Complexity in natural biological ecosystems:

Interactions of physical and biological processes in the formation of small patterned-ground features across the Arctic climate gradient

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Overview of talk

- NSF’s Biocomplexity in the Environment (BE) program.
- Overview of the Biocomplexity of Patterned Ground project
  - What are frost-heave features?
  - Why this is a biocomplexity study.
  - Conceptual models.
- Project components
- Pulling the components the parts together through process modeling.
- Extrapolation beyond the confines of the conceptual models: relevance to the greater Arctic System.
- Lessons learned.
Ecosystems are incredibly complicated

- Traditionally studied with multi-disciplinary approaches,
- involving complicated models,
- examining interactions between many biological and physical variables,
- often through multiple time scales,
- multiple spatial scales
- and involving non-linear processes.

Requires new approaches to study these systems.
NSF’s Biocomplexity in the Environment (BE) Program

• The key connector of BE activities is complexity – the idea that research on the individual components of environmental systems provides only limited information about the behavior of the systems themselves.

• Focuses on problems with:
  – (a) a high degree of interdisciplinarity;
  – (b) a focus on complex environmental systems that includes non-human biota or humans; and
  – (c) a focus on systems with high potential for exhibiting non-linear behavior.
Focus areas in the BE program

- Coupled biogeochemical cycles
- Genome-enabled science and engineering
- Dynamics of coupled natural and human systems
- Material use: science, engineering, and society
- Instrumentation: development for engineering activities
Coupled biogeochemical cycles (CBC)

• How the physical, chemical, geological, and biological processes of Earth's natural systems are functionally interrelated.
• The study of coupled biogeochemical cycles across wide spatial and temporal scales
• Integrative models for the cycling of water, carbon and other bioactive elements.
• Studies of the web of material and energetic pathways connecting environmental processes to the dynamics of life on Earth.
• Stresses a system approach to understanding interrelationships among earth system cycles.
• Linkages between two or more biogeochemical cycles together with the underlying biology and ecology and the fundamental chemical reactions and physical processes that drive them.
To better understand the complex linkages between frost heave, biogeochemical cycles, vegetation, disturbance, and climate across the full Arctic summer temperature gradient in order to better predict Arctic ecosystem responses to changing climate.

Biocomplexity Grid at Green Cabin, Banks Island, Canada, 2003
Project initially focused on “frost boils”

- Patterns caused principally by differential frost heave (Peterson and Krantz 2003).

- Also called:
  - Non-sorted circles (Washburn 1980)
  - ‘Frost medallions’ (Russian term),
  - ‘Mud boil’ (Zoltai and Tarnocai 1981)
  - ‘Frost boi’ (van Everdingen 1998)
  - ‘Frost scar’ (Everett 1966)
  - ‘Spotted tundra’ (pyatnistye tundry, (Dostoyalov and Kudravstev 1967).
Many patterned-ground forms are caused by differential frost heave

- Non-sorted circles
- Earth hummocks
Why focus on small patterned-ground features?

- Some processes involved in the formation of patterned-ground landscapes are not well understood.

- The role of patterned ground with respect to biogeochemical cycling, carbon sequestration and a whole host of ecosystem processes is poorly known.

- An ideal natural system to study vegetation change of disturbed and undisturbed tundra related to differences in climate.
Frost-heave Complexity Questions

• **Self organization.**
  – How do biological and physical processes interact in the process of patterned ground formation?

• **Complex adaptive systems.**
  – How do frost-heave and associated ecosystems change along the arctic climate gradient?
  – How does the vegetation affect the microclimate, ground ice, disturbance, and soils of frost-heave features along the Arctic climate gradient?

• **Scaling issues.**
  – What are the emergent properties of frost-heave systems at different spatial scales?
  – How do frost-heave features affect trace gas fluxes, hydrological systems, and patterns of wildlife at landscape, regional and global spatial scales?
Conceptualizing the components of the non-sorted circle system

Linkages between components:

**Vegetation-Ice lenses:**
1. Insulation by mosses and shading by vascular plants (-).
2. Disturbance by cryoturbation (-).

**Ice Lenses-Soil:**
3. Frost heave and cryoturbation of horizons (-).
4. O-horizon development and insulation (-).

**Vegetation-Soil:**
5. Accumulation of organic matter and soil nutrients (+).
6. Available nitrogen (+).
Conceptualizing the System

Vegetated inter-circle area

Sparsely vegetated circle

Courtesy of C. Tarnocai
The **bold arrows** indicates interactions and feedbacks between **elements** (frost boils and inter frost boils):

1. Water and material flow from circles to inter-circle areas during summer.
2. Flow of water to freezing front by cryostatic suction during winter.

