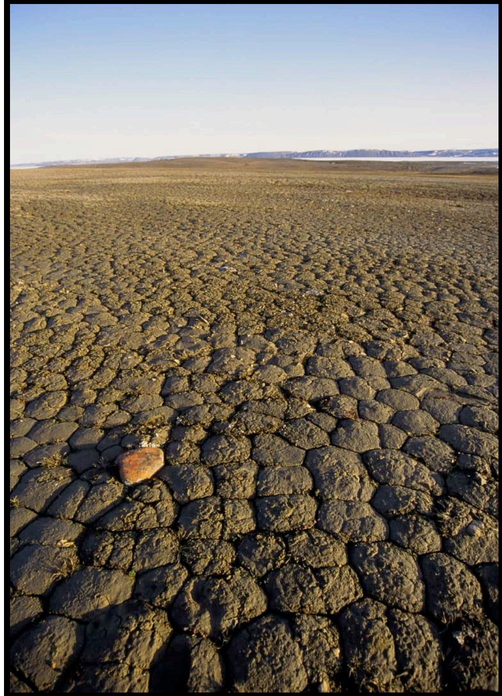
Biocomplexity of Arctic Patterned Ground:



Photos: Ina Timling and D.A. Walker

A tale of cracking, heaving, and smothering!

D.A. (Skip) Walker, Institute of Arctic Biology, UAF

Invited talk at the 2008 Dynamics of Complex Systems: Common Threads Workshop, Univ. of Alaska Fairbanks, 6 Aug 2008

Co-authors:

Ronnie Daanen[1], Howard Epstein[2], William Gould[3], Grizelle Gonzalez[3] Anja Kade[1], Alexia Kelley[2], William Krantz[4], Patrick Kuss[1], Gary Michaelson[5], Corinne Munger[1], Dmitri Nickolsky[1], Rorik Peterson[1], Chien-Lu Ping[5], Martha Raynolds[1], Vladimir Romanovsky[1], Charles Tarnocai[6], and Corinne Vonlanthen[1]

[1]IAB, University of Alaska Fairbanks, [2] Univ.Virginia, [3]USDA Inst. Trop. Forest., San Juan, PR, [4]Dept. Chem. Mater. Eng., Univ. Cincinnati, [5]UAF Ag. And Forestry Exp. Sta., Palmer, AK, [6]Ag. and Agri-Food Canada, Ottawa, CAN

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Arctic patterned ground

- Ubiquitous features of Arctic landscapes.
- Caused by the presence of permafrost.
- Numerous scales of patterns.

Photos: D.A. Walker

Central Questions

Howe Island, AK.
Photo; D.A. Walker

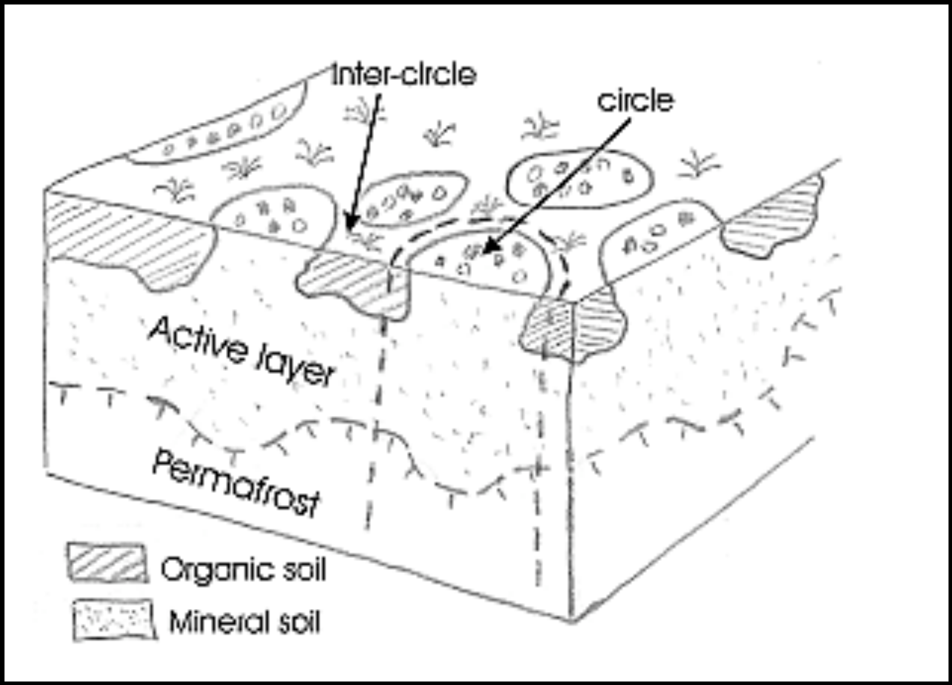
- How do biological and physical processes interact to form small patterned-ground ecosystems?
- How do these systems change across the Arctic climate gradient?

Why focus on small patterned-ground features?

- They are interesting.
- Self-organization processes not well understood.
- Important to biogeochemical cycling, and other ecosystem processes.
- Ideal system to study the effects of disturbance across the Arctic climate gradient.

