Snow management to reduce ground temperatures beside a road in the boreal forest near Mayo, Yukon

Patrick A. Jardine[1], Christopher R. Burn[1], Jennifer K. Humphries[1], Blaine Peter[2], Gary Hope[2], Jamie Phillips[2] & Lawrence D. McLaren[2]

[1]*Department of Geography and Environmental Studies, Carleton University, Ottawa, Ontario, Canada*

[2]*Lands Branch, First Nation of Na-Cho Nyäk Dun, Mayo, Yukon, Canada*

Abstract

A field experiment was conducted in winter 2020–21 adjacent to the South McQuesten Road, central Yukon, to determine the effect of snow compaction on ground surface temperatures. At two sites, snow machines were used to compact the snow beside the road from late November to March. Data loggers were placed at the base of the snowpack to record the temperature at compacted and untreated plots at each site. The thickness of snow layers, and their density, hardness, and grain shape and size were recorded in snow pits after each compaction. By March, the snowpack was 35–40 cm thicker at the untreated plots and on average 156 kg m^{-3} denser at the compacted plots. The depth hoar layer, 10–15 cm thick at the untreated plots, was almost entirely crushed during compaction. Over the winter, daily ground surface temperatures at the compacted plots were 2–3 °C lower on average than at the undisturbed plots. A reduction in annual mean surface temperature of 0.9–1.3 °C may be expected due to snowpack compaction. Seasonally, the *n*-factors at the compacted plots were 0.25 and 0.15 higher than at the undisturbed plots (0.37 and 0.41, respectively). These data indicate the efficacy of a local approach to mitigating ground warming beside highways.

1 Introduction

The design and construction of roads in regions of permafrost requires the use of design standards tailored to protecting the underlying frozen ground from thawing (Zubeck and Doré 2009). In regions of discontinuous permafrost, such as south and central Yukon, road design can be especially challenging, as routes cross terrain with variable permafrost conditions and ground ice contents. Snow cover is one of the dominant controls on ground temperature (Goodrich 1982). The accumulation of snowbanks on the sides of a road can lead to significant changes in the ground thermal regime of the road (Darrow 2011).

Various techniques have been examined at the Beaver Creek test section in SW Yukon to lower embankment temperatures (Malenfant-Lepage et al. 2012), but none so far have been implemented over extensive lengths of highway, partly due to expense. Thermosyphons have been installed at km 1842 on the Alaska Highway near Dry Creek at a cost of $4M over 0.5 km as a solution to embankment thaw (M. Idrees, pers. comm., 2022).

This paper discusses the results of a field experiment conducted on South McQuesten Road, north of Mayo, YT (Figure 1), to test whether ground surface temperatures beside a highway embankment may be lowered by compacting snow. This may be a relatively cost-effective technique to achieve thermal stability in the embankment.

Deep snow accumulates alongside highway embankments from plowing of the driving lanes and deposition by wind (Auerbach 1997). The high thermal resistance of snow impedes release of heat from the embankment shoulder and raises ground temperatures (Nicholson and Granberg 1973). For example, at km 124 of the Dempster Highway temperatures at the embankment toe were about 4 °C higher than at the highway centreline, where snow is cleared (Stockton et al. 2019). If ice-rich permafrost underneath the embankment shoulder degrades then it can undercut support for the side of the road. This may cause longitudinal cracking to develop on the driving surface, and, if left unmitigated, may result in shoulder rotation and separation from the sides of the road (Doré et al. 2016).

Compaction of the snowpack is intended to reduce its thermal resistance by lowering its thickness and increasing its density (Goodrich 1982; Zhang 2005). O'Neill and Burn (2017), modelled conditions on Peel Plateau, Northwest

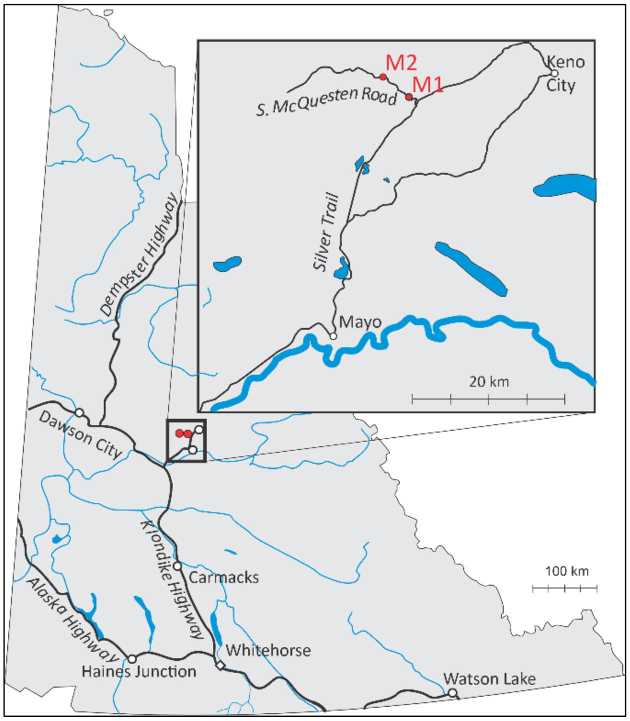

Figure 1. Location map for study sites in central Yukon.

