Post-fire ground, vegetation, and snow conditions at three sites in the coastal boreal forests of Nunatsiavut, Labrador, northeastern Canada

Yifeng Wang[1,2], Antoni G Lewkowicz[2], Robert G Way[3], Luise Hermanutz[4], Frederic Dwyer-Samuel[5,6], Alain Cuerrier[5,6], Carissa Brown[7], Lucas Brehaut[8]
[1]*Natural Resources Canada, Geological Survey of Canada, Ottawa, ON, Canada*
[2]*Department of Geography, Environment and Geomatics, University of Ottawa, Ottawa, ON, Canada*
[3]*Department of Geography and Planning, Queen's University, Kingston, ON, Canada*
[4]*Department of Biology, Memorial University, St. John's, NL, Canada*
[5]*Department of Biological Sciences, Université de Montréal, Montreal, QC, Canada*
[6]*Montreal Botanical Garden, Montreal, QC, Canada*
[7]*Department of Geography, Memorial University, St. John's, NL, Canada*
[8]*Natural Resources Canada, Canadian Forest Service, Corner Brook, NL, Canada*

ABSTRACT
Forest fires lead to permafrost thaw and related landscape change, but these impacts are understudied in northeastern Canada where fire intervals are long and snowpacks are deep. We present interdisciplinary field investigations following fire at three sites in the sporadic discontinuous permafrost zone in Nunatsiavut, Labrador. Electrical resistivity tomography surveys were conducted across burned to unburned transitions, and soil, vegetation, and snow data were collected concurrently. Frozen ground conditions varied between sites. Patches of permafrost were identified near Nain (56.5°N), while only seasonally frozen ground was found near Postville (54.9°N). Statistical analyses demonstrated complexity in the post-fire ecosystem. Canopy cover and snow depth co-varied, underlining the importance of an intact canopy in the ecological protection of permafrost. This post-fire response broadly agrees with studies from the western North American boreal forest.

RÉSUMÉ
Les feux de forêt provoquent le dégel du pergélisol, mais ces impacts sont peu étudiés dans le nord-est du Canada où les intervalles des incendies sont longs et les accumulations de neige sont importantes. Nous présentons des études de terrain menées après des incendies sur trois sites situés dans la zone de pergélisol discontinu sporadique du Nunatsiavut, au Labrador. Des études par tomographie de résistivité électrique ont été menées sur les transitions brûlées/non brûlées, et des données de sol, de végétation et de neige ont été collectées simultanément. Les conditions de pergélisol varient d'un site à l'autre. Le pergélisol a été identifié près de Nain (56.5°N), tandis que seul un sol gelé saisonner a été identifié près de Postville (54.9°N). Les analyses statistiques démontrent la complexité de l'écosystème post-incendie. Le couvert forestier et l'épaisseur de la neige covarient, soulignant l'importance d'une forêt intacte dans la protection écologique du pergélisol. Ces résultats concordent largement avec les études réalisées dans la forêt boréale de l'ouest de l'Amérique du Nord.

1 INTRODUCTION

Fire is a natural phenomenon that allows for renewal and regeneration of forest ecosystems, but recent climate changes have caused an increase in the frequency and intensity of fires across northern and permafrost landscapes (Hanes et al. 2019). Following fire, forests undergo succession, with progressive establishment of vegetation that drives the response of underlying frozen ground (Shur and Jorgenson 2007). Post-fire increases in soil temperature and moisture (Fisher et al. 2016) and snow depth (Burles and Boon 2011, Gleason et al. 2013) have been linked to active layer thickening and permafrost thaw (Burn 1998, Smith et al. 2015, Holloway et al. 2020). However, these observations are geographically concentrated in the western North American boreal forest (Holloway et al. 2020). Comparable research has not been undertaken in the coastal forests of the eastern Canadian Subarctic, where the climate and fire history are different.

This study examines post-fire forest and frozen ground conditions at three burned sites in Nunatsiavut, two near the community of Nain (*Nunainguk*) and the third near Postville (*KipukKak*) (Figure 1). Based on studies conducted in western North America (Burn 1998, Smith et al. 2015), we hypothesized that ground temperatures would be lower in undisturbed forest than in adjacent burned areas, due to greater snow interception by the canopy, a thicker organic mat, and greater ground shading. Burned areas were expected to have thinner organic mats, higher ground temperatures, and taller and denser shrubs, leading to snow-trapping and greater snow depths. Permafrost, where present, was expected to be located beneath the unburned forest but to be absent or degrading in burned areas.

