Reduction of ground surface temperatures beside highway embankments by snow compaction, central Yukon, Canada.

By

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Abstract

Snowbanks accumulate beside roads in permafrost regions, raise ground temperatures, may degrade permafrost locally, and lead to deterioration of the embankment. Field experiments were conducted at tundra and taiga sites to determine whether compaction of snowbanks by snowmobiles would reduce ground temperatures, as simulated previously by numerical modelling. In taiga, compaction affected the whole snowpack. Mean snow depth was reduced from 71 cm at undisturbed sites to 40 cm in compacted snow. The mean snowpack density increased from 185 kg m\(^{-3}\) to 327 kg m\(^{-3}\). In tundra, compaction principally affected depth hoar: snow depths were reduced from 70 to 61 cm and densities increased from 271 to 311 kg m\(^{-3}\). Compaction reduced temperatures by 2 - 3 °C at both sites, despite estimated mean thermal resistance reductions of 8.5 to 1.2 m\(^2\)KW\(^{-1}\) in taiga and 5.9 to 3 m\(^2\)KW\(^{-1}\) in tundra, suggesting greater thermal influence of depth hoar in tundra.
Acknowledgements

This thesis is based on field experiments which took place near Mayo and in the Blackstone Uplands between November, 2020, and June, 2021, during the COVID-19 pandemic. It would not have been possible without extensive support and adaptability from a multitude of individuals and organizations.

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Chapter 1: Overview and Objectives

1.1 Introduction

This thesis examines snowpack compaction as a method for improving the thermal stability of linear infrastructure built in permafrost terrain. Snow has a lower thermal conductivity than most ground surface materials, primarily due to the pores within the snowpack being filled with air (Zhang, 2005). This limits heat flow out of the ground during the freezing season. The extent of insulation provided by the snowpack is negatively associated with the density of the snowpack and positively associated with its depth (Zhang, 2005). O’Neill and Burn (2017) indicated that compaction of the snowpack may increase thermal conductivity, reduce ground temperatures, and, in some cases, prevent permafrost degradation.

Reducing ground temperatures is of practical interest because it may lower the risk of infrastructure damage from thaw subsidence in regions underlain by ice-rich permafrost. Highway embankments built on permafrost are designed to preserve the permafrost beneath the driving surface by raising the permafrost table into the applied materials (Zubeck and Doré, 2009). This practice accommodates a thicker active layer common within the embankment. However, deep snowpacks frequently form at the lateral toe of the embankment, which may cause the underlying permafrost there to degrade (Auerbach et al., 1997; O’Neill et al., 2015). As a result, the road may be damaged by differential settlement due to thaw subsidence (Malenfant-Lepage et al., 2010).

There is currently rapid climate warming in the Western Arctic, increasing the risk of damage to highway infrastructure damage (Burn et al., 2015; Vincent et al., 2015). The risks to the embankment are multifaceted, stemming from extreme events, including landslides and washouts, as well as the thaw of permafrost beneath and beside the embankment (Stockton et al.,
2019). Numerical simulations of the Dempster Highway embankment on Peel Plateau, NWT, show that compaction or removal of the snowpack may mitigate the risk of thaw subsidence by restoring permafrost conditions (O’Neill and Burn, 2017).

This thesis reports the results of field experiments designed to test the effectiveness of snowpack compaction at reducing ground surface temperatures under a variety of field conditions. A positive result may provide a new tool for ground maintenance crews to reduce costs and extend the service life of northern infrastructure. The field sites are in central Yukon, along the southern Dempster Highway and Silver Trail, Yukon highways 5 and 11, respectively.

1.2 Snow and ground temperatures

The effect of snow accumulation on ground temperatures in permafrost was demonstrated by Mackay and McKay (1974) in field measurements at Garry Island, NWT. By expanding on equations developed by Nicholson and Granberg (1973), they determined that, in the winter, the temperature of the ground at 90 cm depth had a positive logarithmic relation with snow depth. The extent to which this relation is modified by variation of the snow cover was later described by Goodrich (1982), who simulated ground temperatures under different soil, atmospheric, and snow conditions. His results suggest that the influence of snow cover on ground temperatures varies with the time of year and thermal properties of the snowpack. Goodrich (1982) indicated that the thermal influence of snow was greatest early in the freezing season, when an insulating layer of snow may extend the freeze-back period.

Along with timing, the influence of snow on heat flow between the atmosphere and ground surface is controlled by a variety of factors including the density, structure, thickness, albedo, emissivity, and absorptivity of the snowpack (Zhang, 2005). Overall, a higher albedo
and thermal emissivity of the snow cover will reduce ground temperatures, while a lower thermal conductivity and absorptivity will lead to reduced cooling of the ground. In most snowpacks the insulative effect dominates for the majority of the winter, leading to an overall warming influence on the ground (Goodrich, 1982; Smith & Riseborough, 2002; Zhang, 2005).

1.3 Risk to highway embankments

The Canadian western Arctic is currently experiencing some of the most rapid climate change on Earth (Burn et al., 2021; Schetselaar et al., 2023), and permafrost temperatures have responded by rising more than 2°C in some areas (Burn and Kokelj, 2009; O’Neill et al., 2015). This has contributed to the degradation of permafrost underlying some northern roads and, in some cases, the functional capacity of the infrastructure has been threatened (Doré et al., 2016). These unstable conditions make roads particularly vulnerable to the thermal effects of deep snow drifts.

The thermal effects of snow are distributed unevenly across a road, since the driving surface is cleared regularly and snow accumulates on the sides of the embankment, which also acts as a windbreak. As wind speed is reduced, the carrying capacity of the wind declines and excess snow is deposited (Doré et al., 2016). Deep snowdrifts often accumulate at the embankment sides and on the lateral toes as a result. At sites on the Dempster Highway, due to the differences in snow cover, permafrost below the driving surface was measured as being stable or cooler than in the surrounding environment, while mean annual permafrost temperatures underneath the embankment toe were about 4 °C higher than at the highway centreline (Stockton et al., 2019). These conditions increase the risk of road damage from differential thaw settlement (Fig. 1.1) (Doré et al., 2016).

Thaw settlement can occur due to the degradation of ice-rich permafrost. The ice holds
Figure 1.1: Longitudinal cracking observed on the Alaska Highway in 2009 (Malenfant-Lepage et al., 2010, Fig. 1).
together soil particles in a matrix of relatively high strength, and when the permafrost thaws the cohesion provided by the ice is lost, and soil stability is reduced (Williams and Smith, 1989). Thawing permafrost may induce ground consolidation from the decline in volume of melting ice, from meltwater draining deeper into the ground, and by allowing soil particles to shift so that they may be packed more closely by the pressure of the overlying soil. When the volume of meltwater within the soil exceeds the pore space, the pore water will bear the weight of the overlying soil or embankment until drainage, when the pore pressure reaches a new stable equilibrium (Morgenstern and Nixon, 1971). When permafrost thawing underneath the embankment shoulder is induced by snow cover but the permafrost underneath the centerline remains stable, the embankment shoulder can lose support, putting strain on the driving surface (Fig. 1.2). This strain may cause longitudinal cracking to develop, and, if the loss of support is severe enough, the embankment shoulder may separate and rotate from the rest of the road (Doré et al., 2012).

1.4 Mitigation Efforts
Numerous techniques have been developed to control ground temperatures and preserve permafrost underlying infrastructure. Generally, these techniques attempt to either limit heat flow into the permafrost or extract heat from within the permafrost. Some examples of the former include installing insulation to increase the thermal resistance of the embankment, covering the road with high albedo surface materials, and installing sun sheds to keep the ground shaded (Malenfant-Lepage et al., 2012). Examples of the latter include using air convection embankments (ACE), which have large rocks in the embankment to promote convection in the pore spaces, as well as the installation of air ducts, heat drains, and thermosyphons (Fig. 1.3).
Figure 1.2: Embankment shoulder rotation and longitudinal cracking of the driving surface caused by loss of support from permafrost degradation from snow accumulation alongside the embankment (Doré et al. 2016, Fig. 2).
Fig. 1.3: Experimental test site at Beaver Creek, YT, where a variety of techniques were tested to reduce ground temperatures including the installation of heat drains, construction of air convection embankments, and regular snow clearing (Malenfant-Lepage et al., 2012, Fig. 4).
While these techniques have shown some degree of success in lowering ground temperatures, their widespread implementation has been limited by cost, durability, and safety concerns. For example, thermosyphons were installed to mitigate thaw beneath less than 500 m of the Alaska Highway near Dry Creek in western south Yukon at a capital cost of CAD $4 million in 2020 (Schetselaar et al., 2023). Simulation results from O’Neill and Burn (2017) suggest that regular snowpack compaction may be an effective alternative method of significantly reducing ground temperatures along thaw sensitive northern infrastructure.

1.5 Research objectives

This thesis reports the results of field experiments on snowpack compaction in central Yukon. The objectives of this research were to:

1. investigate how snowpack compaction affects ground temperatures adjacent to the embankments of the Silver Trail and South McQuesten road near Mayo and Dempster Highway in the Blackstone Uplands;
2. investigate how compaction affects the structure and density of the snowpack.

The research hypothesis is that snow compaction will cause a reduction in ground surface temperatures by lowering the thermal resistance of the snowpack.

1.6 Research activities

Four field sites were established alongside the embankment of the Silver Trail and South McQuesten road near Mayo, YT, and five sites were established at km 96 of the southern
Dempster Highway, in the Blackstone Uplands, YT (Fig. 1.4). Each site consisted of two adjacent plots of equal dimensions, one of which was compacted using snowmobiles, while the other was undisturbed. Compaction followed a regular schedule throughout the winter. This configuration allowed for the timing and frequency of compaction to be modified between sites. The site locations were selected to represent a variety of northern settings where snow conditions varied significantly.

Compaction was carried out by land guardians of the First Nation of Na-Cho Nyäk Dun, based in Mayo, YT. All four field sites near Mayo were compacted once every month, while the Dempster Highway sites were compacted following the schedule outlined in Table 1.1. Ground surface temperatures were monitored throughout the study period by data loggers encased in protective pipes and placed at the bottom of the snowpack. Snow properties were measured at all plots in the days following compaction. The temperature, hardness, density, grain size, and shape of snow crystals were determined for each layer of the snowpack by digging to the bottom of the snow and measuring these properties through the profile. The beginning of the field work was delayed by uncertainty about travel regulations during the COVID-19 pandemic. Because of this delay, the ground surface was already frozen upon arrival in the study area, and the sites were snow covered. This prevented data loggers from being installed to measure temperatures below the surface. Snow compaction began in early December 2020 and continued until April 2021. The final field visit, to retrieve data loggers, was made in June 2021.

1.7 Thesis Structure

The thesis is divided into six chapters. The following chapter presents a background literature review of how snow influences ground temperatures, and how this may affect infrastructure in
Figure 1.4: Snow surface conditions at an undisturbed site (a) and a site that had recently been compacted (b) site alongside the Dempster Highway, 8 January 2021. The site in (b) had also been compacted in early December 2020.
Table 1.1: The compaction schedule that was followed for the five test plots at the Dempster Highway site. The timing and frequency of compaction varied between plots to determine what effect this may have on ground temperatures.

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regions underlain by ice-rich permafrost. Chapter 3 describes the study area and the field methods. Chapter 4 presents the results of the field experiments and describes how ground temperatures and snow properties developed throughout the winter. Chapter 5 analyzes and discusses the field measurements. Chapter 6 describes limitations of the study, summarizes the principal conclusions, and discusses potential future research.
Chapter 2: Background Research

2.1 Introduction

This chapter discusses the influence of snow on ground temperatures, the risk that snow-induced warming poses to highway embankment stability in permafrost terrain, and the potential for snowbank compaction to mitigate this risk by increasing heat flow out of the ground. First, the ground thermal regime of permafrost terrain is described. This is followed by a discussion of the surface energy balance and the seasonal thermal boundary layer provided by snow cover. Snowpack development, and the types of snow found in northern tundra and taiga environments are then discussed. Variation of heat transfer within the snowpack with snow structure is also considered. Finally, existing research on the thermal effects of snow compaction is discussed.

2.2 Ground thermal regime of permafrost

Permafrost is ground in which the temperature remains at or below 0 °C for two or more years (Muller, 1943). Heat in the ground originates from two sources: geothermal energy from Earth’s interior and solar energy at the ground surface. Under equilibrium conditions, the flow of geothermal heat at a given location remains constant, and ground temperatures increase with depth. Solar energy entering or leaving the ground surface varies temporally on a daily, seasonal, and annual basis, and the resulting near-surface ground temperature variation dissipates with depth. As a result, a layer of seasonally thawed ground above permafrost, the active layer, develops when air temperatures are above 0 °C.

The presence of permafrost ultimately depends on climate, but the distribution of permafrost within regions of discontinuous permafrost is also governed by the surface energy balance. Sporadic permafrost may form with mean annual ground surface temperatures as high
as 1 °C, while continuous permafrost develops where the regional mean annual ground temperature is ≥ -6 °C (Smith and Riseborough, 2002).

2.3 Surface energy balance

The ground surface energy balance (eq. 2.1), relates the various inflows and outflows of energy (W m\(^{-2}\)) at the ground surface (Williams and Smith, 1989):

\[
Q^* = Q_H + Q_{LE} + Q_G
\]

Q* is the net exchange of radiation at the ground surface, Q\(_H\) is the transfer of sensible heat, Q\(_{LE}\) is the transfer of latent heat, and Q\(_G\) is the conduction of heat into or out of the ground. As energy cannot be created or destroyed, the component fluxes of eq. 2.1 must remain balanced. The value of each component of the energy balance fluctuates constantly with changing surface conditions and diurnal and seasonal cycles. Schematic net energy fluxes during the day and night for ground without snow cover are shown in Fig. 2.1. When snow is present, it modifies the surface energy balance by acting as an insulative barrier between the ground surface and atmosphere. Each component of the energy balance is affected by the snow to varying degrees.

2.3.1 Radiative heat flux

Net radiation refers to the amount of short-wave (K) and long-wave (L) radiation that enters or exits the ground. Short-wave radiation originates from the Sun, and the amount that reaches the ground is governed by a wide variety of site-specific factors including shading by vegetation, snow cover, slope angle, aspect, zenith angle, and cloud cover (Brown, 1973). Long-wave radiation is radiation that has been emitted from terrestrial sources such as vegetation or cloud cover.

The amount of short-wave radiation that is absorbed by the ground is controlled by the
Figure 2.1: Diurnal variation of the surface energy balance for ground without snow cover and with sun exposure during the day (Williams and Smith 1989, Fig. 3.3). The $Q^*$ component of the energy balance is positive when energy is absorbed into the ground, while the $Q_H$, $Q_{LE}$ and $Q_G$ fluxes are positive when energy is released from the ground, so that inflow and outflow of energy at the surface remain balanced.
albedo (reflectivity) of the ground surface. During the day, the net radiative heat flux is generally positive outside the high latitudes, where there is limited or no sunlight during the winter. At night there is no incoming short-wave radiation, so the radiative heat flux becomes negative as energy absorbed by the ground during the day is emitted as long-wave radiation. Snow cover increases the amount of short-wave radiation that is reflected at the surface due to its high albedo compared to most soils and ground cover. Snow albedo ranges from as high as 0.95 for fresh snow to as low as 0.4 for old and melting snow (Berry, 1981; Zhang, 2005). In comparison, bare fields have typical albedo values ranging from 0.12 – 0.25, tundra 0.15 – 0.20, and forests 0.03 – 0.2 (Berry, 1981). The albedo of road surfaces is also low, with typical values of about 0.2 for paved surfaces and 0.15 – 0.18 for crushed gravel embankments (Bai et al., 2022). The greater proportion of short-wave energy reflected by the snow cover causes a reduction in $Q^*$ during the daytime.

Snow also has higher absorptivity and emissivity of long-wave radiation than many common ground materials (Zhang, 2005). The impact this has on $Q^*$ depends on the amount of downwelling long-wave radiation that is emitted by clouds and water vapour in the atmosphere. During cold, clear, and dry days, atmospheric downwelling will be limited by a low effective sky temperature, and the long-wave radiation emitted from the snowpack may be greater than the long-wave radiation absorbed. Under these conditions $Q^*$ will be reduced, which may lead to surface cooling, and development of a low-level temperature inversion (Zhang, 2005). When the atmosphere is more humid and has greater cloud cover, the amount of long-wave radiation absorbed from atmospheric downwelling may be greater than the amount of long-wave radiation emitted by the snowpack, causing an increase in $Q^*$ (Zhang, 2005). Overall, an increase in
downwelling long-wave radiation from cloud cover may hasten snowmelt by up to a month in the Arctic and Subarctic (Zhang et al., 1996).

2.3.2 Sensible heat flux

The sensible energy flux refers to heat transferred to or from the surface by air flow that leads to a change in temperature. During the day ground surface temperatures are typically higher than air temperatures, so air is warmed as it contacts the ground surface before rising away, causing $Q_H$ to be positive. At night the ground is typically colder, which causes the air to instead warm the ground and $Q_H$ to be negative. When wind speeds are higher, or the ground surface rougher, turbulence increases. Turbulence leads to more vertical air movement, increasing convective heat transfer. Snow cover smooths the ground surface, reducing turbulence and convective heat transfer at the snow surface (Walter et al., 2005). Heat is also transferred, albeit slowly, through convective currents within the snowpack. The base of the snowpack is usually warmer than its surface, causing $Q_H$ to be positive as heat flows away from the ground. Convective heat transfer through the snowpack increases with greater porosity, but accounts for only a small portion of overall heat transfer through the snowpack even in very porous snow (Sturm et al., 1992).

2.3.3 Latent heat flux

The latent energy flux refers to the energy absorbed or released through water undergoing phase change. During the thawing season, moisture at the ground surface evaporates during the daytime, absorbing energy equal to the latent heat of vapourization of water and causing $Q_{LE}$ to be positive. At night, as temperatures decline, water vapour condenses as dew, releasing energy and causing $Q_{LE}$ to be negative.

When snow is present, latent heat transfer occurs within the snowpack through the sublimation and recrystallization of ice and water vapour. This occurs because air within the
snow is saturated, and the amount of water vapour that the air can hold increases with temperature according to the saturation vapour pressure curve (Fig. 2.2). Higher temperatures near the ground surface create a temperature gradient through the snowpack. The resulting vapour pressure gradient causes water vapour to diffuse upwards, before accumulating on crystals at lower temperatures, where the saturation vapour pressure is lower (Walter et al., 2005). The water vapour is supplied near the base of the snowpack by continued sublimation of snow or evaporation of soil moisture (Smith and Burn, 1987). The process continues as long as the temperature gradient is maintained, eventually transforming the snow into depth hoar.

As ice near the base of the snowpack sublimates, it absorbs energy equal to the latent heat of fusion of water, $3.3 \times 10^5$ J kg$^{-1}$, and the latent heat of vaporization, $2.45 \times 10^6$ J kg$^{-1}$, totaling $2.78 \times 10^6$ J kg$^{-1}$ (Williams and Smith, 1989). This increases $Q_{LE}$, cooling the ground. The process is temperature dependent, because the rate of heat transfer increases as the slope of the saturation vapour pressure curve rises near 0°C (Fig. 2.2). At temperatures as low as about -20 °C heat transfer through vapour diffusion is highly limited, even in very porous snow, due to the low vapour pressure gradients (Sturm and Johnson, 1992). The snowpack also influences the latent heat fluxes during the spring by absorbing energy equal to the latent heat of fusion as it melts. This delays ground temperatures from rising above 0 °C until all the snow has melted.

2.3.4 Conductive heat flux

$Q_G$ is the energy conducted into the ground from the ground surface. $Q_G$ is positive when the ground surface is warmer than the ground below, and negative when the ground surface is colder. The magnitude of $Q_G$ is governed by the temperature gradient and the thermal conductivity of the ground materials. At sites without snow cover during daytime, the influx of short-wave radiation from the Sun causes temperatures to increase at the ground surface,
Figure 2.2: The relation between the partial pressure exerted by vapour molecules in the air, and air temperatures, over a plane of pure water. The inset graph shows the difference in the saturation vapour pressure curve between water and ice below 0 °C (Oke, 1987, Fig. 2.15).
reaching a maximum around 2 pm. At night, as temperatures at the ground surface fall due to the lack of solar energy, the thermal gradient is reversed and heat instead flows upwards through the ground (Oke, 1978).

When snow is present it limits heat flow between the ground surface and atmosphere by acting as an insulative boundary layer. The thermal conductivity of snow varies greatly depending on snow conditions, ranging from about 100 – 600 W m⁻¹ K⁻¹ (Calonne et al., 2011). This is lower than other ground materials because snow contains a high proportion of air (Zhang, 2005). Since the air is trapped within the snow it moves very slowly, and most heat transfer occurs through conduction rather than convection. Air has low thermal conductivity, as the large spaces between molecules make it difficult to transfer kinetic energy between them. Generally, the thermal insulation provided by the snow dominates the overall thermal influence of the snowpack, causing mean annual ground temperatures to be higher than mean annual air temperatures (Goodrich, 1982). Air and ground surface temperatures may be similar in summer but distinctly different in winter due to the snow pack (Karunaratne and Burn, 2004).

### 2.4 Temperature offsets

#### 2.4.1 Surface offset

The cumulative effect that the surface energy balance has on mean annual ground surface temperatures compared to mean annual air temperatures is the surface offset. This is the difference between annual mean air and annual mean ground surface temperatures. It is comprised of two components, the vegetative offset and the nival offset. The vegetative offset is the summary effect of processes that occur when no snow is present, primarily shading and evapotranspiration, which generally cool the ground. The nival offset represents the thermal
influence of snow. The relatively high albedo of the snowpack as well as sublimation at the
ground surface both have a cooling influence, but this is generally outweighed by the thermal
insulation that the snow provides above the ground surface. As a result, the nival offset is nearly
always positive. An exception to this rule occurs with thin snow cover. Under such conditions
the high albedo and emissivity of the snow may cause radiative heat loss to become great enough
that the snow instead has a cooling influence (Zhang, 2005). A cooling influence has been
observed in snowpacks with depths up to 40 cm in an alpine environment (Keller and Tamas,
2003), but the effect is normally restricted to much thinner snowpacks.

In permafrost regions, air temperatures are below 0 °C for longer than they are above 0
°C, so the ground surface is influenced by the nival offset for longer than it is influenced by the
vegetative offset. The disparity between the vegetative and nival offsets is great enough that the
role of vegetation in enhancing snow accumulation may have a larger influence on mean annual
ground surface temperatures than the cooling offset provided by the vegetation itself (Smith and
Riseborough, 2002; Way and Lapalme, 2021).

