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Experimental Alteration of Vegetation on Nonsorted Circles: Effects on Cryogenic Activity and Implications for Climate Change in the Arctic

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Abstract

Nonsorted circles are relatively barren patterned-ground features common in most arctic tundra regions. We studied how vegetation changes on nonsorted circles might affect cryogenic processes, which is of relevance as arctic vegetation responds to climate change. Twenty-eight circles at a moist nonacidic tundra site in northern Alaska received one of four treatments: (a) vegetation removal; (b) vegetation removal and sedge transplants; (c) vegetation removal and moss transplants; or (d) no manipulation. We monitored soil-surface temperatures, thaw depth, frost heave, and soil-surface instability as indicators of cryogenic processes for three years.

Vegetation removal led to 1.5 °C (22.3%) warmer summer soil-surface temperatures, 4.8 cm (6.2%) deeper mean thaw depth, 3.5 cm (26.2%) greater frost heave and a drastic increase in an index of soil instability when compared to the control. In contrast, moss additions lowered soil-surface temperatures by 2.8 °C (41.8%) in the summer, delayed freezing by almost two weeks and thawing by one week, decreased mean thaw depth by 10.3 cm (14.9%), and decreased frost heave by 6.6 cm (52.4%) when compared to the control. The sedge treatment had intermediate effects on thaw and heave. This study indicates that increases in plant cover and particularly moss cover on nonsorted circles due to a warming climate would decrease the heat flux between the atmosphere and the mineral soil and result in shallower thaw and less frost heave, leading to regional reductions in the activities of nonsorted circles.

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Introduction

Small geometric patterned-ground forms such as nonsorted circles, earth hummocks, and small nonsorted polygons are common in permafrost and periglacial environments (Washburn, 1980), and the soil disturbance associated with these features affects the composition and distribution of plant communities within the tundra (Chernov and Matveyeva, 1997; Anderson and Bliss, 1998; Cannone et al., 2004; Walker et al., 2004; Kade et al., 2005). Here we focus on the effects of nonsorted circles (Fig. 1), which are relatively bare, patterned-ground features measuring 0.5 to 3 m across. Other terms for nonsorted circles include frost scars (Sigafoos, 1951; Johnson and Neiland, 1983), frost boils (Gartner et al., 1986; Chernov and Matveyeva, 1997; Walker et al., 2004), mud boils (Zoltai and Tarnocai, 1981), and spot medallions (Popov et al., 1963).

Differential frost heave, the lateral non-uniform heave that occurs when ice lenses form in soils during winter, plays a major role in the formation of most nonsorted circles. The soils within the circles thaw more deeply and heave more than the surrounding tundra (Walker et al., 2004). Peterson and Krantz (2003) have described the process of self-organization of nonsorted circles in the Differential Frost Heave model. More free-moving water migrates to the freezing front in the nonsorted circles than in surrounding terrain due to cryostatic suction, resulting in a three-dimensional heaving surface. (Williams and Smith, 1989). Greater heave occurs within the circles due to greater unfrozen water content within the circles and additional water migrating from the surrounding tundra during freezing (Peterson and Krantz, 2003). Differential frost heave may not be the only driver of nonsorted-circle formation; aggradation or degradation of near-surface ice-rich permafrost (see Kokelj et al., 2005) also contributes to the evolution of nonsorted circles. Changes to the vegetation due to fire have been shown to modify the heave, thaw, and morphology of frost-heave features in the Inuvik vicinity, Canada (Mackay, 1995).

Disturbance of the surface soil by frost heave and needle-ice formation maintains the barren appearance of nonsorted circles (Peterson and Krantz, 1998; Walker et al., 2004). *Needle ice* consists of elongated ice crystals that grow just beneath the soil surface when steep diurnal temperature gradients exist (Hallet, 1990), often pushing the surface layer upwards. Strong soil-surface disturbance due to needle-ice formation and contraction cracking, caused by rapid ground freezing and/or desiccation, has a negative impact on plant roots and results in little vegetation cover and shallow organic horizons in the centers of the active circles. In turn, the sparse plant canopy provides only minimal insulation at the soil surface, which results in deeper thaw depths in late summer and more heave during the winter than the surrounding vegetated tundra.

Several studies have investigated the effect of patterned ground on plant distributions (Sigafoos, 1951; Johnson and Neiland, 1983; Jonasson and Sköld, 1983; Gartner et al., 1986; Matveyeva, 1994; Chernov and Matveyeva, 1997; Anderson and Bliss, 1998; Cannone et al., 2004; Walker et al., 2004) and the influence of tundra vegetation on soil temperatures and thaw depth (Price, 1971; Nelson et al., 1998; Beringer et al., 2001; Klene et al., 2001; Pavlov and Moskalenko, 2002; Walker et al., 2003).