2 STUDY AREA

Coastal Labrador is strongly influenced by its proximity to the cold Labrador Current, which runs southwards along the Atlantic coast (Banfield and Jacobs 1998, Roberts et al. 2006). Winters are long and cold, and summers are short and cool (Banfield and Jacobs 1998). The mean annual air temperature at Nain (56.5°N) is -2.2°C (1991-2020) and total annual precipitation is 871 mm, divided almost equally between rain and snow (Environment and Climate Change Canada 2025).

According to the Permafrost Map of Canada (Heginbottom et al. 1995) (Figure 1), both Nain and Postville are located within the sporadic discontinuous permafrost zone. Near Nain, the forest is comprised of black spruce (*Picea mariana*), white spruce (*Picea glauca*), balsam fir (*Abies balsamea*), and eastern larch (*Larix laricina*) (Roberts et al. 2006). Near Postville, the forest is dominated by black spruce with some balsam fir. The regional fire interval is longer than in the western North American boreal forest due to the cool, wet climate (Foster 1983, Hanes et al. 2019).

Two study sites are located about 25 km from Nain, along the northern edge of Tikkoatokak Bay (TB; 56.708°N, 62.209°W) and the southern edge of Webb's Bay (WB; 56.756°N, 61.870°W). These two fires covered areas of 3 km^2 and 1 km^2 in the summers of 2001 and 2004, respectively. At TB and WB, the surficial materials mainly consist of sand, with slightly more silt at TB. Erratics are evident at both sites, and bedrock also outcrops in places at TB. The Beaver River site (BR; 54.780˚N, 59.808˚W) is located about 15 km southwest of Postville, along the southern shore of the innermost segment of Kaipokok Bay. The BR fire occurred in summer 1996 and burned ~150 km^2 of black spruce-dominated forest. Surficial materials consist of a mixture of silt and fine sand, with scattered erratics.

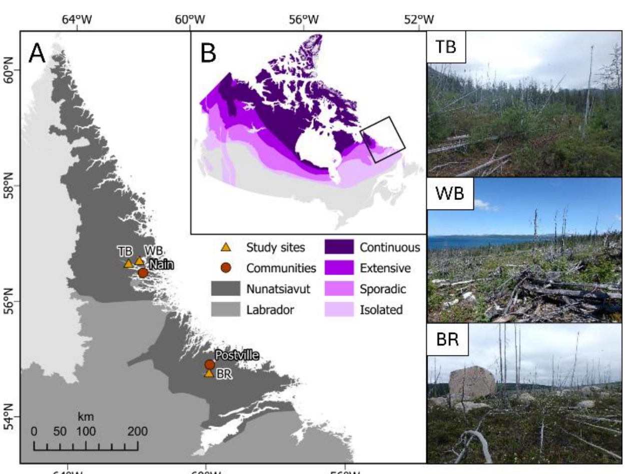

Figure 1. A) Study site locations relative to nearby communities of Nain (*Nunainguk*) and Postville (*KipukKak*) within Nunatsiavut, Labrador, northeastern Canada. B) Inset map showing location of Nunatsiavut relative to permafrost distribution zones in Canada (Heginbottom et al. 1995). Field photos from the Tikkoatokak Bay (TB), Webb Bay (WB), and Beaver River (BR) study sites.

3 METHODOLOGY

3.1 Site setup

Field investigations were conducted in 2017, 2018, and 2019. Two parallel transects spaced 60-100 m apart, measuring 80 m at TB and WB and 40 m at BR, were established perpendicular to the unburned forest edge.

Bihourly air temperature measurements were collected using Hobo Pro v2 Temperature/Relative Humidity U23-001 Data Loggers (±0.21°C accuracy) for two years at TB and WB (TB: August 2017-2019, WB: July 2017-2019) and one year at BR (July 2018-2019) (Table 1). Seasonal snow cover was derived from a series of vertically arranged Thermochron iButtons (resolution 0.5°C, accuracy ±1°C), installed on stakes in burned and unburned parts of the study sites. Snow depths and related metrics were interpreted by examining the attenuation of temperature fluctuations along the stake (Lewkowicz 2008) (Table 1).

Table 1. Air temperature and snow-related metrics at the study sites. Mean annual air temperature (MAAT), thawing degree days (TDD), and freezing degree days (FDD) were measured in the unburned forest. Snow depth days (SDD) and maximum snow depth (MSD) were measured in both burned (B) and unburned (UB) sections.