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Territories, and indicated that compaction of the snowpack may reduce ground temperatures, and, in some cases, prevent permafrost degradation. The objectives of this research are to investigate: (1) whether compaction with snow machines can cause a significant reduction in snow depth and increase in density; (2) how compaction alters the structure of the snowpack and shape of snow grains; and (3), if, as a result, there is a significant reduction in ground surface temperatures.

2 Study Area

Mayo and its surroundings are in Stewart Plateau, where uplands are separated by broad river valleys (Wahl et al. 1987). Vegetation is dominated by closed canopy boreal forest, commonly interspersed with wetlands (O'Donoghue 2006). The area has widespread discontinuous permafrost with thickness up to 40 m in valleys and up to 130 m at higher elevations (Burn 1991). Typical active layer depths are 0.65–1 m (Burn 2006). Permafrost in the area is commonly found beneath organic soils, which provide insulation during the summer (Williams and Burn 1996).

The continental climate of central Yukon has short, warm summers and long, cold winters. The mean annual temperature for 1991–2020 at Mayo Airport was -2.2 °C and the mean for December to February was -18.9 °C (ECCC 2023). Throughout winter, inversions may cause temperatures to drop below -50ºC in valleys (Wahl et al. 1987). Mean snowfall from December to February was 52 cm. The mean hourly wind speed at Mayo Airport during the study was 3 km h^{-1}, with a maximum of 21 km h^{-1}. Wind speeds were commonly too low for much snow redistribution.

3 Field Methods

3.1 Site Selection

Two sites were selected in relatively flat, uniform terrain within a clear-cut right-of-way beside South McQuesten Road, an infrequently plowed road 35 km north of Mayo. One site, M1, was in an undisturbed forest 3 km from the Silver Trail, that leads north from Mayo, while M2 was in forest that had burned in 2019, 3 km farther down the road (Figure 2). The soil at the field sites was dry and without peat, so we assume they were permafrost free (Williams and Burn 1996). Snow depths were less than 1 m throughout the winter and the snow was loosely packed due to the low wind speeds. Arrival at the field sites was delayed until 26 November 2020, due to travel restrictions associated with the COVID-19 pandemic, by which time deep snow covered the ground.

3.2 Study Design

At each field site, two 50 m by 5 m plots were marked using wooden stakes, parallel to the road and beginning from the shoulder. A 5 m width was chosen to remain within the right-of-way of the road, while the 50 m length was selected to facilitate compaction. One plot at each site was compacted four times at approximately monthly intervals between late-November and mid-March, 2020–21.

