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Arctic patterned-ground ecosystems: A synthesis of field studies and models along a North American Arctic Transect

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[1] Arctic landscapes have visually striking patterns of small polygons, circles, and hummocks. The linkages between the geophysical and biological components of these systems and their responses to climate changes are not well understood. The "Biocomplexity of Patterned Ground Ecosystems" project examined patterned-ground features (PGFs) in all five Arctic bioclimate subzones along an 1800-km trans-Arctic temperature gradient in northern Alaska and northwestern Canada. This paper provides an overview of the transect to illustrate the trends in climate, PGFs, vegetation, *n*-factors, soils, active-layer depth, and frost heave along the climate gradient. We emphasize the thermal effects of the vegetation and snow on the heat and water fluxes within patterned-ground systems. Four new modeling approaches build on the theme that vegetation controls microscale soil temperature differences between the centers and margins of the PGFs, and these in turn drive the movement of water, affect the formation of aggradation ice, promote differential soil heave, and regulate a host of system properties that affect the ability of plants to colonize the centers of these features. We conclude with an examination of the possible effects of a climate warming on patterned-ground ecosystems.

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1. Introduction

[2] Several generations of Arctic explorers and scientists have puzzled over the genesis of the more or less symmetrical networks of small polygons, circles and hummocks that cover large areas of the Arctic (Figure 1). Hypotheses for the formation of these patterned-ground features (PGFs) include desiccation cracking, dilation cracking, salt cracking, seasonal frost cracking, permafrost cracking, primary frost sorting, mass displacement, differential frost heaving, and differential thawing [*Washburn*, 1980, Table 5.1]. Recent studies have shown that vegetation also plays an important role in the genesis of these features [e.g., *Walker et al.*, 2004; *Kokelj et al.*, 2007]; however, comprehensive mathematical models of patterned-ground formation still elude scientists who study these phenomena [*Mann*, 2003]. Furthermore the role of patterned ground in arctic ecosystem function and the possible response of these forms to climate change have not been addressed.

[3] The "Biocomplexity of Patterned-Ground Ecosystems" project specifically examined the interactions between the biological and physical components of patterned-ground ecosystems along a bioclimate gradient in North America (Figure 2). Complex interactions between, climate, permafrost, vegetation, soils, and hydrology produce patterned ground features (Figure 3). The strength of the biological components, specifically accumulation of plant biomass, increases as one moves from cold to warm climates. We hypothesized that the insulative effect of the vegetation on soil heat flux would strongly affect and eventually over-

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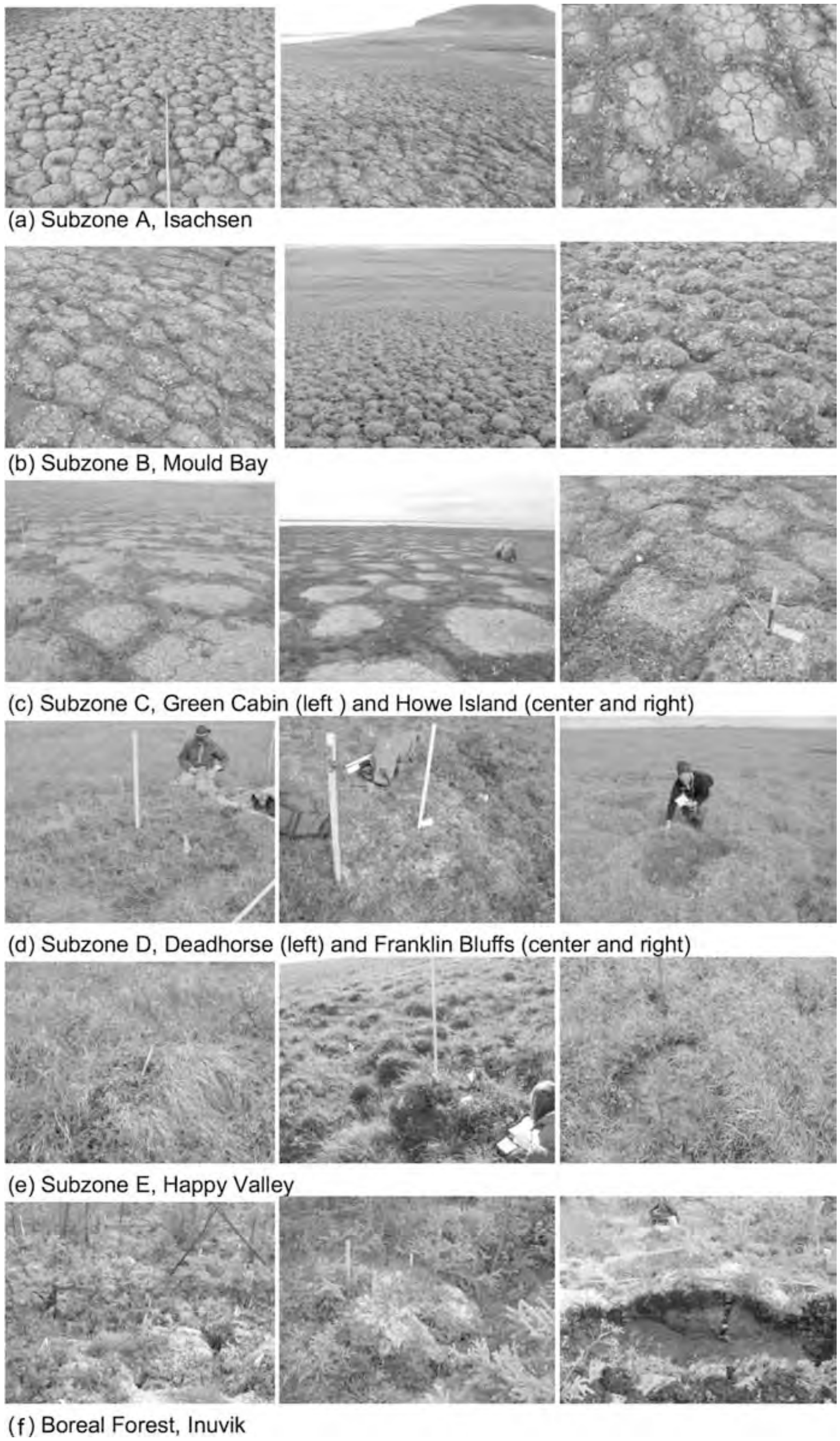

Figure 1. Patterned-ground forms along the North American Arctic Transect. (a) Subzone A: Small nonsorted polygons (Isachsen). (b) Subzone B: small nonsorted polygons (left) and turf hummocks (center and right) (Mould Bay). (c) Subzone C: Well-developed nonsorted circles (left, Green Cabin, and center, Howe Island) and nonsorted polygons (right, Howe Island). (d) Subzone D: Barren nonsorted circles (left, Deadhorse, and right, Franklin Bluffs) and partially vegetated nonsorted circles (center, Franklin Bluffs). (e) Subzone E: Medium-size hummocks (left and center, Happy Valley) and small barren nonsorted circle between tussocks (right, Happy Valley). (f) Boreal Forest: Medium-size hummocks (left and center, Inuvik). Bowl shaped permafrost table beneath the hummock, and well-developed organic soil horizon and vegetation mat covering the hummock at Inuvik (right).

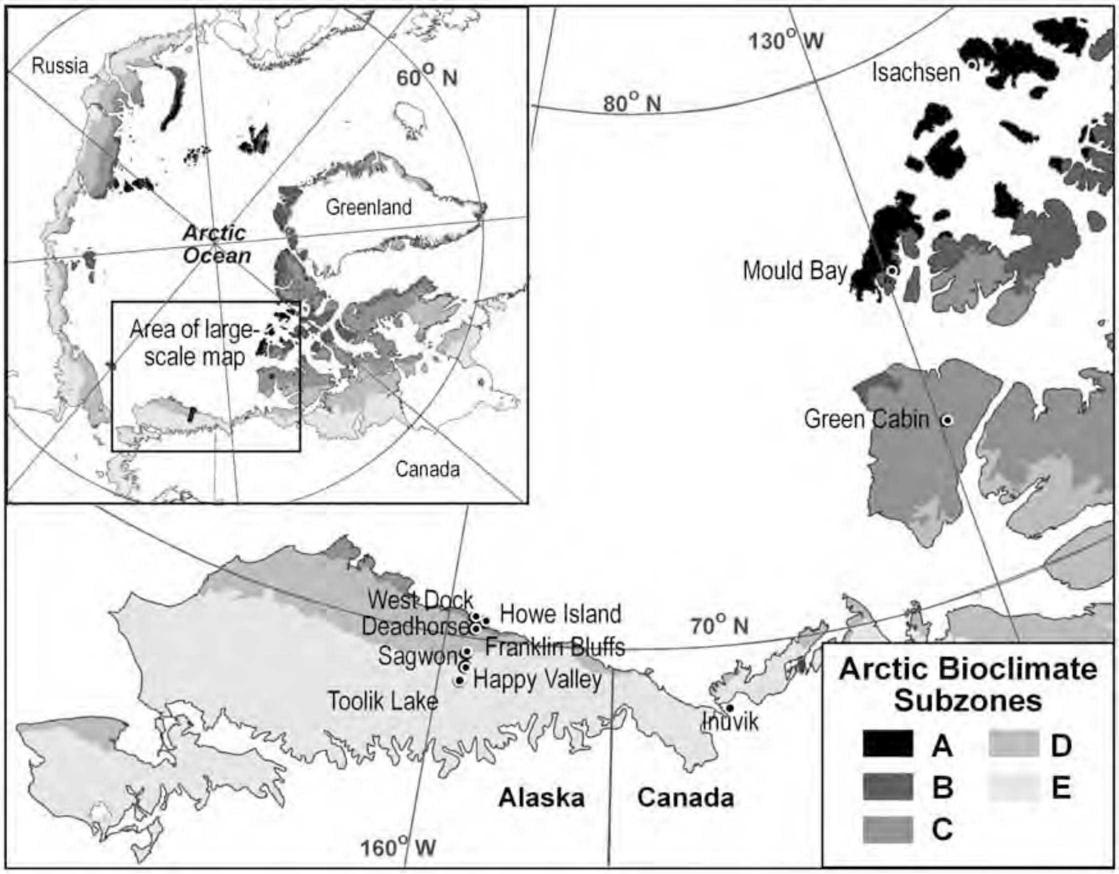

Figure 2. Study locations within the five Arctic bioclimate subzones [*CAVM Team*, 2003]. The subzones are defined by a combination of summer temperatures and the character of the vegetation. Approximate mean July temperatures within each subzone are: A = 0–3°C, B = 3–5°C, C = 5–7°C, D = 7–9°C, E = 9–12°C.°C, E = 9–12°C.