2.4.2 Thermal offset

In addition to the surface offset, mean annual temperatures may decline through the active layer
because water within the pore space of the soil freezes during the winter, altering the thermal
conductivity of the ground. The thermal conductivity of ice, 2.24 W m⁻¹K⁻¹, is four times greater
than that of water, 0.56 W m⁻¹K⁻¹. The increase in thermal conductivity in winter is proportional
to the volume of water within the active layer (Williams and Smith, 1989). Although the amount
of energy that leaves the ground while the active layer is frozen is equal to the amount of energy
that enters the ground while it is thawed, the long winters in permafrost regions provide more
time for energy to leave the ground than enter during the summer, so the thermal gradient must
be greater during the summer to maintain thermal equilibrium. Mean annual temperatures become progressively lower with depth through the active layer by up to about 2 °C. This temperature difference is the thermal offset (Goodrich, 1982). The combined effect of the surface and thermal offsets on mean annual ground temperatures is shown in Fig. 2.3 (Smith and Riseborough, 2002, Fig. 3).

2.5 Available thermal energy at the ground surface and atmosphere

2.5.1 Degree Days

A surface energy balance approach provides a theoretical framework for describing the relation between atmospheric temperatures and ground surface temperatures, but its use is limited in field experiments due to the required high frequency collection of data to address each component of the energy balance accurately. To avoid this limitation, air and ground surface temperatures have been summarized using degree days as a proxy representative of available thermal energy. The Celsius degree day for one day is equal to the difference between the mean daily temperature and 0 °C (Kavanaugh, 1985). Degree days are therefore always positive, regardless of temperature. Degree days are often calculated seasonally through the integration of temperatures over the duration of the thawing or thawing season, when air temperatures are above and below 0 °C, respectively (Fig 2.4). The total degree days during the freezing and thawing seasons are the freezing and thawing indices, which are measures of the combined duration and magnitude of temperatures during the respective season (Karunaratne and Burn, 2003; Karunaratne et al., 2008).

2.5.2 The n-factor

Using degree days, available thermal conditions over a period can be estimated for the ground
Figure 2.3: Ground temperature profile showing the thermal and surface offsets shifting mean annual ground surface temperatures (MAGST) and temperatures at the top of permafrost (TTOP) relative to the mean annual air temperature (MAAT). From Smith and Riseborough (2002, Fig. 3).
Figure 2.4: Seasonal degree days divided into the freezing season (blue) and thawing season (red) over the duration of an idealized year with an annual mean temperature of 0 °C and a temperature amplitude of 25 °C.
surface and the air. This allows for the calculation of \( n \)-factors: an index that has been used for over fifty years in engineering studies to represent the net effect that the complex interactions of the surface energy balance have on ground surface temperatures (Klene et al., 2001). Due to snow cover, the ground surface energy balance is different during the freezing and thawing seasons in northern climates, so \( n \)-factors are also divided into the freezing and thawing seasons:

\[
\begin{align*}
\text{(2.2a)} & \quad n_F = \frac{FDD_s}{FDD_a} \\
\text{(2.2b)} & \quad n_t = \frac{TDD_s}{TDD_a}
\end{align*}
\]

Where \( n_F \) is the freezing \( n \)-factor, \( n_t \) is the thawing \( n \)-factor, \( FDD_s \) and \( FDD_a \) are the freezing degree days for the ground surface and air, and \( TDD_s \) and \( TDD_a \) are the values for the thawing season. Air degree days are typically measured about 1.5 m above the ground or snow surface, while ground surface degree days are measured just below the ground surface (Kavanaugh, 1984). The \( n \)-factor does not have a specific time period over which it must be calculated, however, conventionally, \( n \)-factors are presented over the duration of a freezing or thawing season. Operationally, the freezing and thawing seasons for the air and for the ground should begin and end on the same days. This can make it difficult to determine which length of season to select, as changes in surface temperature often lag changes in air temperature, especially during transitions between seasons. Surface temperatures have been used to determine \( n \)-factor season length, rather than air temperatures, because of the lower variability (Klene et al., 2001).

Because the calculation of \( n \)-factors only requires measurement of degree days, typical \( n \)-factor values have been derived empirically for a variety of common ground surfaces, e.g., freezing and thawing \( n \)-factors of 0.21 and 0.76, respectively, in peatlands near Yellowknife (Karunaratne et al., 2008), and 0.2 to 0.55, respectively, in the boreal forest of northwestern Canada (Burn, 2004).
Once $n$-factors for a surface have been assessed they can be used as a scalar with air temperatures to estimate the surface temperature of the ground. All $n$-factors above 1 amplify ground temperatures relative to air temperatures for their respective season. For example, dark asphalt absorbs radiation more than most materials causing its thawing $n$-factor to be between 2 and 3 (Klene et al., 2001). When $n$-factors are below 1 they reduce the magnitude of ground temperatures, representing the dampening effect the surface energy balance has on that surface. Because snow cover controls the surface energy balance during the freezing season, $n_f$ is mostly determined by the ability of a surface to trap snow (Kropp et al., 2021), as well as soil moisture content (Karunaratne and Burn, 2004). Deeper snow cover causes a reduction in $n_f$, as the ground is better insulated from atmospheric temperatures, while shallower snow cover has the opposite effect. Typical values of $n_f$ for natural surfaces are $0.1 – 0.7$ (Klene et al., 2001).

The thawing $n$-factor is controlled by a wider variety of factors, but the most influential is generally the presence of vegetation, due to cooling from evapotranspiration and shade. This was demonstrated in an experiment in which vegetation was removed from a northern spruce forest with brush and moss over peat soil. The thawing $n$-factor was initially 0.37 when the vegetation was left undisturbed. Once the brush and trees were removed, $n_t$ rose to 0.73. When the moss was removed as well so that bare soil was exposed, $n_t$ further increased to 1.22. In contrast, $n_f$ increased by only 0.08 (Lunardini, 1978). In boreal and arctic ecosystems, larger vegetation including trees and tall shrubs ($<40$ cm) may have a reduced ground surface cooling effect, and in some cases may cause ground surface temperatures to instead increase (Kropp et al. 2021). Thawing $n$-factors under tall vegetation typically range from $0.5 – 1$, with higher values more commonly observed in vegetation where the canopy is elevated further from the ground (Way and Lapalme, 2021).
A drawback of using $n$-factors is that they only show the net effect that the surface energy balance has on ground temperatures, without indicating which components of the energy balance are responsible. In some cases, differences in $n$-factors may also be explained by subsurface conditions. In Mayo, permafrost was found to be a controlling factor for $n_t$ when snow depths were similar, as sites without permafrost have latent heat released from the freezing front throughout the winter, warming the ground and causing $n_t$ to be lower. If the freezing front reaches permafrost this release of latent heat diminishes and the ground cools, increasing $n_t$ (Karunaratne and Burn, 2004). During the summer the thermal diffusivity of the ground was found to be a controlling factor for $n_t$, as ground with low thermal diffusivity would delay ground thawing, causing ground surface temperatures to be substantially lower than air temperatures and lowering $n_t$ (Karunaratne and Burn, 2004).

Because of the complex interactions that contribute to the $n$-factors, they must be interpreted with consideration towards the environment in which they were collected. Nonetheless, they provide an excellent tool for modelling air-ground surface interactions. This is relevant for snow compaction, as the technique may lower $n_t$ values so that ground surface temperatures are more closely coupled with atmospheric temperatures in the freezing season.

### 2.6 The TTOP model of ground temperatures

By combining $n$-factors and degree days, the temperature at the top of permafrost can be calculated to closely resemble empirical values at a regional scale (Smith and Riseborough, 2002). By modelling the relation between temperatures in the air, at the ground surface, and at the top of permafrost, the effect of snow compaction can be isolated to estimate the influence it may have on the ground thermal regime.
To calculate temperatures at the top of permafrost, first the mean annual air temperature is divided into two components, representing each of the seasons, as shown in Eq. 2.2 (Smith and Riseborough, 2002).

\[
[2.3] \quad \text{MAAT} = \frac{\text{DDT}_a - \text{DDF}_a}{P}
\]

Where MAAT is the mean annual air temperature (°C) and P is the 365 days of the annual period. In regions where DDF\(_a\) is much greater than DDT\(_a\), permafrost will be widespread regardless of local ground conditions, except beneath water bodies or glaciers. When DDF\(_a\) and DDT\(_a\) are closer, the distribution of permafrost will depend on conditions at or near the ground surface. These surface conditions can be represented by applying n-factors as a scalar for atmospheric degree days, allowing for the calculation of mean annual ground surface temperatures (°C) (Smith and Riseborough, 2002).

\[
[2.4] \quad \text{MAGST} = \frac{n_t \text{DDT}_a - n_f \text{DDF}_a}{P}
\]

The surface offset can be isolated to compare its freezing season and thawing season components by subtracting Eq. 2.3 from Eq. 2.4 (Smith and Riseborough, 2002):

\[
[2.5] \quad \text{Surface Offset} = \frac{\text{DDF}_a (1 - n_f)}{P} - \frac{\text{DDT}_a (1 - n_t)}{P}
\]

The first term on the right side of the equation is positive, and represents the warming influence of snow cover. The second term is negative, and represents cooling from shade and evapotranspiration. In permafrost regions, DDF\(_a\) is much greater than DDT\(_a\), so the thermal effect of snow cover is likely to have a greater influence on mean annual ground surface temperatures than cooling processes during the thawing season (Smith and Riseborough, 2002).
In addition to atmospheric temperatures and the surface offset, temperatures at the top of permafrost are also controlled by the thermal offset. The thermal offset depends on the seasonally variable thermal conductivity of the ground, introduced in Eq. 2.6:

\[ \text{Thermal Offset} = \frac{n_t DDT_a (r_k - 1)}{P} \]

where \( r_k \) is the ratio of the thermal conductivities of the ground when thawed and frozen. The value of \( r_k \) depends on the volume of water within the soil pore space. Soil that has more water will have a more seasonally variable thermal conductivity, causing more heat to escape during the winter and ground temperatures to decline. In tundra and forest \( r_k \) is generally near 1, and slightly lower in forest (Way and Lewkowicz, 2021). In organic soils \( r_k \) can vary depending on moisture content, from 0.3 or lower under saturated conditions to near 1 under dry conditions (Smith and Riseborough, 2002).

By adding the equation for MAGST from equation 2.4 to equation 2.6, atmospheric temperatures indices, the surface offset, and the thermal offset are combined to complete the TTOP model:

\[ \text{TTOP} = \frac{r_k DDT_a n_t - DDF_a n_f}{P} \]

This model closely agrees with published ground temperature values across Canada (Smith and Riseborough 2002). The presence of permafrost at equilibrium can be predicted where \( n_t DDF_a \) is greater than \( r_k DDT_a n_t \), causing TTOP to be negative. Measurement of TTOP can be used to estimate \( r_k \) and the thermal offset. Because compaction modifies \( n_t \), its influence on ground temperatures will be greatest where \( DDF_a \) is largest, i.e. at far northern latitudes and high elevation. As \( DDT_a \) becomes larger in comparison, either at more southern latitudes or through
continued climate change, TTOP becomes more dependent on $n_t$ and $r_k$, and snow compaction may be less effective at lowering ground temperatures.

Snow compaction may indirectly reduce $n_t$ by shortening the thawing season of the ground if it takes longer for the compacted snow to melt. On ski trails, compaction of the snow from ski-grooming has been observed to delay snowmelt by about four weeks compared to natural conditions (Keller et al., 2004). Snow compaction may also cause an increase in the thermal offset by expediting freeze-up of the active layer, if the treatment causes more heat to escape the ground early in the freezing season. The inverse was observed in simulations from Goodrich (1982), where rapid snow buildup early in the freezing season caused the thermal offset to be reduced, since freeze-up of the active layer was delayed. This result has since been validated by modelling and field observations indicating that deeper snow depths early in the winter results in higher subsurface temperatures (Jan & Painter, 2020). This effect may cause permafrost warming even without a change in mean annual air temperature (Sannel et al., 2006).

Compaction may provide a simple method of lowering TTOP, but the effectiveness of the technique depends on the physical and thermal properties of the snowpack. In the following section, the variables affecting heat transfer through the snowpack are described, followed by assessment of how they may be modified by compaction. Typical snowpack development in forested and tundra regions is then discussed so that the impact of snowpack compaction can be assessed in a variety of environments.

2.7 Snow and ground temperatures

Thermal properties of the snowpack are determined by its depth, density, structure, and temperature (Sturm et al., 1997; Zhang, 2005). The rate of heat transfer through the snowpack,
including all components of the energy balance, is governed by the effective thermal conductivity of the snowpack and the temperature gradient. In this section the effects of varying snow physical properties, timing, and temperature on the effective thermal conductivity of the snowpack are examined, followed by a description of snowpack development and structure, and how this may be modified by compaction.

2.7.1 Snow Depth

As snowpack depth increases, the thermal resistance of the snowpack, the inverse of thermal conductivity, rises. The thermal resistance of the snow increases at an exponentially decreasing rate with snow depth (Mackay and McKay, 1974). It can be calculated by dividing snow depth by its thermal conductivity, and the total thermal resistance of a snowpack can be calculated by combining the resistance of each layer (Lunardini, 1981, eq. 3.12):

\[
\sum_{i=1}^{n} \frac{L}{\lambda_i}
\]

Where \( L \) is the thickness of a snow layer in m, \( \lambda_i \) is its effective thermal conductivity in W m\(^{-1}\) K\(^{-1}\), and snowpack thermal resistance is in m\(^2\) K W\(^{-1}\). A snowpack with a higher thermal resistance will provide greater insulation from low atmospheric temperatures during the winter, increasing ground temperatures. In areas with long, cold winters, snow depths may have a greater influence on mean annual ground temperatures than variations in air temperature (Kotlyakov and Sosnovsky, 2022). Using compaction to reduce snow depths is therefore expected to have a significant effect on ground temperatures by lowering the thermal resistance of the snowpack, because \( L \) is reduced and \( \lambda \) increased.

2.7.2 Snow Density

Snow density can range from as low as 100 kg m\(^{-3}\) in fresh snow and depth hoar, to as high as 600 kg m\(^{-3}\) in wind-hardened snow in the tundra or when melting (Zhang, 2005). The density of a snowpack is determined by the proportions of interstitial air and ice within the snow. Ice has a
density of 917 kg m\(^{-3}\) and a thermal conductivity of 2.24 W m\(^{-1}\) K\(^{-1}\) at 0 °C, while the density of air is 1.2 kg m\(^{-3}\) and the thermal conductivity is 0.025 W m\(^{-1}\) K\(^{-1}\) (Williams and Smith, 1989). Since air within the snow is trapped in small spaces, there is little convection (Sturm et al., 1997), and heat transfer instead occurs mostly by conduction. This causes the thermal conductivity of snow to rise with density, at a rate depending on the structure of the snowpack (Fig 2.5). The variation in density and structure causes the thermal conductivity of snow to vary from as high as about 0.7 W m\(^{-1}\) K\(^{-1}\) to as low as 0.02 W m\(^{-1}\) K\(^{-1}\) in depth hoar (Zhang, 2005).

In addition to increasing thermal conductivity, a snowpack of higher density also limits convective and latent heat transfer within the snowpack as pore space and connections between pores are reduced. The movement of water vapour (convection) is responsible for about 37% of heat transfer within a snowpack with a density of 100 kg m\(^{-3}\), but at a density of 500 kg m\(^{-3}\) water vapour movement accounts for only about 8% of heat transfer (Langham, 1981). Vapour diffusion effectively increases the thermal conductivity of the snowpack by transferring heat in the same direction as the thermal gradient, but because the amount of heat transferred is much less than through conduction, increasing the density of a snowpack will still cause its effective thermal conductivity to rise despite the reduction in vapour diffusion (Fig. 2.5). There is significant variation within measured thermal conductivity values of snow, even at the same density, due to differences in snow structure, temperature, and measurement technique (Sturm et al., 1997; Calonne et al., 2011), but a positive relation between density and thermal conductivity has been firmly established in all types of snow.

2.7.3 Snow Temperature

The thermal conductivity of a snowpack is governed by three temperature-dependent processes, thermal conduction through air, thermal conduction through ice, and vapour diffusion
Figure 2.5: The relation between effective thermal conductivity and snow density from a variety of studies using different measurement techniques, from Calonne et al. (2011, Fig. 1). Grey symbols indicate measurements using a needle-probe method, sorted by shape for different snow types, while the “T” shape symbols are computed values sorted by colour for different snow types. The yellow and black triangles show experimental and numerical data, respectively. The yellow diamond shows experimental data from Calonne et al. (2011) that was collected by temperature sensors at the top and bottom of a snow slab, while the brown diamond shows needle-probe measurements from the same snow slab. The labels “this study” and “this work” refer to Calonne et al. (2011).
(Sturm et al., 1997). The thermal conductivities of air and ice have opposite relations with temperature (Fig. 2.6). The thermal conductivity of air increases with temperature, as higher kinetic energy increases the rate of particle collisions. The thermal conductivity of ice decreases as temperature increases because the crystal lattice of the ice expands, increasing the distance between ice molecules. The rate of vapour diffusion, and latent heat transfer that occurs in the process, is governed by the saturation vapour pressure gradient (Fig. 2.2). At higher temperatures the vapour pressure gradient increases and vapour diffusion occurs at a higher rate. Between 0 and -20 °C, heat transferred at the higher rate of vapour diffusion may increase the effective thermal conductivity of the snow by 0.1 W m⁻¹ K⁻¹ (Sturm et al., 1997).

Compaction of the snowpack will reduce the volume of air within the snow by increasing its density. The porosity of a snowpack is approximately 1 – ρ, where ρ is bulk density of the snowpack. For example, the volume of ice of 1 cm³ of snow with a density of 0.2 g cm⁻³ is equal to 0.2g / 0.917 g cm⁻³, 0.218 cm³. The volume of air is therefore 0.781 cm³, or 78%. At ambient temperatures for air and ice, the difference in thermal conductivity between 0 and –20 °C is only about 4% (Fig. 2.6), and this is unlikely to cause a significant difference in the thermal conductivity of a snowpack since it is less than the variation displayed in Fig. 2.5. However, temperatures at the field sites reached as low as -48 °C during cold snaps, enough for the thermal conductivity of ice to increase by 20%, and the thermal conductivity of air to decrease by 12%. Compaction is expected to limit ground cooling from vapour diffusion while temperatures are between 0 and -20 °C by restricting vapour flow, and may be slightly more effective at reducing thermal resistance of the snowpack during periods of extremely low temperatures.

2.7.4 Snow timing and duration

The thermal effect of snow on ground temperatures varies on a daily time scale with the radiative
Environmental temperatures during field experiments in this thesis typically remained between -40 and 0 °C.
heat flux and, hence, the temperature gradient between the atmosphere and ground surface (Zhang, 2005). Early in the freezing season, when snow cover is shallower than about 20 cm, the radiative heat flux may play a greater role than the conductive heat flux. This causes the snowpack to be more likely to have a cooling effect on average, but on cloudy days, longwave radiation from the atmosphere that is absorbed at the snow surface may reduce the cooling provided by the snow, or cause it to instead warm the ground. As snow accumulates and the thermal resistance of the snowpack increases, the dampening effect it has on relations between air and ground temperatures eventually dominates its thermal influence.

The influence of snow cover on annual mean ground temperatures is greatest early in the freezing season, when it influences how quickly the active layer freezes (Goodrich, 1982; Jan & Painter, 2020). As the active layer freezes, its temperature remains near 0 °C until the soil water has changed state, an effect called the “zero curtain” (Outcalt et al., 1990). If deep snow cover accumulates early in the winter it extends the duration of the zero curtain, thereby reducing the length of the freezing season at the top of permafrost, and increasing annual mean ground temperatures.

Snow cover also extends the zero curtain at the ground surface during the spring. Snow melt occurs relatively quickly, however, and so has less influence on annual mean ground temperatures (Zhang, 2005). In Barrow, Alaska, the combination of late snow cover in autumn and late snow melt in spring was found to reduce ground temperatures by up to 2 °C compared to average conditions, while early snow cover and snow melt increased ground temperatures by up to 1.5 °C (Zhang, 2005). Compaction of the snowpack is expected to have the greatest influence on mean annual ground temperatures early in the freezing season by accelerating freeze-up of the active layer.
2.8 Snowpack Development

2.8.1 Snow deposition

The structure of a snowpack is the result of meteorological conditions influencing the development of ice crystals in the atmosphere, followed by wind, topographic and vegetation conditions influencing snow deposition, and metamorphic processes once the snow has accumulated. In the atmosphere, snow formation begins with the development of ice crystals from supercooled water nucleating around aerosol particles (Schemenauer et al., 1981). From this stage, the ice crystals may grow through the deposition of water vapour until they become snow crystals, which have more complex crystalline structures and are visible to the naked eye. Snow crystals may fall intact, aggregate with other snow crystals to form snowflakes, or grow through the deposition of cloud droplets in a process called riming (Schemenauer et al., 1981). With sufficient riming, the snow crystals may develop into rounded pellets called graupel.

As snow falls, its shape is further influenced by wind conditions. Light winds allow snow crystals to aggregate into larger snowflakes, which can form a snowpack with a density as low as 20 kg m$^{-3}$ upon deposition (Langham, 1981; Calonne et al., 2011). If the snowfall consists of mostly graupel, then the density may be as high as 500 kg m$^{-3}$ under the same wind conditions. Wind speeds near the snow surface determine how incoming snow crystals are packed. When wind speeds are sufficiently high, snow crystals are broken up in the turbulent boundary layer near the snow surface, causing them to become smaller and more well-rounded (Langham, 1981). Further weathering occurs as crystals are dragged along the surface through saltation, or as blowing snow. This causes the crystals to become more tightly packed, increasing snowpack density. Large-scale snow transport typically occurs once wind speeds reach 8-10 m s$^{-1}$, or 29-36 km h$^{-1}$ (Li and Pomeroy, 1997).
Because snow cover accumulates from a number of separate snowfall and redistribution events with different meteorological conditions, it is usually stratified into distinct layers. If snow particles are consistently rounded by high winds, they may form especially dense layers or wind slabs, which are comprised of well-rounded snow grains and range in density from about 350 – 550 kg m$^{-3}$ (Sturm et al., 1997). This is most common in open environments such as the tundra or prairies, where the lack of tree cover creates a longer fetch for the wind (Pomeroy et al., 1993).