	2017-2018		2018-2019		
	TB	WB	TB	WB	BR
MAAT (°C)	-2.4	-2.5	-3.0	-3.1	-1.9
TDD (° days)	1221	1166	1132	1111	1429
FDD (° days)	2112	2083	2214	2246	2131
SDD (m days)	UB:187 B:125	UB:177 B:176	UB:161 B:144	UB:158 B:153	UB:253 B:200
MSD (cm)	UB:130 B:90	UB:140 B:130	UB:140 B:130	UB:140 B:140	UB:160 B:150

3.2 Electrical resistivity tomography surveys

Ground conditions were assessed using electrical resistivity tomography (ERT) with an ABEM Terrameter LS profiling system, supported by frost probing and instantaneous temperature measurements using Onset Hobo UX120-006M 4-Channel Analog Data Loggers (±0.15°C accuracy) (Way et al. 2021). ERT is a geophysical technique that is used to differentiate frozen versus unfrozen ground based on differences in resistivity of ice versus water (Herring et al. 2023). Apparent resistivities were converted to best-estimate values using the robust inversion method in the RES2DINV software. Inversion iterations were run until convergence, marked by a change in the RMSE between consecutive iterations of less than 5% or until the fifth iteration. Topography along the transects was recorded with a clinometer and profiles were incorporated into the inversion process. Near-surface resistivity values (mean modelled resistivity from 0.5 to 1.05 m) were extracted from the processed inversions and assigned to the nearest metre along the profile.

3.3 Snow, soil, and vegetation conditions

Snow, soil, and vegetation-related variables were measured along the study transects. Snow depths were measured using a 230 cm-long avalanche probe in March 2018 (TB and WB) and February 2019 (BR). Organic layer thicknesses were measured by inserting a 50 cm-long aluminum rod to the depth where the mineral soil resisted penetration. Soil temperature (±1.5°C accuracy) and moisture (±0.03 cm^3/cm^3 accuracy) were recorded with a WET Sensor and HH2 Moisture Meter Version 2.3. Hemispherical images were obtained using a fisheye lens at the ground surface and at a height of 1.3 m to estimate total and upper canopy cover. Upper canopy coverage was subtracted from total canopy coverage at each location to calculate understory coverage, attributed to shrubs. Canopy openness and gap light transmission were estimated by automatic thresholding and binary conversion, followed by pixel counts in the ImageJ software. The number of shrub ramets and the height of the tallest shrubs of each species were measured within 0.25 m^2 plots. Common shrub species included Labrador tea (*Rhododendron groenlandicum*), dwarf birch (*Betula glandulosa*), willow (*Salix* spp.), and green alder (*Alnus viridis*). Shrubs under 25 cm in height were omitted, as they were expected to cause limited snow-trapping and ground-shading.

3.4 Exploratory statistical analyses

Principal component analysis (PCA) was performed to reduce the dimensionality of eight numerical variables collected along the study transects: snow depth, near-surface resistivity, organic layer thickness, soil temperature, soil moisture, canopy cover, maximum shrub height, and shrub density. A correlation matrix was applied to the PCA to account for the range of scales used for variable measurements. Principal components (PC) were retained according to the Kaiser Rule, requiring eigenvalues above 1. Variables with loadings that exceeded 0.4 were retained for interpretation.

4 RESULTS

4.1 Snow

Snow cover persisted at the study sites from October to May/June. Seasonal patterns showed greater maximum snow depths and longer snow-on-ground seasons in the unburned forest than in the burned areas (Table 1). SDD were greater in the unburned forest than the burned region by 11% at TB, 3% at WB, and 21% at BR for 2018-2019.

Late-winter snow surveys provided additional information on spatial differences between the burned areas and the undisturbed forest. Average late season snow depths were greater in the unburned region than the burned region at WB (UB: 143 cm, B: 110 cm) (Figure 2-A). In contrast, burned and unburned average snow depths were similar at TB (UB: 114 cm, B: 120 cm), and lower snow depths were observed in the unburned portions than in the burned parts at BR (UB: 155 cm, B: 173 cm).

