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Introduction to special section on Biocomplexity of Arctic Tundra Ecosystems

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1. Introduction

[1] The Arctic tundra biome is the treeless fringe of land that surrounds the Arctic Ocean (Figure 1, inset map). The terrestrial area of the biome, excluding glaciers and alpine areas, cover about 5.14 million km^2, an area about the half the size of the US or 3.4% of the total land surface of the world. A deeper understanding of the complex interactions between climate, permafrost, and the biological systems is needed, particularly in light of the recent rapid reduction of perennial arctic sea-ice cover [*Comiso et al.*, 2008; *Nghiem et al.*, 2007] that has raised concern regarding how terrestrial areas of the Arctic will be affected by a rapidly changing climate.

[2] The nature of the interactions among climate, permafrost, hydrology, and arctic ecosystems was the topic of a "Biocomplexity, Hydrology and Frozen Ground in Cold Regions" session at the 2006 Fall Meeting of the American Geophysical Union (AGU). The intent of the session was to bring together researchers from several Arctic projects that were funded under the National Science Foundation's (NSF) Biocomplexity in the Environment (BE) initiative. The purpose of the BE initiative was to understand complex environmental systems in which the dynamic behavior of living organisms is linked to the physical and chemical processes of the environment. BE was a priority area of research across several directorates within NSF [*NSF*, 2001].

[3] "Biocomplexity" with respect to Arctic terrestrial systems refers in part to understanding (a) the nonlinear response of arctic systems to perturbations, (b) the magnitude and extent of positive and negative feedback processes involved in such key processes as heat, CO$_2$ and water vapor exchange between the biosphere and the atmosphere, (c) the dynamics of self organization in processes governing patterned-ground formation (e.g., nonsorted circles and stripes), and (d) the high degree of interdisciplinary research required to understand the interactions of biological, physical, and chemical processes in these systems.

[4] The 2006 Fall Meeting at AGU offered an opportunity for the BE researchers working in the Arctic to present their first results in a common setting. Most of the papers in this special section of *JGR-Biogeosciences* are related to the first two Arctic projects funded in the BE inititiative: (1) "Biocomplexity associated with biogeochemical cycles in arctic frost-boil ecosystems," now called the "Biocomplexity of patterned ground" project, and (2) "Biocomplexity in NW Greenland: Physical-chemical-biological controls on carbon cycling in a cold, dry ecosystem, now called the "Biocomplexity in NW Greenland" project. Interactions between physical and biological processes, as they affect and control biogeochemistry (particularly carbon) and the formation processes of patterned ground (a form of self organization), were the unifying themes of these projects. This thematic venue of the Arctic Biocomplexity projects is especially relevant today as the Arctic has globally important soil carbon pools that are vulnerable to warming [*Callaghan et al.*, 2005], yielding strong feedbacks to climate through CO$_2$ source-sink dynamics [*Welker et al.*, 2004; *Chapin et al.*, 2005]. Recently, the role of patterned ground features and processes has been identified as being important for the arctic carbon cycle. Frost cracking, differential frost heave, and down slope motion create patterned-ground features, including polygons, circles, and stripes of various sizes that are a keystone feature of arctic landscapes. One of the most noteworthy findings of the BE studies is that cryoturbation processes involved in patterned-ground formation are locking large amounts of carbon into the permafrost. This could help reduce the load of carbon in the atmosphere, contrary to the general notion that permafrost tables are degrading across the whole Arctic.

2. Biocomplexity of Patterned Ground Project

[5] Patterned-ground features dominate most landscapes in the Arctic and have been extensively studied by geomorphologists and permafrost scientists, but the ecological importance of these features has generally not been recognized; thus the roles of frost heave and ground-ice formation with respect to biogeochemical cycling, carbon sequestration and other ecosystem processes were poorly known prior to these BE efforts.