Photo: D.A. Walker

The patterned ground system

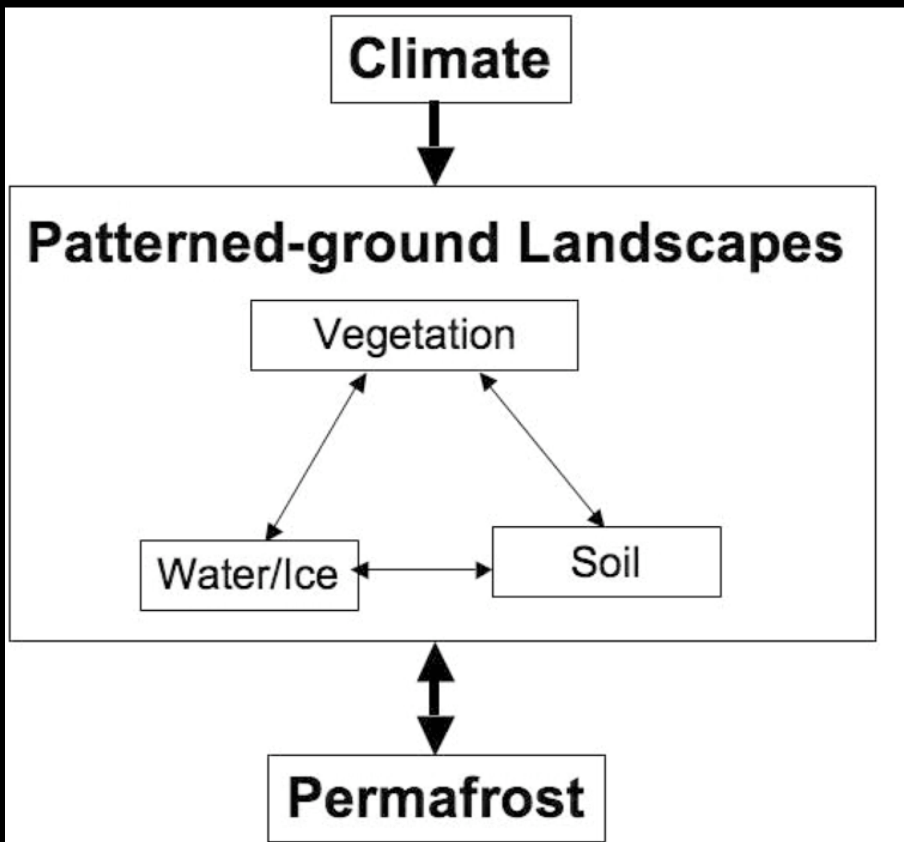


Nicolsky et al. 2008, *JGR-Biogeosciences*

Major elements of system:

- Patterned ground feature (e.g. Circle)
- Between-patterned ground feature (e.g. Inter-circle area)

The patterned ground system



Walker et al. 2008, *JGR-Biogeosciences*

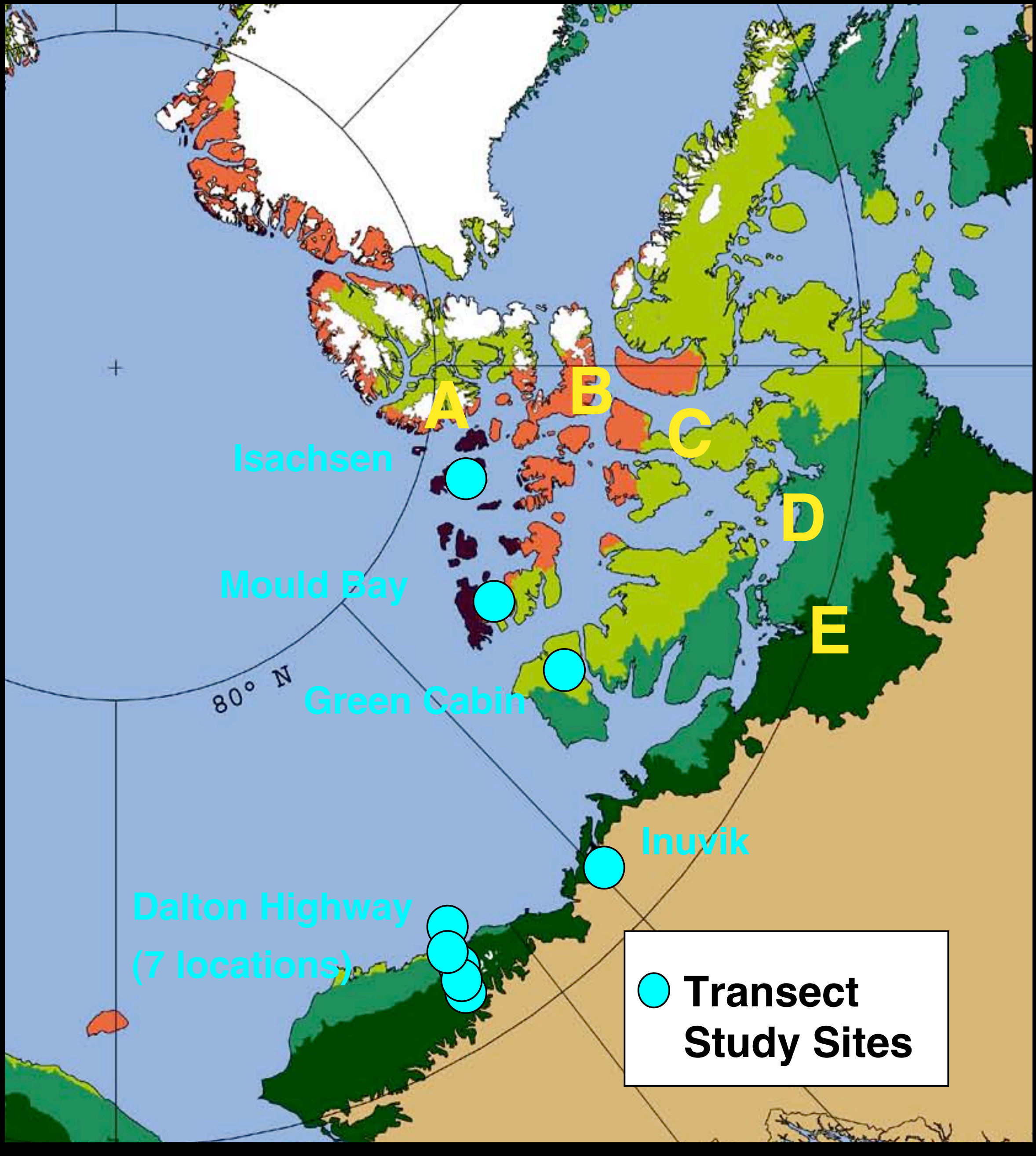
Major components of patterned ground system:
- Water/ice
- Soil
- Vegetation