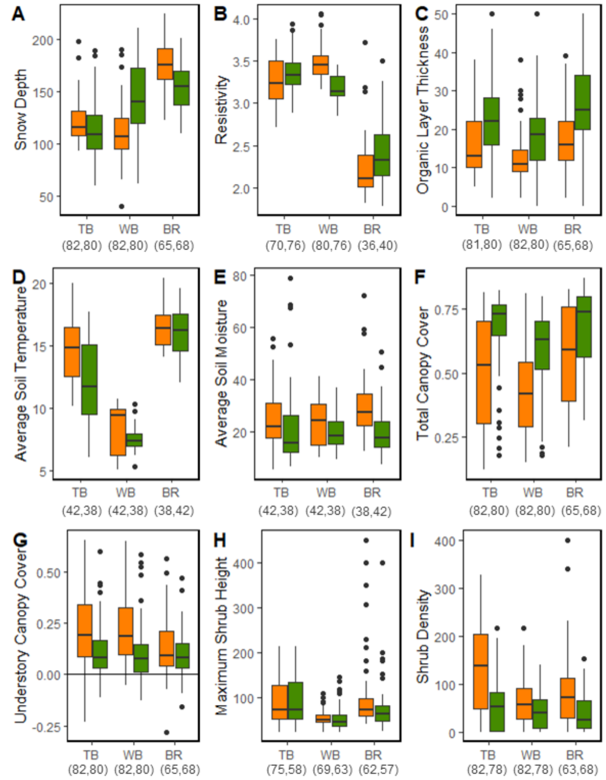

Figure 2. Boxplots of measurements from burned (orange) and unburned (green) portions of transects at the TB, WB, and BR sites: (A) snow depth (cm) based on late season surveys; (B) near-surface resistivity (Ωm; logarithmically-transformed); (C) organic layer thickness (cm); (D) average soil temperature (°C); (E) average volumetric soil moisture (cm^3/cm^3); (F) total canopy cover; (G) understory canopy cover; (H) maximum shrub height (cm); and (I) shrub density (stems/m^2). The number of observations (n) for each boxplot are included in brackets.

4.2 Ground conditions

Tomograms for one ERT survey per site are presented (Figure 3). At TB, the correlation of the defined frost table and the resistivity pattern suggests permafrost presence beneath the forest and absence in the burned area. High resistivities in the forest exceeding 10 kΩm at depths of at least 7 m may be frozen ground or bedrock. The tomogram for WB shows a four-layered system, interpreted as an active layer over thin permafrost over unfrozen sediments and bedrock. Areas of high resistivities of up to 16-26 kΩm in the burned area were found to correspond to deposits of dry sand. Frost probing and temperature measurements within the forest confirmed the presence of frozen ground to depths of 5 m beneath dense tree stands, with modelled resistivities exceeding 3.2 kΩm. The tomogram at BR shows a two-layered system, with dry higher resistivity materials overlying a low resistivity layer (<0.1 kΩm) of saturated, unfrozen soils. An undulating bedrock surface likely results in higher resistivity anomalies. Permafrost is therefore absent at BR.