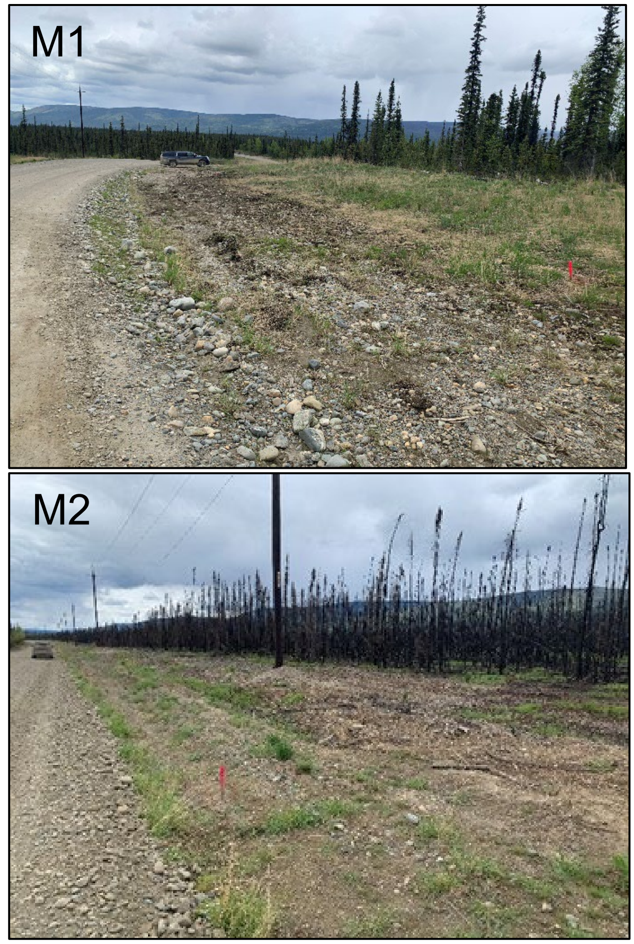

Figure 2. M1 and M2 field sites during site inspections on 4 June 2021. The coloured stakes indicate the boundary between the plots that were left undisturbed and plots that were compacted.

Onset HOBO H08-004-02 temperature loggers were used to measure temperatures at the centre of the plots. The resolution of each temperature measurement was ±0.25 °C, and the factory-specified accuracy is between ±0.5 °C and ±1 °C. The ground surface was frozen upon arrival at the field sites so burying the loggers in the ground was impractical. Instead, they were encased in PVC pipe cut to size, with plastic caps covering each end of the pipe and sealed by a layer of electrical tape. The loggers were placed at the base of the snowpack at the edge of the plot, and then pushed into place in the centre of the plot using a snow probe, with disturbed snow being replaced. Freezing *n*-factors were calculated by dividing temperatures at the base of the snowpack by air temperatures from Mayo Airport.

Figure 3. Land Guardians from the First Nation of Na-Cho Nyäk Dun compacting the snowpack at the M2 field site on 29 November, 2020.

Land Guardians from the First Nation of Na-Cho Nyäk Dun compacted one plot at each site using snow machines (Figure 3). They drove over the snowpack repeatedly until repetitions did not cause further reductions in snow depth. The snow compressed easily, and the process only took about 5 minutes. The other plot was left undisturbed.

Following compaction, snow depths were measured at the centre of the plots every 10 m along the length, to provide four measurements per plot. A snow pit was dug at each of the plots after compaction 2–3 m away from the previous visit's pit. Snow pits from undisturbed and compacted plots are shown in Figure 4. Density, hardness, and grain size and shape were measured within each layer of snow observed in the pits. Snow density was measured by weighing samples collected using a 100 ml volumetric scoop. The hardness of the layers was assessed using a semi-quantitative five-point scale including penetration with a closed fist, four fingers, one finger, a pencil, and a knife, following Fierz et al. (2009).

Grain size and shape were estimated by placing the snow grains on fine-scale graph paper and observing them with a hand lens. Snow grain shapes were categorized based on the amount of faceting they had undergone through temperature-gradient metamorphism. Temperature-gradient metamorphism can lead to development of depth hoar, i.e., loosely packed faceted crystals commonly found at the base of the snowpack (Perla and Martinelli 1978).

4 Results

4.1 Snow Depth

Mean snow depths from the four depth probe measurements collected after compaction each month are shown in Figure 5. Mean snow depths over the winter at M1 were 66 cm at the undisturbed plot and 37 cm at the compacted plot; at M2 the mean snow depths were 69 cm and 39 cm, respectively. Snow depths at the undisturbed plots rose gradually throughout the winter to a peak of about 75 cm in April. At the compacted plots, snow depths peaked

