Final Report for Period: 10/2006 - 09/2007 **Submitted on:** 01/11/2008
Principal Investigator: Walker, Donald A. **Award ID:** 0120736
Organization: U of Alaska Fairbanks
Title:
Biocomplexity associated with biogeochemical cycles in arctic frost-boil ecosystems

Project Participants

Senior Personnel

Name: Walker, Donald
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Epstein, Howard
Worked for more than 160 Hours: Yes
Contribution to Project:
Heads up the Vegetation Modeling component

Name: Gould, William
Worked for more than 160 Hours: Yes
Contribution to Project:
Heads up the Teaching component

Name: Krantz, William
Worked for more than 160 Hours: Yes
Contribution to Project:
Heads of the Differential Frost Heave Modeling component

Name: Ping, Chien
Worked for more than 160 Hours: Yes
Contribution to Project:
Heads up the Soil component

Name: Romanovsky, Vladimir
Worked for more than 160 Hours: Yes
Contribution to Project:
Heads up the Climate and Permafrost component

Name: Shur, Yuri
Worked for more than 160 Hours: Yes
Contribution to Project:
Collaborator and coauthor on paper

Name: Daanan, Ronnie
Worked for more than 160 Hours: Yes
Contribution to Project:
Modeller and participant in field work

Post-doc

Name: Kuss, Patrick
Worked for more than 160 Hours: Yes
Contribution to Project:
Visiting graduate student and participant in 2004, research on Prince Patrick I and Ellef Ringnes Island.

Post Doc in 2007.

Name: Vonlanthen, Corinne

Worked for more than 160 Hours: Yes

Contribution to Project:

Corinne Vonlanthen is a post-doc working on vegetation analysis of vegetation on High Arctic patterned-ground features.

Name: Peterson, Rorik

Worked for more than 160 Hours: Yes

Contribution to Project:

Rorik Peterson worked on the differenential frost heave model during the first year of the project. He was partially funded the first year and has continued to help in the project during annual meetings and is helping to move the DFH model forward.

Graduate Student

Name: Kade, Anja

Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Kelley, Alexia

Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Bickley, Joe

Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Timling, Ina

Worked for more than 160 Hours: Yes

Contribution to Project:

Graduate student working on micorrhizal associations along the arctic bioclimate gradient

Name: Borden, Patrick

Worked for more than 160 Hours: Yes

Contribution to Project:

Patrick is a Masters student, examining the soil characteristics and mineralogy across the boundary of moist acidic and nonacidic tundra at the Sagwon study site.

Name: Xu, Chunhao

Worked for more than 160 Hours: Yes

Contribution to Project:

Chunhao Xu is examining the physical fractionation and biogeochemical character of the deep carbon in Arctic soils.

Name: Nickolsky, Dmitry

Worked for more than 160 Hours: Yes

Contribution to Project:

Nickolsky is developing a Ph.D. project to model the thermo-mechanical properties of frost-heave features.

Undergraduate Student

Name: Johnson, Jeanne

Worked for more than 160 Hours: Yes

Contribution to Project:

Jeanne Johnson is an undergraduate student who has helped with biomass sorting from the permanent vegetation plots.

Name: Burton, Linda

Worked for more than 160 Hours: Yes

Contribution to Project:

Linda Burton is an undergraduate student who has helped with biomass sorting from the permanent vegetation plots.

Technician, Programmer

Name: Raynolds, Martha

Worked for more than 160 Hours: Yes

Contribution to Project:

Laboratory assistant, data analysis, logistics coordinator

Name: Maier, Hilmar

Worked for more than 160 Hours: Yes

Contribution to Project:

Laboratory assistant, GIS manager, systems administrator

Name: Martin, Christine

Worked for more than 160 Hours: Yes

Contribution to Project:

Laboratory assistant, lab manager

Name: Michaelson, Gary

Worked for more than 160 Hours: Yes

Contribution to Project:

Soils lab technician

Name: Tipenko, Gennady

Worked for more than 160 Hours: Yes

Contribution to Project:

Modeler working on the differential frost heave model

Name: Sergueev, Demitri

Worked for more than 160 Hours: Yes

Contribution to Project:

Technician for climate and permafrost component

Other Participant

Name: Tarnocai, Charles

Worked for more than 160 Hours: No

Contribution to Project:

Charles Tarnocai is a Canadian collaborator who is advising us on soils and vegetation of the Canadian High Arctic. He has extensive experience with frost boils and hummocks throughout northern Alaska. In 2003 he accompanied us to Banks Island and did research on the soils and turf-hummock formation. The grant has paid for his field expenses and transport to the resarch sites.

Name: Matveyeva, Nadya

Worked for more than 160 Hours: Yes

Contribution to Project:

World renowned expert on Polar Desert Vegetation. Participated in the 2005 field season at Isachsen. Helped with the vegetation field studies and the Braun-Blanquet classfication.

Name: Makorova, Olga

Worked for more than 160 Hours: Yes

Contribution to Project:

World renowned expert on Polar Desert invertebrates. Participated in the 2005 field season at Isachsen. Helped with the invertebrate and animal field studies.

Name: Daniels, Fred

Worked for more than 160 Hours: Yes

Contribution to Project:

World renowned expert on phytosociological methods and arctic vegetation. Helped with field sampling of wet and snowbed plant communities and with Braun-Blanquet analyhsis.

Research Experience for Undergraduates

Name: Munger, Corinne

Worked for more than 160 Hours: Yes

Contribution to Project:

Corinne presented a poster and abstract at the 54th Arctic Science Conference, Fairbanks, AK 21-24 Sep 2003

C.A. Munger and D.A. Walker. 2003. Vegetation of the Upper Kuparuk River region in relationship to glacial geology and surficial geomporphology.

Years of schooling completed: Junior

Home Institution: Same as Research Site

Home Institution if Other: University of Santa Cruz

Home Institution Highest Degree Granted(in fields supported by NSF): Bachelor's Degree

Fiscal year(s) REU Participant supported: 2003

REU Funding: REU supplement

Name: Cushing, Erin

Worked for more than 160 Hours: Yes

Contribution to Project:

Years of schooling completed: Junior

Home Institution: Same as Research Site

Home Institution if Other:

Home Institution Highest Degree Granted(in fields supported by NSF): Bachelor's Degree

Fiscal year(s) REU Participant supported: 2002

REU Funding: REU supplement

Name: Pamperin, Nathen

Worked for more than 160 Hours: Yes

Contribution to Project:

REU worink on GIS applications

Years of schooling completed: Junior

Home Institution: Same as Research Site

Home Institution if Other:

Home Institution Highest Degree Granted(in fields supported by NSF): Doctoral Degree

Fiscal year(s) REU Participant supported: 2004

REU Funding: REU supplement

Organizational Partners

UNIVERSITY OF VIRGINIA

Other Collaborators or Contacts

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

The attached activities pdf file is a synthesis paper entitled 'Arctic patterned-ground ecosystems: asynthesis of studies along a North American Arctic transect', which provides the essense of the field studies, findings, and modeling activities for the Biocomplexity of Patterned-Ground Ecosystems project. The following narrative provides more details regarding the the yearly activities and the results of each of the subprojects.

Our project studied small patterned-ground ecosystems along the arctic bioclimate gradient in North America. These features are unique to permafrost regions and are a significant component of nearly all arctic landscapes. Prior to this study, these features have been studied by geomorphologists but their role in ecosystems has been largely unstudied. These systems are of particular interest because: (1) Some processes involved in the formation of patterned-ground landscapes are not well understood; (2) the role of cryogenic processes with respect to biogeochemical cycling, carbon sequestration and a whole host of ecosystem processes is poorly known; and (3) they are an ideal natural system to study the response of disturbed and undisturbed tundra to differences in climate. Recently, these features have been linked to a wide variety of ecosystem properties including sequestration of carbon in the permafrost, the flux of energy, water, and nutrients to the land surface, watersheds and the atmosphere (Bockheim et al., 1998; Nelson et al, 1998; Walker et al, 1998) and even the forage quality for wildlife (Walker et al, 2001). The project is focusing on how climate influences the interactions between vegetation, soils, and patterned ground formation in order to better understand how climate change might affect these systems. We are focusing on soil biogeochemical processes, hydrothermal processes, and vegetation patterns.

Briefly, the patterned ground features studied here include non-sorted circles (frost boils), earth hummocks, small non-sorted polygons, and turf hummocks (Washburn 1980). Non-sorted circles and earth hummocks are 1 to 3-m diameter, often circular, patches that are caused by frost heave and are spaced from 1 to 10 m apart. Small non-sorted polygons are caused by contraction cracking within the active layer, either by desiccation or by frost cracking. Turf hummocks generally occur on slopes and are small non-sorted polygons that have been modified by eolian deposition and erosion.

This report describes the major field activities during the five years of the project, including research expeditions in to Green Cabin on Banks Island NWT (2003), Mould Bay on Prince Patrick Island, NWT (2004), and Isachsen on Ellef Ringnes Island (2005). It also describes the major educational activities (1 post-doctoral students, 5 graduate students, 4 REU students, and 25 undergraduate students). The project has received 3 supplements for Research Experience for Undergraduates. This report describes results from several aspects of the field and modeling studies that will be used to develop a monograph on the ecology of arctic patterned-ground ecosystems.

METHODS

The studies were conducted along an 1800-km transect through Arctic Alaska and northern Canada. This transect includes sites in all 5 Arctic bioclimate subzones (Walker et al. 2005) and one site in the northern boreal forest. During the first two years of the project (2001-2002), research focused on frost-heave features (non-sorted circles and earth hummocks) in the Low Arctic along the Dalton Highway in northern Alaska. In 2003 -2005, the primary focus of the research moved to the High Arctic, where small non-sorted polygons caused by cracking of the soils are the dominant features.

Summer 2002
During June 10-July 1, 2002 field season all the investigators and students involved in the project met at Prudhoe Bay and presented results and plans for research and visited all the Biocomplexity sites along the Dalton Highway. We mapped maximum snow depth, maximum active layer thickness, and plant communities on all the sites. Frost heave was monitored at all sites using a specially designed frame. Air and ground temperatures and snow cover were monitored continuously. Vegetation and soils were characterized at all the sites. Nitrogen mineralization experiments were started,and detailed studies of biomass, leaf-area index, and the normalized difference vegetation index were conducted along transects at each site. During July 14-July 31, 2002. Skip Walker, Bill Gould and Grizelle Gonzales did a site selection reconnaissance by flying from Inuvik to Mould Bay and Satellite Bay on Prince Patrick Island.

Summer 2003
During 28 Jun to 20 Jul 2003 nearly all the project members participated in an expedition to Green Cabin on northern Banks Island. The expedition included 13 scientists and 6 students in the Arctic Field Ecology course. The work involved the same activities as those on the Arctic Slope, Dalton Highway sites. We also spent half a day at Mould Bay, Prince Patrick Island (Bioclimate Subzone B). Extensive ecosystem, snow, and ground-temperature data were available from several sites in this region (Romanovsky and Osterkamp, 1995, 1997). In Northern Alaska, twelve 10x10-m grids were established along a bioclimate gradient at 6 locations (Howe Island, West Dock, Deadhorse, Franklin Bluffs, Sagwon, and Happy Valley). A data report and addendum describe the field activities in detail (Munger et al. 2004; Raynolds 2005). Work also continued on the Arctic Slope with field trips in April to measure and monitor snow cover and ground surface temperatures, and a trip in August to finish the vegetation sampling and continue work on the thesis research of Anja Kade and Alexia Kelley.

Summer 2004
2004 Mould Bay Expedition
During July 11-28, 2004, 24 people from the University of Alaska Fairbanks and other organizations worked at Inuvik, NWT and Mould Bay, Prince Patrick Island, NWT. The field party consisted of 11 research scientists, 1 teacher participating in the TREC (Teaachers and Researchers Exploring and Collaobrating) program, 5 graduate student, 4 students in an Arctic Field Ecology course, 2 native hunters from the village of Sachs Harbor, and cook. The main objective of the reserch was to examine the small patterned ground features that are more common in the High Arctic including turf hummocks and small non-sorted polygons, along with larger hummocks. A data report describes the field activities in detail (Munger et al. 2005).

2004 Cape Thompson expedition
Another expedition went to Cape Thompson in northwestern Alaska, 22-26 Jun 2004, to revisit the frost-boil study sites of Dr. Al Johnson, who has turned over his legacy of research to the project and to the Arctic LTER site. The expedition consisted of Al Johnson, Skip Walker, Corinne Munger, and Carrie McCalley. Photos of all his study sites and the hand-written data sheets have been digitized and stored on CD-ROMs, and archived with the Arctic LTER data manager. During the 3 days in the field, we visited several of the old study sites, and photographed the plots. This valuable data set is one of the oldest (1960s) most complete vegetation studies in Alaska, and one where it would be possible to revisit and photograph the exact localities of photos taken in the 1960s of 325 non-sorted circles. It would be highly desirable to resample all the vegetation plots. This will require a proposal, a willing graduate student, and close collaboration with the villagers at Point Hope.

Summer 2005
The 2005 expedition to Isachsen was the largest collaborative group of researchers to ever

visit this remote outpost, located on Ellef Ringnes Island in the Sverdrup group of islands in the Canadian Archipelago. Of the four Biocomplexity expeditions to the Canadian Islands, the one to Isachsen was logistically the most difficult because of the size of the group (25 scientists, students, and support staff), and remoteness of Ellef Ringnes Island. Two reconnaissance flights in 2004 were unable to land at Isachsen because of poor weather. This year, a preliminary group preceded the the main expedition so that ground-based weather reports could be provided from Mould Bay and Isachsen to the Ken Borek pilots coming from Inuvik. The research camp was supported by VECO Polar Resources (Figs. 7 to 9), and the expedition went flawlessly until the very last flight out of Isachsen, when a DC-3 got stuck in mud, and it took two days of digging to free it.

Isachsen is near the extreme cold end of the summer temperature gradient in Canada. It was the site of a joint U.S.-Canadian climate station from 1948 until 1971, when the United States withdrew its participation at the site. This led to Isachsen's decommissioning in 1978. An automated weather station was placed at the site in 1989 and is monitored by satellite. Isachsen is the only North American facility that is within Bioclimate Subzone A on the Circumpolar Arctic Vegetation Map. Subzone A is characterized by very low summer temperatures and low biological diversity and productivity. The mean July temperature at Isachsen is 3? C, and only 51 species of vascular plants grow there. There are no sedge species, nor any woody species growing on zonal sites. There were few birds and animals present while we were there, but there were tracks and sign of polar bears, muskoxen, Peary caribou, wolves, arctic foxes, arctic hares, and weasels. Collared lemmings were common around camp.