Snow layering is laterally heterogenous, as the type of snow falling varies, and some snow cover may be shielded from the wind by vegetation or variations in topography as it is deposited, creating pockets of lower density snow cover. In forested environments the presence of trees reduces fetch, reducing wind speeds so that snow is deposited more gently. This allows the snow to maintain its original crystalline shape and pack together more loosely, causing the snowpack to have lower density. A higher proportion of the snow is also intercepted by vegetation before reaching the ground (Komarov and Sturm, 2023).

Snow layers may be interspersed by layers of ice, caused by freezing rain or surface snow-melt (Langham, 1981). This occurs in both tundra and forested environments. Once the snow has been deposited, the structure of the snowpack is then determined by the processes of snow metamorphism.

### 2.8.2 Snow metamorphism

Snow metamorphism refers to changes in snow texture that occur from temperature or pressure conditions within the snowpack. Snow metamorphism can be divided into three categories: equitemperature, firnification, and temperature-gradient metamorphism (Schemenauer, 1981).

Equitemperature metamorphism occurs from the transfer of water vapour between
convex and concave snow crystal surfaces (Fig. 2.7). Convex surfaces of a snow crystal, such as the tips of branches of a snowflake, are able to support a higher vapour pressure than a concave surface. Water vapour will then flow from the convex surface to the concave one along the vapour pressure gradient (Perla and Martinelli, 1976). This has two general effects on snow texture. Individual snow crystals become well-rounded, as the increased sublimation at the convex surfaces transfers their mass to the concave surfaces, until the surfaces have equalized. Individual snow grains also become conjoined with other snow grains in a process called sintering. Sintering increases snow density by filling pore space within the snowpack. It can occur regardless of whether a temperature gradient is present through the snowpack, since even a large temperature gradient will cause little effective temperature difference in the space between snow grains.

Firnification includes melt-freeze and pressure metamorphism. Melt-freeze metamorphism occurs when liquid water enters the snowpack, either from rainfall or snowmelt. When temperatures at the snow surface are below 0 °C rain will freeze on contact, creating an ice-layer, but when temperatures reach 0 °C, either from warm weather or sustained rainfall, liquid water will then enter the snowpack (Perla and Martinelli, 1976). The greatest snowmelt is typically found at the surface of the snowpack, due to the influx of radiation. Once liquid water enters the snowpack it percolates through the snow before freezing when it reaches a sufficiently cold portion of the snowpack, an impermeable layer within the snow, or as temperatures drop at night. Pressure metamorphism is a result of deformation and rearrangement of snow grains from the pressure of overlying snow so that they can be packed more tightly. When combined with melt-freeze metamorphism, pressure metamorphism can potentially change the snowpack into firn, which can have a density of up to 830 kg m\(^{-3}\).
Figure 2.7: Water vapour transfer from convex to concave ice grain surfaces (Perla and Martinelli, 1976, Fig. 59).
Temperature-gradient metamorphism occurs as a result of the transfer of mass from water vapour diffusion and sublimation along a temperature gradient, as described above. As water vapour rises through the snowpack and deposits onto snow crystals, it causes the crystals to expand in the direction of the temperature gradient, developing a faceted, angular structure. In the advanced stages of temperature-gradient metamorphism snow crystals morph into depth hoar, where crystals have distinct faces and corners and grow to about 8 mm in diameter (Perla and Martinelli, 1976). Since the temperature gradient within the snowpack is greatest early in the freezing season, when ground temperatures are still at or near 0 °C, depth hoar is usually found at the base of the snowpack (Domine et al., 2018). The transition to depth hoar is gradual, where snow crystals are more faceted towards the base of the snowpack and progressively more rounded towards the surface, with new snow at the top. This stratification is illustrated for a subarctic snowpack in Fig 2.8 (Sturm and Johnson, 1992).

Depth hoar development also depends on wind conditions and soil moisture content. If wind speeds are high enough to turn the snow into wind slabs, then the permeability of the snow will be reduced. Depth hoar development will then be limited by the restricted movement of vapour transport within the snow (Domine et al., 2018). In soils where the moisture content is very low the ground freezes rapidly in the fall. When freeze up occurs quickly the zero curtain is shortened, and the temperature gradient through the snowpack is reduced, limiting depth hoar development (Domine et al., 2018). In combination these factors may prevent depth hoar from forming even when climatic conditions are favourable for temperature-gradient metamorphism (Domine et al., 2018).

Snowpacks will naturally densify throughout the winter due to a mix of metamorphic processes and pressure applied by the weight of the overlying snow. A snow layer with an initial
Figure 2.8: Five metamorphic layers found in subarctic snow cover (Sturm and Johnson, 1992). Layer 1 is new snow, layer 2 contains small crystals with some faceting, layers 3 and 4 contain a mix of cup-shaped and elongated crystals with progressively more faceting, and layer 5 contains depth hoar.
density of 100 kg m\(^{-3}\) may densify up to 400 kg m\(^{-3}\) (Perla and Martinelli, 1976). Compaction is expected to influence this process in a variety of ways. When compressive force was applied to a snow sample in a laboratory it put strain on the ice skeleton of the snow, causing it to deform. If the force was applied gradually, the snow grains and necks slid and warped to fill pore space and, theoretically, the snow could eventually be metamorphized into ice (Perla and Martinelli, 1976). When the force was applied rapidly and the ice skeleton did not have time to deform, it fractured, breaking apart the necks between grains. Compaction of a snowbank is expected to behave similarly. If the force of compaction is strong enough to overcome the compressive strength of the snow, then there will be a significant reduction in depth as the snow skeleton fractures and the snow grains settle into pore space. The greater number of contact points between the snow grains of the fractured ice skeleton will then promote equitemperature metamorphism, further increasing the density of the snow over time.

The extent to which snow resists the effects of compaction depends on the compressive strength of the snow. Compressive strength increases exponentially with density, so a snowpack with a density of 400 kg m\(^{-3}\) can resist about 150 – 400 kPa of pressure, while a snowpack with a density of 200 kg m\(^{-3}\) can only resist about 4 – 15 kPa (Mellor, 1974). The compaction treatment is therefore expected to be most effective at increasing snow density where the initial density is low. Once the snow has been compacted, subsequent compaction is expected to be less effective, as the higher density will increase its compressive strength. In tundra, the majority of the snowpack commonly consists of dense, wind-slab layers with high compressive strength. The effectiveness of the compaction treatment will depend on whether the force of compaction is sufficient to crush softer snow within the snowpack that has undergone significant temperature gradient metamorphism, such as depth hoar. This may have a disproportionate impact in
reducing the overall thermal resistance of the snowpack due to the low thermal conductivity of the depth hoar layer.

2.9 Thermal properties of depth hoar

The thermal conductivity of a snowpack is governed by its density and structure, including grain size, shape and bonding (Sturm et al., 1997). A general relation between snow thermal conductivity and density has been firmly established (Fig. 2.4), but the effect of structure is less clear. One reason for the uncertainty is that snow measurement methods for thermal conductivity are not standardized, and different techniques may produce different results (Calonne et al., 2011). Additionally, the structure of snow is difficult to preserve throughout sample collection, transportation to a lab, and measurement of its thermal properties (Riche and Schneebeli, 2013).

The uncertainty about the role of snow structure in determining thermal conductivity is most evident with depth hoar. Sturm and Johnson (1992) used a needle probe to measure the thermal conductivity of well-developed depth hoar near Fairbanks, Alaska, with density values ranging from 154 – 220 kg m$^{-3}$, and found that its thermal conductivity was two to seven times lower than would be expected in rounded snow grains with the same density. In contrast, Calonne et al. (2011) measured the thermal conductivity of alpine and lab-grown depth hoar with a density of 315 kg m$^{-3}$ by using a needle probe, and then heat flux plates along with direct measurement of the temperature gradient, to calculate the thermal properties of the snow, and recorded thermal conductivity values of depth hoar that were near those of other snow types. Riche and Schneebeli (2013) measured the thermal conductivity of alpine depth hoar samples with densities ranging from 209 – 291 kg m$^{-3}$ using the same techniques as Calonne et al. (2011), and also found that thermal conductivity values were similar for depth hoar and rounded grains.
One contributing factor towards the differing results between studies is that the depth hoar sampled by Sturm and Johnson (1992) was more developed than that tested by Calonne et al. (2011) or Riche and Schneebeli (2013). Sturm and Johnson (1992) observed a reduction in thermal conductivity and cohesion as snow grains progressed through the first four metamorphic stages, shown in Fig 2.8. At layer 4 the snow structure was weak enough that it fell apart at the slightest disturbance, and microscopic examination showed that the points of contact between snow grains were only thin and sharp edges, suggesting that snow with this texture provides limited pathways for conduction. Once the snow metamorphized to layer 5, it re-gained cohesion and its thermal conductivity increased. The depth hoar samples from Calonne et al. (2011) were lab-grown, while the samples from Riche and Schneebeli (2013) were collected from a natural snowpack near Davos, Switzerland, where annual temperature variation is far less than in central Yukon, limiting temperature-gradient metamorphism. No indication was given of the metamorphic stage of the depth hoar in either study, and their higher densities suggest they may not have reached the layer 4 snow texture.

A second contributing factor towards the differing thermal conductivity measurements between studies is that Sturm and Johnson (1992) did not consider the anisotropy of conduction in depth hoar. Both Calonne et al. (2011) and Riche and Schneebeli (2013) observed that depth hoar conducts heat up to 50% more vertically than horizontally, where rounded grains are almost isotropic or conduct heat better horizontally. Depth hoar samples were collected horizontally from snow pits (Sturm and Johnson, 1992), and this may account for some of the two to seven times lower thermal conductivity that was observed. Other contributing factors are that the depth hoar was being compared to dense wind-slab layers as opposed to softer snow types (Sturm et al., 1997), the tests were generally conducted at a lower temperature than in other studies (Sturm
et al., 1997), and the needle probe measurement technique may produce thermal conductivity values lower than other methods (Calonne et al., 2011).

Sturm and Johnson (1992) measured depth hoar thermal conductivity values ranging from 0.026 – 0.105 W m⁻¹K⁻¹, while Calonne et al. (2011) measured depth hoar thermal conductivity as 0.25 W m⁻¹K⁻¹. Since this uncertainty is of an order of magnitude, the extent of influence of depth hoar on the thermal resistance of the snow pack is not precisely defined, but if the depth hoar had metamorphized to stage 4 then it is likely significant. If the thermal conductivity measurements from Sturm and Johnson (1992) are accurate, then numerical simulations from Zhang et al. (1996) suggest that a reduction in the depth hoar fraction of a tundra snowpack from 0.6 to 0 may reduce mean annual ground surface temperatures by 5.5 °C, and expedite active-layer freeze-up by several months.

2.10 Research on snowpack compaction

No research has been published detailing the results of field studies testing the effects of snow compaction on ground temperatures along linear infrastructure. Snow compaction was simulated numerically by O’Neill and Burn (2017), who found that reducing the depth of the snowpack and increasing its density caused a reduction in mean ground temperatures of up to 4.4 °C. Malenfant-Lepage et al. (2012) tested the thermal effects of snow removal on a highway embankment, and found that the heat balance of the embankment was similar to that of the reference site, although this result may have been influenced by groundwater flowing underneath the embankment. At the same site, the thermal effects of a shed that was constructed to limit snow accumulation and shade the ground indicated it was among the most effective techniques at ground cooling.
Barón Hernández et al. (2019) constructed an embankment with a gentle slope which limited snow accumulation, and it outperformed both ACE and heat drains in reducing ground temperatures, causing 4.5 m of permafrost aggradation. In northern Japan, snow plowing (yukiwari) is a technique used for agricultural purposes to prevent the growth of unharvested potato crops as weeds by increasing frost depths. Shinoda et al. (2015) tested snow compaction as a method of controlling frost depths more precisely. Snow depths were reduced from about 50 – 60 cm to about 20 – 30 cm by driving over the snow with a tractor, and snow density was increased from 200 to 600 kg m\(^{-3}\). Frost penetration reached over 50 cm at a site that was compacted eight times, while only reaching 4 cm at an undisturbed site. Snow depths less than 20 cm were observed to cause an increase in frost depth (Shinoda et al. 2015).

The variability in the thermal response of the ground to snow manipulation experiments is high due to the influence of the timing of the experiment as well as changes in vegetation and soil moisture conditions caused by the manipulation (Rixen et al., 2022).

### 2.11 Summary

The intent of compacting the snowpack over a highway embankment shoulder is to increase heat extraction in winter, thereby raising \( n_c \), so that temperatures at the surface of the shoulder will be more closely coupled with air temperatures. Heat transfer through the snowpack is complex, and includes conductive, sensible, and latent heat fluxes, with radiative heat transfer at the snow surface. Compaction will modify each form of heat transfer to some degree, but, typically, heat flow through the snow is dominated by conduction, and the thermal conductivity of the snowpack will increase as snow depth is reduced, and density increased.
The effectiveness of the compaction treatment will depend on the initial depth, density and structure of the snowpack. Density is of particular importance, as it is highly correlated with the compressive strength of the snow (Perla and Martinelli, 1976). Following compaction, increased contact points between snow grains may promote equitemperature metamorphism, causing further increases in density over time. In regions where the snowpack is exposed to high temperature gradients, a depth hoar layer might form, which has a low-density structure with high thermal resistance (Sturm and Johnson, 1992; Zhang et al., 1996). Due to these properties, compaction of depth hoar may cause a large reduction in overall snowpack thermal resistance.
Chapter 3: Study area and methodology

3.1 Introduction

Field experiments were conducted to examine how compaction of a snowpack modifies its insulative properties and, hence, ground surface temperatures. The experiments took place at five locations beside roads in central Yukon to test these effects under a variety of conditions. One of the field sites was at km 96 of the southern Dempster Highway (Yukon Highway 5). Two were along the Silver Trail (Yukon Highway 11), and two were along the South McQuesten Road, with less traffic and snow clearance than the other sites (Fig. 3.1). At each site, data were collected on snowpack properties and ground surface temperatures. This chapter describes the location, physiography, regional climate, and local characteristics of the field sites. It then describes site selection, the snowpack compaction schedule that was followed, and measurement of ground temperatures and snowpack properties.

3.2 Regional setting

The Dempster Highway site is in the Blackstone Uplands of Ogilvie Mountains. It is at the southern edge of the Taiga Cordillera ecozone, above tree line. The elevation of the site is 1107 m. The site is in the highway Right-of-Way through Tombstone Territorial Park, 87 km northeast of Dawson City, YT. Vegetation in the valley floor is dominated by shrubs including shrub birch (Betula nana), willows (Salix arctica), Labrador tea (Rhododendron tomentosum), horsetail (Equisetum), and blueberries (Vaccinium uliginosum) (Wahl et al., 1987).

The Silver Trail and South McQuesten field sites are located within 35 km of Mayo, YT, and lie in valleys incised in Stewart Plateau (Wahl et al., 1987). This region consists of rounded, flattish hills separated by broad river valleys. The sites are below tree line and have vegetation
Figure 3.1: Location of study areas and field sites in central Yukon.
characteristic of the Boreal Cordillera ecozone, dominated by closed canopy boreal forest, commonly interspersed with wetlands (O'Donoghue, 2006). The elevations of the field sites are between 530 m and 736 m.

3.2.1 Climate
Temperatures in central Yukon are highly variable depending spatially on elevation and temporally on season (Burn, 2006a). Overall, the climate of the region is Subarctic continental (Wahl et al., 1987), characterized by long, cold winters and short, warm summers. Precipitation is limited in central Yukon due to the St. Elias – Coast Mountains reducing the saturation of air masses arriving from the Pacific Ocean by acting as an orographic barrier (Wahl et al., 1987).

The Dempster Highway site is situated within the Ogilvie-Mackenzie Mountains climatic zone. Temperatures vary considerably with elevation in this area. Winter inversions often develop in mountain valleys, which can result in temperatures as low as -40 to -50 °C (Wahl et al., 1987). Precipitation is typically higher throughout the mountains than at lower elevations in central Yukon. The closest climate station to the Dempster site is the Klondike Maintenance Camp (Fig. 3.2a), at km 65 on the southern Dempster Highway, 31 km south of the field site, and 150 m lower in elevation. The camp is close to, but below treeline, while the field sites are in tundra.

Climate data were recorded at the camp from 1966-2010, although there are large periods of missing data throughout this record. Only sporadic months of data are available from 2007 onward, and 2003 is missing 265 days. To avoid these years, a reference period of 1992-2002 was selected to estimate average temperature and precipitation conditions in the area, as this was the most recent period with mostly complete data. On average, there were 43 days missing during these years, with a maximum of 95 days in 1992 and a minimum of 9 days in 1997 and
Figure 3.2a: Mean monthly temperature and precipitation (1992-2002) at Klondike Maintenance Camp, (64.45°N, 138.22° W). The mean annual temperature was -5.3 °C, and the mean annual precipitation was 466 mm. Data from Environment and Climate Change Canada (Climate ID: 2100679).

Figure 3.2b: Mean monthly temperature and precipitation (1992-2002) for Mayo Airport, YT (63.62°N, 135.87° W). The mean annual temperature was -2.1 °C, and the mean annual precipitation was 301 mm. Data from Environment and Climate Change Canada (Climate ID: 2100702).
The most recent long-term air temperature records available near the study site are from Chapman Lake Airstrip, at km 124 of the Dempster Highway. Chapman Lake Airstrip is located within the same mountain valley as the study site, at a similar elevation. Air temperatures for 2014-18 were collected by Stockton et al. (2019). In 2018-21 air temperatures were compiled by Yukon Highways and Public Works. The mean temperature from 2014-21 was -6.7 °C.

The climate station closest to the study site with data available from both 1992-2002 and 2014-21 is at Dawson City Airport (Climate ID: 2100LRP). Here, the mean temperature from 1992-2002 was -3.8 °C, while from 2014-21 it was -3.2 °C, an increase of 0.6 °C. Because Dawson City is only 87 km away from the study site, mean temperatures at the site may have experienced a similar increase of about 0.5-1 °C between the 1992-2002 reference period and when the study took place. If the Klondike Maintenance Camp did experience the same amount of warming, the 1992-2002 mean temperature of -5.3 °C at Klondike Maintenance Camp, and the 2014-2021 average temperature of -6.7 °C at km 124 suggest that average temperatures at the camp are about 2 °C higher than those at km 124 and at the study site, due to the lower elevation.

Mayo is situated within the central Yukon basin climatic zone on the floor of Stewart River valley (Wahl et al., 1987). The low seasonal solar radiation often leads to the development of temperature inversions during winter. For direct comparison with Klondike Camp, the seasonal climate variation at the Mayo sites is represented by 1992-2002 temperature and precipitation averages observed at Mayo Airport (Fig. 3.2b). The Mayo Airport climate records had no missing data during this period. Mean annual air temperature in 1992-2002 was -2.1 °C, and mean total annual precipitation was 301 mm. Mayo Airport is 33 km south of the furthest study site on South McQuesten Road. Despite the close proximity to the study sites, winter
temperatures may be lower at the airport due to deeper inversions. Mean air temperature in 2014 – 21 at Mayo was -1.7 °C (T.S. Andersen, personal communication, 2022).

The 1992 – 2002 period at Mayo Airport had conditions typical of the 1991 – 2020 climate normal (Table 3.1). The overall difference in mean daily temperature was less than 0.1 °C, both overall and during the winter (Nov-Apr). No climate normal data were available for the Klondike Maintenance Camp, however, mean daily temperatures during the 1992 – 2002 period were highly correlated ($R^2 = 0.91$) with the 1992 – 2002 period from Mayo Airport. Therefore, it is likely that the 1992 – 2002 period represented typical conditions at the maintenance camp as well.

The mean daily temperature at Mayo Airport in 1992-2002 ranged from 17 °C in July to -31 °C in January. This variation is greater than at the Klondike Maintenance Camp, where the range was from 13.5 °C to -24 °C. Precipitation was significantly lower at Mayo Airport than at Klondike Camp throughout the year. In Mayo the average date of the first snow fall was October 1st, while the average date of the last snow fall was April 19th. The mean maximum snow depth was 42 cm, on February 21st. At Klondike Maintenance Camp, the average date of first and last snow fall were September 25th and May 11th, respectively, and mean maximum snow depth was 71 cm, on February 26th.

3.2.2 Study period weather

Yukon Highways operate a road camera at km 97.1 of the Dempster Highway, with air temperatures monitored at the same site. Fig 3.3a shows mean daily air temperatures from km 97.1 from December 4th, 2020 to April 25th, 2021, and mean daily air temperatures during the same period from the 1992-2002 climate record at Klondike Maintenance Camp. Historical air temperatures are not available at Klondike camp after 2010. Fig 3.3b shows mean daily air
Table 3.1: Mayo Airport average monthly temperatures during 1992-2002 reference period (Environment and Climate Change Canada, 2022) and 1991-2020 climate normal (T.S. Andersen, personal communication, Feb 17, 2022)

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<td>Nov</td>
<td>-15.7</td>
<td>-13.9</td>
<td>-1.8</td>
</tr>
<tr>
<td>Dec</td>
<td>-19.9</td>
<td>-19.7</td>
<td>-0.2</td>
</tr>
<tr>
<td>Annual</td>
<td>-2.26</td>
<td>-2.20</td>
<td>-0.06</td>
</tr>
</tbody>
</table>
Figure 3.3a: Daily mean temperatures during the study period, December 4th, 2020, to April 25th, 2021 at km 97.1 of the south Dempster Highway (Yukon Highways Transport and Engineering Branch, 2021), and between the same dates for 1992-2002 at Klondike Maintenance Camp (Environment and Climate Change Canada, 2022).

Figure 3.3b: Daily mean temperatures at Mayo A during the study period, November 29th, 2020, to April 21st, 2021 and for the same dates from the 1992-2002 climate mean (Environment and Climate Change Canada, 2022).
temperatures during the study period at Mayo Airport, and mean daily temperatures from the 1992-2002 climate record. The mean temperature of -18.1 °C during the study period at km 97.1 was significantly lower than the Klondike Camp average of -15.2 °C, and about the same as the mean temperature at Dawson City, -18.3 °C. The climate normal for this period in 1981 – 2001 was -16.5 °C, slightly higher than the study period. Early in the study period daily mean temperatures were generally the same or higher than at Klondike Camp, indicating relatively warm weather for the area. On January 25th air temperatures dropped from -14 °C to -30 °C. After this, temperatures remained generally lower at km 97.1 for the remainder of the study (Fig 3.3a). The standard deviation of daily temperature was 10.3 °C, slightly above the standard deviation of 9.0 °C from 1992 – 2002. The minimum temperature of -44.5 °C was lower than any temperature recorded during the 1992 – 2002 reference period.