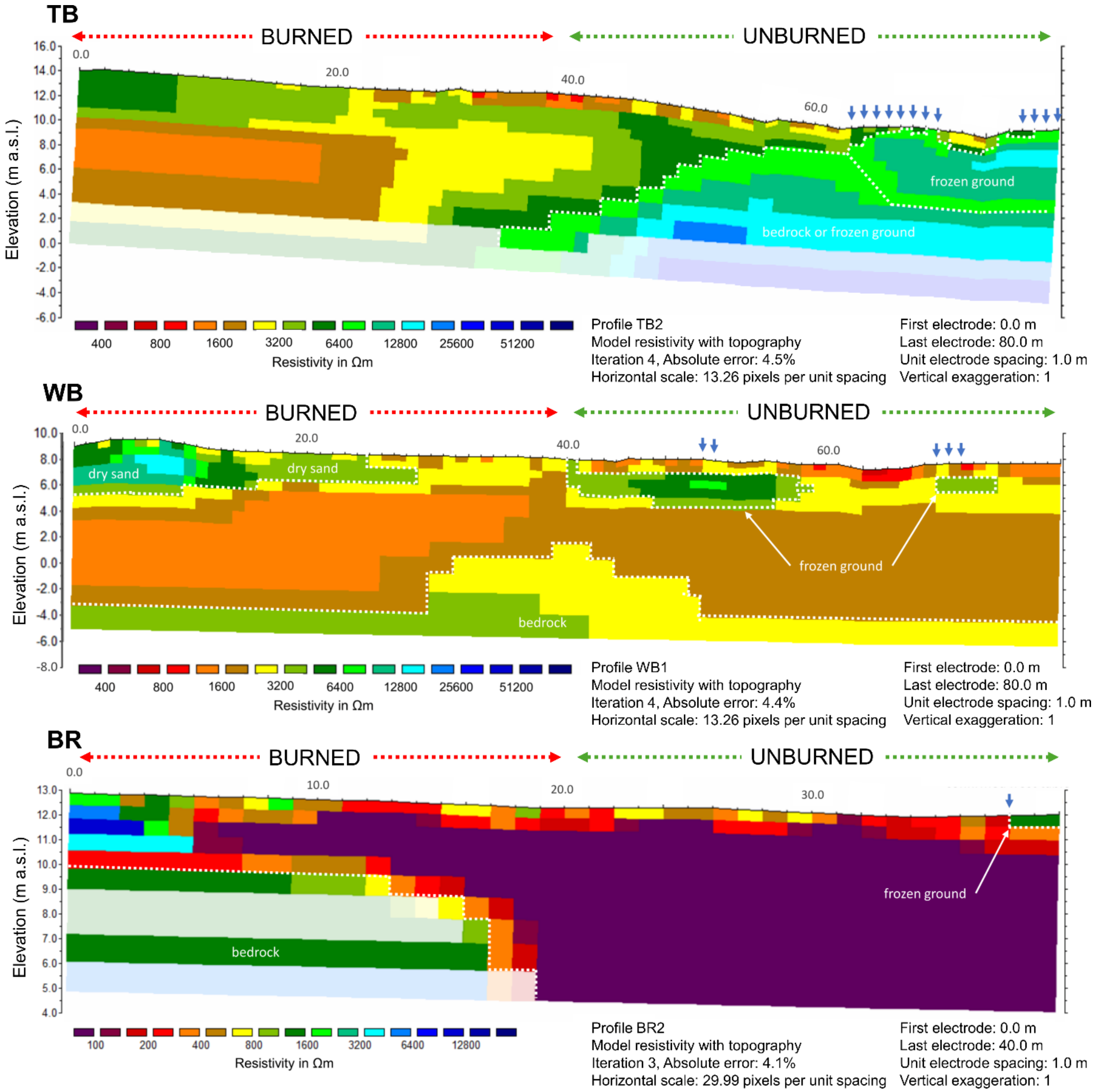

Figure 3. Modelled resistivities across burned to unburned transects at TB, WB, and BR. Confirmed frost tables within the upper 120 cm of the ground surface, using both a frost probe and instantaneous temperature measurements, are identified by blue arrows. Tomograms are faded in areas where sensitivity values are less than 0.1.

The resistivities in the tomograms show no consistent general pattern between burned and unburned areas due to similar resistivities for dry, unfrozen coarse-grained sediments and frozen soils with low ice contents (Figure 2-B). The median value is higher beneath the forest than in the burned area at TB, but the reverse is true at WB. The most obvious difference is between the higher median values at the two sites near Nain and the lower ones at BR, and this is due to wetter and finer-grained soils at the latter.

Soil temperatures were 0.3 to 2.6°C higher in the burned area than in the unburned forest (Figure 2-D). Differences were larger at TB and WB, where near-surface frozen ground was present in the forest. Soil moisture was higher in the burned area than in the unburned forest (Figure 2-E), possibly reflecting lower rates of evapotranspiration following fire (Holloway et al. 2020).

4.3 Organics and vegetation

Organic layer thicknesses in the burned areas were less than in the undisturbed forest due to loss by combustion. Average values differed by 6 to 10 cm, while maximum values differed by 11 to 12 cm. Substantial overlaps in the distributions (Figure 2-C) reflect the low intensity nature of the initial fire disturbances, with combustion causing relatively little loss of organic material (Brehaut and Brown 2020). The thickest organic mat was observed at BR, the oldest fire site, while the thinnest was observed at WB, the youngest fire site.

Median total canopy cover in the unburned areas varied from 60 to 68% (Figure 2-F). The value was lowest at WB, indicating that the forest was most open at this site. Burned regions exhibited lower total canopy coverage (44-57%) and higher variance. The understory canopy coverage was higher in the burned region than the unburned region at all sites (Figure 2-G). This difference was most pronounced at TB and WB, where the mean understory canopy coverage in the burned regions (21-22%) was double that in the unburned regions (10-11%).

WB had the shortest shrubs of the three sites (Figure 2-H). Few willows and alders were observed at this site, especially in the burned area. Shrubs were tallest at BR and exceeded 4 m in both burned and unburned areas, with groupings of tall willows and alders. Shrub densities were consistently higher in the burned areas (Figure 2-I), ranging up to over 300 stems/m^2 at the TB and BR sites, where layering of willow and alder branches occurred. High shrub density measurements in the burned regions at all three sites are consistent with high patterns of understory coverage in the burned area (Figure 2-G).

4.4 Intra-site variable interactions

The PCA provides an overview of relationships among the field variables at the three sites (Table 2). The first three PCs accounted for similar percentages of the total variance at each site: 64.0% at TB, 66.9% at WB, and 62.3% at BR. No consistent relationships or associations between the variables were identified through the various biplot combinations (Figure 4), and variables are similarly loaded on the various PCs (Table 2).

