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The N-Factor of Nonsorted Circles Along a Climate Gradient in Arctic Alaska

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ABSTRACT

Three study sites were selected on zonal sites from north to south along a climate gradient in Arctic Alaska. Air and mineral soil surface temperatures of nonsorted circles and adjacent well-vegetated tundra plots were monitored from September 2003 through September 2004, and the depths of vegetation, soil organic horizons and snow were measured. N-factors, the ratio of ground-surface temperature to air temperature, were determined for the summer and winter seasons. N-factors and thaw depths were greater for relatively barren nonsorted circles than for adjacent well-vegetated tundra. Along the climate gradient, the thickness of vegetation, soil organic layer and snow increased from north to south, while n-factors and thaw depths decreased at bare circles from 1.43 ± 0.02 to 0.74 ± 0.01 and from 81.2 ± 1.4 cm to 59.5 ± 2.4 cm, respectively, and at the tundra from 0.99 ± 0.02 to 0.17 ± 0.01 and from 62.6 ± 1.4 cm to 21.0 ± 2.8 cm, respectively. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: arctic tundra; plant cover; snow characteristics; soil temperature; thaw depth

INTRODUCTION

The depth of the active layer of the soil, the zone above the permafrost table that thaws annually, is a significant focus of arctic research because changes in the thickness of this layer due to climate or anthropogenic causes have major implications for the entire ecosystem (e.g. Nelson *et al*., 1997, 1998; Romanovsky and Osterkamp, 1997; Hinzman *et al*., 1998; Klene *et al*., 2001a, 2001b). To date, most research on variations in active-layer depth has examined the effects of broad-scale changes to climate and vegetation patterns. However, small-scale patterned ground features have been repeatedly shown to have major effects on average regional active-layer depths (Nelson *et al*., 1997; Walker *et al*., 2003, 2004). In this study, we examine the insulative effect of different vegetation types on soil-surface temperatures and thaw depths at a micro-scale, distinguishing between small-scale patterned ground features (nonsorted circles) and the surrounding well-vegetated tundra.

Nonsorted circles are patterned ground features measuring 0.5 to 3 m across that dominate the landscape in many arctic tundra regions (Washburn, 1980). Compared to the surrounding tundra areas, these features typically have little or no vegetation cover and greater thaw depths (Walker *et al*., 2004; Kade *et al*., 2005). Nonsorted circles are caused by differential frost heave that occurs when ice lenses form in soils during winter. The soils within nonsorted circles heave more than in the surrounding tundra due to a deeper active layer where more ice lenses can form (Peterson and Krantz, 2003). In addition, free-moving water with high free energy migrates from the surrounding tundra soils to the freezing front of nonsorted circles due to

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cryostatic suction (Williams and Smith, 1989), resulting in differentially greater frost heave, more soil disturbance and relatively barren soils.

The energy balance at the soil surface is a major factor influencing the development of nonsorted circles (Peterson and Krantz, 1998; Peterson *et al*., 2003); however, it is difficult to determine due to the interaction of several energy fluxes. The n-factor, the ratio of seasonal thawing or freezing degree-day sums at the soil surface to that in the air, integrates the effects of all surface factors of the soil thermal regime. It is a simple indicator of the energy balance at the ground surface, and it was developed in arctic engineering studies to estimate temperatures of homogeneous artificial surfaces from air temperatures (Carlson, 1952). Recently, n-factors have been calculated for natural systems to assess the surface thermal regime under a variety of natural vegetation types (Klene *et al*., 2001b; Taylor, 2001; Karunaratne and Burn, 2004), and to estimate permafrost temperatures and active-layer thickness over large areas (Smith and Riseborough, 1996; Klene *et al*., 2001a). However, the original concept of the n-factor is problematic when considering heterogeneous natural landscapes, and the term 'soil surface' needs to be defined when dealing with different plant canopy types and the presence of soil organic horizons. Here, we compare the air temperature to (a) temperatures just below live vegetation and (b) temperatures below the soil organic horizon at the mineral soil surface. The n-factors of this study are site-specific and depend on the thickness and type of vegetation present and snow cover during winter.

The focus of this research is two-fold: We examine (a) contrasts in the n-factor between zonal tundra and nonsorted circles within the study sites and (b) variation of the n-factor from north to south along a natural climate gradient in Arctic Alaska. We show the insulative effect of live vegetation and soil organic horizon on the mineral soil thermal regime in summer, and the insulative effect of vegetation, soil organic horizon and snow in winter for nonsorted circles and adjacent tundra. In addition, mean annual temperatures for air and the mineral soil surface were calculated to evaluate the annual net insulative effect of vegetation and snow on mineral soil.