- Acted upon by climate from above and permafrost from below.
- Two-way interaction with permafrost.

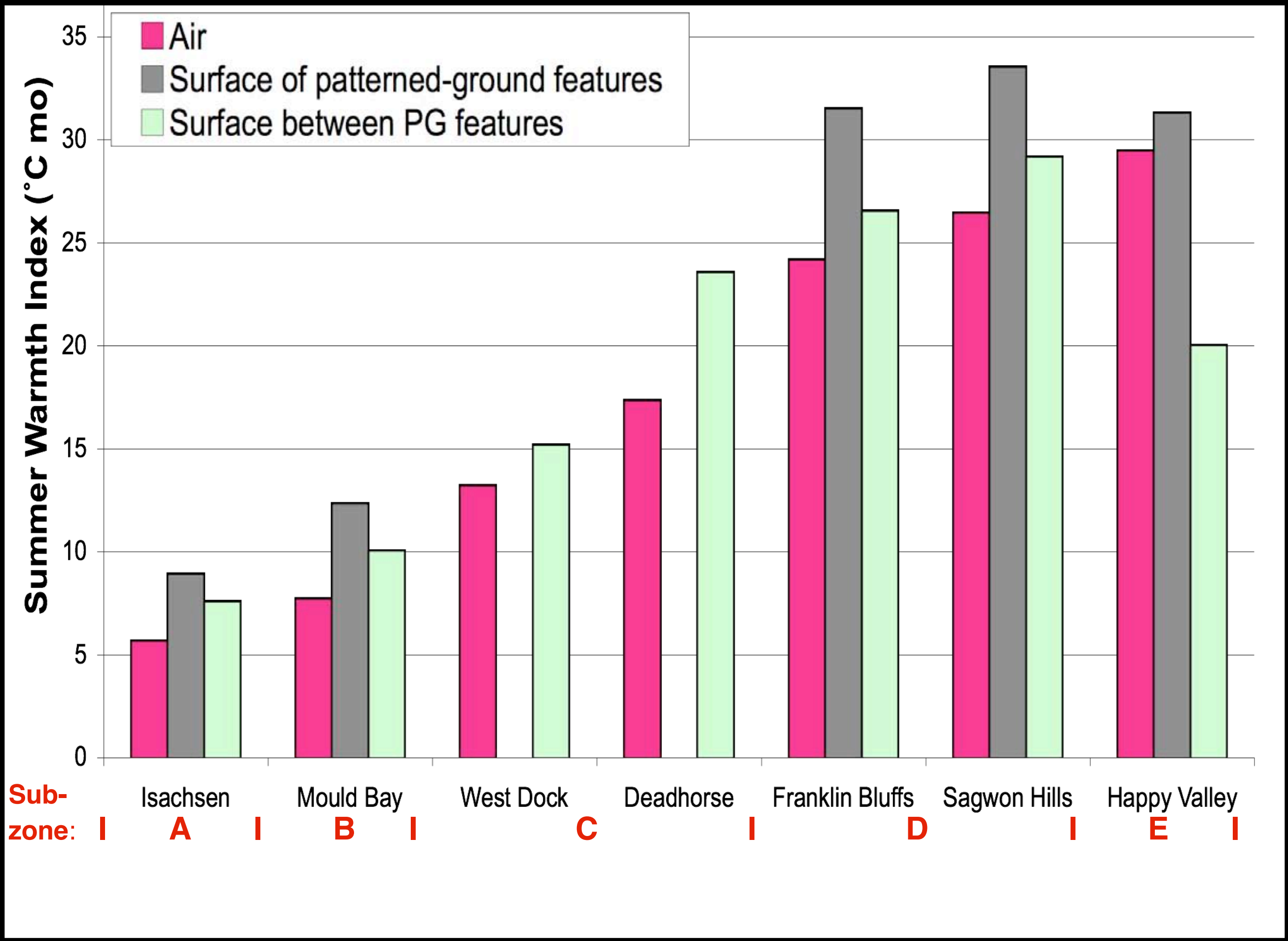
North American Arctic Transect

Arctic Bioclimate Subzones

Sub-zone	Mean July Temperature (°C)
A	<3
B	3-5
C	5-7
D	7-9
E	9-12
Forest	>12



Summer warmth index along the transect



Modiefed from Walker et al. 2008, *JGR-Biogeosciences*

- 5x increase in total summer warmth (red bars).
- Surface temperatures are generally warmer than air temperatures.
- Barren patterned ground features are warmer than the adjacent tundra.