The expedition included 5 students that participated in the Arctic Field Ecology course taught by Bill Gould and Grizelle Gonzalez through the University of Minnesota. The students actively participated in the research and attended nightly lectures conducted in a large yurt that was the camp's center of activity. Participants in the expedition came from Russia, Canada, France, Germany, Puerto Rico, Switzerland, and the US.
The expedition members were: Robin Austin (Antioch New England), Fred Daniels (Germany), Howard Epstein (University of Virginia), Grizelle Gonzalez (US Forest Service, Puerto Rico), Bill Gould (US Forest Service, Puerto Rico), Anja Kade (UAF), Alexia Kelley (University of Virginia), Manny Kudlak (Sachs Harbor, NWT), Constance Lareau (France), Greta Lewanski (Evergreen State College), Trevor Lucas (Sachs Harbor, NWT), Nadya Matveyeva (Russia), Olga Makarova (Russia), Gary Michaelson (UAF), Corinne Munger (UAF), Jordan Okie (Carleton College), Chien-Lu Ping (UAF), Martha Raynolds (UAF), Maria Rivera (University of Puerto Rico), Vladimir Romanovsky (UAF), Sharon Rae Spain (VECO Polar Resources), Charles Tarnocai (Canada), Ina Timling (UAF), Corinne Vonlanthen (Switzerland), Skip Walker (UAF).

Field activities were the same as those in earlier years except with the addition of expanded soil fauna studies with the participation of Dr. Olga Markorova from the Severtsov Institute of Ecology and Evolution in Moscow, and expanded vegetation analysis studies by Dr. Nadya Matveyeva from the Komarov Botanical Institute in St. Petersburg, Dr. Fred Daniels of the Institue of Plant Ecology at the University of Muenster, Germany, and Dr. Corinne Vonlanthen from the University of Bern, Switzerland. These people allowed for a much expanded sampling of the vegetation and soil fauna at this northern extreme of the gradient.

2006 Field Activities:
Three expeiditions along the Dalton Highway monitored spring snow conditions, collected biomass data, and recored end of season active layer depths.

A spring expedition to the Canadian Arctic islands (Banks Island, Mould Bay, Isachsen) made end of season snow measurements and observations.

WORKSHOPS and SYNTHESIS ACTIVIES (Howie Epstein and Skip Walker):

Annual workshops are held each year to focus on the modeling aspects of the project. There are four major process models under development: (1) the Differential Frost Heave (DFH) model, (2) the thermo-mechanic frost-heave model, (3) the ArcVeg model, and (4) a model of ice formation within frost boils. In 2002, the workshop was a traveling workshop that met at Prudhoe Bay and then visited all the study sites along the Dalton Highway. The major goals of this workshop were to familiarize all the investigators including the modelers with the field sites in northern Alaska and to interact with the students to help them develop biocomplexity-related research projects.

In 2003, 2004 and 2005, three-day modeling workshops were held at the University of Alaska Fairbanks in mid-March. The focus of both these workshops were to (1) coordinate the field activities with the needs of the models, (2) develop linkages between the modeling efforts, (3) develop themes for syntheses efforts in 2006, and (4) plan for the summer field activities.

The major synthesis activity for the project was a special session at the 2006 Fall AGU meeting. The papers presented at the meeting are being published in a special section of the Journal of Geophysical Research - Biogeosciences.

Additional synthesis products are planned including a book and additional synthesis publications to the Journal of Vegetation Science, Ecology, and Nature.

Data reports are available for the Dalton Highway, Green Cabin, Mould Bay, and Isachsen (see list of publications).

Findings:

The following summary presents the findings from each of the subprojects.

Summary of results:

Conceptual model of small patterned ground formation (Skip Walker and Yuri Shur). The study initially focused on frost-boils (non-sorted circles) on zonal sites, and a conceptual model was developed from these observations (Walker et al. 2003). As we moved both south and north from our initial study sites in northern Alaska, we found that the dominant morphology of the patterned ground features changed. Using the terminology of Washburn, to the south, the non-sorted circles grade into earth hummocks, and in the north, they grade into large and small non-sorted seasonal frost-crack polygons. A conceptual model developed by Yuri Shur addresses the relationship between the permafrost intermediate layer (an ice-rich layer at the top of the permafrost table) and vegetation succession. We are currently formulating a conceptual model of the polygenetic origin of small patterned-ground forms that incorporates the ideas of both the Walker et al. and Shur models. The model identifies three primary processes that create or modify patterned ground forms: frost cracking, differential heave, and vegetation succession. Each of these processes is strongest in different parts of the bioclimate gradient. Contraction cracks are most strongly developed in the extreme High Arctic (subzones A and B). Differential frost heave affects pattern most strongly in the Middle Arctic areas (subzones C and D) where barren non-sorted circles are mixed with well-developed inter-circle vegetation. Vegetation has the strongest effect for stabilizing heave effects in the Low Arctic (Subzones D and E) where vegetation completely masks contraction cracks and non-sorted circles. Soil texture influences the form of the patterned ground features in the following ways, again using the terminology of Washburn (1980): Sorted circles form in rocky soils; earth hummocks in clayey soils; sorted circles without hummocks in silty soils; and sandy soils are generally featureless without circles or hummocks.

Air Temperature and Frost heave (Vlad Romanovsky). Air temperatures and ground temperatures have been recorded at all sites and will be reported in a publication once data are available from Isachsen. Summer air temperatures are most critical for plant growth along the transect.

Very significant seasonal frost heave within the non-sorted circles on the North Slope. The maximum heave of non-vegetated circles reaches 20 cm. It is up to ten times larger than we could expect if the heave was generated only by 10% increase of soil water during freezing. It means that there is very substantial redistribution of soil moisture during the freezing and extensive ice lenses formation within the frost-boil system. Frost heave on the barren silty non-sorted circles is in the order of 12-20 cm, compared to less than 5 cm in well-vegetated inter-boil areas. Preliminary studies by Su Shun Li along the boundary between acidic and nonacidic tundra at the northern edge of the foothills suggest that interferometry using time sequence of SAR images may offer a means to identify areas with greater frost heave, and by inference, regions with more frost boils.

Thaw-layer relationships (Skip Walker, et al.). The greatest thaw occurred in subzones C and D (Green Cabin to Franklin Bluffs). The shallowest active layers occurred in Subzones A and B, and at the cold coastal site at West Dock (Subzone C), where peaty soils overlie alluvial gravels, and there are no patterned ground features. In the Low Arctic of Alaska (Howe Island to Happy Valley), summer warmth was inversely related to thaw-layer thickness. The seemingly paradoxical relationship is primarily caused by more dense vegetation toward the south, which insulates and shades the soils. On Howe Island, at the northern end of the transect where the mean July temperature is 4 ?C, the mean active layer depths are 65 cm. At Happy Valley, where the mean July temperature is about 12 ?C, the end-of-summer active-layer depths are about 40 cm. The longer warmer summers in the southern portion of the gradient, promotes deeper moss layers, and more diverse and more active vegetation that is better able to colonize and stabilize the frost boils. Patterned ground formation in the foothills is consequently much suppressed.

Differential Frost Heave Model (Rorik Peterson and Bill Krantz). The differential frost-heave (DFH) model was developed by Rorik Peterson and William Krantz (Peterson and Krantz 2003, Peterson et al. 2003). Publications outlining the development of this model have appeared in the Proceedings of the 8th International Permafrost Conference and in the Journal of Glaciology. The DFH model considers geophysical self-organization owing to a symmetry-breaking mechanism associated with seasonal or diurnal freezing of water-rich soils. The DFH model is based on linear stability theory whereby one explores whether the one-dimensional freezing process is stable to small perturbations. These small perturbations could be in the form of heterogeneities in the soil properties, variations in the ground or snow cover, or fluctuations in the ecosystem variables such as the wind speed or air temperature. A small perturbation can cause a corrugation in the ground surface and underlying frost-penetration front. This in turn can increase the heat transfer from the system owing to a minute increase in the surface area. This causes a corresponding acceleration in the rate of freezing accompanied by an increase in the capillary suction that draws unfrozen water upward. However, a perturbation can be unstable only under certain conditions with respect to the soil and ecosystem variables. The DFH model can predict the conditions required for differential frost heave to occur. The latter can be manifest in the form of frost boils, earth hummocks, sorted stone polygons, and other forms of patterned ground. The model predicts that patterned ground forms emanating from DFH are more likely to form in silty soils that provide an optimal combination of permeability and significant capillary suction. The modeling work to date has focused on linear stability theory that is capable of describing the conditions required for the inception of patterned ground formation and the characteristics of the patterns that initially form. Future work on the DFH model should focus on solving the evolution equations for the nonlinear problem. It would also be of value to incorporate into the linear DFH model the effects of the desalting that occurs upon freezing of water drawn up owing to capillary suction. The basic physics behind the DFH model appear to be valid, but the current model can only be used for predicting conditions at the inception of frost-boil formation in situations with homogeneous topography and homogeneous soil conditions and no vegetation cover. The self organization of the frost boils into their existing forms involves more factors than are currently accounted for in the model. Patterned-ground forms are the product of interactions between the climate, soils, vegetation, and ice-lenses. Once hetrerogeneities develop, the problem becomes much more complex. We, therefore, were not able to validate the DFH model from field observations and the focus shifted to developing a numerical model of frost heave.

Thermo-mechanical and hydrological frost heave models (Vladimir Romanovsky, Dmitry Nickolsky, Gennadiy Tipenko, Ronnie Daanen). Strong progress has been made on a sophisticated 2-D frost-heave numerical model with radial symmetry as part of a Ph.D. thesis project of Dmitry Nickolsky (Nickolsy et al. 2004). The model addresses how changes in surface conditions such as vegetation, snow cover and climate affect the seasonal dynamics of water and heat within frost-boil systems. A coupled thermo-mechanical model is based on principles of thermodynamic equilibrium and continuum mechanics. Comparison between the first results of this model and measured soil temperature and moisture dynamics show a good agreement.

Another model being developed by Ronnie Daanen, Debasmita Misra, and Howard Epstein examines the hydrology of non-sorted circles and how changes in the surface thermal properties due to vegetation affect heave. The WIT3D physical relations are the non-linear RichardÆs equation for liquid water movement of variably saturated soils and FourierÆs law for heat transfer with convection. Phase change is determined trough the General Calpeyron equation which shows the equilibrium conditions between the liquid water temperature, liquid water pressure and the ice pressure. When the soil temperatures change the phase change is corrected accordingly. When both liquid water and ice are present in the soil then the liquid water pressure, which determines liquid water flow, can be directly related to the temperature of the soil. The amount of ice formed is calculated through a constitutive relation between the liquid water pressure and the liquid water saturation of the soil, also known as the water retention curve. The result of this model is a three dimensional field of temperatures and ice contents in the freezing active layer.

The upper domain boundary temperature is determined through an iterative solution of the heat flux through the upper layer of the soil and the heat flux through the dynamic insulation layer. The insulation layer is updated between freezing periods. These periods are 30 days for freezing under measured air temperature conditions, where the total active layer is frozen after the 30 day period. The update is based on vegetation type biomass that was calculated with ArcVeg. The Biomass of each square simulated for each type is converted to an insulation factor through a unique parameter per vegetation type. Within this insulation value it needs to be considered that each vegetation type has its own insulation capability and each plant affects the micro climate differently. Snow is an important aspect for insulation during the freezing period and snow is trapped by vegetation due to its wind breaking ability.

The combination of models WIT3D with ArcVeg gives an opportunity to have two processes interact: the vegetation development and the movement of liquid water through the active layer based on differential insulation at the soil surface. Considering the time needed for vegetation succession, it is necessary to simulate many freezing periods so that the vegetation can adapt to the calculated heave pattern and visa versa. We use a variable time for development of the vegetation. This means that each simulation starts with a completely randomized vegetation development for a single year, calculate the heave pattern and simulate further vegetation growth with that particular heave pattern, the growth of vegetation increases the insulation at the soil surface and results in greater differential cooling of the active layer and a new heave pattern can be calculated. The pattern develops until the liquid water is distributed equally between the non-sorted circles after freezing is complete. Liquid water movement in the active layer during the freezing process causes areas of ice accumulation. Water and energy fluxes are limited by the physical characteristics of the soil and therefore control where ice is formed. In a simplified representation of the system, ice accumulation occurs along temperature gradients induced by the vegetation and organic matter, which act as an insulation mat between the above- and below-ground environment. in using the WIT3D/ArcVeg model. Modeling visualization of 3-D simulation of the formation of non-sorted circles is being done in the Arctic Regional Supercomputer CenterÆs Discovery Lab at UAF. The model simulates a systematic pattern of the vegetation, similar to a pattern found in a natural situation. Water redistributes within the active layer during freezing. The redistribution of liquid water from the vegetated to the bare soil causes a greater ice accumulation in the bare soil areas and a greater amount of heave. Simulated climate warming reduces the movement of water in the active layer during freezing and the potential changes in vegetation reduce the water movement even further.

Turf-hummock formation (Charles Tarnocai). Turf hummocks are small 11-20 cm high, 18-50 cm diameter mounds that commonly form on slopes in Arctic terrain. They appear to be related to the small nonsorted polylgons that form on flat surfaces. This study characterizes the hummocks and examines their genesis and the role they play in arctic ecosystems. A hypothesis of four stages in turf-hummock formation has been developed (Tarnocai and Walker 2005). The hummocks are initiated from small nonsorted polygons on flat surfaces. On hill slopes the polygons develop into small mounds through the erosion of the cracks and deposition of eolian material on the centers of the polygons. Vegetation on the hummocks (Dryas and Cassiope and mosses) traps eolian material, thereby increasing the relief of the hummock. Radiocarbon dates from buried organic-rich layers in turf hummocks at Green Cabin varied from 450 to 2060 y BP.

Snow (Anja Kade and Skip Walker). Snow depths have been measured along the Alaska portion of the gradient every spring for the past four years. Snow depths increase from the coast inland. Average end-of-winter snow depths at West Dock have been about 15 cm during this study, and depths at Happy Valley have been about 50 cm. There is also inter-plot variation in snow depth and snow density related to the microrelief associated with the frost boils. Insulation caused by deeper snow results in warmer soil-surface temperatures during the winter of heave features (nonsorted circles and hummocks) and the surrounding tundra. The inter-circle areas areas generally have thicker depth-hoar layers than the barren nonsorted circles. Dwarf shrubs and sedges growing in the stable tundra areas between the circles create voids in the snow and appear to promote the development of depth hoar. Consequently, the overall snow density is lower above the stable tundra than above the heave features.