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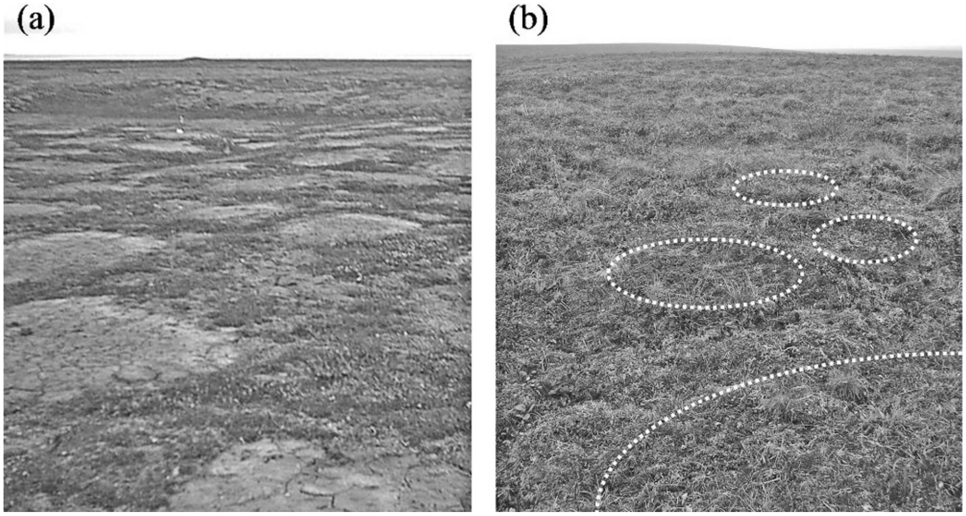

FIGURE 1. Nonsorted circles. (a) Circles at Howe Island, Alaska, in subzone C where the circles are unvegetated and easy to see. (b) Circles at the Sagwon Hills study site as indicated by the dotted lines. These circles are partially vegetated and more difficult to discern.

This study focuses on the effect of vegetation on the thermal properties and cryogenic processes associated with patterned-ground features. Shifts in species composition and increased vegetation growth due to climate warming could alter cryogenic processes such as frost heaving and soil churning within nonsorted circles and lead to new landscape patterns. This could change a wide variety of ecosystem properties that are affected by the presence of nonsorted circles, including species diversity, plant biomass, decomposition rates, soil moisture and nutrient status, carbon sequestration, and heat and trace gas fluxes (Walker et al., 1998, 2004). We investigate following question: How does vegetation affect several cryogenic properties such as the thermal regime, thaw depth, frost heave, and soil-surface stability within nonsorted circles? We manipulated the vegetation canopy on nonsorted circles and examined over the course of three years how these variables are affected by (a) the absence of vegetation, (b) vascular plants with an extensive, soil-stabilizing root system, or (c) a thick, insulating moss carpet.

Study Area

We conducted the experiment in the Sagwon Hills near the Dalton Highway in northern Alaska (Fig. 2; 69°25′58″N, 148°40′23″W, elevation 280 m). The study site is situated at the northern flank of the Arctic Foothills overlooking the Arctic Coastal Plain about 100 km south of Deadhorse. Broad rounded hills with elevations up to 350 m dominate the landscape. Mean annual air temperatures range from −7 to −10 °C, and mean annual precipitation ranges from 140 to 270 mm, 40% of which falls as snow (Haugen, 1982). The site has a thin loess mantle over Tertiary outwash gravel. The soils have developed on fine-textured materials, mainly silt loams, and are calcareous (Bockheim et al., 1998). The soils contain permafrost within 1 m of the soil surface and show strong signs of soil mixing due to cryoturbation (Ping et al., 1998).

The vegetation and nonsorted circles at the study site are broadly representative of those found near the southern edge of bioclimate subzone D of the Circumpolar Arctic Vegetation Map (CAVM Team, 2003). Nonsorted circles are common and cover approximately 30% of the local landscape. They measure 1 to 1.5 m in diameter and are spaced about 5 m apart. They are nearly flat in the summer and moderately well vegetated but are still recognizable by their distinctive vegetation patterns (Fig. 1b). The zonal vegetation, which occurs between the nonsorted circles, is non-tussock sedge, dwarf shrub, moss tundra belonging mainly to the plant association Dryoado integrifoliae–Caricetum bigelowii (Walker et al., 1994). (Note: Plant association names use the Braun-Blanquet nomenclature accepted by the International Botanical Congress [Weber et al., 2000].) This vegetation has continuous cover and is dominated by *Dryas integrifolia*, several