METHODS

Study Area

The study was conducted along a bioclimate gradient from the coast of the Arctic Ocean to the Arctic Foothills along the northern segment of the Dalton Highway, Alaska (Figure 1). From north to south, we investigated three study sites. Howe Island (lat. 70° 18′ N, long. 147° 59′ W, elevation 8 m asl) is a small island just north of the coast of the Coastal Plain at Prudhoe Bay. According to the Circumpolar Arctic Vegetation Map (CAVM Team, 2003) and Walker (2000), Howe Island is part of bioclimate subzone C (prostrate dwarf-shrub subzone), with mean July temperatures from 5 to 7°C. Farther south, Franklin Bluffs (lat. 69° 40′ N, long. 148° 43′ W, elevation 130 m asl) is located in the Arctic Coastal Plain, with many thaw lakes dotting the landscape. This site is classified as bioclimate subzone D (erect dwarf-shrub subzone), with mean July temperatures from 7 to 9°C. The southernmost site is Happy Valley (lat. 69° 08′ N, long. 148° 50′ W, elevation 315 m asl) in the Arctic Foothills, where rolling hills and broad valleys dominate the landscape. Happy Valley belongs to bioclimate subzone E (low-shrub subzone), with mean July temperatures from 9 to 12°C. The climate of the area varies with distance from the Arctic Ocean and

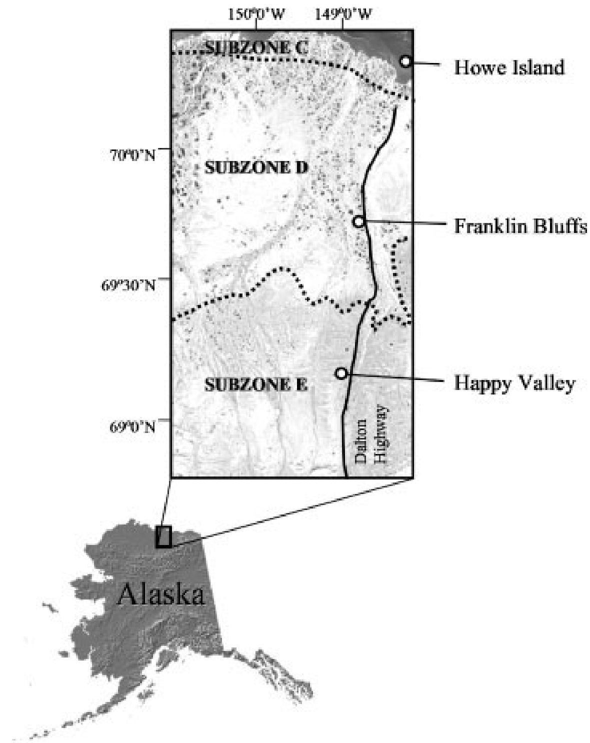

Figure 1 Location of the three study sites and the respective bioclimatic subzones along the northern segment of the Dalton Highway, Alaska.

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elevation. Temperature and precipitation increase from north to south. On the Arctic Coastal Plain, the mean annual precipitation ranges from 125 to 140 mm and 50% fall as snow. In the Arctic Foothills, mean annual precipitation ranges from 140 to 270 mm, with 40% falling as snow (Zhang *et al*., 1996).

All sites are located in the zone of continuous permafrost (Péwé, 1975), and all soils experience frost heave due to ice-lens formation (Ping *et al*., 1998; Walker *et al*., 2003). Nonsorted circles are a common part of the landscape, and their morphology changes along the bioclimatic gradient (Figure 2). Large, almost barren nonsorted circles about 3 m in diameter dominate the landscape on Howe Island. At Franklin Bluffs, nonsorted circles are bare to slightly vegetated and smaller (1 to 2 m in diameter). At Happy Valley, there are two distinctive types of nonsorted circles: (1) small, barren nonsorted circles (0.5 m in diameter) that are located between tussocks, and (2) larger well-vegetated nonsorted circles that are less expressed due to thick vegetation mats.

Data Collection

Nonsorted circles typical for the area and adjacent tundra plots were selected at each study site. At Howe Island, five barren nonsorted circles and five tundra plots with typically thin vegetation mats were chosen. At Franklin Bluffs, ten barren to sparsely vegetated nonsorted circles and ten tundra plots with intermediate to thick soil organic horizons were selected. At Happy Valley, five small, barren nonsorted circles located between sedge tussocks, five well-vegetated nonsorted circles and five tundra plots with thick soil organic horizons were selected. At each study plot, one temperature logger (iButton, Maxim Integrated Products) was buried at 1-cm depth in the mineral soil to represent the 'mineral soil surface', and it recorded soil temperatures every 4 h during 1 September 2003 until 31 August 2004. In addition, one temperature logger was installed at the interface of the live vegetation and the soil organic horizon at well-vegetated study plots (Figure 3). A calibration of