The winter studies have also permitted examination of the heave features during winter. These features are not normally visible due to snow cover. Excavation of non-sorted circles that are flat during the summer reveals well-developed mounds in the winter. Consequently, the maximum snow depth is generally shallower on the heave features than on the adjacent tundra.

Soils (Chien Lu Ping and Gary Michaelson
Cryoturbation plays a controlling role in carbon sequestration across a bioclimate transect from Subzone A to the boreal forest in Arctic Canada and Alaska. The forms of cryogenic surface features/patterns that are expressed at the surface result in differing carbon-distributions throughout the soil profile. The soils of hummock features tend to store more C in the upper permafrost than in the active layer whereas carbon sequestered in nonsorted circles is more evenly divided between the upper permafrost and the surface active-layer. This could result in differing impacts and feedbacks to the carbon balance of these ecosystems under changing climate conditions.

Two types of heave features occur at the southern end of the gradient. The first are small, less than 30-cm diameter, barren patches that form between tussocks. These are often wet sites, and boils have abundant cryptogamic crusts composed primarily of liverworts (e.g., Anthelia juratzkana). The other forms are well-vegetated relatively large 1-2-m diameter, stable hummocks. The latter appear to be remnants of formerly large active frost boils. These features have soils with thin A horizons and relatively shallow O horizons compared to the inter-frost boil areas. Active layer depths on these features is over 50 cm compared to about 30 cm in the inter-hummock areas. Frost boils were once probably much more common in the southern portion of the region when the vegetation was less dense (e.g., late-Pleistocene). C14 dates from the base of the organic horizons are not yet available.

Cryptobiotic crusts composed of lichens, small mosses, liverworts and algae species of are of considerable importance for stabilizing the barren soils and for nitrogen fixation. Studies of the taxonomy of the crusts and characterization of the soil properties have been initiated (Michaelson et al. 2002, and 2005 submitted). Soil mineral substrates and their chemical character have important influences on the nature of soils under both cryptobiogic crusts and for bare-surface soils. Crusts developed on boils with calcium-rich (nonacidic) substrates as those found on the coastal plain accumulate Ca salts at the surface of the crust and in vegetated areas whereas the bare areas of the boil show even distribution of Ca near the surface consistent with more active and mixing of seasonal frost processes. Areas with significant sodium in soil substrates (i.e., coastal areas or other areas with marine sediments) show salt redistribution effects with frost boil formation. This redistribution of salts could be contributing to persistence of the surface vegetation pattern with accumulation of sodium in the bare boil centers and segregation of calcium under crusts developed on the edges and inter boil areas. Perhaps the most important impacts of crust and vegetation mat establishment result from the accumulation of OC, N, acidity and nutrients in the soil system affecting soil fertility. An important direct and immediate result of SOM cycling in crusts is the release of soil acidity (protons). In soils from more temperate regions these processes work primarily from the surface down or a static horizontal layering of soil horizons. But for systems associated with nonsorted circles, the surface effects are mixed to depth (down as far as the top of the permafrost table) and affect the physiochemical dynamics of the whole active layer over a longer time.

Two students are developing soils theses. Patrick Borden is examining soils on deposits across the boundary of Moist Acidic Tundra (MAT) and Moist Non-Acidic Tundra (MNT) in AlaskaÆs Arctic Foothills. The differences seen today in soil exchange complexes, mineralogy and clay mineralogy of corresponding soil horizons can be attributed to changes caused by acidification, biochemical and physical weathering. The natures of the soil exchange complexes and clay mineralogy are affected by nonsorted circle (frost boil) development and vegetation succession between the MAT and the corresponding horizons of MAT and MNT. Chunhao Xu is examining the the distribution and turnover rates of deep soil organic carbon in arctic tundra soils. Soil organic carbon storage in arctic tundra soils was found to be nearly double the amount estimated in previous studies due to increased excavation depth to include the cryoturbated carbon in lower active layers and upper permafrost at 60-120 cm. The turnover rates are estimated by using stable isotope 13C, 15N, 13CNMR spectroscopy and the 14C dating, coupled with physical and chemical fractionation.

Vegetation (Anja Kade, Skip Walker, Tako Raynolds, Corinne Vonlanthen, Patrick Kuss).
Vegetation analysis has been
completed for the Low Arctic portion of the gradient (Kade et al. 2005 in press). We established 117 relevÚs in frost-heave features and surrounding tundra and classified the vegetation according to the Braun-Blanquet sorted-table method. We identified four communities and five associations, three of which are newly described. We used Detrended Correspondence Analysis to analyze relationships between vegetation and environmental variables. The ordination displayed the vegetation types with respect to complex environmental gradients. The first axis of the ordination corresponds to a

bioclimate/pH gradient, and the second axis corresponds to a disturbance/soil moisture gradient. Frost-heave features are dominated by lichens, whereas the adjacent tundra supports more dwarf shrubs, graminoids and mosses. Frost-heave features have greater thaw depths, more bare ground, thinner organic horizons and lower soil moisture than the surrounding tundra. The morphology of frost heave-features changes along the climatic gradient, with large, barren nonsorted circles dominating the northern sites and vegetated, less active earth hummocks dotting the southern sites.

Vegetation cover, biomass, and the normalized difference vegetation index increase along the temperature gradient from north to south (Walker et al. 2003). Landscape heterogeneity is maximum in Subzone C. where non-sorted circles have large barren patches 1.5 m in diameter, with only a few widely scattered high-arctic forbs and grasses and the inter-circle areas At the southern end of the gradient (subzone E), the mean size of frost boils is 30 cm, are generally well vegetated with many hypoarctic shrubs and mosses. The percent cover of recognizable frost boils (bare soil and vegetation associated with the rims of nonsorted circles) decreases from about 70% at Howe Island to about 10% at Happy Valley. Bare soil decreases from about 25% to less than 1%. Vascular plant diversity and height increases toward the southern portion of the coastal plain. Moss biomass increases from 100 g m-2 at West Dock to nearly 500 g m-2 at Sagwon. The tussock tundra at Happy Valley has much taller plants (30-40 cm) compared to the sedge, prostrate dwarf-shrub tundra at the coast (less than 10 cm). There is greater cover of non-sorted circles north of the major vegetation boundary at the northern edge of the foothills. This boundary is also a boundary between acidic and nonacidic soils. Vegetation classification and ordination of the High Arctic sites is in progress. Dr. Nadya Matveyeva from the Komarov Botanical Institute in St. Petersburg, Dr. Fred Daniels of the Institute of Plant Ecology at the University of Muenster, Germany, and Dr. Corinne Vonlanthen from the University of Bern, Switzerland participated in the 2005 vegetation studies at Isachen, which allowed a much expanded sampling of the vegetation at this northern extreme of the gradient. The focus of research in the coming year will be classification and ordination of the High Arctic vegetation, and synthesis of the data from the full gradient.

We also experimentally studied the influence of the plant canopy and plant functional types on cryogenic activity (Kade et al. 2005a, and submitted). We selected twenty-eight similar nonsorted circles at a moist nonacidic tundra site in northern Alaska. An area of 0.5 m2 was marked in the center of each plot and received one of four treatments. (a) Vegetation removal. (b) Vegetation removal and graminoid transplants. (c) Vegetation removal and transplanting a moss carpet. (d) No manipulation. We monitored soil-surface temperature, frost heave, thaw depth and soil-surface stability. Vegetation removal led to greater heat fluxes at the soil surface, increasing frost heave by 4.2 cm and thaw depth by 3.1 cm when compared to the control plots. The soil-surface stability was reduced. In contrast, moss plots showed reduced soil temperatures in the summer and delayed freezing and thawing. When compared to the control plots, moss treatments decreased frost heave by 5.0 cm and thaw depth by 8.8 cm, and the soil-surface stability was increased. The sedge seedlings in the graminoid plots did not expand their root systems during the experiment, presumably due to frost heaving and needle-ice formation. This study suggests that biomass increases due to global warming could suppress frost heave and active-layer thickness significantly in parts of the bioclimate gradient, especially where canopy cover is currently open.

We examined the insulation effect of the vegetation and soil organic layer on mineral soils in the summer and the insulation effect of snow in the winter by determining the modified n-factor (nÆ-factor) for nonsorted circles and the surrounding tundra along a climate gradient (Kade et al. submitted). The nÆ-factor is a simple indicator of the energy balance at the mineral soil surface, and it is defined as the ratio of seasonal degree-day sums at the mineral soil surface to that in the air. The nonsorted circles have warmer summer and cooler winter soil temperatures, deeper thaw depths, drier soils, shallower snow depth and greater snow densities than the surrounding tundra (Fig. 18). The summer nÆ-factor is greater for nonsorted circles (Howe Island nÆ=1.4; Franklin Bluffs nÆ=1.0; Happy Valley nÆ=0.7) than for the adjacent stable tundra (Howe Island nÆ=1.0; Franklin Bluffs nÆ=0.4; Happy Valley nÆ=0.2) The difference in the winter nÆ-factor is not as pronounced between nonsorted circles (Howe Island nÆ=0.9; Franklin Bluffs nÆ=0.7; Happy Valley nÆ=0.4) and the surrounding tundra (Howe Island nÆ=0.9; Franklin Bluffs nÆ=0.5; Happy Valley nÆ=0.3). Along the climate gradient, the nÆ-factor declines from north to south with increasing thickness of the vegetation and soil organic layer and snow depth, which insulate the mineral soil. Increased vegetation growth and snow depth associated with a warming climate might decrease the nÆ-factor and active-layer depth in the northern subzones, and the morphological differences between nonsorted circles and the surrounding tundra might become less pronounced.

Nitrogen cycling (Alexia Kelley and Howie Epstein). Studies of the nitrogen cycle in non-sorted-circle ecosystems along the arctic bioclimatic gradient are quatifying nitrogen in important pools (such as soil organic nitrogen, plant-bound nitrogen, and available nitrogen in the soil) as well as important fluxes (such as nitrogen mineralization and fixation). To date we have visited seven sites and have collected and begun processing samples from all of these sites. Initial results indicate large differences between nitrogen content in non-sorted circles as compared to the adjacent inter-circle tundra. Rates of net nitrogen mineralization vary between non-sorted circles and inter-circle tundra and also along the bioclimatic gradient. The differences appear to be driven by organic matter content as well as climate (with greater microbial-driven mineralization and immobilization in the inter-circle tundra and at the lower, warmer latitudes). Plant biomass is greater in the more southern sites, and also in the inter-circle tundra (as compared to the on the non-sorted circles).

Remote sensing (Howie Epstein). Throughout the course of the project, we have been measuring the Normalized Difference Vegetation Index (NDVI) for various plant communities at our field sites along the climate gradient. The NDVI is essentially an index of green vegetation or photosynthesizing material in plant communities. Our observations will allow us to understand the trends in photosynthesis along the climate gradient and across different vegetation types. We use a hand-held spectroradiometer to measure wavelength reflectances from the land surface, and from these we calculate the NDVI. NDVI data for the North Slope of Alaska were collected as part of the NSF ATLAS study, and Alexia Kelley measured NDVI on and off non-sorted circles as part of her Biocomplexity Research. Over the past three years, we have measured NDVI at our study grids at Green Cabin, Mould Bay and Isachsen (Ellef Ringnes). NDVI varies with several factors, including topographic position (D = dry; M = mesic; W = wet) and as expected vegetation cover (B = bare ground; M = mixed vegetated/bare; V = vegetated). NDVI also varies with climate; NDVI at Isachsen (Ellef Ringnes) was substantively lower than NDVI at either Mould Bay or Green Cabin. Mean NDVI at Green Cabin was only slightly greater than the mean NDVI at Mould Bay.

The ArcVeg Model (Howie Epstein and Alexia Kelley): Non-sorted circles have been incorporated into the ArcVeg arctic vegetation dynamics model. A module within ArcVeg stochastically generates a random-uniform pattern of non-sorted circles on the landscape, using a set of physically based rules for self-organizing pattern. Within ArcVeg, there is now an insulation effect of vegetation on frost heave and a disruptive effect of frost heave on plant growth. The next steps are to adjust rates of nitrogen fixation according to the presence of different plant types, rather than the present function which is based solely on plant biomass; and to examine the co-development of non-sorted circles and vegetation communities/biomass during primary succession (i.e. new landscapes without a store of organic matter).

Decomposition (Grizelle Gonzalez). Litter decay rates are surprisingly high at the cold High Arctic sites. At Mould Bay, Luzula nivalis decayed significantly over time (10 % mass loss /

yr) and decayed faster in the inter-circle areas than in the circles, (but not yet significantly different at $p = 0.05$). At Green Cabin, C. misandra decayed significantly over time (15 % mass loss / yr), but showed no effect of position. It decayed faster below the surface compared to the soil surface. Total microbial biomass, using Substrate Induce Respiration (RIS) was not significantly different for Green Cabin and Mould Bay. Bacterial counts are greater in MB than in GC at low T (from MPN û 7 ?C). However, at high temperatures there is no difference in bacterial counts between MB and GC (from MPN û 25 ?C); but then differences in position could be more evident.

Mycorrhizae (Ina Timling): On Prince Patrick Island, roots of 28 vascular plant species have been collected along a moisture gradient from dry to wet. The mycorrhizal status of these plant species and the identity of the fungal symbionts will be determined by microscopy and molecular methods. Ectomycorrhizal plant species, Dryas integrifolia, Salix arctica and Polygonum viviparum were morphotyped. Salix arctica showed the highest diversity of morphotypes, with eight morphotypes at the mesic site and nine at the dry site. For Dryas integrifolia three morphotypes were identified for the mesic site and seven for the dry site, while Polygonum viviparum occurred only at the wet site, with 4 different morphotypes. On Banks Island, two ectomycorrhizhal species, Dryas integrifolia, Salix arctica, were sampled and morphotyped. The morphotype diversity was greater than on Prince Patrick Island, with 11 morphotypes in the dry and mesic sites for Salix arctica and 10 (mesic) and four (dry) morphotypes for Dryas integrifolia. All morphotypes will be identified with molecular methods (DNA extraction, PCR with fungal specific primers, LSU and ITS sequencing). Fungal fruiting bodies were collected on Prince Patrick Island. Eleven taxa were collected. They comprise decomposing Asco- and Basidiomycetes.