whelm the dominant physical processes of frost heave and frost cracking. We directed a variety of studies at small relatively homogeneous PGF landscapes that included climate, vegetation, water/ice, soil, and permafrost components [*Raynolds et al.*, 2008]. This paper provides a synthesis of the main data sets to illustrate how PGFs change in concert with the climate, soils, and vegetation along the transect. We focus on aspects of the vegetation and snow cover that most directly affect the thermal properties of the soil and influence the depth of summer thaw and soil heave. We then summarize four modeling approaches that were used to help understand how vegetation affects the formation of patterned ground. We conclude with a discussion of the role of PGFs within the Arctic terrestrial system and the likely response of PGFs to climate change. Table S1 contains a summary of the data used in this paper (available as auxiliary material).[1]

2. Description of the North American Arctic Transect (NAAT)

2.1. Study Site Locations

[4] In 2001–2006 we studied patterned-ground landscapes at 11 locations in Canada and Alaska (Figure 2

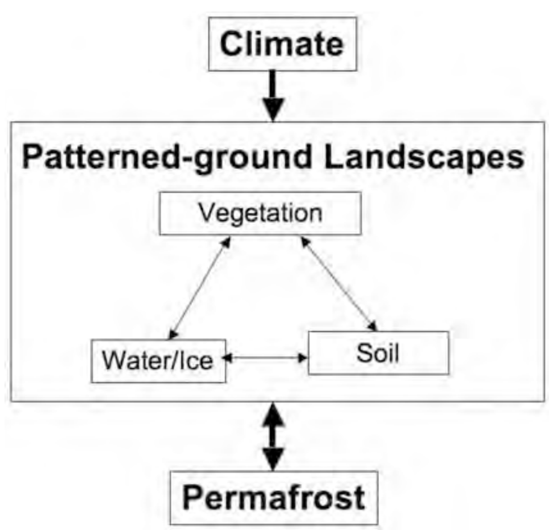

Figure 3. The patterned-ground system. Note that linkage between climate and patterned ground landscapes is primarily a one-way interaction, whereas the linkage with permafrost is a strongly two-way interaction.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007JG000504.

and Table S1). The locations were chosen as representative of zonal conditions within each of five Arctic bioclimate subzones [*CAVM Team*, 2003; *Walker et al.*, 2005]. Zonal refers to vegetation and soils that develop on mesic fine-grained soils under the influence of the regional climate, without the confounding influences of extremes of soil moisture, soil texture, snow, unusual soil chemistry, or major disturbances [*Razzhivin*, 1999; *Sochava*, 1934; *Vysotskii*, 1901]. We follow the zonation approach used by the Circumpolar Arctic Vegetation Map [*CAVM Team*, 2003], which is a modification of the approach used by *Yurtsev* [1994]. A crosswalk has been drawn between the CAVM zonation approach and other systems commonly used in North America [e.g., *Bliss and Matveyeva*, 1992; *Tedrow*, 1968] and elsewhere [see *Walker et al.*, 2005].

[5] Bioclimate zonation in the Arctic has been described in relationship to mean July temperature (MJT) and the characteristics of the vegetation [*Walker et al.*, 2005]. Briefly: In subzone A (cushion-forb (*Papaver*) subzone), MJT = 0–3°C; in subzone B (prostrate dwarf-shrub (*Dryas*) subzone), MJT = 3–5°C; in subzone C (hemi-prostrate dwarf shrub (*Cassiope*) subzone), MJT = 5–7°C; in subzone D (the erect-dwarf shrub (*Betula nana/exilis*) subzone), MJT = 7–9°C; and in subzone E (the low-shrub (*Alnus*) subzone), MJT = 9–12°C [*Walker et al.*, 2005]. The sites chosen for the study were Isachsen (Ellef Ringnes Island, Nunavut, Canada) in subzone A; Mould Bay (Prince Patrick Island, Northwest Territories (NWT), Canada) in subzone B; Green Cabin (Banks Island, NWT), Howe Island, and West Dock (northern Alaska) in subzone C; Deadhorse and Franklin Bluffs (northern AK) in subzone D; Sagwon (northern AK) on the boundary between subzones D and E; Happy Valley (northern AK) in subzone E; and Inuvik (NWT) in the northern boreal zone (Figure 2). Table S1 gives the coordinates of each location along with a summary of key environmental data.

2.2. Geology and Soils

[6] Although a concerted attempt was made to locate all the studies on fine-grained sediments that are conducive to the formation of nonsorted patterned-ground features, the geology varied considerably across the transect, so the locations had unavoidable variation in soil texture and pH. The Isachsen site was located on clay-rich soils derived from marine shales of the Christopher Formation [*Heywood*, 1957; *Stott*, 1960]; Mould Bay was located on soils derived from mixed sedimentary rocks of the Wilke Point and Griper Bay Formations [*Everett*, 1968; *Tedrow*, 1968]; the Green Cabin plots were located on glacial till deposited during the middle Pleistocene [*Vincent*, 1982, 1990]; and the Inuvik site was on fine grained till in a mature black spruce-lichen woodland with a thick organic ground cover [*Kokelj et al.*, 2007]. In northern Alaska, there was less variation than in the Canadian portion of the transect; most sites were on fine-grained soils derived from calcareous Sagavanirktok-River loess, but there was still some substrate variation. The Sagwon MAT (moist acidic tundra site), Happy Valley, and Inuvik locations had acidic soils (pH < 5.5), and all the others had nonacidic soils including the Sagwon MNT (moist nonacidic tundra sites) (Table S1).

[7] Several sites (Howe Island, Green Cabin, Deadhorse, Franklin Bluffs) had soil pH values exceeding 8.0. Total soil organic carbon in the upper one meter of soil ranged from 15.2 kg m^{-2} at Isachsen to 72.6 kg m^{-2} at Deadhorse (Table S1). High soil carbon values above 55 kg m^{-2} occurred primarily in the Low Arctic and coastal plain sites at West Dock, Deadhorse, and Franklin Bluffs. Relatively low values below 30 kg m^{-2} occurred mainly in the dry High Arctic at Isachsen, Mould Bay, Green Cabin, Howe Island and also at the moist nonacidic tundra site at Sagwon.

[8] Despite the substrate variation, at all locations it was possible to select study plots on fine-grained sediments with representative zonal vegetation. The sites that were most representative of the zonal situations were Isachsen (Subzone A), Mould Bay (Subzone B), Green Cabin (Subzone C), Franklin Bluffs (Subzone D), and Happy Valley (Subzone E).

2.3. Climate

[9] Climate stations were established at each NAAT location [*Romanovsky et al.*, 2008]. The installations are also part of the Permafrost Observatory Network [*Osterkamp*, 2003; *Romanovsky et al.*, 2003] and the Circumpolar Active Layer Monitoring network [*Brown et al.*, 2000]. We monitored air and ground temperatures and snow depths at each site.

[10] We use the summer warmth index (*SWI*) as a measure of total summer warmth: $SWI = \Sigma\ T_{mm}$, where T_{mm} is the mean monthly temperatures that exceed 0°C and is expressed as thawing-degree months (°C mo). The index was first used to examine the temperature limitations of arctic plant species, and is easily derived from monthly mean temperatures [*Young*, 1971]. Figure 4 shows the *SWI* values at the study sites for the air (SWI_a), ground-surface on the PGF features (SWI_p) and the tundra between PGFs (SWI_b). There was more than a 10-fold increase in SWI_a along the transect, from 3.0°C mo at Isachsen to 40.2°C mo at Inuvik. Temperatures on the PGFs were 2–13°C mo warmer than the air temperatures. Temperatures between the PGFs were generally 2–5°C mo cooler than temperatures on the PGFs. The SWI_p and SWI_b values generally follow the air-temperature gradient except at Howe Island and Happy Valley. Howe Island is a small island with little vegetation. The winds off the cold ocean keep the summer air temperatures near freezing, but there is strong solar heating at the barren soil surface and the SWI_p exceeded 27°C mo, comparable to the Sagwon MNT site at the southern boundary of subzone D. At Happy Valley in subzone E, the vascular vegetation and microtopography (i.e., tussocks) had a significant shading effect, and soil temperatures between the PGFs were much cooler than even the air temperatures.

2.4. Patterned-Ground Features

[11] Terminology used to describe patterned ground is confusing and incorporates terms in many languages. Table 1 presents a simple classification that we used for mapping PGFs [*Raynolds et al.*, 2008]. The terms are based on the morphology and size of the features and do not consider their genetic origin. Where possible, we followed *Washburn*'s [1980] approach to classifying patterned ground and the more recent glossary of permafrost and related ground-ice terms [*van Everdingen*, 2005]; however, it was not always possible to use existing terminology if the origins of the

