into surrounding wetlands (Rydin and Jeglum 2013a).

Significant difference in vegetation composition between permafrost condition occurs at all sites. The introduction of *Sphagnum spp*. and the loss or reduction of *Cladina spp*., *Vaccinium vitis-idaea*, and *Rhododendron groenlandicum* in degraded permafrost areas largely influence this difference. Identifying the occurrence of these species could be used to recognize permafrost thaw in peatlands. This is highlighted by the relative position of vegetation plots at JMR 1 (Figure 2.6.1-1). A pocket of lower resistance ground seen in the ERT survey (light green at 85 m) corresponds with *Sphagnum spp.* in the intact permafrost area. Permafrost is likely beginning to degrade here, which could be identified by the presence of different species. This area also corresponds with a thickening of the active layer, linked to permafrost thaw and increased surface moisture (Anisimov and Nelson 1996; Christensen 2004).

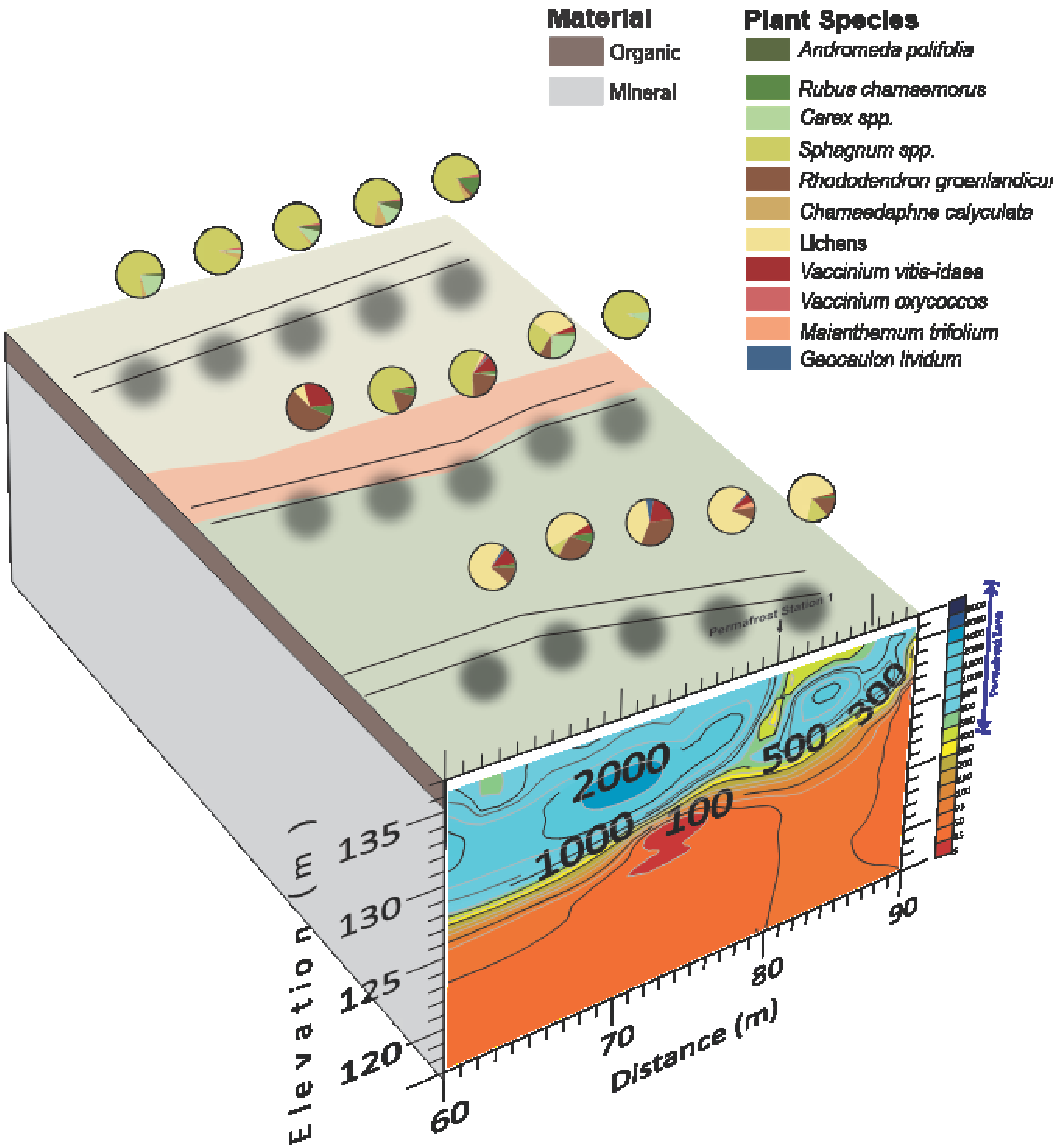


Figure 2.6.1-1. Location of vegetation transects in relation to permafrost condition and ERT surveyed at Jean Marie River in 2018 at JMR 1. Species percent cover is graphically represented in the location of 1x1 m survey plots along the vegetation transects.

Sites surveyed in Southern Yukon have greater diversity in site conditions than those surveyed in Jean Marie River (JMR). However, all show a significant difference in vegetation composition associated with permafrost thaw. This suggests that thawing permafrost may have drastic implications for vegetation composition and structure and resultant habitat for species associated with these systems. Although different plant species were surveyed, patterns in vegetation difference were similar to those observed in JMR peatlands. Areas of intact permafrost support species adapted to drier conditions than those found in areas of degraded permafrost. The range in vegetation difference is demonstrated by a shift to varying ecosystem types in degraded areas. In some instances, permafrost degradation led to wetland ecosystems with standing water, sedges (*Carex spp.),* and aquatic species like *Nuphar variegatum* and *Ranunculus gmelinii*. Forest cover, vegetation, and organic layer thickness on intact permafrost areas varied between these sites, although all had moss or peat cover.

Other sites shifted to *Salix* and *Carex spp.* dominated vegetation with permafrost thaw, with minor pooling or signs that water had pooled but subsequently drained. Similar to sites transitioning to wetlands, intact areas at these sites had different vegetation characteristics, and organic layer thickness varied. More variability in post-thaw conditions was observed at sites that had undergone disturbance. YT 2 is very close to the road, and disturbance in the form of cut lines and trails was present. At this site, moss (*Hylocomium/Pleurozium*) remained but at a lower percent cover, and the area was partially taken over by *Equisetum arvense* and *Carex spp*. At YT4, a mixed forest (*Pinus contorta, Populus tremuloides, Picea glauca*) with minimal organic cover and *Salix spp.* understory shifted to *Potentilla anserina* dominated vegetation with grasses. This site experienced a burn in 1958, resulting in an earlier successional forest than at other sites.

Although site conditions varied in Yukon, an increase in *Carex spp*. and a reduction in *Hylocomium/Pleurozium* mosses in degraded areas were largely responsible for the difference between plant communities in intact and degrading permafrost areas. This is observed in both transitional and degraded transects, making these species differences potential indicators for the beginning of permafrost thaw. An increase in *equisetum spp.* in transitional areas may also be an early indicator of permafrost thaw. At sites where less severe degradation occurred, an increase in *Salix spp.* is a potential indication of permafrost degradation.

As in JMR peatlands, this can be directly observed when overlaying vegetation composition and ERT surveys. Thickening of the active layer and a low resistivity pocket at 116 m is correlated with the presence of *Salix spp*., not present in any other intact quadrats (Figure 2.6.1-2).

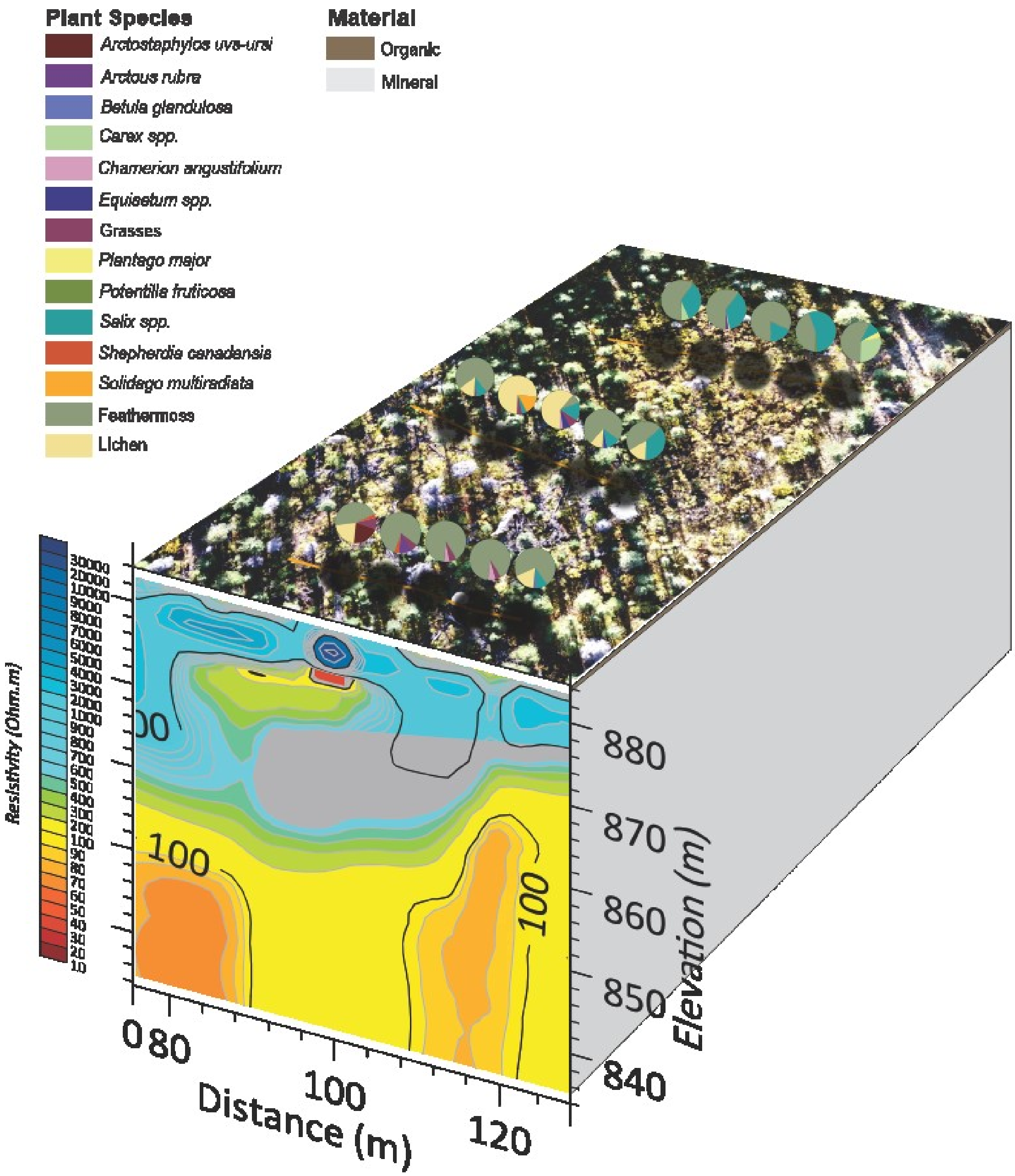


Figure 2.6.1-2. Location of vegetation transects in relation to permafrost condition and ERT surveyed in southern Yukon in 2019 at YT 5. Species percent cover is graphically represented in the location of 1x1 m survey plots along the vegetation transects.

2.6.2. Forest response

In most cases, areas of permafrost degradation become unforested. This is due to an increase in moisture and a loss of ground stability, creating unfavorable conditions for trees (Camill et al. 2001; Baltzer et al. 2014). However, some sites remain forested after permafrost has degraded. Dependent on the volume of ice, type of surface materials, topography, and overall size and distribution of ground ice, the extent of surface modifications triggered by permafrost thaw can vary (Lawson 1986). Sites that remain forested after degradation exhibit one or a combination of lower ground ice content, thinner permafrost, increased drainage, or less relief than those with forest loss. These conditions generate less excess water from permafrost thaw and allow for better drainage of surface moisture, as well as less surface subsidence. The exception to this was YT 2, which had all three of these features but was unforested in the degraded transect. This is likely because the degraded transect overlapped with a cut line, and the forest was removed by human disturbance, not permafrost thaw. In areas where the forest has been lost due to permafrost degradation, broken stumps and fallen trees can be observed. This is not the case at YT 2.

Boreal forest occurring on permafrost peatlands in NWT as well as on palsas and lithalsas in southern Yukon exhibit these patterns, with varying forest condition on intact permafrost in these areas varies. Knowledge of permafrost characteristics and their link to forest condition after thaw could further our knowledge of the role of permafrost thaw on forest loss and fragmentation in boreal forests of Northern Canada.

2.6.3. Relationship between permafrost characteristics and differences in vegetation composition

As previously discussed, the severity of surface modifications caused by permafrost degradation is directly influenced by permafrost characteristics (Lawson 1986), subsequently affecting surface moisture and species presence in degraded areas. Examination of variability in individual sites during this study illustrates these patterns.

In JMR peatlands, sites with permafrost extending into mineral soil exhibit different shifts in species characteristics than where it occurs only in peat. This may be because segregated ice is more likely to form in mineral soils than in peat (Gurney 2001), creating more ice-rich permafrost, higher permafrost mounds, and subsequently, more severe subsidence (Lawson 1986). At JMR 1, ice-rich mineral sediment, more significant relief, and a respectively large body of permafrost leads to vegetation in degraded permafrost dominated by *Sphagnum spp., Chamaedaphne* *calyculata,* and sedges. JMR 2 exhibits similar permafrost conditions, and therefore similar vegetation characteristics in degraded areas. Conversely, at JMR 3, respectively thin and sparse permafrost, less relief, and lower excess ice content lead to degraded permafrost areas dominated by *Rhododendron groenlandicum*. Although there is still a significant difference, vegetation present in degraded areas more closely resembles that present on intact permafrost. JMR 4 has a much thicker organic layer than JMR 1 but exhibits comparable excess ice content and relief. Drilling does not extend to the base of permafrost, and no ERT exists for comparison, so it is challenging to speculate permafrost conditions beyond drilling. However, a thick organic layer does not appear to influence differences in vegetation composition, as they are very similar to those seen at JMR 1.

On permafrost mounds in Southern Yukon, the general trend follows that observed in peatlands. However, a broader range of vegetation conditions is observed. At YT 6, respectively, high excess ice content, a large body of permafrost, and more extreme relief, combined with poorly draining sediments (silt, clay, sand), led to the most extreme subsidence and pooling of water relative to other sites. This led to dominant species of aquatic and emergent vegetation (*Carex spp.).* Similar conditions are observed at YT7. However, near-surface materials allow for slightly better drainage. Combined with lower excess ice content, this results in less persistent pooling of water. While some aquatic species exist, the dominant vegetation is emergent (*Carex spp.*).

At YT 5, ice-rich permafrost is limited to 1.35 m, below which is ice-poor gravel. The permafrost mound at this site is respectively low in comparison to those at YT 6 and 7. Based on the interpretation of ERT profiles and drilling, ice-rich cores are likely located at the surface with coarser, more ice-poor material below. It is possible, yet unlikely, that coarser content may affect resistivity values and influence ERT profile interpretation. Evidence of a large thermokarst pool is present, likely created by ice-rich permafrost cores near the surface. However, this has drained, and many components of the original ecosystem are preserved, indicating water was not present for an extensive period. This results in vegetation dominated by sedges, *Salix spp.,* and moss (*Hylocomium/Pleurozium*).

Permafrost occurring at YT 1 has ice-rich materials extending to at least 5 m. With depth, ice content declines, corresponding to an increase in coarser sediments. In combination with gently undulating topography and small permafrost mounds, a large thermokarst lake does not occur. Instead, small cavities form due to ground subsidence, developing shallow pools that subsequently drain. Higher moisture content leads to dominating vegetation of *Carex* and *Equisetum* species, but components of the original terrestrial ecosystem are preserved.

At YT 4, permafrost is ice-rich to a depth of at least 20 m, and sediments include silt, sand, and clay. Vegetation in degraded areas is different from all other sites. There appears to be a disconnect between the landscape and observed permafrost conditions. Vegetation and surface characteristics of the intact area are unlike that which often indicate permafrost, including an early succession deciduous mixed forest and virtually no organic layer. In this area, permafrost may be relict, leading to a disconnect between permafrost conditions and current environmental conditions. A fire occurred in the area in 1958, resetting ecosystem conditions, deepening the active layer (Burn 1998), and removing organic cover that may have previously been present. Dominant vegetation in degraded areas includes grasses and forbs. However, species indicating previously higher soil moisture are present at lower percentages (*Juncus arcticus*, *Ranunculus cymbalaria*). This site occurs on a large slope rather than distinct permafrost mounds. A thermokarst pond is located further downslope, and species present in the degraded area indicate that it was likely larger at one point but is slowly draining.

Topography at YT 2 is comparable to that at YT 1, gently undulating with a small permafrost mound. However, permafrost is thin, reaching only 1.8 m. Along with a cobble layer at 0.9 m and a high content of coarse, well-draining surficial materials, some small pools form but larger thermokarst lakes or cavities are not present. Components of the intact ecosystem are preserved. However, this site is very close to the road, and multiple cut lines and trails are present, increasing the level of disturbance and likely influencing species present in degraded areas.

At YT 3, peat is comparably thick (~3.6 m), respective to other YT sites surveyed. Although geotechnical analysis of cores has not been completed, observations of cores do not indicate highly ice-rich permafrost. Beyond this, frozen clay interspersed with cobble occurs. In the surveyed degraded area, there is standing water, and vegetation resembles wetland conditions. Ground subsidence along with a high cover of *Carex spp*. make it evident that permafrost thaw has led to the smaller scale pooling of water in other areas surrounding the site, which have subsequently drained. Permafrost mounds are of moderate size and height, with respect to other sites surveyed. It is possible that although permafrost is not very ice-rich, water is draining to one large thermokarst pond. Although some coarse material was present in the clay, it is possible that mineral sediments below the peat are preventing drainage of the large thermokarst pond. A DSM shows this area as a low point compared to the surrounding area. This could account for the drastic change in ecosystem conditions in this area. An example of variation in post thaw conditions is shown by Figure 2.6.3-1 below.