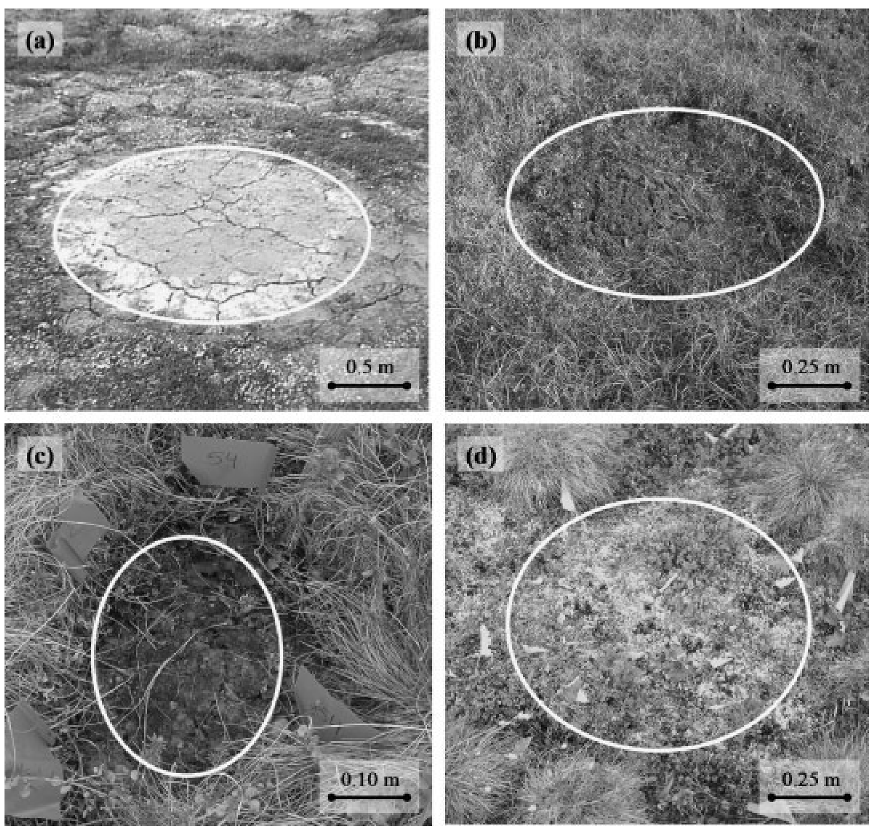

Figure 2 Nonsorted circles and adjacent tundra at the three study sites. (a) Bare nonsorted circle at Howe Island. (b) Bare to slightly vegetated nonsorted circle at Franklin Bluffs. (c) Bare nonsorted circle at Happy Valley. (d) Vegetated nonsorted circles at Happy Valley.

iButton loggers against 0°C in an ice bath in the lab showed that 75% of the loggers deviated between 0 to 0.5°C from 0°C, and in no case exceeded 1°C. The sites are part of the permafrost observatory study sites (Osterkamp and Romanovsky, 1999), and air temperatures were recorded hourly with Campbell Scientific temperature monitoring systems. Also, air and soil-surface temperature data were recorded from 1999 to 2003 at Franklin Bluffs and used to investigate year-to-year variability in mean annual temperatures. The volumetric soil water content in the active layer of the mineral soil was recorded with a Hydra-Probe (Advanced Measurement and Control Company). At each study plot, the thickness of the overlying live moss and vegetation mat and, if present, the soil organic horizon was recorded. The maximum snow depth and the overall snow density of each plot were measured in mid-April 2004. In addition, one subjectively chosen representative snow profile was recorded at each study site. The maximum thaw depth of the mineral soil was measured in early September 2004 by pushing a rod through the active layer and subtracting the depth of the organic horizon.

Daily mean temperatures were obtained for air, the base of live vegetation and the top of the uppermost mineral soil horizon. Thawing degree-day sums for air (TDD_a), live vegetation (TDD_v) and the top of the mineral soil surface (TDD_m) were calculated by summing daily mean temperatures from the first to the last day of the season that the mean soil-surface temperature rose above 0°C. Similarly, freezing degree-day sums were determined for air (FDD_a), live vegetation (FDD_v) and the mineral soil surface (FDD_m) by summing daily mean temperatures from the first to the last day of the season that the mean soil-surface temperature dipped below 0°C. The following n-factors were determined for each study plot (Figure 3):

- Summer n-factor for live vegetation: $n_v = TDD_v/TDD_a$
- Summer n-factor at the mineral soil surface: $n_m = TDD_m/TDD_a$
- Winter n-factor for live vegetation: $n_v = FDD_v/FDD_a$
- Winter n-factor at the mineral soil surface: $n_m = FDD_m/FDD_a$

Data were analysed using SAS (SAS Institute Inc., 2004). The environmental variables were compared between nonsorted circles and tundra plots performing univariate one-way analyses of variance. The mean annual temperatures in air and at the mineral soil surface were determined for the three study sites from 1 September 2003 through 31 August 2004.