**Light arrows** between **components** of each element (ice lenses, soils, and vegetation) (see previous slide).
How do the linkages change across the Arctic climate gradient?

- **Cold climate (subzone A)**
  - Non-sorted circles: Ice Lenses → Soil → Vegetation
  - Inter-circle areas: Ice Lenses → Soil → Vegetation

- **Moderate climate (subzone C)**
  - Non-sorted circles: Ice Lenses → Soil → Vegetation
  - Inter-circle areas: Ice Lenses → Soil → Vegetation

- **Warm climate (subzone E)**
  - Non-sorted circles: Ice Lenses → Soil → Vegetation
  - Inter-circle areas: Ice Lenses → Soil → Vegetation
Examination of frost heave features across the Arctic bioclimate gradient

From the *Circumpolar Arctic Vegetation Map, 2003.*

<table>
<thead>
<tr>
<th>Sub-zone</th>
<th>Mean July temperature (°C)</th>
<th>Dominant plant growth forms</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2-3</td>
<td>Cushion forbs, mosses, lichens</td>
</tr>
<tr>
<td>B</td>
<td>3-5</td>
<td>Prostrate dwarf shrubs</td>
</tr>
<tr>
<td>C</td>
<td>5-7</td>
<td>Hemi-prostrate dwarf shrub, sedges</td>
</tr>
<tr>
<td>D</td>
<td>7-9</td>
<td>Erect dwarf shrubs, sedges mosses</td>
</tr>
<tr>
<td>E</td>
<td>9-12</td>
<td>Low shrubs, tussock sedges, mosses</td>
</tr>
</tbody>
</table>
Temperature gradient

Mean July temp. = 3°C
Summer warmth index = 4°C mo

* Missing for 2004, data from long-term mean
2004 was generally a warm year
Data: Vlad Romanovsky
Examples non-sorted circles and hummocks in different climates

Subzone A: Satellite Bay, Prince Patrick I.

Subzone C: Bernard R., Banks Island

Subzone B: Mould Bay, Prince Patrick I.

Subzone E: Kurishka, Kolyma R., Russia
Components of the project were based on the components in the model

- **Climate and Permafrost:**
  - Monitoring and modeling: Vlad Romanovsky, Dimitri Nicolsky, Ronnie Daanen
  - Differential frost-heave model: Bill Krantz, Rorik Peterson

- **Soils:**
  - Soil descriptions, analysis, cryptogamic crusts: (Chien-Lu Ping, Gary Michaelson)

- **Vegetation:**
  - Classification, Mapping: (Skip Walker, Anja Kade, Corinne Vonlanthen, Martha Raynolds, Bill Gould, Corinne Munger)
  - Modelling, Nitrogen mineralization, Remote Sensing: (Howie Epstein, Alexia Kelley)

- **Other components (contributed by guest investigators):**
  - Invertebrate studies: Grizelle Gonzalez, Olga Markarova
  - Turf and earth hummocks: (Charles Tarnocai)
  - Arctic Field Ecology Course: (Bill Gould, Grizelle Gonzalez)
  - Mycorrhizal relationships: (Ina Timling)
  - High Arctic vegetation classification: Fred Daniels, Nadya Matveyeva
The Ice Lens Component

- Ice lenses drive frost heave.

- Numerous closely spaced lenses form as the soil freezes downward from the surface.

- The increased volume of the water causes heave.

- Heave also is caused by water moving from the inter-circle area by cryostatic suction.

Frozen soil core from a frost boil
Photo Julia Boike
Ice lenses cause frost heave

- Differential heave occurs when thermal properties of adjacent soils are different. This affects the size and number of ice lenses.

- Example: Deep organic layer of inter-circle areas insulates the soil reducing the active-layer thickness, the number of lenses, and the amount of heave.

- Cryostatic suction may pull additional water from the inter-circle areas to increase the amount of heave within the circle.
Differential Frost Heave (DFH) model describes self-organization in frost-heave systems (Peterson and Krantz 1998)

- Heat (and water) preferentially escapes from the surface at high points (irregularities) in the surface. These high points of heat and water flux lead to increased ice-lens development, and more heave.

- These irregularities self-organize into larger heave features. The spacing of the heave features is controlled by mechanical properties of the soil (e.g., texture, active layer thickness).