The mean temperature during the study period at Mayo Airport was -15.5 °C, slightly lower than the mean of -13.5 °C during 1992 – 2002. As on the Dempster Highway, temperatures were higher than average until late January, when temperatures declined from – 4.1 °C on January 19th to -37 °C on January 28th. The standard deviation of daily temperature during the study period was 10.3 °C, slightly lower than the standard deviation of 12.7 °C from 1992 – 2002.

Precipitation recorded at Mayo Airport from when the temperature loggers were activated on November 28, 2020, until April 12th, 2021, was 72 mm. During the same period from 1992-02 mean precipitation was 75 mm. Only total precipitation was available, so data after April 12th, when mean daily temperatures first rose above 0 °C, were excluded so that rainfall would not be counted. Because no precipitation data were available near the Dempster Highway study site during the study period, there is insufficient information to determine directly whether conditions were typical for the area.
However, snow depth data are available at Klondike Maintenance Camp for the 1992–2002 reference period. Snow depth measurements at km 96 were collected in a roadside ditch, causing the expected depths to be greater than in undisturbed terrain. The maximum snow depths at the camp ranged from 53 cm to 89 cm, with a mean value of 72 cm. The maximum snow depths recorded at plots that were left undisturbed during this study ranged from 73 cm to 110 cm, with a mean value of 92 cm. While the snow depth at the study site was significantly higher, this is to be expected given the lack of tree cover, the added depth of the ditch, and snow from road clearance.

3.2.3 Surficial geology

Mayo is located within the Selwyn Basin, a geological region consisting mostly of Paleozoic schist, shale and chert (Roots, 2006). The Blackstone Uplands are located on the Mackenzie Platform, underlain by the Cordilleran Foreland Fold and Thrust Belt (Wahl et al., 1987). Both the Mayo area and the Blackstone Uplands underwent valley glaciation during the Wisconsinan period (Duk-Rodkin, 1999; Burn, 2006a). As a result, the valley bottoms near Mayo are mostly covered in a layer of glacial till or alluvium, and valleys in the Blackstone Uplands are covered with a layer of till and colluvial deposits (Burn, 2006a; Grinter et al., 2018). These types of soil are susceptible to the development of segregated ground ice, which has been found at both locations (Burn, 2006c; Grinter et al., 2018). Gravel pits adjacent to the Dempster Highway were used to gather glacial and glaciofluvial sediments for the embankment’s construction. The nearest of these pits is about 3 km north of the study site.

3.2.4 Permafrost distribution

Between 50% and 90% of central Yukon is underlain by permafrost (Heginbottom et al., 1995). In regions with discontinuous permafrost, local distribution of permafrost depends on site
specific factors that control the flow of heat at or near the ground surface (Smith and
Riseborough, 2002). These factors include snow cover, vegetation, moisture content, zenith
angle, and the thermal properties of the soil. In Mayo, snow cover was found to have a
significant influence on surface temperatures (Karunaratne and Burn, 2004), making permafrost
less likely to form in areas where deep snowpacks develop. During the summer, the presence of
organic soil provides sufficient insulation that commonly leads to the preservation of permafrost
(Williams and Burn, 1996). Where permafrost is present near Mayo, the active layer depth is
typically between 65 cm and 1 m (Burn, 2006d). Permafrost thickness of up to 40 m has been
measured in valleys, and up to 135 m at higher elevations (Burn, 1991).

The Blackstone Uplands are on the boundary between continuous and extensive
discontinuous permafrost, indicating that permafrost underlies around 90% of the region
(Heginbottom et al., 1995). The mountain valley where the study site is located contains
extensive ice rich permafrost to depths greater than 8 m (Pollard and French, 1984). Active layer
depth in the area typically ranges from 0.5 m to 1 m in mineral soil, but is much shallower in soil
covered by an organic layer (Grinter et al., 2018). Average temperatures recorded at the top of
permafrost at Chapman Lake Airstrip, located 28 km north of the Dempster Highway study site,
were between -0.9 °C and -1.6 °C in 2014-18 (Stockton et al., 2019). In 1983, ground
temperatures near the study site were estimated as being between -2 °C and -8 °C (Pollard and
French, 1984). Geomorphic features indicating the presence of permafrost including thaw
slumps, ice wedges, and solifluction lobes on hillslopes can be found throughout the Blackstone
Uplands (Grinter et al., 2018).
3.3 Study design and site conditions

Snow compaction may offer a technique for northern road maintenance agencies to reduce ground temperatures in areas with ice-rich permafrost, thereby reducing or mitigating the risks of subsidence. On the Dempster Highway, permafrost degradation has increased maintenance costs and may threaten road stability (Doré et al., 2016). Measurements from several sites along the highway show that ground temperatures are consistently higher at the embankment toe, where deep snowbanks accumulate during the winter and insulate the ground (Stockton et al., 2019). Numerical simulations based on conditions at Peel Plateau, NT, suggest that compaction of the snowpack may reduce this warming (O’Neill and Burn, 2017).

For this study, field experiments were conducted to test the effectiveness of this technique. Ten adjacent 5 m by 50 m plots were delineated at the Dempster Highway site using wooden stakes. Every month from December to April, some plots were compacted by a Lands Guardian from the Na-Cha Nyâk Dun First Nation (NND) using a snowmobile (Table 1.1), while the others were left undisturbed. Five of the plots were untreated throughout the winter as control sites. The timing and frequency of compaction varied between the other plots to determine the effect on ground surface temperatures.

In addition to the field sites along the Dempster Highway, four additional sites were established along roads near Mayo. Each of these sites had two adjacent 5 m by 50 m plots, one of which was compacted monthly, while the other remained undisturbed. These sites were chosen to test the efficacy of snowpack compaction under a wide range of conditions.

3.3.1 Site selection

Site selection did not occur until late November as a result of delays due to the COVID-19 pandemic. By that time snow had already accumulated throughout central Yukon, making it
difficult to evaluate vegetation, topography, and drainage conditions during site selection. Despite this challenge, field sites were identified with help from NND Land Guardians Blaine Peter, Lawrence David McLaren, and Gary Hope near Mayo, and permafrost researchers Fabrice Calmels and Louis-Phillipe Roy on the Dempster Highway, all of whom have extensive local knowledge of the areas. The Dempster Highway field site was selected along a straight, flat stretch of road with low lying vegetation on either side (Fig. 3.4a).

The site within the Blackstone River valley corridor is approximately 250 m west of the Blackstone River at its nearest point. It was chosen because there was sufficient space for all field plots to be set up adjacent to each other on the same side of the road. With this configuration the plots have similar topography and vegetation regimes as well as similar wind and road clearance conditions. Using a handheld GPS, the length of the embankment where vegetation rising out of the snow and topographic conditions appeared to be most homogenous was measured at approximately 650 m long (Fig. 3.4b). This length was divided into twelve 50 m sections, two of which were omitted from the study due to the presence of culverts. Snow was not pushed on to the plots in most cases, but some spillover was observed throughout the study at the three southernmost plots, DU1, DC1 and DU2.

The four field sites near Mayo were set up to test how a variety of roadside conditions may affect snowpack development and compaction (Fig. 3.5). M1 was located adjacent to the Silver Trail, west of Mayo. It is the most heavily trafficked of the field sites and is plowed often. M2 was also located adjacent to the Silver Trail, but north of Mayo. This area has less traffic than at M1 but is also plowed often. The growth of stunted spruce trees here indicates the presence of permafrost. M3 and M4 were set up alongside South McQuesten road. This road receives significantly less traffic than the Silver Trail, and is plowed less frequently. M3 was
Figure 3.4 a) Southwards view of the Dempster Highway field site near km 96 (64.68°N, 138.40°W), taken on December 1st, 2020, before the test plots were established on the west side of the road. (b) Ten 50 m by 5 m field plots at the site. DC1 was compacted monthly, DC2 bi-monthly, DC3 only once during the middle of the winter, DC4 during the first three months, and DC5 during the last three months. All of the plots labelled DU were left undisturbed to establish baseline site conditions. The sections between DC2 and DU3, and between DU4 and DC4 were left unused due to the presence of culverts in these sections.
Figure 3.5: Study sites near Mayo taken on November 27\textsuperscript{th}, before the first snowpack compaction on November 29th, 2020.
located in forest about 3 km from the junction with the Silver Trail, while M4 is located a further
3 km from the junction within coniferous forest that had recently been burned.

3.3.2 Topography

At the study site, the Dempster Highway is positioned along a gentle slope decreasing in
elevation from west to east in the floor of Blackstone River valley. The land is generally flat on
the west side of the road where the study plots were located (Fig. 3.6). The ditch was about 1 m
deep, about 6 m from the toe of the embankment. The Mayo field sites were also mostly flat,
with the exception of M2 (Fig. 3.7). The M1 and M3 sites both had a shallow ditch with a depth
of about 50 cm located 5 m from the edge of the road, while M4 had no ditch and rose slightly
near the edge of the road. The compacted plot at M2 had a larger drop of about 120 cm with a
bottom about 11 m from the road. The undisturbed plot could not be measured as it had a similar
drop off, but into flooded, swampy terrain at the bottom.

3.3.3 Saturation

3.3.3.1 Dempster Highway km 96 site

Localized wetlands are common in valley floors of central Yukon. Permafrost inhibits drainage,
forcing groundwater to flow within the active layer towards lower elevations (Wahl et al., 1987).
The poor drainage in valley floors near the Dempster Highway study site leads to development
of frost blisters (Pollard and French, 1984).

The study site itself lies between the Surfbird Mountain range to the west, and Blackstone
River to the east (Fig. 3.4a). Despite two culverts in the study section (Fig. 3.4b), the field plots
were mostly saturated during inspection on June 2\textsuperscript{nd}, 2021 (Table 3.2a). It was raining
periodically during the inspection, and the snow at the sites had only melted recently as some
patches were still present within nearby depressions.
Figure 3.6: Elevation measured every metre from the edge of the driving surface of the Dempster Highway at four points located at the northern edge of the four northernmost test plots (5x vertical exaggeration). The red points were from the northernmost plot, DC5, while the green, blue and yellow points were measured to the south, at DU5, DC4 and DU4 respectively.
Figure 3.7: Elevation measured every 10 m from the northernmost edge of the test sites near Mayo (5x vertical exaggeration). The dotted line indicates the undisturbed plot while the solid line indicates the compacted plot. The topography at MU2 could not be measured due to flooding.
Table 3.2a: Qualitative soil surface moisture conditions observed at the Dempster Highway field plots during site inspection on June 2\textsuperscript{nd}, 2021.

<table>
<thead>
<tr>
<th>DC1</th>
<th>DU1</th>
<th>DC2</th>
<th>DU2</th>
<th>DC3</th>
<th>DU3</th>
<th>DC4</th>
<th>DU4</th>
<th>DC5</th>
<th>DU5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial Flooding</td>
<td>Partial Flooding</td>
<td>Partial Flooding</td>
<td>Mostly Flooded</td>
<td>Partial Flooding</td>
<td>Partial Flooding</td>
<td>Damp</td>
<td>Damp</td>
<td>Damp</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.2b: Qualitative soil surface moisture conditions observed at the Mayo field plots during site inspection on June 4\textsuperscript{th}, 2021.

<table>
<thead>
<tr>
<th>MU1</th>
<th>MC1</th>
<th>MU2</th>
<th>MC2</th>
<th>MU3</th>
<th>MC3</th>
<th>MU4</th>
<th>MC4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>Dry</td>
<td>Mostly Flooded</td>
<td>Partial Flooding</td>
<td>Dry</td>
<td>Dry</td>
<td>Dry</td>
<td>Dry</td>
</tr>
</tbody>
</table>
3.3.3.2 Mayo sites

Saturation conditions during inspections of the field sites near Mayo on June 4th, 2021, are shown in Table 3.2b. The weather was clear during inspections, and the only wet site was M2, at Halfway Lakes. This site was located at the edge of a flooded wetland environment, commonly found near low-lying lakes in the area (O’Donoghue, 2006). The undisturbed plot was mostly submerged beyond the embankment, while the compacted plot was partially flooded towards the south side, but rose out of the wetland terrain and was mostly dry on the north side.

3.3.4 Vegetation

3.3.4.1 Dempster Highway km 96 site

The Dempster Highway site was located above treeline in alpine tundra (Fig. 3.4a). The road stretched along a gently sloping mountain valley where drainage was poor due to the presence of permafrost. In this environment, sedge tussocks (*Carex stricta*) along with small shrubs including Labrador tea (*Rhododendrom tomentosum*) and shrub birch (*Betula nana*) typically dominate the vegetation (Yukon Ecoregions Working Group 2004). Shrubs grow largest directly beside the highway embankment. Beyond the edge of the embankment, the plots were filled with sedge tussocks separated by grasses and moss. The vegetation distribution at each plot is summarized in Table 3.3a.

3.3.4.2 Mayo Sites

All four of the sites near Mayo (Fig. 3.8) were located along roads within heavily forested lowland valleys, mostly dominated by white (*Picea glauca*) and black spruce (*Picea mariana*). Vegetation conditions at the sites are summarized in Table 3.3b. At M1 the field plots were mostly covered with a mix of low-lying grasses, kinnikinnick (*Arctostaphylos uva-ursi*), and
Table 3.3a: Vegetation distribution at the Dempster Highway field plots. Vegetation cover of less than 100% indicates the presence of gravel from the highway embankment on the plot. The average shrub coverage was 37%, grass 19%, moss 24% and tussock 15%.

<table>
<thead>
<tr>
<th>Vegetation Type</th>
<th>DU1</th>
<th>DC1</th>
<th>DU2</th>
<th>DC2</th>
<th>DU3</th>
<th>DC3</th>
<th>DU4</th>
<th>DC4</th>
<th>DU5</th>
<th>DC5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shrub</td>
<td>40%</td>
<td>30%</td>
<td>55%</td>
<td>45%</td>
<td>25%</td>
<td>30%</td>
<td>20%</td>
<td>35%</td>
<td>35%</td>
<td>50%</td>
</tr>
<tr>
<td>Grass</td>
<td>15%</td>
<td>60%</td>
<td>30%</td>
<td>20%</td>
<td>5%</td>
<td>30%</td>
<td>1%</td>
<td>15%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>Moss</td>
<td>30%</td>
<td>5%</td>
<td>5%</td>
<td>30%</td>
<td>68%</td>
<td>27%</td>
<td>20%</td>
<td>20%</td>
<td>15%</td>
<td>15%</td>
</tr>
<tr>
<td>Tussock</td>
<td>15%</td>
<td>5%</td>
<td>10%</td>
<td>5%</td>
<td>2%</td>
<td>3%</td>
<td>5%</td>
<td>20%</td>
<td>20%</td>
<td>15%</td>
</tr>
</tbody>
</table>

Table 3.3b: Estimated vegetation coverage based on visual observation at field plots near Mayo, YT. A lack of vegetation indicates bare soil or gravel. Vegetation coverage between sites was too varied for average values to be meaningful.

<table>
<thead>
<tr>
<th>Vegetation Type</th>
<th>MU1</th>
<th>MC1</th>
<th>MU2</th>
<th>MC2</th>
<th>MU3</th>
<th>MC3</th>
<th>MU4</th>
<th>MC4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium shrubs</td>
<td>5%</td>
<td>15%</td>
<td>40%</td>
<td>30%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small shrubs</td>
<td>1%</td>
<td>1%</td>
<td>20%</td>
<td>20%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Undergrowth</td>
<td>30%</td>
<td>35%</td>
<td>0%</td>
<td>30%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grass</td>
<td>65%</td>
<td>50%</td>
<td>40%</td>
<td>20%</td>
<td>10%</td>
<td>10%</td>
<td>15%</td>
<td>5%</td>
</tr>
</tbody>
</table>
Figure 3.8: Photos of Mayo area study site locations taken during site inspections on June 4th, 2021
sparse shrubs. Beyond the cleared area adjacent to the road, there is a thin cover of larger shrubs separating a second clearing beneath a power line. On the other side of this path is coniferous forest interspersed with aspen trees (*Populus tremuloides*).

M2 was located within mostly saturated, swampy terrain. This environment is common next to low-lying lake shores near Mayo (O’Donoghue, 2006). Most of the undisturbed plot was flooded upon site inspection on June 4th, 2021, due to recent snow melt. The site supported willows and dwarf shrubs along with some tall grasses. The compacted plot was much drier and contained a higher proportion of grasses. The embankment was steep throughout this site, and a layer of taller shrubs and weeds grew at its edge along both plots. At the compacted plot, large vegetation was cleared within 10 m of the road embankment, and beyond this point the vegetation was dominated by spruce trees with a ground cover of mosses. At the compacted plot the swampy vegetation extended about 30 m from the road before reaching similar ground cover.

M3 and M4 were located about three kilometres apart on the South McQuesten road within a dense black spruce forest. The forest around the site near M4 was burned the previous year, while the forest at M3 was undisturbed. Vegetation within 20 m of the embankment had been cleared from both sites, leaving behind mostly bare ground interspersed with small shrubs at the fire disturbance site, and a mix of gravel and grasses at the undisturbed forest site.

### 3.3.5 Wind conditions

#### 3.3.5.1 Dempster Highway km 96 site

Wind speeds of at least 8 – 10 m s⁻¹ (29 – 36 km h⁻¹) are required to transport snow (Li and Pomeroy, 1997). When wind speeds are consistently above this threshold, the snowpack will become wind packed, increasing its hardness and density. The nearest available wind data for the
Dempster Highway site are from km 80 and km 124, where hourly average wind speed and
direction were recorded throughout the study period by Yukon Highways & Public Works (Fig.
3.9). At km 124, the average hourly was wind speed was 1.85 m s\(^{-1}\) (6.7 km h\(^{-1}\)), and the
maximum was 14.28 m s\(^{-1}\) (51 km h\(^{-1}\)), recorded on April 5\(^{th}\). The winds were typically south-
westerly or north- easterly, funneled through the valley by the surrounding mountains. At km 80,
winds speeds were generally faster, averaging 3 m s\(^{-1}\) (11 km h\(^{-1}\)), however the maximum speed
of 9.39 m s\(^{-1}\) (34 km h\(^{-1}\)) was lower. Due to the orientation of the valley, the winds were funneled
through the valley at this location from the south-east and north-west.

The average hourly wind speeds suggest that winds only infrequently reached the 8 – 10
m s\(^{-1}\) (29 – 36 km h\(^{-1}\)) threshold required for snow transport, but observations suggest that the
speed of wind gusts at the field site was considerably higher. Wind speeds are reported as an
average of measurements in the last 10 minutes of each hour. As a result, gusts are commonly
missed. The force of the winds could often be felt in the vehicle used for field work, which is
consistent with the description of a near gale, where wind speeds reach 13.9 – 17.1 m s\(^{-1}\) (50 – 61
km h\(^{-1}\)) (Barua, 2019). On windy days there was noticeable resistance when walking against the
wind, loose objects would risk blowing away, and vehicle doors would be blown shut. This
suggests that wind gusts may have approached 17.1 – 20.7 m s\(^{-1}\) (61 – 75 km h\(^{-1}\)), where it
becomes difficult to walk against the wind. The hourly average speed may not have captured the
speed of wind gusts, which occur more briefly. Based on these observations, the hard and wind-
packed snow may be a result of wind speeds at the study site above 8 – 10 m s\(^{-1}\).

3.3.5.2 Mayo

The nearest available wind data to the Mayo study sites are from Mayo Airport, located 33 km
away from M4. Hourly average wind speed and direction are displayed in Fig. 3.10. The average
Figure 3.9: Average hourly wind speed and direction recorded by Yukon Highways and Public Works during the study period from December 4th, 2020 to April 28th, 2021 at (a) Dempster Highway km 124 (Chapman Lake) and (b) Dempster Highway km 80, with wind speeds under 0.5 m s⁻¹ excluded. Wind speeds are categorized by the Beaufort Wind Scale (Barua 2019): light air flow (0.2 – 1.5 m s⁻¹), slight breeze (1.5 – 3.3 m s⁻¹), gentle breeze (3.3 – 5.4 m s⁻¹), moderate breeze (5.4 – 7.9 m s⁻¹), fresh breeze (7.9 – 10.7 m s⁻¹), and strong breeze (10.8 – 13.8 m s⁻¹).
Figure 3.10: Average hourly wind speed and direction during the study period from November 29th, 2020 to April 21st, 2021 at Mayo Airport (Yukon Highways and Public Works, 2022). Wind speeds are categorized by the Beaufort Wind Scale (Barua, 2019): light air flow (0.2 – 1.5 m s⁻¹), slight breeze (1.5 – 3.3 m s⁻¹), gentle breeze (3.3 – 5.4 m s⁻¹), moderate breeze (5.4 – 7.9 m s⁻¹).
hourly wind speed was 0.82 m s\(^{-1}\) (3 km h\(^{-1}\)), while the maximum was 5.95 m s\(^{-1}\) (21.4 km h\(^{-1}\)). The conditions were typically calm, with wind rarely surpassing a light breeze. This matches field observations, where the wind was rarely noticeable. Wind speeds high enough for significant snow transport were rare, and as a result the snow at the Mayo field sites was far softer and lighter than the snow at the Dempster Highway site. Wind direction varied considerably, but was predominantly from the west.

### 3.4 Field methods

#### 3.4.1 Snowpack compaction

Snow compaction was carried out by Land Guardians from the First Nation of Na-Cho Nyäk Dun using snowmobiles. They operated in teams of two, and drove over the snow repeatedly in opposite directions, using the ends of the plot to turn. This process would continue until the entire plot was compacted enough that subsequent runs did not reduce snow depth further. This would typically take 5 to 10 minutes for each plot.

The plots near Mayo were compacted on Nov 29\(^{th}\), Jan 6\(^{th}\), Feb 10\(^{th}\), and March 9\(^{th}\). By April 6\(^{th}\), the South McQuesten Road had been widened at the field sites (Fig. 3.11), and the final compaction at these sites was not completed. The Dempster Highway plots were compacted following the schedule in Table 1.1.

#### 3.4.2 Temperature sensors

Due to travel restrictions in response to the COVID-19 pandemic, arrival at the field sites was delayed until November 26\(^{th}\). This meant that installing temperature sensors within the ground was impractical, as it was already frozen and covered in deep snow that was to be disturbed as little as possible. Instead, the sensors were placed in protective casing and pushed to the bottom
Figure 3.11: The M3 and M4 sites on South McQuesten Road on April 6\textsuperscript{th}, after the road was widened, disturbing the field plots.
of the snowpack.