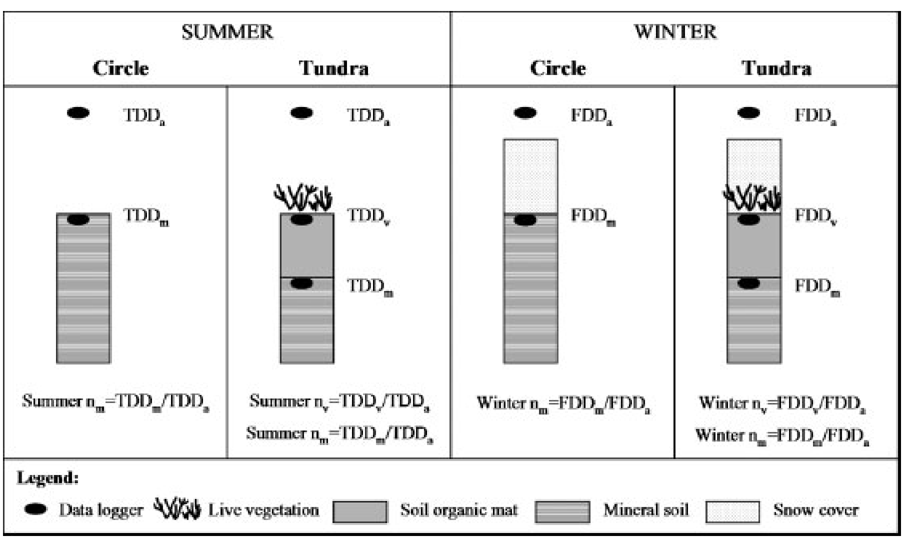

Figure 3 Diagram showing location of the temperature loggers in nonsorted circles and adjacent tundra. For each logger position, the derived thawing degree-day sums for air (TDD_a), under live vegetation (TDD_v) and at the top of the mineral soil (TDD_m) are indicated for summer, and freezing degree-day sums for air (FDD_a), under live vegetation (FDD_v) and at the top of the mineral soil (FDD_m) are indicated for winter. Calculations for the n-factor as an index of thermal insulation under live vegetation (n_v) and at the mineral soil surface (n_m) are shown.

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RESULTS AND DISCUSSION

Intrasite Comparisons

Howe Island, Subzone C.

On Howe Island, barren nonsorted circles had very high summer n_m factors averaging 1.43 (Table 1), which was likely the result of low air temperatures due to proximity to the Arctic Ocean. Cool air temperatures from the ocean differed greatly from the soil-surface temperatures of barren nonsorted circles (Figure 4), which absorbed direct solar radiation and were considerably warmer. The summer n_m-factor of adjacent tundra was much lower (mean 0.99), where the 2-cm thick vegetation insulated the soil and resulted in similar average soil and air temperatures. The adjacent tundra soils did not have a noticeable organic horizon (Figure 5b). The maximum thaw depth of the mineral soil was deeper in nonsorted circles (mean 81 cm, Figure 5c) than in adjacent tundra (mean 63 cm). Although summer air temperatures were colder at Howe Island than at Franklin Bluffs or Happy Valley, the thaw layer of the tundra was deepest here. The deep active layer in both circles and tundra may be due to a combination of absent or relatively thin vegetation mats and sandy soils with relatively low water content. The soil water content of the upper mineral horizon was lower for nonsorted circles (mean 25%) than for the surrounding tundra (mean 36%), where the vegetation layer apparently reduced evaporation (Figure 5d).

Insulation of the soil surface due to the blanket of snow resulted in a lower n_m-factor during winter, and both nonsorted circles and stable tundra had similar winter n_m-factors with means of 0.94 and 0.87, respectively (Table 1). The maximum snow depth was shallower for nonsorted circles (mean 5.8 cm, Figure 5e) than for adjacent tundra (mean 11 cm), which can be explained by the effect of wind removing the snow from the heaved bare sites and vegetation trapping snow at the vegetated tundra plots. The nonsorted circles heaved about 5 cm more than the surrounding tundra, thus decreasing the distance from the ground surface to the surface of the snow layer. The tundra plots had deeper depth-hoar layers than barren nonsorted circles (Table 2). The overall snow density was lower at the tundra (mean 0.30 g/cm^3, Figure 5f) than at nonsorted circles (mean 0.41 g/cm^3), which can be explained by the low density of the large and loosely packed depth-hoar crystals of the surrounding tundra.

Franklin Bluffs, Subzone D.

Most soils at Franklin Bluffs remained near saturation throughout summer, slowing decomposition rates and resulting in thick peaty muck horizons in the tundra. In summer, the soil temperature and the summer n-factor decreased with increasing height of the overlying vegetation and thickness of the soil organic horizon (Table 1, Figure 4). The mean summer n_m-factor reached 0.97 at relatively bare nonsorted circles, declining to 0.91 under about 8 cm of live vegetation and 0.35 under 21-cm thick organic horizons in adjacent tundra. The thaw depth of the mineral soil decreased with increasing vegetation and organic horizon thickness, averaging 94 cm for

Table 1 Summer and winter n-factors for nonsorted circles and adjacent tundra plots at the three study sites.