On Ellef Ringnes Island 31 vascular plant species and fruiting bodies of 15 fungal taxa, composed of Asco- and Basidiomycetes have been collected. Furthermore soil samples were taken to determine fungal diversity and fungal biomass of vegetated and non vegetated areas. The only ectomycorrhizal host obtained was Salix arctica from an a-zonal site. Four morphotypes, corresponding to Lactaria spp., Laccaria spp. and Cenococcum geophilum, were identified based on morphological features. This indicates a decrease on morphotypes with increase in latitude.

All obtained roots, including the separated morphotypes and soils will be analyzed for their fungal diversity, by applying molecular methods (DNA extraction, PCR with fungal specific primers,

Training and Development:

ARCTIC FIELD ECOLOGY (Bill Gould and Grizelle Gonzalez)
Arctic Field Ecology class has involved 16 students from the United States, Canada, France, Brazil, Germany, and Puerto Rico. The class has also involved two graduate teaching assistants and five Inuit natives including one village elder from Omingmaktok, Canada in the project. The class has visited the Alaskan Inupiaq village of Nuiqsut, established a remote camp with local Inuit in the Bathurst Inlet area of Canada, and we are in the process of developing a youth-elder-science camp for 2005 near Bathurst Inlet.
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Seven posters have been presented by students or instructors at national and international meetings, three students have been invited to present research results at scientific meetings (Adriana Quijano, Patrick Kuss, Francisco Rivera), three students have been asked to participate with the research team as graduate and postdoctoral students or as field assistants.

The class has offered seminars on the following topics:
The Arctic landscape: Climate, geochemistry, and topography û hierarchical controls on landscape patterns.
The Arctic ecosystem: The role of temperature, light, nutrients, disturbance, and

organisms in above and belowground ecosystems.
Vegetation ecology: Landscape patterns and ecological controls on community composition.
Cryoturbation: The influence of glaciers, permafrost, snow cover, and freeze/thaw cycles on landforms, soils, vegetation, and ecosystem processes.
Soil ecology/biology: Soil development and classification, ecosystem processes and soil organisms.
Traditional Ecological Knowledge: Understanding 'Nuna' (the land) from Inuit/Inuvialuit/ Inupiaq perspectives.
Global change research: Climate and land-use, detecting environmental change.
Arctic transitions: Extrapolating in space and time û from field measures to modeling.
Biocomplexity: Understanding complex biological systems in the Arctic.
Vertebrate ecology: Behavioral and physiological adaptations to the arctic environment.
Human history and current affairs: Inuit land use, archaeological sites, mining, oil, recreation.

The class has initiated the following research activities:
Frost-boil morphology. How do boil and interboil differences in thaw depth and vegetation cover vary along the arctic climatic gradient.
Litter decomposition experiments: Linking ecosystem pattern and process in frost-boil ecosystems. How do litter decay rates vary between boil and interboil areas, above and belowground, and along a toposequence. Led by Grizelle Gonzßlez.
Biodiversity transects: How do plant biodiversity patterns vary between boil and interboil areas within a given site and along the arctic climatic gradient. Beta diversity (plant compositional differences) between boil and interboil areas is greatest in subzone D, where plant diversity is relatively high and barren frost boil surfaces are distinct from vegetated interboil areas.
Phytosociology studies. Variation in plant communities along climatic and topographic gradients. Student Patrick Kuss investigated vegetation zonation within snow beds on Banks Island.
Microbial biomass studies. Student Francisco Rivera is investigating variation along climatic gradients as well as toposequences in microbial biomass related to boil/interboil soils. Led by Grizelle Gonzßlez.
Soil invertebrate studies. How do soil invertebrate diversity, functional groups, and biomass vary between boils and interboils and along the climatic gradient. Led by Grizelle Gonzßlez.

POST-DOCTORAL AND GRADUATE TRAINING
Four post doctoral students are wholly or partially supported by the project.
1. Dr. Rorik Peterson was supported for one year to help develop the differential frost heave model .
2. Dr. Ronnie Daanan was supported for 3 years to develop a model of hydrological processes in frost heave features.
3. Corinne Vonlanthen, was supported for 1 year by a grant from the Swiss Government and this grant to work on the classification and ordination of the patterned-ground vegetation in the High
Arctic.
4. Dr. Patrick Kuss,from Germany, worked on the synthesis of the phytosociologcial information from the study.

Seven graduate students were supported by the project.
Anja Kade, Ph.D., UAF, graduated 2006.
Alexia Kelley, Ph.D., UVa, graduated 2007.
Ina Timling, Ph.D., UAF, in progress.
Dmitry Nickolsky, Ph.D. UAF, graudated 2007.
Corinne Munger, M.S., UAF, graudated 2007.
Patrick Borden, M.S., UAF, graduated 2007.

Chunhao Xu, M.S. UAF, in progress

REU ACTIVITIES
The project has received support for several REU students.
1. In 2002, Ms. Erin Cushing did a field project examining vegetation and geophysical properties of non-sorted circles on substrates with contrasting soil pH. She presented a poster at the 53rd Arctic Science Conference in Fairbanks, entitled ôDifferences in vegetation and thaw depths of frost boils and inter-boils in acidic and nonacidic tundraö. The project described differences in biomass, leaf area index and the normalized difference vegetation index (NDVI) on acidic and nonacidic substrates, and the information will be used in regional characterization of the vegetation with complex frost-boil ecosystems.

2. Corinne Munger, in 2002, developed project to characterize the vegetation types on different glacial systems in the Toolik Lake vicinity. Her work involved the use of the Toolik Lake Hierarchic Geographic Information System. She was first author on a poster at the 54th Arctic Science Conference. She is also coauthor on a book chapter that will be part of the Toolik LTER book. Corinne recently decided to go to graduate school and is working on a project related to the Biocomplexity project and greening in the Arctic.

3. In 2003, Nathen Pamperin, worked with Andrew Balsar, Toolik Lake GIS Manager, to analyze geospatial information in the Toolik Lake GIS. His project was to develop a method for simulating air-photo ortho-rectification for air photos lacking fiducial marks and camera models. He was a full participant in the scoping and planning of the field work and analysis. The method involved collecting field data for ground control and developing comprehensive ground-control sets on a frame-by-frame basis. A series of higher-order polynomial transformations were tested for fidelity to the terrain. The end product is a series of mosaicked, high-resolution air-photo lines for the Toolik Field Station. He learned remote sensing techniques that he is now employing in his masterÆs degree work at UAF.

In 2004, we received REU funds in May, but were unable to recruit a student in time for the field season. These funds were reallocated to the University of Virginia, where four REU students were employed:

Research Experience for Undergraduates û Students Advised by Epstein at the University of Virginia

Leyland del Re (2005) û Ms. Re spent the summer of 2005 with graduate student Alexia Kelley at the Toolik Lake Research Facility on the North Slope of Alaska. She worked at sites along the Dalton Highway, examining seedbanks and seedling establishment on and off of patterned-ground features across the latitudinal gradient. Her work has led to a paper in preparation by Kelley et al.

Sara Wozniak (2006) û Ms. Wozniak (now Mrs. Felker) spent the summer of 2006, also with graduate student Alexia Kelley, at the Toolik Lake Research Facility on the North Slope of Alaska. Her research involved examining factors that control the flux of CO_2 from arctic soils across several sites on the Dalton Highway. Her work led to a Distinguished Majors thesis entitled ôFactors influencing soil CO_2 flux along a latitudinal gradient in northern Alaska.ö She presented her work at the Fall 2006 American Geophysical Union Meetings in San Francisco:

Wozniak, S., A. Kelley, and H.E. Epstein. Factors influencing soil respiration along a latitudinal transect in northern Alaska. American Geophysical Union Fall Meeting, San Francisco, CA, December 2006.

In May of 2007, she graduated from the Department of Environmental Sciences at UVA with High Distinction, and also receiving our Wallace-Poole Prize for our most outstanding graduating student.

George McFadden and Taylor Martin (2007) û Misters McFadden and Martin worked with Dr. Epstein in the spring of 2007. They conducted a research project to examine vegetation along several latitudinal gradients throughout the arctic tundra. They analyzed both the spatial patterns of a remote sensing index of vegetation (NDVI û Normalized Difference Vegetation Index) and its temporal dynamics, testing the hypothesis that areas with high spatial heterogeneity of vegetation (as indexed by the NDVI) were also the areas with the greatest temporal variability. Their work has contributed to a paper in preparation by Epstein et al.

Anne Stine (2007) û In the summer of 2007, Ms. Stine worked with Dr. Epstein and now Dr. Kelley on repeat photographic images of patterned-ground features near Toolik Lake, Alaska. She began the comparison of a set of photographs taken by Dr. Deborah Roach in 1980, with photographs taken of the same plots by Alexia Kelley in 2005. The objective was to determine if the composition of plants on non-sorted circles changed over the twenty-five year period. The work on this is still ongoing.
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Outreach Activities:

Stacy Golden participated in the 2004 expedition as a member of Teachers and Researchers Exploring and Collaborating (TREC) program. Stacy participated in all aspects of the science field program and prepared daily reports for her students in Sitka. She wrote this about her experience:

I was given the opportunity to accompany Dr. Walker's research team to Prince Patrick Island in July of 2004. The trip was amazing and has left a lasting impression on me as a person and as a teacher. Various aspects of the trip from the time I left Fairbanks to drive north to Inuvik to our time in Prince Patrick, and our day trip to Banks Island have proven to be excellent anecdotes in teaching 8th grade science. I have used a lot of the hard work, focus, dedication, trouble shooting, and excitement by the team to relate real world science to the kids and to teach the scientific method to the kids. I have also used the trip in my Marine Biology class in teaching the kids about polar areas. The most amazing thing is that although I specifically use certain parts of the trip in a unit I constantly find myself relating things to the journey and believe that will always continue. Most importantly, the trip helped to rekindle my passion for science and open my eyes to a new world of research which I hope to pass on to my students for years to come.

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Web/Internet Site

URL(s):

www.geobotany.uaf.edu/cryoturbation/index.html

Description:

This site is the site where all information relevant to the project is posted. It inlcudes information on all the research sites, data reports, publications, and photographs.

Other Specific Products

Product Type:

Data or databases

Product Description:

Raynolds, M.K, and D. A. Walker. 2003 Biocomplexity of frost boil ecosystems: Banks Island Expedition, July 2003 Field Report. Alaska Geobotany Center, Institute of Arctic Biology, University of Alaska Fairbanks.19 pages.

Sharing Information:

Hard copy field report also available via the web site.

Product Type:

Data or databases

Product Description:

Walker, D.A., M.K. Raynolds, C.R. Martiin. 2003. Biocomplexity of Frost-boil ecosystems: Data Report: Snow on the Alaska North Slope Grids, April 2003. Alaska Geobotany Center, Insitute of Arctic Biology, Univeristy of Alaska Fairbanks, Fairbanks, AK 99775.

This data report contains snow depth, snow water equivalent, and snow density, and snow pit descriptions from 12 biocomplexity grids along the Dalton Highway.

Sharing Information:

Hard copy data report. Also availble on the web site and through JOSS.

Product Type:

Data or databases

Product Description:

Raynolds, M.K., D.A. Walker, and C.R. Martin. 2004. Biocomplexity of frost-boil ecosystems snow data report, Alaska North Slope, April 2004. Alaska Geobotany Center, University of Alaska Fairbanks. 29 pp.

Sharing Information:

Data currently available as hard copy data report. It will be incorporated onto a DVD containing all the data from the project.

Product Type:

Data or databases

Product Description:

Raynolds, M.K. 2005. Addendum to the 2003 Green Cabin, Banks Island Data Report. Alaska Geobotany Center, University of Alaska Fairbanks. 39 pp.

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Data or databases

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Munger, C., M.K. Raynolds, A. Kade and D.A. Walker. 2005. Biocomplexity of patterned ground, Mould Bay Expedition, July 2004 61. Alaska Geobotany Center, University of Alaska Fairbanks. Data Report, 61 pp.

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Product Type:

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Product Type:

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Product Description:

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Sharing Information:

Hard copy data report available through the Alaska Geobotany Center.

Product Type:

Data or databases

Product Description:

Barreda, J.E., J. Knudson, D.A. Walker, M.K. Raynolds, A. Kade, and C. Munger. 2006.

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Sharing Information:

Hard copy data report available through the Alaska Geobotany Center.

Contributions

Contributions within Discipline:

1. Most importantly the project is documented the important role that patterned ground plays in ecosystem processes in the Arctic. Patterned ground includes a wide variety of geomorphic features at several scales, including ice-wedge polygons, non-sorted circles, stripes, and hummocks. These features are a ubiquitous aspect of tundra ecosystems and have been studied extensively by geomorphologists, but the role of these features in arctic ecosystem dynamics has been largely overlooked until the BE program. One reason for this is that the scale of patterned ground falls between the plot scale of most ecosystem science and the hill-slope scale of most hydrological studies. Patterned ground generally is below the detection limit of space-based satellite imagery, but it is profoundly important with respect to arctic energy budgets, active layer dynamics, trace-gas fluxes, soil carbon storage, hydrological patterns, and nutrient cycling.

2. This project is contributing to our basic understanding of how climate, soils, vegetation, and disturbance processes interact in complex ways to develop the systems that we see in nature. The frost-boil biocomplexity project is examining how frost boil systems self-organize through the process of differential frost heave, and how the vegetation interacts with this process to create the varied patterned ground froms along the arctic bioclimate gradient, from treeline to the coldest parts of the Arctic. How these patterns manifest at various spatial scales, including unique emergent properties at each scale, is also a major component of the project.

2. A comprehensive theory of the polygenetic origin of small patterned ground features is emerging from two conceptual models and detailed field work. The models recognize the clear role that vegetation succession plays in patterned-ground morphology, the development of cryogenic soil structures, and formation of buried carbon in arctic ecosystems. Field studies are revealing the interactions between several processes at different scales including ice-lens formation and the resulting frost heave, cracking of soils at small scales due to desiccation or cold temperatures, vegetation succession and the formation of organic soil horizons that reduce heat flux in the patterned-ground systems, and the control that soil texture exerts on the morphology of patterned-ground features.

3. Another of major contribution has been an understanding of how greenness of the vegetation changes along the Arctic climate gradient and how patterns of greenness have responded to warming in the Arctic. The project has documented a 17% increase in greenness, and probably biomass, over the period 1981-2001. This coincides with a general warming of northern Alaska and a major reduction in sea ice in the Beaufort Sea.

4. The project has also revealed at least two-fold more buried soil carbon in the High Arctic than has been previously reported.

5. The project also has a unique educational component whereby students actively participate in the project by accompanying the investigators on all the research expeditions as part of the Arctic Field Ecology course (Univ. of Minn.)