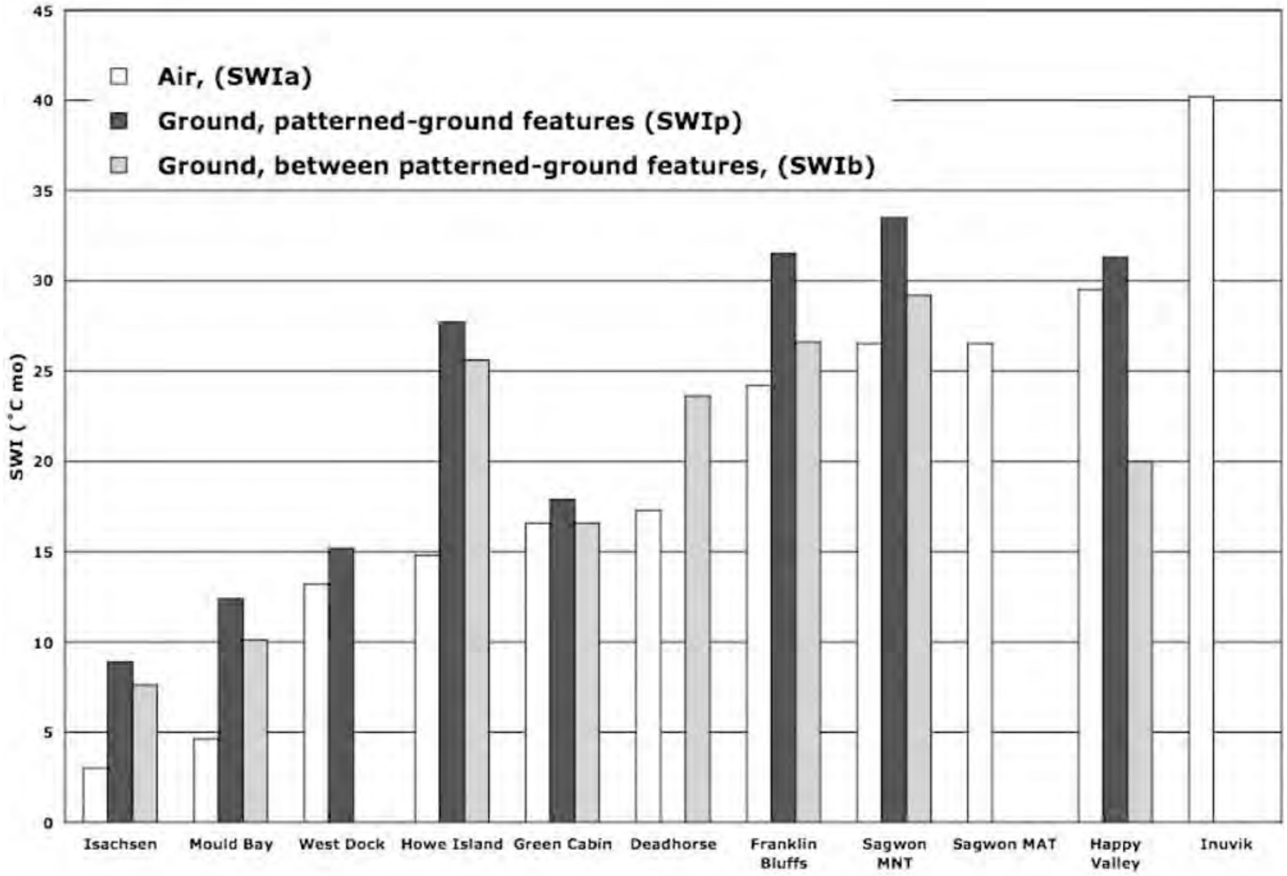

Figure 4. Trend in the summer warmth index along the NAAT for the air (SWI_a), and soil surface within patterned-ground features (SWI_p), and soil surface between patterned-ground features (SWI_b). Air temperature data for Isachsen, Mould Bay, and Green Cabin are from Environment Canada (http://climate.weatheroffice.ec.gc.ca/climate_normals/). Deadhorse data are from the USA system station: 70637–27406. Other data are from the Romanovsky NAAT climate stations for August 2005 to July 2006.

forms were not known especially for so-called "turf hummocks," "earth mounds," "thufurs" and similar features. The classification presented in Table 1 is meant only as a means for simplifying our references to these PFGs and is not meant to replace existing nomenclature systems that readers may be more familiar with.

[12] We do not address sorted PGFs that occur in coarse-textured soils nor stripe patterns that occur on slopes because these have received considerable recent attention elsewhere [e.g., *Werner and Hallet*, 1993; *Kessler and Werner*, 2003]. We also do not address larger features such as ice-wedge polygons nor pingos which have diameters greater than 10 m because these features are at scales beyond the 100-m^2 landscape units that we chose for studying patterned ground; also, the processes involved in the genesis of these larger features are generally well understood [e.g., *Lachenbruch*, 1962].

[13] *Raynolds et al.* [2008] classified the PGFs, mapped 20 10 × 10-m grids, and summarized the trends of PGF size and density along the transect. Here we briefly summarize the dominant processes (Figure 5a) and patterned-ground forms (Figure 5b). (Also see Figure 1 for photos of the

Table 1. Zonal Patterned-Ground Features Mapped Along a North American Arctic Transect[a]

Feature	Definition	Subtype	Typical Dimensions
Nonsorted Polygons	Polygonal forms without a border of stones, delineated by a crack or trough between adjacent polygons	Small Medium	10–30 cm diam. 30–200 cm diam.
Nonsorted Circles	Circular forms without a border of stones. Less vegetated in centers, and more vegetated on margins (synonyms include mud boils, frost boils, frost medallions, spotted tundra)	Small Medium Large	10–50 cm diam. 50–200 cm diam. >200 cm diam.
Hummocks	Dome-shaped features with raised center and depression or trough between hummocks	Small Medium	15–30 cm diam. 10–20 cm high 100–200 cm diam. 30–60 cm high

[a]From *Raynolds et al.* [2008].

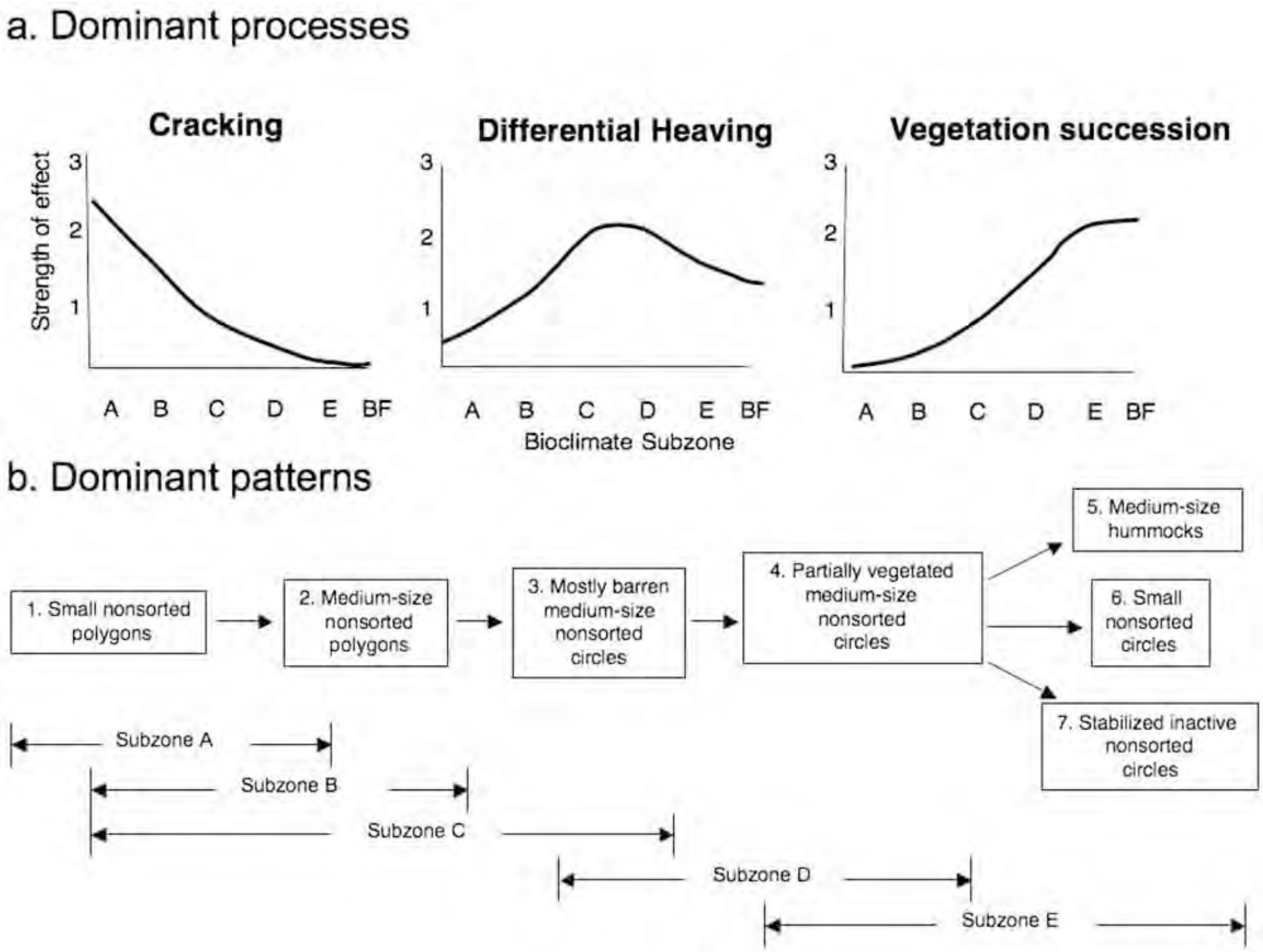

Figure 5. Dominant genetic processes (a) and patterns (b) involved in patterned-ground formation on zonal sites along the Arctic bioclimate gradient.

PGFs along the climate gradient; and *Raynolds et al.* [2008] for maps and analysis.)

[14] In the High Arctic at Isachsen, Mould Bay, and Green Cabin, contraction cracking caused by desiccation and/or extreme cold was the dominant process forming small and medium-size nonsorted polygons (Figure 5b, boxes 1 and 2).

[15] Differential heave was the dominant process in the middle parts of the gradient (subzones C and D) forming medium-size nonsorted circles (Figure 5b, boxes 3 and 4). Differential heaving also occurred in the medium-size hummocks in the southern part of the gradient (Subzone E) (Figure 5, box 5).

[16] Vegetation succession modified existing PGFs and changed their morphology, especially in the southern part of the transect. In the middle part of the climate gradient, well-developed plant communities occurred in the relatively stable areas between PGFs, but not on the PGFs themselves, which were too cryogenically active to support most plants. Further south in subzone E, longer warmer growing seasons allowed more robust plants to occupy both the margins and centers of the PGFs. In subzone E, vegetation colonization around the margins of nonsorted circles reduced the circles to small features less than 50 cm in diameter (Figure 5b, box 6), or they were completely vegetated and inactive (Figure 5b, box 7), or in some places the nonsorted circles were converted to medium-size mounds because of alterations to the permafrost table, a process that is described more thoroughly in section 3.4. A more full discussion of the various patterned-ground forms encountered along the transect is in *Raynolds et al.* [2008] and in forthcoming publications.

2.5. Variation in Factors Contributing to Insulation of the Soil Surface

[17] A summary of the variation in key factors that contribute to insulating the soil surface and reducing the soil heat flux are shown in Figure 6.

2.5.1. Vegetation

[18] The zonal vegetation varied from nearly barren surfaces with scattered mosses, lichens and very small forbs in subzone A to knee-high shrub-dominated tundra with thick moss carpets in subzone E, and open black-spruce forest with a thick moss and lichen understory in the northern boreal forest site at Inuvik [*Kade et al.*, 2005; *Vonlanthen et al.*, 2008]. The height of the vascular plant canopy on the patterned ground features increased from 1 cm at Isachsen to 13 cm at Happy Valley and 40 cm in the lichen woodland at Inuvik (Figure 6). The height of the vascular plant canopy between the PGFs increased from 1 cm at Isachsen to 26 cm at Happy Valley and 40 cm at Inuvik.