Study site (subzone)	Summer		Winter	
	n_v-factor	n_m-factor	n_v-factor	n_m-factor
Howe Island (C)				
Bare circle ($N = 5$)	—	1.43^a (0.02)	—	0.94^a (0.01)
Tundra ($N = 5$)	—	0.99^b 0.02)	—	0.87^b (0.01)
Franklin Bluffs (D)				
Bare circle ($N = 10$)	—	0.97^a (0.03)	—	0.73^a (0.01)
Tundra ($N = 10$)	0.91 (0.01)	0.35^b (0.01)	0.57 (0.01)	0.53^b (0.02)
Happy Valley (E)				
Bare circle ($N = 5$)	—	0.74^a (0.01)	—	0.35^a (0.01)
Vegetated circle ($N = 5$)	0.89^a (0.01)	0.34^b (0.01)	0.41^a (0.01)	0.34^{a,b} (0.01)
Tundra ($N = 5$)	0.76^b (0.01)	0.17^c (0.01)	0.35^b (0.01)	0.32^b (0.01)

Note: The n-factors were recorded at the interface of live vegetation and organic matter (n_v), and at the surface of the mineral soil (n_m). The sample size (N) is indicated for each plot type. Means are shown with standard errors in parentheses. Superscript letters indicate significant differences at $\alpha = 0.01$ between circles and tundra within a study site for each season and for each n_v- and n_m-factor.

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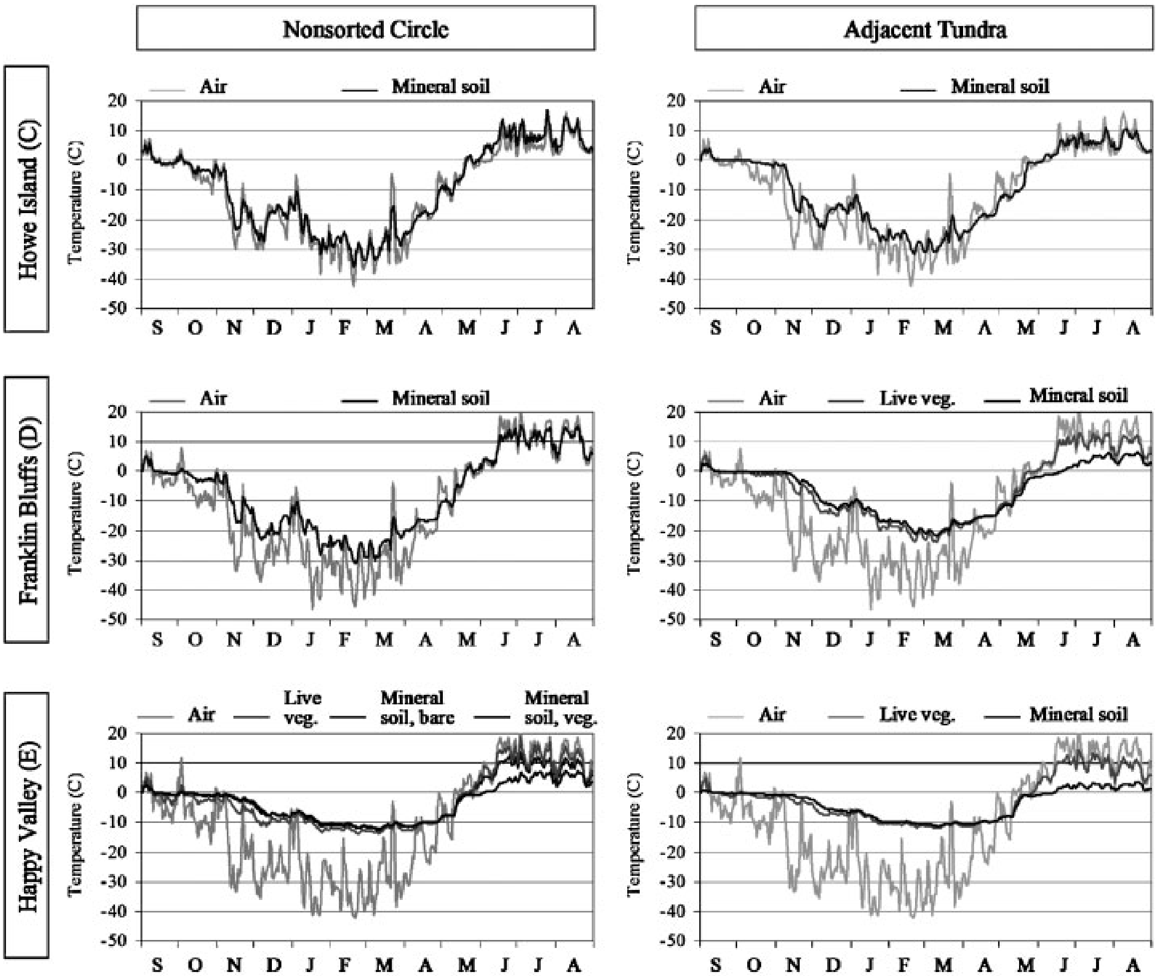

Figure 4 Daily mean temperatures from 1 September 2003 to 31 August 2004 for air (2 m height), under live vegetation and at the surface of the mineral soil for nonsorted circles and adjacent tundra at the three study sites.

nonsorted circles and 46 cm for adjacent tundra with thick organic horizons (Figure 5a-c). Soil water content was lower at nonsorted circles (mean 40%) than in the surrounding tundra (mean 45%, Figure 5d).