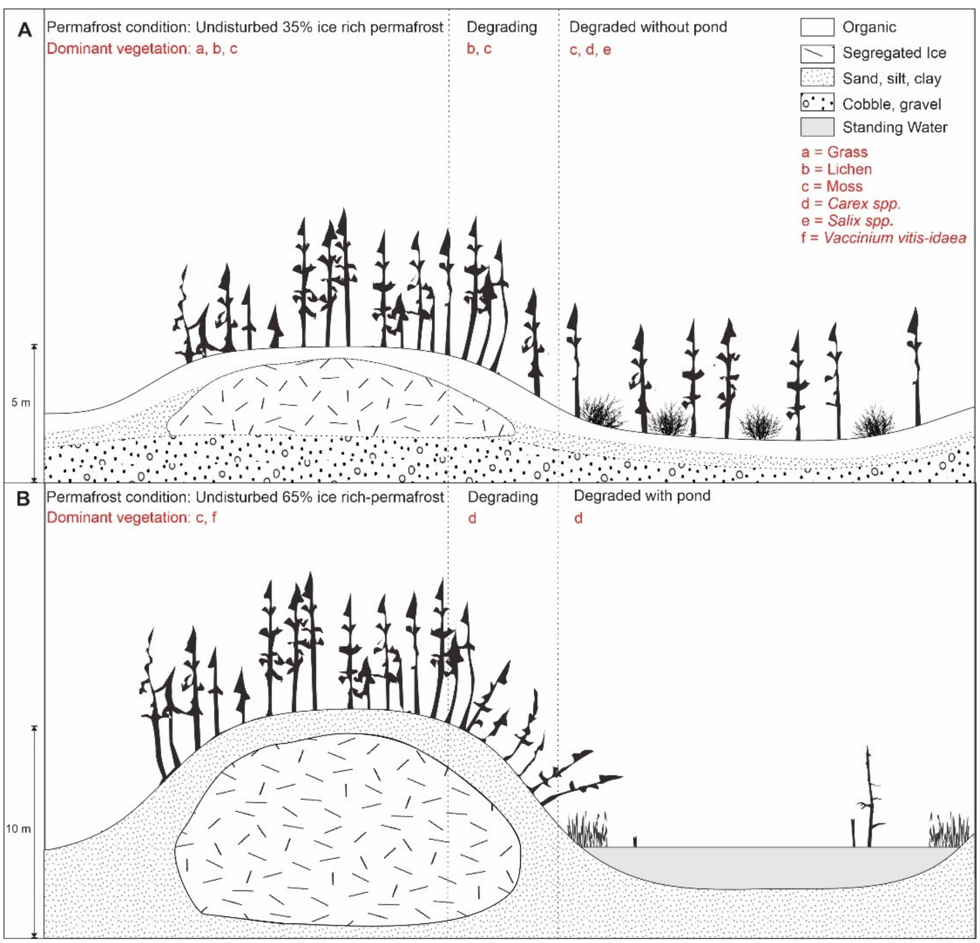


Figure 2.6.3-1. Example of the variation in post-thaw conditions based on permafrost characteristics. A) Smaller permafrost body with less extreme topography and presence of cobble layer, improving drainage of water created by thaw of excess ice. This leads to the retention of some ecosystem components, including forest. B) Larger permafrost body with more extreme topography and poorly draining sediment, slowing drainage of water created by thaw of excess ice. This leads to the formation of a shallow water wetland and complete ecosystem conversion.

2.7. Conclusion

Permafrost thaw resulted in significant differences in vegetation composition between intact, transitional, and degraded permafrost conditions. In JMR permafrost peatlands, the incursion of *Sphagnum spp*. and the reduction of *Cladina spp., Vaccinium vitis-idaea,* and *Rhododendron groenlandicum* in degraded permafrost may be indicators of permafrost degradation. In boreal forests located in southern Yukon, an increase in *Carex and Salix spp*. and a reduction in *Hylocomium/Pleurozium* mosses in degraded areas may indicate permafrost thaw. Additionally, an increase in *Equisetum spp*. in transitional areas may be an early indicator of permafrost thaw. Although vegetation composition on intact permafrost is linked to permafrost characteristics, it appears to have less influence on resulting vegetation shift than permafrost characteristics.

Permafrost characteristics influence the severity of surface modification that occurs with thaw (Lawson 1986), including the amount of excess water and ground subsidence. Areas with greater excess ice content, larger permafrost bodies, poorly draining surficial materials, and more extreme topography led to greater ground subsidence and water pooling. This impacts ecological change, as surface stability and moisture are essential factors in vegetation composition. These results indicate that observations of permafrost characteristics may predict the type of ecosystem change resulting from permafrost thaw. Species type and functional group differences may help identify thawing permafrost and estimate post-thaw habitat value to boreal species.

3. **Chapter 3**: Transition of a permafrost landscape in a changing climate

Thawing permafrost alters surface topography (Lawson 1986), influencing the structure and function of ecosystems (Osterkamp et al. 2009). As permafrost thaws, ground structure is lost, and moisture and nutrient availability to plants is altered (Camill et al. 2001; Baltzer et al. 2014). The rate at which permafrost thaws and the level of surface modification that occurs upon thaw is impacted by permafrost characteristics (Lawson 1986), which in turn are influenced by the history of permafrost aggregation and degradation (Froese et al. 2008). Areas of discontinuous permafrost with mean annual temperatures around 0 degrees Celsius are particularly susceptible to environmental change triggered by an increase in air temperature and are already experiencing the reshaping of ecosystems (Christensen 2004; Vitt et al. 2010). Modeling of permafrost thaw in 21st-century climate scenarios points towards large-scale degradation of permafrost in the remainder of the century, with as little as 1% of near-surface permafrost remaining in 2100 (Lawrence and Slater 2005). Jean Marie River, Greater Whitehorse, and Kluane study areas are all vulnerable to landscape transition in the face of a changing climate. These ecosystems support habitat for many species, notably boreal and northern mountain caribou populations, which are already threatened or species of concern, respectively (Government of Canada 2018). These populations rely on large extents of continuous habitat (Government of Northwest Territories 2019). Understanding how landscape may transition post-thaw reduces uncertainty of how habitat quality may be altered for boreal caribou in a changing climate.

3.1. Background

3.1.1. Jean Marie River

Jean Marie River First Nation's (JMRFN) traditional territory is located in the Great Slave Plain Mid-Boreal ecoregion, which spans the northwestern portion of the Taiga Plains Mid-Boreal ecoregion within the Taiga Plains Ecozone (Ecosystem Classification Group 2009; Calmels, Laurent, et al. 2015). This area is characterized by extensive lakebed plains left behind by glacial Lake McConnel. Widespread peat deposits are present in low, poorly drained areas. Areas underlain by permafrost are dominated by black spruce and lichen, while shrubs and *Sphagnum* *spp*. characterize unfrozen wetlands. Upland areas are characterized by deciduous mixed and coniferous forests (Ecosystem Classification Group 2009).

The geological history surrounding Jean Marie River has influenced the development and distribution of permafrost. During the Wisconsin Glaciation (110,000 – 10,000 years ago), permafrost was absent from the area. With the retreat of glacial ice, lakes formed. Glacial Lake Mackenzie flooded the Jean Marie River Area, depositing lacustrine silt and clay. Later (~10,000 years ago), flooding of glacial Lake Agassiz pushed runoff northwards through glacial lakes McConnell and Mackenzie, passing up the Mackenzie Valley and creating a paleochannel (Smith 1994; Couch and Eyles 2008). Some of the lacustrine clay was eroded by this paleochannel, which deposited boulders during the initial heavy flood, and subsequently diamicton of fluvial origin. Fine sands of aeolian origin are also found on the surface of emerged terrains.

The community of Jean Marie River lies within the depression of this channel (Smith 1994; Couch and Eyles 2008). In areas where lacustrine deposits were exposed at the surface, thick organic cover developed (Calmels, Laurent, et al. 2015). As discussed in section 1.3.2, poorly drained fine sediment overlain by peat are conductive of cryosuction and subsequent formation of permafrost mounds (French 2007). Consequently, permafrost in this area is linked to thick organic cover (Calmels et al. 2015).

The traditional territory of JMRFN extends beyond this channel, where extensive wetlands cover lacustrine sediments left by glacial Lake Mackenzie. Permafrost mounds in this area tend to be associated with forested peatland. Similar to permafrost occurring in the paleochannel, permafrost in surrounding areas is associated with thick organic cover. However, observations show that it is more widespread and extends deeper into the mineral soil. This is likely why mounds in this area sometimes exceed 5 m, while those in the paleochannel are closer to 1-2m (Calmels, Laurent, et al. 2015).

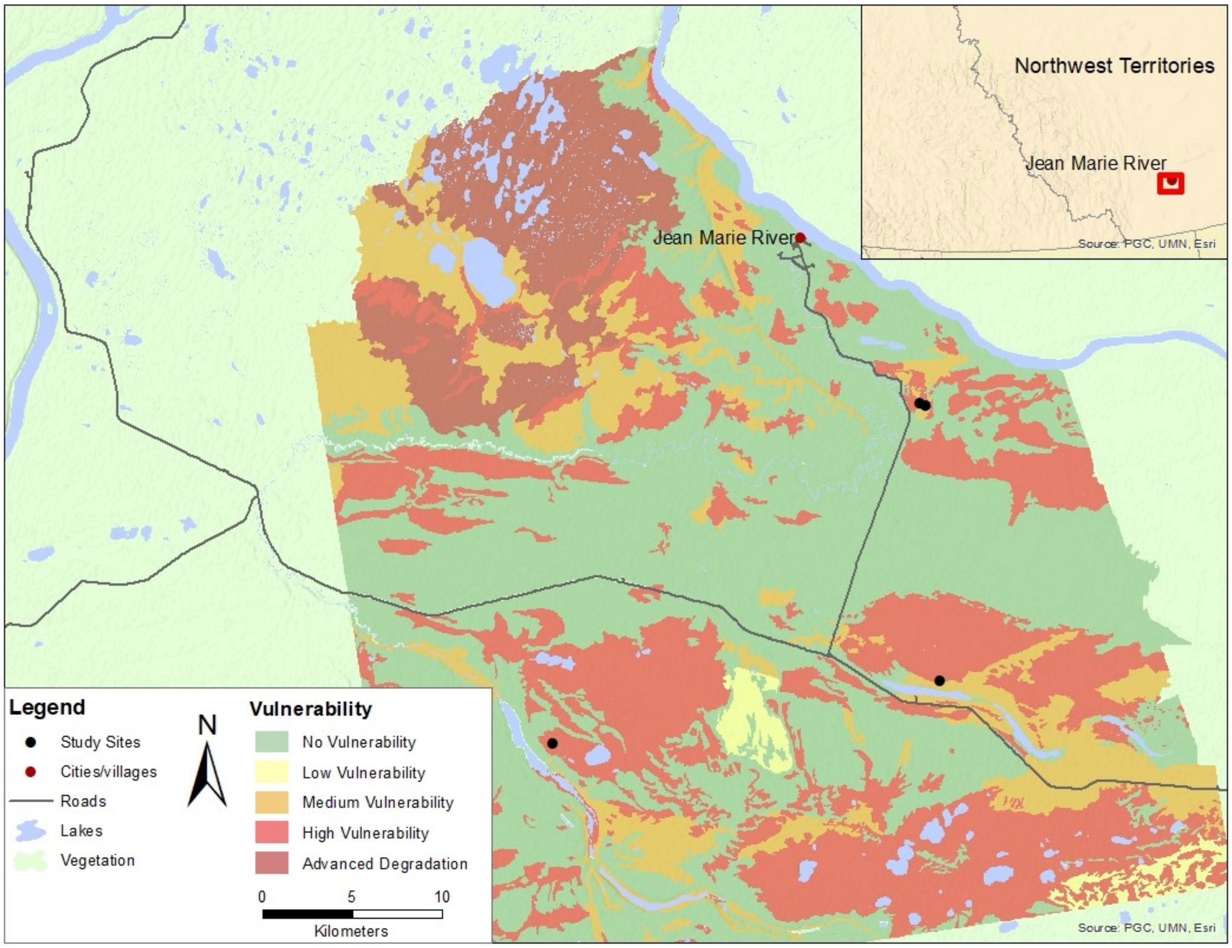


Figure 3.1.1-1. Vulnerability of permafrost to thaw in the traditional territory of Jean Marie River First Nation. Permafrost hazard polygons developed by Laurent, 2018-2019.

The traditional territory of the JMRFN has highly variable permafrost conditions, as it lies between sporadic discontinuous and extensive discontinuous permafrost zones. It is expected that between 10% and 90% is underlain by permafrost (Heginbottom et al. 1995; Calmels, Laurent, et al. 2015). Permafrost in the area is warm (close to 0^{o} C) and thin (<10 m thick), making it very sensitive to climate warming and vulnerable to thaw (Smith and Burgess 2000; Calmels, Laurent, et al. 2015). Results of extensive vulnerability mapping completed by JMRFN and Yukon Research Centre, Yukon University, show that 52% of JMRFN traditional territory is vulnerable to permafrost thaw, with 38% of this at high risk of thaw (Figure 3.1.1-1).

3.1.2. Greater Whitehorse

The Greater Whitehorse Area is located on the traditional territory of Kwanlin Dün First Nation and Ta'an Kwäch'än Council and falls in the Southern Lakes Boreal Low Zone within the Boreal Cordillera ecozone (Environment Yukon 2017). This area is characterized by cool temperatures, low humidity, and low precipitation. Temperature ranges are less extreme than in other areas of the Yukon due to a less continental climate and occasional incursions of warm coastal air in winters. Continuous forests of both deciduous mixed and coniferous stands extend across the ecoregion (McKenna and Flynn 2017). The northwestern end of the study region experienced a severe burn in 1958, stripping the organic layer and leading to an earlier succession forest (deciduous mixed) than southeastern areas covered by mature spruce forests (Burn 1998; McKenna and Flynn 2017).

In the greater Whitehorse area, permafrost did not develop until after the most recent McConnell glaciation, which occurred approximately 20,000 years ago and is mainly responsible for the geological features present now (Kotler 2003; Bond 2004). Surficial deposits in the area vary from dense, poorly draining basal till including poorly sorted coarse fragments mixed with silt and sand to fine-grained silts and clays (Jackson and Fuller 2009; Smith et al. 2015). These were deposited as the glacier retreated, glacial lakes drained, and multiple meltwater channels were carved across the landscape (Bond 2004). In the city of Whitehorse itself, deposits are primarily moraine and glaciofluvial. Peat may be present in poorly drained areas but does not generally exceed 5 m in depth. Permafrost is typically thin (2-3 m) and present at higher elevations. However, ice-rich permafrost may be present along the valley bottom associated with finer-grained sediments (Lipovsky and Yoshikawa 2009; Hennessey and Striecker 2011).

West of the city center in the Takhini Valley, deposits are primarily silt and clay with fine sand covering a glaciolacustrine plain (Burn 1998). Glacial Lake Champagne covered this area before it drained through the current path of the Yukon River. These deposits are usually over 30m thick (Foothills Pipe Lines (south Yukon) Ltd. 1979). In this area, permafrost is ice-rich and likely relic. It is disconnected from the landscape's topography.

Between 10% and 50% of the Greater Whitehorse area is expected to be underlain by permafrost, as it falls within the sporadic discontinuous permafrost zone (Heginbottom et al. 1995). More detailed probability modeling by Bonnaventure et al. (2012) indicates that the study area is more likely at the lower end of this range, with 10-30% underlain by permafrost (Figure 3.1.2-1).

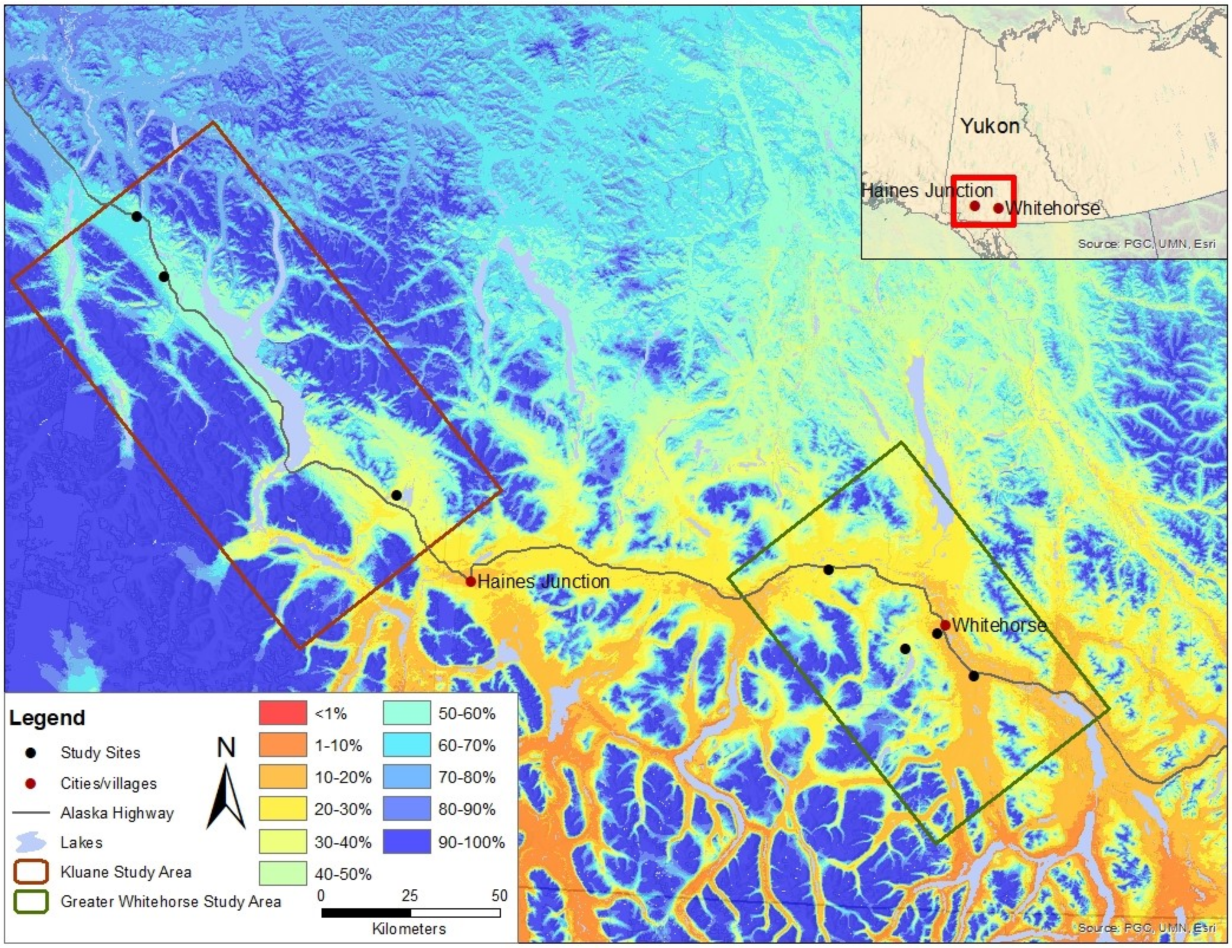


Figure 3.1.2-1. Bonnaventure et al. (2012) model of permafrost probability in the Greater Whitehorse and Kluane study areas, showing 50-70% of permafrost underlying the landscape at the north end of the Kluane study area, while 20-40% underlays the southern end. In the Greater Whitehorse study area, the model shows that 10-30% of the landscape may be underlain by permafrost.