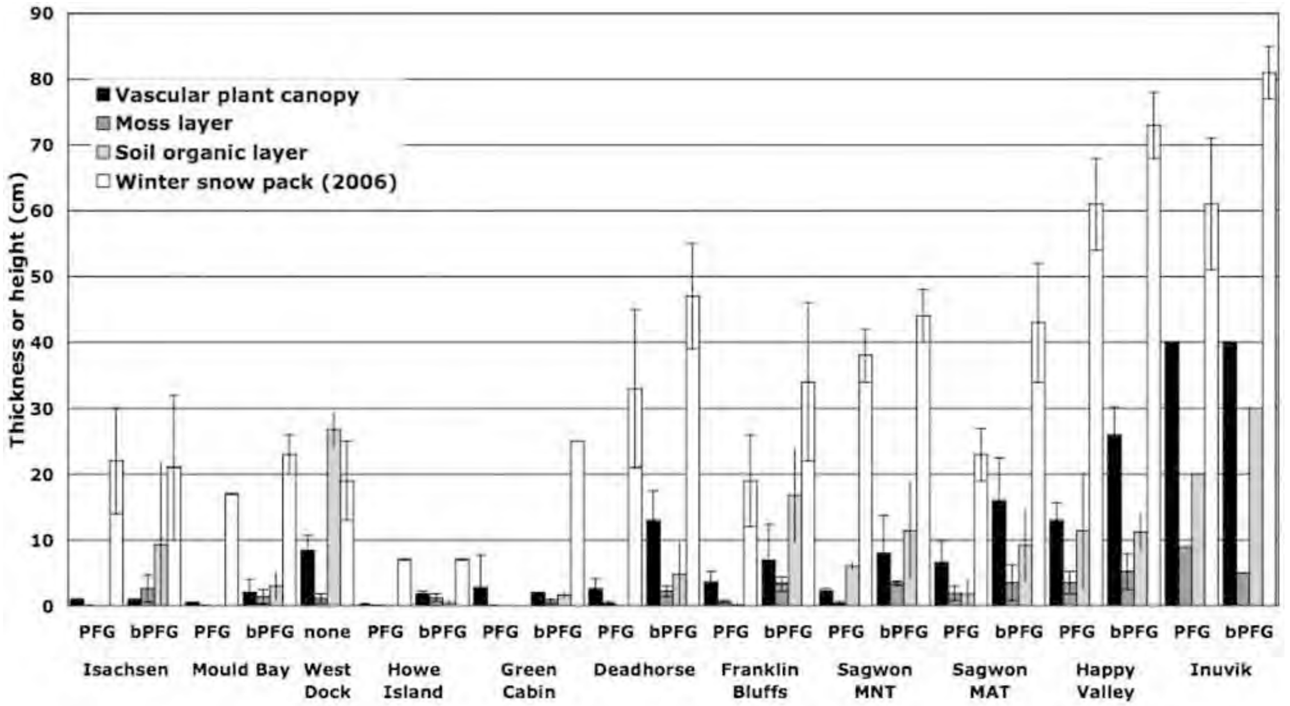

Figure 6. Factors contributing to insulation of the surface along the NAAT: vascular plant canopy thickness, moss layer thickness, soil organic horizons, and winter snowpack. Error bars are standard deviations. Data are from the vegetation study plots at each location, with generally 5–7 plots represented by each bar, except at Inuvik, where only one plot was sampled and the snow data are from the 10 × 10-m grid, and Green Cabin, where there were snow data for a single point from a sonic snow sensor.

The thickness of the live green portion of the moss layer was very thin on PGFs in subzones A, B, C, and D (Isachsen to Sagwon MNT, 0 to 1.1 cm). In subzone E, the moss layers of PGFs increased noticeably with 1.9 cm at Sagwon MAT, to 3.5 cm at Happy Valley, and 20 cm at Inuvik.

[19] From north to south and excluding the boreal forest site at Inuvik, there was about a 20-fold increase in the amount of biomass on the centers of PGFs (39 g m^{-2} at Isachsen to 734 g m^{-2} at Sagwon MAT), versus about a twofold increase in biomass of the vegetation between the features (369 g m^{-2} at Isachsen to 758 g m^{-2} at Sagwon MAT) (Figure 7). *Raynolds et al.* [2008] calculated landscape-level biomass values for the areas within the 10 × 10-m grids. The dry site at Isachsen had 1.25 kg/100 m^2 biomass compared to 75 kg/100 m^2 biomass at the Happy Valley zonal site.

2.5.2. Thickness of the Soil Organic Horizons

[20] Organic soil horizons generally reflect the trend in biomass. O horizons were generally thin on small patterned-ground features in subzones A, B, C, and the northern part of subzone D (Table S1 and Figure 6). South of Deadhorse, the average thickness of organic soil horizons on PGFs increased from 0.1 cm at Franklin Bluffs to 20 cm at Inuvik. Soil organic horizons were generally much thicker between PGFs. Even at the northernmost site of Isachsen, thick accumulations of dead moss bases and lichens occurred in the cracks between polygons (Figure 6).

[21] In the Low Arctic, organic soil horizons between PGFs generally increased in thickness from north to south (Figure 6). The thinnest organic soil horizons occurred in the more continental site at Green Cabin (1.6 cm), and at Howe Island (0.4 cm). The thickest organic soil horizons between PGFs occurred on the Arctic Coastal Plain of Alaska (26.8 cm at West Dock, 16.2 cm at Deadhorse, 16.8 cm at Franklin Bluffs) and at Inuvik (30 cm) more or less following the trend in soil organic carbon.

2.5.3. Snow Cover

[22] From north to south along the NAAT, there was a general increase in the thickness of the end-of-winter snow depth (Figure 6). The High Arctic Islands and West Dock all had about 20 cm in microsites between PGFs. The relatively calm sites at Happy Valley and Inuvik had over 70 cm of snow, the windy coastal site at Howe Island had the least (less than 10 cm). There was also a distinctive trend of deeper snowpack in areas between the PGFs compared to the patterned ground features, due in part to frost heave of the features during the winter, or to generally higher micro-topography associated with the features, such as the earth hummocks at Happy Valley and Inuvik.

2.5.4. *n*-Factor

[23] A full treatment of the total energy gained or lost at the soil surface as affected by the vegetation and snow cover is complex to model because the thermal properties of the organic blanket and the snowpack continually change with the season and the moisture conditions. We use the *n*-factor [*Carlson*, 1952] as an integrator of the total insulative effect of the vegetation, soil organic, and snow layers. The original *n*-factor was developed for engineering and construction purposes to relate ground temperatures to air temperatures. More recently the index has been applied to natural landscapes and to predict the active-layer depth [*Jorgenson and Kreig*, 1988; *Kade et al.*, 2006; *Klene*

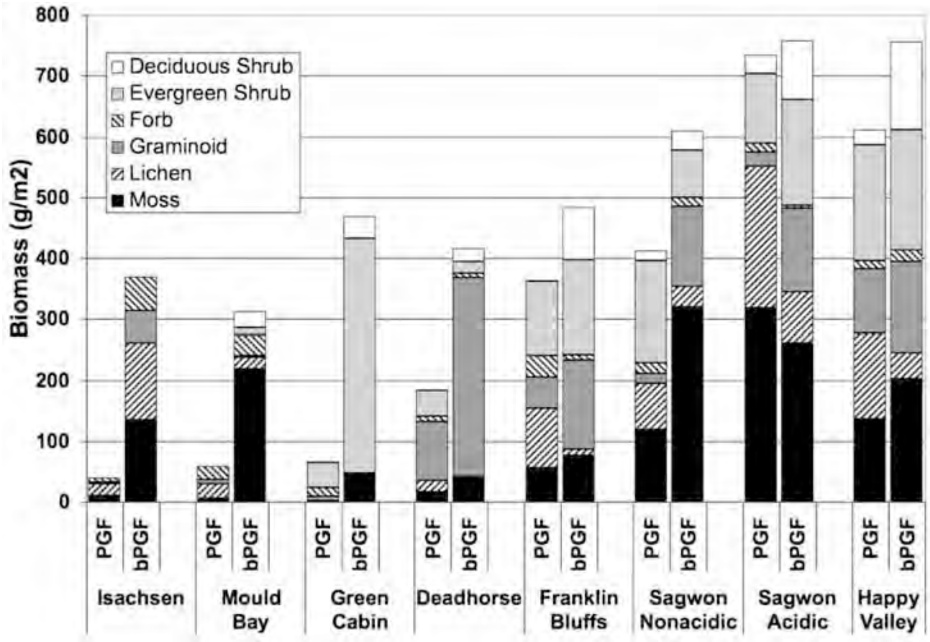

Figure 7. Biomass on patterned-ground features (PGF) and between patterned-ground features (bPGF) along the NAAT. No biomass data were collected at Inuvik and there were no PGFs at West Dock.

et al., 2001a, 2001b; *Shur and Slavini-Borovskiy*, 1993; *Taylor*, 1995, 2001]. The *n*-factor is defined here as the ratio of the seasonal degree-day sum at the top of the uppermost mineral soil horizon to that of the air at 2 m above the surface (standard climate-station temperature instrument height). We define two different *n*-factors, a summer *n*-factor (n_s) and a winter *n*-factor (n_w): $n_s = TDD_m/TDD_a$ and $n_w = FDD_m/FDD_a$ where TDD_m is the annual sum of thawing degree-days (TDD or mean daily temperatures above 0°C) at the top of the mineral horizon, and TDD_a is the annual sum of the thawing degree-days of the air at 2 m. Similarly, FDD_w is annual sum of the freezing degree-days (mean daily temperatures below 0°C) at the top of the mineral soil, and FDD_a is the freezing degree-days of the air at 2 m.

[24] Figure 8 shows the summer and winter *n*-factors for representative sites in each bioclimate subzone. The summer *n*-factors above 1 indicate that the soil-surface temperatures are warmer than the air temperatures. (1) The summer *n*-factors were mostly above 1.0 at the High Arctic sites, particularly on the centers of the PGFs, indicating that the nearly barren mineral soils were considerably warmer than the air temperatures in this region. (2) Relatively low n_s values occurred in the areas between the PGFs at all locations indicating that the vegetation had a strong cooling effect during the summer on the mineral soils of these microsites. (3) n_s was strongly correlated with the thickness of the live green moss layer ($r^2 = 0.899$, Figure 8b, left), the height of the plant canopy ($r^2 = 0.892$), and the thickness of the soil organic horizons ($r^2 = 0.785$), but poorly correlated with the total moss biomass ($r^2 = 0.386$), most likely because of large variations in the bulk density of the moss layers. (4) Winter *n*-factors were all less than 1, indicating warmer soil temperatures than air temperatures, and were strongly correlated with the depth of the winter snow cover ($r^2 = 0.870$) (Figure 8b, right). The small difference in n_w for PGFs and areas between PGFs indicate that the moss and soil organic layers of the areas between PGFs had little insulative effect in the winter.