The difference between the n-factors of nonsorted circles and stable tundra plots decreased in winter due to the added insulative effect of snow, with winter n-factors ranging from 0.73 to 0.53 (Table 1) depending on snow depth and snow density. The nonsorted circles had a shallower snow pack with thinner depth-hoar layers and greater overall snow densities than adjacent tundra (Figure 5e and f, Figure 6). The difference in snow depth can be partly explained by differential frost heave during freeze-up, with nonsorted circles heaving approximately 12 cm more than adjacent tundra and thus resulting in shallower snow depth. The loosely packed depth-hoar crystals have very low thermal conductivity (Sturm *et al*., 1997), and deep snow and low snow density at adjacent tundra insulated the soil surface, resulting in

Figure 5 Environmental parameters for bare and vegetated nonsorted circles and adjacent tundra at the three study sites from north to south. (a) Thickness of live vegetation, (b) thickness of the soil organic layer, (c) thaw depth of the mineral soil, (d) soil moisture of the mineral soil, (e) snow depth, (f) snow density, (g) summer n_m-factor, (h) winter n_m-factor. Letters indicate significant differences at $\alpha = 0.05$ between circles and tundra within a study site. Means with standard errors are shown. Sample size: five circles and tundra plots at Howe Island and Happy Valley, ten circles and tundra plots at Franklin Bluffs.

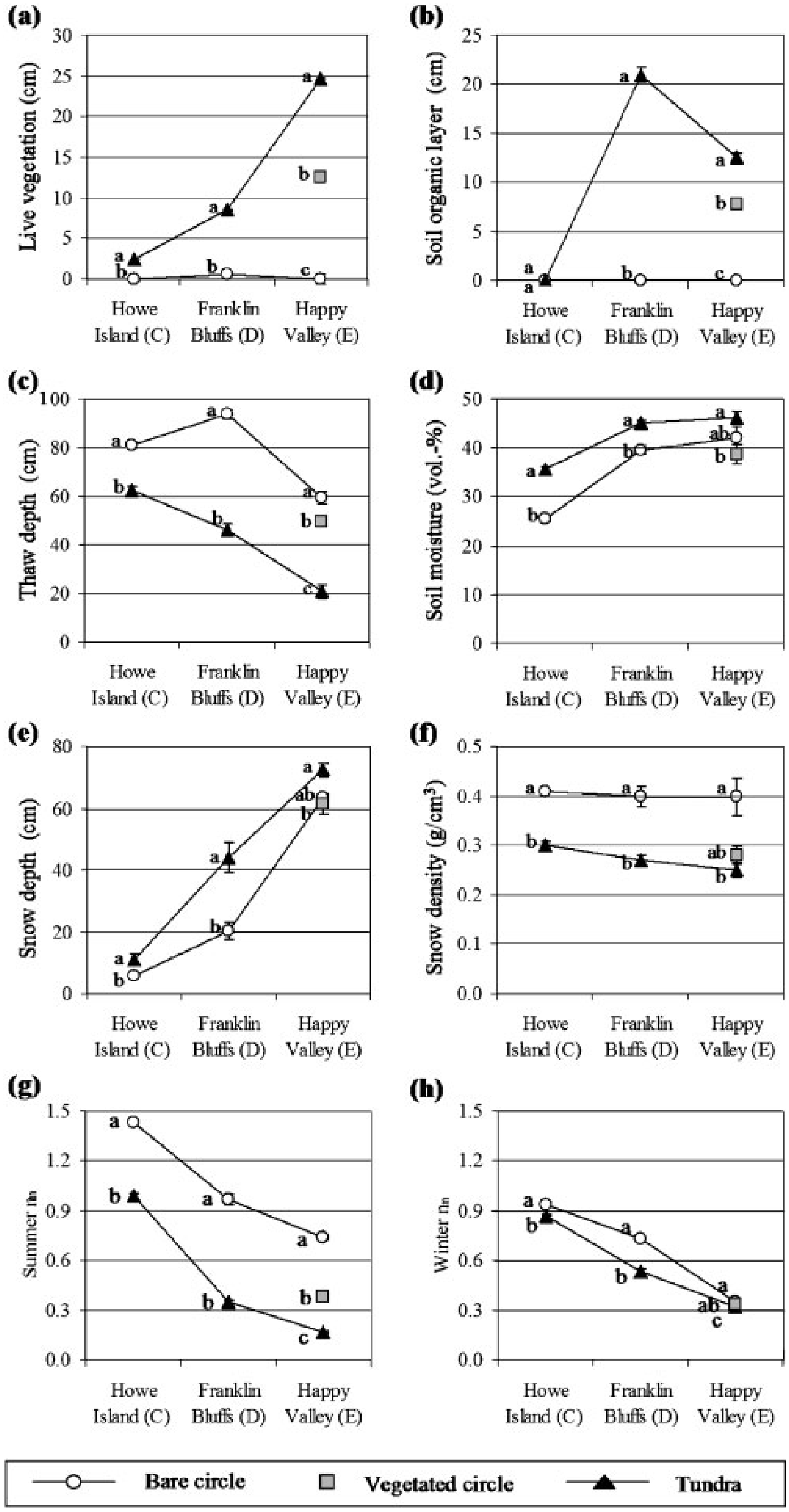

Figure 5 (*Continued*)

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Table 2 Snow profiles of representative nonsorted circles and adjacent tundra plots at the three study sites recorded in mid-April 2004.