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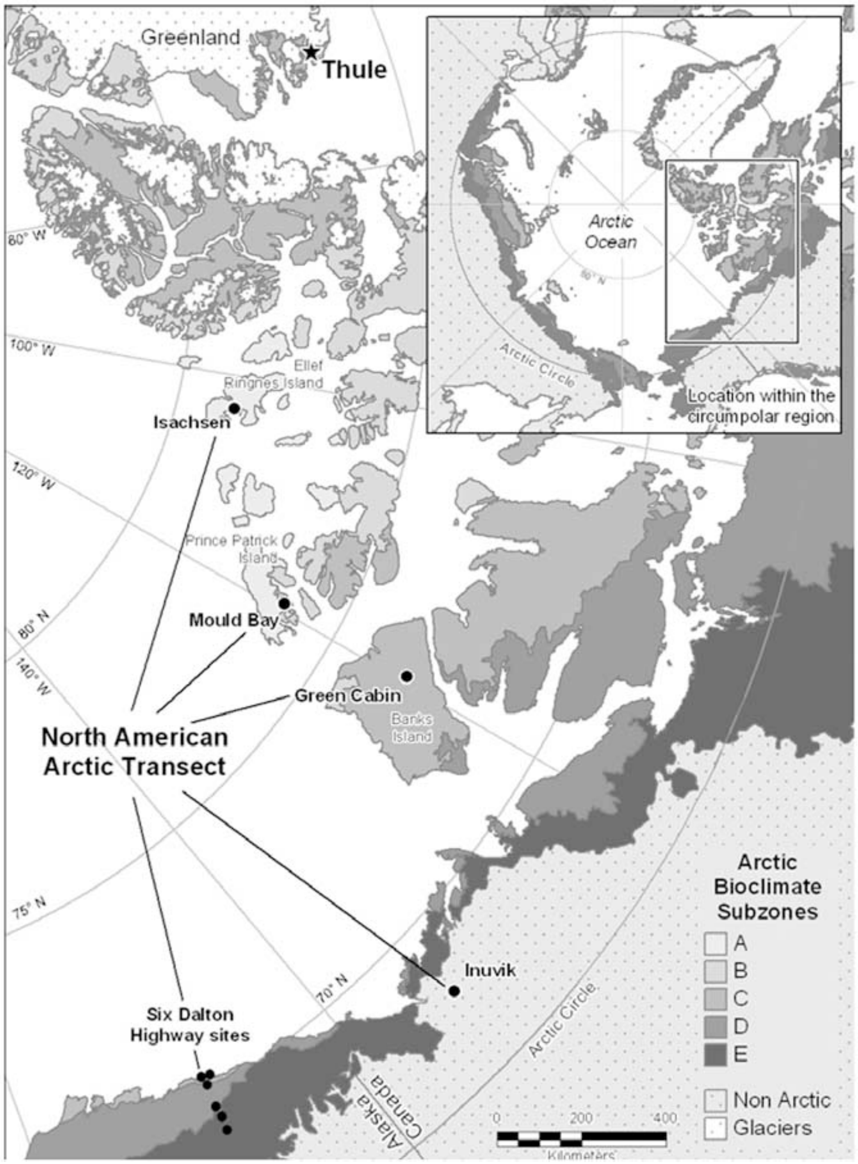

Figure 1. Locations of the study sites for the the Biocomplexity in NW Greenland project (at Thule) and the Biocomplexity of Patterned-Ground project (North American Arctic Transect). The Arctic tundra bioclimate subzones are from the Circumpolar Arctic Vegetation Map [*Walker et al.*, 2005]. The inset map shows the circumpolar distribution of the Arctic tundra biome.

[6] Eight papers in this section are from the Biocomplexity of Patterned Ground project, which studied small patterned-ground ecosystems along an 1800-km North American Arctic Transect (NAAT) from the polar deserts of northern Canada to shrub-tundra systems in Alaska (Figure 1) [*Walker et al.*, 2008]. The goal was to understand the complex linkages among climate, biogeochemical cycles, vegetation, soils, permafrost and disturbance across the full temperature gradient in the Arctic, in order to better predict Arctic ecosystem responses to changing climate. Earlier papers described the conceptual framework for the study [*Walker et al.*, 2004]; the plant communities along the southern portion of the transect [*Kade et al.*, 2005]; experimental alteration of the plant communities and the effects on soil heat fluxes, thaw and soil heave [*Kade et al.*, 2006; *Kade and Walker*, 2008]; the interactions among climate, vegetation and the active layer [*Kelley et al.*, 2004]; a differential frost heave model [*Peterson et al.*, 2003]; and a model of active-layer hydrology in nonsorted circle ecosystems [*Daanen et al.*, 2007].

[7] The paper by *Walker et al.* [2008] presents an overview of the field observations and models, and focuses on the insulative effects of vegetation, organic soil layers, and snow on the active layer and frost heave. Four other papers describe how elements of patterned-ground systems change along the climate gradient, including the vegetation [*Raynolds et al.*, 2008; *Epstein et al.*, 2008], and soils [*Michaelson et al.*, 2008; *Ping et al.*, 2008]. The paper by *Epstein et al.* [2008] quantifies the biomass of different plant growth forms along the arctic climate gradient on nondisturbed zonal sites and on patterned ground features that are disturbed by cryoturbation processes. The paper by