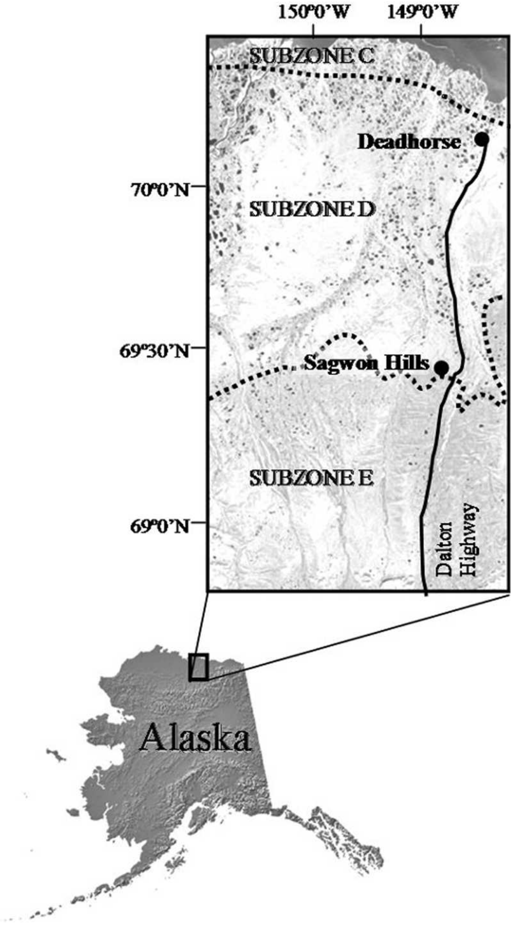

FIGURE 2. Location of the study site and the bioclimate subzones (CAVM Team, 2003) along the northern portion of the Dalton Highway, Alaska.

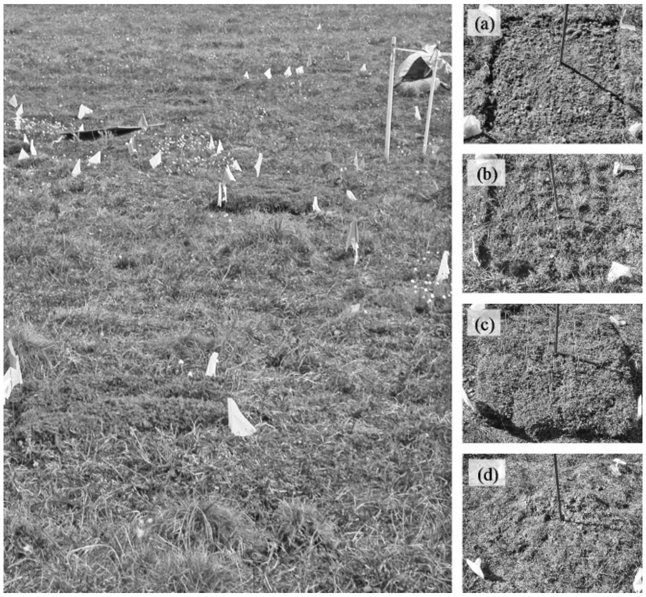

FIGURE 3. Overview of the study area and the four treatment groups of the nonsorted circles. (a) Vegetation removal. (b) Sedge transplants. (c) Moss transplants. (d) Control. The plots measure 0.5 m^2.

willow and sedge species, and thick moss mats consisting mainly of *Hylocomnium splendens* and *Tomentypnum nitens*. Well-developed organic soil horizons (about 15 cm thick) overlay the loamy mineral soil. The thin vegetation mat on the nonsorted circles belongs to the association Junco biglumis–Dryadetum integrifoliae (Kade et al., 2005) and consists mainly of the dwarf shrub *Dryas integrifolia* and several lichen species. Small bare areas are exposed as a result of active soil churning. The soil organic horizon is very thin (less than 1 cm thick), and the upper mineral soil has a loam texture.

Materials and Methods

We selected 28 nonsorted circles with similar environmental characteristics within a total area of about 400 m^2, and we marked an area of 0.5 m^2 (0.7 m × 0.7 m) in the center of each circle for manipulation. In July 2002, four groups of seven nonsorted circles were randomly selected to receive one of the following treatments (Fig. 3). (a) Vegetation removal: We cleared the existing vegetation mat from the nonsorted circles with a knife, and the underlying mineral soil was exposed. (b) Vegetation removal and sedge transplants: We collected small *Eriophorum vaginatum* tussocks from the surrounding tundra, which we transplanted at 10 cm intervals into the nonsorted circles after the vegetation was removed. Each plot received a total of 49 small tussocks, which were about 10 cm tall. (c) Vegetation removal and moss-carpet transplants: We cut moss slabs consisting mainly of *Hylocomium splendens* and *Tomentypnum nitens* of about 15 cm thickness from the surrounding tundra and placed them on the nonsorted circles once the vegetation was removed. (d) Control: The plots were not manipulated. Each summer, we weeded the experimental plots to maintain the treatment.