2.6. Depth of Summer Thaw

[25] The depths of thaw reported here are measurements made on the vegetation study plots [*Kade et al.*, 2005; *Vonlanthen et al.*, 2008] during a 2-week period in late August 2006. The depth of summer thaw did not follow the trend in summer temperatures (compare Figures 9 and 4). The somewhat cooler surface temperatures of the tundra between the PGFs combined with the insulative effect of the thick vegetation mats and soil organic horizons greatly reduced the depth of summer thaw in the southern part of the climate gradient. For example, the mean depth of thaw at the end of August 2006 in the vegetated tundra between PGFs was comparable at Sagwon MAT, the site with warmest soil-surface temperatures (thaw layer = 36 cm), to that at Isachsen, the coldest site (31 cm). Deep thaw, greater than 75 cm, occurred on the relatively barren centers of PGFs at Howe Island, Deadhorse, Franklin Bluffs, and Sagwon MNT.

[26] The difference in the thaw layer of the PGFs compared to the adjacent tundra roughly reflects the difference in n_s of these adjacent microsites, but the effect varied with the size of the features and the type of vegetation involved. For example, at Isachsen (subzone A) there was about 300 g m^{-2} difference in the total biomass of cracks compared to the centers of the polygons, but the cracks were very narrow and there was only about a 4-cm difference in the thaw-layer thickness of these two adjacent microsites. In subzone D, there was a 20–25 cm difference in the active layer depth between the centers of the PGFs and their margins, reflecting the large contrast in biomass of these adjacent microsites

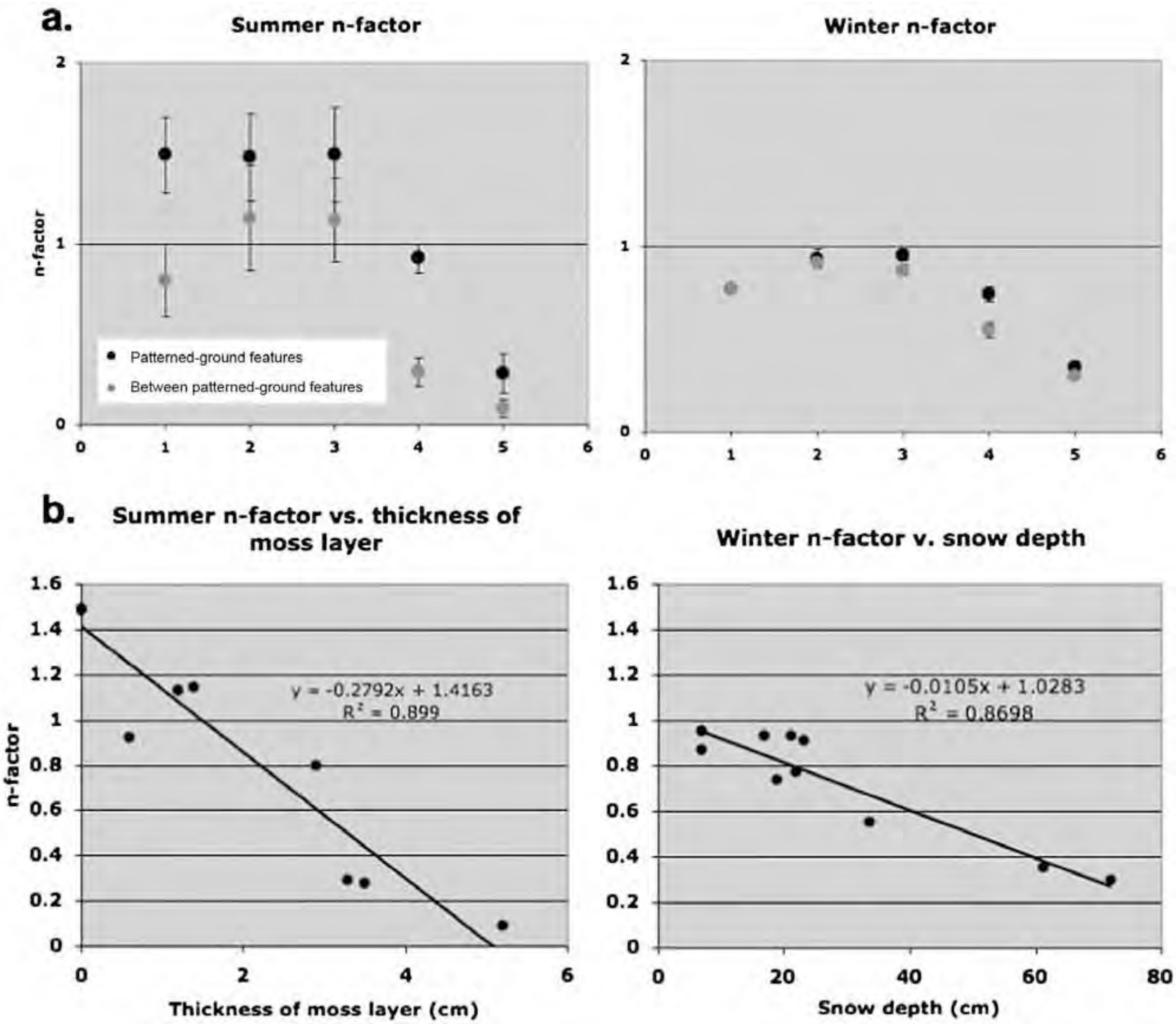

Figure 8. (a) Mean (±s.d.) summer and winter n-factors at representative sites in each subzone along the NAAT. Summer n-factors above 1 and winter n-factors below 1 indicate the top-of-mineral-horizon temperatures are warmer than the air temperatures. (b) Summer n-factor versus thickness of the green moss layer (left) and winter n-factor versus snow depth measured in May 2006 (right).

combined with the fact that both microsites covered large portions of the landscape. In subzone E, where there was considerable biomass on both the hummocks and inter-hummock areas (and similar low n_s values), we would expect little difference in thaw between the centers and the margins, but there was 10–27 cm difference (Figure 9). This large difference may have been due to warmer and better-drained soil conditions on the elevated hummocks compared to the cold wet soil conditions between hummocks.

2.7. Frost Heave

[27] Frost heave was monitored on and between the PGFs using two types of heave instruments described by *Romanovsky et al.* [2008]. Frost heave was greatest in the centers of PGFs on relatively wet silty loess soils at Deadhorse, Franklin Bluffs, and Sagwon MNT (20, 19 and 15 cm respectively) (Figure 10). Intermediate amounts of heave occurred on the clay soils at Isachsen, and the acidic loam soils at Sagwon MAT (9 cm) and Happy Valley (9.5 cm). Heave was least at West Dock (0.4 cm), where there was a thick organic soil layer overlying alluvial gravels and no patterned ground. Differential heave (difference between heave on the PGF and the areas between PGFs) was also greatest at Deadhorse and Franklin Bluffs (17 cm) where there was also strong contrast in the vegetation on and between the patterned ground features. Differential heave was least (0 cm) at Isachsen, where the zones between PGFs were very narrow. Low amounts of heave also occurred in the sandier soils at Mould Bay, Howe Island, and Green Cabin.

[28] *Daanen et al.* [2008] measured landscape-level heave on a 10 × 10-m grid at Franklin Bluffs, where the elevations at 1681 points within the grid were surveyed with reference to the top of a nearby frost-stable 30-m bore- pipe hole [*Romanovsky et al.*, 2003] in Aug 2006 and at the time of maximum heave in April 2007. The mean heave for the entire grid was 12 cm and the maximum heave was 28 cm. Generally, heave

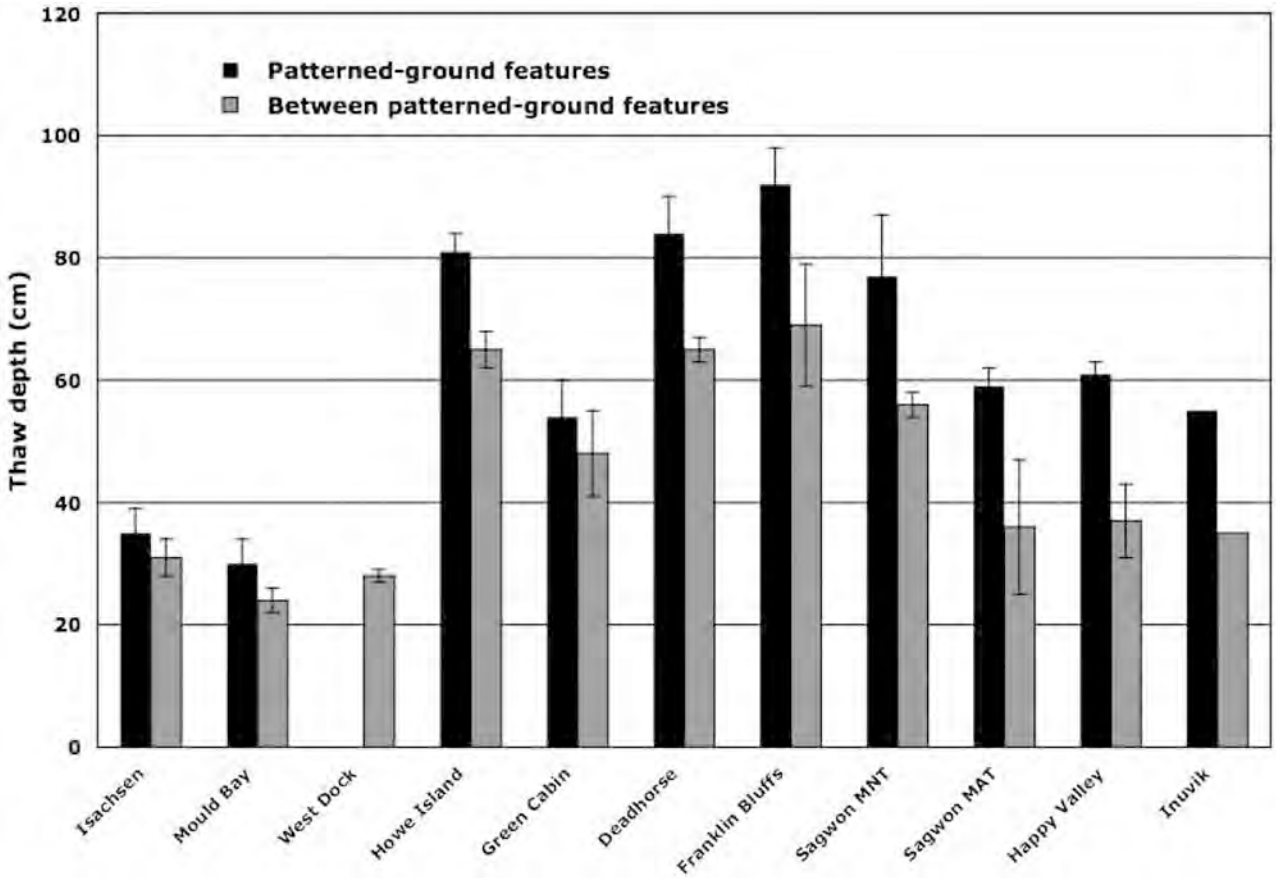

Figure 9. Mean thaw-depth (±s.d.) along the NAAT in late August 2006. Data are from the vegetation study plots of the dominant vegetation types on and between PGFs of zonal sites at each location; n = 5–7 except at Inuvik where n = 1.

was greatest on the tops of nonsorted circles, which also had deep thaw, shallow snow cover, low vegetation biomass, and barren soils [*Daanen et al.*, 2008].