3.1.3. Kluane Region

The Kluane study area is located in the traditional territory of The White River, Kluane, and Champagne Aishihik First Nations within the Ruby Range Boreal Low Zone, which falls in the Boreal Cordillera ecozone (McKenna and Flynn 2017). The area is characterized by short summers and long winters and is one of the Yukon driest regions (Shorthouse 2010; McKenna and Flynn

2017). Although winters are very cold, periodic incursions of coastal air lead to mild spells (Shorthouse 2010). Boreal forest dominated by white spruce is present on lower slopes and in valley bottoms of this region, with grasslands present on some southern slopes (Shorthouse 2010; McKenna and Flynn 2017).

The McConnell glaciation is also primarily responsible for the landforms present in the Kluane study area. Ice flowed northwest across the region through the Shakwak Trench, which spans from eastern Alaska to Haines Alaska and separates the Kluane and Ruby Ranges (Northern Climate ExChange 2013). The topography in the area is undulating, and low points between glacial hills are commonly filled with poorly draining glaciofluvial deposits (silt, sand, clay, gravel, and boulders). More recent fluvial deposits overlay glacial and glaciofluvial deposits (silt, sand, clay, gravel). Poorly drained depressions in the region favor the development of organic material and often lead to very ice-rich permafrost (Calmels, Roy, et al. 2015). Moraine deposits consisting of gravel suspended in a sandy to silty matrix are common and often contain ice-rich permafrost (Yukon Ecoregions Working Group 2004; Northern Climate ExChange 2013). The development of permafrost in the area was epigenetic, or permafrost that formed through lowering of the permafrost base in previously deposited sediment, limiting its depth (Calmels, Roy, et al. 2015).

Between 10% and 90% of the Kluane study area is expected to be underlain by permafrost, as it lies on sporadic discontinuous and extensive discontinuous permafrost zones (Heginbottom et al. 1995). More detailed probability modeling by Bonnaventure et al. (2012) indicates that the northern end of the study area is likely 50-70% underlain by permafrost while the southern end is closer to 30-40% (Figure 3.1.2-1). More extensive permafrost vulnerability mapping was carried out along the Alaska Highway corridor through the Kluane area by Calmels et al. (2015), estimating that between 34% and 38% of this area is considered highly vulnerable to thaw, and 40-44% is moderately vulnerable to thaw (Calmels, Roy, et al. 2015). Additionally, vulnerability mapping was carried out in the Destruction Bay/Burwash landing area, which is central to the study area, indicating that 80% of the area is at moderate to high vulnerability of thaw (Northern Climate ExChange 2013).

3.2. Severity of ecosystem change

The traditional territory of JMRFN is undergoing heavy permafrost degradation and landscape change (Ireland et al. 2013; Calmels, Laurent, et al. 2015). Findings from Chapter 0 indicate that as permafrost degrades, associated forested ecosystems are converted to wetlands. However, there is also evidence that the severity of this change is dependent on the characteristics of permafrost. In many cases, forest was lost, *Sphagnum spp*. took over, and other species adapted to bog and fen conditions invaded (Figure 3.2-1 A). This coincided with permafrost with respectively high excess ice content, deep permafrost that reaches mineral sediment, and large permafrost bodies. Where permafrost was thinner, only present in peat, and had lower topography, some ecosystem components were retained with thaw (Figure 3.2-1 B), and forest cover was not lost.

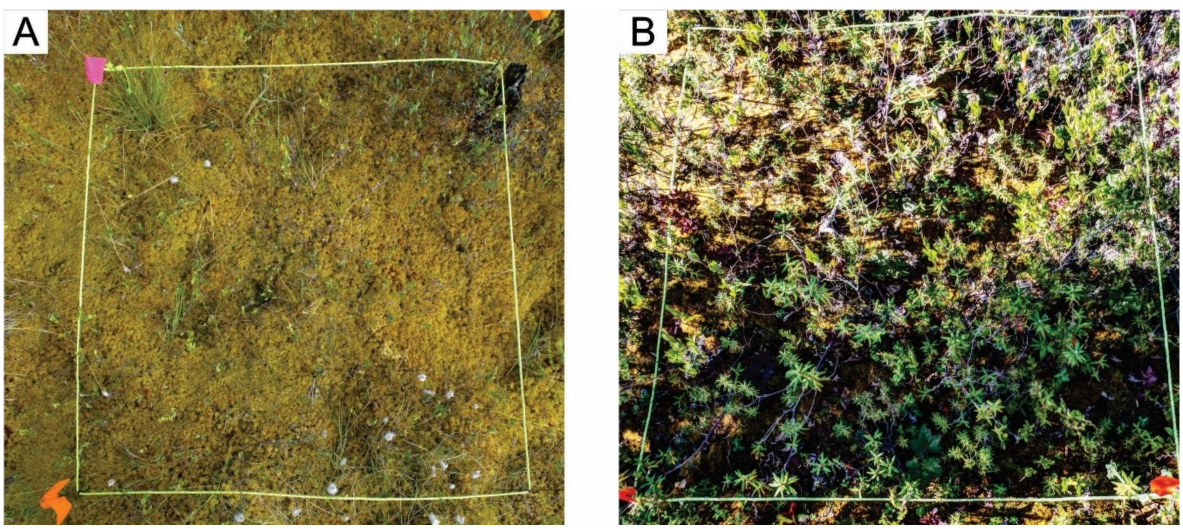


Figure 3.2-1. 1x1 m vegetation quadrats showing a comparison of vegetation and ground cover in degraded areas of site with more severe vegetation change (A) and less severe vegetation change (B) on degraded permafrost in the Jean Marie River study area.

Permafrost degradation is also evident in the greater Whitehorse study area (Lipovsky and Yoshikawa 2009), although site conditions are more varied than in JMR and Kluane. In addition, two of the study sites were disturbed by conditions other than permafrost thaw. Therefore, a less clear connection between permafrost characteristics and vegetation condition was observed. Sites that were disturbed had either more or less severity of change than expected based on permafrost characteristics, dependent on the type of disturbance. In the case of disturbance by wildfire, ecosystems in intact and degraded permafrost conditions were more similar than expected, likely because “intact” vegetation had already experienced a disturbance. Conversely, where intact and transitional areas were undisturbed, but the degraded area experienced additional human disturbance, vegetation characteristics in intact and degraded areas were less similar than may be anticipated based solely on permafrost thaw. In this case, the degraded area experienced multiple forms of disturbance, exacerbating the difference in vegetation composition. At undisturbed sites, the variation of severity in vegetation change was associated with permafrost thickness, ice content, drainage of sediments, and more extreme topography similar to JMR and Kluane study areas.

The Kluane area exhibits evidence of substantial permafrost degradation and landscape change, especially along the highway corridor (Calmels, Roy, et al. 2015). A clear indication of variation in severity of thaw was observed in this study area. At sites with large bodies of ice-rich permafrost, fine sediments, and respectively high permafrost mounds, ecosystems shifted to unforested wetland conditions (Figure 3.2-2 A). Where permafrost was thinner and coarser sediments were present, forest remained on degraded permafrost, and many of the original ecosystem components were preserved (Figure 3.2-2 B).

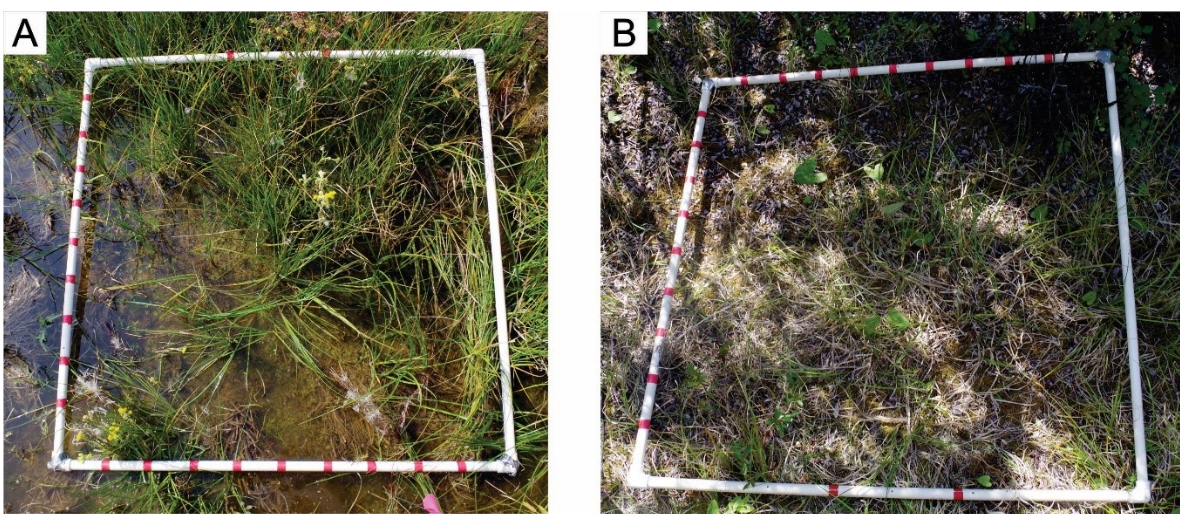


Figure 3.2-2. Comparison of ground cover and vegetation in degraded areas of site with more severe vegetation change (A) and less severe vegetation change (B)on degraded permafrost in the Kluane study area

3.3. Thaw related transition of landscape

Although permafrost development and decay in peatlands is naturally cyclical (Seppala 1982a; Seppala 1988; Zoltai 1993; Gurney 2001; Delisle and Allard 2003), climate warming is unlikely to support conditions for reestablishment of permafrost in JMR (Lantz and Kokelj 2008; Vitt et al. 2010; Rydin and Jeglum 2013a). Sites surveyed in this area were relatively uniform in species composition and site type on intact permafrost but varied in permafrost characteristics. In areas where permafrost characteristics led to more severe landscape change, species characteristic of intact palsas were lost. A small number of *Picea mariana* seedlings present in degraded areas indicate that there may be eventual regrowth of forest, and areas may transition to a treed fen. However, due to the requirement of direr conditions created solely by the presence of permafrost (Vitt et al. 1994; Christensen 2004), the unlikelihood of permafrost reestablishment (Lantz and Kokelj 2008; Vitt et al. 2010; Rydin and Jeglum 2013a), and the presence of fine sediments that do not support drainage (Calmels, Laurent, et al. 2015) in a wetland environment, conditions for reestablishment of original ecosystem components are unlikely to occur.

In areas where ecosystem change appears to be less severe, landscape change did not occur as abruptly, and there was not as clear a delineation between permafrost conditions. Patches of lichens, moss (*Hylocomium/Pleurozium*), and *Vaccinium vitis-idaea* remained on degraded permafrost. Even so, species present on palsas occur due to the separation of the ground surface from the water table, creating a drier environment (Zoltai and Tarnocai 1975; Vitt et al. 1994; Camill 1999). Without the reformation of permafrost, it is unlikely that these species will persist, considering surrounding wetland conditions and poor drainage of surficial materials. It is more probable that species composition will shift further to resemble that of the surrounding wetland. However, degradation of this site had been observed for approximately seven years, with higher moisture content observed in earlier years (2013), which has subsequently drained (2018). Species preserved with degradation had persisted for this time, which could indicate that they may continue to do so as permafrost thaws in areas where permafrost is very thin (>2m), has respectively lower excess ice content and less severe topography.

Climate warming drives the continued thaw of permafrost (Lantz and Kokelj 2008; Vitt et al. 2010; Rydin and Jeglum 2013b), meaning degraded permafrost in Southern Yukon is also unlikely to reform. As previously discussed, sites in the Greater Whitehorse study area had the most variability in conditions, and some were disturbed. At sites disturbed by factors other than permafrost thaw, landscape change is likely to progress differently from those where it was not. At the western end of the study area (Takhini Valley), there was disturbance due to a burn, and permafrost was disconnected from the landscape. Unlike at other sites, there were no landforms to indicate permafrost other than those that were thaw-related. Subsidence was evident in the form of thermokarst ponds and depressions. Species adapted to wetter areas like *Juncus arcticus* and *Ranunculus cymbalaria, and t*hose adapted to drier areas like grasses and *Solidago multiradiata* were present on degraded permafrost, indicating partial drainage of the thermokarst pond at the base of the surveyed depression. Post-fire vegetation regeneration at the survey site was slow, with little to no reestablishment of the organic layer. Because of this, long-term permafrost degradation is likely to continue. Burn (1998) approximated it would take over a millennium for the ice-rich permafrost in this area to thaw. Projections of permafrost thaw in 21st-century climate conditions indicate that the majority of permafrost will have thawed by the end of the century (Froese et al. 2008), so this site may likely thaw more rapidly with continued climate warming and the absence of organic layer regeneration. Given the dry conditions, continued disturbance due to permafrost thaw, and species present in degraded areas, the landscape may transition from boreal forest to grassland over time. Meadowy areas on permafrost free ground were present close to the survey area (Burn 1998).

Sites in the central to southwestern Greater Whitehorse study area were located in the Yukon River valley and had gently undulating topography. Where permafrost was thicker and more ice-rich, the surrounding topography was still relatively flat, unlike sites in the northern portion of the Kluane study area. Well, draining materials are present deeper in the permafrost profile. Pockets of ground subsidence occurred, leaving hollows in the ground and leading to forest loss due to loss of ground stability. However, water from excess ice subsequently drained, which has thus far prevented the large-scale formation of wetland conditions along with the relatively flat topography. These circumstances mean that although forest cover and many of the species present on intact permafrost are lost when permafrost degrades, some of the original ecosystem components may be retained as the landscape transitions.

Where permafrost was very thin (<2m) and surficial materials promoting drainage were present, survey sites included human disturbance on degraded permafrost. This makes it difficult to anticipate how the landscape will evolve. However, it may be reasonable to predict that permafrost will thaw with some ground subsidence, but excess water will drain relatively quickly, and the ecosystem will remain partially intact. Small pools of water were present in transitional areas, but these appear to have drained once permafrost has thawed.

The greatest amount of ecosystem changes in the study area was observed where wetland conditions naturally surround permafrost mounds. As in JMR, increased moisture from thawing permafrost was causing permafrost mounds at this site to be absorbed into the surrounding bog. Due to the presence of poorly draining surficial materials at the base of the bog (Jorgenson et al. 2001; Brown et al. 2015), the low likelihood of permafrost reformation, and the natural presence of a wetland in the area, it is likely that ecosystem conditions previously present on permafrost mounds will be permanently lost, and the area will transition to a permafrost free bog.

Sites surveyed in the Kluane area were all located in a mature boreal forest. Sites in the study area's northern potion had slightly moister conditions on intact permafrost with a thick moss (*Hylocomium/Pleurozium*) layer. These had more severe degradation, and species previously present on intact permafrost have been lost. However, in contrast to JMR, these sites were not surrounded by the wetland conditions they were transitioning into. Thermokarst ponds and wetlands generated by permafrost thaw may persist for many years in areas due to poor drainage (Jorgenson et al. 2001; Brown et al. 2015), especially if extensive bodies of ice-rich permafrost are present in surrounding areas. Once permafrost has fully thawed, it may eventually drain, and ecological succession may occur, helped along by the proximity of intact permafrost conditions. However, given that 50-70% of this area is likely underlain by permafrost and degradation will occur for many years, wetland conditions may spread and persist. With climate change creating drier conditions (Streicker 2015) on an already dry landscape (Shorthouse 2010), this may mean these areas eventually transition to grassland ecosystems present in other portions of the ecozone.

In the southern portion of the Kluane area, less severe ecosystem change was observed, and many of the species that were initially present on intact permafrost were preserved. Subsidence occurred due to thaw of ice-rich permafrost, but the presence of coarse surficial materials supported drainage (Nossov et al. 2013), meaning resulting water drained relatively quickly and less difference in vegetation occurs between intact and degraded permafrost. With a partially intact ecosystem surrounded by intact forest, the degraded area may eventually return to its original state or retain many of its original components.

3.4. Impacts on woodland caribou habitat

Landscape transition raises concerns about the sustainability of northern ecosystems that support habitat for numerous boreal species, many of which are traditionally relied upon as country food by Indigenous communities. A species of note in the traditional territory of the Jean Marie River First Nation is the boreal subpopulation of woodland caribou (*Rangifer tarandus*). This species is culturally important to the community (Decho First Nation 2011) and is listed as threatened by the Species at Risk Act (Government of Canada 2018).