At the Dempster Highway sites, HOBO MX2201 pendant loggers were encased in metal pipes for protection. The snow was wind-packed, and walking on it created little disturbance. A depth probe was used to make a hole through the snow at the centre of each plot, and the sensors were pushed through it to the ground surface. The hole was then filled with snow. At the sites near Mayo, HOBO Onset H08-004-02 Loggers were encased in PVC pipe that was cut to size. Plastic caps were placed on either end, then the edges of the caps were covered by electrical tape. The snow was loose at these sites, so the sensors were placed at the bottom of the snowpack beside the plots, and then pushed into position without disturbing the snow above. The only site where this technique was not feasible was M2, where the embankment slope was too steep (Fig. 3.7). Instead, the sensors were placed by reaching over from the edge of the plot and pushing them to the bottom of the snow as near the centre of the plot as possible.

3.4.3 Snow depth probing

Snow depth was measured using a snow probe at all of the field plots in the days following compaction. Depth measurements were taken every 10 m along the length of the plots, beginning at 10 m, for a total of four measurements at each plot. The distance from the driving surface at which the measurements were taken varied between the Dempster Highway and Mayo sites. At the Dempster Highway site, the snow was strong enough to easily support the weight of a person, so measurements were taken from the centre of each plot. At the Mayo sites the snow was too soft to walk on, so measurements were taken by standing at the edge of the plot and reaching inwards as far as possible while still directing the snow probe straight downwards.

The harder snow at the Dempster Highway sites also allowed for a detailed survey of snow conditions on December 2nd, before the first compaction took place. Snow depth was
probed at 1.25 m, 2.5 m and 3.75 m along the width of the plots. The measurements were taken every 10 m along the length of the plots, beginning at 5 m, for a total of 15 measurements at each plot. This was not done at the Mayo plots to avoid disturbing the snowpack.

3.4.4 Snow pits

Snow properties for each layer of the snowpack were measured by digging snow pits. At the Mayo sites, pits were dug near each other in the compacted and undisturbed plots. At the Dempster Highway site, pits were dug at the northern end of each plot. During subsequent months the pits were dug progressively towards the centre of each plot, about 5 m apart, or however far it took to reach snow that had not been affected by digging during the previous field visit.

Snow layers were identified both visually and by feeling the texture of the snow. Once identified, they were marked using sticks and their depth was measured. The temperature was recorded for each layer using a probe thermometer. Then, 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 the standard international classification method for estimating snow hardness (Fierz et al., 2009). Density was measured by filling a 100 ml snow sampler, placing the contents into a bag, and then weighing it using a spring scale. Grain size and shape were determined visually by placing grains of snow on a piece of laminated 1 mm grid paper and observing them using a hand lens.

3.5 Summary

Mean air temperatures near the field sites during the study, -18.1 °C at km 97 of the Dempster Highway, and -15.1 °C at Mayo Airport, were slightly lower than mean temperatures from 1992-
2002, despite average regional warming of about 0.6 °C since 1992-2002. Vegetation at the Dempster Highway site was dominated by small shrubs, and without trees to break the wind, the snow was hard and wind-packed in the area. The Mayo sites were located within spruce forest. The wind was calm at each of the study sites, resulting in loose and light snow. Snow conditions were measured using monthly snow-pits at all sites, while temperatures at the ground surface beneath the snowpack were measured using loggers. The results are presented in the following chapter.
Chapter 4: Results

4.1 Introduction

This chapter presents and describes data collected at the Mayo and Dempster Highway field sites for the purpose of determining how compacting roadside snowbanks using snowmobiles modifies the structure and thermal properties of the snow, and the resulting effects on ground surface temperature. Results were obtained for wind-packed snow at the Dempster Highway site, and loose snow conditions at the Mayo sites. First, changes in snow depth are presented. Monthly data taken from snow pits are then given, including the layer structure of the snowpack and the hardness and density of each layer. Finally, temperatures from loggers that were encased in protective pipes and buried beneath the snowpack are provided.

4.2 Initial snow depth

4.2.1 Dempster Highway km 96 Site

On December 2nd, 2020, the day before the snowpack was first compacted, three snow depth measurements were taken every 10 m along the length of the field plots. The measurements were taken progressively further from the road to determine where the deepest snow drifts developed. They were taken 1.25 m, 2.5 m, and 3.75 m from the edge of the plots nearest the road. The mean snow depths from the 5 measurements at these distances for each plot are presented in Table 4.1. The deepest snow was most often found at 2.5 m, where the mean depth from all plots was 51 cm, with a standard deviation (std) of 9.6 cm. The mean snow depth at 1.25 m was slightly lower, at 49 cm, with std of 10.5 cm, but the difference in snow depths between these distances was not statistically significant (Student’s t-test with $\alpha = 0.05$). The shallowest snow was at 3.75 m, with a mean depth of 43 cm and std of 10.7 cm. The snow depths here were
Table 4.1: Mean of five snow depth measurements taken at varying distances from the road at the Dempster Highway plots on December, 2, 2020, prior to initial compaction the next day. The edge of the study plot was about 1 m from the driving surface, and temperature loggers were buried 2.5 m from the edge of the plot.

<table>
<thead>
<tr>
<th>Distance from roadside edge of plot</th>
<th>1.25 m (n = 5)</th>
<th>2.5 m (n = 5)</th>
<th>3.75 m (n = 5)</th>
<th>Mean</th>
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<tbody>
<tr>
<td>DU1</td>
<td>51.4</td>
<td>50.2</td>
<td>49.8</td>
<td>50.5</td>
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<tr>
<td>DC1</td>
<td>43.8</td>
<td>47.4</td>
<td>40.4</td>
<td>43.9</td>
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<td>DU2</td>
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<td>54.2</td>
<td>44</td>
<td>48.7</td>
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<td>45.7</td>
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<td>39.6</td>
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<td>40.2</td>
<td>42.8</td>
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<td>40.2</td>
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<td>39.9</td>
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<td>DU5</td>
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<td>63.4</td>
<td>46.2</td>
<td>54.5</td>
</tr>
<tr>
<td>DC5</td>
<td>50.4</td>
<td>54.8</td>
<td>51.6</td>
<td>52.3</td>
</tr>
<tr>
<td>Mean</td>
<td>48.7</td>
<td>50.9</td>
<td>42.6</td>
<td>47.4</td>
</tr>
</tbody>
</table>
significantly lower than at either 1.25 m or 2.5 m ($\alpha = 0.05$). The plots with the deepest average snow depth were DU5 and DC5, located at the north end of the field site. The higher snow depths here were likely due to the ditch running through the plots, along with a higher percentage of shrub coverage (Table 3.3a), creating better conditions for trapping snow.

4.2.2 Mayo Sites

The snow at the field sites near Mayo was much less dense than at the Dempster Highway and it could not support the weight of a person. To avoid disturbing the snowpack and affecting the experiment, no initial snow-depth measurements were taken before compaction took place.

4.3 Snow depth progression

4.3.1 Dempster Highway km 96 Site

Snow-depth measurements were taken 2.5 m from the edge of the study plots following compaction each month. The measurements were taken every 10 m along the length of the plots, beginning at 10 m, for a total of four measurements per plot. In December, five measurements were taken instead, beginning at 5 m and ending at 45 m. The mean snow depth of all measurements taken at the compacted plots ($n = 104$) was 61 cm, significantly lower ($\alpha = 0.05$) than the 70 cm mean snow depth at the undisturbed plots ($n= 104$).

Monthly mean snow depths at the plots are shown in Fig. 4.1. As in the initial measurements, the deepest snow at the beginning of the study period was measured at DU5, with a depth of 63 cm. By April, the undisturbed average snow depth at DU1 was greatest, at 110 cm. The greatest difference between the compacted and undisturbed plots was at D1, with monthly compaction. Here, the mean snow depth at the compacted plot was, on average, 27 cm shallower than at the undisturbed plot throughout the winter. This difference increased over time,
Figure 4.1: Mean snow depths from four measurements taken from the centre of the study plots (2.5 m) following compaction each month. The solid line indicates the plots that were compacted, while the dotted line indicates the plots that were left undisturbed. Months where compaction occurred are in red. The mean difference (cm) between compacted and undisturbed sites is given for each treatment.
beginning at 3 cm in December and reaching a maximum of 45 cm in March. At D2, with bi-monthly compaction, the compacted plot was 11.5 cm shallower than the undisturbed plot on average. The snow was initially 6 cm deeper at the compacted plot in December, but in January the snow depths were about equal, and over the remainder of the winter the undisturbed plot had deeper snow. The difference in snow depths increased steadily throughout the winter to a maximum of 30 cm in April.

At D3, with mid-winter compaction, the plots had mean snow depths within 3 cm during the first two months, before compaction took place. Following compaction in February, the compacted plot had a mean depth that was 25 cm less. This difference diminished over the following months, and the plots had mean snow depths within 3 cm in April. D4, with early compaction, had the 2nd largest difference in mean snow depth between the compacted and undisturbed plots, at 20 cm. Here, the compacted plot was 15 cm shallower after the first compaction, and remained between 15 cm and 29 cm shallower each month for the remainder of the winter. Unlike at D3, the shallower snow at the compacted plot persisted even after compaction had ceased. D5 (late compaction) had different snow conditions than the other plots, as discussed in section 4.1.1. Here, the compacted plot had deeper snow than the undisturbed plot due to the ditch and higher bushes.

In general, the undisturbed plots had snow depths near those of the compacted plots in December, but by the end of the winter they typically had accumulated about 1 m of snow, while there were about 70 cm at the compacted plots. The 45 cm difference in snow depth between DC1 and DU1 in March was 15 cm greater than any observed at the other plots throughout the study. This result suggests that increasing the frequency of compaction increases the reduction in snow depth. Because of the delayed start to the study and the differing snow
conditions at D5, which was compacted late in the winter, it is unclear whether the timing of compaction during the winter influenced the extent to which it reduced snow depths. Nevertheless, the greatest differences between compacted and uncompacted plots at the end of winter occurred where compaction was initiated early in the season.

4.3.2 Mayo Sites

As at the Dempster Highway site, snow depth was measured monthly following compaction by using a snow tube every 10 m along each plot, for a total of four measurements per plot. At the undisturbed plots, the measurements were taken by reaching over the plot from the edge of the embankment. This method allowed for sampling from about 1 - 2 m away, depending on the steepness of the embankment slope. At the compacted plots, the snow tube required more force to get through the snow, so it was used while standing directly on the snowpack at the same distance from the embankment as where the undisturbed snow was sampled. Mean snow depths are shown in Fig. 4.2. Compaction was carried out monthly at each of the Mayo sites.

The mean snow depth of all measurements taken at the compacted plots (n = 70) was 40 cm, significantly lower ($\alpha = 0.05$) than the mean snow depth at the undisturbed plots (n = 69), 71 cm. At the Dempster Highway field site, the difference was only 9 cm, much smaller than the 31 cm difference at the Mayo field sites. This is because the soft, low-density snow compressed more easily under the weight of the snowmobiles.

The site with the deepest snow was M2, where the undisturbed plot had a mean snow depth of 80 cm, and the compacted plot had 43 cm. This was likely due to this site having the steepest embankment slope, allowing for more snow to collect at its base. At M1, the undisturbed snow had a mean depth of 69 cm, while the compacted snow was 41 cm. The difference in undisturbed snow depth at M1 compared to M2 was much greater than the difference in
Figure 4.2: Mean snow depths at Mayo sites, December 2020-April 2021. The solid lines with red circles show the plots that were compacted, while the dotted lines with white circles show the plots that were left undisturbed. The mean difference between compacted and undisturbed sites is given for each site.
compacted snow depth, and this may indicate that the snow was fully compressed at this depth. Snow depth increased steadily throughout the winter at both sites, aside from a sudden drop in April at M1. It is unclear why this drop occurred only at M1, but it was consistent at both the undisturbed and compacted plots.

M3 and M4 had very similar snow conditions. The mean snow depths at the undisturbed plots were 66 and 69 cm, respectively, while at the compacted plots they were 37 and 39 cm. Snow depths at the undisturbed plots mostly levelled off following the first month, increasing by only 8 cm at MU3 and 2 cm at MU4 over the remainder of the winter. In contrast, the snow depth at the compacted plots decreased in February and March, despite the continued accumulation of snowfall. During the field visits to these sites the effects of the previous month’s compaction were clearly visible compared to the other sites. No data are reported for April due to disturbance at the sites (Fig. 3.11).

4.4 Snowpack structure

4.4.1 Dempster Highway km 96 Site

Snow pits were dug monthly at the north end of each plot to monitor how compaction modified the structure of the snowpack. New pits were dug several metres away from the previous pit to avoid including snow that had been disturbed. Snow layers were identified within the pits based on visual distinction and hardness. The average depth of accumulation of each snow type is presented in Fig. 4.3. The top of the snowpack commonly had a thin layer of loose dendritic snow. This layer was occasionally missed in the snow pits, as it was difficult to discern where it began due to disturbance from digging. There was no significant difference ($\alpha = 0.05$) in the depth of dendritic snow accumulation between the compacted and undisturbed plots, probably
Figure 4.3: Mean accumulation of snow types found within snow pits dug monthly at each of the Dempster Highway plots, five pits in total for each plot. Layers are stacked in the order of their most common positioning within the snowpack.
because the snow pits were dug one or two days after compaction, providing time for wind-blown snow to replace the compacted snow. The dendritic snow layer may have had a significant effect on ground temperatures, as dendritic snow had the second lowest density on average of all of the recorded snow types, and thus has a disproportionate influence on the insulation provided by the snowpack.

Beneath the dendritic snow, there were hard, wind-packed layers of well rounded and moderately rounded snow. These layers were intermixed, but the moderately rounded snow was more commonly found deeper in the snowpack. It contained some cup-shaped crystals along with rounded fine grains, and the snow grains were larger than the well-rounded snow. There was no significant difference ($\alpha = 0.05$) in moderately rounded snow accumulation between the undisturbed plots and compacted plots, which both had an average of 13 cm. The compacted plots had significantly more well-rounded snow ($\alpha = 0.05$), averaging 22 cm of accumulation compared to 16 cm at the undisturbed plots. The increase in well-rounded snow at the compacted plots may be due to an increased rate of snow sintering and metamorphism caused by compaction.

Beneath the wind-packed layers was snow with some angular facets, which was a mix of both smaller, rounded crystals and faceted crystals with a smaller grain size than those found in depth hoar. The undisturbed plots had a mean accumulation of 13 cm, while the compacted plots had 12 cm. The difference was not statistically significant ($\alpha = 0.05$). Depth hoar was found in 24 of 25 of the snow pits in undisturbed plots, but only 14 of the 25 snow pits in compacted plots. Overall, the undisturbed plots had 13.6 cm of depth hoar on average, while the 6.4 cm at the compacted plots was significantly less ($\alpha = 0.05$).
After the first compaction on December 5th, the undisturbed plots had a mean of 12 cm of depth hoar while the compacted plots had 9 cm. The undisturbed plots also had more snow with some angular facets, with 14 cm compared to 11 cm at the compacted plots. Over the winter the mean depth hoar at the undisturbed plots remained within 3 cm of the original 12 cm. At the compacted plots, the mean depth hoar accumulation decreased to only 4 cm, 5 cm, and 4 cm in January, February and March respectively, before increasing back to 9 cm in April, perhaps due to spatial variation in depth hoar distribution.

Snow pits with typical snow conditions after repeated compaction are shown in Fig. 4.4. The photos were taken from snow pits at the DU1 and DC1 plots the day after DC1 was compacted for the fourth time. They show layers of well-developed depth hoar in the undisturbed plot, which had an accumulation of 23 cm with crystal lengths up to 8 mm. In contrast, the compacted plot only had 10 cm of depth hoar, with a maximum crystal length of 5 mm. The thick hoar frost layers that developed at DU1 appear to have been crushed and mixed into a mostly homogenous layer with the remainder of the snowpack at DC1.

Overall, the statistically significant changes between the compacted and undisturbed plots were that the compacted plots had, on average, less depth hoar and more well-rounded snow. All five of the compacted plots had less depth hoar accumulation than the undisturbed plots, and this aligns with field observations of the depth hoar being crushed, so it appears that in an alpine tundra environment compaction causes a significant decrease in depth hoar accumulation. In contrast, the increase in well-rounded snow was only observed at DC4 and DC5. This was influenced by these plots being positioned at the north end of the field site, where a shallow ditch was present, and bush coverage was greater than at the other plots. Because of the lack of a consistent response to compaction between the different field plots, it cannot be concluded that
Figure 4.4: Images of DU1 and DC1 snow pits taken on March 13th, 2021, the day after DC1 was compacted for a fourth time. Snow layers are delineated with short sticks.
compaction causes an increase in well-rounded snow accumulation despite the significant
difference overall between compacted and undisturbed plots.

4.4.2 Mayo Sites

The depth of accumulation of different snow types near Mayo recorded within monthly snow pits is shown in Fig. 4.5. Because the plots were shielded from the wind by the surrounding forest, loose dendritic snow was able to accumulate at the top of the snowpack. At the undisturbed plots, the mean accumulation was 10 cm (n = 18), but at the compacted plots only one layer of dendritic snow was able to accumulate at the top of the snowpack, a 5 cm layer found at MC2 in February. Despite the snow crystals retaining their structure, the density of this snow layer, 300 kg m\(^{-3}\) was about twice that of the dendritic snow at the undisturbed plots, 149 kg m\(^{-3}\). Because the dendritic snow is very light and usually rests at the top of the snowpack, the snowmobiles pushed some out of the plot as they drove. Remaining dendritic snow that was caught under the treads was crushed, losing its shape and mixing in with the harder snow below. Some dendritic snow was present at the other plots, but only in small volumes, usually between snowmobile tread marks, rather than in a continuous layer. The M2 field plots had a steeper embankment than the other field plots (Fig. 3.8), and the deepest snow (Fig. 4.2).

Along with having less dendritic snow, the average thickness of depth hoar at the compacted plots was also much lower. During the first month, a mean of 5.6 cm of depth hoar remained at three of the four compacted plots. After January, no further depth hoar development was recorded at the compacted plots for the remainder of the study, as the depth hoar was mixed in with the overlying snow layers. As a result, the structure of the snowpack became more homogenous (Fig. 4.6). In contrast, depth hoar was recorded at 15 of the 18 snow pits in undisturbed plots, and the mean thickness was 12 cm. There was also significantly less snow (\(\alpha\)
Figure 4.5: Mean accumulation of snow types found within snow pits dug monthly at each of the Mayo plots, five pits in total for each plot. Layers are stacked in the order of their most common positioning within the snowpack.
Figure 4.6: Images of undisturbed (top) and compacted (bottom) snow pits dug the day following compaction. M1 images taken on January 5\textsuperscript{th}, following the second compaction, M2 images taken on April 7\textsuperscript{th}, following the fifth compaction, M3 and M4 images taken on March 10\textsuperscript{th}, following the fourth compaction.
= 0.05) with some angular facets at the compacted plots, with a mean of 7 cm of accumulation compared to 17 cm at the undisturbed plots.

The undisturbed plots had a mean accumulation of 11 cm of moderately rounded snow, while the mean accumulation at the compacted plots was 9 cm. Calculation of mean accumulation at the compacted plots was heavily influenced by one outlier layer that was 41 cm thick at MC3 in April. Removing this layer, the mean was only 7.6 cm. Nevertheless, the difference between compacted and undisturbed plots was not significant (α = 0.05). The only type of snow which had greater accumulation at the compacted plots was well-rounded snow, with a mean of 17.6 cm compared to 13.6 cm at the undisturbed plots. This difference was also not significant (α = 0.05).

4.5 Snow physical properties

4.5.1 Dempster Highway km 96 Site

Snow grain shape and size along with density and hardness were measured at each layer identified within the snow pits. Mean values are displayed in Table 4.2. Grain size was measured by observing samples using a hand lens. Depth hoar was the only snow type that had a statistically lower (α = 0.05) mean grain size at the compacted plots, with 4 mm at the undisturbed plots and 3.5 mm at the compacted plot. This may be due to the large crystals breaking apart from the pressure caused by compaction. Well rounded snow was the only type which had significantly larger mean grain sizes at the compacted plots, with 1.3 mm compared to 0.9 mm at the undisturbed plots (α = 0.05). This increase may be due to pressure from compaction promoting equitemperature metamorphism. Moderately rounded snow had no significant change in grain size (α = 0.05). It was usually deeper in the snowpack than the
Table 4.2: Mean physical properties of snow types from five monthly snow pits at Dempster Highway site

<table>
<thead>
<tr>
<th>Snow Type</th>
<th>DU1</th>
<th>DC1 (compacted monthly)</th>
<th>DU2</th>
<th>DC2 (compacted bi-monthly)</th>
<th>DU3</th>
<th>DC3 (single compaction)</th>
<th>DU4</th>
<th>DC4 (early compaction)</th>
<th>DU5</th>
<th>DC5 (late compaction)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thickness (cm)</td>
<td>Hardness</td>
<td>Density (kg m(^{-3}))</td>
<td>Grain Size (mm)</td>
<td>Thickness (cm)</td>
<td>Hardness</td>
<td>Density (kg m(^{-3}))</td>
<td>Grain Size (mm)</td>
<td>Thickness (cm)</td>
<td>Hardness</td>
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<td>DC1 (compacted monthly)</td>
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<td>DC2 (compacted bi-monthly)</td>
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<td>DC3 (single compaction)</td>
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<td>DU5</td>
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<tr>
<td>DC5 (late compaction)</td>
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</table>
well rounded snow, shielding it from the compaction.

Hardness was measured semi-quantitatively by testing how easily the snow was penetrated. The compacted snowpacks had a mean hardness of 2.5, which was significantly greater ($\alpha = 0.05$) than at the undisturbed plots, where the hardness was 1.8. The well-rounded snow was the hardest, with a mean of 2.6 at the undisturbed plots and 3.3 at the compacted plots. The dendritic snow and depth hoar were the softest, with mean measurements of 1.2 and 1.1, respectively, at the undisturbed plots, and 1.7 for both snow types at the compacted plots. Each of the snow types was harder at the compacted plots, but only the difference between the moderately rounded and well-rounded snow were significant ($\alpha = 0.05$).

Density was measured by weighing 100 cm$^3$ snow samples using a spring scale. As with hardness, the mean density of the compacted plots, 301 kg m$^{-3}$, was significantly greater ($\alpha = 0.05$) than that of the undisturbed plots, 255 kg m$^{-3}$. The well-rounded snow had the highest density, with a mean of 382 kg m$^{-3}$ at the compacted and 337 kg m$^{-3}$ at the undisturbed plots. Depth hoar had the lowest mean density, with 233 kg m$^{-3}$ at the compacted plots and 185 kg m$^{-3}$ at the undisturbed. All of the snow types had higher mean density at the compacted plots compared to the undisturbed plots, but only the differences between depth hoar and well-rounded snow were significant ($\alpha = 0.05$).