3. New Modeling Approaches for Patterned-Ground Formation

[29] The data collected from the transect are being used to parameterize and validate a variety of models that were developed to explain the PGF formation. When the project began, most of the focus was on nonsorted circles, so all these models primarily focused on the processes of differential heave related to nonsorted-circle and medium-size hummock formation. Each model has its unique applications to the nonsorted circle environment. Here we briefly summarize each of the models. Readers should refer to the cited information for more details regarding the models.

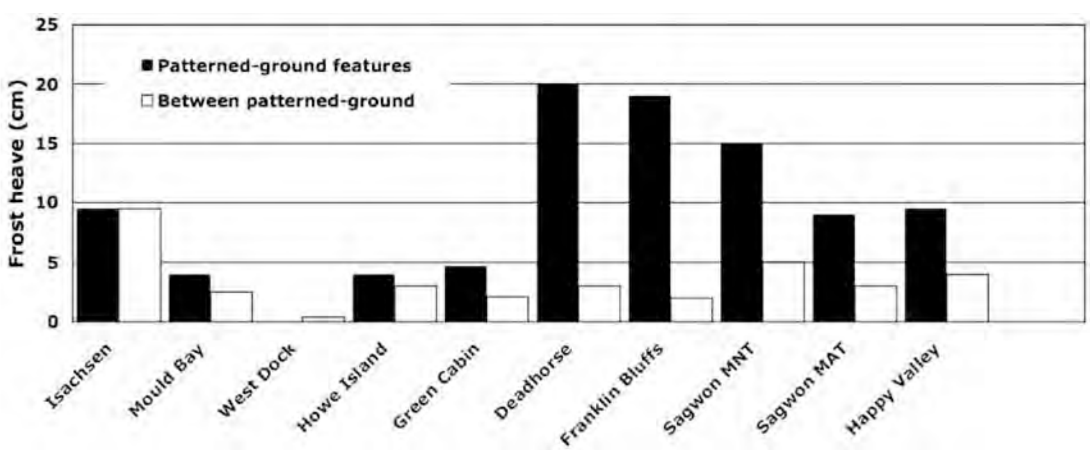

Figure 10. Frost heave on and between patterned-ground features along the NAAT.

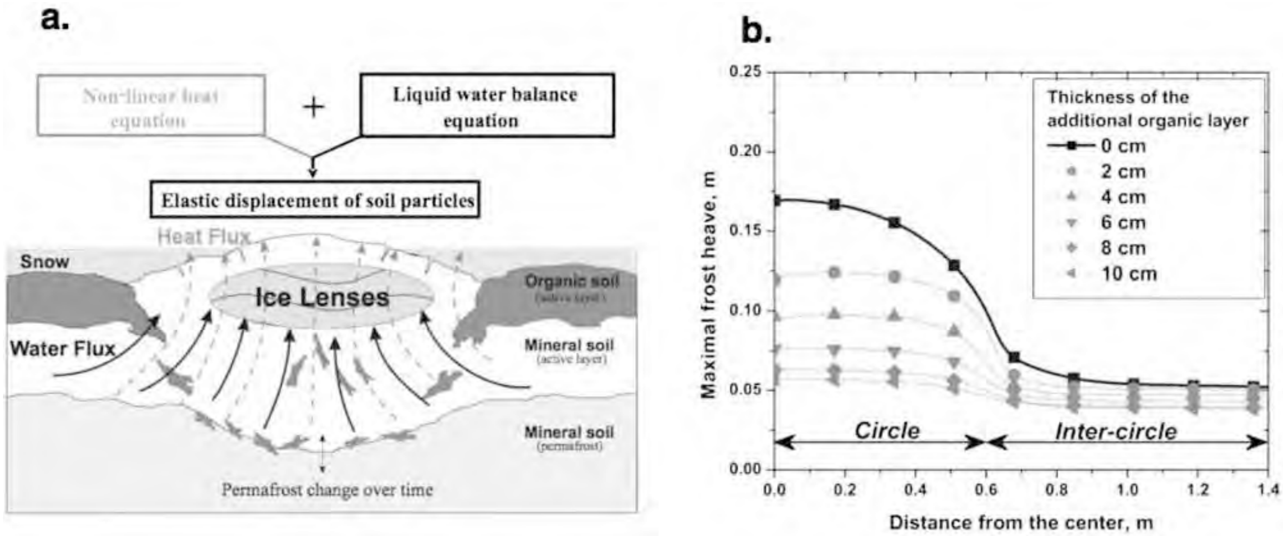

Figure 11. (a) Conceptual nonsorted-circle system for the Thermomechanical Model of frost heave. (b) Sensitivity analysis showing the effect on frost heave of adding different thicknesses of moss layer to the surface of the circle (adapted from *Nicolsky et al.* [2008]).

3.1. Thermomechanical Model of Nonsorted Circle Formation

[30] The thermomechanical model (TMM) is a detailed simulation of the heaving process within nonsorted circles [*Nicolsky et al.*, 2008]. TMM includes mass, momentum, and energy conservation laws for water, ice, and soil and simulates soil movement in a nonsorted circle based on ice accumulation and deformation of the frozen soil (Figure 11a). The model accounts for the observation that heave within nonsorted circles is considerably greater than that which is accounted for strictly by the freezing of the volume of water in the soil. For example, the soils at the Franklin Bluffs heave about 15 cm, but the water within the active layer beneath the circles can only account for about 3.0 to 3.5 cm of this heave. During freezing, a strong temperature differential between the poorly insulated centers of the circles and well-vegetated (and thus heavily insulated) margins of the circles cause a flow of heat out of the circle to the atmosphere. Water moves along the temperature gradient and creates a pressure differential that pulls water from areas outside the boundaries of the nonsorted circle to the freezing surfaces of ice lenses within the soil. The soil heaves as ice accumulates within the soil column. As the soil heaves the thickness of the snowpack above it is reduced because the snow surface is continually leveled by wind action. The thinner less-insulative snow above the circle compared to the deeper snow in the areas between the circles further enhances the thermal gradient across the circle (Figure 11a).

[31] Another central concept of the model is that the hydraulic conductivity of the soil, which determines how fast water can move to the freezing front, is a function of the soil temperature and soil porosity. A great deal of unfrozen water remains in soils well below 0°C. This is due to the high energy of water that is hygroscopically bound to the soil particles. As the soil water freezes, the interstitial pore sizes are reduced, restricting the flow of water to the freezing front. Water ceases flowing into the nonsorted circles at temperatures considerably below freezing, and this point varies according to the characteristic unfrozen water content curve of a given soil.

[32] Sensitivity analyses examined the response of the model to the addition or removal of a vegetation layer on the circle (Figure 11b). The modeled results showed that heave was nearly completely subdued by adding a 10-cm thick layer of moss. The results compare favorably with an experiment that both removed and added a vegetation mat to nonsorted circles at the Sagwon location [*Kade and Walker*, 2008]. Removal of vegetation on nonsorted circles increased the mean summer soil temperature 1.4°C, the depth of the thaw layer 6%, and heave 26% compared to the controls. The addition of 10-cm thick moss layer resulted in the opposite effect – a 2.8°C decrease in mean summer soil temperature, a 15% decrease in the thaw layer, and a 58% decrease in heave. Other sensitivity analyses examined the effect on heave of varying the size of the nonsorted circle and the hydraulic conductivity of the soil, and showed that the most active development of differential frost heave occurs within nonsorted circles in waterlogged areas with strong upper-soil-layer heterogeneity caused by vegetation.

3.2. Differential Frost-Heave Model

[33] One of the most puzzling aspects of nonsorted circle formation is the self-organization process that forms the regular patterns that are so characteristic of spotted-tundra landscapes. The DFH model is an initiation model that explains how an initial pattern of nonsorted circles could spontaneously develop in the absence of a vegetative cover [*Peterson and Krantz*, 2003, 2008]. The model takes soil parameters, including the freezing characteristic curve, the hydraulic conductivity as a function of water content, and thermal conditions, and returns a pattern size and the relative amplitude of heave. This distance is then used to form the most likely potential pattern found in the tundra. A hexagonal pattern is very likely, because the distances between features, such as circles or hummocks, are then always the same. Secondary processes like vegetation

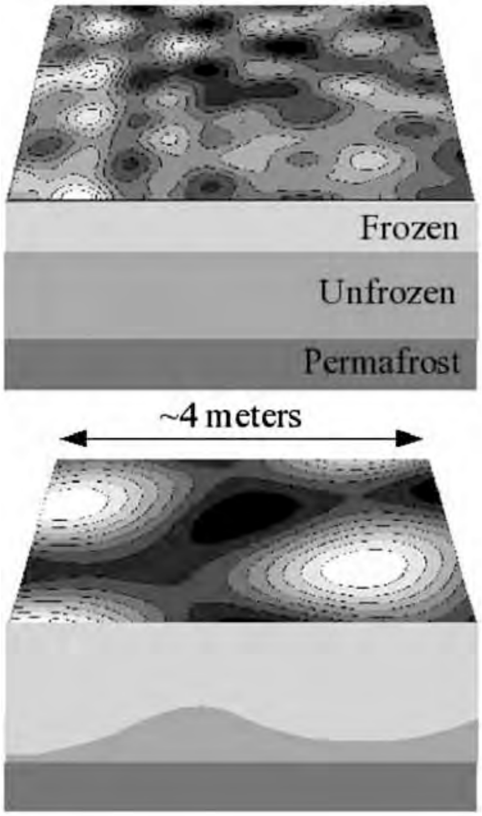

Figure 12. Generation of nonsorted-circle pattern by the DFH model: Contour plot of the surface topography soon after spontaneous initiation of differential frost heave (top) and after 16 complete freeze cycles of the entire active layer (bottom). Vertical cross-sections show a representation of how the frozen/unfrozen interface also develops as DFH progresses. The initial surface is a numerical approximation of white noise with a maximum amplitude less than 1 mm that develops into a semi-regular pattern with a spacing of about 4 m and an amplitude greater than 1 cm. This characteristic spacing is strongly dependent on the elastic properties of the frozen soil. Here it is shown for a purely elastic Young's Modulus of 250 MPa. (Figure courtesy of R. Peterson.)

dynamics and microscale terrain irregularities are assumed to be responsible for variations in the pattern found in the tundra.