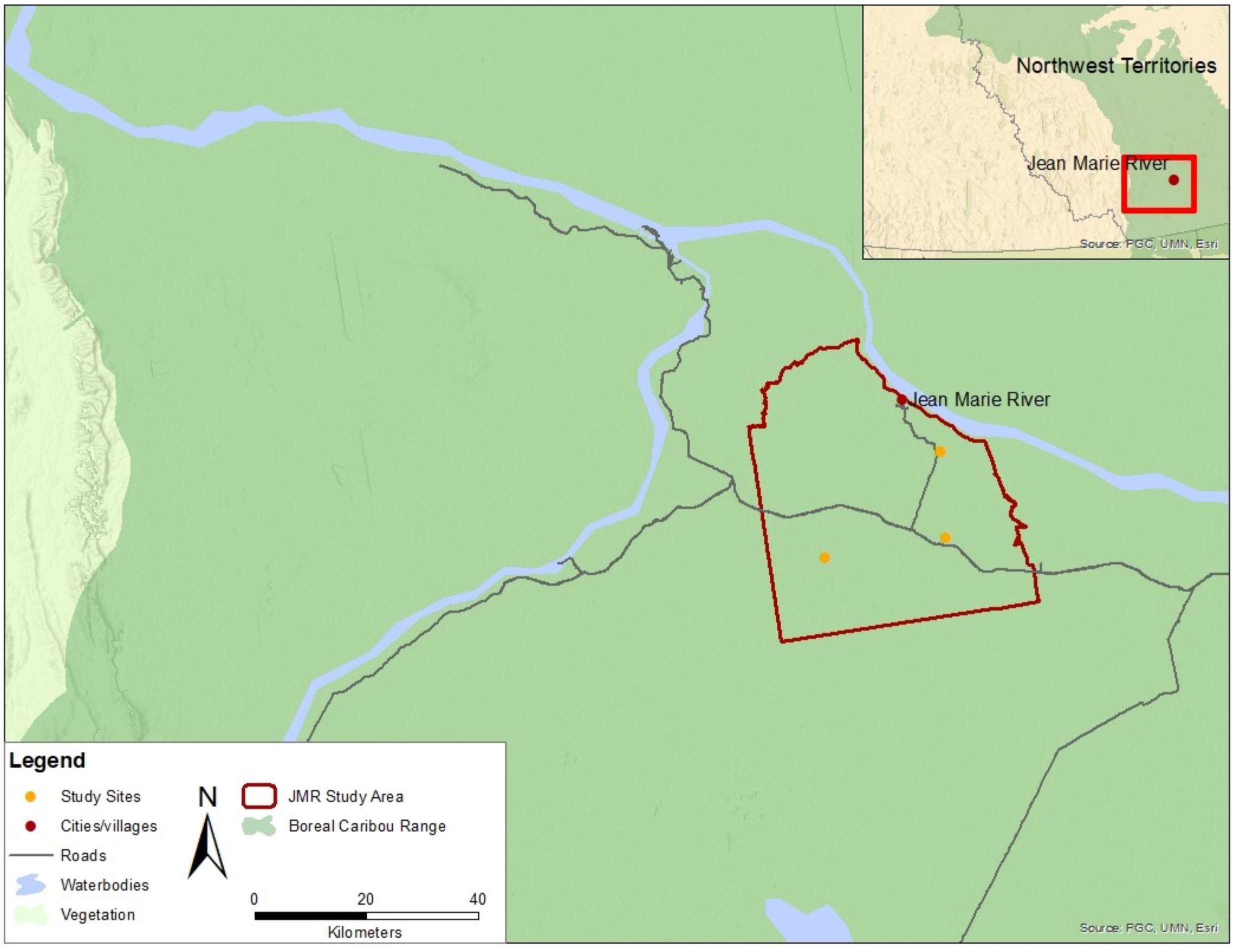


Figure 3.4-1. Map of range of boreal caribou habitat in the area surrounding Jean Marie River, NT.

The potential impact of permafrost thaw on boreal caribou habitat in the traditional territory of JMRFN was assessed by Laurent et al. (2018). It was determined that 88% of boreal caribou habitat in the area is underlain by permafrost vulnerable to thaw. Boreal caribou in the area do not migrate and rely heavily on the available habitat in JMRFNs traditional territory (Government of Northwest Territories 2019). In winter, boreal caribou depend on densely forested areas with high lichen cover. In a large portion of the study area, these conditions occur on permafrost plateaus. Consequently, the degradation of permafrost may contribute to substantial loss of critical habitat for an already threatened species (COSEWIC 2014).

Permafrost thaw also contributes to forest fragmentation (Baltzer et al. 2014), which could be detrimental to a species that relies on large extents of continuous habitat (Government of Northwest Territories 2019). In summer, sedges are a primary food source for woodland caribou

(Oosenbrug and Theberge 1980). They spend more of their time in the wetland areas where they can cool down. These areas are also a haven from predators during calving (Decho First Nation 2011). Given the widespread transformation of palsas to wetlands and an increase in sedges associated with permafrost thaw, preferred summer habitat may be increasing. Although quality summer habitat can reduce the importance of quality winter range (Reimers 1983), access to preferred conditions during winter was deemed critical for caribou survival (Decho First Nation 2011).

In Southern Yukon, the northern mountain subpopulation of woodland caribou (*Rangifer tarandus*) experienced a historic decline, and since the 1990s, has been the focus of extensive recovery efforts (Environment Canada 2012). This population was listed as a species at risk until 2002, when it was downgraded to a species of concern under the Species at Risk Act (COSEWIC 2014). Northern mountain caribou rely on high-quality winter habitat, which includes low elevation mature pine or mixed pine-spruce forests with abundant terrestrial, and in some cases, arboreal lichen (Heard and Vagt 1998; Francis and Nishi 2015). Summer habitat includes high elevation subalpine plateaus, where they feed on sedges and dwarf shrubs (Oosenbrug and Theberge 1980; Francis and Nishi 2015).

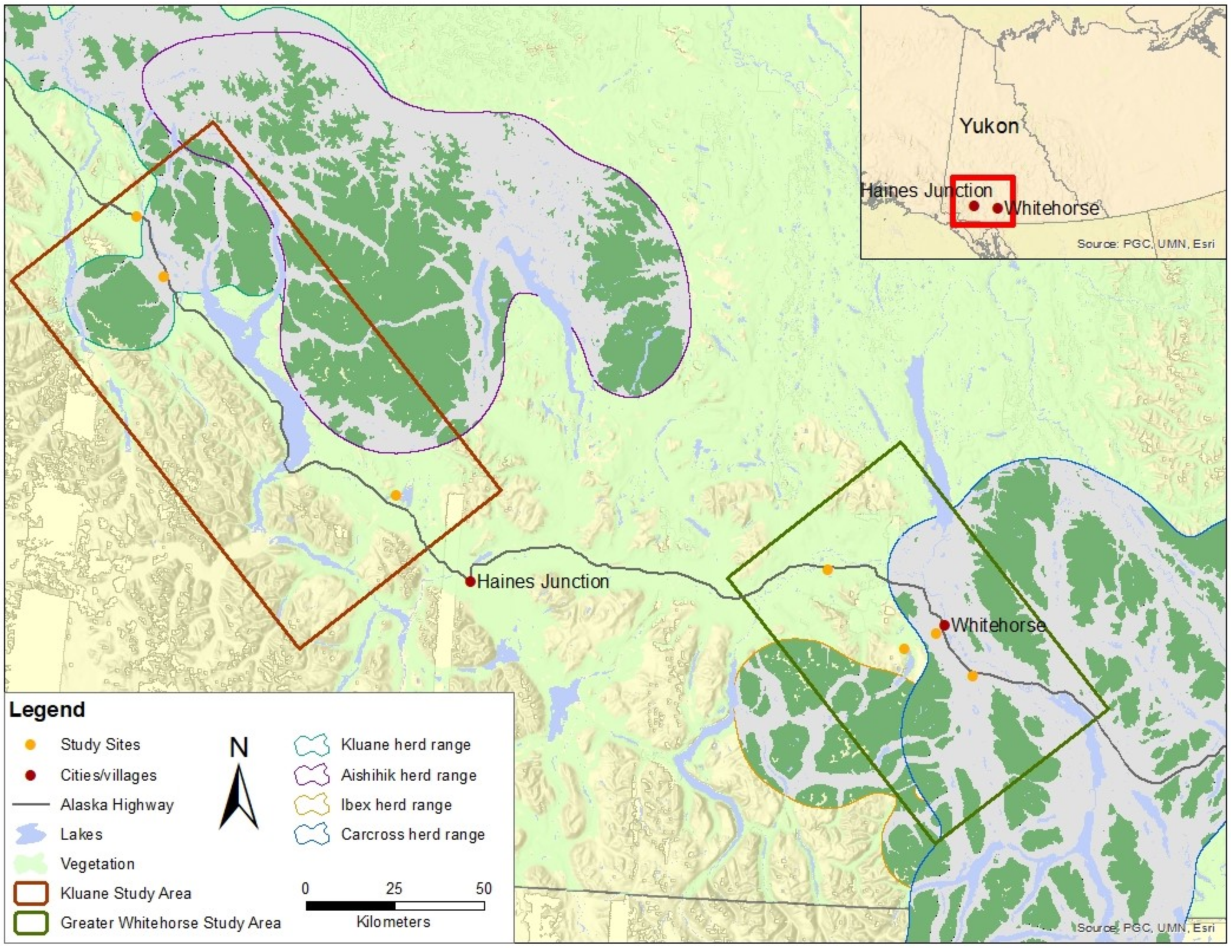


Figure 3.4-2. Map of the ranges of the Kluane, Aishihik, Ibex, and Carcross herds in the Greater Whitehorse and Kluane study areas. Vegetation and permafrost survey locations are shown as yellow points. Polygons for caribou range developed by (Gonet 2020).

The Greater Whitehorse study area overlaps the range of Carcross and Ibex caribou herds (Figure 3.4-2. Map of the ranges of the Kluane, Aishihik, Ibex, and Carcross herds in the Greater Whitehorse and Kluane study areas. Vegetation and permafrost survey locations are shown as yellow points. Polygons for caribou range developed by *(Gonet 2020)*.), which inhabit the traditional territories of Carcross Tagish First Nation, Kwanlin Dun First Nation, and the Ta'an Kwach'an Council (Environment Yukon 2004). The Carcross and Ibex herds, along with the Atlin herd, are collectively known as the Southern Lakes caribou herds (Environment Canada 2012; Francis and Nishi 2015). Oral history indicates that these herds were once part of a much larger group of caribou inhabiting the Southern Lakes region. Although some population recovery has taken place, human disturbance continues to encroach on large portions of critical habitat, and it is unlikely that they will regain historic population levels (Francis and Nishi 2015). Although only 10-30% of the Greater Whitehorse study area is underlain by permafrost (Bonnaventure et al. 2012), habitat loss associated with its thaw may impact the habitat of an already stressed population. Francis and Nishi (2015) concluded that the Carcross herd's range was likely facing the most substantial habitat pressure of all northern mountain herds in Yukon due to human development. Landscape transition with permafrost thaw leads to loss of forest cover and loss of lichen species, both of which are critical to caribou's winter survival.

Although the sites surveyed in the Greater Whitehorse study area technically fall into the winter range of the Carcross herd, for the most part, they do not meet the criteria of high-value winter habitat. These sites transitioned to species like *Carex* and *Salix*, which are relied upon in summer, but elevation at study sites is too low to make suitable summer habitat. A more likely negative impact on the herd is further forest fragmentation due to thaw-related forest loss increasing difficulty of movement between intact habitats, which are required by northern mountain caribou populations (Environment Canada 2012). Additionally, thawing terrain often leads to unstable landscapes and deadfall, which could also impede movement and alter habitat connectivity.

The Kluane study area overlaps the range of the Kluane and Aishihik caribou herds (Figure 3.4-2), which occupy the traditional territory of the White River First Nation, Kluane First Nation, and Champagne and Aishihik First Nation (Environment Yukon 2004). These herds may experience less habitat pressure than those in the greater Whitehorse study area as there is less human disturbance. However, the Alaska highway runs through the Kluane herd's winter habitat, and increased numbers of bison hunters are accessing the range of the Aishihik herd by snow machine (Environment Canada 2012). Compared to the Whitehorse study area, a larger portion of the landscape is underlain by permafrost (30-70% vs. 10-30%) (Bonnaventure et al. 2012), and much of this is at high risk of thaw (Northern Climate ExChange 2013; Calmels, Roy, et al. 2015). (Northern Climate ExChange 2013; Calmels, Roy, et al. 2015). The southern portion of the study area where the landscape is underlain by permafrost met many of the criteria of quality winter habitat, including mature open spruce forests with both ground and arboreal lichens (Heard and Vagt 1998; Environment Canada 2012; COSEWIC 2014).

Conversely, mature open spruce stands with little to no ground lichens are more common to landscape underlain by permafrost in the northern portion of the study area. However, some arboreal lichens are present, which are an important winter resource when snow is thick or crusted (Heard and Vagt 1998; Environment Canada 2012). These areas may contribute to winter habitat but are in an area of connectivity between habitat on the east and west side of the Alaska Highway. As in the Greater Whitehorse area, permafrost thaw may lead to forest loss and fragmentation, unstable landscapes, and increased deadfall, which could reduce habitat connectivity, and subsequently, overall habitat quality for northern mountain caribou in this region.

3.5. Summary

All sites surveyed in the traditional territory of JMRFN were located in areas at high risk of thaw, indicating that the patterns observed are likely to occur on at least 38% of the landscape. However, there was variability in the severity of post-thaw ecosystem transition, which correlates to permafrost characteristics. Higher excess ice content, deeper permafrost, and larger permafrost bodies coincided with a near-complete loss of previous ecosystem components upon degradation. Where permafrost was thinner, only present in peat, and had lower excess ice content, some ecosystem components were preserved, and landscape change was less abrupt. Intact permafrost creates isolated environments that are unlikely to persist with thaw. In areas with more severe ecosystem transition, permafrost was lost, ground subsides, and wetland vegetation colonized areas previously supporting species requiring direr conditions. The reestablishment of permafrost in current climate conditions is unlikely. Therefore, it is also unlikely that conditions required to support original ecosystem components will reoccur, leading wetland conditions to persist after permafrost thaws. Where it is less severe, some ecosystem components were retained for a substantial amount of time (since 2013). Although they may continue to persist, it is more likely that species composition will shift further to resemble that of the surrounding wetland without the reformation of permafrost. Understanding the variability in how ecosystems may change and at what rate and severity improve understanding of how permafrost thaw may impact ecosystems and which ecosystems and associated habitat may be at the highest risk of change or loss due to permafrost thaw. Environments supported by permafrost in Jean Marie River comprise critical habitats for boreal species, notably boreal caribou. Intact permafrost on peatlands supports critical winter habitat for caribou, and habitat loss with degradation may further impact an already threatened population.

In the Greater Whitehorse study area, the landscape is underlain by the lowest percentage of permafrost of all the study areas examined here, with only 10-30% of the landscape potentially impacted by changes in permafrost conditions (Bonnaventure et al. 2012). Moreover, there were many additional sources of disturbance due to the proximity of the study area to Whitehorse. This makes it harder to predict how the landscape may transition. However, undisturbed sites showed similar variation in severity of ecosystem change to those observed in other study areas. Areas with thicker permafrost, more severe topography, higher excess ice content, and poorly draining surficial materials showed more severe ecosystem transition than those with thinner, less ice-rich permafrost located on better draining surficial material. More severe ecosystem transition led to the conversion of drier conditions previously supported by permafrost to wetland conditions with aquatic and emergent vegetation and standing water. In forested areas, forest cover was lost. Where topography was flatter and surficial materials better supported drainage, the large-scale formation of wetland conditions was prevented, and some ecosystem components were retained. Given current climate warming trends, degraded permafrost in Southern Yukon is unlikely to reform (Lantz and Kokelj 2008; Vitt et al. 2010; Rydin and Jeglum 2013b). Where permafrost thaw has led to a more severe transition, it is unlikely that ecosystems will return to their original conditions. However, surrounding conditions are likely to influence eventual transition. In areas where permafrost characteristics led to less severe transition, conditions may support the reestablishment of original ecosystem components. As in Jean Marie River, intact permafrost in the Greater Whitehorse study area overlaps with caribou habitat. Northern mountain caribou in this area are already under significant pressure due to human activity and have low capacity to manage additional stressors (Francis and Nishi 2015), so even low amounts of additional disturbance due to permafrost-induced habitat loss and landscape changes may present challenges to local populations.

In the Kluane study area, thaw-related ecosystem change may impact a substantial amount of the landscape, as 30-70% is underlain by permafrost (Bonnaventure et al. 2012). This study area showed a clear differentiation in the severity of ecosystem change related to permafrost characteristics. Patterns followed those observed in the Jean Marie River and Greater Whitehorse study areas, with thicker, more ice-rich permafrost, more extreme topography, and poorly draining surficial materials leading to more severe ecosystem transition. Wetland conditions and forest loss followed degradation in these conditions. Where permafrost was thinner and less ice-rich, topography was flatter, and more well-draining surficial materials were present, forest cover was retained along with some other ecosystem components. In areas of more severe ecosystem transition, the high proportion of ice-rich permafrost underlaying surrounding landscape combined with poorly draining surficial materials is likely to cause the wetland conditions to persist for long periods. However, with eventual drainage and climate change driving increasingly dry conditions (Streicker 2015) in an already dry ecozone (Shorthouse 2010), these areas may eventually transition to grasslands present in other areas of the ecozone. In areas that experience less severe ecosystem transition, a partially intact ecosystem surrounded by intact forest may eventually return to its original state or retain many of its original components over time. The Kluane study area is mostly undisturbed other than the Alaska Highway running through and small settlements. Although areas underlain by permafrost in portions of this study area resemble quality habitat for northern mountain caribou, much of the potential ecosystem impacts for this species will be related to forest fragmentation and reduced passage between quality habitats. Given that so much of the landscape is underlain by permafrost, this could have substantial impacts. However, areas that most resembled quality habitat occurred on areas where less severe ecosystem change occurred. This could provide some indication that areas of critical habitat are more likely to be associated with these conditions rather than the permafrost conditions that create more severe ecosystem change.

4. **Chapter 4:** Conclusion

4.1. Summary of findings

This thesis incorporates ecological and geomorphological field investigations to bridge the knowledge gap between understanding changes induced by permafrost thaw and how vegetation and wildlife may react to these changes. It addresses the complex interactions between characteristics of permafrost and resulting vegetation and ecosystem changes.