Study site	Circle: Layer (cm)	Tundra: Layer (cm)	Grain shape	Hardness
Howe Island (C)	5–6	11–12	Surface hoar	Very low
	4–5	9–11	Loose, small rounded grains	Medium
	1–4	5–9	Wind slab	High
	0–1	0–5	Cup crystals	Very low
Franklin Bluffs (D)	16–20	25–36	Loose, small rounded grains	Low
	10–16	18–25	Wind slab	Medium
	9–10	16–18	Ice layer	High
	4-9	13–16	Loose, small rounded grains	Medium
	0–4	0–13	Columns of depth hoar	Very low
Happy Valley (E)	42–61	55–73	Loose, small rounded grains	Very low
	27–42	33–55	Wind slab	Medium
	25–27	31–32	Ice layer	High
	14–25	20–31	Loose, large rounded grains	Medium
	0–14	0–20	Columns of depth hoar	Very low

Note: Snow layers are described from top to bottom.

warmer soil than air temperatures and a lower winter n-factor.

Happy Valley, Subzone E.

The small, barren nonsorted circles at Happy Valley were sparse and hidden under *Eriophorum vaginatum* tussocks. Shading from the tall surrounding vegetation and low position within the microrelief led to a relatively cool soil temperature in summer (Figure 4) and low summer n_m-factors (mean 0.74, Table 1). The larger, vegetated nonsorted circles had lower n_v- and n_m-factors (means 0.89 and 0.34, respectively). The surrounding tundra was characterised by tall tussocks and low shrubs and thick mucky peat horizons: the mean n_v-factor was 0.76 and the mean n_m-factor was 0.17 in summer. The thaw depth of the mineral soil was greatest for bare nonsorted circles and lowest for the surrounding tundra with means 60 cm and 21 cm, respectively (Figure 5c). Soil water content was greater in adjacent tundra (mean 46%) than in bare circles (mean 42%) and vegetated circles (mean 39%, Figure 5d).

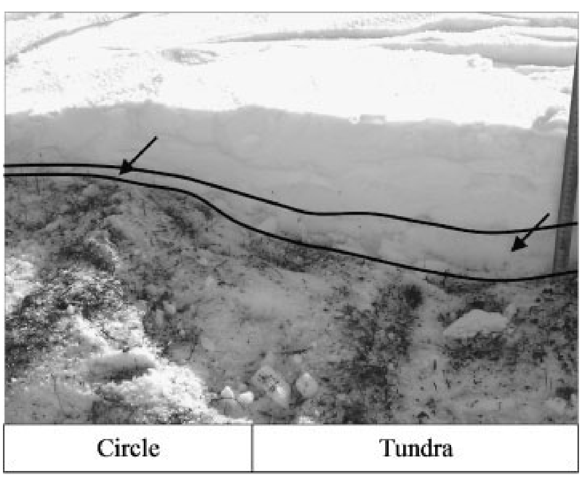

Figure 6 Snow profile across a nonsorted circle and adjacent tundra at Franklin Bluffs. The arrows indicate the depth-hoar layer.

The snow profiles were similar for nonsorted circles and adjacent tundra, the major difference being the shallower depth-hoar layer of nonsorted circles (Table 2). The stable tundra had deeper snow and lower snow densities (means 73 cm and 0.25 g/cm^3, Figure 5e and f) than barren nonsorted circles (means 64 cm and 0.28 g/cm^3, respectively). However, deeper snow depth at the stable tundra plots had only a minor additional warming effect on soil temperatures (Figure 4), and the winter n-factor differed little among the plots, ranging from 0.32 to 0.41 (Table 1).

Intersite Comparisons

At all sites, bare nonsorted circles had significantly thinner live vegetation (Figure 5a) and soil organic mats (Figure 5b) than adjacent tundra. The low insulation resulted in greater summer n-factors (Figure 5g) along with deeper active layers (Figure 5c) for nonsorted circles. Similarly in winter, thinner snow depth for nonsorted circles (Figure 5e) combined with thinner

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Table 3 Mean annual temperatures for air, soil surface and soil at 0.7 m depth, and the summer n-factor for undisturbed, moist nonacidic tundra at Franklin Bluffs.