[34] The model is a linear instability analysis of top-down one-dimensional freezing of a frost-susceptible soil. The physics used in the linear stability analysis accounts for the upward velocity of the ground surface and the downward movement of the freezing front [*Fowler and Krantz*, 1994]. These two coupled vector velocities are functions primarily of the type of soil and the thermal conditions at the ground surface.

[35] Random perturbations to the soil parameters are added to the variable field of the model. Very small perturbations can affect many properties of the system, most importantly, the direction of the thermal gradient at the freezing front, and the ice content in the partially frozen soil. In addition there will be changes in the hydraulic properties of the partially frozen soil. Depending on the wavelengths of these perturbations relative to the current depth of freezing, the system can become "linearly unstable." This instability arises when tiny fluctuations have a positive feedback to all other system properties, causing the perturbations to grow in amplitude and further differentiate themselves (Figure 12).

3.3. Hydrological Frost Heave Model Combined With a Vegetation Dynamics Model

[36] Another modeling approach to forming patterns combines a water-ice-temperature model (WIT) [*Daanen et al.*, 2007], with an arctic vegetation dynamics model (ArcVeg [*Epstein et al.*, 2001a]).

3.3.1. WIT Model

[37] The WIT portion of the model simulates the liquid water movement in the active layer during the freezing process. The model simultaneously solves the highly non-linear relationships between temperature, unsaturated liquid water movement and ice accumulation. Simplifications within the model make it possible to simulate domain sizes of 16–100 m^2 in three dimensions. The model identifies ice accumulation regions within the freezing active layer (Figure 13, upper panel). Water redistributes within the active layer during freezing as a direct result of horizontal differences in soil temperature. The model solves the modified Richards equation to simulate liquid water movement [*Daanen et al.*, 2007]. Heterogeneous insulation of the soil surface, caused by patchy vegetation or an irregular snowpack, results in temperature differentials that drive the heat and water flow, and ice accumulates in areas with little surface insulation.

3.3.2. ArcVeg Model

[38] The arctic vegetation dynamics model (ArcVeg [*Epstein et al.*, 2001a, 2001b]) is used in combination with WIT to simulate vegetation development, a key component of the upper boundary description in the WIT model. The ArcVeg model controls the dynamics of the surface insulation by simulating vegetation succession on small patches of disturbed tundra. ArcVeg simulates vegetation growth as expressed by a variety of different plant functional types, including grasses, sedges, mosses, lichens, forbs, and evergreen and deciduous shrubs. Each plant type has its own germination probability, and each year new seeds can germinate and either initiate or contribute to the biomass of that plant type. The plant-functional-type compositions of the communities are also affected by competition among types for plant-available nitrogen in the soil. Each plant functional type has its own sensitivity to the climate (temperature in this case), and therefore the composition of the vegetation changes depending on the climatic conditions. The model stochastically generates disturbed patches on the landscape due to frost heave and simulates the feedbacks that occur between frost heave and vegetation growth. The patches disturbed by frost heave gradually proceed through vegetation succession until ultimately the accumulation of vegetation is in balance with the continuing occurrence of frost heave.

3.3.3. Coupled WIT/ArcVeg Model

[39] The ArcVeg model interacts with the WIT model in three ways; (1) ice accumulation (e.g., ice lenses or needle ice) in a soil column or its neighboring columns, causes a reduction in live vegetation biomass for that node, due to

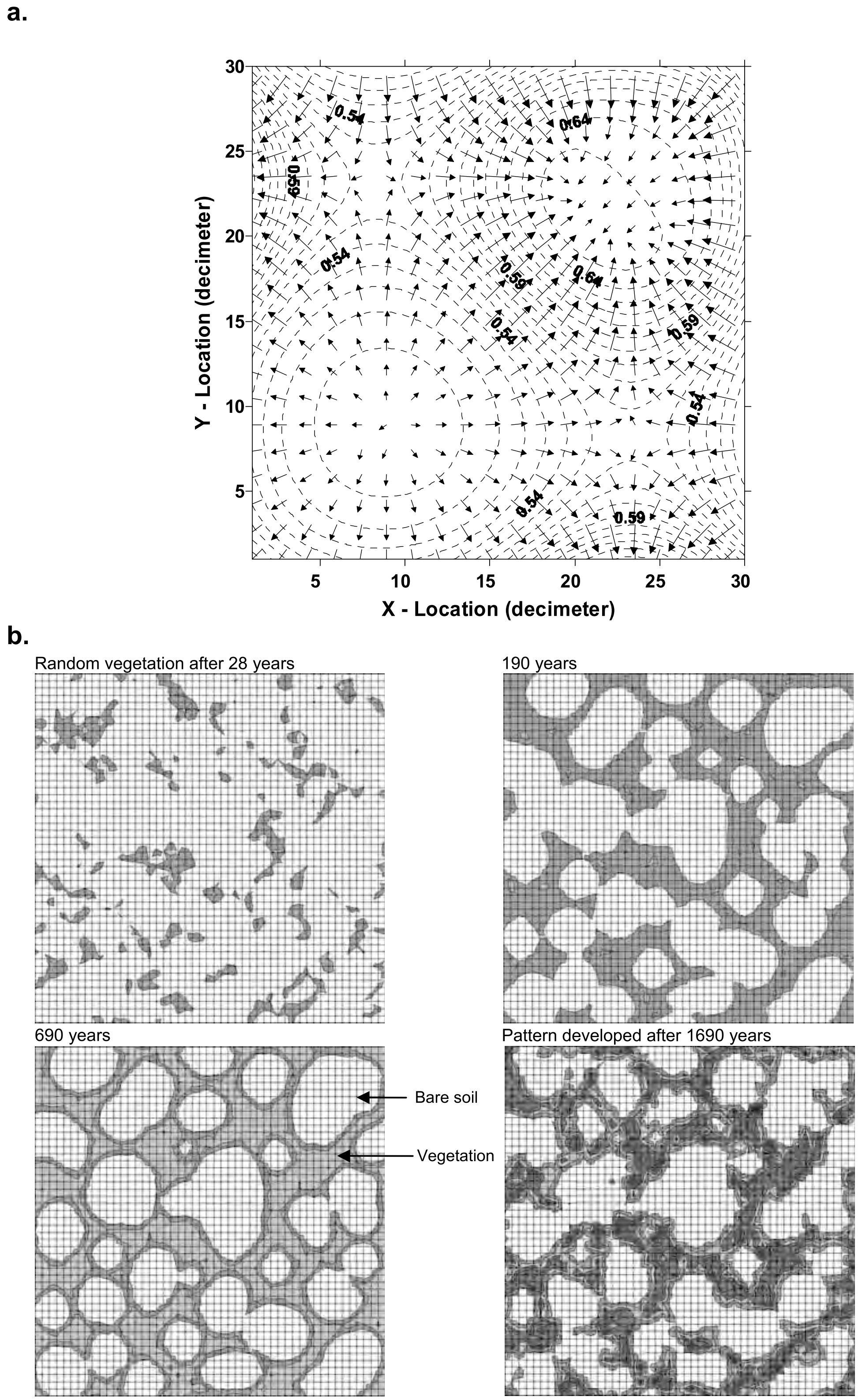

Figure 13. (a) Upper panel: Ice content distribution at a depth of 5 cm depth (light isolines) as obtained from the numerical model WIT. The arrows represent the direction of the liquid water movement across the 3 × 3 m area. (b) Lower four panels: Output from the combined WIT/ArcVeg model showing a simulated pattern of vegetation that develops after 1690 years in combination with heaving is simulated by the WIT model. The darker vegetation tones represent vegetation with greater amounts of plant biomass. The spatial domain in the lower diagram is 5 × 5 m. The model incorporates feedbacks between the vegetation and the amount of heave. (Figures courtesy of R. Daanen.)

root damage and resulting plant mortality; (2) vegetation biomass provides insulation which determines the upper boundary temperature for the WIT model; (3) soil organic matter calculated by ArcVeg affects the freezing characteristic and hydraulic conductivity curves for the soils in WIT. As ArcVeg simulates vegetation production during each growing season, warmer years lead to greater productivity and plant community development than in colder years. Annual frost heave on patches that have minimal insulation from vegetation inhibits vegetation from colonizing these areas. Disturbed patches therefore tend to persist on the landscape due to disturbance feedbacks associated with frost heave and vegetation. The model is typically allowed to run until an equilibrium vegetation community is established. Figure 13 (lower 4 panels) shows the patterns generated by WIT/ArcVeg with a model run of 1690 years.

3.4. Conceptual Model for Permafrost: Patterned-Ground Interactions

[40] A new conceptual model illustrates the important role that permafrost plays in the development of nonsorted circles and medium-size hummocks on zonal situations in the Low Arctic [*Shur and Ping*, 2003; *Shur et al.*, 2005a, 2005b] (Figure 14). This model also incorporates frost cracking, unlike any of the other models. The process starts with thermal contraction cracks that are spaced at 1–3 m (Figure 14, Stage 2). Mosses and lichens initially colonize the cracks, followed by other plant species and eventually the development of an organic soil that insulates the crack (Stage 3). This causes a cooler soil thermal regime and a reduced active layer beneath the cracks compared to the polygon centers. Deeper thawing in the polygon centers compared to the cracks causes bowl-shaped depressions to develop in the permafrost table beneath the circles. Soil water containing dissolved organic material flows into the bowls from the peaty areas surrounding the polygon center, and an organic-rich mineral soil horizon develops at the base of the bowls. Differential frost heave in the center of the polygons creates a barren nonsorted circle in the polygon centers (Stage 4). Over time, particularly in warmer environments, vegetation colonizes the margins of the nonsorted circles and spreads over the centers; increased insulation caused by the vegetation reduces the active layer, first at the edges and then in the centers of the circles, leading to an aggrading permafrost table, which moves upward and inward toward the centers of the bowls. This process causes more differential heave resulting in a mound (Stage 5). Eventually, the vegetation fully covers the mounded material, and the active layer decreases further (Stage 6). As the vegetation mat thickens and the soils cool further, the permafrost fully incorporates the organic-enriched layer beneath the hummocks (Stage 7).

[41] The differential frost heave associated with hummock development occurs as a result of long-term changes to the permafrost table and is distinctly different from the annual differential heave observed in the nonsorted circles that we studied in northern Alaska [*Daanen et al.*, 2008; *Nicolsky et al.*, 2008; *Romanovsky et al.*, 2008]. As the permafrost table aggrades, the soils in the center of the circles are forced radially inward and upward forming the hummocks and resulting in a semi-stable mound that does not collapse annually; whereas the nonsorted circles we studied on the Arctic Coastal Plain require open hydrological systems to account for the amount of annual heave that was observed.