- Vegetation and/or snow cover can affect the amount of heave by changing the soil surface temperature and the active layer thickness.
Differential heave across the climate gradient (V. Romanovsky)

- Heave greatest in northern Alaska on silty soils
- Differential heave is the greatest in subzone D, where centers are unvegetated but areas between features are well-vegetated.
It gets more complex in the High Arctic: small contraction crack polygons are the dominant patterned-ground features

- Small non-sorted polygons (Washburn 1980).
- Occur on most sandy to clayey soils in the High Arctic (Subzones A, B, C).
- May be caused by either desiccation cracking or seasonal frost cracking (Washburn 1980).

Photos: D.A. Walker
Cracking patterns occur at several scales

10 m. Permafrost crack nonsorted polygons (ice-wedge polygons), Kupar;uk R., Alaska

10-100 cm. Small non-sorted polygons, cracking occurs only in the active layer. Green Cabin.

2-5 cm Very small polygons within small non-sorted polygons, Mould Bay.
In some areas, contraction cracking interacts with differential frost heave

Photo by Anja Kade

Howe Island, AK

Scale 2 m
Small non-sorted polygons caused by cracking

Small non-sorted polygons (35-50 cm)

Howe Island, AK

Scale 2 m

Photo by Anja Kade
Non-sorted circles caused by heave

Frost-heave non-sorted circles (90-200 cm)

Scale 2 m

Howe Island, AK

Photo by Anja Kade
Larger non-sorted polygons: also caused by cracking

Howe Island, AK

Photo by Anja Kade
Organization of non-sorted circles and polygons at Howe Island

Large non-sorted polygon 200 cm
Small non-sorted polygon 35 cm
Non-sorted circle 90 cm

Photo: Anja Kade
Even larger non-sorted polygons: also caused by cracking

Large non-sorted permafrost crack polygons (20-30 m diameter) Howe Island
Photo: D.A. Walker
In general:

- Circular forms are caused by differential heave resulting in circles and earth hummocks.

- Polygonal forms are caused by cracking (thermal or desiccation):
  - Large low- and high-centered polygons (thermal contraction cracking penetrates deep into the permafrost)
  - Small non-sorted polygons (contraction cracking confined to zone of seasonal thaw)

- Both differential heave and cracking can occur at a variety of scales forming complex landscape patterns.

- The forms can be modified by a wide variety of processes including sorting (sorted forms), erosion and eolian deposition (turf hummocks, high-centered polygons), down-slope soil movement (stripes and lobes).
Soils component
Role of soil texture

Rocky soils: sorted circles and polygons, Mould Bay, Elevation Belt A

Clayey soils: earth hummocks, Inuvik, NWT, N; Boreal Forest

Silty soils: sorted circles without earth hummocks, Prudhoe Bay, AK, Subzone D

Sandy soils: no circles nor hummocks, Atkasuk, AK, Subzone D

Clayey soils: earth hummocks, Inuvik, NWT, N; Boreal Forest
Modification of small polygons to form turf hummocks

- Erosion and eolian deposition modify the basic forms resulting in turf hummocks (Broll and Tarnocai 2003).

Turf hummocks on slopes with *Dryas integrifolia* and *Cassiope tetragona*, Green Cabin. Photo: D.A. Walker
Soil pits in the Arctic have traditionally looked at only the active layer

- Chien-Lu and Corinne Munger digging soil pit at Isachsen to 1-m depth.
Sequestered carbon at depth caused by cryoturbation (Subzone D: Franklin Bluffs)

Carbon-rich horizon at base of non-sorted circle

<table>
<thead>
<tr>
<th>Component</th>
<th>kg OC m$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active layer</td>
<td>37</td>
</tr>
<tr>
<td>Permafrost</td>
<td>19</td>
</tr>
<tr>
<td>Total</td>
<td>56</td>
</tr>
</tbody>
</table>

Carbon-rich horizon at base of non-sorted circle
Recent and Historical Estimates of C-stores in the Arctic

Recent Findings (Ping et al., 1992-2005)

Historical Estimates (Post et al., 1982)
The vegetation component

Plant cover:
- Insulates the surface decreasing the heat flux and summer soil temperatures.
- Stabilizes cryoturbation and limits needle-ice formation.
- Promotes nitrogen and carbon inputs to the soil.