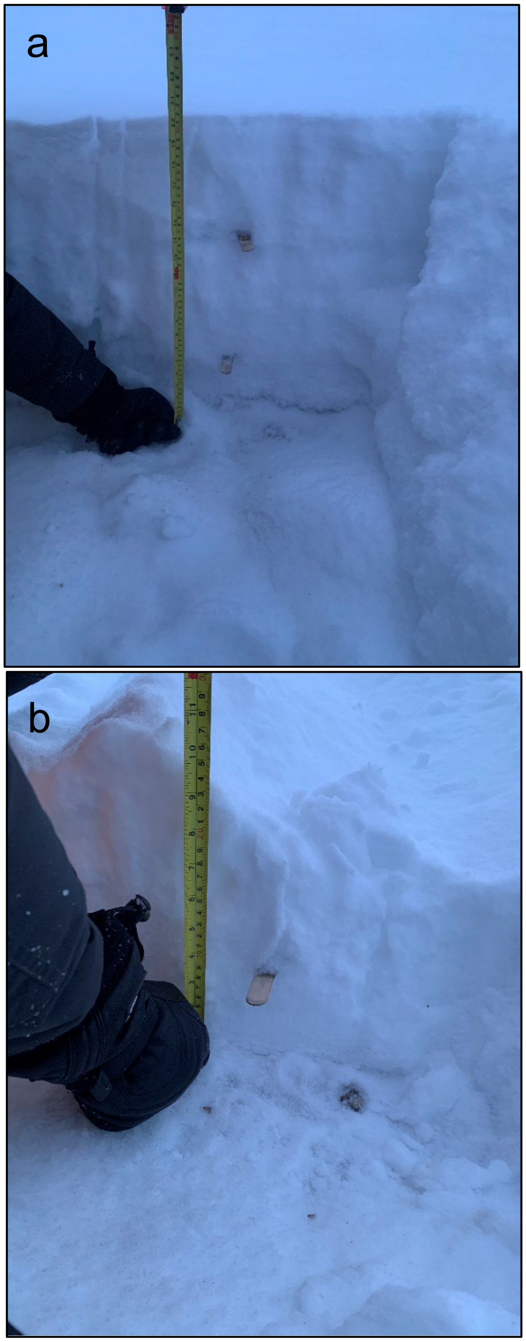

Figure 4. Snow pits dug at the M2 (a) undisturbed plot, with a depth of 53 cm and (b) compacted plot, with a depth of 23 cm, on 5 January 2021, after the second compaction.

in January at 48 and 59 cm before declining to about 40 cm for the remainder of the winter.

4.2 Snow Density and Hardness

Weighted mean density and hardness were calculated by multiplying the values for each snow layer by the thickness of the layer as a proportion of the total snowpack, then

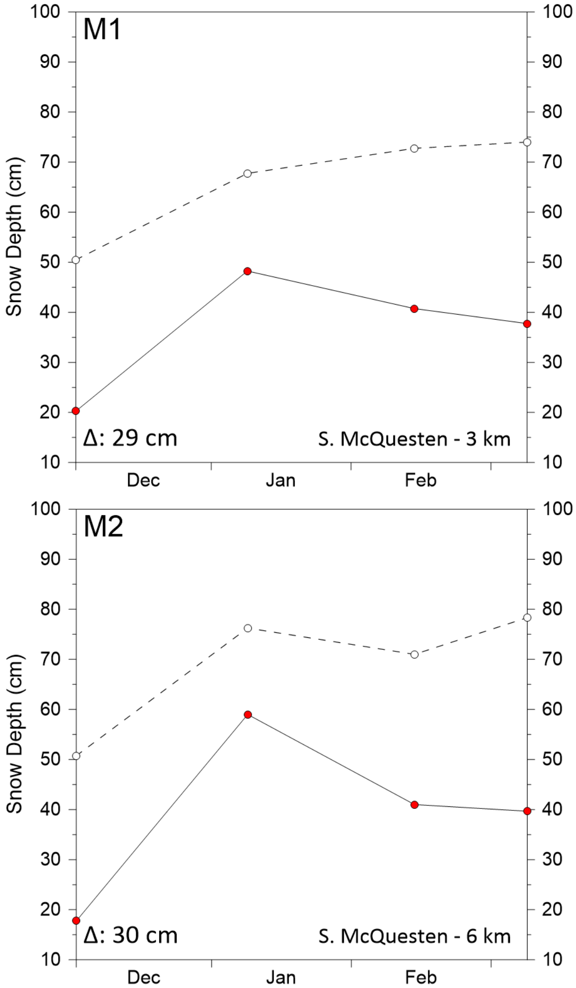

Figure 5. Snow depths (cm) at the undisturbed (white) and compacted (red) sites beside South McQuesten Road, central Yukon. Δ Indicates the mean difference between the treatments over the winter.