North American Arctic Transect

Measurements

- 21 Grids and maps
  - Active layer
  - Vegetation
  - Snow
- Climate /permafrost
  - Met station
  - Soil temperatures
  - Frost heave
- Soils
  - Characterization
  - Nitrogen mineralization
  - Decomposition
- Remote sensing
  - NDVI
  - Biomass

Photo: D.A. Walker

Processes: Cracking

Isachsen,

Mould Bay

Howe Island

Photos: D.A. Walker

- Small non-sorted polygons (Washburn 1980).
- Desiccation cracking or seasonal frost cracking (Washburn 1980).
- Very important in the High Arctic, but not studied in detail nor modeled in this study.

Processes: Heaving

Earth mounds, Mould Bay, Nunavut.

Non-sorted circles, Howe Island, AK,

Earth mound, Inuvik, NWT

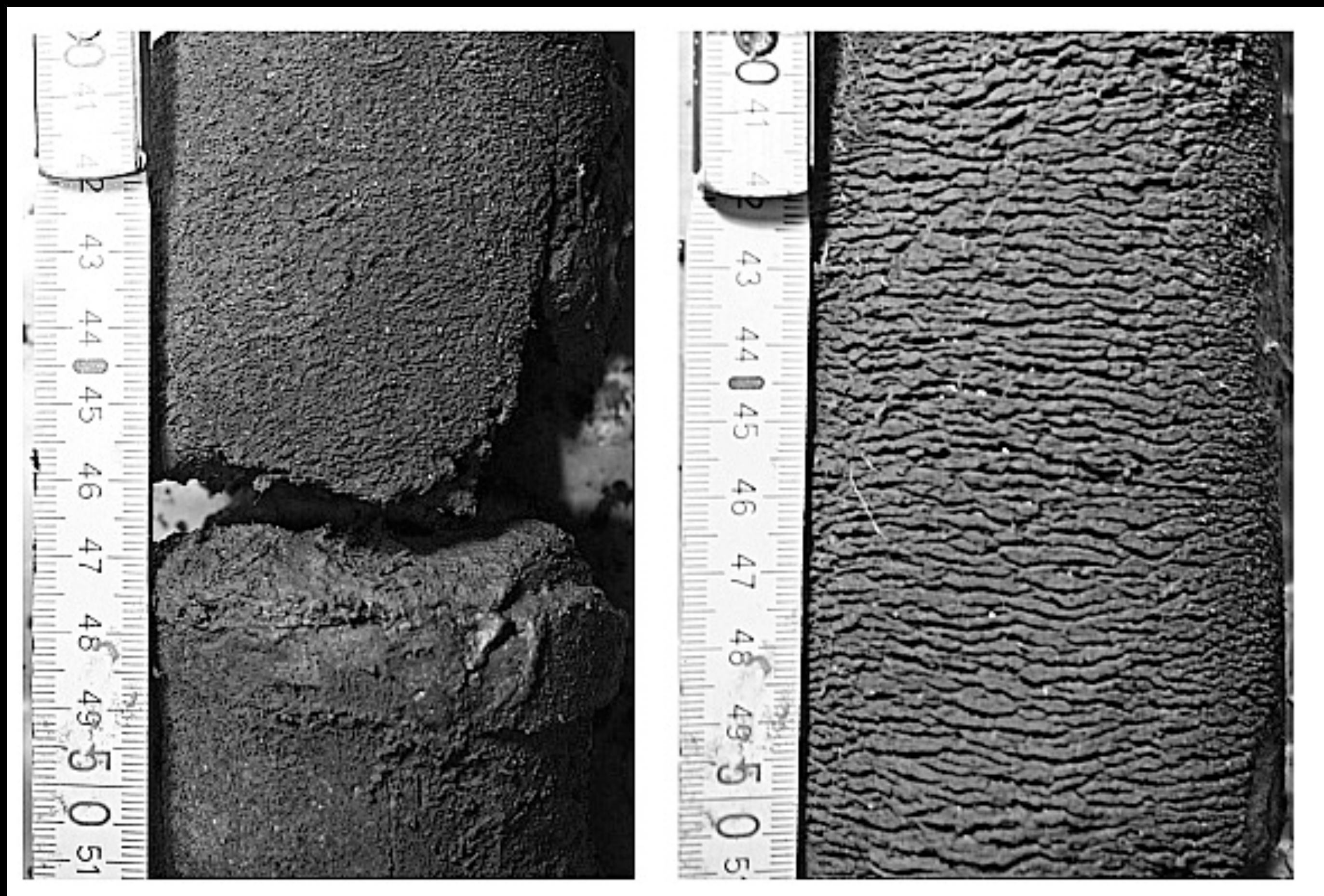
- Non-sorted circles and earth mounds
- Caused by differential frost heave.
- Most common in the Mid- and Low Arctic (subzones C and D).
- Major focus of this study, several models.