Permafrost thaw was associated with significant differences in vegetation composition between intact, transitional, and degraded permafrost conditions across three study areas in a broader study region encompassing permafrost peatlands and southern lakes boreal forest ecosystems. Species present under intact permafrost conditions are adapted to drier soils, while species that colonized degraded permafrost areas are more tolerant of moisture. With degradation, there is a loss of characteristic boreal forest species, including lichens (*Cladina, Cladonia, Cetraria*), berries (*Vaccinium vitis-idaea, Empetrum nigrum*, *Shepherdia canadensis*), and forbs (*Lupinus arcticus, Galium boreale*).

The vegetation differences documented appear to have a direct link to permafrost conditions. In degraded areas where species functional characteristics were most different from those found on intact permafrost, the topography was generally more extreme, and surficial material did not support drainage (silt, clay, sand). There is an abrupt change from intact permafrost to degraded areas due to this topography, and poor drainage of surficial materials causes water to pool. Forest cover is lost due to standing water. Conversely, sites with thinner permafrost, lower excess ice content, less relief, and better drainage, tended to show less difference in species composition and functional groups. In some cases, forest cover may remain.

This has many implications for these ecosystems and the species that inhabit them, including the distribution and abundance of woodland caribou habitat. Thawing permafrost in peatlands overlaps with a large proportion of boreal caribou habitat in the southwestern NWT region, and conditions present on intact permafrost represent critical winter habitat. Thawing permafrost in southern Yukon's boreal forest may impact northern mountain caribou habitat. Although areas underlain by permafrost in portions of the study area resemble quality habitat for northern mountain caribou, much of the potential ecosystem impacts for this species will be related to forest fragmentation and reduced passage between quality habitats.

My results indicate that ecosystem transition resulting from permafrost thaw may be predicted by observations of permafrost characteristics, potentially supporting the development of adaptive management strategies in a changing environment. Concomitant with this, species type and functional group change may help identify thawing permafrost and estimate post-thaw habitat value to boreal species. The current ability to predict impacts of permafrost thaw on vegetation and wildlife habitat is low, even without considering climate change. The extent of change appears to be linked to permafrost characteristics, and understanding these relationships can improve predictive abilities and response to a rapidly changing landscape condition.

4.2. Research limitations and future research directions

This research represents preliminary investigative studies that are limited by the type of permafrost and ecosystems surveyed, as well as the scope of the surveys conducted, and subsequently only provides indications that a meaningful relationship exists. It represents the results of a small sampling scheme with 3-4 study sites in each of three study regions, limiting its ability to capture ecosystem variability that may occur with varying permafrost conditions and thaw. Due to the high cost of fieldwork and equipment in the North, study locations were often chosen with accessibility limitations in mind. At times, planned survey sites could not be accessed due to logistical or financial constraints; for example, lack of helicopter time. Much of the site selection was based on the pre-existence or planned implementation of permafrost monitoring stations for other projects to reduce the cost and equipment required for this research. The sites surveyed are thus unlikely to represent the whole study area.

Several sites were limited in methods of permafrost assessment (e.g., boreholes, ERT, drone surveys), requiring assumptions or extrapolations be made. Addition of site-specific data would have improved the scope and accuracy of interpretation at these sites. As well, anthropogenic and natural disturbances occurred at two of the sites. Although I hypothesized how this might influence results at these sites, they can not be tested, as no sites with similar disturbance exist in the survey.

To gain a more robust understanding of how permafrost conditions relate to the type and severity of potential ecosystem change, more intense surveys would be needed within the same ecosystem type across different permafrost conditions. JMR surveys most resembled this, but a larger-scale survey with multiple replicates of similar site types would establish more robust evidence of trends. Despite these limitations, this research represents an important connection between observations of permafrost thaw, landscape transition, and ecosystem change in permafrost peatlands in Jean Marie River, Northwest Territories, and boreal forests in southern Yukon.

This work also provides a platform for considering how such connections may affect species dependent on these systems. The preliminary qualitative examination completed here for woodland caribou suggests there could be substantive implications for the amount and distribution of important seasonal habitats, with related considerations of landscape connectivity for both boreal and northern mountain populations. Future work could build on this by incorporating more detailed habitat requirements into landscape projection models informed by permafrost vulnerability and anticipated vegetation change to evaluate range-level changes in habitat suitability for caribou.

References

Allard M, Rousseau L. 1999. The international structure of a palsa and a peat plateau in the Rivière Boniface region, Québec: Interferences on the formation of ice segregation mounds. Géographie Phys Quat. 53(3):373–387. doi:10.7202/004760ar.

Allen MR, Dube OP, Solecki W, Aragón-Durand F, Cramer W, Humphreys S, Kainuma M, Kala J, Mahowald N, Mulugetta Y, et al. 2018. Framing and Context. In: Masson-Delmotte V, Zhai P, Pörtner H-O, Roberts D, Skea J, Shukla PR, Pirani A, Moufouma-Okia W, Péan C, Pidcock R, et al., editors. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,. IPCC.

Anisimov OA, Nelson FE. 1996. Permafrost distribution in the northern hemisphere under scenarios of climatic change. Glob Planet Change. 14(1–2):59–72. doi:10.1016/0921-8181(96)00002-1.

Baltzer JL, Veness T, Chasmer LE, Sniderhan AE, Quinton WL. 2014. Forests on thawing permafrost: Fragmentation, edge effects, and net forest loss. Glob Chang Biol. 20(3):824–834. doi:10.1111/gcb.12349.

Bond J. 2004. Late Wisconsinan McConnel glaciation of the Whitehorse map area (105D), Yukon. Emond DS, Lewis LL, editors. Yukon Explor Geol 2003.:73–88.

Bonnaventure PP, Lewkowicz AG, Kremer M, Sawada MC. 2012. A Permafrost Probability Model for the Southern Yukon and Northern British Columbia, Canada. Permafr Periglac Process. 23(1):52–68. doi:10.1002/ppp.1733.

Brown DRN, Jorgenson MT, Douglas TA, Romanovsky VE, Kielland K, Hiemstra C, Euskirchen ES, Ruess RW. 2015. Interactive effects of wildfire and climate on permafrost degradation in Alaskan lowland forests. J Geophys Res G Biogeosciences. 120(8):1619–1637. doi:10.1002/2015JG003033.

Burn CR. 1998. The response (1958-1997) of permafrost and near-surface ground temperatures to forest fire, Takhini River valley, southern Yukon Territory. Can J Earth Sci. 35(2):184–199. doi:10.1139/e97-105.

Calmels F, Allard M, Delisle G. 2008. Development and decay of a lithalsa in Northern Québec: A geomorphological history. Geomorphology. 97(3–4):287–299. doi:10.1016/j.geomorph.2007.08.013.

Calmels F, Laurent C, Brown R, Ireland M. 2015. How Permafrost Thaw May Impact Food Security of Jean Marie River First Nation, NWT. In: GéoQuébec. Québec.

Calmels F, Roy L-P, Laurent C, Pelletier M, Kinnear L, Benkert B, Horton B, Pumple J. 2015. Vulnerability of the North Alaska Highway to Permafrost Thaw. Whitehorse, YT: Yukon University.

Camill P. 1999. Patterns of boreal permafrost peatland vegetation across environmental gradients sensitive to climate warming. Can J Bot. 77(5):721–733. doi:10.1139/cjb-77-5-721.

Camill P. 2005. Permafrost thaw accelerates in boreal peatlands during late-20th century climate warming. Clim Change. 68(1–2):135–152. doi:10.1007/s10584-005-4785-y.

Camill P, Lynch JA, Clark JS, Adams JB, Jordan B. 2001. Changes in biomass, aboveground net primary production, and peat accumulation following permafrost thaw in the boreal peatlands of Manitoba, Canada. Ecosystems. 4:461–478. doi:10.1007/s10021-001-0022-3.

Christensen TR. 2004. Thawing sub-arctic permafrost: Effects on vegetation and methane emissions. Geophys Res Lett. 31. doi:10.1029/2003GL018680. http://doi.wiley.com/10.1029/2003GL018680.

COSEWIC. 2014. COSEWIC assessment and status report on the Caribou Rangifer tarandus, Northern Mountain population, Central Mountain population and Southern Mountain population in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa, ON: COSEWIC.

Couch AG, Eyles N. 2008. Sedimentary record of glacial Lake Mackenzie, Northwest Territories, Canada: Implications for Arctic freshwater forcing. Palaeogeogr Palaeoclimatol Palaeoecol. 268(1–2):26–38. doi:10.1016/j.palaeo.2008.06.011.

Decho First Nation. 2011. Decho Traditional Knowledge Assessment Summary. Gov Canada. [accessed 2021 Jan 30]. https://www.canada.ca/en/environment-climate-change/services/species-risk-public-registry/publications/woodland-caribou-aboriginal-knowledge-summary-report/part-1.html#_doc004.

Degré-Timmons G, Warkentin M, Telgen M van, Bill K, Tom I, Day N, Johnstone JF, Turetsky M, Baltzer JL. 2018. Impacts of wildfire extent and severity on caribou habitat: from woodland to barren ground: Field protocol for establishment of permanent sample plot network to enhance our understanding of post-fire forest recovery in the southwestern Northwest Territori.

Delisle G, Allard M. 2003. Numerical simulation of the temperature field of a palsa reveals strong influence of convective heat transport by groundwater. In: 8th International Conference on Permafrost, July 21-25. Zurich. p. 181–186.

Ecosystem Classification Group. 2009. Ecological Regions of the Northwest Territories – Taiga Plains. Yellowknife, NT: Department of Environment and Natural Resources, Government of the Northwest Territories.

Environment and Climate Change Canada. 2019. Canada’s Changing Climate Report. Bush E, Lemmen DS, editors. Ottawa, ON: Government of Canada.

Environment and Climate Change Canada. 2020. Canadian Climate Normal, 1981 - 2020. [accessed 2020 Aug 12]. https://climate.weather.gc.ca/.

Environment Canada. 2012. Management plan for the Northern Mountain Population of Woodland Caribou (Rangifer tarandus caribou) in Canada. Ottawa, ON: Environment Canada.

Environment Yukon. 2004. Traditional Territories of Yukon First Nations and Settlement Areas of Inuvialuit and Tetlit Gwich'in. Whitehorse, YT: Yukon Government.

Environment Yukon. 2017. Southern Lakes Boreal Low Subzone (BOLsl): A field guide to ecosite identification. Whitehorse, YT: Yukon Government.

Foothills Pipe Lines (south Yukon) Ltd. 1979. Environmental Impact Statement For the Alaska Highway Gas Pipeline Project. Whitehorse, YT: Foothills Pipe Lines.

Francis S, Nishi J. 2015. Range assessment as a cumulative effects management tool: Assessment of the Carcross Caribou Herd Range in Yukon. Whitehorse, YT: Enviroment Yukon Fish and Wildlife Branch.

French HM. 2007. The Periglacial Environment. Third Edit. Chishester, West Sussex: John Wiley & Sons Ltd.

Froese DG, Westgate JA, Reyes A V., Enkin RJ, Preece SJ. 2008. Ancient permafrost and a future, warmer arctic. Science (80-). 321(5896):1648. doi:10.1126/science.1157525.

Gaanderse AJR, Wolfe SA, Burn CR. 2018. Composition and origin of a lithalsa related to lake-level recession and Holocene terrestrial emergence, Northwest Territories, Canada. Earth Surf Process Landforms. 43(5):1032–1043. doi:10.1002/esp.4302.

Gonet JMG. 2020. Influences on Recruitment of Northern Mountain Caribou (Rangifer tarandus caribou). University of Alberta.

Government of Canada. 2018. Woodland Caribou (Rangifer tarandus caribou), Boreal population: progress report on unprotected critical habitat 2018. Ottawa, ON: Government of Canada.

Government of Northwest Territories. 2019. A Framework for Boreal Caribou Range Planning. Yellowknife, NT: Environment and Natural Resources, Government of the Northwest Territories.

Gurney SD. 2001. Aspects of the genesis, geomorphology and terminology of palsas: Perennial cryogenic mounds. Prog Phys Geogr. 25(2):249–260. doi:10.1191/030913301670177237.

Harris SA. 2015. Permafrost. In: The Canadian Encyclopedia. Historica Canada.

Harris SA, French HM, Heginbottom JA, Johnston G., Ladanyi B, Sego D., van Everdingen RO. 1988. Glossary of Permafrost and Related Ground-Ice Terms. Ottawa, ON: National Research Council Canada.

Heard DC, Vagt KL. 1998. Caribou in British Columbia: A 1996 status report. Rangifer. 18(5):117. doi:10.7557/2.18.5.1548.

Heginbottom JA, Dubreuil MH, Harker PT. 1995. Canada, Permafrost. Natl Atlas Canada 5th Ed.

Hennessey R, Striecker J. 2011. Whitehorse climate change adaptation plan. Whitehorse, YT: Northern Climate ExChange, Yukon College.

Ireland M, Brown R, Calmels F, Laurent C, Pivot F. 2013. Permafrost Vulnerability Assessment and Landscape Changes Related to Climate Change in the Jean Marie River First Nation.

Whitehorse, YT: Yukon University.

Jackson L, Fuller T. 2009. Quaternary geology of the Carmacks map area, Yukon territory. Whitehorse, YT: Yukon Geological Survey.

Jorgenson MT, Osterkamp TE. 2005. Response of boreal ecosystems to varying modes of permafrost degradation. Can J For Res. 35(9):2100–2111. doi:10.1139/x05-153. http://www.nrcresearchpress.com/doi/10.1139/x05-153.

Jorgenson MT, Racine CH, Walters JC, Osterkamp TE. 2001. Permafrost degradation and ecological changes associated with a warming climate in central Alaska. Clim Change. 48(4):551–579. doi:10.1023/A:1005667424292.

Jorgenson MT, Romanovsky V, Harden J, Shur Y, O'Donnell J, Schuur EAG, Kanevskiy M, Marchenko S. 2010. Resilience and vulnerability of permafrost to climate change. Can J For Res. 40(7):1219–1236. doi:10.1139/X10-060. http://www.nrcresearchpress.com/doi/10.1139/X10-060.

Kotler E. 2003. Characteristics of permafrost and ice-rich ground surrounding placer mining operations, Yukon Territory: guidelines for management practices. Whitehorse, YT: Department of Fisheries and Oceans. http://emrlibrary.gov.yk.ca/Characteristics of permafrost.pdf.

Lantz TC, Kokelj S V. 2008. Increasing rates of retrogressive thaw slump activity in the Mackenzie Delta region, N.W.T., Canada. Geophys Res Lett. 35(6):1–5. doi:10.1029/2007GL032433.

Laurent C, Perrin A, Ireland M, Bull H. 2018. Elders' stories of Jean Marie River: Impacts of permafrost thaw and forest fires on boreal caribou habitat. Whitehorse, YT: Yukon University.

Lawrence DM, Slater AG. 2005. A projection of severe near-surface permafrost degradation during the 21st century. Geophys Res Lett. 32(24):1–5. doi:10.1029/2005GL025080.

Lawson DE. 1986. Response of permafrost terrain to disturbance: a synthesis of observations from northern Alaska, USA. Arct Alp Res. 18(1):1–17. doi:10.2307/1551209.

Lipovsky PS, Yoshikawa K. 2009. Initial results from the first year of the Permafrost Outreach Program, Yukon, Canada. Weston L., L.R. B, editors. Whitehorse, YT: Yukon Geological Survey.

McKenna K, Flynn N. 2017. The Boreal Low Zone of Yukon. In: Southern Lakes Boreal Low Subzone (BOLsl): A Field Guide to Ecosite Identification. Whitehorse, Yukon: Environemnt Yukon.

Murton J. 2019. Periglacial Processes and Deposits. In: Editor(s): David Alderton SAE, editor. Encycolopedia of Geology. Second Edi. Academic Press. p. 857–875.

Northern Climate ExChange. 2013. Burwash Landing and Destruction Bay Landscape Hazzards: Geological Maiiping for Climate Change Adaptation Planning. Whitehorse, YT: Yukon University.

Nossov DR, Torre Jorgenson M, Kielland K, Kanevskiy MZ. 2013. Edaphic and microclimatic controls over permafrost response to fire in interior Alaska. Environ Res Lett. 8(3):1–12.

doi:10.1088/1748-9326/8/3/035013.

Oksanen AJ, Blanchet FG, Friendly M, Kindt R, Legendre P, Mcglinn D, Minchin PR, Hara RBO, Simpson GL, Solymos P, et al. 2020. Package ‘ vegan .’

Oosenbrug SM, Theberge JB. 1980. Altitudinal Movements and Summer Habitat Preferences of Woodland Caribou in the Kluane Ranges, Yukon Territory. Arctic. 33(1):59–72. doi:10.14430/arctic2548.

Osterkamp TE. 2007. Characteristics of the recent warming permafrost in Alaska. J Geophys Res Earth Surf. 112(2). doi:10.1029/2006JF000578.

Osterkamp TE, Torre Jorgenson M, Schuur EAG, Shur YL, Kanevskiy MZ, Vogel JG, Tumskoy VE. 2009. Physical and Ecologicla Changes Associated with Warming Permafrost and Thermokarst in Interior Alaska. Permafr Periglac Process. 20:235–256. doi:10.1029/2010WR009341.Citation.

Osterkamp TE, Viereck L, Shur Y, Jorgenson MT, Racine C, Doyle A, Boone RD. 2000. Observations of Thermokarst and Its Impact on Boreal Forests in Alaska, U.S.A. Arctic, Antarct Alp Res. 32(3):303–315. doi:10.1080/15230430.2000.12003368.

Pissart A. 2002. Palsas, lithalsas and remnants of these periglacial mounds. A progress report. Prog Phys Geogr. 26(4):605–621. doi:10.1191/0309133302pp354ra.

Railton JB, Sparling JH. 1973. Preliminary studies on the ecology of palsa mounds in northern Ontario. Can J Bot. 51:1037–1044.

Reimers E. 1983. Growth Rate and Body Size Differences in Rangifer , a Study of C a U S E S. Rangifer. 3(1):3–15.

Riseborough DW. 2002. The mean annual temperature at the top of permafrost, the TTOP model, and the effect of unfrozen water. Permafr Periglac Process. 13(2):137–143. doi:10.1002/ppp.418.

Rydin H, Jeglum JK. 2013a. Peatland succession and development. In: The Biology of Peatlands Second Edition. p. 127–143.