At TB, observations from the unburned forest vary more than those in the burned area, and considerable overlap of burned and unburned scores occurs in all biplot combinations (Figure 4-ABC). The overlap of disturbed and undisturbed scores suggests that the change from burned to unburned conditions at TB is gradual and less distinct than at the two other sites, despite the recency of this fire. Organic layer thickness and soil moisture demonstrate similar loadings on the first two PCs, but they have strongly opposing loadings on PC3 (Table 2). Soil temperature is most strongly loaded on PC2, and it is well-associated with snow depth in all biplot combinations (Figure 4-ABC), suggesting that locations with greater snow depths tend to have higher soil temperatures. This relationship between snow depth and soil temperature agrees with post-fire increases in soil temperature and active layer thicknesses reported in the western boreal forest (Smith et al. 2015).

At WB, the observations collected in the burned section demonstrate greater variance when compared to those from the unburned region (Figure 4-DEF), suggesting greater forest homogeneity. The biplot of PC3 versus PC1 shows the greatest overlap in the distribution of burned versus unburned scores (Figure 4-F). Therefore, PC2, which is positively correlated with snow depth and total canopy cover and negatively correlated with shrub density (Table 2), is responsible for distinct differences between the burned and unburned areas at WB (Figure 4-DF). This agrees with observations of greater snow depth and canopy coverage in the unburned forest (Table 1), and thicker and taller shrubs in the burned area at WB.

The BR site demonstrates greater variance in the unburned region, particularly along PC2 (Figure 4-GI), which is inversely related to soil temperature, maximum shrub height, and shrub density (Table 2). Plotting of PCs 2 and 3 shows almost complete overlap in the scores for burned and unburned areas (Figure 4-I), demonstrating that PC1 is responsible for distinct differences between the disturbed and undisturbed regions at this site (Figure 4-GH). This supports observations of greater canopy coverage in the unburned forest, and greater snow depths and wetter soil conditions in the burned area at BR (Table 1).

Table 2. Summary of loadings, variance, and eigenvalue of retained principal components for the BR, TB, and WB sites. Loadings >0.4 or <-0.4 are shown in green or red, respectively.

	TB (n=69)			WB (n=78)			BR (n=76)		
	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3
Eigenvalue	2.5	1.6	1.0	2.3	1.7	1.3	2.2	1.7	1.1
Variance (%)	31.6	19.5	12.9	28.9	21.5	16.5	27.4	21.0	13.9
Snow depth	0.20	0.48	0.27	0.10	0.41	0.50	0.41	0.07	0.32
Organic layer thickness	0.22	-0.30	0.67	0.46	0.16	-0.01	-0.22	0.00	0.81
Near-surface resistivity	-0.53	0.08	-0.01	-0.40	-0.32	-0.18	-0.47	-0.28	-0.19
Soil temperature	0.30	0.46	0.19	0.32	-0.24	-0.56	0.02	-0.60	0.26
Soil moisture	0.30	-0.32	-0.55	-0.54	0.03	0.28	0.45	0.14	0.11
Total canopy cover	-0.11	-0.52	0.37	0.18	0.53	-0.16	-0.43	-0.18	0.19
Maximum shrub height	0.41	-0.30	-0.03	0.35	-0.34	0.39	0.23	-0.54	-0.29
Shrub density	0.53	0.07	-0.09	0.27	-0.50	0.38	0.35	-0.47	0.12