Year	Mean annual temperature (°C)			Summer n-factor
	Air (2.0 m)	Soil surface (0.07 m)	Soil (−0.7 m)	
1999	−13.2	−3.6	−4.3	1.20
2000	−11.9	−5.6	−5.9	1.17
2001	−12.0	−6.1	−5.9	1.21
2002	−9.6	−3.5	−4.3	1.20
2003	−10.7	−4.6	−5.1	1.24

Note: The height of temperature recording is shown in parentheses.

vegetation and soil organic mats provided little insulation at nonsorted circles and resulted in greater winter n-factors than adjacent tundra (Figure 5h) at all study sites.

The thickness of live vegetation, soil organic horizon and snow increased from north to south along the climate gradient, resulting in a corresponding decrease in both summer and winter n-factors from north to south. In addition, the decreasing influence of the cool ocean air farther inland probably contributed to a lower n-factor. From Howe Island to Happy Valley, the summer n_m-factor decreased by about 50% for bare nonsorted circles and by about 80% for stable tundra plots. Shur and Borovskiy (1993) mapped n-factors in northern Russia and also found that the n-factor was greatest at the sea coast and declined inland towards more continental locations.

The active-layer depth was closely linked to the summer n_m-factor and the thickness of the overlying vegetation and soil organic horizons. The thaw depth of the mineral soil decreased from north to south by about 27% for nonsorted circles and by 66% for adjacent tundra. The differences between n_m-factors and thaw depths of bare nonsorted circles and adjacent tundra increased toward the south, where very thick soil organic horizons overlie stable tundra. The thaw depth of barren nonsorted circles was greatest at Franklin Bluffs. At Howe Island, the cooler temperatures limited thaw depth of the mineral soil; whereas at Happy Valley, small nonsorted circles were shaded by the tall vegetation of adjacent tundra.

This research monitored temperature data over the course of only 1 year and longer term records would be desirable. However, the mean annual temperatures for air, soil surface and in the upper soil horizon at Franklin Bluffs varied only slightly over a 5-year period (Table 3), and the summer n_m-factor calculated from air and soil-surface temperatures varied only minimally over the same time period. Also, Shur and Slavin-Borovskiy (1993) found that the n-factor for a whole season was stable from year to year and that there was definite regularity in its geographical variation.

Effect of Surface Conditions on Permafrost Temperature

The temperature at the top of the permafrost table is the major parameter determining permafrost stability and vulnerability of the permafrost to climate change. Here, we used the mean annual mineral soil-surface temperature (MAST) as an approximation for permafrost temperature. The bare soils of nonsorted circles were warmer in summer and colder in winter when compared to well-vegetated adjacent tundra (Table 4). However, the MAST at nonsorted circles and adjacent tundra within the same study site did not differ greatly, and interactions among vegetation, snow depth and frost heave cancelled out the insulative effect on the temperature regime. When compared along the climate gradient, the mean annual air temperature differed little among the three study sites. In contrast, the MAST increased from north to south, mainly due to the insulative effect of snow at the southern end of the gradient. Here, the warming effect of snow outweighed the summer cooling effect of the vegetation, and a possible increase in winter precipitation due to climate change might lead to permafrost degradation.

CONCLUSIONS

The nonsorted circles dotting the arctic tundra had warmer summer and cooler winter temperatures, thinner vegetation mats and organic horizons, drier soils and deeper thaw depths than adjacent terrain, forming a heterogeneous, patchy landscape. From north to south, both the summer n_m-factor and thaw depth of the mineral soil decreased for nonsorted circles by 50% and 27%, respectively, and for adjacent tundra by 80% and 66%, respectively. The nonsorted

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Table 4 Mean annual, July and January temperatures for the hydrological year September 2003 through August 2004 for air and the mineral soil surface at the three study sites.

Study sites	Mean annual temp. (°C)		Mean July temp. (°C)		Mean January temp. (°C)	
	Air	Mineral soil	Air	Mineral soil	Air	Mineral soil
Howe Island (C)	−10.9		6.2		−24.3	
Bare circle		−9.6 (0.1)		8.6 (0.1)		−23.1 (0.2)
Tundra		−9.3 (0.1)		6.6 (0.1)		−21.0 (0.2)
Franklin Bluffs (D)	−11.3		12.0		−29.1	
Bare circle		−7.5 (0.2)		11.5 (0.2)		−19.6 (0.4)
Tundra		−6.5 (0.2)		4.3 (0.3)		−13.5 (0.4)
Happy Valley (E)	−10.2		13.2		−28.0	
Bare circle		−2.3 (0.1)		9.7 (0.2)		−9.1 (0.1)
Vegetated circle		−3.4 (0.1)		5.5 (0.1)		−8.7 (0.3)
Tundra		−3.6 (0.1)		2.4 (0.1)		−7.9 (0.1)

Note: Mean annual temperatures at the mineral soil surface are shown for bare and vegetated nonsorted circles and adjacent tundra plots, with standard errors in parentheses.

circles had shallower snow depths, partly due to greater differential frost heave, and greater overall snow densities than adjacent tundra. Although the seasonal soil thermal regime differed between nonsorted circles and adjacent tundra, the mean annual soil temperatures were similar as the interactions among vegetation, snow depth and frost heave cancelled out the insulative effect on the temperature regime.

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