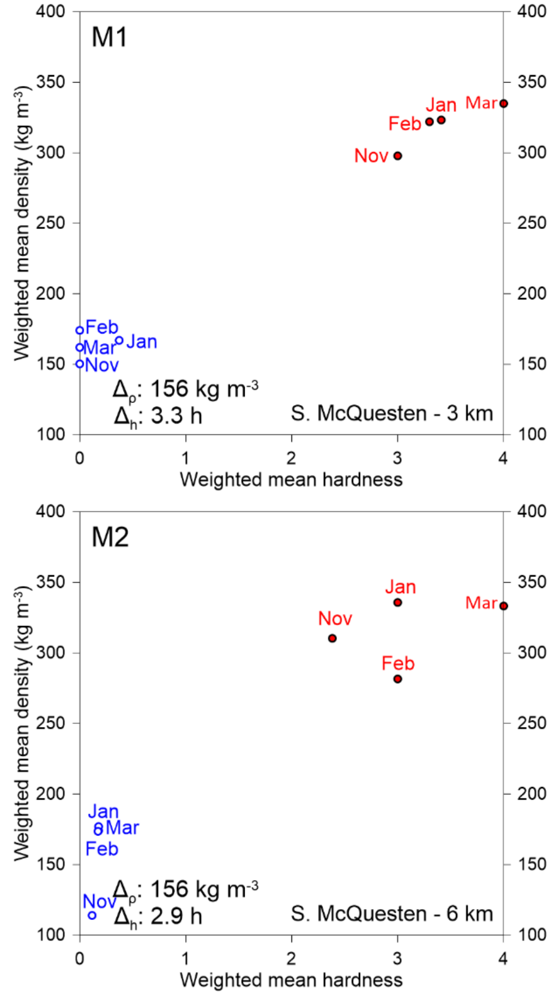

Figure 6. Weighted mean snow pack hardness and density of undisturbed (blue) and compacted (red) sites each month during winter 2020–21. The mean density and hardness were weighted by the thickness of each layer within the snowpack.

adding all layers together. Figure 6 displays the weighted average density and hardness of the snowpack from the four pits that were dug each month after compaction. Over the entire winter, the plots that were left undisturbed had mean densities of 163 and 160 kg m^{-3} at M1 and M2, respectively. At the compacted plots, mean snow densities at M1 and M2 were 319 and 315 kg m^{-3}, respectively. The mean hardness of the snowpack was near 0 at the undisturbed plots, while at the compacted plots it was 3.4 and 3.1 at M1 and M2, respectively, indicating that the snow could be penetrated by a single finger or a pencil.

The density of the snow at the undisturbed plots (Figure 6) was low compared to typical densities for settled snow (200–300 kg m^{-3}; Paterson 1994), likely due to low wind speeds and infrequent plowing at the field sites, which allowed loosely packed snow to accumulate. Compaction increased snow density to slightly greater than this range on average, and maximum densities were 335 kg m^{-3} at both plots.

4.3 Changes in Snow Structure

Figure 7 presents the mean snow-layer thickness and structure at the four plots over winter 2020–21. Dendritic snow, found at the top of the snowpack, had fresh, loosely packed grains that had retained their crystalline shape. Snow with some angular facets had undergone limited temperature-gradient metamorphism but had not fully metamorphized into depth hoar. Moderately rounded snow often had a mix of faceted and rounded snow grains.

The greatest reductions in snow depth at the compacted plots compared to the undisturbed plots were in dendritic snow and depth hoar, both of which were absent at the compacted plots after January. Dendritic snow had a mean density of 140 kg m^{-3}, which was lower than the other snow types, which all had mean densities of about 180 kg m^{-3}. At the compacted plots, dendritic snow near the surface became rounded and well-packed, depth hoar became an icy mass of partially broken faceted crystals, and the bulk of

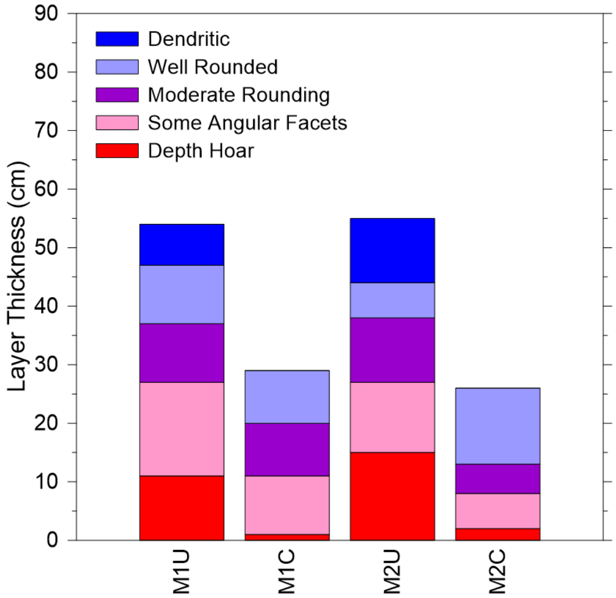

Figure 7. Mean snow structure within the snowpack at each site. The thickness of each layer is the mean value of four months of measurements.

the snowpack became a mix of closely packed rounded and faceted snow crystals. The density of the compacted snowpacks varied little between layers, ranging from 290–330 kg m^{-3}.

4.4 Daily Mean Temperatures at the Base of the Snowpack

Mean daily temperatures at the base of the snowpacks are displayed in Figure 8, along with air temperatures at Mayo Airport, 35 km south of the field sites. Over the winter, mean temperatures at the undisturbed plots were -5.2 and -5.5 °C at M1 and M2, respectively. At the compacted plots, mean temperatures were -8.4 and -7.7 °C.