At each plot, the soil temperature at 1 cm depth was recorded hourly during September 2002 through August 2005 with a Hobo H8 Pro Temp data logger with an accuracy of ±0.2 °C (Onset Computer Corporation, 2000). We measured thaw depth in early September 2003–2005 by pushing a 1-cm-diameter rod through the active layer. We pounded 1.5-cm-diameter rebar at least 80 cm into the permafrost at the center of each study plot at the time of maximum thaw and measured the distance from the top of the bar to the ground surface in the summer and at the end of the winter. The heave was calculated as the difference between the summer and winter measurements of the respective year, thus avoiding measurement errors in case the rebar heaved. We recorded frost heave and snow depth in mid April 2003–2005. Based on experience in previous years, thaw depth is near maximum in early September, and snow depth and frost heave are near maximum in mid-April. We determined soil-surface instability with the help of a soil instability index, which corresponded to the "toothpick index" of Gartner et al. (1986). In July 2002, each plot received 25 evenly distributed 6-cm-long toothpicks or 30-cm-long shish kebab sticks depending on the physiognomy of the plant cover. The toothpicks were inserted upright half their length (3 cm) into the ground in the control, bare, and sedge plots. The moss treatments required longer sticks to penetrate the moss, so the shish kebab sticks were used. Although not directly comparable, we inserted the shish kebab sticks to the same depth as the toothpicks (3 cm). After one year, we recorded the number of straight, visibly tilted or expelled toothpicks and shish kebab sticks (here referred to jointly as picks). Picks that were moved upwards due to frost action and expelled from the soil but still supported by the surrounding vegetation were reported as expelled. We transformed the data into an index of soil-surface instability. We multiplied the number of straight picks by 0, tilted picks by 1, and expelled picks by 2, and summed the scores for each plot, with the maximum possible soil-surface instability being a total score of 50. We repeated the pick measurements over the course of three years.

Data were analyzed using SAS (SAS Institute Inc., 2004). We performed repeated measure analyses for each response variable (soil temperature, thaw depth, frost heave, snow depth, and soil-surface instability) to determine whether the four treatment groups had simultaneously similar response patterns over the three years of the study (Winer, 1971). The results for an effect of time were non-significant for most response variables, and we report the data of the last experimental year. We used univariate one-way analyses of variance with Tukey's W procedure ($\alpha = 0.05$) to estimate treatment differences (Tukey, 1953).

Results

SOIL TEMPERATURES

Daily mean soil temperatures at 1 cm depth ranged from 15 °C in the summer to −25 °C in the winter in the control plots (Fig. 4a). Soil temperatures varied greatly among treatments in the summer, with the bare and sedge plots being up to 4 °C warmer than the control, and the moss treatments up to 8 °C cooler (Fig. 4b). The vegetation-removal treatments increased the mean summer soil temperatures (June through August) by 1.5 °C or 22.3% when compared to the control, and the moss-addition treatments decreased the mean summer soil temperatures by 2.8 °C or 41.8% (Table 1). The sedge plots had a relatively large portion of bare soil, and the mean summer soil temperatures were only slightly less than for the bare plots. In the summer, the vegetation-removal and sedge treatments also had greater daily soil temperature fluctuations when compared to the control, whereas the moss-addition treatments showed very little daily fluctuation (e.g., Fig. 5a). As an example, from 04:00 to 15:00 on 18 July 2004, the hourly mean soil temperature at the bare plots increased 11 °C, from 10 to 21 °C, while the soil temperature at the moss plots increased 2 °C, from 8 to 10 °C. The insulation