Rydin H, Jeglum JK. 2013b. Hydrological systems, hydromorphology and peatland patterns. In: The Biology of Peatlands Second Edition. p. 199–226.

Schuur EAG, Crummer KG, Vogel JG, Mack MC. 2007. Plant species composition and productivity following permafrost thaw and thermokarst in Alaskan tundra. Ecosystems. 10(2):280–292. doi:10.1007/s10021-007-9024-0.

Seppala M. 1982a. Present-day periglacial phenomenon in northern Finland. Biul Peryglac. 29.

Seppala M. 1982b. An experimental study of the formation of palsas. In: Proceedings of the Fourth Canadian Permafrost Conference MArch 2-6 1981. Calgary, AB.

Seppala M. 1988. Palsas and related forms. In: M.J Clark (Ed.) Advances in periglacial geomorphology. p. 247–278.

Seppala M. 1990. Depth of snow and frost on a palsa mire, Finnish Lapland. Geogr Ann. 72(2):191–201.

Shorthouse JD. 2010. Ecoregions with graslands in British Columbia, the Yukon, and southern Ontario. In: Shorthouse JD, Floate KD, editors. Arthropods of Canadian Grasslands (Volume 1): Ecology and Interactions in Grassland Habitats. Vol. 1. Biological Survey of Canada. p. 83–103.

Smith DG. 1994. Glacial lake McConnell: Paleogeography, age, duration, and associated river deltas, mackenzie river basin, western Canada. Quat Sci Rev. 13(9–10):829–843. doi:10.1016/0277-3791(94)90004-3.

Smith SL, Burgess M. 2000. Ground Temperature Database for Northern Canada. Geol Surv Canada Open File 3954.

Smith SL, Lewkowicz AG, Ednie M, Maxime A, Bevington A. 2015. Characterization of Permafrost Thermal State in the Southern Yukon. In: 68e Conférence Canadienne de Géotechnique et 7e Conférence Canadienne sur le Pergélisol.

Streicker J. 2015. Yukon Climate Change Indicators and Key Findings 2015. Whitehorse, YT: Northern Climate ExChange, Yukon College.

Vitt DH, Halsey LA, Zoltai SC. 1994. The Bog Landforms of Continental Western Canada in Relation to Climate and Permafrost Patterns. Arct Alp Res. 26(1):1–13.

Vitt P, Havens K, Kramer AT, Sollenberger D, Yates E. 2010. Assisted migration of plants: Changes in latitudes, changes in attitudes. Biol Conserv. 143(1):18–27. doi:10.1016/j.biocon.2009.08.015.

Washburn LA. 1983a. What is a Palsa. Seattle, WA: Quaternary Research Centre, University of Washington.

Washburn LA. 1983b. Palsas and Continuous Permafrost. In: Permafrost: Fourth International Conference Proceedings. Calgary, AB.

Worsley P, Gurney SD, Collins PEF. 1995. Late Holocebe “Mineral Palsas” and Associated Vegetation Patters: A Case Study From Lac Hendry, Northern Quebec, Canada and Significance for European Pleistocene Thermokarst. Quat Sci Rev. 14:179–192.

Yukon Ecoregions Working Group. 2004. Ecoregions of the Yukon Territory: Biophysical Properties of Yukon Landscapes. C.A.S. Smith JCM and CFR, editor. Summerland, BC: Agriculture and Agri-Food Canada. http://www.env.gov.yk.ca/animals-habitat/documents/ecoregions_of_yukon_reduced.pdf.

Yukon Research Centre Permafrost and Geoscience. 2020a. Permafrost Investigations Hamilton Boulevard, Whitehorse, Yukon: Case-study #2, Greater Whitehorse Permafrost Project. Whitehorse, Yukon.

Yukon Research Centre Permafrost and Geoscience. 2020b. Permafrost investigations Cowley Creek, Yukon: Case Study #1, Greater Whitehorse Permafrost Project. Whitehorse, Yukon.

Zhang T. 2005. Influence of the Seasonal Snow Cover on the Ground Thermal Regime: An Overview. Rev Geophys. 43. doi:10.1029/2004RG000157.

Zoltai SC. 1975. Tree ring record of soil movements on permafrost. Arct Alp Res. 7(4):331–340. doi:10.1657/1523-0430(06-051).

Zoltai SC. 1993. Cyclic development of permafrost in the peatlands of northwestern Alberta, Canada. Arct Alp Res. 25(3):240–246. doi:10.2307/1551820.

Zoltai SC, Tarnocai C. 1975. Peremially Frozen Peatlands in thr Western Arctic and Subarctic of Canada. Can J Earth Sci. 12:28–43.

Zuidhoff FS, Kolstrup E. 2005. Palsa development and associated vegetation in northern Sweden. Arctic, Antarct Alp Res. 37(1):49–60. doi:10.1657/1523-0430(2005)037[0049:PDAAVI]2.0.CO;2.

Appendix

Permafrost and geotechnical analysis

ERT

Electrical resistivity tomography (ERT) is a geophysical method that passes an electrical current through stainless steel electrodes driven into the ground surface. A terrameter located at a central “station” measures the subsurface resistivity distribution between electrode pairs. Resistivity is the mathematical inverse of conductivity and indicates an electrical current's ability to pass through a material. Mineral materials (except for specific substances such as metallic ores) are mostly non-conductive. Variation in the resistivity of soil or rock profiles is governed primarily by the amount and resistivity of pore water present in the profile and arrangement of pores. Therefore, ERT is very well suited to permafrost and hydrology applications. Because most water content in frozen ground is in the solid phase and typically has a higher resistivity than unfrozen water content, permafrost distribution can be inferred based on changes in resistivity between frozen and unfrozen ground.

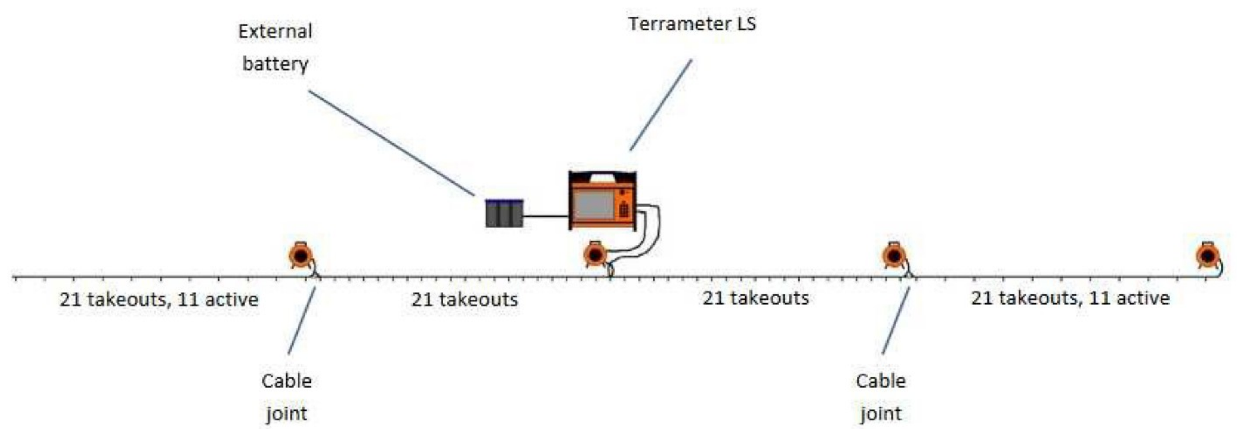


Figure A1. Instrument setup for ERT surveying

Two different electrode configurations or arrays were used during the surveys: the Wenner and dipole-dipole arrays. These arrays differ in how they pair current and potential electrodes (Figure). A direct current electrical pulse is sent from the resistivity meter along the survey line in two current electrodes (C1 and C2), and the measurement is performed by two potential electrodes (P1 and P2). The resulting data consists of a cross-sectional (2D) plot of the ground's resistivity (ohm·m) versus depth (m) for the length of the survey.

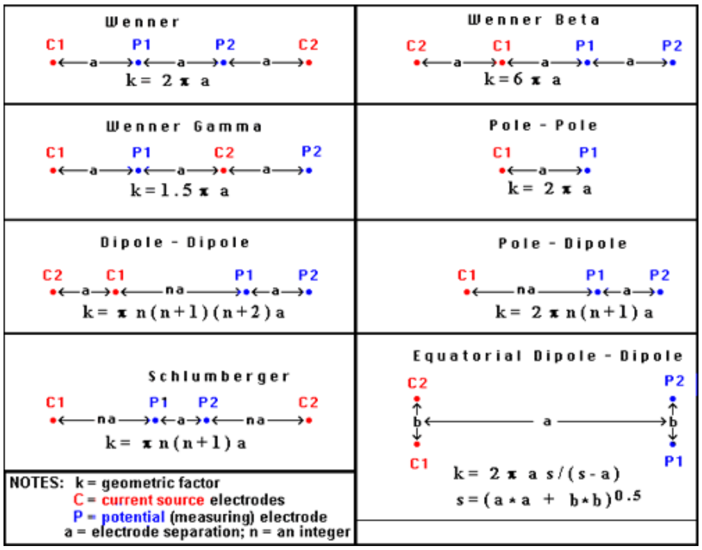


Figure A2. Survey configurations or "arrays" for ERT surveying.

There is no single model that fits the observed resistivities. Instead, the modeled results converge by iteration with the measured values. The operator chooses when to stop iteration in the RES2DINV software. Too few iterations lead to large Root Mean Square (RMS) errors (i.e., the model does not fit the measurements). Too many iterations can result in model 'over-fit' in which the broad patterns are lost. The profiles are presented with a linear depth scale and no vertical exaggeration. ERT profiles were interpreted in conjunction with the results of frost probing along the profiles, field descriptions of vegetation cover at the site, borehole and laboratory analyses undertaken by the research team, and surficial mapping. The surveys' results are post-treated and analyzed at the YRC using inversion software (Res2DInv 64 and Res3DInv 32).

Drilling and sample collection

Sites were selected in advance through a desktop interpretation based on available maps, aerial photos, satellite images, and consultation with community members (property owners, infrastructure and land managers, consultants, and industry).

A sample of every unfrozen layer was collected from each borehole. Each sample was photographed and described in situ (e.g., soil type, soil moisture, presence or absence of organic matter, any particularities). The sample was identified with the borehole name and depth and put in sealed poly bags for laboratory analyses. Frozen samples were also collected and described on site. Each core was cleaned to remove the drilling mud and photographed.

Geotechnical analysis

Sieve and hydrometer analysis of grain size were performed following a specifically modified American Standard and Testing Method protocol (ASTM D422-63, 2000). The sieves used were 4, 2, 1, 0.5, 0.25, 0.125 and 0.063 mm. The data was then compiled in GRADISTAT to generate the statistical analysis.

The volume of excess ice content was calculated using:

$V_{tot} – V_{sed} = Vice$

where V_{tot} is the total frozen core volume, and V_{sed} is the dry soil volume. The volumetric excess ice content (V_{ice}) is then divided by the total frozen core volume (V_{tot}) and expressed as a percentage (fundamentally meaning cm^3/cm^3). This method is valid for mineral soils only.

Ground temperature and climate monitoring

For ground temperature monitoring, newly drilled boreholes are instrumented with HOBO (UX120-006M) four-channel external data loggers. This stand-alone logger can record data at various intervals and uses a direct USB interface for fast data offload. The logger requires two AAA lithium batteries. The batteries typically last one year when logging intervals are greater than one minute. The data loggers are placed in a sealed 15-cm x 15-cm junction box to ensure uninterrupted operation, which is connected to the borehole casing. All borehole casings are made of electrical-grade PVC filled with silicone oil. The temperature sensors (TMC6-HD to TMC50-HD) can accurately record temperatures ranging from –20°C to +70°C, with interchangeability to a tolerance of +/–0.25°C from 0°C to 50°C. They have a resolution of 0.03°C at 20°C.

Imagery processing

Coordinates were set to lat, long, and the coordinate system was set to WGS 84. Blurry or out of focus photos were eliminated from the photo set (image scores < 0.6). A sparse point cloud was then generated:

- Accuracy parameters: High
- Generic preselection looks for tie points in all the photos (time communing)
- Key Point Limit: 40,000
- Tie Point Limit: 1000 – 2000

Ground control points were placed in images. Photos were filtered by marker, and markers were aligned with the center of DGPS surveyed targets (GCPs). Filter by marker was repeated 2-3 times to ensure newly overlapping photos were accounted for. Photo alignment was optimized to include GCPs. A dense point cloud was built:

- General: quality set to high
- Advanced: Aggressive (recommended for vegetated areas, terrain with changes in elevation)

A mesh map was built using the dense point cloud:

- Surface type: height field (2.5D)
- Face count: high
- Advanced parameters: enable interpolation. check calculate vertex color

Texture was built:

- Mapping mode: adaptive orthophoto
- Blending mode: mosaic
- Advanced check both boxes

DSM built:

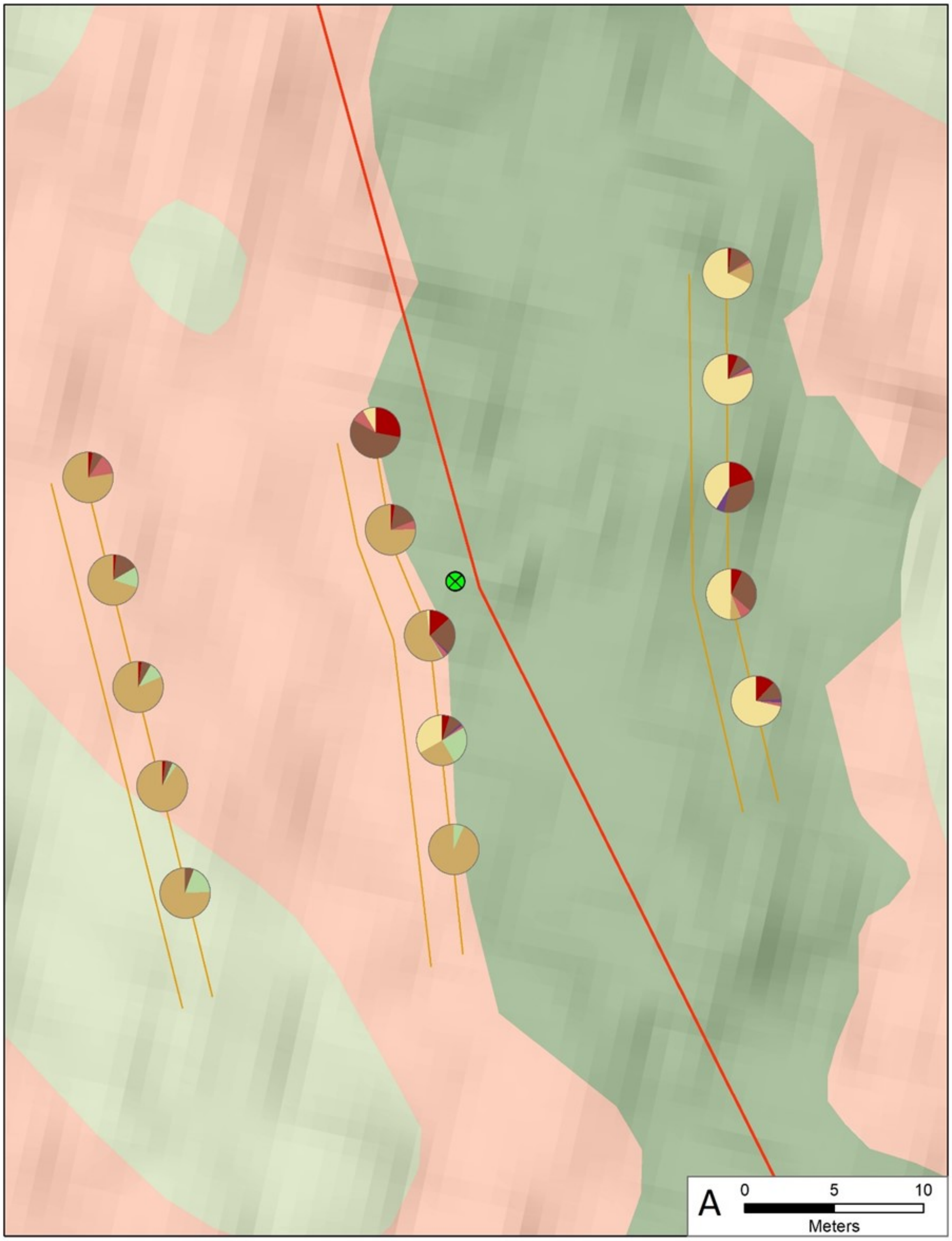
- Projection: Yukon Albers: Source data is dense point cloud
- Interpolation enabled