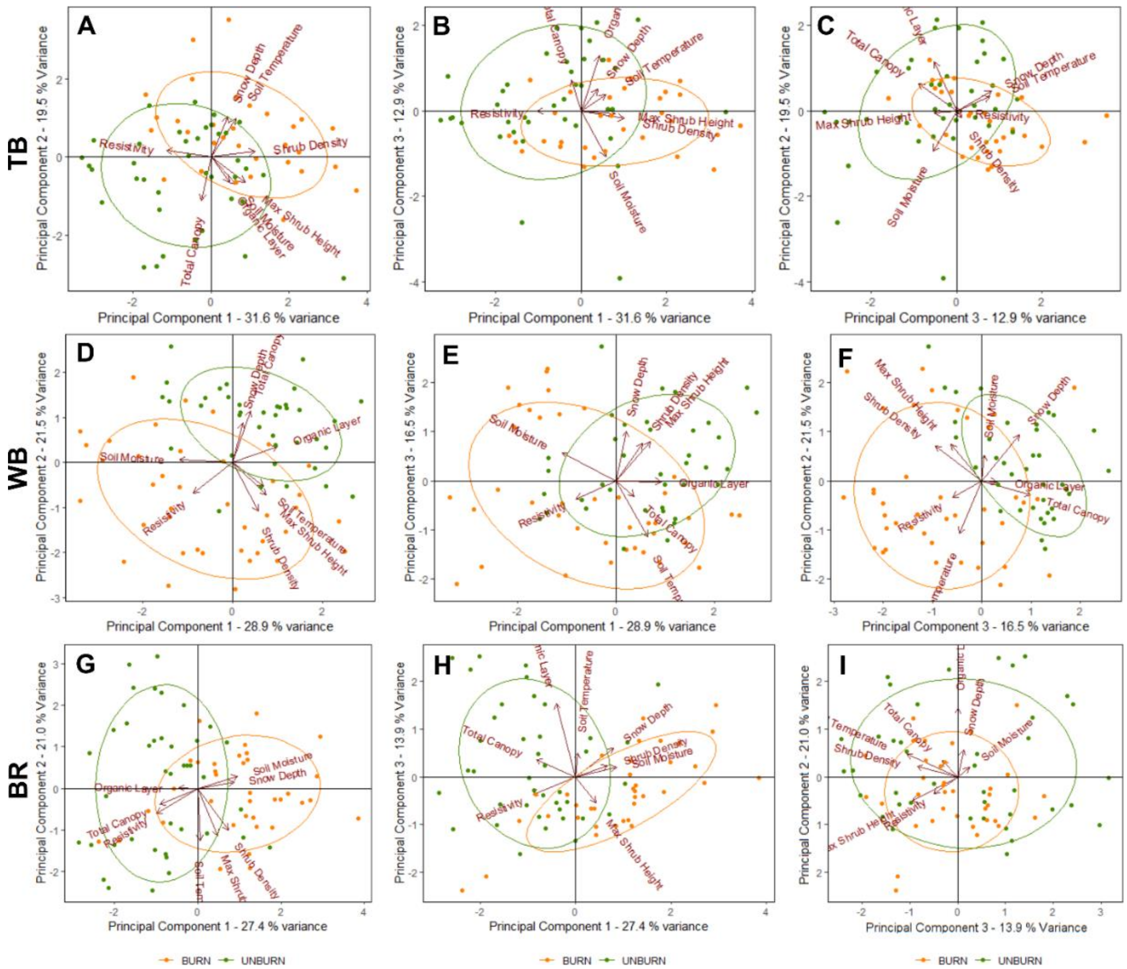

Figure 4. Biplots of burned and unburned observations on (A-D-G) principal components 1 and 2, (B-E-H) principal components 1 and 3, and (C-F-I) principal components 2 and 3 at the TB, WB, and BR sites. Burned and unburned observations and their normal data ellipses (68% confidence intervals) are shown in orange and green, respectively.

5 DISCUSSION

5.1 Post-fire vegetation conditions

Shrub densities were greater in the burned areas where vegetation growth was facilitated by warmer soil temperatures and a lack of competing vegetation (Foster 1983, Brehaut and Brown 2020). Ground temperatures tend to be higher on south-facing slopes due to enhanced insolation, and this is reflected in inter-site differences in shrub height and abundance. The south-facing TB and BR sites had patches of willows and alders exceeding 2 and 4 m in height, respectively. In contrast, shrubs at the north-facing WB site did not exceed 1.5 m in height and consisted mostly of Labrador tea. WB also exhibited the smallest thawing index and the largest freezing index, resulting in the lowest MAAT of the three sites, the longest snow-on-ground season, and the shortest growing season (Table 1). Enhanced vegetation cover at BR relates to its higher annual mean air temperature, shorter snow-on-ground period, and longer growing season.

The long fire intervals for the coastal Labrador region result in slow, continuous recruitment of trees over many decades (Brehaut and Brown 2020), unlike the pulse recruitment that occurs within the first decade following fire in the western North American boreal forest (Johnstone et al. 2004). The slow regeneration extends the period when the canopy does not intercept snow in winter or provide shade in summer and provides an extended opportunity for understory development (Foster 1983, Brehaut and Brown 2020). Under a warming climate, permafrost is especially vulnerable in this post-disturbance stage, particularly if the ecological protection that is typically offered by a regenerating forest canopy is delayed. The multi-decadal post-fire forest regeneration process that is associated with the longer fire intervals of the coastal Labrador region therefore accelerates the post-fire loss of frozen ground, particularly where snowpacks are thick.

5.2 Snow and vegetation dynamics

As hypothesized, average snow depths along the survey lines were higher in the burned than unburned regions at TB and BR. Greater snow in burned areas is consistent with investigations in the West (Burles and Boon 2011, Gleason et al. 2013). At WB, the snow surveys indicated a thicker snowpack in the forest, attributed to its low tree density (0.86 stems/m^2) (Brehaut and Brown 2020) that creates an open canopy with less protection against wind redistribution (Revuelto et al. 2015).