Contributions to Other Disciplines:

Contributions to Human Resource Development:

The project has exposed 16 students to Arctic research through participation in the Arctic Field Ecology Course.

4 Post docs, 7 Ph.D. students, 3 Masters students.

4 undergraduates have participated in the REU project.

1 TREC K-12 teacher has accompanied the field expeditions.

Contributions to Resources for Research and Education:

The education component of the project has developed unique interactions between researchers, students, and the native people in several villages including Inuvik, and Sachs Harbor. The project has exposed 16 students to Arctic research through participation in the Arctic
Field Ecology Course.

3 Post docs, 4 Ph.D. students, 3 Masters students are being trained.

4 undergraduates have participated in the REU project.

1 TREC K-12 teacher has accompanied the field expeditions.

Contributions Beyond Science and Engineering:

Categories for which nothing is reported:

Contributions: To Any Other Disciplines

Contributions: To Any Beyond Science and Engineering

Arctic Patterned-Ground Ecosystems: a Synthesis of Studies Along a North American Arctic Transect

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Abstract

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 fluxes within patterned-ground systems. Four new modeling approaches build on the theme that vegetation controls micro-scale 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.

Index terms: 0702 permafrost, 0768 thermal regime, 0768 tundra, 1865 soils, 1630 impacts of climate change

1 Introduction

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 (Fig. 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, a full understanding of formation of these features, including comprehensive mathematical models, still eludes scientists who study these phenomena [*Mann*, 2003]. Furthermore their role in arctic ecosystem function and their possible response to climate change have not been addressed. The "Biocomplexity of Patterned-Ground Ecosystems" project specifically addressed the interactions between the biological and physical components of patterned-ground ecosystems in an attempt to understand how a warming climate will affect these ecosystems and the permafrost beneath them.

The approach we used to examine the possible consequences of climate change was to study PGF landscape/ecosystem variation along the natural present-day north-to-south climate gradient in North America (Fig. 2). This approach also established a baseline of long-term study sites against which future changes can be compared. We directed a variety of studies at small relatively homogeneous PGF landscapes that included climate, vegetation, water/ice, soil, and permafrost components (Fig. 2).

This paper provides an overview of the some of the main data sets from the transect to illustrate how PGF forms change in concert with the climate and vegetation. We include trends in air and soil temperatures, PGFs, vegetation properties, *n*-factors, soils, active-layer depth, and frost heave. We use the *n*-factor as an index of the relative insulating value of vegetation, soil, and snow across the climate gradient and examine how the depth of thaw and soil heave are affected by differences in the vegetation. 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 ecosystem role of PGFs within the Arctic system and the likely response of PGFs to climate change. An on-line appendix contains a summary of the data used in this paper.

2 Description of the North American Arctic Transect (NAAT)

2.1 Study site locations

In 2001-2006 we studied patterned-ground landscapes at 11 locations in Canada and Alaska (Fig. 2 and Appendix A). The locations were chosen as representative of zonal conditions within each of five Arctic bioclimate subzones [*CAVM Team, et al.*, 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 adapted 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 others systems commonly used in

North America [e.g., *Bliss and Matveyeva*, 1992; *Tedrow* 1966] and elsewhere [see *Walker et al.* 2005].

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 (Fig. 2). Appendix A gives the coordinates of each location along with a summary of key environmental data.

2.2 Geology and soils

Although a concerted attempt was made to locate all the studies on fine-grained sediments conducive to the formation of non-sorted 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, 1969]; Mould Bay was located on soils derived from mixed sedimentary rocks of the Wilke Point and

Griper Bay Formations [Everett, 1968; Tedrow, et al., 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) (Appendix A).

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 (Appendix A). 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 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.

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

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.

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 in thawing-degree months (˚C mo). The index was first used by Steve Young 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 air temperatures along transect, from 3.0˚C mo at Isachsen to 40.2˚C at Inuvik. Temperatures on the PGFs were 2-13˚C mo warmer than the air temperatures. Temperature 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 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

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 this volume]. The terms are based on the morphology and size of the features and does 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* 1998 revised 2005]; however it was not always possible to use existing terminology if the origins of the 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 us to keep our terminology straight in mapping and is not meant to replace existing nomenclature systems that readers may be more familiar with.

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 Hallett,* 1993; *Kessler and Werner*, 2003]. We also do not address larger features such as ice-wedge polygons or pingos with 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].

Raynolds et al. (2008 this volume) classified the PGFs, mapped 20 10 x 10-m grids and summarized the trends of PGF size and density along the transect. Here we briefly summarize the dominant processes (Fig. 5a) and patterned-ground forms (Fig. 5b).

(Also see Fig. 1 for photos of the PGFs along the climate gradient; and *Raynolds* et al. (2008, in press this volume) for maps and analysis).

In the High Arctic at Isachsen, Mould Bay, and Green Cabin, desiccation and frost *cracking* were the dominant processes forming small and medium-size nonsorted polygons (Fig. 5b, boxes 1 and 2) . *Differential heave* was the dominant process in the middle parts of the gradient (subzones C and D) forming medium-size nonsorted circles (Fig. 5b, boxes 3 and 4). Differential heaving also occurred in the medium-size hummocks in the southern part of the gradient (Subzone E) (Fig. 5, box 5). *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 (Fig. 5b, box 6), or they were completely vegetated and inactive (Fig. 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 2.11. A more full discussion of the various patterned-ground forms encountered along the transect is in *Raynolds et al.* [2008, this volume] and in forthcoming publications.

2.5 Variation in factors contributing to insulation of the soil surface

A summary of the variation in key factors that contribute to insulating the soil surface and reducing the heat flux into the tundra in summer and out of the tundra in winter are shown in Figure 6.

2.5.1 Vegetation

The zonal vegetation varied from nearly barren surfaces with scattered mosses, lichens and very small forbs in the 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.*, 2007 (in press)]. 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 (Fig. 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. 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.

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), vs. about a two-fold increase in biomass of the vegetation between the features (369 g m^{-2} at Isachsen to 758 g m^{-2} at Sagwon MAT) (Fig. 7). *Raynolds, et al.*, 2008, [this volume] calculated landscape-level biomass values for the areas within the 10 x 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

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 (Appendix A, Fig. 6). There were no organic soil horizons on the centers of PGFs on zonal sites at Isachsen, Mould Bay, Howe Island, Green Cabin, and Deadhorse (Subzones A, B, C, and northern subzone D). 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 (Fig. 6).

In the Low Arctic, organic horizons between PGFs generally increased in thickness from north to south (Table 2 and Fig. 5). 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

From north to south along the NAAT, there was a general increase in the thickness of the end-of-winter snow depth (Fig. 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 area 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 microtopography associated with the features, such as the earth hummocks at Happy Valley and Inuvik.

2.5.4 **n-*factor.***

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, et al.*, 2001a; *Klene, et al.*, 2001b; *Shur and Slavini-Borovskiy*, 1993; *Taylor*, 1995; 2001]. The *n*-factor is defined here as ratio of the seasonal degree-day sum at the ground surface to that of the air at standard screen 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 standard instrument height (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 atmosphere at standard instrument height.

Fig. 8 shows the summer and winter *n*-factors for representative sites in each bioclimate subzone. (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, Fig. 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 strongly correlated with the depth of the winter snow cover (r^2 = 0.870) (Fig. 8b, right). The small little 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

The depth of thaw reported here are measurements made on the vegetation study plots [*Kade, et al.*, 2005; *Vonlanthen, et al.*, 2007 (in press)]. Data reported here are from 2006, when thaw was measured at all the locations within a two-week period in late August.

The depth of summer thaw did not follow the trend in summer temperatures (compare Fig. 9 and Fig. 2). 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.

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 combined with the fact that both microsties 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 (Fig. 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

Frost heave was monitored on and between the PGFs using two types of heave instruments described in *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) (Fig. 5). 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.

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

3 New modeling approaches for patterned-ground formation

The data collected from the transect is 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 non-sorted circle environment. Here we briefly summarize each of the models. Readers should refer to the cited information for more details regarding the models.

3.1 Thermo-mechanical model of nonsorted circle formation

The thermo-mechanical model (TMM) is a detailed simulation of the heaving process within nonsorted circles [Nicolsky, et al., 2008, this volume]. TMM includes mass, momentum, and energy conservation laws for water, ice, and soil and simulates soil movement in a non-sorted circle based on ice accumulation and deformation of the frozen soil (Fig. 11a). The model accounts for the observation that heave within nonsorted circles is considerably greater than that which is accounted for only 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. (Fig. 11a).

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.

Sensitivity analyses examined the response of the model to the addition or removal of a vegetation layer on the circle (Fig. 11b). The modeled results showed that heave was nearly completely subdued with 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*, 2007, in press]. 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

One of the most puzzling aspects of non-sorted 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 non-sorted circles could spontaneously develop in the absence of a vegetative cover [*Peterson and Krantz*, 2003]. 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 than used to form the most likely potential pattern found in the tundra. The hexagonal pattern is very likely, because the distances between features such as circles are than always the same. Secondary processes like vegetation dynamics are assumed to be responsible for any irregularities in the pattern found in the tundra.

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.

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 (Fig. 12).

3.3 Hydrological frost heave model combined with a vegetation dynamics model

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.*, 2000]).

3.3.1 The WIT model

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 nonlinear 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 (Fig. 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 The ArcVeg model

The arctic vegetation dynamics model (ArcVeg, Epstein et al. 2000, 2001) 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 proceed (albeit gradually) through vegetation succession until ultimately the accumulation of vegetation is in balance with the continuing occurrence of frost heave.

3.3.3 The coupled WIT/ArcVeg model

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 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.

3.3.4 Conceptual model for permafrost—patterned-ground interactions

A conceptual model proposed by Yuri Shur 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, et al.*, 2008 submitted to this volume] (Fig. 14). This model also incorporates frost cracking, which is not done in any of the other models. The process starts with thermal contraction cracks that are spaced at 1-3 m (Fig. 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 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).

The differential frost heave associated with hummock development is distinctly different than the annual differential heave observed in the nonsorted circles that we studied in northern Alaska [*Daanen, et al.*, 2008, in press; *Nikolsky, et al.*, 2008, this volume; *Romanovsky, et al.*, 2008]. Heave within the hummocks is due primarily to changes in the permafrost table – 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.

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.

A critical step in Shur's model is the development of the organic- and ice-rich *intermediate layer* that forms at the top few centimeters of the permafrost table [*Shur, et al.* 2005]. 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 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; *Ping and Michaelson*, 2008 submitted to this volume]. Accumulation of organic matter at the lower part of the active layer contributes to a further decrease in the active-layer depth. This carbon is important with regard to the potential effects of climate change. Although the carbon can potentially be released to the atmosphere as soil temperatures warm, the formation of the intermediate layer also tends to stabilize the active layer because of the large amount of latent heat required to melt the ice [*Shur, et al.*, 2008 submitted to this volume].

4 Importance of patterned ground to ecosystem processes and expected responses to climate change

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.

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 snow packs. The vegetation, however, may not shift in concert with the clijmate. In general, most areas of the Arctic will likely accumulate additional above-ground 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 these landscapes, but the overall response is likely to be slower than in warmer Low Arctic environments.

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.

At present it is not possible to extrapolate these results in a meaningful way to patterned-ground landscapes altered by climate change, other than to say at the boundary between subzone D and E, increased plant production is likely to cause a reduction in heat flux and increased carbon sequestration. 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 PGF. 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

1. Climate differences along the north-south Arctic transect cause major differences in the patterned-ground types occurring on zonal sites. Toward the north, cracking is the dominant process, resulting in small and medium-size nonsorted polygons. In the south, the dominant genetic factor is differential frost heave, which results in nonsorted circles and medium-size hummocks.

2. Vegetation plays a key role affecting the morphology of non-sorted PGFs by insulating the soil surface and decreasing the heat flux from the soil, stabilizing of the soil with roots and developing of organic soil horizons, and masking and effectively smothering the effects of cracking and heaving. In the middle parts of the Arctic (bioclimate suzones C and D) large soil-temperature differences occur between the relatively poorly vegetated centers and well-vegetated margins of PGFs. These temperature differentials control the flow of heat and water within PGFs, and promote the development of differential frost heave and aggradation ice.

3. The summer *n*-factor, an index of the total insulative effect of the soil organic horizons, vegetation, and snow, is most strongly correlated with the thickness of the green moss layer, and also showed strong correlations the total height of the vegetation and the thickness of the soil organic horizons. In winter the *n*-factor is highly correlated with the depth of the snow pack. Experiments that have removed and added vegetation to nonsorted circles have confirmed the strong effect that vegetation has on both soil heave the active-layer thickness.

4. Major strides have been made in modeling the processes within nonsorted circles systems. Four separate models were developed to examine (a) the thermo-mechanical processes within individual non-sorted circles, (b) the self-organization of nonsorted circle landscape through spontaneous differential heave, (c) the formation of patterned ground through feedback interactions between vegetation and the hydrological-thermal processes, and (d) the interactions between the permafrost and vegetation in the formation of circles and mounds. These models present several alternative hypotheses for the formation of nonsorted circles that will require more detailed field observations and

experiments to validate. A comprehensive mathematical understanding of patterned-ground formation and vegetation colonization on these features will need to also address the cracking process, needle-ice development, and formation of aggradation ice.

7. We expect that as climate warms zonal climate boundaries will shift northward, but the responses of the vegetation will likely be more complex than simple boundary shifts. Vegetation responses will likely be different on the centers of PGFs compared to the areas between PGFs. In subzones C and 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. It is less clear how the High Arctic patterned-ground systems would respond to moister and warmer climates, but the response will likely to much slower than in the warmer environments of the Low Arctic. A previous study in northern Alaska examined landscape-level fluxes of heat, water, and CO_2 in adjacent areas with few and many nonsorted circles and showed that these systems have strongly contrasting ecosystem-level functioning. 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 along the arctic transect will serve as baseline against which existing models can be tested and future changes in the ecosystems can be compared.