4.5.2 Mayo Sites

Mean snow physical properties at the Mayo sites are shown in Table 4.3. The dendritic snow layer at the top of the snowpack was completely crushed at the plots following compaction, aside from one outlier at MC2 in February. The depth hoar layer was nearly crushed as well, but thin layers ranging in thickness from 4 cm to 6.7 cm remained at MC2, MC3 and MC4 following the first compaction. Despite the crystalline structure of the depth hoar persisting, its physical
Table 4.3 Physical properties of snow types from five monthly snow pits at Mayo sites

<table>
<thead>
<tr>
<th>Snow Type</th>
<th>MU1</th>
<th>MC1</th>
<th>MU2</th>
<th>MC2</th>
<th>MU3</th>
<th>MC3</th>
<th>MU4</th>
<th>MC4</th>
</tr>
</thead>
<tbody>
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<td>Thickness (cm)</td>
<td>Hardness</td>
<td>Density (kg m(^{-3}))</td>
<td>Grain Size (mm)</td>
<td>Thickness (cm)</td>
<td>Hardness</td>
<td>Density (kg m(^{-3}))</td>
<td>Grain Size (mm)</td>
</tr>
<tr>
<td>Dendritic</td>
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<td>0.0</td>
<td>157</td>
<td>0.8</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate Rounding</td>
<td>6</td>
<td>1.0</td>
<td>200</td>
<td>2.3</td>
<td>7</td>
<td>2.7</td>
<td>283</td>
<td>2.5</td>
</tr>
<tr>
<td>Well Rounded</td>
<td>20</td>
<td>0.5</td>
<td>197</td>
<td>1.3</td>
<td>26</td>
<td>3.0</td>
<td>349</td>
<td>1.1</td>
</tr>
<tr>
<td>Some angular facets</td>
<td>18</td>
<td>0.4</td>
<td>194</td>
<td>2.4</td>
<td>7</td>
<td>3.0</td>
<td>360</td>
<td>1.8</td>
</tr>
<tr>
<td>Depth Hoar</td>
<td>15</td>
<td>0.9</td>
<td>213</td>
<td>3.6</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Snow Types:
- Dendritic
- Moderate Rounding
- Well Rounded
- Some angular facets
- Depth Hoar
properties after crushing were very different from those at the undisturbed plots. The mean density and hardness were 320 kg m\(^{-3}\) and 3, respectively, while at the undisturbed plots the mean density and hardness were only 179 kg m\(^{-3}\) and 0.4. The mean grain size was also less than half as large, 1.8 mm at the compacted plots compared to 3.8 mm at the undisturbed plots. This difference in physical properties shows that the depth hoar was modified by compaction, rather than the differences in accumulation between the plots being due to spatial variation. No depth hoar remained at any of the compacted plots after the first month.

The remaining snow types, well rounded, moderately rounded, and snow with some angular facets, were all found frequently within the snow pits at both the compacted and undisturbed plots. All had significantly greater (\(\alpha = 0.05\)) density and hardness at the compacted plots, but no significant difference (\(\alpha = 0.05\)) in grain size. There was little variance in density for each snow type, ranging from 189 to 196 kg m\(^{-3}\) at the undisturbed plots and from 322 to 336 kg m\(^{-3}\) at the compacted plots. The hardness values were also very close, ranging from 0.2 to 0.4 at the undisturbed plots, while all of the compacted plots had an average hardness rating of 3.1. All snow types had a larger change in density and hardness in response to compaction at the Mayo plots compared to the Dempster Highway site. The snow types which had the greatest difference in response between locations were the snow layers with the lowest density and hardness, depth hoar, and dendritic snow. At the Dempster Highway, these snow types had significantly altered physical properties, but remained generally intact as recognizable layers. At the Mayo sites, they were instead crushed and mixed in with the surrounding snow.
4.6 Weighted mean density and hardness

4.6.1 Dempster Highway km 96 Site

Weighted mean density and hardness values were calculated by multiplying the values for each snow layer by the thickness of the layer in proportion to the total snowpack thickness, then adding all layers together. Figure 4.7 shows the monthly results for each plot. The mean snow density at the compacted plots over the course of the winter was 311 kg m$^{-3}$, significantly greater ($\alpha = 0.05$) than that of the undisturbed plots, 271 kg m$^{-3}$. The mean hardness of the compacted snow was also significantly greater ($\alpha = 0.05$), at 2.7 compared to 1.9 for the undisturbed snow. The relation between hardness and density was generally positive, but varied between plots.

There was high variation in the density of the undisturbed snow, which ranged from 179 to 347 kg m$^{-3}$. This variation was not spatially biased, as the undisturbed plots at both ends of the field site had values within 10 kg m$^{-3}$ of the plot on the opposite end. Most of the measured densities were typical for settled snow, but lower than the 350 to 400 kg m$^{-3}$ expected for wind-packed snow (Paterson, 1994). The snow at the sites that were compacted more than once (excluding DC3) had higher densities with less variation, ranging from 296 to 375 kg m$^{-3}$. The hardness of the snowpack followed a similar pattern, with a range of 0.7 to 2.6 at the undisturbed plots compared to 2.2 to 3.6 at the compacted plots, omitting D3 and D5 before they were compacted.

The hardest and most dense snow on average was at DC1 (compacted monthly), with mean values of 339 kg m$^{-3}$ and 3.1, respectively. The softest and least dense snow among the compacted plots was at DC3 (mid-winter compaction), with values of 2.1 and 263 kg m$^{-3}$. DC2 (compacted bi-monthly), DC4 (early compaction) and DC5 (late compaction) all had close mean density values, ranging from 322 to 311 kg m$^{-3}$. The mean hardness at these plots was also close,
Figure 4.7: Scatter plot of snow pit weighted mean density and hardness for each set of numbered plots at the Dempster Highway site. The red circles indicate compacted sites, while the blue indicates sites that have been left undisturbed. $\Delta$ indicates the mean difference in density ($\rho$) and hardness ($h$) between the compacted and undisturbed plots over the duration of the study period.
but DC5 was slightly softer with a mean of 2.4 compared to 2.9 at DC2 and DC4.

The difference in density and hardness between the plot that was compacted only once, DC3, and the plots that were compacted three times, DC2, DC4 and DC5, was greater than the difference between those plots and DC1, which was compacted 5 times. This suggests that the frequency of compaction has a positive relation with both hardness and density, but that the relation diminishes as further compactions take place. Because all of the sites that were compacted three times had similar mean density and hardness values regardless of when compaction occurred, the data also suggest that the effect of compaction on hardness and density is consistent throughout the winter, although this may be influenced by the timing of the experiment, which only began on December 4th.

4.6.2 Mayo Sites

Snowpack weighted mean hardness and density values from the field sites near Mayo are presented in Fig. 4.8. The snowpacks at the undisturbed plots had a mean density of 185 kg m$^{-3}$, slightly lower than the typical 200 – 300 kg m$^{-3}$ of settled snow (Paterson, 1994), and were very soft, with a mean hardness of 0.3. There was less variation than at the Dempster Highway site, despite the plots being kilometers apart. Density values ranged from 114 to 237 kg m$^{-3}$, and hardness values from 0 to 1.4. The reduced variation was due to reduced snow transport caused by the lower wind speeds (Fig. 3.11) and less hummocky ground at the Mayo plots, which allowed snow to accumulate more evenly.

MU1 and MU2, located on the Silver Trail, had slightly higher density and hardness values of about 190 kg m$^{-3}$ and 0.5, compared to values of about 160 kg m$^{-3}$ and 0.1 at MU3 and MU4, on South McQuesten Road. The different snow conditions between the plots can be explained by the South McQuesten Road being disturbed less frequently by plowing. At the
Figure 4.8: Scatter plot of snow pit weighted average density and hardness for each set of numbered plots at the Mayo sites. The red circles indicate compacted sites, while the blue indicates sites that have been left undisturbed. $\Delta$ indicates the mean difference in density ($\rho$) and hardness ($h$) between the compacted and undisturbed plots over the duration of the study period.
compacted plots, mean density and hardness values were about the same as those at the Dempster Highway, averaging 327 kg m$^{-3}$ and 3.1, compared to 317 kg m$^{-3}$ and 2.7. The range of values was also similar at both locations.

4.7 Temperature at the base of the snowpack

4.7.1 Dempster Highway km 96 Site

Temperature loggers were buried on December 3rd, 2020, and activated at 01:00 the following day. They operated continuously, recording the temperature every 4 hours, until they were retrieved on June 6th, 2021. Figure 4.10 shows the mean daily temperatures recorded by the loggers from when they were buried to when the first logger rose above 0 °C on April 25th, indicating that the overlying snow had melted.

Total degree days, mean temperature, and minimum temperatures at the field plots are displayed in Table 4.4. The plots that were compacted multiple times (excluding DC3) had mean temperatures at the base of the snowpack 2.1 to 3.1 °C lower than the undisturbed plots, and minimum temperatures 4.2 to 9.1 °C lower. Prior to a period of rapid cooling beginning on January 20th, air temperatures were relatively mild, even rising above the ground surface temperatures at the compacted plots on several occasions. While the compacted plots were still generally colder than the undisturbed plots during this period, their greater response to these warming events limited the extent to which their temperatures diverged.

This effect was most prominent in DC1, which had a mean temperature only 1.1 °C lower than DU1 during this time, and was even briefly warmer than DU1 during four of the warming events. DC2 and DC4 had mean temperatures that were 2.9 and 3.5 °C lower than their corresponding undisturbed plots, respectively. DC3, which was not compacted early in the
Figure 4.10: Daily mean temperatures recorded by HOBO pendant loggers at the base of the snowpack, and daily mean air temperatures at km 97.1, Dempster Highway (Trevor Andersen, pers. comm., 2022), from December 4th, 2020, to April 25th, 2021, the day before the snowpack finished melting. Δ Indicates the average difference in mean daily temperatures (°C) between the compacted and undisturbed plots.
Table 4.4 Mean air temperatures and temperatures at the base of the snowpack at the Dempster Highway site, over 5 months during the study period. Presented with mean temperatures (°C) between compaction dates.

<table>
<thead>
<tr>
<th>Plot</th>
<th>Air Temp.</th>
<th>DU1</th>
<th>DC1</th>
<th>DU2</th>
<th>DC2</th>
<th>DU3</th>
<th>DC3</th>
<th>DU4</th>
<th>DC4</th>
<th>DU5</th>
<th>DC5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degree Days</td>
<td>-2669</td>
<td>-835</td>
<td>-1291</td>
<td>-556</td>
<td>-987</td>
<td>-830</td>
<td>-976</td>
<td>-645</td>
<td>-1100</td>
<td>-917</td>
<td>-1229</td>
</tr>
<tr>
<td>Mean Temp (°C)</td>
<td>-18.3</td>
<td>-5.7</td>
<td>-8.8</td>
<td>-3.8</td>
<td>-6.8</td>
<td>-5.7</td>
<td>-6.7</td>
<td>-4.4</td>
<td>-7.5</td>
<td>-6.3</td>
<td>-8.4</td>
</tr>
<tr>
<td>Min Temp (°C)</td>
<td>-44.5</td>
<td>-10.0</td>
<td>-19.1</td>
<td>-7.0</td>
<td>-12.2</td>
<td>-12.0</td>
<td>-13.3</td>
<td>-8.4</td>
<td>-12.6</td>
<td>-11.2</td>
<td>-15.7</td>
</tr>
<tr>
<td>Dec 4 - Jan 9</td>
<td>-19.4</td>
<td>-5.7</td>
<td>-6.8</td>
<td>-3.4</td>
<td>-6.4</td>
<td>-6.1</td>
<td>-6.6</td>
<td>-3.9</td>
<td>-7.7</td>
<td>-6.1</td>
<td>-8.7</td>
</tr>
<tr>
<td>Jan 10 - Feb 14</td>
<td>-20.3</td>
<td>-6.2</td>
<td>-9.4</td>
<td>-4.1</td>
<td>-7.2</td>
<td>-6.2</td>
<td>-6.5</td>
<td>-4.5</td>
<td>-7.9</td>
<td>-6.5</td>
<td>-8.8</td>
</tr>
<tr>
<td>Feb 15 - Mar 11</td>
<td>-20.0</td>
<td>-7.0</td>
<td>-11.8</td>
<td>-4.5</td>
<td>-8.8</td>
<td>-6.6</td>
<td>-8.0</td>
<td>-5.6</td>
<td>-8.6</td>
<td>-7.6</td>
<td>-10.4</td>
</tr>
<tr>
<td>Mar 12 - Apr 7</td>
<td>-20.4</td>
<td>-6.0</td>
<td>-11.9</td>
<td>-4.5</td>
<td>-7.5</td>
<td>-6.3</td>
<td>-8.4</td>
<td>-5.4</td>
<td>-8.7</td>
<td>-7.5</td>
<td>-9.1</td>
</tr>
<tr>
<td>Apr 7 - Apr 28</td>
<td>-8.1</td>
<td>-3.1</td>
<td>-4.2</td>
<td>-2.3</td>
<td>-3.3</td>
<td>-2.1</td>
<td>-3.5</td>
<td>-2.6</td>
<td>-3.8</td>
<td>-3.2</td>
<td>-3.8</td>
</tr>
</tbody>
</table>
winter, had temperatures at the base of the snowpack that were closely coupled with DU3 during this period, with a difference of 0.5 °C. DC5, which was also not compacted early, still had snow base temperatures that were 2.4 °C lower than at the undisturbed plot. This suggests that snow conditions varied between the logger locations of the plots from the beginning of the experiment, potentially due to deeper snow depth or greater depth hoar development.

On January 20th, air temperatures dropped from -3 to -12 °C, before continuing to decline to a minimum of -43 °C on February 8th. In response to the decline in air temperatures, the temperatures of the compacted plots decreased more rapidly than those of undisturbed plots. The difference in mean daily temperatures between DC1 and DU1 increased from 1 °C prior to January 20th, to 5 °C between January 20th and April 12th, when air temperatures began to warm rapidly during spring. The maximum difference between the plots was 9.6 °C, on February 9th. The average difference between DC2 and DU2 only increased from 2.9 to 3.6 °C during the same period, while the maximum difference was 6.8 °C. This suggests that the monthly compaction treatment caused a greater reduction in thermal resistance than bi-monthly compaction.

At DC3, immediately following the plots only compaction on February 16th, the daily mean temperature of DC3 dropped to 1°C below that of DU3, and this difference further increased to a maximum of 3.7 °C over the remainder of the winter. This result demonstrates that even a single compaction may have a noticeable effect on ground temperatures.

The average difference in temperature between DC4 and DU4 increased by just 0.2 °C between the January 20th cold period and the beginning of the spring thaw in April, suggesting that the lower thermal resistance persisted even after compaction had ceased, but not to the same extent as the plots that were still actively undergoing compaction. At DC5 the difference in snow
base temperatures increased from 2.4 °C to 2.9 °C during the same period, but due to the difference in initial snow conditions it is unclear to what extent this was caused by compaction.

The compacted plots also warmed more rapidly than the undisturbed plots during the spring. Between April 11th and April 15th, air temperatures rose from -21.3 °C to -0.7 °C. Prior to this warming, the temperature difference between the plots was near its maximum, but the more rapid warming at the compacted plots caused their temperatures to quickly equalize, and both sets of plots reached the zero curtain at about the same date, April 16 – 17th.

Overall, the mean daily air temperature prior to January 20th was -17.2 °C, and it was -22.4 °C between January 20th and April 11th. The mean daily snow base temperature at the undisturbed plots was -4.7 °C, on average, prior to January 20th, and it was -6.7 °C between January 20th and April 11th. At the compacted plots, mean daily snow base temperatures were -6.1 °C on average prior to January 10th, and -9.3 °C on average between January 20th and April 11th.

4.8.2 Mayo Sites

Temperatures at the base of the snowpack were measured at the centre of the Mayo plots using HOBO temperature loggers in protective pipes, activated on November 29th, 2020. The data collected was limited by a missing logger at MC1, a malfunctioning logger at MU2, and road widening at M3 and M4, which occurred at some time following the 4th compaction on March 9th. Daily mean snow basal temperatures are plotted in Fig. 4.11, while the mean and minimum temperatures along with degree days are presented in Table 4.5.

M3 and M4 were located on S. McQuesten Road. The snow cover was shallower (Fig. 4.2) and softer (Fig. 4.8) at these sites than at the sites on the Silver Trail. Mean ground surface temperatures of MU3 and MU4 were similar throughout the field experiment, averaging -5.2 °C
Figure 4.11: Daily mean temperatures recorded by HOBO pendant loggers at the ground surface, and daily mean air temperatures at Mayo Airport from November 29th, 2020 to April 22nd, 2021, the day before the snowpack finished melting. Data from Environment and Climate Change Canada (Climate ID: 2100701). Δ Indicates the average difference in mean daily temperatures (°C) between the compacted and undisturbed plots.
Table 4.5. Air and ground surface temperatures at Mayo sites over 5 month study period.

<table>
<thead>
<tr>
<th></th>
<th>Plot</th>
<th>Air Temp</th>
<th>MU1</th>
<th>MC2</th>
<th>MU3</th>
<th>MC3</th>
<th>MU4</th>
<th>MC4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degree Days</td>
<td>-2260</td>
<td>-1045</td>
<td>-661</td>
<td>-745</td>
<td>-1201</td>
<td>-785</td>
<td>-1100</td>
<td></td>
</tr>
<tr>
<td>Mean Temp (°C)</td>
<td>-16.1</td>
<td>-7.1</td>
<td>-4.5</td>
<td>-5.2</td>
<td>-8.4</td>
<td>-5.3</td>
<td>-7.5</td>
<td></td>
</tr>
<tr>
<td>Min Temp (°C)</td>
<td>-37.8</td>
<td>-11.7</td>
<td>-12.0</td>
<td>-11.1</td>
<td>-22.1</td>
<td>-9.8</td>
<td>-18.3</td>
<td></td>
</tr>
<tr>
<td>Nov 29 - Jan 3</td>
<td>-17.9</td>
<td>-6.2</td>
<td>-4.3</td>
<td>-4.2</td>
<td>-4.5</td>
<td>-4.7</td>
<td>-5.2</td>
<td></td>
</tr>
<tr>
<td>Jan 4 - Feb 9</td>
<td>-18.6</td>
<td>-7.0</td>
<td>-4.4</td>
<td>-4.5</td>
<td>-8.3</td>
<td>-5.2</td>
<td>-7.2</td>
<td></td>
</tr>
<tr>
<td>Feb 10 - Mar 9</td>
<td>-20.3</td>
<td>-9.8</td>
<td>-6.7</td>
<td>-7.3</td>
<td>-14.2</td>
<td>-7.1</td>
<td>-11.8</td>
<td></td>
</tr>
<tr>
<td>Mar 9 - Apr 7</td>
<td>-12.8</td>
<td>-7.8</td>
<td>-4.5</td>
<td>-5.7</td>
<td>-10.2</td>
<td>-6.3</td>
<td>-8.9</td>
<td></td>
</tr>
<tr>
<td>Apr 7 - Apr 22</td>
<td>-3.6</td>
<td>-4.3</td>
<td>-1.8</td>
<td>-4.6</td>
<td>-3.2</td>
<td>-3.3</td>
<td>-4.1</td>
<td></td>
</tr>
</tbody>
</table>
and -5.5 °C, respectively, but mean snow base temperatures at MC3 were 0.9 °C lower than MC4, averaging -8.4 °C and -7.7 °C.

The mean daily temperatures of the undisturbed and compacted plots diverged mostly during a period of cold weather beginning on January 10th, when mean daily air temperatures dropped from -2 °C to -37 °C by the end of January. Prior to January 10th, mean daily snow base temperatures were -4.1 °C at MU3, and -4.7 °C at MU4. At the compacted plots, mean daily temperatures were -5 °C and -5.4 °C at MC3 and MC4, respectively. Between January 10th and the beginning of the thawing season on April 13th, mean daily temperatures lowered to -5.7 °C at MU3 and -5.8 °C at MU4, while mean daily temperatures at MC3 and MC4 lowered to -9.4 °C and 8.7 °C, respectively.

Mean daily snow base temperatures at the compacted plots were 1.6 °C and 1.1 °C lower, on average, than at the undisturbed plots prior to January 10th; and 4.4 °C and 3.3 °C lower afterwards. The mean daily air temperature was -16.5 °C prior to January 10th, and -17.7 °C between January 10th and April 12th. All sites reached the zero curtain between April 15th and 17th.

### 4.8 Conclusion

At the Dempster Highway field site, the mean snow depth of all compacted plots was 9 cm shallower than the mean snow depth of the undisturbed plots, averaging 61 cm compared to 70 cm (Fig. 4.1). At the Mayo field sites, the mean snow depth was 30 cm shallower at the compacted plots, averaging 40 cm and 71 cm (Fig. 4.2). (Fig. 4.3). At the Dempster Highway site, the only type of snow that had significantly less accumulation at the compacted plots was depth hoar, and the compacted plots also had significantly more well-rounded snow. At the
Mayo sites, all snow types had less accumulation at the compacted plots compared to the undisturbed plots, aside from well-rounded snow, which was slightly deeper at the compacted plots (Fig. 4.5).

At the Dempster Highway field site, on average, the compacted plots had a weighted mean density of 311 kg m$^{-3}$, and hardness of 2.7. The undisturbed plots had a weighted mean density of 270 kg m$^{-3}$, and hardness of 1.9 (Fig. 4.7). In Mayo, the weighted mean density and hardness of the compacted plots were 325 kg m$^{-3}$, and 3.1. At the undisturbed plots, the weighted mean density and hardness were 176 kg m$^{-3}$, and 0.3 (Fig. 4.8).

The Dempster Highway and Mayo field sites had similar differences in mean daily temperatures at the base of the snowpack between the compacted and undisturbed plots, with both being 2-3 °C lower at the compacted plots on average (Fig. 4.10, Fig. 4.11). The divergence in temperature between the plots occurred mostly after a period of sustained cold weather during late January and throughout most of February at both locations.
Chapter 5: Discussion

5.1 Introduction

This chapter discusses the results of the snow compaction field experiments to assess the effectiveness of the technique at modifying snow conditions and lowering temperatures at the base of the snowpack. The chapter begins by considering the conditions at the field sites and how they influenced the results of the experiments. Next, physical differences between the undisturbed and compacted plots are compared to assess how the snowpacks reacted to the treatment, including differences between the taiga environment near Mayo and the tundra environment in the Blackstone Uplands. Snow density measurements are then used to estimate the thermal conductivity and resistivity of the snowpacks. Snowpack $n$-factors are presented and then discussed. Finally, the effectiveness of the technique for road maintenance is considered.