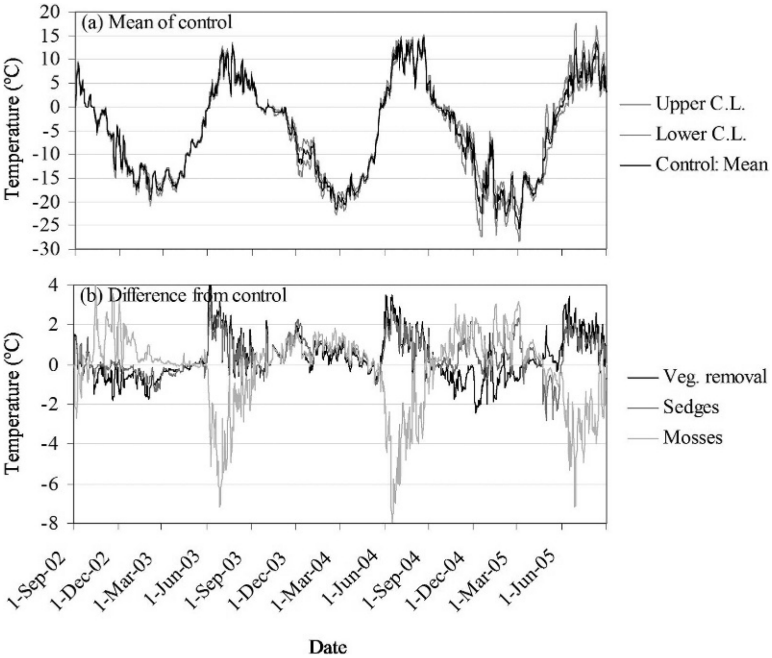

FIGURE 4. Near-surface soil temperatures (°C) from September 2002 through August 2005. (a) Daily mean temperatures for the control plots, with upper and lower 95% confidence limits. (b) Residuals of the daily mean temperatures for all four treatments.

provided by the moss carpet delayed fall freezing by almost two weeks and spring thawing by one week when compared to the other treatments (Table 2).

During the winter months, the soil thermal properties of the frozen soil varied less than the thawed conditions. The differences between the daily mean near-surface soil temperatures among the treatments were more compressed than in the summer months (Fig. 4b) due to the relatively uniform insulation of the snow cover (see discussion below). The bare plots were generally slightly cooler than the control, and the moss plots were consistently warmer (Fig. 4b). The differences among the treatments were minimal during the winter 2003/2004, when the overall snow depth was uncharacteristically deep. (The mean snow depth of the control plots was 27 cm in spring 2003, 37 cm in spring 2004, and 20 cm in spring 2005.) The mean winter soil temperatures (December through February) were lowest at the bare plots (mean = −18.7 °C, −5.1% from the control; Table 1) and greatest at the moss plots (mean = −16.5 °C, +7.3% from the control). The hourly temperature fluctuations in the winter were negligible for all treatments (Fig. 5b).

TABLE 1

Mean summer temperature (MST), winter temperature (MWT), and annual temperature (MAT) at the soil surface, mean thaw depth, frost heave, snow depth, and index of soil-surface instability for the last year of the experiment (2004/2005). Means are shown with standard error in parentheses, and significant differences between treatments as indicated by Tukey pairwise comparisons are noted with different letters ($\alpha = 0.05$).

	Treatment			
Response variable	Veg. removal	Sedges	Mosses	Control
MST$_{\text{soil-surface}}$ (°C)	8.2^{a} (0.3)	7.9^{ab} (0.1)	3.9^{c} (0.3)	6.7^{b} (0.4)
MWT$_{\text{soil-surface}}$ (°C)	–18.7^{b} (0.4)	–17.5^{ab} (0.3)	–16.5^{a} (0.4)	–17.8^{ab} (0.5)
MAT$_{\text{soil-surface}}$ (°C)	–6.5^{a} (0.2)	–6.2^{a} (0.1)	–6.7^{a} (0.2)	–6.6^{a} (0.2)
Thaw depth (cm)	82.4^{a} (0.5)	77.0^{b} (1.0)	66.0^{c} (0.6)	77.6^{b} (0.6)
Frost heave (cm)	15.9^{a} (0.5)	13.3^{b} (0.4)	6.0^{c} (0.4)	12.6^{b} (0.6)
Snow depth (cm)	22.9^{a} (2.6)	22.4^{a} (0.8)	15.7^{b} (2.1)	20.1^{a} (1.5)
Index of soil instability	48.1^{a} (0.4)	24.9^{b} (1.6)	2.0^{d} (0.4)	6.6^{c} (1.4)

Although the vegetation had a large effect on the soil-surface temperatures in the summer and winter, the net effect on the mean annual soil temperatures was negligible. The mean annual soil temperatures did not differ significantly among the treatments, ranging from −6.2 to −6.7 °C (Table 1). On the vegetated plots, the cooler soil temperatures in the summer were offset by the warmer soil temperatures in the winter. The temperature differences among the treatments were greater in the summer than in the winter, indicating that the winter conditions were more