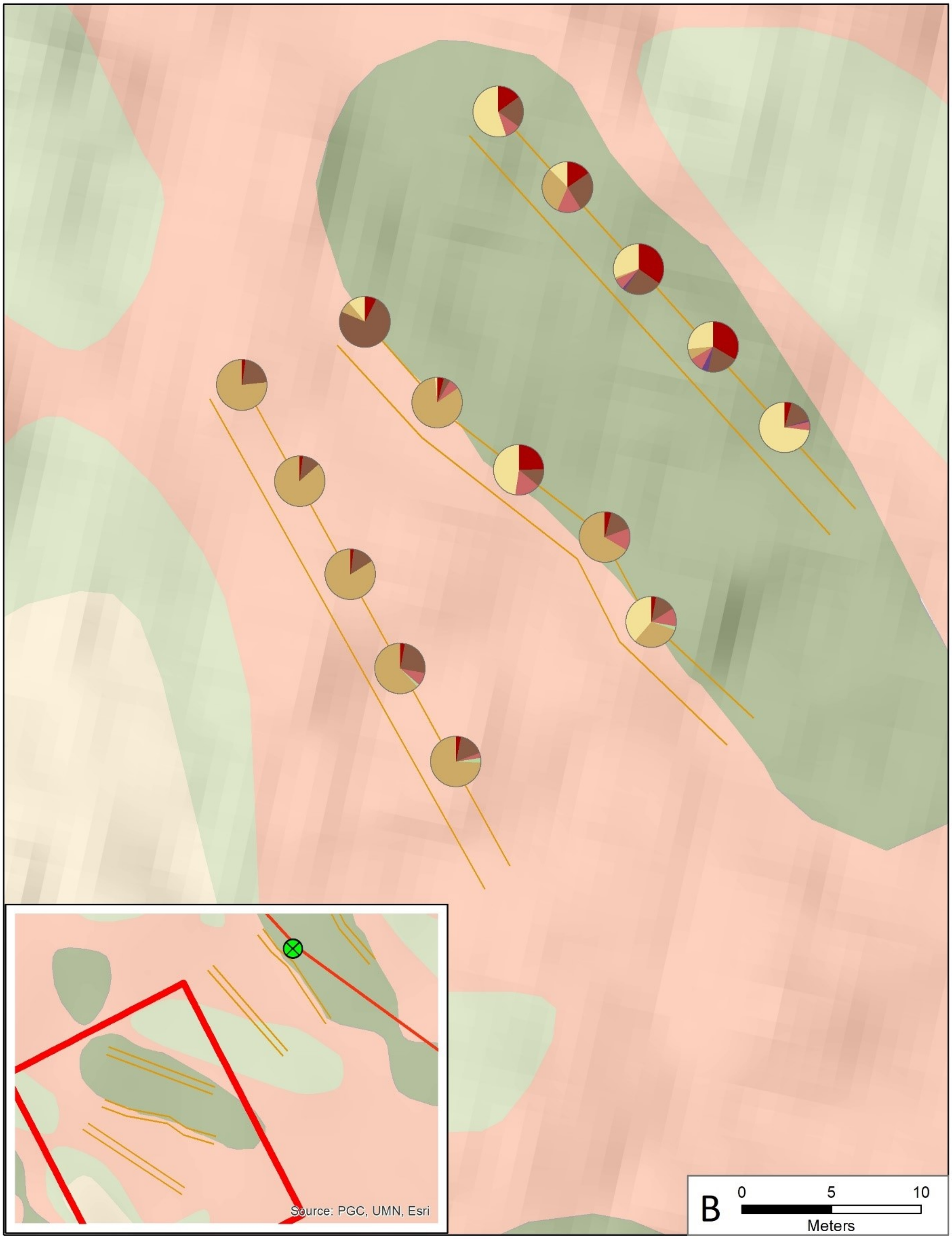
Orthomosaic built:

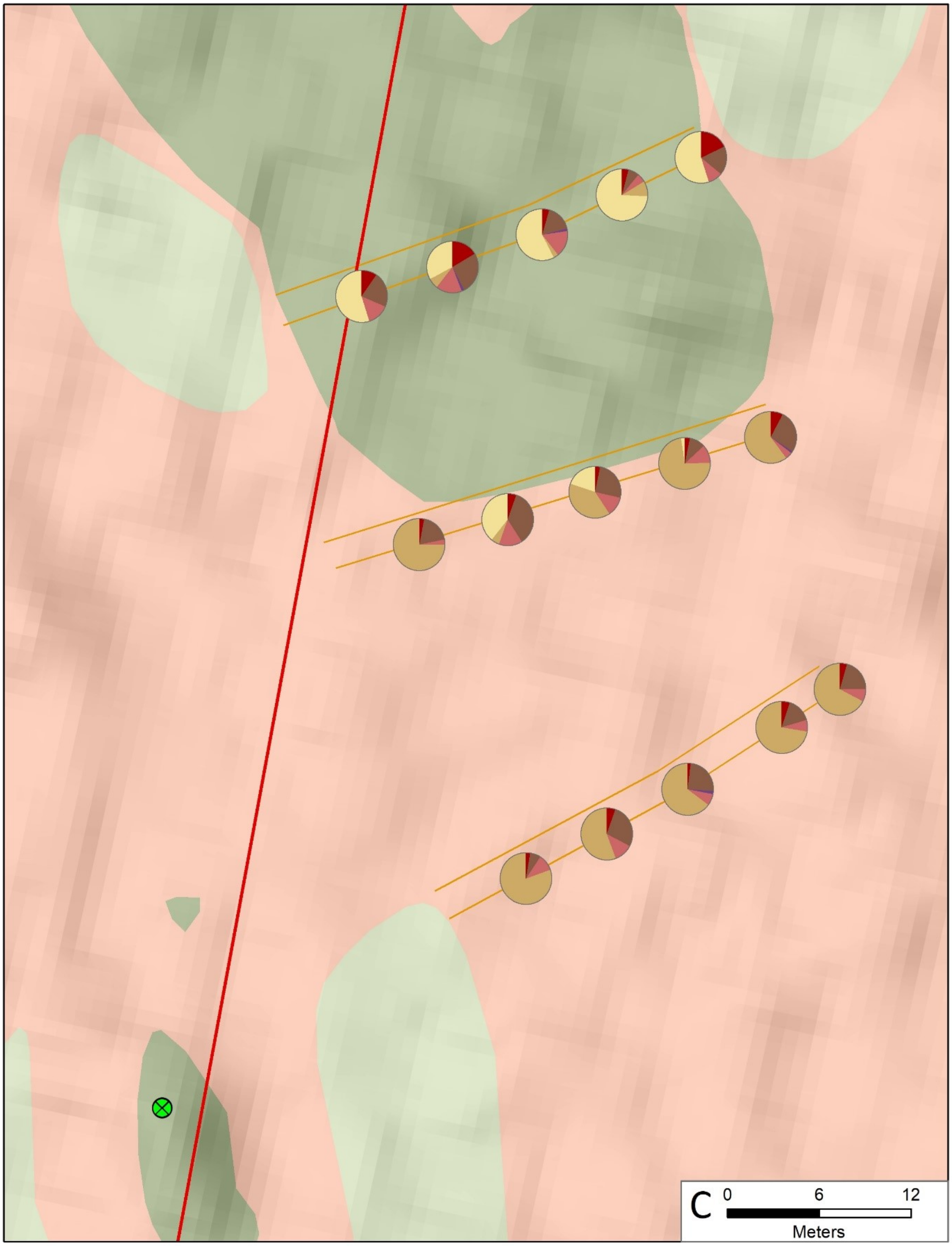
- Surface: DEM
- Blending mode: mosaic

Full page figures

Figure 2.4.4-1 as full-page site maps




Source: PGC, UMN, Esri
B
0
5
10
Meters


C
0
6
12
Meters

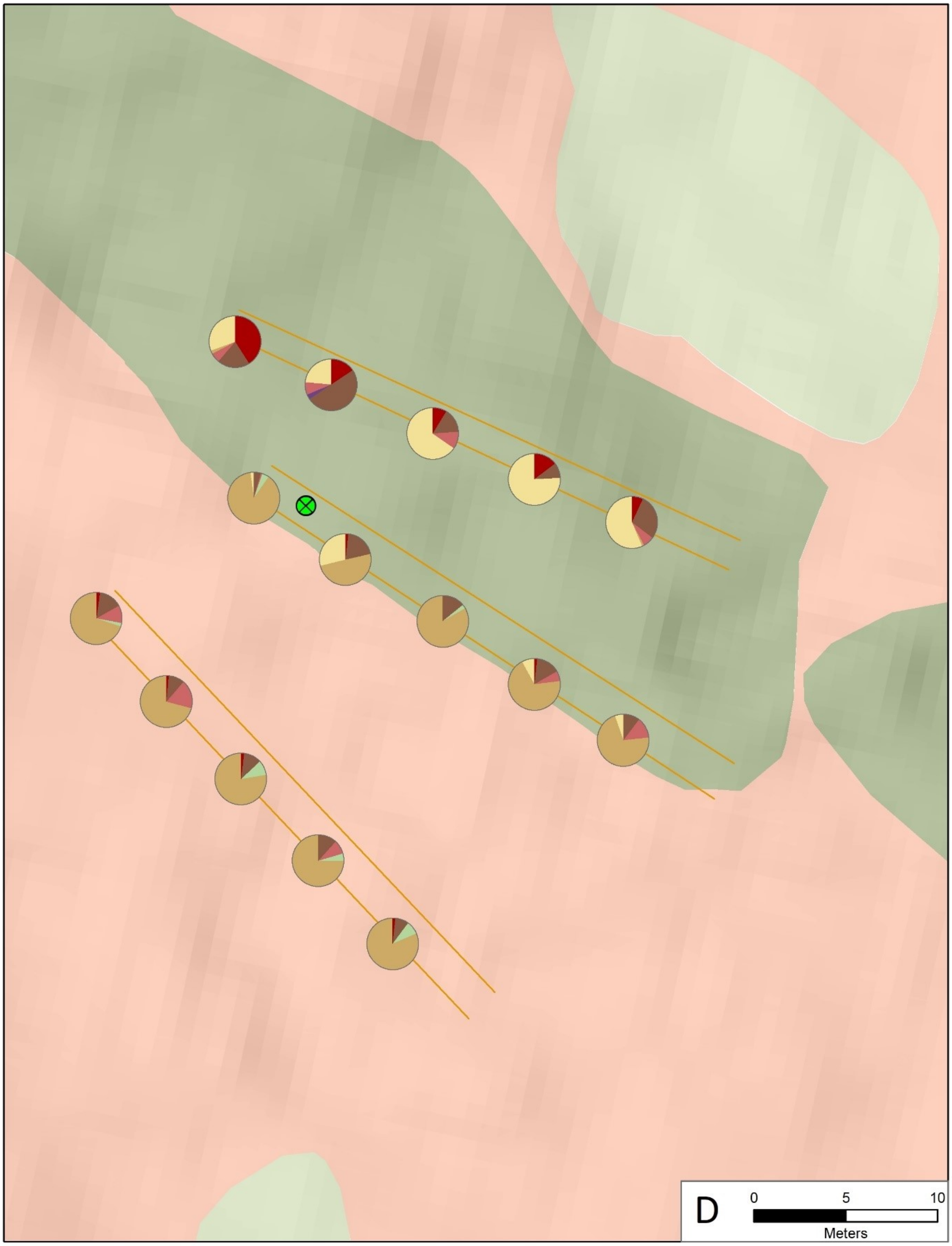
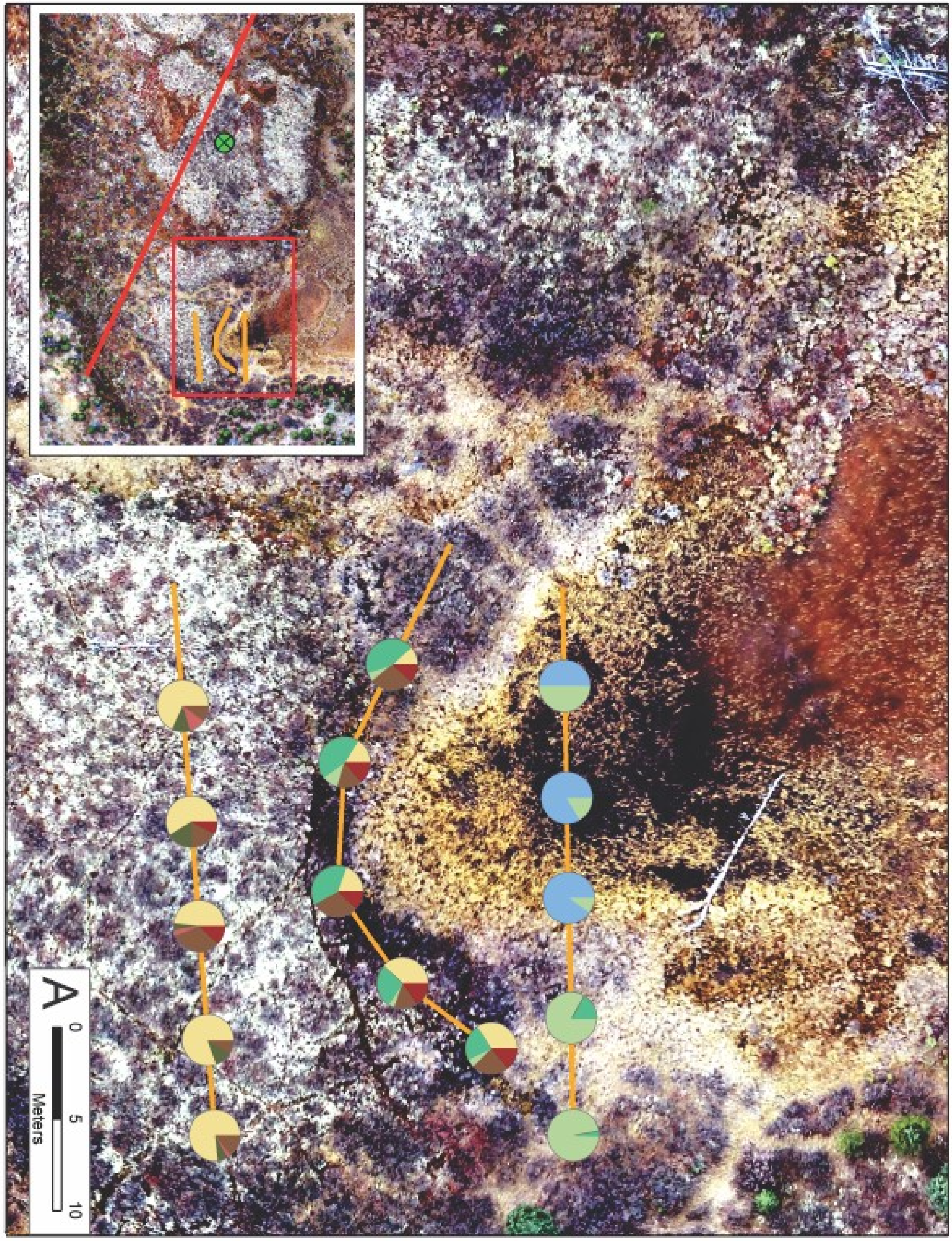
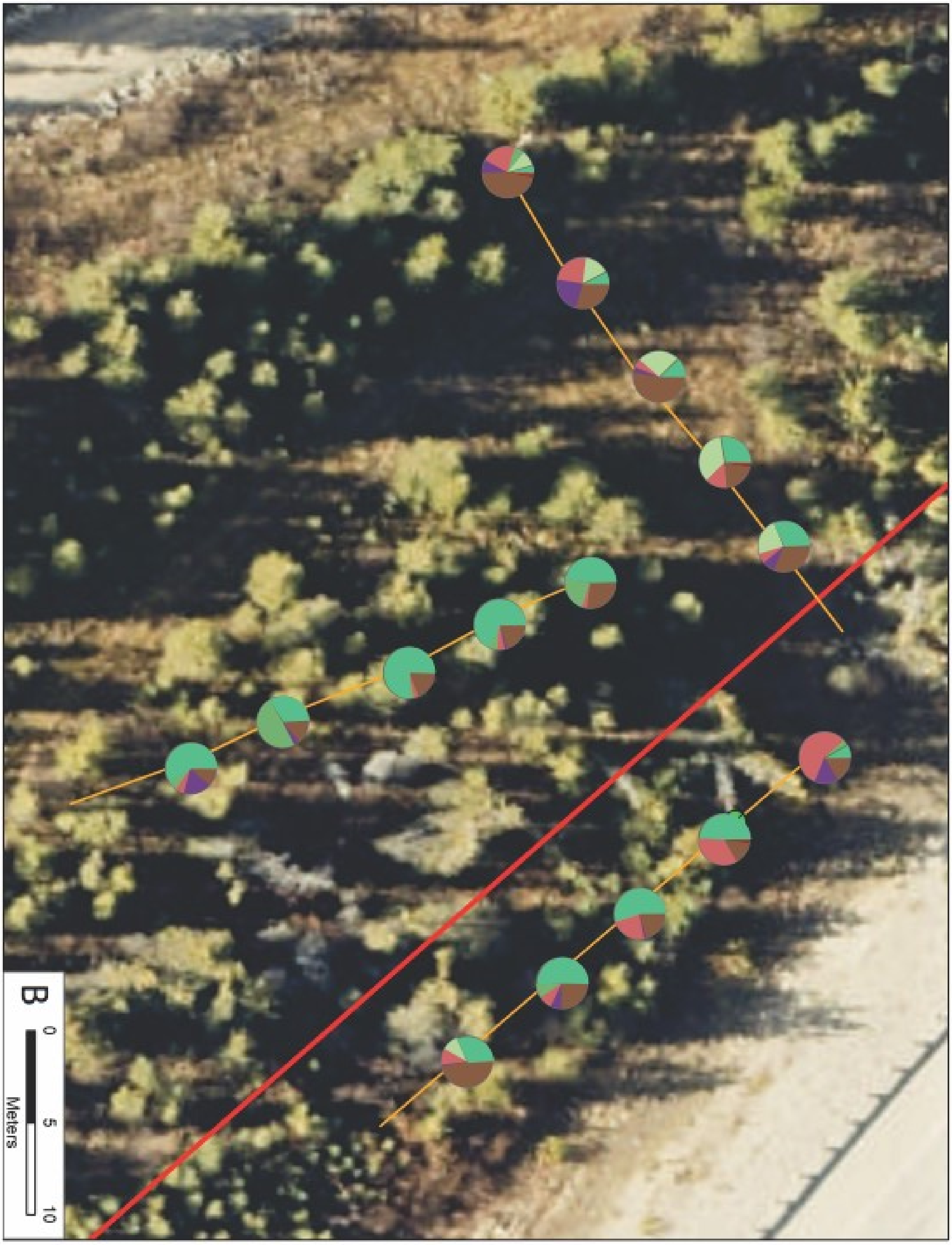
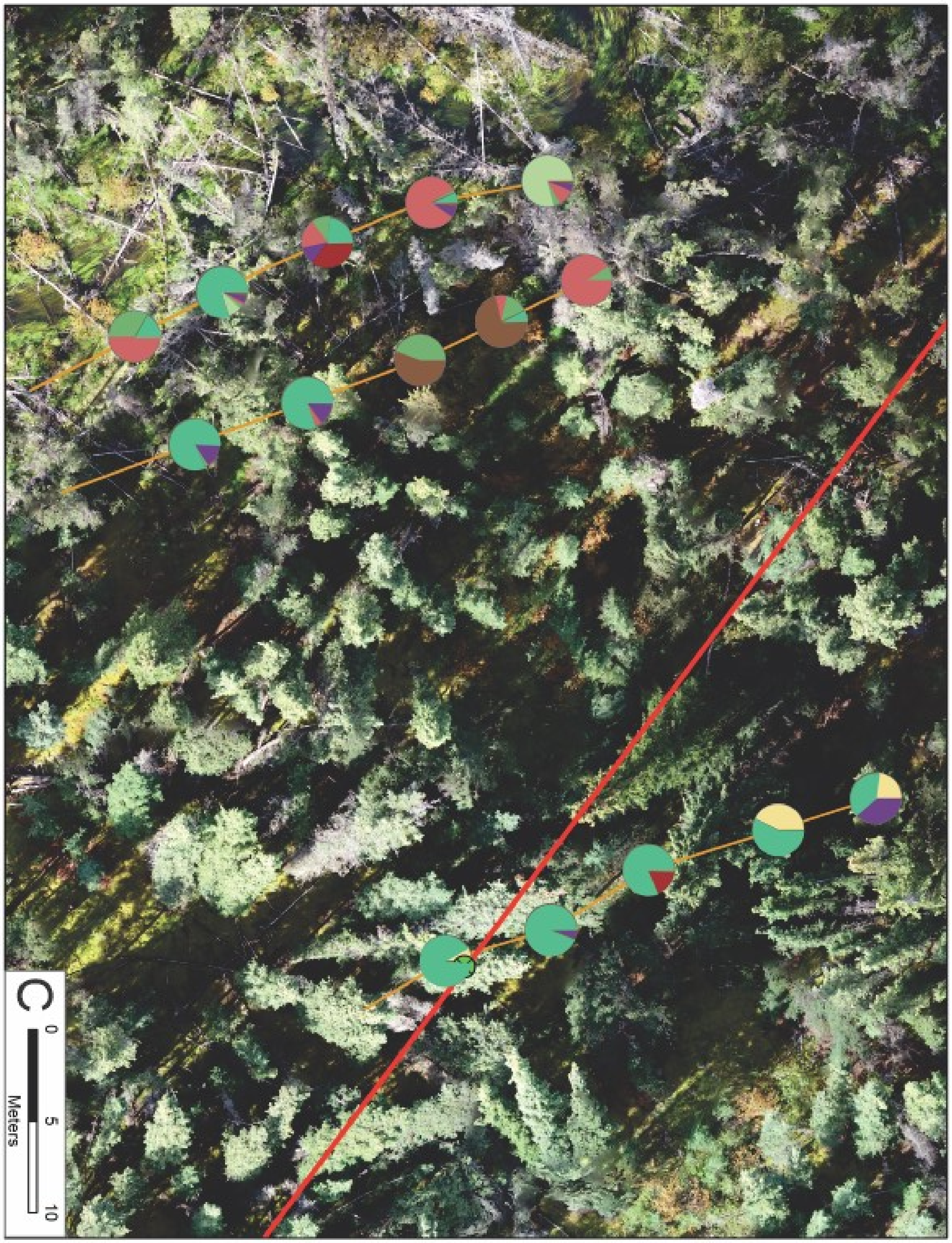