How does regional temperature influence the effects of vegetation on patterned-ground morphology?
Vegetation in relationship to patterned ground across the bioclimate gradient

Modified from Chernov and Matveyeva 1997

Bioclimate subzones

Modified from Chernov and Matveyeva 1997
Subzone A

Isachsen, Ellef Ringnes Island, mean July temperature = 3 ˚C, SWI = 4 ˚C mo
Subzone B

Mould Bay, Prince Patrick Island, MJT = 4 °C, SWI = 5 °C mo
Subzone C

Howe Island, Ak and Green Cabin, Banks Island, MJT, 8 °C, SWI = 16 °C mo
Subzone D

Ambarchik, Russia, Franklin Bluffs, AK, MJT = 10 °C, SWI = 27 °C mo
Subzone E

Tuktuyaktuk, NWT, Happy Valley, AK, MJT = 12 °C, SWI = 30 °C mo
Northern Boreal subzone

Inuvik, NWT, MJT = 14 °C, SWI=36
Effect of vegetation on thaw layer thickness

- Expect to see thaw layer increase with warmer temperatures.
- This is true in the High Arctic (Subzones A, B, C) where there is little vegetation.
- But the trend is opposite in the Low Arctic (Subzone D and E).

Increasing temperature
Vegetation of patterned ground features: Anja Kade
Classification and ordination of vegetation (A. Kade and C. Vonlanthen)

Kade et al. 2006 in press. Phytocoenologia
Vegetation Effect on Cryogenic Activity: Transplant experiment (A. Kade)

- **Vegetation removal.** What influence does the lack of plant canopy have on thermal insulation and frost heave of nonsorted circles?

- **Transplant *Eriophorum vaginatum* plants.** How do vascular plants with an extensive root system affect cryogenic activity?

- **Transplant moss carpet.** What effect does an insulating moss carpet have on cryogenic activity?

- **Control**
Putting it all together

Interacting factors controlling patterned ground

- Climate
- Differential frost heave
- Soil properties (water, organic matter, and texture)
- Vegetation succession and stabilization
- And Seasonal frost cracking
Response of the system across the Arctic bioclimate gradient

Non-sorted circles

**Cold climate (subzone A)**
- Vegetation
- Ice Lenses
- Soil

**Moderate climate (subzone C)**
- Vegetation
- Ice Lenses
- Soil

**Warm climate (subzone E)**
- Vegetation
- Ice Lenses
- Soil

Inter-circle areas

**Cold climate (subzone A)**
- Vegetation
- Ice Lenses
- Soil

**Moderate climate (subzone C)**
- Vegetation
- Ice Lenses
- Soil

**Warm climate (subzone E)**
- Vegetation
- Ice Lenses
- Soil

- Physical processes (Frost heave, needle-ice development) dominate in both elements of the system.

- Physical processes dominate on the circles. Biological processes (organic mat development) control the system in the inter-circle.

- Biological processes are dominant in both the circle and inter-circle elements.
Strength of influence of cracking, differential heave and vegetation succession on small patterned ground forms along the arctic climate gradient.
Polygenetic origins of small periglacial surface forms

Soil Texture

- Clay:
  - Recracking and enhancement

- Silt:
  - Cracking

- Sand:

Seasonal Frost Cracking

- Erosion + deposition

- Small nonsorted polygons

Differential Frost Heave

- Large nonsorted polygons and incipient earth hummocks

- Non-sorted circles

- Featureless

Vegetation succession and stabilization

- Earth hummocks

- Stabilized inactive non-sorted circles

- Featureless

Time

- Disturbance

- Vegetation succession

- Warmer climate
ArcVeg – Arctic tundra vegetation dynamics model (Epstein et al. 2001)

ArcVeg – Stochastic generation of pattern and vegetation succession.

Subzone C
Non-Sorted Circle Disturbance

Total Biomass

Soil Organic Nitrogen

Average total biomass for frost boils and inter-bolll areas over time series:

Average SON for frost boils and inter-bolll areas over time series:
Biomass – Inter-Circle Areas
Biomass – On Circles
Salix
Mosses
Dryas
Lichens
Carex
Mosses
Forbs

Howie Epstein, in progress
ArcVeg – Plant growth form response disturbed and undisturbed conditions (Howie Epstein and Alexia Kelley)

Subzone C

Howie Epstein, in progress

Biomass – On Circles
Linking modeling efforts

Ice-lens Component (Krantz, Peterson, Romanovsky, Daanen et al.)

Soil Component (Ping, Michaelson et al.)