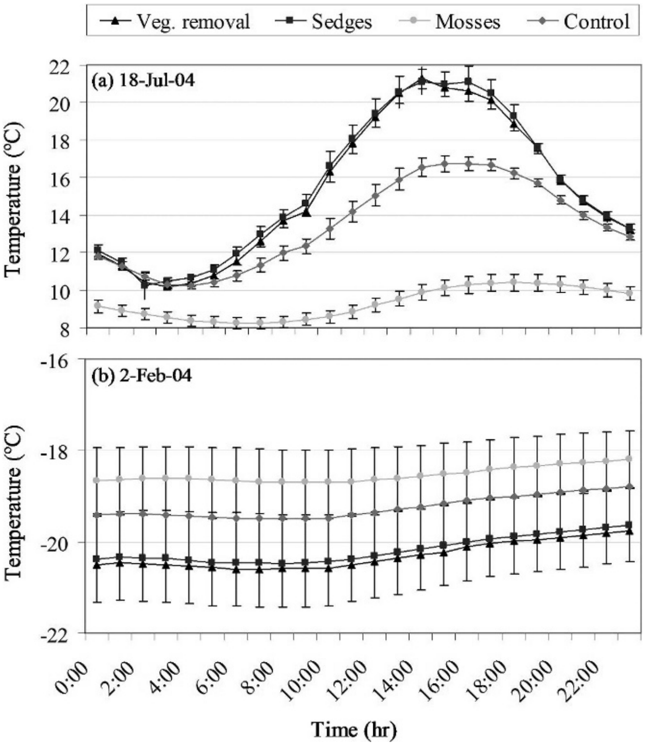

FIGURE 5. Hourly mean soil temperatures (°C) at 1 cm depth for the four treatments, shown with standard errors. (a) A typical day in the summer. (b) A typical day in the winter.

TABLE 2

Dates of soil freezing and thawing at 1 cm depth for the four treatments.

		Treatment			
		Veg. removal	Sedges	Mosses	Control
Freeze	2002	04 Oct	04 Oct	10 Oct	05 Oct
	2003	06 Oct	05 Oct	12 Oct	04 Oct
	2004	13 Sep	13 Sep	20 Sep	14 Sep
Thaw	2003	01 Jun	01 Jun	12 Jun	03 Jun
	2004	22 May	23 May	06 Jun	22 May
	2005	27 May	28 May	10 Jun	28 May

important in determining the overall annual temperatures at the mineral soil surface, thus overriding the summer differences.

THAW DEPTH

The bare plots had the greatest thaw depths (mean 82.4 cm, +6.2% from the control; Table 1), and the sedge and control plots had slightly shallower thaw depths (means 77.0 and 77.6 cm, respectively). The thaw depth was least at the moss plots (mean 66.0 cm, −14.9% from the control).

FROST HEAVE

The frost heave of the control plots averaged 12.6 cm (Table 1). The bare plots heaved about 3.3 cm more (+26.2%) than the control plots, while the sedge plots experienced heave similar to the control plots. The moss-addition treatments heaved about 6.6 cm less (−52.4%) than the control plots.

SNOW DEPTH

The snow measurements reflected the effect of the vegetation treatments on the relative elevation of the plot surface. The moss treatment had a relatively higher surface than the other treatments because of the addition of thick moss slabs. The bare plots had a lower surface after the removal of the vegetation but were mounded in the winter as a result of high frost heave. The snow formed a relatively level cover across the landscape that masked the variations in microtopography. Therefore, the moss plots had significantly thinner snow cover (mean 15.7 cm) than the other treatments, which did not differ from one another (Table 1). Despite the shallower snow on the moss plots, winter soil surface temperatures were warmer than the control because of the overwhelming insulative effect of the dry moss.

SOIL-SURFACE INSTABILITY

The movement of the soil surface was reflected in the soil instability index, where a high value corresponded to a large number of tilted or expelled picks. This index gives only an impression of the degree of soil movement; it does not indicate quantitative differences in stability because an expelled pick does not indicate twice the cryoturbation amount of a tilted pick. The soils of the control and moss plots were very stable, whereas the bare plots had the greatest soil-surface instability, with most toothpicks being expelled from the soil after one year (Table 1). The soil instability index of the sedge plots decreased over the course of the experiment (42 in 2003, 40 in 2004, and 25 in 2005). After the first year, most sedge transplants did not expand their rooting system and were heaved about 3 cm out of the ground. We pushed the sedge transplants back into the soil each summer; and at the end of the experiment, all transplants put out fibrous roots into the surrounding soil, leading to more stable soils.