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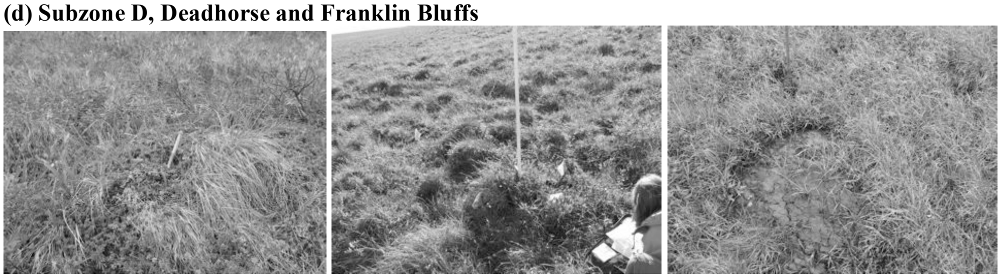
(a) Subzone A, Isachsen

(b) Subzone B, Mould Bay

(c) Subzone C, Green Cabin and Howe Island

(d) Subzone D, Deadhorse and Franklin Bluffs



(e) Subzone E, Happy Valley

(f) Boreal Forest, Inuvik

Figure 1. Patterned-ground forms along the North American Arctic Transect. (a) Subzone A: Small non-sorted polygons (Isachsen). (b) Subzone B: small non-sorted polygons (left) and turf hummocks (center and right) (Mould Bay). (c) Subzone C: Well-developed non-sorted circles (left, Green Cabin, and center, Howe Island) and non-sorted polygons (right, Howe Island). (d) Subzone D: Barren nonsorted circles (left, Deadhorse, and right, Franklin Bluffs) and partially-vegetated non-sorted 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). 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).

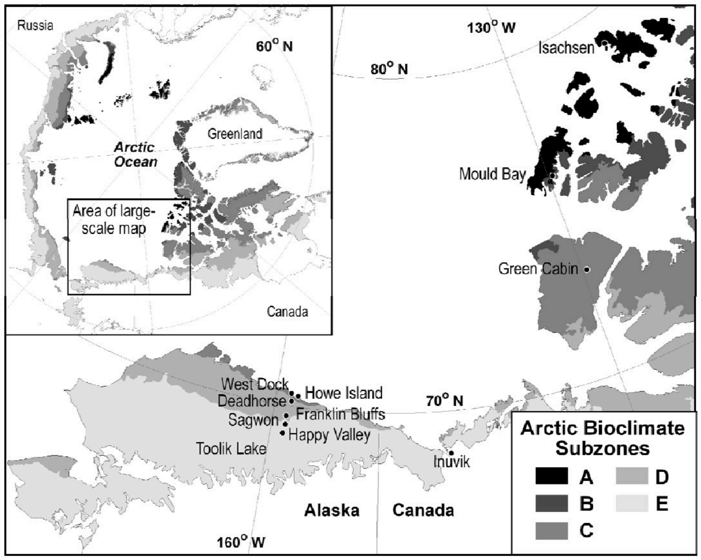


Figure 3. Study locations within the five Arctic bioclimate subzones [*CAVM Team, et al.*, 2003]. The subzones are defined by a combination of summer temperatures and the character of the vegetation. Approximate mean July temperatures within each subzone are: A = 0-3 ˚C, B = 3-5 ˚C, C = 5-7 ˚C, D = 7-9

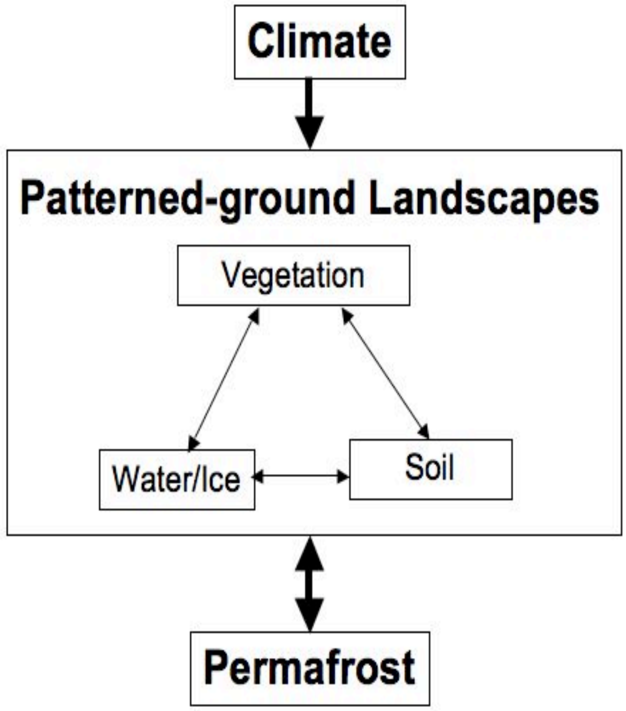


Figure 3. The patterned-ground system. Note that linkage between climate and patterned ground landscapes is primarily a one-way interaction, whereas the linkage with permafrost is a strongly two-way interaction.

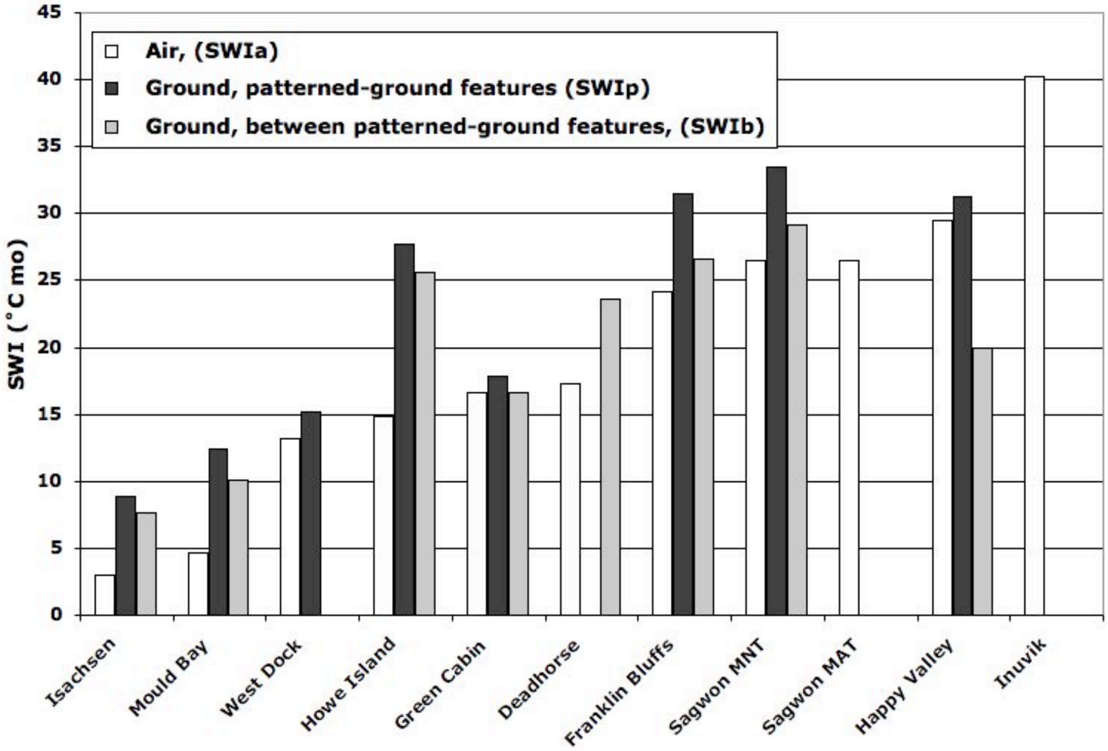


Figure 4. Trend in the summer warmth index along the NAAT for the air (*SWI_a)*, and soil surface within patterned-ground features (*SWI_p)*, and soil surface between patterned-ground features (*SWI_b)*. Data for Isachsen, Mould Bay, and Green Cabin are from Environment Canada (http://climate.weatheroffice.ec.gc.ca/climate_normals/).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

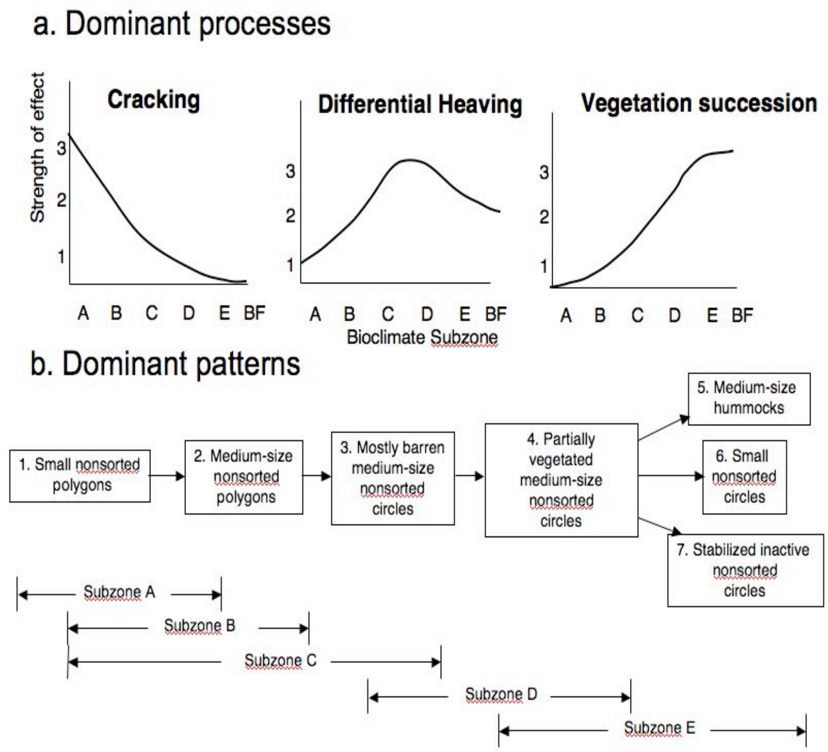


Figure 5. Dominant genetic processes (a) and patterns (b) involved in patterned-ground formation on zonal sites along the Arctic bioclimate gradient.

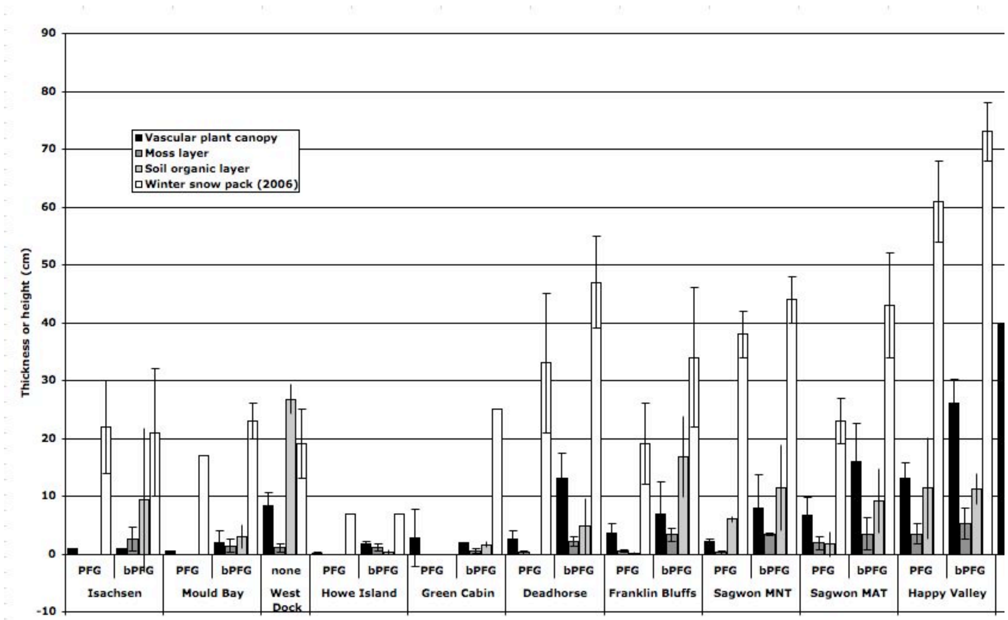


Figure 6. Factors contributing to insulation of the surface along the NAAT: vascular plant canopy thickness, moss layer thickness, soil organic horizons, and winter snow pack. Error bars are standard deviations. Data are from the vegetation study plots at each location, with generally 5-7 plots represented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

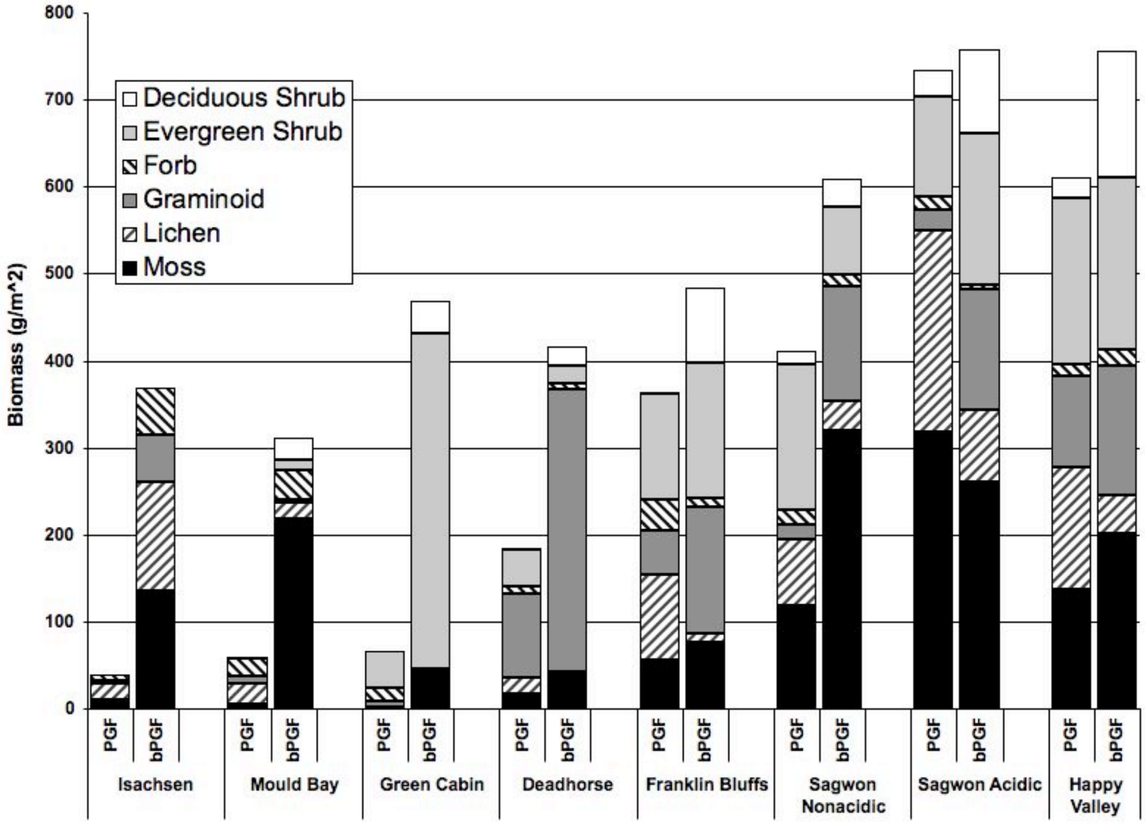
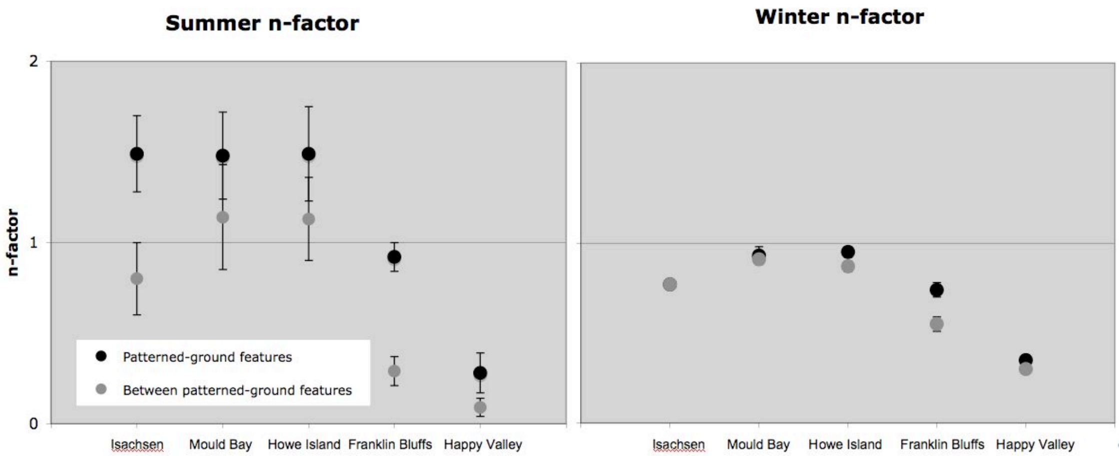


Figure 7. Biomass on patterned-ground features (PGF) and between patterned-ground features (bPGF) along the NAAT.

a.



b.