Raynolds et al. [2008] analyzes 21 maps of 10-m × 10-m patterned ground features, plant communities, biomass, active-layer thickness, and snow depth, and illustrates the trends in pattern type and biomass and the nearly ubiquitious control that patterned-ground features have on key arctic site factors: the depth of the active layer and the fine-scale distribution of snow. Two papers describe the soil and soil processes along the transect: *Ping et al.* [2008] describe the major soil-forming processes, including cryoturbation and horizon development, related to patterned-ground features and the wide variety of cryogenic structures in the soils. They point out that at the southern end of the transect the actual density of patterned-ground forms is higher than that mapped by *Raynolds et al.* [2008] because many of the features are masked by vegetation. They also describe how considerable amounts of carbon are locked in the intermediate layer, the ice-rich and carbon-rich upper-most portion of the permafrost, via cryoturbation and gradual upward aggradation of the permafrost table that occurs with vegetation succession on these features. *Michaelson et al.* [2008] add to this by describing the detailed physical and chemical properties of cryoturbated soils and how they vary along the arctic temperature gradient.

[8] These baseline observations provide input for three models of patterned-ground formation. Many small-scale patterned-ground features are caused by differential heaving of soils that results in regularly spaced circles or mounds, 1–3 m in diameter. The Differential-Frost-Heave (DFH) model indicates that the process of uniform frost heave (the upward movement of soil during freezing) across the entire soil surface is unstable, and once frost heave is initiated, it will spontaneously develop into the observed, self organized patterns [*Peterson and Krantz*, 2008]. A thermo-mechanical model provides a detailed look at basic thermodynamic principles: energy, momentum and mass-conservation laws, and simulates the observed frost heave in nonsorted circles and how heave is altered by the presence of a vegetation cover [*Nicolsky et al.*, 2008]. An alternative explanation for the initiation of heave is presented by the WIT-ArcVeg model, which provides a landscape-scale perspective of patterned-ground formation, focusing on the horizontal and vertical movement of water during ice-lens formation, and how this is affected by changes in soil thermal properties related to vegetation succession [*Daanen et al.*, 2008b]. The initial stochastic distribution of plants affects the flow of heat and water that generate ice-lenses, and that the flow paths change over time and eventually evolve into the regular distribution of patterned-ground features observed in nature. A fourth model is a conceptual description of how changes in the permafrost table caused by thermal cracking, accumulation of biomass in the cracks, and an aggrading permafrost table, which leads to the evolution of nonsorted circles and hummocks [*Shur et al.*, 2005] (described briefly by *Walker et al.* [2008]). The Shur model illustrates the important role of cracking in the formation of fine-scale patterned-ground features, but considerable additional work is needed to incorporate cracking in the numerical models. As a group, these models describe three different pathways for the initiation of differential frost heave — spontaneous differential frost heave (DFH), differences in soil thermal properties initiated by stochastic variation in vegetation distribution (WIT-ArcVeg), and cracking leading to subsequent nonhomogeneous distribution of vegetation and organic matter (the Shur model). All of the models recognize vegetation as a strong actor in the formation of patterned ground. Other pathways exist as in the formation of sorted patterned ground features in totally unvegetated areas [*Kessler and Werner*, 2003; *Werner and Hallet*, 1993].

[9] Additional papers from the Biocomplexity of Patterned-Ground project that are in press elsewhere describe the climate and frost heave patterns along the transect [*Romanovsky et al.*, 2008], a high resolution examination of frost-heave dynamics in a nonsorted circle landscape [*Daanen et al.*, 2008a], and the plant communities in the High Arctic portion of the bioclimate transect [*Vonlanthen et al.*, 2008].

3. Biocomplexity in NW Greenland Project

[10] Four papers in this section are from the Biocomplexity in NW Greenland project [*Welker et al.*, 2006], while additional findings from this project have appeared elsewhere [*Steltzer and Welker*, 2006; *Sullivan and Welker*, 2007; *Sullivan et al.*, 2008b]. For the past five years, experimental and observational studies have been conducted near Thule, in northwest Greenland, a region that is undergoing some of the largest temperature increases in the Arctic [*Box*, 2002; *Sullivan et al.*, 2008a], resulting in reductions in ice sheet volume [*Sterns and Hamilton*, 2007; *Fettweis et al.*, 2007] and ice sheet thinning along the margins, which has exposed new landscapes to the modern atmosphere [*Jones et al.*, 2000; *Welker et al.*, 2002; *Thomas et al.*, 2006]. The premise of this project was that physical, chemical and biological processes interact to control carbon dynamics and that nonlinear behavior would be common. The project tests and articulates complexity theory in a High Arctic landscape through: (a) the use of experimental increases in temperature, precipitation and soil nutrients, and measurements of carbon and nitrogen cycling, (b) observations of genetic variation in a key woody arctic plant (*Salix arctica)* and its feedback effect on ecosystem carbon exchange, and (c) examination of patterned-ground formation processes, especially as related to soil carbon traits.