Discussion

INTERACTIONS AMONG SYSTEM COMPONENTS

The effects of vegetation removal and moss addition on thaw depth and frost heave in this experiment are illustrated in Figure 6. The thaw depth was closely linked to the soil-surface temperatures during the summer months, and the warm bare plots had the greatest thaw depths. In contrast, the moss carpets delayed the onset of thawing, shaded and reduced the heat flux into the underlying mineral soil in the summer, and prevented it from warming during the summer, resulting in shallower thaw depths. Several previous studies have reported the linkage between vegetation and thaw depth (Price, 1971; Anderson and Bliss, 1998; Nelson et al., 1998; Beringer et al., 2001; Klene et al., 2001; Pavlov and Moskalenko, 2002; Walker et al., 2003; Kade et al., 2005, 2006). The vegetation canopy and snow cover act as a buffer layer between the atmosphere and the ground by decreasing the heat flux into the ground during the summer and out of the ground during the winter, thus strongly affecting soil-surface and permafrost temperatures (Luthin and Guymon, 1974). This experiment found that altering the vegetation cover had large effects on the summer soil-surface temperatures, but had no significant effect on the *annual* mean soil temperatures at the top of the mineral soil. Although we did not measure the temperatures at the top of the permafrost table, this result suggests that permafrost temperatures were not affected locally by the experimental manipulations. Pavlov and Moskalenko (2002) monitored the thermal regime of tundra soils on the Yamal Peninsula in western Siberia and found a 0.5 to 1.5 °C cooling effect on the mean annual soil temperature after the addition of a 5-cm-thick vegetation and litter layer. It is still unclear what the net effect of vegetation removal or addition is on mean annual soil and permafrost temperatures. Additional factors such as local moisture conditions, which we did not monitor in this experiment, may play an important role in some situations and explain the difference between our results and those of Pavlov and Moskalenko (2002).

Frost heave is caused by ice-lens formation during the winter and the resulting increase in the soil volume. Our vegetation-removal plots heaved 26.2% more than the control plots (Table 2), which can partly be explained by the deeper thaw depth allowing for more ice lenses to form. The moss treatments reduced mean frost heave 52.4% when compared to the control, presumably as a result of decreased thaw depth and thus reduced water for ice-lens formation. The final heave of the moss-covered circles is comparable to the frost heave of the stable tundra at the study site (Walker et al., 2004), and the addition of the 15-cm-thick moss carpet may have essentially eliminated differential frost heave at this site. The depth of the active layer directly affected the amount of frost heave of the nonsorted circles. In both bare and moss plots, the percentage change in frost heave was about three to four times the percentage change in the thaw depth. If the heave was due to only the water in the soil column of the nonsorted circle, the percentage change of heave should be the same as the percentage change in the thaw depth when compared to the control. The excess water for ice-lens formation had to come from the adjacent tundra areas, possibly either through the slow movement of ground water or through cryostatic suction.

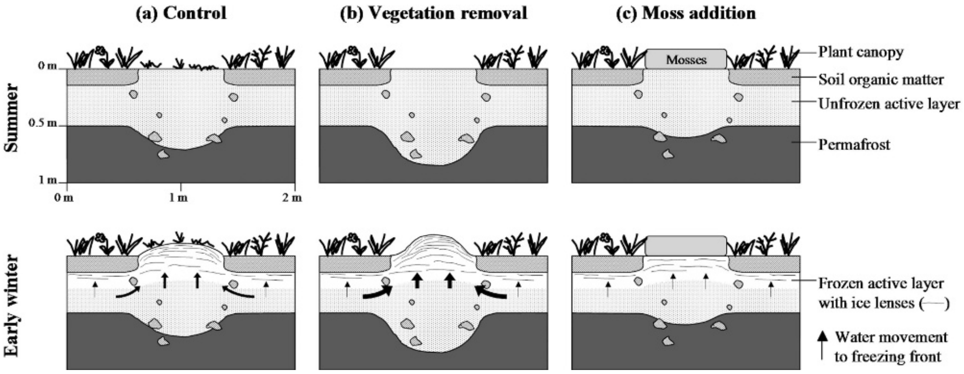

FIGURE 6. Idealized cross section of the control and experimentally altered nonsorted circles showing the thaw depth in the summer and the frozen active layer with ice lenses, water movement due to cryostatic suction, and frost heave in early winter during freeze-up. (a) Slightly vegetated nonsorted circle (control treatment). (b) Bare nonsorted circle after vegetation removal showing deeper active layer in summer and enhanced heave in winter. (c) Nonsorted circle with the addition of a moss carpet showing reduced active layer in summer and reduced heave in winter. Note the entrapment of organic matter in the aggrading permafrost table in (c). The arrows depict water movement to the freezing front of ice lenses during winter, and the size of the arrows corresponds to the amount of water movement.

The vegetation had a major impact on soil-surface instability. The soils of the control and moss plots were relatively stable, whereas the bare plots had the greatest soil-surface instability. This agrees with Gartner et al. (1986), who reported greater surface stability as indicated by toothpick movement in vegetated tundra micro-habitats of lichen and moss mats than in unvegetated nonsorted circles. Although we did not study needle ice (or pipkrakes) *per se*, we observed needle ice on the soil surface of the bare plots and the bare portions of the sedge and control plots early in the summer and noticed a loose and crumbly "cottage cheese" soil structure as the result of needle-ice formation (Hallet, 1990). Needle-ice crystals form during the early summer and fall, when steep temperature gradients exist between the air and soil (Washburn, 1980). The organic-rich soils of the stable tundra may decrease the thermal gradient between the air and mineral soil and thus the formation of needle ice. In contrast, the needle ice pushes the soil-surface layer upwards and decreases soil-surface stability where the vegetation is absent.