5.2 Site Conditions

The climate of central Yukon is characterized by long, cold winters, and short, hot summers (Fig. 3.2). This was consistent with the weather during the field experiments (Fig. 3.3). The mean air temperature at km 124 of the Dempster Highway was -18.1 °C during the study period, while at Mayo Airport it was -15.5 °C. The continental climate causes the ground to warm up quickly during the summer and in winter the heat is unable to escape the ground efficiently due to the high thermal resistance of snow cover. This creates a large temperature gradient through the snowpack. The heat flux ($q$) through the snow is governed by the thermal conductivity of the snow ($\lambda$), and the temperature gradient ($\Delta T$) (Eq. 5.1).

\[ q = -\lambda \Delta T \]
The units of \( q \) are \( \text{W m}^{-2} \), of \( \lambda \) are \( \text{W m}^{-1} \text{K}^{-1} \), and of \( \Delta T \) are \( ^\circ \text{C m}^{-1} \). Because snow compaction increases the thermal conductivity of the snowpack, it is effective at promoting heat flow in regions where the temperature gradient through the undisturbed snow cover is significant. This likely contributed towards the effectiveness of the technique at the field sites.

A high temperature gradient also promotes the development of depth hoar through temperature-gradient metamorphism (Fig. 2.8). A well-developed basal depth hoar layer was usually present in the undisturbed snow at the Dempster Highway and Mayo field sites. The M2 site near Mayo, and many of the sites at the Dempster Highway had high ground saturation (Table 3.2a, Table 3.2b), which may have contributed towards greater depth-hoar development, as high soil moisture will delay ground cooling so that the temperature gradient is greater, and there is more time for temperature gradient metamorphism to take place (Domine et al. 2018). The high ground saturation also increases the outward flux of water vapour from the ground, but the contribution of this water vapour towards depth-hoar development may be very small (Burn and Smith, 1987).

### 5.3 Physical effects of compaction

The mechanical behaviour of snow under compressive force is different from most solids and granular materials. If the pressure on the snowpack is below a critical value, the structure of the snow will remain intact, and it will behave as a low-compressibility solid. Once a critical amount of pressure is reached, the snow structure will collapse, causing it to undergo a large and irreversible reduction in volume, and changing its mechanical properties (Mellor, 1974). The critical value for compressive failure increases exponentially with snow density. A compressive failure curve of dry snow with varying densities under rapid uniaxial loading, derived from 11
studies using empirical testing, is presented in Fig. 5.1 (Mellor, 1974). Figure 5.1 characterizes brittle fracture for ice under high strain rates (10^{-2} - 10^{-4} \text{s}^{-1}) and low temperatures (\leq -10 \degree C). At lower strain rates or higher temperatures, where failure is more likely to occur through ductile deformation before fracturing, the curve overestimates the strength of the snowpack.

When brittle fracture occurs and the intergranular bond structure of the snowpack is destroyed, it may become fluidized, losing its ability to resist shear. Fluidization can occur when snow is blown by wind, during avalanches, or when the snow is violently disturbed by vehicle tracks or snow ploughs (Mellor, 1974). When the snowpack is in a fluidized state under compression, shearing can take place within it, causing the snow to shift to disperse the pressure before settling.

5.3.1 Estimating the force of compaction

The snowpack was compacted by different drivers using a variety of mid-sized snowmobiles throughout the winter. A common tread size for snowmobiles capable of riding off trails is 3.48 m by 0.46 m. The length of tread which contacts the snow when the vehicle is being operated varies, but it is typically about 1.27 m, in which case the contact area of the tread is 0.52 m^2. A standard trail runner for deep snow (Ski-doo/Lynx 8350 Model) is 0.2 m by 0.5 m. Usually about 0.3 m of length comes in contact with the snow surface, although this varies considerably during use. Assuming 0.3 m of contact length, the contact area for each trail runner is 0.06 m^2, and the total contact area of a snowmobile in operation is about 0.64 m^2. Dry weight for mid-sized snowmobiles can range from 186 – 300 kg. A variety of models were used during the field experiments. Using the weight of a Skidoo Summit X 165 Model, 206 kg, a full tank of gas weighing 27 kg, and the average weight of a Canadian male, 85 kg, for a total weight
Figure 5.1: Strength of dry snow under rapid loading uniaxial stress, derived from empirical data from 11 studies (Mellor, 1974, Fig. 17).
of 318 kg. This weight dispersed over 0.64 m² exerts a pressure of 4.96 kPa (0.05 bar). In Fig. 5.1, 0.05 bar intercepts with the compressional failure curve at a density of 0.22 g cm⁻³ (220 kg m⁻³). For comparison, a typical density for settled snow is 200 – 300 kg m⁻³ (Paterson, 1994)

5.3.2 Effectiveness in reducing snow depth

Compaction was significantly more effective at reducing snow depths at the Mayo field sites than at the Dempster Highway. Undisturbed snow depths were similar at both locations, with mean depths of about 50 cm in December, increasing to about 80 - 100 cm in April (Figs. 4.1, 4.2). At the Dempster Highway, compaction initially caused little change in snow depth, as the average depth was 50.7 cm at both the compacted and undisturbed plots in December. Over the course of the winter snow depths at the compacted plots diverged from the undisturbed plots, only rising to about 70 cm in April.

In Mayo, compaction immediately reduced snow depths to 20-25 cm in December, about 30 cm less than at the undisturbed plots. This difference in depth persisted throughout the winter, with an average snow depth of 40 cm at the compacted plots, 31 cm less than the undisturbed plots. These data demonstrate that, with similar snow depths, the hard and dense tundra snow pack in the Blackstone Uplands resisted the force of compaction to a much greater extent than the soft, loose snow of the taiga near Mayo.

5.3.3 Changes in snow structure

The reduction in snow depth was not distributed evenly among snow layers at either the Dempster Highway or Mayo compacted plots. At the Dempster Highway site, the high wind speeds caused hard wind slab layers to develop, consisting primarily of moderately rounded and well-rounded snow, with mean densities of 277 and 338 kg m⁻³, respectively. Depth hoar was
present near the base of the snowpack, with a mean density of 184 kg m$^{-3}$, and snow with some angular facets of mean density 256 kg m$^{-3}$. Dendritic snow was only present in thin, usually discontinuous layers, and had a mean density of 205 kg m$^{-3}$.

Aside from dendritic snow, depth hoar was the only snow type with a mean density below the 220 kg m$^{-3}$ necessary to resist compressive failure (Fig. 5.1). This may explain why depth hoar was the only snow type which had significantly less accumulation at the compacted plots, averaging 7.6 cm compared to 13.4 cm at the undisturbed plots. Depth hoar was also the only snow type which had a smaller average grain size at the compacted plots. Although other snow types did not experience a significant reduction in layer thickness, all snow types increased in density and hardness with compaction.

Based on these results, it appears as though the wind-slab snow layers were able to support the weight of the snowmobiles, and responded by becoming more tightly packed with minimal reduction in volume. The depth hoar layer could not support the increased pressure, causing the large snow crystals to break and the layer to collapse. Because the mean reduction in depth hoar thickness was 7 cm, and the mean reduction in total snow depth was 9 cm, it appears as though the majority of the reduction in snow depth came from the depth hoar layer collapsing.

In Mayo, the physical properties of different snow types were more homogenous than at the Dempster Highway site. All snow layers, aside from dendritic snow, had mean densities ranging from 187 kg m$^{-3}$ to 196 kg m$^{-3}$. Dendritic snow had a mean density of 149 kg m$^{-3}$. The snow types that were most susceptible to compaction were dendritic snow and depth hoar, which were almost entirely absent from the compacted plots. Snow with some angular facets also had significantly less accumulation, averaging 17 cm at the undisturbed plots and only 7 cm at the compacted plots. There was only slightly less moderately rounded snow at the compacted plots,
and, as at the Dempster Highway, the compacted plots had significantly greater accumulation of well-rounded snow. Following compaction, all snow types had very similar density values, ranging from 300 kg m\(^{-3}\) to 336 kg m\(^{-3}\). These results suggest that when snow layers throughout the snowpack are not able to support the weight of compaction, then it is the softest snow layers that will fail first (depth hoar and dendritic snow).

Although the average weighted mean density of the undisturbed plots at the Mayo sites was 185 kg m\(^{-3}\), compared to 271 kg m\(^{-3}\) at the Dempster Highway site, at the compacted plots average weighted mean densities were similar, at 327 and 317 kg m\(^{-3}\), respectively. Weighted mean hardness was also similar at the compacted plots, averaging 3.1 and 3.7, respectively. These results suggest that compaction using snowmobiles can only increase snow density to slightly greater than what is typically seen in settled snow (200-300 kg m\(^{-3}\)), regardless of initial snow conditions.

There was a significant increase in accumulation of well-rounded snow at the compacted plots at the Mayo and Dempster Highway sites. At the Dempster Highway, the well-rounded snow also had a significantly larger average grain size, averaging 1.3 mm compared to 0.9 mm at the undisturbed plots. Other snow types generally had larger grain sizes at the compacted plots, aside from depth hoar, which had a mean grain size that was 0.5 mm smaller (Table 4.2). The increases in grain sizes and well-rounded snow may be indicators of increased rates of sintering through equitemperature metamorphism (Perla and Martinelli, 1976). This could be caused by compaction increasing the number of contact points between snow grains.

The increase in well-rounded grains may also be attributed to physical weathering from compaction, however, and there were no significant differences in grain sizes at the Mayo plots, aside from a reduction in depth hoar, which can be explained by compressive failure from
compaction. At the Dempster Highway, the increase in well-rounded snow was also only observed at the DC4 and DC5 plots, rather than throughout all of the compacted plots. Based on these inconsistencies in the data, there is insufficient evidence to conclude whether or not compaction increases the rate of sintering within the snowpack. If increased rates of sintering are occurring, then it may be related to the fracturing of the ice-skeleton in the tundra snowpack, as the general increases in grain sizes throughout the wind-slab snow layers at the Dempster Highway plots are the strongest supporting evidence.

5.4 Estimating snow thermal conductivity and resistivity

5.4.1 Dempster Highway km 96 Site

Snow thermal conductivity can be estimated using Eq. 5.2 (Goodrich 1982, Table 1):

\[ \lambda = 2.9 \rho^2 \]

where \( \rho \) is the bulk density of the snowpack. This method produces results consistent with data in tundra environments (Morse and Burn, 2014), but it overestimates field measurements for low density depth hoar presented by Sturm and Johnson (1992). This problem is shared with even advanced snow-models, including ISBA-ES, CROCUS, CLM 5.0, and Snowpack (Dutch et al., 2022). Typically, snow is simulated as having low density near the surface, and high density near the base, as is the case in alpine snowpacks. Field results have shown this method is inaccurate for modelling thermal conductivity of snow in tundra, as it does not account for the thermal influence of depth hoar or vapour flow (Domine et al., 2019).

At Trail Valley Creek, NWT, modelling using CLM 5.0 overestimated measured snow thermal conductivity in a tundra environment by nearly 400% (Dutch et al., 2022). Snow parameters in the model were adjusted to match those from four studies on thermal conductivity
in tundra, including Sturm et al. (1997) and Calonne et al. (2011). The model still overestimated measured thermal conductivities by about 300% using data from each of the studies, except Sturm et al. (1997), which only slightly overestimated thermal conductivity (0.11 W m\(^{-1}\) K\(^{-1}\) simulated, 0.08 W m\(^{-1}\) K\(^{-1}\) measured).

According to measurements from Sturm and Johnson (1992), the thermal conductivity of a slab of wind-packed snow with a density of 500 kg m\(^{-3}\) is 0.700 W m\(^{-1}\) K\(^{-1}\), while depth hoar with a density of 200 kg m\(^{-3}\) has a thermal conductivity of 0.063 W m\(^{-1}\) K\(^{-1}\). Using equation 5.2, a snowpack with a bulk density of 500 kg m\(^{-3}\) would have an estimated thermal conductivity of 0.725 W m\(^{-1}\) K\(^{-1}\), while the snowpack with a density of 200 kg m\(^{-3}\) would have a thermal conductivity of 0.116 W m\(^{-1}\) K\(^{-1}\). The estimate for the thermal conductivity of wind-packed snow is very close to that of Sturm and Johnson (1992), but the estimate for depth hoar is nearly twice as high as measured values. To adjust for this disparity, thermal conductivity was first estimated for each of the snow layers using eq. 5.2, and the thermal conductivity of the depth hoar layer was multiplied by 0.54. Using the effective thermal conductivity estimates, the thermal resistance of the snowpack was estimated with Eq. 2.8 (Lunardini, 1981).

Mean effective thermal conductivity and total resistivity of the snowpack at each plot over the duration of the study period are presented by snow type in Table 5.1. The mean thermal conductivity of all snow layers at the undisturbed plots was 0.199 W m\(^{-1}\) K\(^{-1}\), while at the compacted plots it was significantly lower, 0.262 W m\(^{-1}\) K\(^{-1}\). Snow naturally has a wide range in thermal conductivity, typically between 0.01 – 0.7 W m\(^{-1}\) K\(^{-1}\) (Calonne et al., 2011), and all snow layers were within this range.

The mean monthly thermal resistance of the snowpack at each plot is presented in Fig. 5.2. Aside from one outlier at DU5 in December, the maximum thermal resistance at each of the
### Table 5.1: Snowpack mean density and estimated thermal properties by layer at Dempster Highway site

<table>
<thead>
<tr>
<th>Snow Type</th>
<th>DU1</th>
<th>DC1 (compacted monthly)</th>
<th>DU2</th>
<th>DC2 (compacted bi-monthly)</th>
<th>DU3</th>
<th>DC3 (single compaction)</th>
<th>DU4</th>
<th>DC4 (early compaction)</th>
<th>DU5</th>
<th>DCS (late compaction)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thickness (cm)</td>
<td>Density (kg m(^{-3}))</td>
<td>Effective λ (W m(^{-1}) K(^{-1}))</td>
<td>Resistivity (m(^{2}) K W(^{-1}))</td>
<td>Thickness (cm)</td>
<td>Density (kg m(^{-3}))</td>
<td>Effective λ (W m(^{-1}) K(^{-1}))</td>
<td>Resistivity (m(^{2}) K W(^{-1}))</td>
<td>Thickness (cm)</td>
<td>Density (kg m(^{-3}))</td>
</tr>
<tr>
<td>----------------------------</td>
<td>--------------------------</td>
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<td>--------------------------</td>
<td>--------------------------</td>
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<td>--------------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>Dendritic</td>
<td>2</td>
<td>235</td>
<td>0.20</td>
<td>0.55</td>
<td>2</td>
<td>345</td>
<td>0.33</td>
<td>0.17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate Rounding</td>
<td>6</td>
<td>198</td>
<td>0.11</td>
<td>0.73</td>
<td>14</td>
<td>318</td>
<td>0.30</td>
<td>0.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well Rounded</td>
<td>20</td>
<td>350</td>
<td>0.35</td>
<td>0.54</td>
<td>22</td>
<td>391</td>
<td>0.44</td>
<td>0.61</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Some angular facets</td>
<td>11</td>
<td>221</td>
<td>0.14</td>
<td>0.93</td>
<td>3</td>
<td>215</td>
<td>0.13</td>
<td>0.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth Hoar</td>
<td>13</td>
<td>234</td>
<td>0.10</td>
<td>3.27</td>
<td>5</td>
<td>243</td>
<td>0.10</td>
<td>1.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>270</td>
<td>0.27</td>
<td>0.63</td>
<td>1</td>
<td>370</td>
<td>0.38</td>
<td>0.15</td>
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<td></td>
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<tr>
<td>Moderate Rounding</td>
<td>11</td>
<td>293</td>
<td>0.27</td>
<td>1.71</td>
<td>7</td>
<td>347</td>
<td>0.34</td>
<td>0.37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well Rounded</td>
<td>28</td>
<td>351</td>
<td>0.35</td>
<td>0.83</td>
<td>25</td>
<td>365</td>
<td>0.37</td>
<td>0.64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Some angular facets</td>
<td>19</td>
<td>308</td>
<td>0.29</td>
<td>1.41</td>
<td>8</td>
<td>235</td>
<td>0.16</td>
<td>1.27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth Hoar</td>
<td>12</td>
<td>192</td>
<td>0.06</td>
<td>2.52</td>
<td>8</td>
<td>193</td>
<td>0.06</td>
<td>2.50</td>
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</tr>
<tr>
<td></td>
<td>3</td>
<td>200</td>
<td>0.15</td>
<td>0.67</td>
<td>5</td>
<td>213</td>
<td>0.14</td>
<td>0.68</td>
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<tr>
<td>Moderate Rounding</td>
<td>5</td>
<td>273</td>
<td>0.21</td>
<td>0.43</td>
<td>9</td>
<td>267</td>
<td>0.22</td>
<td>1.12</td>
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<tr>
<td>Well Rounded</td>
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<td>0.24</td>
<td>0.75</td>
<td>8</td>
<td>372</td>
<td>0.40</td>
<td>0.32</td>
<td></td>
<td></td>
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<tr>
<td>Some angular facets</td>
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<td>245</td>
<td>0.18</td>
<td>1.35</td>
<td>13</td>
<td>224</td>
<td>0.15</td>
<td>1.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth Hoar</td>
<td>14</td>
<td>156</td>
<td>0.04</td>
<td>3.76</td>
<td>9</td>
<td>218</td>
<td>0.08</td>
<td>1.67</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>240</td>
<td>0.19</td>
<td>0.58</td>
<td>3</td>
<td>260</td>
<td>0.24</td>
<td>0.84</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate Rounding</td>
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<td>305</td>
<td>0.29</td>
<td>1.39</td>
<td>7</td>
<td>325</td>
<td>0.30</td>
<td>0.39</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well Rounded</td>
<td>14</td>
<td>368</td>
<td>0.39</td>
<td>0.37</td>
<td>25</td>
<td>377</td>
<td>0.41</td>
<td>0.82</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Some angular facets</td>
<td>22</td>
<td>280</td>
<td>0.22</td>
<td>1.09</td>
<td>10</td>
<td>260</td>
<td>0.20</td>
<td>0.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth Hoar</td>
<td>9</td>
<td>150</td>
<td>0.04</td>
<td>3.18</td>
<td>2</td>
<td>310</td>
<td>0.15</td>
<td>0.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>113</td>
<td>0.04</td>
<td>1.27</td>
<td>3</td>
<td>275</td>
<td>0.26</td>
<td>0.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate Rounding</td>
<td>21</td>
<td>321</td>
<td>0.30</td>
<td>0.96</td>
<td>22</td>
<td>324</td>
<td>0.32</td>
<td>0.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well Rounded</td>
<td>11</td>
<td>343</td>
<td>0.33</td>
<td>0.45</td>
<td>30</td>
<td>407</td>
<td>0.40</td>
<td>0.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Some angular facets</td>
<td>8</td>
<td>243</td>
<td>0.22</td>
<td>1.64</td>
<td>25</td>
<td>345</td>
<td>0.34</td>
<td>1.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth Hoar</td>
<td>19</td>
<td>191</td>
<td>0.06</td>
<td>3.83</td>
<td>8</td>
<td>200</td>
<td>0.07</td>
<td>1.39</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 5.2: Estimated thermal resistance of the snowpack at each field plot based on the measured thickness and density of the snow layers found within the monthly snow pits. The solid lines show the compacted plots, while the dotted lines show the undisturbed plots. Red circles indicate the days when compaction occurred.
undisturbed plots was 7.70 to 8.50 m² K W⁻¹, while the maximum thermal resistance of the compacted plots was only 3.30 to 5.35 m² K W⁻¹. At D1 and D2, the resistance of the undisturbed plots rose to a peak in February, while the resistance of the compacted plots remained low in comparison throughout the winter. At D3, the resistances of the compacted and undisturbed plots were less than 0.5 m² K W⁻¹ apart the month prior to compaction, but the compacted plot had 3.31 m² K W⁻¹ lower resistance after compaction. The resistance remained lower throughout the remainder of the winter. At D4, the thermal resistance at the compacted plot was only 0.4 m² K W⁻¹ lower after the first compaction in December, but was 4.10 and 5.36 m² K W⁻¹ lower after the following two compactions, and remained lower throughout the remainder of the winter.

At D5, the undisturbed plot had unusually high thermal resistance of 11.1 m² K W⁻¹ in December. This was due to an 8.5 cm thick accumulation of dendritic snow where the density was only 60 kg m⁻³, much lower than the 200-300 kg m⁻³ commonly found in other snowpacks. The snow pits were dug from the north end of the study plots, and some of the snow pits at DU5 reached a depression that was shielded from the wind and filled with loose snow, explaining the low density. Substituting the density of 60 kg m⁻³ with the mean density of dendritic snow at the other undisturbed plots, 220 kg m⁻³, lowers the thermal resistance to 3.57 m² K W⁻¹, in line with that of the other undisturbed plots in December. The resistance of the compacted plot at D5 rose to a maximum of 5.33 m² K W⁻¹ after it was first compacted in February, then dropped to about 4 m² K w⁻¹ over the following months. DC5 was the only study plot with deeper snow pit depth than at its corresponding undisturbed plot, but the increased density and shallower depth hoar layer caused the resistivity to be about half that of the undisturbed plot. The conditions at D5
made the results from these plots less comparable with other plots at the Dempster Highway Site. For this reason, data from D5 are not emphasized in the conclusions of this thesis.

The reduction in thermal resistivity caused by compaction was consistent among all study plots. This change was primarily due to the depth hoar being crushed, since it has a disproportionately large influence on the overall thermal resistance of the snowpack. Even though the change in snow depth and density were greatest between DU1 and DC1, which was compacted five times, the greatest difference in thermal resistance was instead between DU5 and DC5, followed by DU4 and DC4, both of which were compacted only three times. This was because DU5 had the deepest average depth hoar accumulation of any plot, at 19 cm, causing it to have greater insulation where the snow pits were dug. DC4 had the shallowest average depth hoar of any plot at 2 cm, causing it to have less insulation. Depth hoar distribution is highly variable, and this result demonstrates the impact that this may have on overall snowpack thermal resistivity.

5.4.2 Mayo Sites

The thermal conductivity of the snowpacks at the Mayo sites was calculated using eq. 5.2, and the thermal conductivity of depth hoar was multiplied by 0.54, as it was for the Dempster Highway Site. Thermal resistivity was calculated using eq. 2.8. Mean conductivity and resistivity values over the duration of the study for each snow type are presented in Table 5.2. At the Dempster Highway plots significant change in thermal resistance was limited to the depth hoar layer, but at the Mayo plots all snow types had significantly lower thermal resistance at the compacted plots compared to the undisturbed plots.