Shrubs in burned areas were expected to impact frozen ground through the ground warming effect of snow-trapping (Sturm et al. 2001). However, clear relationships between snow depth and shrub height or density were not evident at our sites. Instead, snow depths may have been more affected by topography (Pomeroy et al. 2006) or by the complexity of the post-fire landscape. Previous studies of snow-shrub interactions have been primarily conducted in tundra environments where topography and shrubs were the only drivers of snow distribution (Sturm et al. 2001, Wilcox et al. 2019). In a post-fire environment, however, the presence of other erect vegetation, including standing dead and regenerating trees, may intercept and reduce the snow-trapping abilities of shrubs. Overall, at our sites, it appears that snow distribution is primarily influenced by local topography and tree canopy closure.

Shrubs can also influence snow dynamics by advancing snowmelt, especially where they protrude through the snowpack (Wilcox et al. 2019), as willows and alders do at TB and BR. Snow always ablated earlier at the burned parts of our sites, allowing the ground to start thawing earlier in the spring. We contend that the complex post-fire landscape and deep snowpacks at our sites in 2017-2019 limit the winter impact of shrubs on the ground thermal regime, but shrub cover may facilitate earlier ground thaw during spring and early summer.

5.3 Frozen ground conditions

The low resistivity values at BR clearly indicate that there is no permafrost along the transects at this southern site. In contrast, thin permafrost is interpreted to be present in the undisturbed forest at both sites near Nain. Given that the fires took place 14 to 22 years before the surveys and that the climate has warmed in the meantime (Way and Viau 2015), a loss of permafrost due to increasing ground temperatures in the burned areas at TB and WB is conceivable. If permafrost has degraded as inferred, this is due to a combination of a thinner organic mat, earlier snowmelt, and loss of shading, but not because of shrubs causing a deeper snowpack as suggested in western Canada. Despite the ambiguity of ground thermal conditions at depth, these observations of perennially frozen ground at TB and WB constitute some of the first present-day findings of permafrost in forested lowland locations in coastal Labrador (Way et al. 2021), where permafrost was previously thought to be absent due to thick snow cover (Way and Lewkowicz 2018).

5.4 Limitations

Several limitations were encountered during the field investigations. Logistical constraints resulted in field visits being conducted in July of 2017 and 2018. The potential presence of seasonal frost at this point in the season led to difficulties in the interpretation of seasonal versus perennially frozen ground. Furthermore, the linear nature of ERT profiles raised issues of spatial dependency, meaning that parametric analyses on complementary vegetation, soil, and site conditions could not be performed. In addition, our short study transects across transition zones are unlikely to address the variability that might exist across the full forest fire extents. Future studies involving longer and separate study transects in burned and unburned areas could provide further insights. Despite these limitations, incorporating methods from permafrost science, ecology, and snow science into this research has provided us with a more profound understanding of the conditions and response of frozen ground following fire disturbance in the coastal boreal forests of the eastern Canadian Subarctic.

6 CONCLUSION

The post-fire response at our sites in northeastern Canada broadly agrees with studies from the western North American boreal forest. Thin permafrost (<5 m) was present in the unburned forest at two sites near Nain, attributed to the cooling effects of the undisturbed forest canopy. Slow tree regeneration and a thin organic mat were deemed to be responsible for the lack of permafrost in burned areas. We contend that snow accumulation is primarily driven by the composition of the forest canopy, and that the deep snowpack and other vegetation may limit the thermal influence of shrubs.

Burned and unburned regions differ in snow depth, near-surface resistivity, soil moisture, total canopy cover, and shrub density, particularly at WB and BR. Inter-site differences, including sediment material properties, site aspect, climate, and conditions of the disturbance itself (i.e., age, size, severity) complicate our interpretation of differences between sites. This study contributes to our understanding of the post-fire response in the coastal boreal forests of the eastern Canadian Subarctic.

7 ACKNOWLEDGEMENTS

We are grateful to the Nunatsiavut Government for permission to conduct research on Labrador Inuit lands (Permit #9222380). Funding was provided by Polar Knowledge Canada, the Northern Scientific Training Program, the Weston Family Foundation, and the Natural Sciences and Engineering Research Council of Canada. We thank the Nunatsiavut Research Centre and the Labrador Institute for logistical and in-kind support, and we acknowledge Caitlin Lapalme, Harold Goudie, Shirley Goudie, Jim Goudie, Gillian Gear, Ches Webb, Joe Webb, William Ikkusek, Edward Sillett, Carla Pamak, Liz Pijogge, Paul McCarney, Rodd Laing, and Michelle Saunders for their support of our field investigations. We thank Denis Lacelle, Konrad Gajewski, Sharon Smith, and an anonymous reviewer for helpful comments on this paper.

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