The instability of the bare soil surfaces of nonsorted circles reduces plant establishment (Johnson and Neiland, 1983; Anderson and Bliss, 1998) and delays succession (Sigafoos, 1951; Haugland and Beatty, 2005). Unstable soils allow only thin vegetation mats composed mostly of lichens, small mosses, and small vascular plants (e.g. *Braya purpurascens*, *Chrysanthemum integrifolium*, *Dryas integrifolia*, *Juncus biglumis*, *Saxifraga oppositifolia*, *Toffieldia coccinea*) to establish in small crevices of the barren surfaces and withstand repeated soil movement. In some cases, the soil disturbance may also be important in providing the main opportunity for some seedlings to regenerate (Gartner et al., 1986; Gough, 2006). For example, *Eriophorum vaginatum* requires mineral soils to establish, so it may find the margins of the barren patches sufficiently stable without getting into the highly disturbed centers or the competitive peaty environment surrounding the circles. Plants can eventually stabilize the soil with their root system once they become established, as indicated in the sedge treatment. In this experiment, it took three years for the sedge seedlings to develop sufficient root systems to keep them from being heaved out of the soil. The annual soil heaving probably prevents *Eriophorum vaginatum* from colonizing the centers of bare nonsorted circles. This sedge species is often found in rings around nonsorted circles. Mosses are very important in stabilizing the soils. Thick moss carpets such as those used in this experiment usually do not occur on nonsorted circles except in the southern parts of the arctic tundra where they develop over long periods of time. Generally, thinner moss carpets develop as the soils become more stable after the establishment of vascular plants with roots that help stabilize the soils.

The insulation caused by snow probably did not affect the cryogenic regime much in this experiment because the winter temperatures were relatively similar among treatments. Although Mackay (1983) has shown that frost heave may continue well into winter, the heaving should be close to its maximum in early winter and not be strongly influenced by soil temperatures throughout the winter. Soil moisture, which is thought to be an important factor in the development of nonsorted circles (Peterson and Krantz, 2003), was not measured continuously in this experiment. Kokelj et al. (2005) have shown that insulating the areas between earth mounds at Inuvik, Canada, enhances frost heave and that vegetation removal eliminates the heave. It would be useful to repeat an experiment similar to ours where vegetation is both added to and removed from the circles and adjacent stable tundra at several localities with different site variables. In addition, the influence of soil moisture, drainage patterns, soil texture, and local climate on the cryogenic regime should be compared.

IMPLICATIONS FOR CLIMATE CHANGE

Climate change in arctic ecosystems is expected to have major effects on vegetation patterns, nutrient cycling, and the permafrost table (Osterkamp and Romanovsky, 1999; Chapin et al., 2004; Hinzman et al., 2005). A warming arctic climate will likely result in increased plant biomass and changes to species composition (Epstein et al., 2000; Dormann and Woodin, 2002). The character of the vegetation growing on the nonsorted circles changes as one travels along a climate gradient from the coast of the Beaufort Sea to the foothills of the Brooks Range in northern Alaska (Kade et al., 2005). From north to south, there is a general increase in both the horizontal density of vegetation and the thickness of the plant canopy growing on the nonsorted circles. Mosses in particular are more abundant in the warmer southern climate. Thus, climate warming would likely favor moss growth in both circle and intercircle areas (Walker et al., 2003), resulting in the cooling of the nonsorted circles and masking the morphological differences between circles and stable tundra. The differential frost heave of nonsorted circles may decrease, potentially resulting in the local disappearance of these patterned-ground features. Furthermore, nonsorted circles provide islands of habitat for certain plant communities (Kade et al., 2005), increasing the diversity of these areas compared to landscapes without nonsorted circles. In some parts of the Low Arctic, especially warmer areas, the loss of nonsorted circles could lead to a decrease in landscape heterogeneity and biodiversity.

Conclusions

The different vegetation types influence the patterned-ground system mainly by affecting near-surface soil temperatures. Thick vegetation mats act as an insulative layer producing cooler summer temperatures and delaying thawing and freezing of the soil. Shallower active layers and delayed freezing result in decreased ice-lens formation and frost heave. In contrast, bare soils allow for deeper thaw depths in the summer and presumably the formation of more ice lenses and thus greater frost heave in winter. The bare soils also experience less soil-surface stability and frost heaving. This in turn retards plant succession and the formation of a continuous vegetation mat, reinforcing cryogenic processes. Increased moss production and/or shifts of vegetation zones as a result of a warming arctic climate would likely decrease the cryogenic activity of nonsorted circles in the Low Arctic. The potential local disappearance of nonsorted circles could result in decreased landscape heterogeneity.

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