Photos: D.A. Walker

Ice Lenses: the cause of frost heave

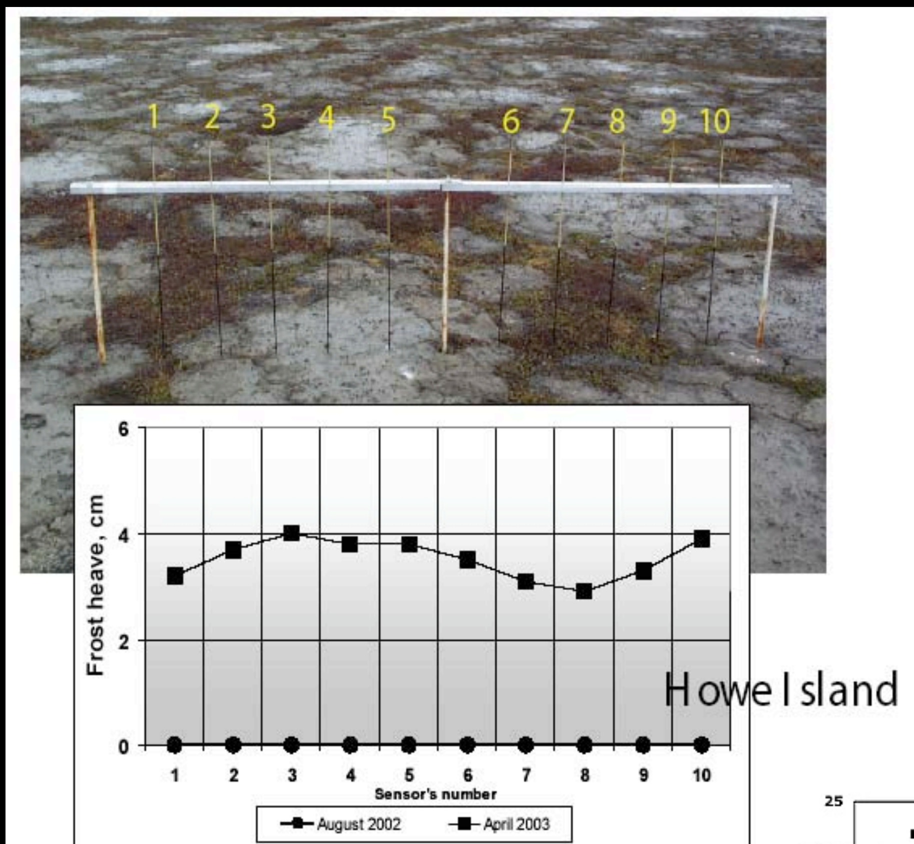
Dry soil: no lenses

Wet soil: many lenses



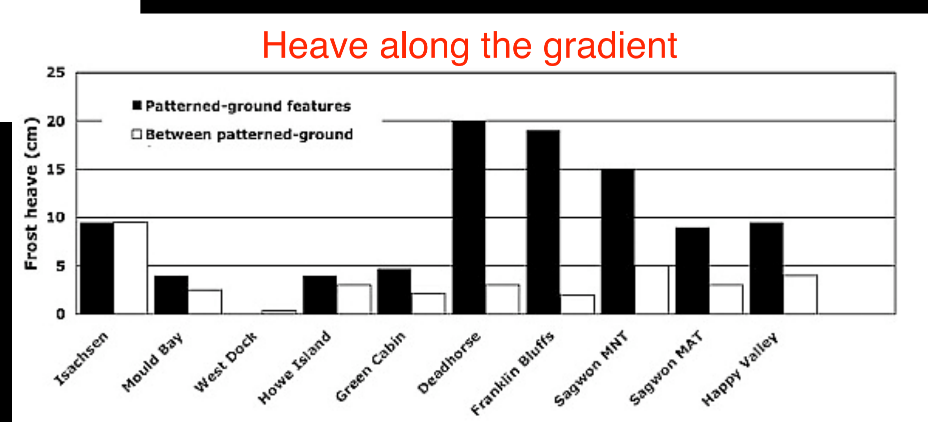
Nicolsky et al. 2008. *JGR - Biogeosciences*

Heave along the bioclimate gradient



- Greatest heave is in the centers of patterned ground features,
- in the central part of the climate gradient,
- and on silt soils (loess).

Romanovsky et al. 2008, *NICOP Proceedings*

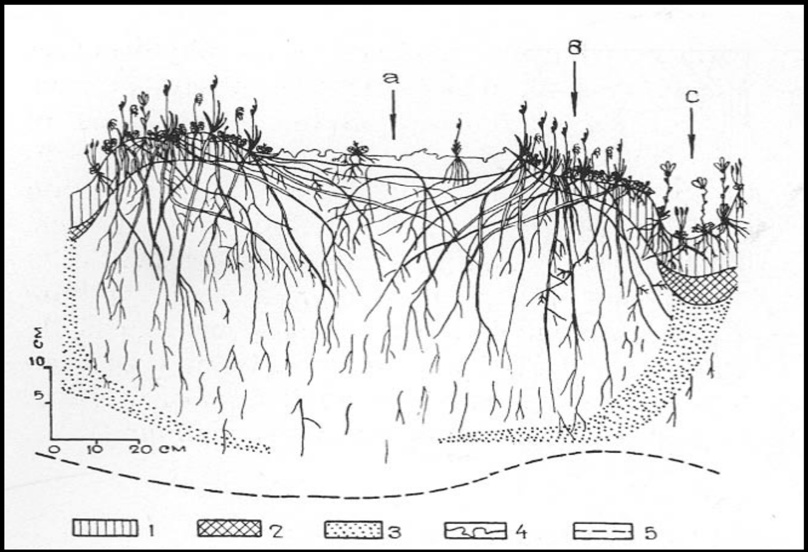


Processes: Vegetation succession

Vegetation and organic soils:

- Insulate the surface.
- Stabilize the soil.
- Mask cracking and heaving.

The effects increase toward the south.