[11] Three field experiments were established to quantify how temperature, precipitation and soil nutrients control the function of High Arctic organisms and biogeochemical cycles [*Sullivan et al.*, 2008a; *Arens et al.*, 2008; *Rogers et al.*, 2007]. In the first experiment, infrared [IR] lamps (120 V, 12.5 amps, 1500 watts) [*Harte et al.*, 1995] were used to implement two levels of soil warming in a replicated experiment [*Sullivan et al.*, 2008a]. With increased soil warming due to the radiation loading, leaf area index, a vegetation growth parameter, exhibits a strong initial increase to low levels of warming, but no progressive increase at the higher warming level [*Steltzer and Welker*, 2006]. The second experiment addressed the effects of fertilizer additions on ecosystem processes [*Arens et al.*, 2008]. Increasing levels of nitrogen resulted in a strong nonlinear increase in ecosystem-level gross photosynthesis in 2005 and in 2006 [*Arens et al.*, 2008]. High degrees of genetic variation could help species adapt to changing climate and affect carbon pools [*Steltzer et al.*, 2008]. For instance, the abundance of *Salix arctica* determines ecosystem CO_2

source-sink traits in NW Greenland. In addition, intraspecific variation may result in a multitude of *S. arctica* plants across the landscape that are differentially adapted to unique weather and climate patterns, potentially assuring the resistence of this species to climate change.

[12] Self-organization in this High Arctic landscape is depicted by the large array of patterned-ground features including stripes, circles, and nets [*Washburn*, 1980; *Kessler and Werner*, 2003]. These features are the result of complex interactions between glacial history and the frost cracking and ice-lens formation that result from the freezing and thawing of water. These features were studied along a 60-m × 2-m × 2-m trench perpendicular to a set of nonsorted stripes. Along this trench soil strata and vegetation were mapped, and soil carbon pools in the upper and lower profile were aged (Δ^{14}C) [*Horwath*, 2007; *Horwath et al.*, 2008]. Ancient soil carbon with a Δ^{14}C date of almost 32,000 ybp appears in pockets and is not spatially correlated with the surface distribution of vegetation [*Horwath et al.*, 2008], suggesting that this carbon was assimilated during prior warm periods in Greenland and that ice temporally advanced and buried this ecosystem, freezing the soil carbon in the permafrost. Additional papers from this project have: (a) developed and tested four alternative models of vegetation effects on the relationship between the normalized difference vegetation index (NDVI) and LAI as part of our scaling studies [*Steltzer and Welker*, 2006], (b) investigated the complexity of high arctic plant leaf gas exchange by testing whether the dual isotope (δ^{18}O and δ^{13}C) approach is capable of revealing the relative contributions of conductance (g_s) and photosynthesis (A_{max}) in determining Δ^{13}C along hydrologic gradients [*Sullivan and Welker*, 2007] and (c) quantified the feedback between high arctic fens and the atmosphere that depict that the C balance of high latitude wetlands is closely tied to microtopography and that changes in the C balance with warming will reflect a complex interplay between climate forcing, biota and the physical controls on wetland microtopography [*Sullivan et al.*, 2008b].

4. Conclusions

[13] Collectively, the observations, experiments and models described in these papers provide new perspectives on how climate, soils, vegetation, and permafrost interact in complex ways to form arctic patterned-ground landscapes and affect the energy, water, and trace-gas budgets of the Arctic. The Biocomplexity of Patterned-Ground project examines variation in the vegetation, soils, and patterned-ground properties along the full arctic bioclimate gradient and will serve as a baseline against which to measure future changes in these systems. The models described here show how differential frost heave, the primary process involved in the formation of many patterned ground features, is affected by a variety of physical and biological properties. A remaining challenge is to include the process of cracking in the numerical models. The Biocomplexity in NW Greenland project is providing insights regarding how modern and ancient carbon cycles are interwoven, the critical role of the woody plant (*S. arctica*) in affecting High Arctic carbon and heat budgets, and how changes to these systems would affect regional climates. Perhaps the most surprising finding and the one with the most important global significance in both projects is the large amount of organic carbon found in the upper layer of permafrost that is a direct consequence of patterned-ground genesis. Despite rising air temperatures in the Arctic, permafrost is aggrading over much of the region because, as is shown in several papers in this issue, warmer temperatures can lead to an accumulation of organic matter, which can reduce the flux of heat into the ground. At present it is unknown what the balance between aggrading and degrading permafrost tables is Arctic-wide and how this varies within and between bioclimate subzones.

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