The largest difference was still in the depth hoar layer, which had a mean resistivity 2.50 m² K W⁻¹ lower at the compacted plots, but dendritic snow and snow with some angular facets
Table 5.2: Mayo snowpack mean density and estimated thermal properties by layer

| Snow Type               | MU1 | MC1 | | Snow Type | MU2 | MC2 | | Snow Type | MU3 | MC3 | | Snow Type | MU4 | MC4 |
|-------------------------|-----|-----|---|-------------------------|-----|-----|---|-------------------------|-----|-----|---|-------------------------|-----|-----|---|
| Dendritic               | 2   | 157 | 0.07 | 0.34 | 0 | 0.00 | 0 | 0.00 |
| Moderate Rounding       | 6   | 200 | 0.12 | 0.49 | 7 | 283 | 0.23 | 0.28 |
| Well Rounded            | 20  | 197 | 0.11 | 1.74 | 26 | 349 | 0.35 | 0.74 |
| Some angular facets     | 18  | 194 | 0.11 | 1.60 | 7 | 360 | 0.38 | 0.18 |
| Depth Hoar              | 15  | 213 | 0.13 | 2.08 | 0 | 0.00 | 0 | 0.00 |
| Snow Type               | MU1 | MC1 | | Snow Type | MU2 | MC2 | | Snow Type | MU3 | MC3 | | Snow Type | MU4 | MC4 |
| Dendritic               | 11  | 158 | 0.07 | 1.46 | 1 | 300 | 0.26 | 0.04 |
| Moderate Rounding       | 12  | 188 | 0.10 | 1.15 | 12 | 314 | 0.29 | 0.42 |
| Well Rounded            | 23  | 268 | 0.21 | 1.12 | 16 | 350 | 0.36 | 0.44 |
| Some angular facets     | 21  | 203 | 0.12 | 1.74 | 6 | 320 | 0.30 | 0.22 |
| Depth Hoar              | 8   | 175 | 0.09 | 1.58 | 1 | 310 | 0.28 | 0.08 |
| Snow Type               | MU1 | MC1 | | Snow Type | MU2 | MC2 | | Snow Type | MU3 | MC3 | | Snow Type | MU4 | MC4 |
| Dendritic               | 7   | 130 | 0.05 | 1.45 | 0 | 0.00 | 0 | 0.00 |
| Moderate Rounding       | 10  | 170 | 0.08 | 1.22 | 9 | 333 | 0.32 | 0.28 |
| Well Rounded            | 10  | 140 | 0.06 | 1.72 | 9 | 328 | 0.31 | 0.30 |
| Some angular facets     | 16  | 178 | 0.09 | 1.72 | 6 | 290 | 0.24 | 0.26 |
| Depth Hoar              | 11  | 180 | 0.09 | 2.20 | 1 | 290 | 0.24 | 0.04 |
| Snow Type               | MU1 | MC1 | | Snow Type | MU2 | MC2 | | Snow Type | MU3 | MC3 | | Snow Type | MU4 | MC4 |
| Dendritic               | 11  | 140 | 0.06 | 1.96 | 0 | 0.00 | 0 | 0.00 |
| Moderate Rounding       | 11  | 190 | 0.10 | 1.03 | 5 | 300 | 0.26 | 0.20 |
| Well Rounded            | 6   | 130 | 0.05 | 1.29 | 13 | 328 | 0.31 | 0.41 |
| Some angular facets     | 12  | 205 | 0.12 | 1.02 | 7 | 313 | 0.28 | 0.23 |
| Depth Hoar              | 15  | 150 | 0.07 | 4.30 | 2 | 360 | 0.38 | 0.04 |
also had average thermal resistance values about 1.30 m² K W⁻¹ lower, while well-rounded snow and moderately rounded snow had 0.99 and 0.68 m² K W⁻¹ lower thermal resistivity at the compacted plots, respectively.

Monthly total thermal resistance of the snowpacks at the Mayo plots is plotted in Fig. 5.3. The mean thermal resistance of the undisturbed snowpacks was 8.56 m² K W⁻¹, and the mean thermal resistance of the compacted snowpacks was 1.15 m² K W⁻¹. The undisturbed snowpack at Mayo was a stronger insulator than at the Dempster Highway, where the mean total thermal resistance was only 5.91 m² K W⁻¹, but the low density of the snow also made it more susceptible to compaction. As a result, the compacted plots at Mayo had a lower thermal resistance than at the Dempster Highway, where the mean was 3.04 m² K W⁻¹. The snowpacks with the softest snow among the Mayo plots, M3 and M4, also had the lowest thermal resistance following compaction, with mean values of 0.93 and 1.00 m² K W⁻¹, respectively. These data indicate, overall, the efficacy of compaction in the forest environment near Mayo.

The softness of the snowpack appears to be a controlling factor governing the effectiveness of the compaction treatment on both a local and regional scale. As a result, compaction of snow in a forested environment is likely less reliant on depth hoar being present for compaction to lower ground temperatures effectively than in a tundra environment. However, a 17 cm layer of depth hoar recorded at MU4 in late November demonstrates the influence that natural depth hoar variation also has on the thermal resistance of the snowpack in a forested environment, as the estimated thermal resistance of 18.41 m² K W⁻¹ at the plot was nearly 10 m² K W⁻¹ greater than the average thermal resistance of the undisturbed plots, and about 7 m² K W⁻¹ higher than the next highest thermal resistance. Because of this, compaction is likely more effective at lowering ground temperatures in areas with high depth-hoar development, even in a
Figure 5.3: Estimated thermal resistance of the snowpack at each field plot based on the measured thickness and density of the snow layers found within the monthly snow pits. The solid lines show the compacted plots, while the dotted lines show the undisturbed plots.
forested environment where snow is generally more susceptible to compaction overall.

5.5 Snowpack basal temperatures

While it is clear that the compaction technique was effective at reducing temperatures near the ground surface in both the taiga and tundra environments, two characteristics of the temperature data are unexpected. First, the compaction technique was about equally effective in both environments, despite different snow conditions, particularly the difference in snow density. Second, the temperatures of the compacted and undisturbed plots remained mostly coupled early in the winter, even during periods of cold weather, and most of the temperature divergence between plots occurred only later, in January and early February, especially at the Mayo plots.

5.5.1 Compaction effectiveness in tundra and taiga

At the Mayo sites the snowpack was compacted to shallower depths and higher densities than at the Dempster Highway. At the undisturbed plots, the snow at the Mayo sites had much lower density than the tundra snowpack, although they were of similar depth. Based on these values, the thermal resistance of the snowpack was estimated to be about 6 – 8 m² K W⁻¹ lower at the compacted plots compared to the undisturbed plots at the Mayo sites, and about 2.6 m² K W⁻¹ lower than at the compacted plots of the Dempster Highway site (Fig. 5.2, Fig. 5.3). This does not align with the differences in measured temperatures, as mean daily temperatures were about 2 – 3 °C lower in both locations (Fig. 4.10, Fig. 4.11)

A contributing factor may be the stage of depth hoar metamorphism (Fig. 2.8). The thermal conductivity of depth hoar was multiplied by the same 0.54 value in both field locations, but it is unclear from the literature whether depth hoar in subarctic taiga has the same exceptionally low thermal conductivity values as have been observed in Arctic tundra (Sturm et
al. 1997, Dutch et al., 2022). Visually, the depth hoar in Mayo appeared to be closer in texture to the rest of the snowpack, and it was of similar density (Table 4.2). At the Dempster Highway site, the crystals formed a more distinct and delicate layer, consistent with field descriptions of advanced depth hoar from Sturm and Johnson (1992). The measured density of the depth hoar was only slightly lower at the Dempster Highway than near Mayo (Table 4.3), but these values may be imprecise, as the depth hoar was more difficult to sample from the bottom of snow pits at the Dempster Highway due to its delicate structure.

One reason why the depth hoar may have reached a higher stage of metamorphism at the Dempster Highway site is moisture availability, as most of the study plots were flooded upon field inspection in spring, while M3 and M4 were completely dry (Domine et al., 2018). Another factor could be the reduced permeability of the wind slab layers in the tundra. This may trap water vapour in a smaller portion of the snowpack, potentially enhancing the rate of depth hoar development there, as more water would crystallize that would otherwise have flowed upwards through the snowpack. Sturm and Johnson (1992) noted an abrupt drop in thermal conductivity of stage 4 depth hoar in comparison to earlier stages of development, so if the depth hoar did progress to stage 4 metamorphism at the Dempster Highway, but not in Mayo, then the thermal conductivity of the depth hoar was likely much lower.

5.5.2 Temperature divergence in January

In Mayo, temperatures at the compacted and undisturbed plots were closely coupled throughout December, only diverging during January, even though the snow responded immediately to the compaction treatment with large changes in depth and density. At the Dempster Highway, a similar pattern was observed at DC1, and to a lesser extent at DC2. This may indicate that the active layer had not finished freezing during the beginning of the study period. Temperatures
below the ground surface were not measured, and if the active layer was not completely frozen by the time the experiment began, then an increase in heat flow out of the ground would result in more rapid freeze-up, rather than lower temperatures. At the Dempster Highway DC1 and DC2 were the southernmost compacted plots, and the study plots at this end of the field site had more ponding than those at the north end during inspection of the field sites in June (Table 3.2a). The higher ground saturation may have delayed freeze-up.

5.6 The n-factors

Weekly n-factors were calculated using air temperatures from Mayo airport and km 124 of the Dempster Highway during the study period (Fig. 5.4, Fig. 5.5). The n-factors after April 10th were excluded at the Dempster Highway, as mean daily air temperatures approached 0 ºC during this week, causing the n-factors to be inflated, and the snow at the study plots reached the zero curtain the following week. The n-factors after April 10th in Mayo were removed for the same reason.

At the Dempster Highway site, the mean \( n_f \) value of the undisturbed plots over the duration of the study period was 0.36, while at the compacted plots it was 0.53, 0.17 higher. DC3 had the lowest \( n_f \) value of the compacted plots at 0.46, since it was only compacted once. Removing DC3 increases the mean \( n_f \) of the compacted plots to 0.55. At the M3 and M4 Mayo sites, the undisturbed plots had a mean \( n_f \) value of 0.39, and the compacted plots had a mean \( n_f \) values of 0.59, an increase of 0.2.

In northwestern Canada, typical freezing n-factors in taiga are between 0.1 - 0.3 due to the deep, soft snow cover that accumulates (Smith et al., 2010). In tundra \( n_f \) values are generally higher, about 0.7 – 1 (Smith et al., 2010). This disparity in n-factors was not observed at the field
Figure 5.4: Weekly $n$-factors calculated using daily mean air temperatures at km 97.1, Dempster Highway (Trevor Andersen, pers. comm., 2022), and temperature logger data from December 6th, 2020 to April 17th, 2021. The compacted plots are shown in red, while the undisturbed plots are in white. $\Delta$ indicates the mean difference in weekly $n$-factors over the study period.
Figure 5.5: Weekly $n$-factors calculated using daily mean air temperatures at Mayo Airport, and temperature logger data from December 6$^{th}$, 2020 to April 17$^{th}$, 2021. The compacted plots are shown in red, while the undisturbed plots are in white. $\Delta$ indicates the mean difference in weekly $n$-factors over the study period. Data from Environment and Climate Change Canada (Climate ID: 2100701).
sites, where the average \( n_f \) values varied by only 0.03 at the undisturbed plots, despite the different snow conditions. The relatively high \( n_f \) in Mayo can be explained by the thinner snow cover near the road, as opposed to in the forest, while the lower \( n_f \) value in tundra can be explained by the deeper snow cover in the ditch. The mean density of the snow at the Dempster Highway was also lower than the 350 – 400 kg m\(^{-3}\) typical of wind-packed snow, which may have contributed to the low \( n \)-factor as well. Overall, compaction increased \( n \)-factors at the base of the snowpack by about 0.2 in each location. This change was consistent among all of the plots that were compacted regularly, indicating that the compaction treatment is able to replicate the thermal influence of a thin snow cover.

At the Dempster Highway there was little evidence for temperature dependence of \( n \)-factors (Sturm et al. 1997), as the average \( n \)-factors at both the undisturbed and compacted plots were lower during the colder period of the field season after January 10\(^{th}\). At the undisturbed plot the \( n \)-factor lowered from 0.42 to 0.38, while at the compacted plot it lowered from 0.58 to 0.5. However, at DC1, the only plot compacted monthly, the \( n \)-factor rose from 0.52 to 0.62 during the colder portion of the winter, when mean daily temperatures were -21 °C compared to -16.5 °C.

At M3 and M4 the average \( n \)-factors were 0.31 and 0.38 at the undisturbed and compacted plots, respectively, prior to a period of cold weather beginning on January 10\(^{th}\). Between January 10\(^{th}\) and the spring thaw, \( n_f \) was 0.42 at the undisturbed plots and 0.68 at the compacted plots. However, this may be due to active layer freezeup at the beginning of the study period, rather than temperature dependent thermal properties of the snowpack, due to the availability of latent heat (Karunaratne and Burn, 2004). If so, then the 0.26 difference in \( n_f \) values from this portion of the study period may be a better representation of the efficacy of
snow compaction in taiga than the 0.2 difference from the entire study period. The largest weekly $n$-factors occurred during the week of January 10th, and were 1.2 and 1 at MC4 and MC3, respectively, while at MU4 and MU3 they were 0.72 and 0.57. This was the same week that temperatures began to decline rapidly, but the highest daily $n_l$ values were recorded early in the week when temperatures were still relatively high, so the elevated $n$-factors were not due to the decline in air temperatures.

5.7 Compaction as a management technique for road maintenance

The compaction treatment reduced temperatures at the base of the snowpack by 2 – 3 ºC at all of the study plots that were compacted regularly. This value is a conservative estimate for the effectiveness of the technique, as compaction was delayed until after the ground was mostly or entirely frozen due to delays associated with the COVID-19 pandemic. At the Dempster Highway the study period was 146 days, while in Mayo it was 145 days. Dividing the study period by 365 days and multiplying by the change in ground temperatures suggests that the temperature reduction from compaction represents a decrease in mean annual temperatures of 1.3 – 0.8 ºC. At DC3, mean annual temperatures were lowered by 0.4 ºC after a single compaction.

Advantages of using snow compaction to cool the ground in comparison with existing methods such as thermosyphons, ACE embankments, or widened embankments, are that the treatment is simple, inexpensive, adaptable, and requires no structural changes to the embankment. These traits are of particular importance in terms of mitigating the risk of permafrost thaw from increasing atmospheric temperatures due to climate change, since existing methods of ground cooling may be rendered ineffective if temperatures exceed their design
parameters. However, the approach requires consistent human resources, which may pose challenges that are beyond the scope of this thesis.

The compaction treatment was effective in both taiga and tundra, but the effectiveness in tundra appears to be reliant on crushing the basal depth hoar layer. In areas with little depth hoar development, or where the snowpack is deep and dense enough to shield the depth hoar from compaction, the treatment is unlikely to have a significant effect on ground surface temperatures.

The increased frequency of compaction at DC1 caused it to have a greater reduction in snow depth (Fig. 4.1) and increase in density (Fig. 4.7) than the other compacted plots at the Dempster Highway, but this did not lead to a greater reduction in daily mean temperatures at the base of the snowpack (Fig. 4.10). The difference in thermal resistivity between DU1 and DC1 was also similar to the other compacted plots (Fig. 5.2). One potential explanation is the low sample size of test plots, especially because snow conditions were not measured directly at the loggers, but instead at snow pits at the northern ends of the plots. The snow may have been shallower above the DU1 logger compared to the other undisturbed snowpacks, or deeper at DC1, counteracting the difference in thermal resistance from the snow compaction treatment.

Another possibility is that, since the majority of the reduction in thermal resistance appears to come from compaction of the depth hoar layer, then subsequent compaction after the depth hoar layer has been crushed may have little effect on the overall thermal resistance of the snowpack, as the rest of the snow has a thermal conductivity that is already high. This would mean that in tundra, only infrequent compaction is required to cause a significant reduction in ground temperatures, as long as the force of compaction is sufficient to reach the basal depth hoar layer. In taiga, compaction is likely to be effective regardless of whether depth hoar is
present since the soft snowpack snow has low thermal conductivity throughout, while also being highly susceptible to compaction due to its low density (Fig 5.1).
Chapter 6: Summary and Conclusions

6.1 Summary

The structural integrity of northern roads is threatened by thawing permafrost as temperatures in the Arctic increase rapidly due to climate change (Schetselaar et al., 2023). The shoulders of highway embankments are particularly susceptible to this risk, as deep snowbanks often accumulate there, increasing the nival offset so that ground temperatures are several degrees higher than the highway centreline (Stockton et al., 2019). This thesis used field experiments to test whether compaction of the snowpack would lower ground temperatures by increasing nf, as simulated by O’Neill and Burn (2017), which suggests that increasing snow density to 400 kg m$^{-3}$ may reduce ground surface temperatures by 3.5 °C over two years.

Mean daily ground surface temperatures were 2-3 °C lower at the compacted plots than at the undisturbed plots field sites in Central Yukon, indicating that the compaction treatment was effective at reducing basal snow temperatures in taiga and tundra environments. In tundra, the effectiveness of the technique likely depends on the compaction of a basal depth hoar layer with high thermal resistance, while in taiga the snowpack was highly susceptible to compaction throughout.

6.2 Conclusions

The following key results were obtained from the snow compaction field experiments:

1) The plots that were compacted by snowmobiles in tundra had snow depths 9 cm lower, and snow densities 40 kg m$^{-3}$ higher on average than the adjacent undisturbed plots.

2) The plots that were compacted by snowmobiles in taiga had snow depths 30 cm lower, and snow densities 142 kg m$^{-3}$ higher on average than the adjacent undisturbed plots.
3) The majority of the reduction in snow depth in tundra was from compaction of the depth hoar layer, while in taiga the reduction in depth was distributed throughout the snowpack.

4) Temperatures at the base of the snowpack were 2 – 3 °C lower at the compacted plots than at the undisturbed plots in both tundra and taiga. The reduction in temperature corresponds with an increase in freezing \( n \)-factors of about 0.2.

Based on these results, the principal conclusions of this thesis are:

1) The snow compaction treatment is effective at reducing temperatures at the base of the snowpack.

2) The reduction in annual mean ground surface temperature was about 1 °C, and this is a conservative estimate of the effectiveness of the treatment due to delays early in the winter associated with the COVID-19 pandemic.

3) Regular compaction of the snowpack over the shoulder of a highway embankment would likely be a cost-effective method for highway maintenance workers to reduce the temperature-differential between the shoulder and driving surface, mitigating the risk of damage from thaw subsidence.

4) Snowmobiles are capable of packing snow to densities slightly greater than what is common in settled snow. In snowpacks where the density is already high, the effectiveness of compaction at reducing ground temperatures is may be reliant on compaction of depth hoar.

6.3 Research implications

The compaction treatment was simple, inexpensive, and effective at reducing temperatures at the base of the snowpack under the conditions of the field experiments, but further research is
warranted to investigate the effectiveness of the technique under a variety of snow conditions, for example in snow that is harder, deeper, or without a depth hoar layer. The force and frequency of compaction could be optimized to maximize the reduction in ground surface temperatures with minimal effort depending on the local environment. The treatment could be supplemented by existing engineering methods of reducing ground temperatures, such as ACE, thermosyphons, or widened embankments. There may be similar opportunities to reduce ground temperatures at the embankment shoulder by manipulating the surface energy balance during the thawing season. For example, by shading the embankment, applying a layer of peat moss or vegetation with high evapotranspiration, or watering the embankment to absorb latent heat through evaporation.

The effectiveness of the technique at reducing ground surface temperatures in tundra by compacting depth hoar is consistent with the exceptionally low thermal conductivity of depth hoar measured in tundra by Sturm and Johnson (1992) and Sturm et al. (1997). The results support the research of Domine et al. (2019) and Dutch et al. (2022), which suggest that the low thermal conductivity of the depth hoar layer and heat transfer from vapour flow are not properly simulated in most snowpack thermal modelling software. This may cause simulated ground surface temperatures to be overestimated by up to 4 °C.

6.4 Study limitations

The effectiveness of the compaction technique and the precision with which its effects could be measured were limited by a variety of factors. The effectiveness of the technique was limited by:

1) The delay in starting the field experiments until November 26th, 2020, due to the COVID-19 pandemic.
2) Only being licensed to compact snow within the right-of-way of the highway (5 m).
3) Only having access to snowmobiles for compaction, and not heavier equipment.
4) Being unable to compact the snowpack more frequently than monthly due to unrealistic logistical requirements.

The precision with which the effects of snow compaction could be measured was limited by the following factors:

1) A lack of subsurface measurements, including ground temperatures, active layer depth, soil composition, and moisture content, making it impossible to judge the effects of compaction on freezeback.

2) Temperature loggers were planted after deep snow had already accumulated, so they were placed on top of a thin layer of snow rather than directly on the ground. This is of particular relevance due to the especially low thermal conductivity of the basal depth hoar layer, which may not have been fully captured by the temperature measurements.

3) There was only one temperature logger at each study plot, placed in the centre, and only one snow pit was dug at each plot every month. Multiple loggers or snow pits would improve assessment of changes in snow conditions that were caused by compaction as opposed to natural variance.

4) Measurements of hardness were imprecise due to the semi-quantitative nature of the penetration test. Measurements of snow density were imprecise due to the difficulty in collecting some snow samples using the 100 ml sampler, especially depth hoar at the base of the snow pack, or thin layers of dendritic snow. Transfer of snow to the weighing bag was also often difficult in windy conditions at the Dempster Highway site.
5) Because temperatures loggers were lost at the M1 and M2 study sites on the Silver Trail, there were no sites where snow was plowed regularly on to the study plots and temperature data was available for both the compacted and undisturbed plots. At the Dempster Highway site maintenance workers avoided dumping snow on the plots, and S. McQuesten road was plowed infrequently.

Limitations 1 and 2 were caused by the field sites being inaccessible prior to freeze-up and the accumulation of deep snow cover. Limitation 5 was caused by equipment failure. Limitations 3 and 4 are in part due to limited equipment availability, but are also a consequence of the study design for this thesis. Due to the exploratory nature of the experiments, it was decided that the available temperature loggers (19) would be distributed to as many field plots as possible, where they would be exposed to a variety of treatments and snow conditions. Measuring snow properties using snow pits supports this strategy by being quick, inexpensive, and done entirely in the field, allowing measurements to be taken at a greater number of field plots, even if precision is reduced. This approach allowed for greater insight to be gained into the mechanisms behind how the compaction treatment worked to reduce temperatures, and, because the results of the treatment were consistent under a wide variety of conditions, greater validation was provided for its effectiveness in the field.
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