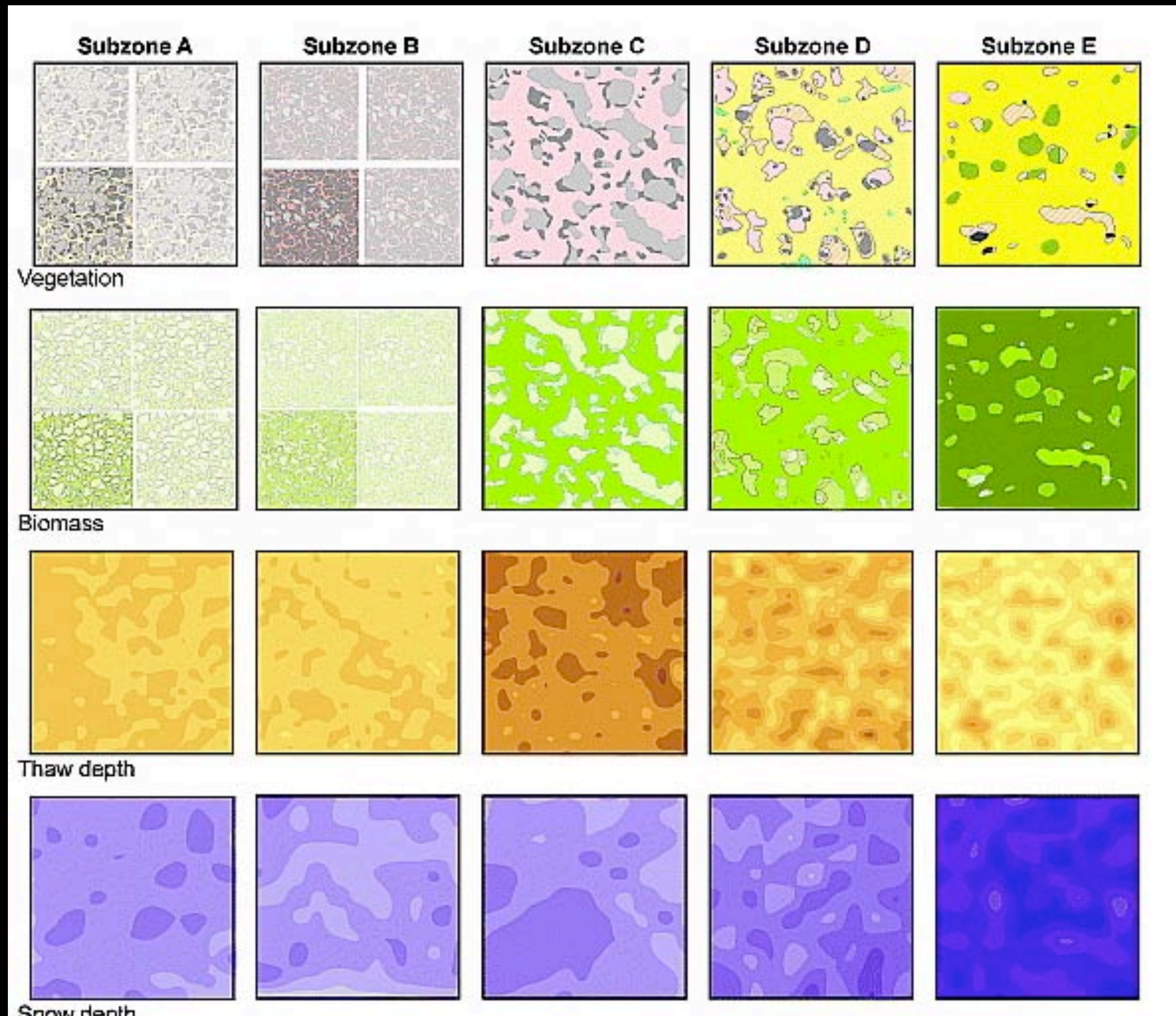


Drawing: Nadya Matveyeva. Photo: D.A. Walker

Maps of vegetation, active layer and snow

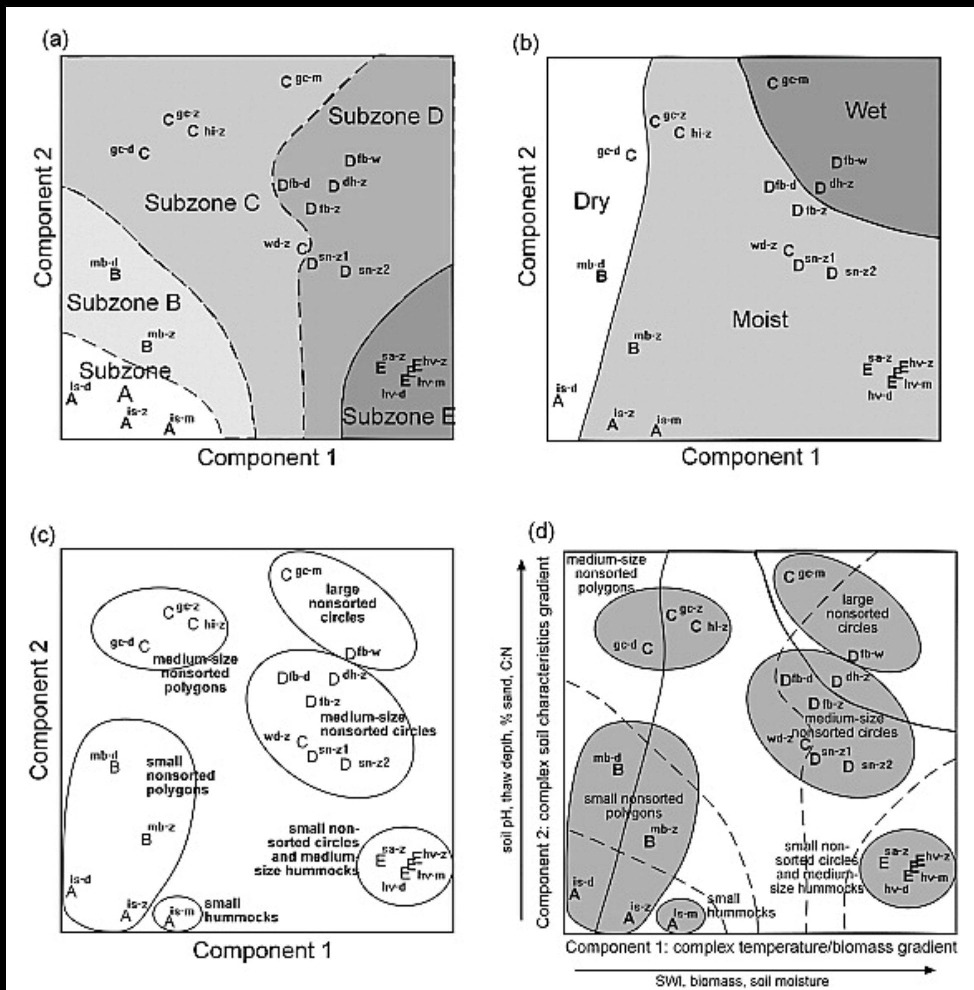
Zonal sites in all 5 subzones

- Vegetation
- Biomass
- Active layer
- Snow depth



Raynolds et al. 2008, *JGR – Biogeosciences*

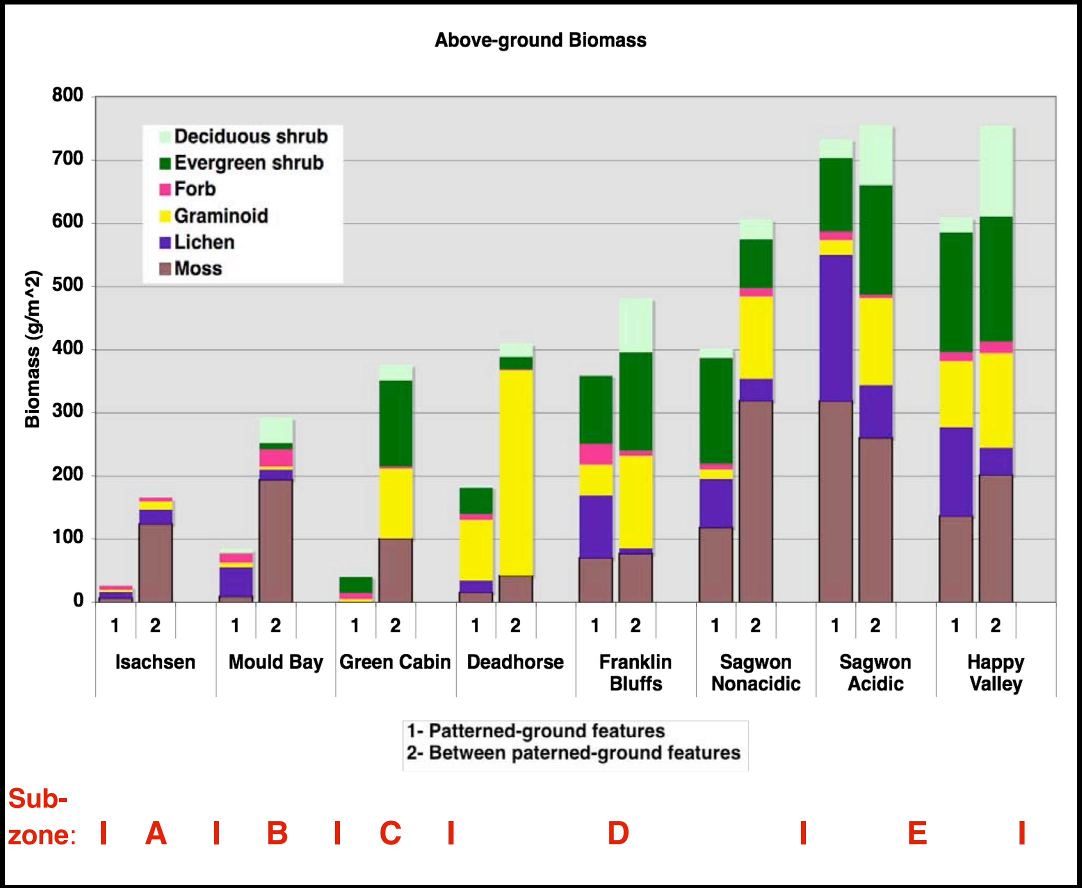
Principal components analysis of controlling environmental variables



Raynolds et al. 2008, *JGR – Biogeosciences*

- First component: Complex air temperature/biomass, gradient
- Second component: Complex soil characteristic gradient (texture, pH, soil carbon, active layer depth)

Biomass responds dramatically to warmer temperatures.