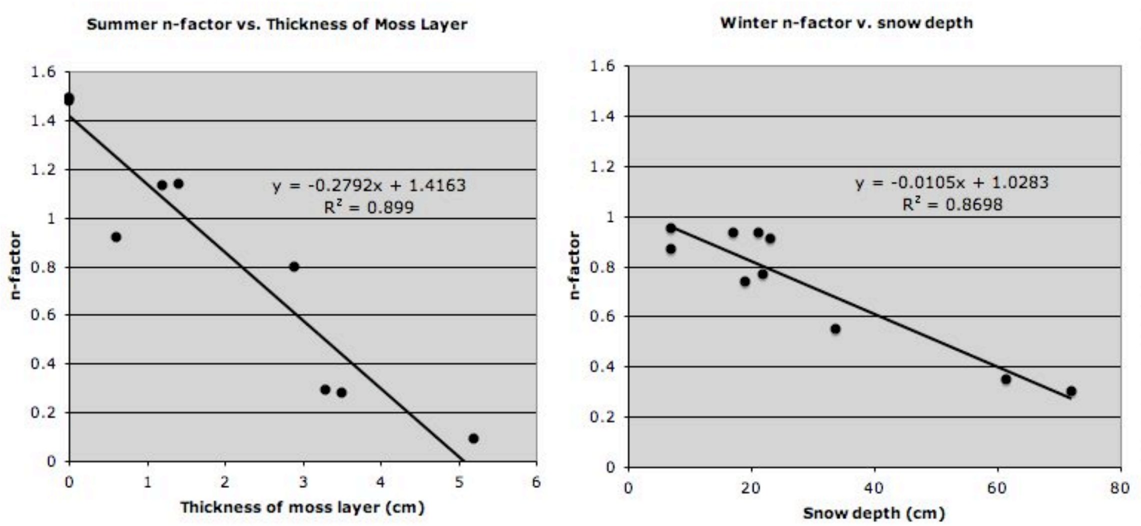


Figure 8. (a) Mean (± s.d.) summer and winter *n*-factors at representative sites in each subzone along the NAAT. (b) Summer *n*-factor vs. thickness of the green moss layer (left) and winter *n*-factor vs. snow depth measured in May 2006 (right).

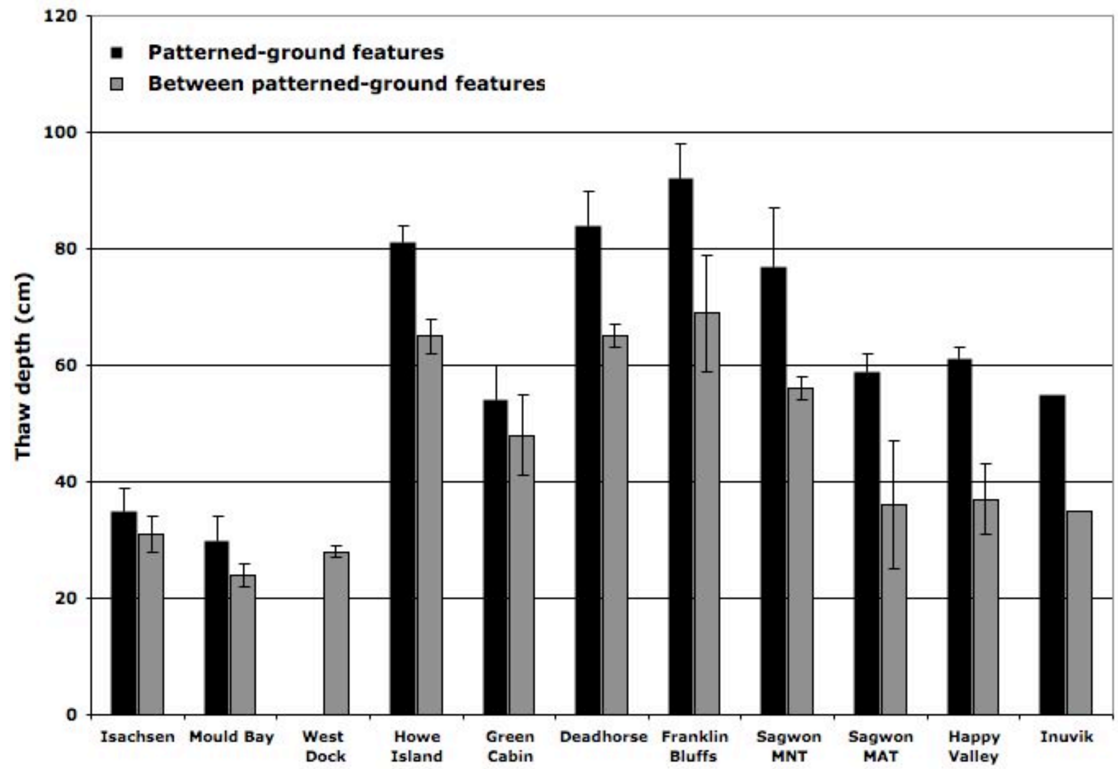


Figure 9. Mean thaw-depth (± s.d.) along the NAAT in late August 2006. Data are from the vegetation study plots of the dominant vegetation types on and between PGFs of zonal sites at each location; n = 5-7 except at Inuvik where n = 1.

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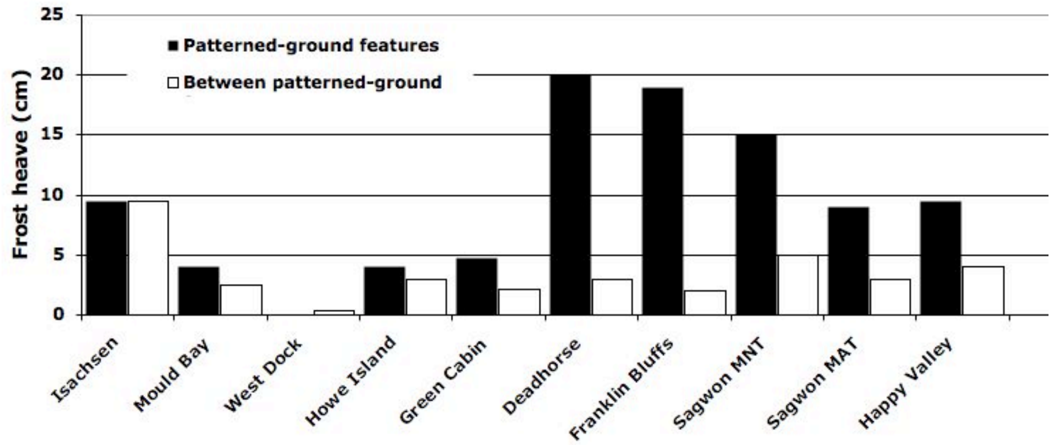

Figure 10. Frost heave on and between patterned-ground features along the NAAT.

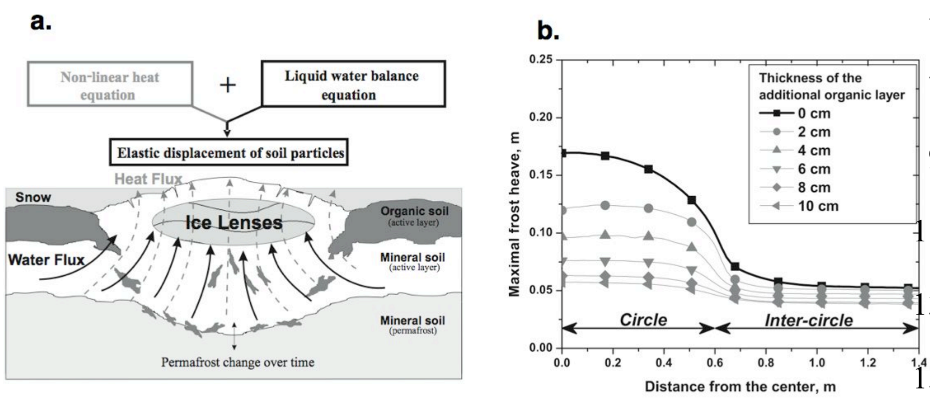

Figure 11. (a) Conceptual nonsorted-circle system for the Thermo-Mechanical Model of frost heave. (b) Sensitivity analysis showing the effect on frost heave of adding different thicknesses of moss layer to the surface of the circle (adapted from Nikolsky et al. 2008, this volume).

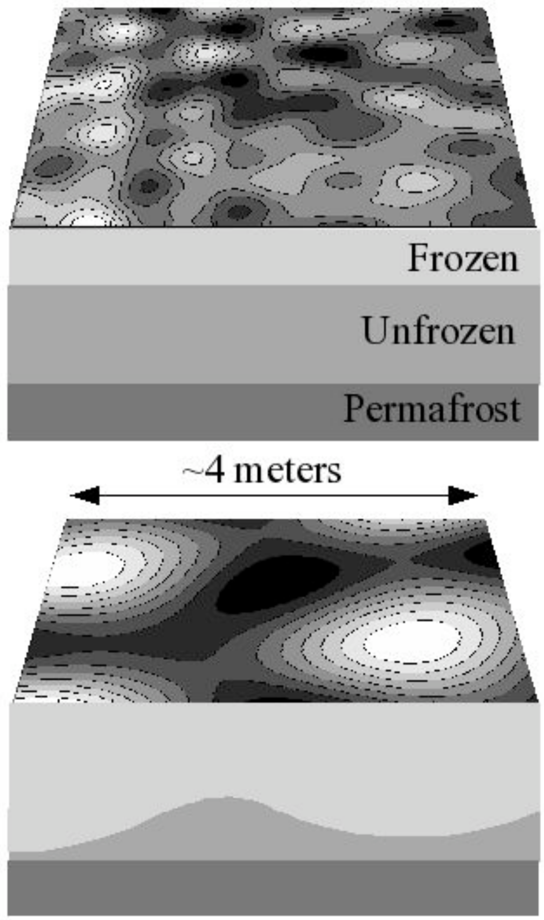

Figure 12. Generation of nonsorted-circle pattern by the DFH model: Contour
1 plot of the surface topography soon after spontaneous initiation of differential frost heave (top) and after 16 complete freeze cycles of the entire active layer (bottom). Vertical cross-sections show a representation of how 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 meters 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 Rorik Peterson.)

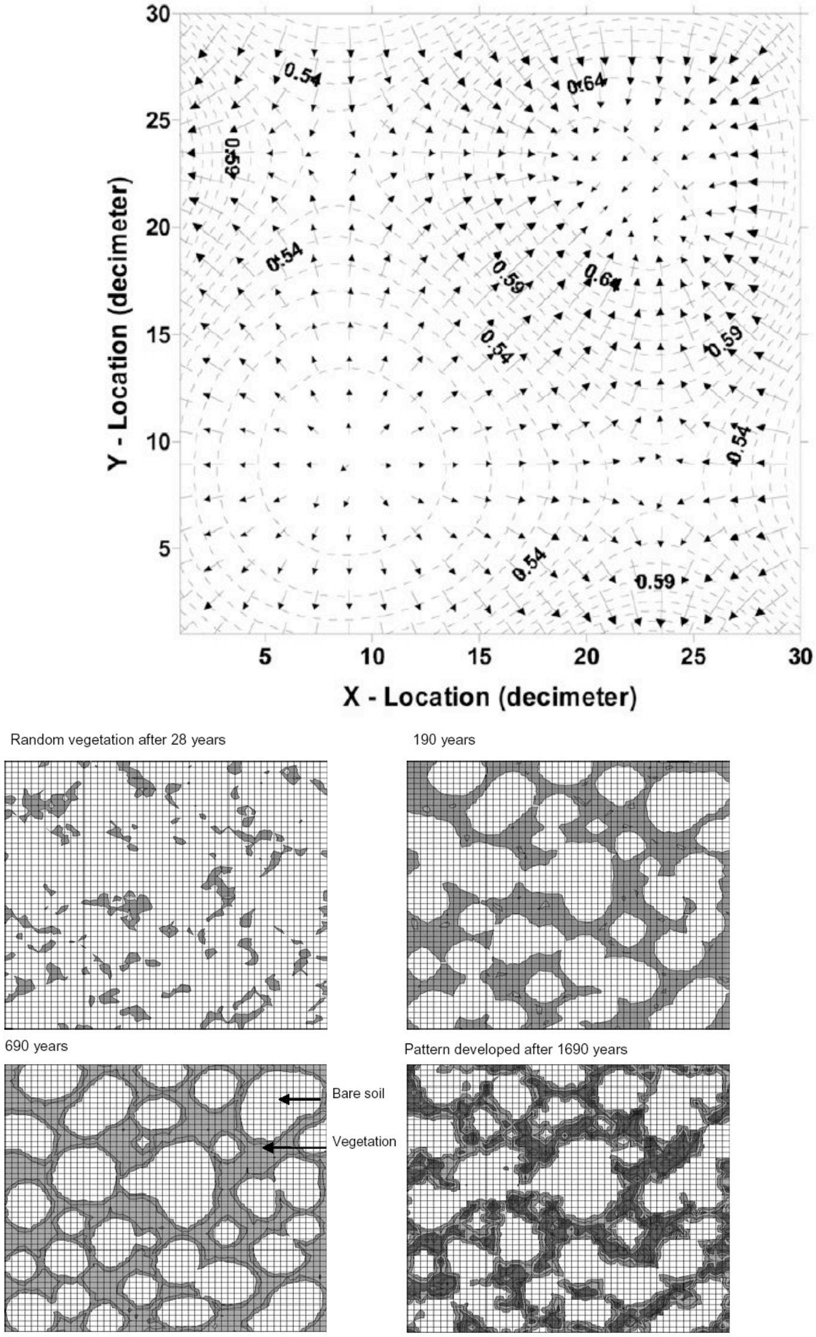

Figure 13. Upper panel: Ice content distribution at a depth of 5 cm depth (light isolines) as obtained from the numerical model WIT. The arrows represent the direction of the liquid water movement across the 3 x 3 m area. Lower four panels: Output from the combined WIT/ArcVeg model showing a simulated 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 x 5 m. The model incorporates feedbacks between the vegetation and the amount of heave. (Figures courtesy of Ronnie Daanen.)