Temperatures at the compacted and undisturbed plots were closely coupled in December, remaining within 1 °C at both sites, even as mean daily air temperatures fell to as low as -32 °C on December 21st. On January 5th, after several weeks of cold weather, the temperatures at the compacted plots dropped to about 2–5 °C lower than at the undisturbed plots. The sudden divergence may indicate a reduction in the latent heat flux from the freezing front towards the surface, that did not occur at the undisturbed sites. This was likely associated with the depth of frost penetration.

From January 26 to February 16 mean daily air temperatures averaged -30 °C, with a low of -38 °C on February 9. During this time divergence between the compacted and undisturbed plots reached its maximum of 12.1 °C at M1 on February 16, and 9.4 °C at M2 on February 15. The difference in temperature between the plots diminished for the remainder of the winter as air temperatures rose to -15 °C.

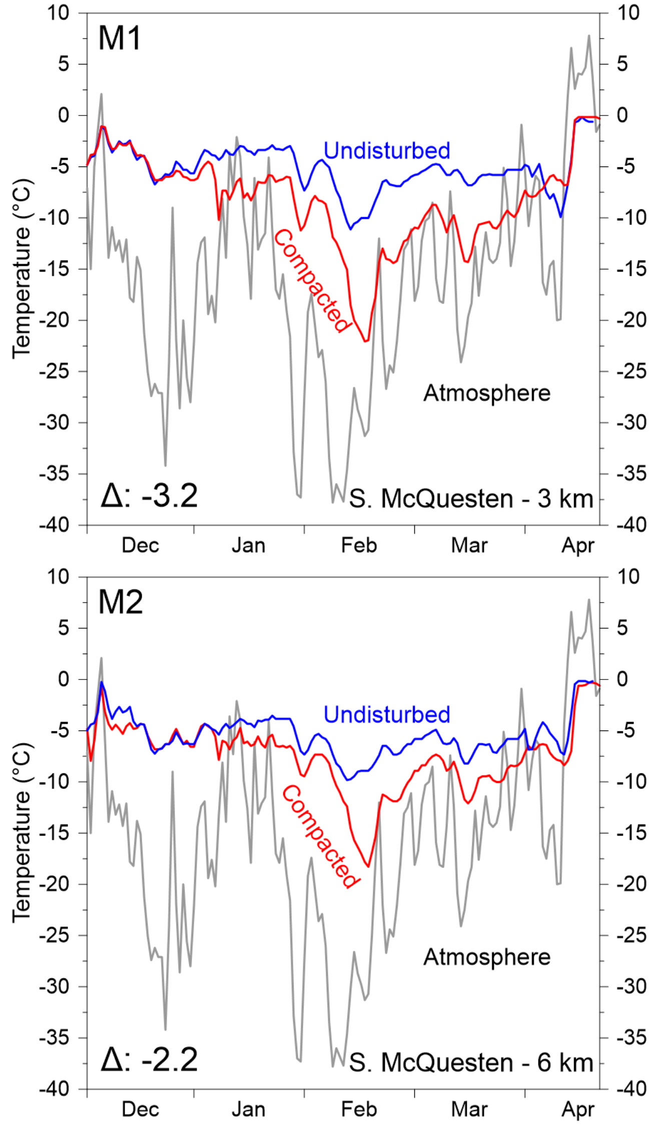

Figure 8. Daily mean temperatures measured at the base of the snowpack beneath undisturbed (blue) and compacted (red) snow. The daily mean air temperature recorded at Mayo A is also given. Data from 29 November to 22 April, 2020–21.

4.5 Weekly *n*-Factors

The weekly *n*-factors for the monitoring period at the undisturbed plots ranged from 0.19 to 0.72, and were on average 0.37 and 0.41 at M1 and M2, respectively (Figure 9). At the compacted plots, *n*-factors ranged from 0.22 to 1.18, and averaged 0.62 and 0.56.

In northwestern Canada, taiga typically has seasonal freezing *n*-factors of 0.1–0.3, while tundra has *n*-factors between 0.7–1, due to shallower and denser snow cover caused by higher wind speeds (Smith et al. 2010). At the undisturbed sites, n_f was slightly higher than published values for taiga, perhaps due to the late start of observations in the season, thereby missing freeze back of the near surface. At the compacted plots n_f was 0.14 and 0.24 higher than the undisturbed plots, and heat flow through the snowpack more closely resembled that of tundra than taiga.