D
0
5
10
Meters

Figure 2.4.4-2 as full-page site maps.




B
0
5
10
Meters


C
0
5
10
Meters

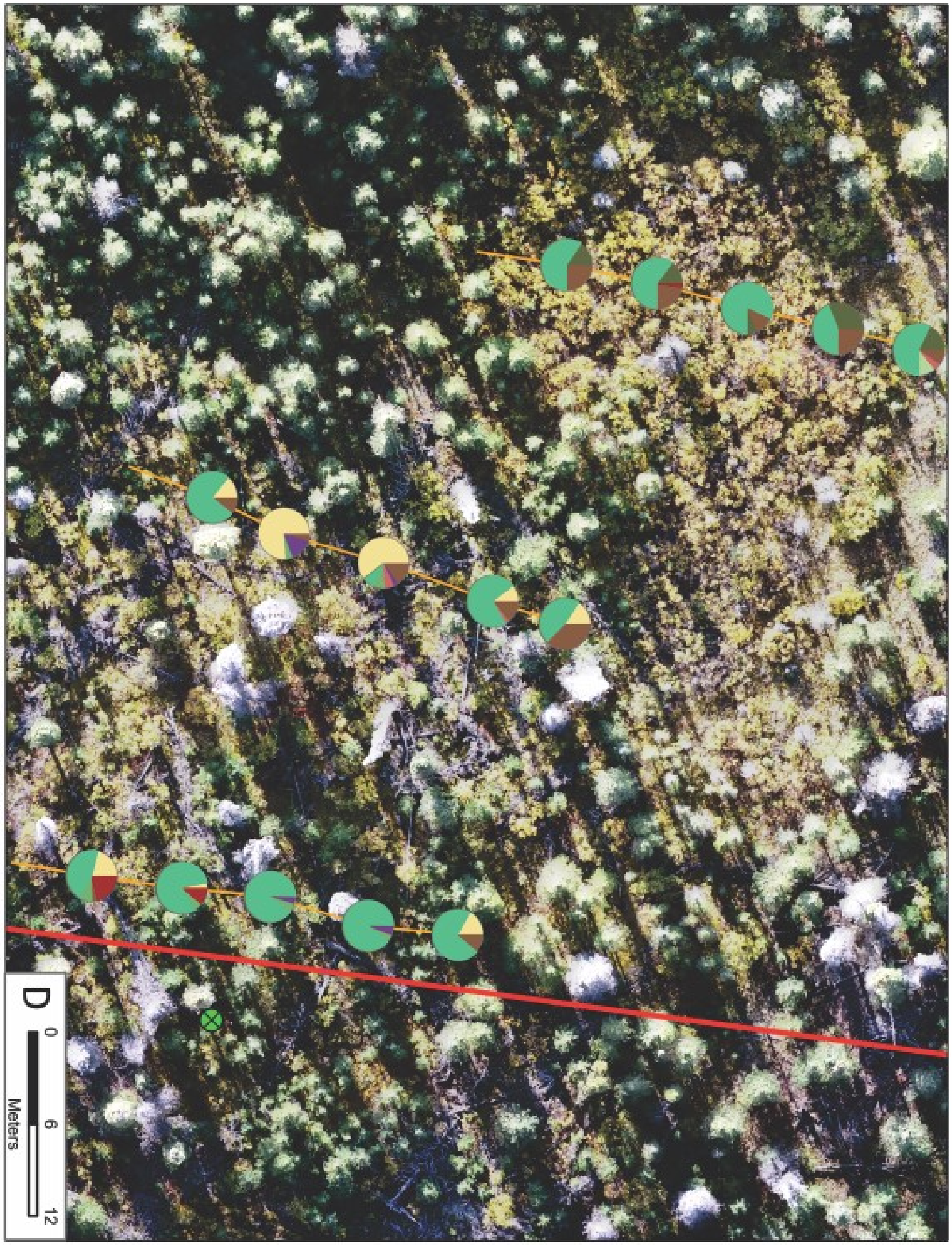
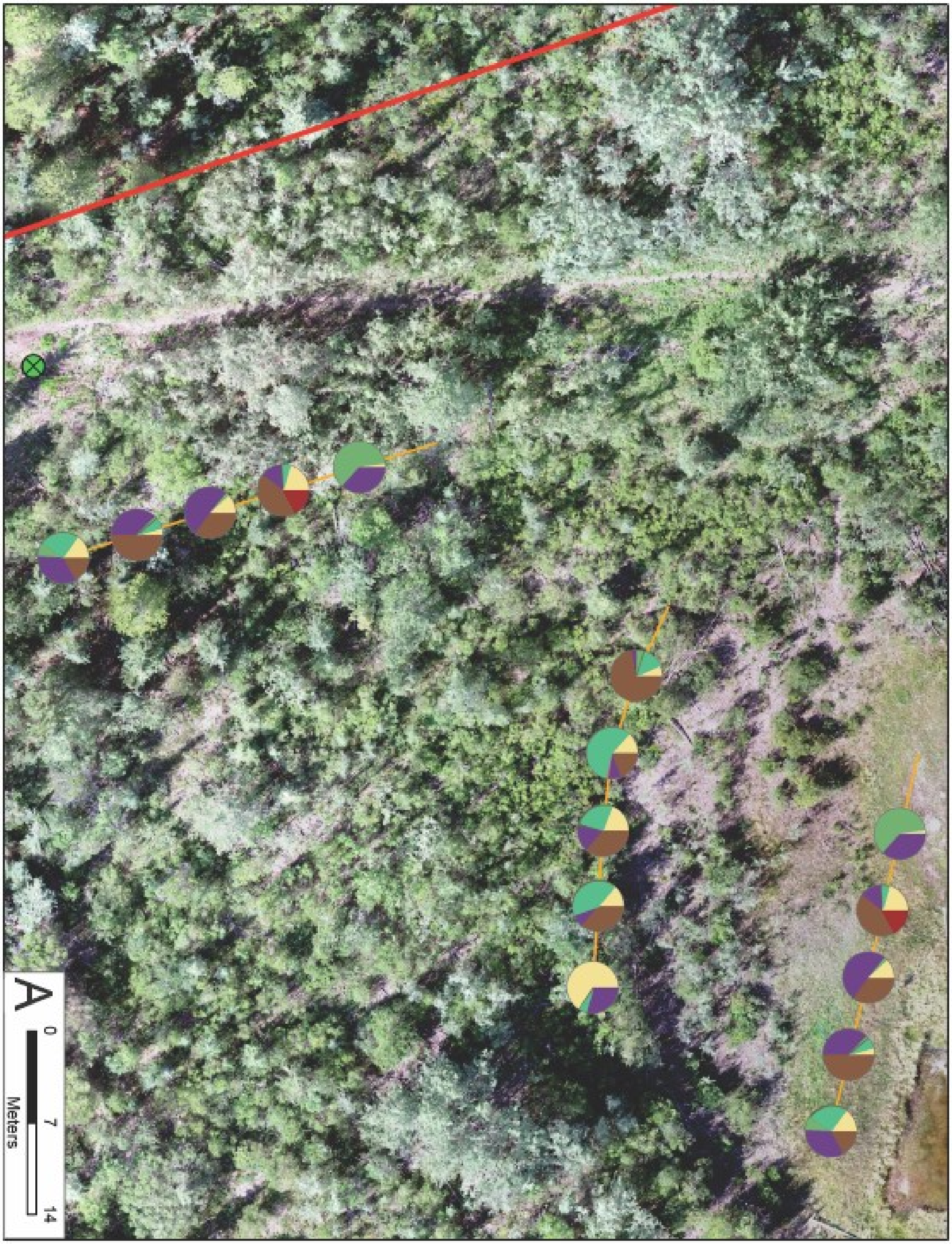
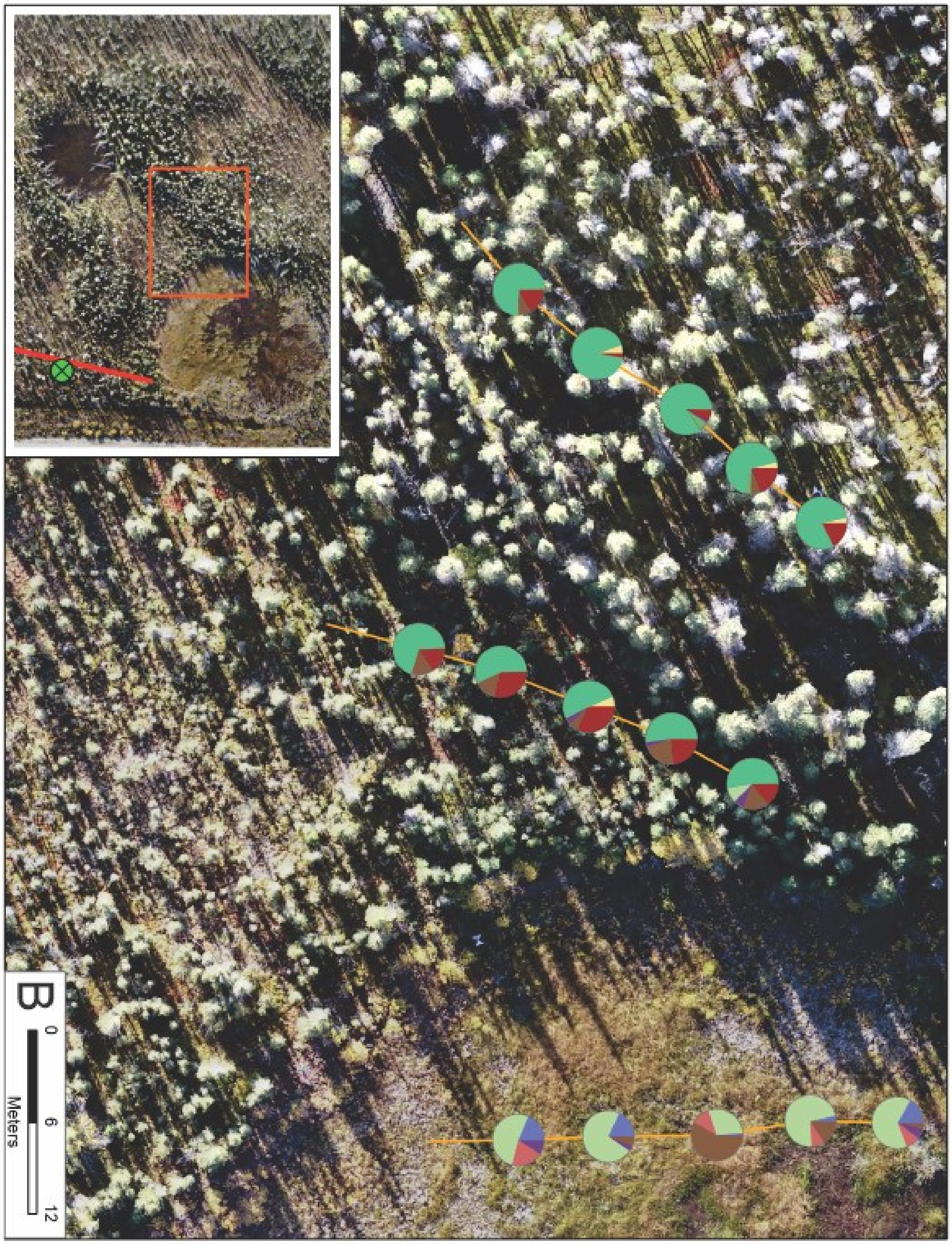
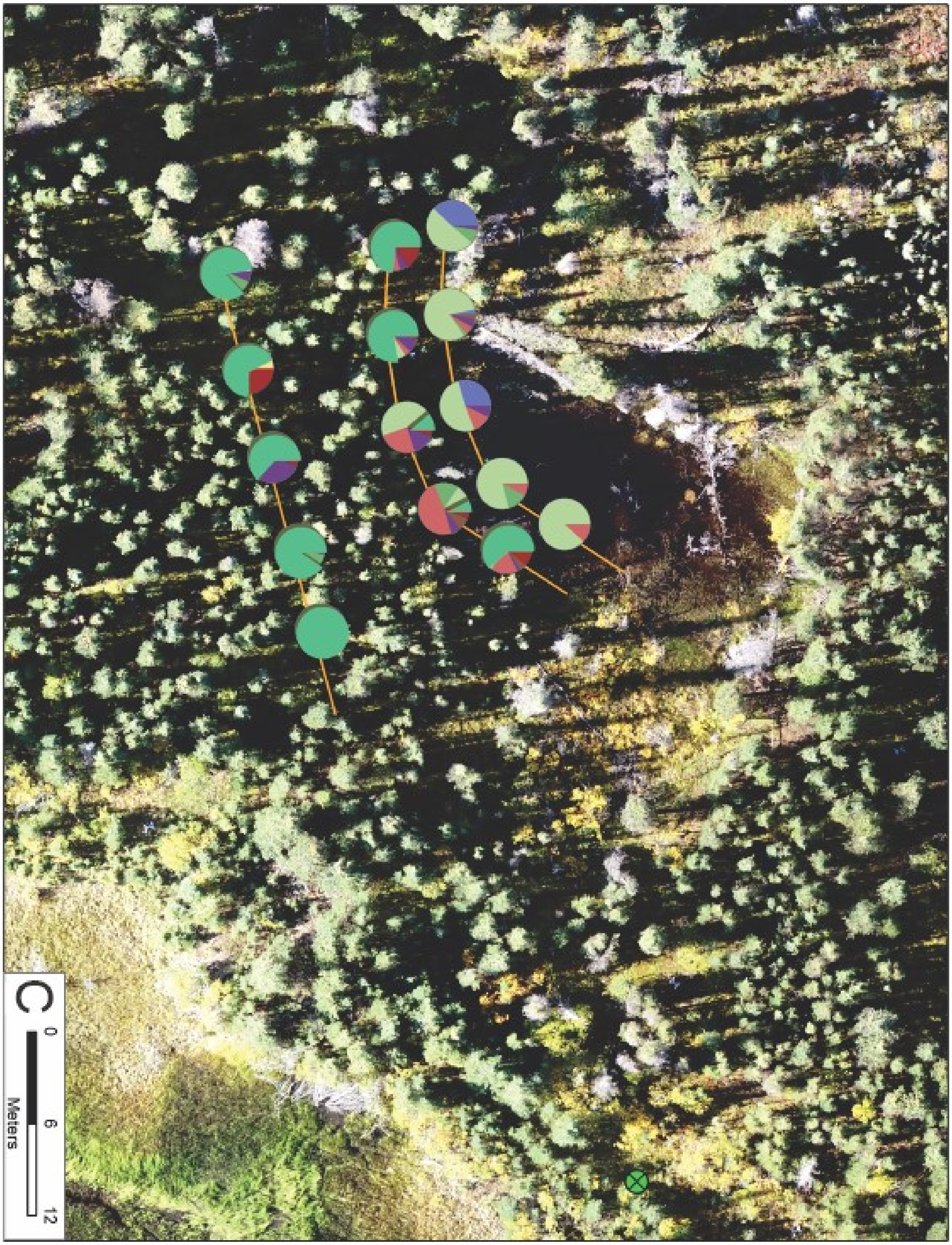

D
0
6
12
Meters

Figure 2.4.4-3 as full-page site maps.




B
0
6
12
Meters


C
0
6
12
Meters