[42] A process of mound formation similar to Shur's hypothesis has been described at the Inuvik site, where hummocks were eliminated by fires and have since regrown as the vegetation mat recovered [*Kokelj et al.*, 2007]. The detailed studies near Inuvik have confirmed that aggradation-ice development is the principal process driving the hummock formation. Establishment of differential thaw and a bowl-shaped permafrost table is associated with colonization of mosses and shrubs in the inter-hummock depressions. *Kokelj et al.* [2007] also showed that the movement of soil inward and upward as the permafrost aggraded caused the hummock heights to increase and the diameters to decrease.

[43] A critical step in Shur's model is the development of the organic-rich and ice-rich intermediate layer that forms at the top few centimeters of the permafrost table [*Shur et al.*, 2005a, 2005b]. This portion of the permafrost table may thaw in some warm years, but it also has distinctly different ice structures and greater organic-matter content than permafrost beneath this layer. As vegetation colonizes toward the centers of nonsorted circles and reduces the heat flux into the soils, the permafrost table aggrades, locking carbon in the permafrost. The large amounts of buried carbon found in Arctic soils is caused to a large degree by the sequestration of dissolved organic matter in the intermediate layer [*Michaelson et al.*, 1996].

4. Importance of Patterned Ground to Ecosystem Processes and Expected Responses to Climate Change

[44] Climates, permafrost conditions, and Arctic ecosystems are currently changing rather quickly in the Arctic [*IPCC*, 2001; *Callaghan et al.*, 2005: *Romanovsky et al.*, 2008; *Williams et al.*, 2007], and it is worth inquiring how landscape patterns might change in response to climate warming and how these changes might affect regional fluxes of energy, water, and carbon.

[45] We expect that climate change will cause zonal climate boundaries to shift northward and upward in elevation in response to warmer summer temperatures and deeper winter snowpacks. The vegetation, however, may not shift in concert with the climate. In general, most areas of the Arctic will likely accumulate additional aboveground biomass and soil organic matter, but the redistribution will not be uniform. Microsites with highly disturbed soils due to cryoturbation, may change more quickly than areas with more stable plant communities. In subzone E and southern parts of subzone D, this will likely result in fewer areas with abundant nonsorted circles and nonacidic soils. In subzones C and northern subzone D, which at present have barren or sparsely vegetated PGFs, additional plant biomass and soil organic matter on the centers of PGFs will likely reduce the soil summer heat flux, active layer depths and soil heave on the centers of the PGFs, and areas between PGFs are likely to be less affected. It is less clear how the High Arctic patterned-ground systems would respond to moister and warmer climates and more biomass on the these landscapes; much depends on the availability of water and nutrients in

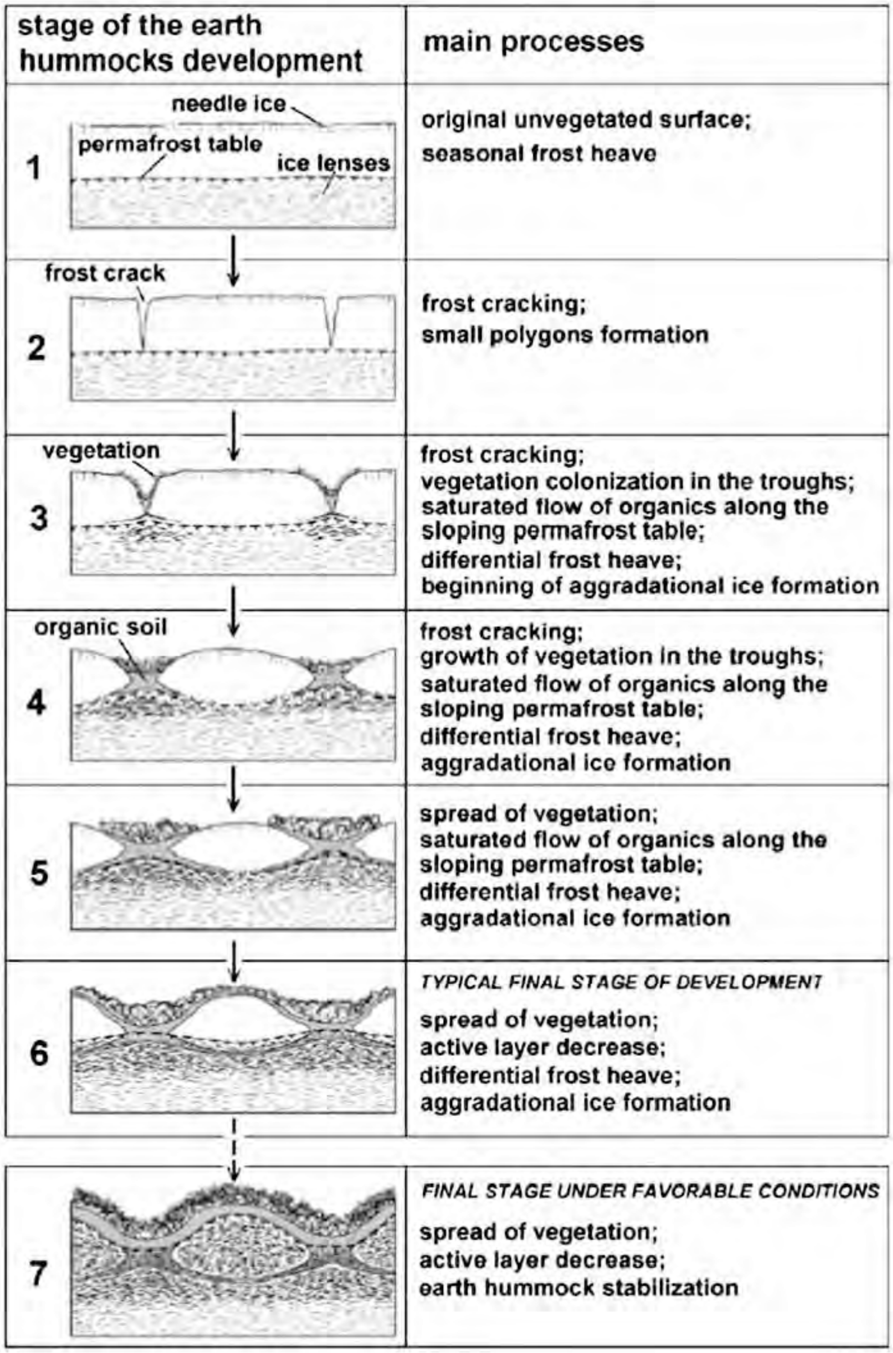

Figure 14. Conceptual model of nonsorted circle and hummock formation that occurs in conjunction with frost cracking. See text for explanation.

these landscapes, but the overall response is likely to be slower than in warmer Low Arctic environments.

[46] These changes will affect landscape- and regional-scale patterns of fluxes of water, energy and trace-gases, and also patterns of biodiversity, and wildlife use. Previous work at the Sagwon location examined the fluxes of heat, water, and CO_2 on either side of a pH boundary that separates tundra with abundant nonsorted circles from an area with few circles [*Walker et al.*, 1998]. This site is also at the boundary between bioclimate subzones D and E. The area north of the boundary had moist nonacidic tundra (MNT) with about 36% cover of partially vegetated nonsorted circles compared to a similar area on the south side of the boundary that had moist acidic tundra (MAT) and less than 1% cover of nonsorted circles. When compared to the area with few circles, the patterned-ground ecosystem had 28% more soil heat flux, 50% of the gross photosynthesis, one-third the respiration, and was less than 50% of the carbon sink, despite the close proximity of the two tundra types and nearly identical climates and surficial geology.

[47] The carbon stored in the intermediate layer of the permafrost is particularly important with regard to the

potential effects of climate change. The intermediate layer is rich in carbon, and that carbon could potentially be released to the atmosphere as soil temperatures warm; however, this organic material also tends to stabilize the active layer because it is ice rich and requires a large amount of latent heat to melt the ice. The accumulation of carbon in the insulative vegetation mat on the soil surface and in the soil-organic horizons plus the difficulty of melting the intermediate layer makes it unclear whether the net effect will be a positive or a negative feedback to atmospheric CO_2.

[48] Much more work is needed to characterize fluxes all along the climate gradient and also to examine a variety of other questions such as how the diversity of animals, insects, and microbes between the various patterned-ground ecosystems are affected by the mosaics of PGFs. These studies are likely to show that microscale variations in soil temperature and heterogeneous plant canopies associated with patterned-ground systems have major influence over nearly all ecosystem properties and processes.

5. Conclusions

[49] We began this project with the assumption that the vegetation, soils and hydrology interacted with climate and permafrost to produce patterned-ground features (Figure 3). We hypothesized that the thermal effects of the vegetation mat modify frost heave and frost cracking, and that the effects would vary strongly along the Arctic climate gradient and play an increasingly important role toward the south. A key discovery was that the vegetation also strongly affects the hydrological gradients within patterned-ground features. Two distinctive types of hydrological systems were observed. Open-system features, whereby water moves into nonsorted circles from the surrounding tundra, have strong annual heave and were common on the coastal plain of northern Alaska. Closed-system features, whereby much of the heave occurs due an aggrading permafrost table, occur in well-vegetated tundra areas and were most common in southern part of the climate gradient.

[50] The Biocomplexity of Patterned Ground Ecosystems project collected climate, soils, vegetation, frost-heave, and active-layer data along an Arctic transect in northern Alaska and Canada. The observations and data from the project were used to develop and calibrate models that answered questions such as how patterned ground features develop, how they persist, how the vegetation affects patterning, and what the important interactions between permafrost, the hydrological system and patterned-ground systems are. The differential frost-heave model explains how freezing soils can self-organize to create patterning from random perturbations. The thermomechanical model explains how the temperature gradient across a pattern creates a freezing front that draws water into the centers of patterns, creating differential frost heave. This model was parameterized using data collected in the field. Sensitivity analyses of this model demonstrated the importance of soil characteristics and vegetation in controlling differential frost heave. The hydrologic/vegetation model combined hydrological processes with vegetation dynamics. The combined WIT/ArcVeg model demonstrated how the interaction between frost heave and vegetation colonization act to perpetuate patterned ground features. The fourth model answers some of the questions regarding the interactions between patterned ground systems and permafrost, describing how vegetation colonization and its insulative effects can create a patterned-ground feature common in the southern Arctic: hummocks with bowl-shaped permafrost and an ice-rich and organic-rich intermediate layer.

[51] Additional studies along the Arctic climate gradient are needed to more fully understand how these systems will respond to climate warming. Additional studies are also needed to determine how patterned-ground systems affect the diversity of a wide variety of organisms. As the Arctic warms during future years, the data collected during this study will serve as a baseline against which existing models can be tested and future changes in the ecosystems can be compared.

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