The *n*-factors for the period after January 10th, excluding the time when the near surface was freezing, were on average 0.41 and 0.44 at the undisturbed plots of M1 and M2, and 0.73 and 0.64 at the compacted plots. The high weekly *n*-factors on January 10 were due to rapidly increasing air temperatures, causing the air to be briefly warmer than the base of the snowpack.

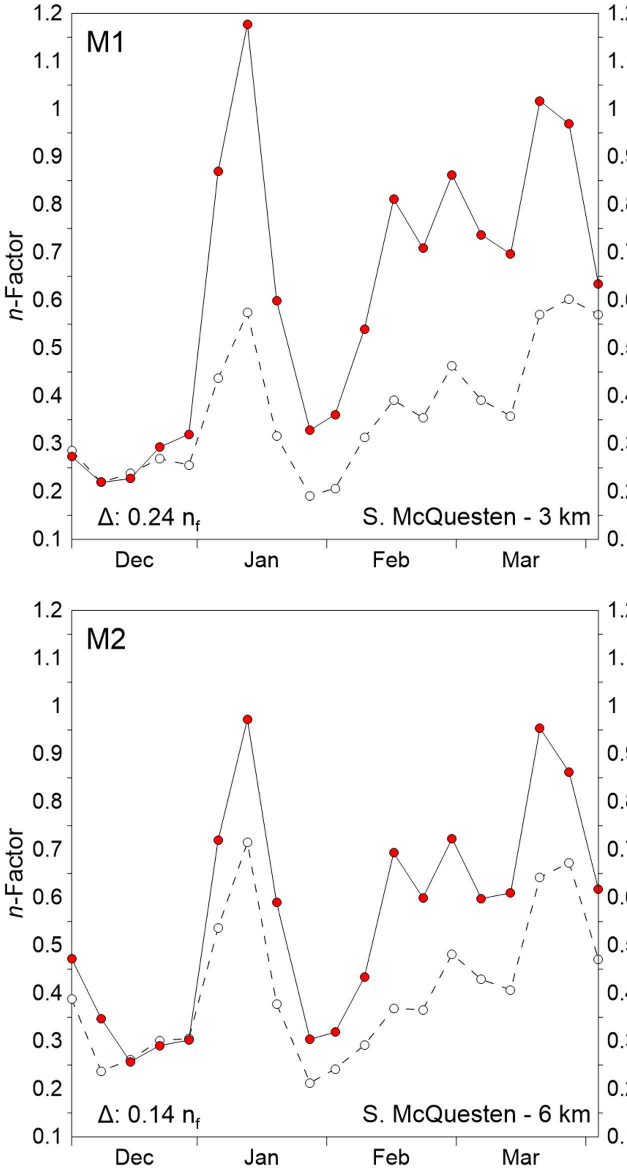

Figure 9. Weekly *n*-factors for undisturbed (white) and compacted (red) plots.

4.6 Summary of Results

The field results are summarized in Table 1. On average, the snowpack at the compacted plots was 30 cm thinner, had density that was slightly higher than is typically found in well-settled snow, and was hard enough that it could only be penetrated using a finger or pencil. Temperatures at the base of the snowpack were 2.7 °C lower, since the *n*-factor increased to values characteristic of thin, dense snow found in tundra. These seasonal adjustments and *n*-factors may underestimate the effectiveness of compaction when conducted throughout the winter including during freeze-back.

Table 1. Snow properties with and without compaction.

	Undisturbed average	Compacted average
Depth (cm)	68	38
Density (kg m^{-3})	161	317
Hardness	0.1	3.3
Mean basal temp. (°C)	-5.3	-8.0
Seasonal *n*-factor	0.39	0.59

5. Discussion

5.1 Influence of Site Conditions

The effect on mean annual ground temperatures caused by thermal insulation from snow cover is greatest in regions with a large annual amplitude in air temperature (Goodrich 1982). The continental climate of central Yukon therefore creates more favourable conditions for reducing the thermal resistance of the snowpack and releasing a large amount of energy from the ground than a temperate climate.

A large temperature gradient through the snowpack also causes the development of depth hoar through temperature-gradient metamorphism. The undisturbed plots had about 10–15 cm of depth hoar on average, and about half of the snowpack had faceted snow grains. The proportion of depth hoar in the snowpack is relevant for heat flow since its low density results in a lower thermal conductivity than other snow types (Zhang et al 1996; Sturm and Johnson 1992). The increased thermal insulation provided by depth hoar may raise ground temperatures by several degrees where it is present (Zhang 2005).