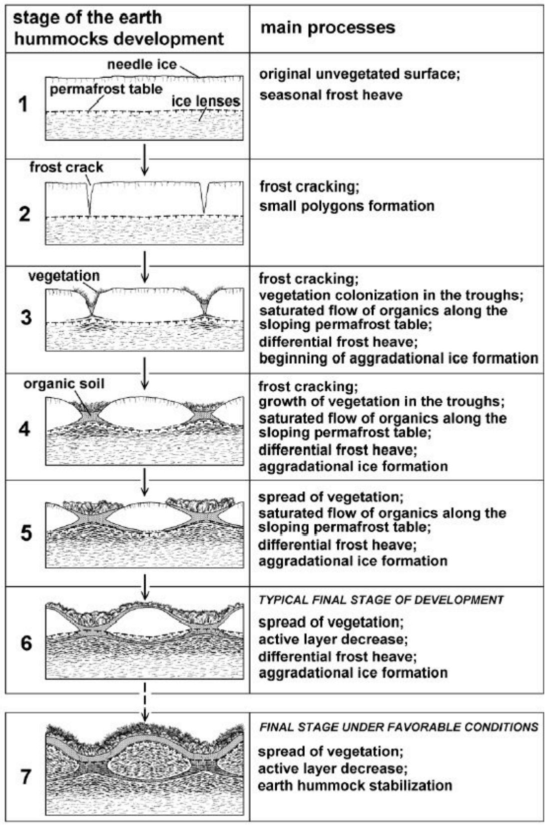

Figure 14. Conceptual model of nonsorted circle and hummock formation that occurs in conjunction with frost cracking [*Shur* et al., 2008 submitted to this volume]. See text for explanation.

Table 1. Patterned-ground features studied in the Biocomplexity of patterned-ground ecosystems project. [From *Raynolds et al*. 2008, this volume]

Feature	Definition	Subtype	Typical dimensions
Nonsorted Polygons	Dominantly polygonal forms without a border of stones, delineated by a crack or trough between adjacent polygons	Small	10-30 cm diam.
		Medium	30-300 cm diam.
Nonsorted Circles	Dominantly circular forms without a border of stones, characteristically margined by vegetation	Small	10-50 cm diam.
		Medium	50-150 cm diam.
		Large	>150 cm diam.
Hummocks	Dominantly dome-shaped features with a raised center and depression or trough between hummocks	Small	10-30 cm diam., 10-25 cm high
		Medium	50-200 cm diam. 30-60 cm high

Appendix A. Summary of key climate, soil, and vegetation data at zonal locations along the Arctic bioclimate gradient arranged from coldest summer temperatures (Isachsen) to warmest (Inuvik). Average values are shown for the centers of patterned ground features (PGF) and between patterned-ground features (bPGF).

Appendix A. Summary of key climate, soil, and vegetation data at zonal locations along the Arctic bioclimate gradient arranged from coldest summer temperatures (Isachsen) to warmest (Inuvik). Average values are shown for the centers of patterned ground features (PGF) and between pattern-ground features (bPGF).

Location	Isachsen		Mould Bay		West Dock		Howe Island		Green Cabin	
GPS (North/West)	78°47'11.9"	103°32'04.7"	76°13'42.6"	119°17'57.9"	70°22'30.2"	148°32'57.7"	70°18'54.6"	147°59'37.0"	73°13'10"	119°33'33"
Subzone	A		B		C		C		C	
Patterned ground type	1		1, 2		None		1, 3		1, 2, 3	
July mean temperature (°C, years of record)	2.0 (1967-1977), 2.4 (2003-2006)		4.0 (1971-2000), 3.2 (2002-2006)		5.53 (1990-2006)		5.68 (2003-2006)		7.4 (1999, 2002-2006)	
SWI (°C mo) (air at 2 m)	3.6 (1967-1977), 3.0 (2003-2006)		5.1 (1971-2000), 4.6 (2002-2006)		13.2		14.8		16.6	
Soil organic carbon (kg m-3)	15.20		21.10		67.70		23.85		27.65	
Dominant soil texture: sand, silt, clay (pct)	Clay: 16, 32, 52		Sandy loam: 66, 28, 6		Loamy sand: 80, 12, 8		Loam: 34, 43, 23		Sandy Loam: 53, 33, 14	
Soil coarse fragments (pct)	1		5		0		0		5	
Variation within patterned ground features:	PFG	bPFG	PFG	bPFG	undifferentiated		PFG	bPFG	PFG	bPFG
SWI at ground surface (°C mo)	8.9	7.6	12.4	10.1	15.2		27.7	25.6	17.9	16.6
Biomass (g m2±s.d.)										
Moss	11	135	6	218	51		0	0	1	39
Lichen	18	127	23	19	4		0	0	0	2
Graminoid	4	53	8	3	32		1	0	7	3
Forb	6	54	21	34	409		1	1	14	3
Evergreen shrub	0	0	0	12	29		0	0	42	385
Deciduous shrub	0	0	2	26	94		0	1	1	37
Total	39	369	58	312	618		2	3	66	468
Height of plant canopy (cm±s.d.)	1±0	1±0	0.5±0	2±2	8.4±2.3		0.1±0.2	1.8±0.4	2.8±4.9	2±0
Thickness of moss layer (cm±s.d.)	0±0	2.9±2.5	0±0	1.4±1.1	1.1±0.7		0±0	1.2±0.6	0±0	0.6±0.4
Thickness of organic soil horizons (cm±s.d.)	0±0	9.3±12.5	0±0	3±2.1	26.8±2.6		0±0	0.4±0.4	0±0	1.6±0.5
Snow depth (cm±s.d.)	22.1±7.9	21.2±11	17±0	23.2±2.9	19.2±5.8		7±0	7±0	25±0	25±0
Summer n-factor	1.49±0.21	0.80±0.20	1.48±0.24	1.14±0.29	NA		1.49±0.26	1.13±0.23	NA	NA
Winter n-factor	0.77±0.01	0.77±0.01	0.93±0.05	0.91±0.01	NA		0.95±0.03	0.87±0.03	NA	NA
Maximum thaw layer (cm±s.d.)	35±4	31±3	30±4	24±2	28±1		81±3	65±3	54±6	48±7
Frost heave (cm)	9.5	9.5	4	2.5	0.4		4	3	4.7	2.1
Soil pH	6.5±0.5	6.4±0.6	7.5±0.2	7.1±0.5	16.5±0.2		8.6±0.4	7.9±0.1	8.4±0.1	7.9±0.1

Location	Deadhorse		Franklin Bluffs		Sagwon MNT		Sagwon MAT		Happy Valley		Inuvik	
GPS (North/West)	70°09'41.2"	148°28'01.3"	69°40'28.5"	148°43'16.4"	69°26'00.3"	148°40'23.2"	69°25'31.9"	148°41'45.5"	69°08'48.7"	148°50'53.9"	68°06'39.3"	133°28'38.2"
Subzone	D		D		D		E		E		Boreal forest	
Patterned ground type	3		3		3		4, 5		4, 5		5	
July mean temperature (°C, years of record)	4.87 (1995-2006)		10.05 (1997-2006)		9.90 (2000-2006)		-		10.77 (2001-2005)		14.2 (1971-2000)	
SWI (°C mo) (air at 2 m)	17.3		24.2		26.5		26.5		29.5		40.2	
Soil organic carbon (kg m-3)	72.55		60.80		27.20		44.30		57.80		96.80	
Dominant soil texture: sand, silt, clay (pct)	Silt loam: 29, 52, 20		Silt loam: 36, 45, 19		Silt Loam: 8, 66, 26		Silt Loam: 20, 54, 17		Loam: 12, 59, 29		Loam: 38, 38, 22	
Soil coarse fragments (pct)	0		0		0		0		0		5	
Variation within patterned ground features:	PFG	bPFG	PFG	bPFG	PFG	bPFG	PFG	bPFG	PFG	bPFG	PFG	bPFG
SWI at ground surface (°C mo)	NA	23.6	31.5	26.6	33.5	29.2	NA	NA	31.3	20	NA	NA
Biomass (g m2±s.d.)												
Moss	17	42	55	77	118	319	319	261	136	202	NA	NA
Lichen	18	0	98	9	77	34	232	83	141	43	NA	NA
Graminoid	97	326	52	146	15	131	23	138	105	190	NA	NA
Forb	9	1	35	9	18	14	15	5	14	18	NA	NA
Evergreen shrub	42	20	123	196	168	78	115	174	190	199	NA	NA
Deciduous shrub	2	22	1	86	16	32	30	97	25	145	NA	NA
Total	185	416	363	483	411	609	734	758	611	796	NA	NA
Height of plant canopy (cm±s.d.)	2.6±1.5	13±4.5	3.6±1.6	6.9±5.5	2.2±0.4	8±5.7	6.6±3.2	16±6.5	13±2.7	26±4.2	40	40
Thickness of moss layer (cm±s.d.)	0.3±0.3	2.2±0.8	0.6±0.2	3.3±1.1	0.3±0.3	3.4±0.9	1.9±1.1	3.5±2.7	3.5±1.7	5.2±2.7	9	5
Thickness of organic soil horizons (cm±s.d.)	0±0	16.2±4.8	0.1±0.3	16.8±7.1	0.6±0.5	11.4±7.4	1.7±2.2	9.2±5.5	11.4±8.8	11±2.7	20	30
Snow depth (cm±s.d.)	32.8±11.7	47.4±7.9	19±7.4	33.7±11.7	37.6±4.0	44.4±4.1	22.6±4.2	43±8.7	61.4±6.9	72.6±5	NA	NA
Summer n-factor	NA	NA	0.92±0.08	0.29±0.08	NA	NA	NA	NA	0.28±0.11	0.09±0.05	NA	NA
Winter n-factor	NA	NA	0.74±0.04	0.55±0.04	NA	NA	NA	NA	0.35±0.03	0.30±0.01	NA	NA
Maximum thaw layer (cm±s.d.)	84±6	65±2	92±6	69±10	77±10	96±2	59±3	36±11	61±2	37±6	55	35
Frost heave (cm)	20	3	19	2	15	5	9	3	9.5	4	NA	NA
Soil pH	8.1±0.1	7.9±0.1	8.1±0.1	8.0±0.1	7.9±0.1	7.6±0.3	5.1±0.2	5.3±0.2	4.8±0.3	5.2±0.1	NA	NA

Notes and Methods:
Subzone: Based on CAVM Team (2003).
Patterned ground type: 1 - Small nonsorted polygons, 10-30 cm diam., 2 - Medium-size nonsorted polygons 1-2-m diam., 3. Medium-size nonsorted circles 1-2 m diam., 4 - Small non-sorted circles <1 m diam., 5 - Medium-size earth mounds 1-3 m diam.
Mean July temperature and SWI: 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.
Soil organic carbon (g m3): Calculated to one meter depth and measured using soil samples from profiles and descriptions of soil pits adjacent to 10 x 10-m grids.
Soil texture: Weight percentage of <2 mm fraction of soil in the top mineral horizon.
Soil coarse fragments: Percent by weight of soil sample from top mineral horizon.
Variation within patterned ground features: Data are from permanent vegetation plots in zonal sites at each location, Kade et al. (2005) and Vonlanthen et al. (2007, in press); average of 5-7 plots except Inuvik which had only one representative plot for each type. Plot sizes vary from 1x1 m to 5x5 m PGF: data are from the most common vegetation type occuring on PGFs at the given location; bPGF: between PGFs are from the zonal vegetation at each location.
SWI at ground surface (°C mo): All data are from the Romanovsky NAAT climate stations for the single year Aug 2005-Jul 2006.
Maximum thaw layer: Late August 2006. 5 measurements on each vegetation plot (Kade et al. 2005) with a graduated rod inserted into the soil to the frozen layer.
Biomass: Aboveground standing crop, 1 clip harvest (20 x 50 cm random areas) per plot, dried at 50°C and sorted according to plant functional types. Values include attached dead component.
Height of plant canopy: Canopy heights were estimated on each plot.
Thickness of moss layer: Includes only the live green layer.
Thickness of organic soil horizons: Measured in a soil pit dug adjacent to each releve. Includes the moss below the live green layer.
Snow depth: May 2006. Snow depth measurements per releve.
Summer n-factor: See methods this paper and Kade et al. (2006).
Winter n-factor: See methods this paper and Kade et al. (2006).
Frost heave (cm): Heave at Alaska locations measured with a 10-pin device described in Walker et al. (2004). Heave at the Canada locations was measured with metal scriber on a copper rod driven into permafrost (described in Romanovsky (this volume).
Soil texture: Data are from top mineral horizon of the soil pits dug adjacent to the 10 x 10-m grids.
Soil pH: Soil was a grab sample from the top of the uppermost mineral horizon from a soil pit dug adjacent to each vegetation plot; pH was etermined using 1:10 soil-water ratio.

Note: This table contains the data used in the paper and should be presented as an on-line supplement as an excel file or pdf of the excel file.

Appendix A. Summary table (see attached Excel file)