Vegetation Component (Epstein, Walker et al.)

- Soil Organic Carbon
- Soil Organic Nitrogen
- Plant-Available Nitrogen
- Plant Carbon/Nitrogen
- Recruitment
- Resorption
- Mineralization
- Climate Cryoturbation
- N\textsubscript{2} fixation
- N loss

CO\textsubscript{2}

BioActivity (bioclimatic & geomorph. factors)
Data flow and linkages between physical and biological models

Environmental Variables

Models

Soil moisture
Vegetation and Pattern
Snow/vegetation insulation and heave

Soil Physics
Soil Chemistry

TMHM
accurate heave

DFH
pattern density

WIT3D
liquid water redistribution

ARCVEG
vegetation succession

vegetation pattern succession

DFH: Differential Heave model
TMHM: Thermo Mechanical Heave Model
WIT3D: 3D Water Ice Temperature model
ARCVEG: Arctic Vegetation succession model

Measured input and/or calibration data
Simulated calibration and/or input data
Feedback
3-D Modeling of patterned-ground formation
(R. Daanen, D. Misra, H. Epstein)

WIT3D/ArcVeg Model in ARSC Discovery Lab.

Photo: Ronnie Daanen
Linkages between the frost-boil system and components of the greater Arctic system and biosphere

- **a** - Effects on forage quality and wildlife habitat.
- **b** - Effects on water flux and water quality.
- **c** - Effects on fluxes of energy and trace gases to the atmosphere.
- **d** - Abundance of wildlife for hunting and viewing.
- **e** - Fish and water resources.
- **f** - Air quality and feedbacks to the atmosphere influencing climate change.
Distinct vegetation boundary on the Arctic Slope, Alaska caused by acidic/nonacidic tundra differences

- Separates moist acidic tundra (soil pH<5.5) to the south from moist calcium-rich tundra (pH>5.5) to the north
  - Higher percentage of nonsorted circles north of the boundary
  - Shrubbierv vegetation to the south

- Possible causes:
  - Major geologic differences
  - Loess deposition from the major river systems
  - Climate
MAT/MNT boundary on false color CIR imagery

Landsat MSS image of boundary near Sagwon, northern edge of Arctic Foothills, Alaska
Conceptual model of climate-snow-cryoturbation-MNT hypothesis
Canopy structure

Organic layer thickness, heat flux, and active layer thickness


MAT plant adaptations to low nutrient environments

- Stress tolerators
- Evergreen leaves
- Small leaves
- Slow growth
- Long-lived perrenials
- Persistent litter
- Lots of secondary metabolites, low palatability to herbivores
- High year-to-year variation in flowering abundance

Betula nana, Ledum decumbens, Rubus chamaemorus
Digestibility, nitrogen and carbon-based defensive compounds in common forage species

Dry Matter Disappearance (IVDMD)

% Dry Weight

Total Nitrogen

Total Non-nitrogen Carbon-based Defensive Compounds

from Kuropat (1984)
Leaf tissue chemistry

Soil calcium

Plant tissue calcium in common forage species
Question I’d like to answer: “Is there a relationship between wildlife distribution and calcium-rich tundra (and non-sorted circle) distribution?”
Factors that would limit animal populations in acidic tundra (often areas with few non-sorted circles and low levels of cryoturbation and nutrient cycling).

- Plants have more secondary metabolites
- Less nitrogen and calcium in plant tissues
- Less diversity of vascular plant species
- Cold, acidic soils limit nutrient cycling
- Shallow active layers are poor habitat for burrowing animals
- Thicker moss carpets and larger tussocks create more difficult footing for migrating mammals
- Less diversity of habitats in acidic landscapes
What we accomplished and did not accomplish

- Deeper understanding of the system components and interactions we originally described in the project conceptual model.
- Characterized the climate, soils, frost heave, patterned ground forms on zonal sites across the full climate gradient.
- Confirmed that vegetation is a critical factor in developing patterned ground forms in that it largely controls the thermal condition of the soils.
- Developed dynamic models of frost heave, vegetation succession and patterned ground formation, applicable to the Low Arctic.
- Learned that the system was more complex than we originally considered. We were not able to model the cracking component of the system within the time constraints of the project.
Keys to studying complex interactions in ecosystems

• Simplify the system to as few components as possible.
• Carefully define the interactions between components.
• Conceptual diagrams are essential.
• Multiple simple models rather than a single grand synthesis model.
• Choose an excellent team dedicated to multi-disciplinary research.