Low wind speeds at the study site and infrequent plowing of the road meant that snow was only slowly replenished by snowfall after being compacted. Tread marks from the previous month's compaction were generally visible at the sites during each field visit. On a road with a higher rate of snow replenishment the treatment may be less effective or may require more frequent compaction to cause the same change in n_f.

The difference in density between M1 and M2 may be due to the burned forest providing a less effective wind break, increasing snow transport, and hardening the snowpack. However, no wind measurements were taken at the plots, and the differences in hardness and density between the plots were small (Figure 5), so the difference may also be a result of other local conditions.

5. 2 Snow Response to Compaction

The compressive strength of snow is highly correlated with its density and structure. Deformation of a snowpack under compressive force occurs partially through shifting of snow grains into air pockets, and partially through elastic bending of the skeletal ice structure (Mellor 1975). At the field sites, the low density of the snowpack (Figure 6) caused them to compress easily as snow grains could shift freely. This caused the undisturbed snowpack to be highly susceptible to compaction at the beginning of the experiment. Snow depths were reduced from approximately 50 cm to 20 cm in November (Figure 5), and density increased to approximately 300 kg m^{-3}, an upper value for settled snow (Paterson 1994).

The increased density of the snow following initial compaction caused it to be more resistant to the effects of subsequent compactions, with limited increases in density and reductions in depth compared to the undisturbed plots for the remainder of the winter.

Dry snow with a density of 200 kg m^{-3} may collapse under pressure of 4–15 kPa, while snow with a density of 400 kg m^{-3} may require 150–400 kPa (Mellor 1974). An average snow machine with rider weighs approximately 350 kg and carries the weight on skis and track of 0.65 m^2, thereby applying a pressure of approximately 5.4 kPa to the snow surface. These data explain the compaction of low-density snow at the field sites.

In addition to density, the strength of a snowpack is also governed by the texture of its snow grains. When snow grains are large in comparison with the snow necks connecting them, the increased leverage when force is applied causes them to break apart more easily (Perla and Martinelli 1978). Depth hoar had the largest snow grains of any snow type at the field site, averaging 3.8 mm, which is likely why it experienced the second largest reduction in snow depth, behind only dendritic snow (Figure 7).

5. 3 Temperature Reduction at the Base of the Snowpack

Compaction was effective at lowering basal snow temperatures at both test plots. The reductions in mean daily temperatures of 2.2 and 3.2 °C over 145 days suggests that mean annual temperatures at the base of the snowpack may be reduced by about 0.9–1.3ºC. The sudden drop in temperature at the compacted plots on January 5 suggests that compaction expedited freeze up of the near surface, since the undisturbed plots did not experience a similar drop in temperature until near the end of January. Had compaction begun shortly after the first snow fall then it may have caused the ground to freeze still earlier, increasing the effectiveness of the technique in reducing ground surface temperatures.

Due to the possibility of reduced frost penetration from the delay in beginning the compaction until late-November, 2020, 1 °C is a reasonable estimate of the immediate potential reduction in mean annual ground surface temperatures beside the road beneath a compacted snowpack. The numerical study of Goodrich (1982) suggests that a reduction in snow depth from 50 cm to 25 cm may cause a reduction in mean annual ground surface temperatures of 3–4 °C. Simulation results from O'Neill and Burn (2017) suggest that by compacting snow to a density of 400 kg m^{-3}, a 3–4 °C reduction in ground surface temperatures could be achieved in as little as two years at tundra sites. This study indicates that, in forest, compaction using light, accessible equipment, such as snow machines, may be effective at reducing ground surface temperatures.

6 CONCLUSIONS

Compaction was effective at reducing snow depths by over 50% after a single treatment, and the difference in snow depth persisted throughout the winter. The snow types that experienced the greatest reduction due to compaction were dendritic snow and depth hoar. These snow types have a low thermal conductivity due to their low density, so their susceptibility to compaction increases the efficiency of the technique in reducing snowpack thermal resistance.

By modifying the physical properties of the snowpack to more closely resemble a thin, dense snow cover, similar to a tundra snowpack, compaction caused a significant reduction in ground surface temperatures, and the effect would likely have been greater had the treatment begun at the beginning of the winter. Due to the effectiveness of the technique, along with its simplicity and low-cost, further research is warranted towards its large-scale use in northern road maintenance to mitigate the risk of damage from thawing ice-rich permafrost. In the first case, research should be conducted to determine the efficacy of compaction throughout the winter, including freeze-back. Subsequently it may be appropriate to determine the practicality of implementation of the technique along specific highways.

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