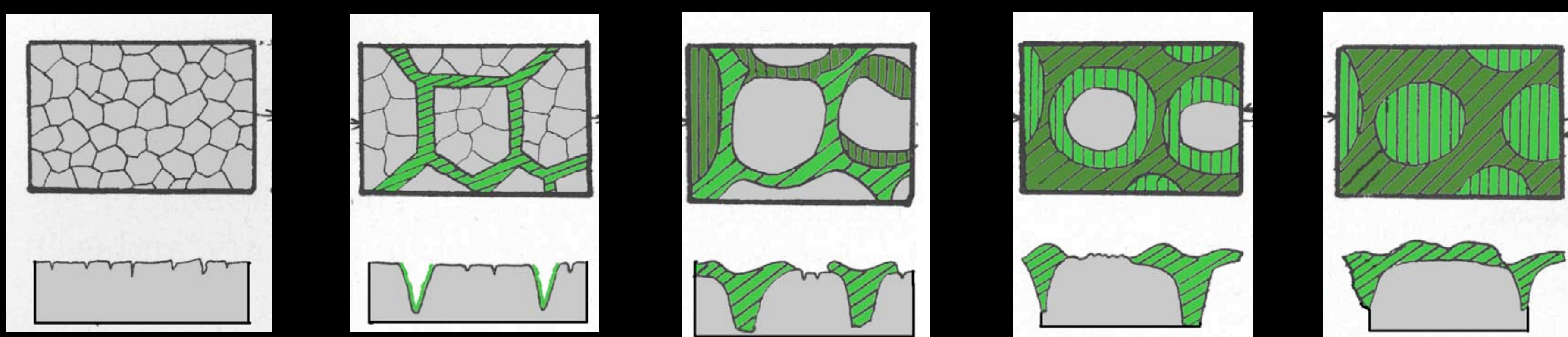


Walker et al. 2008, *JGR-Biogeosciences*

- 5-fold increase on zonal sites (between patterned ground features).
- 30-fold increase on patterned-ground features.
- Shift in dominant growth forms with temperature on zonal sites.
- Different suite of plant growth forms on the features vs. between features.

Conceptual model of patterned-ground trends along the Arctic bioclimate gradient

Sub-zone: A B C D E

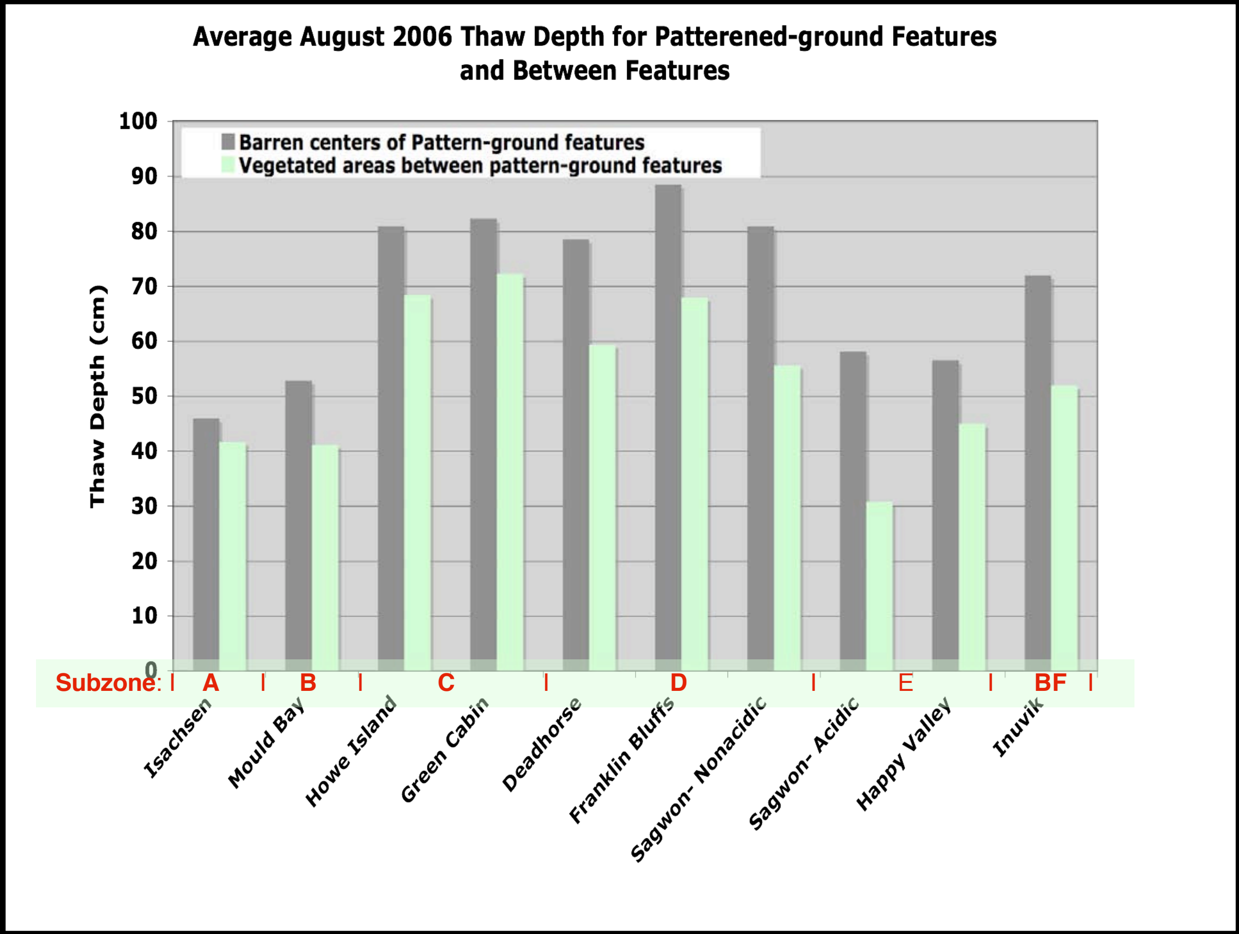


Cracking ***Heaving*** ***Smothering***

Drawings modified from Chernov and Matveyeva 1997

Thaw depths along the bioclimate gradient: Plant cover strongly affects the thaw layer.

- Thaw is deepest in the middle part of the climate gradient (subzones C and D).
- End of Aug thaw is about 10-20 cm deeper on barren patterned ground features than in the adjacent tundra areas.
- Contrast much greater at the beginning of the thaw season (not shown).



Walker et al. 2008, *JGR-Biogeosciences*

Vegetation removal and transplant experiment

Control

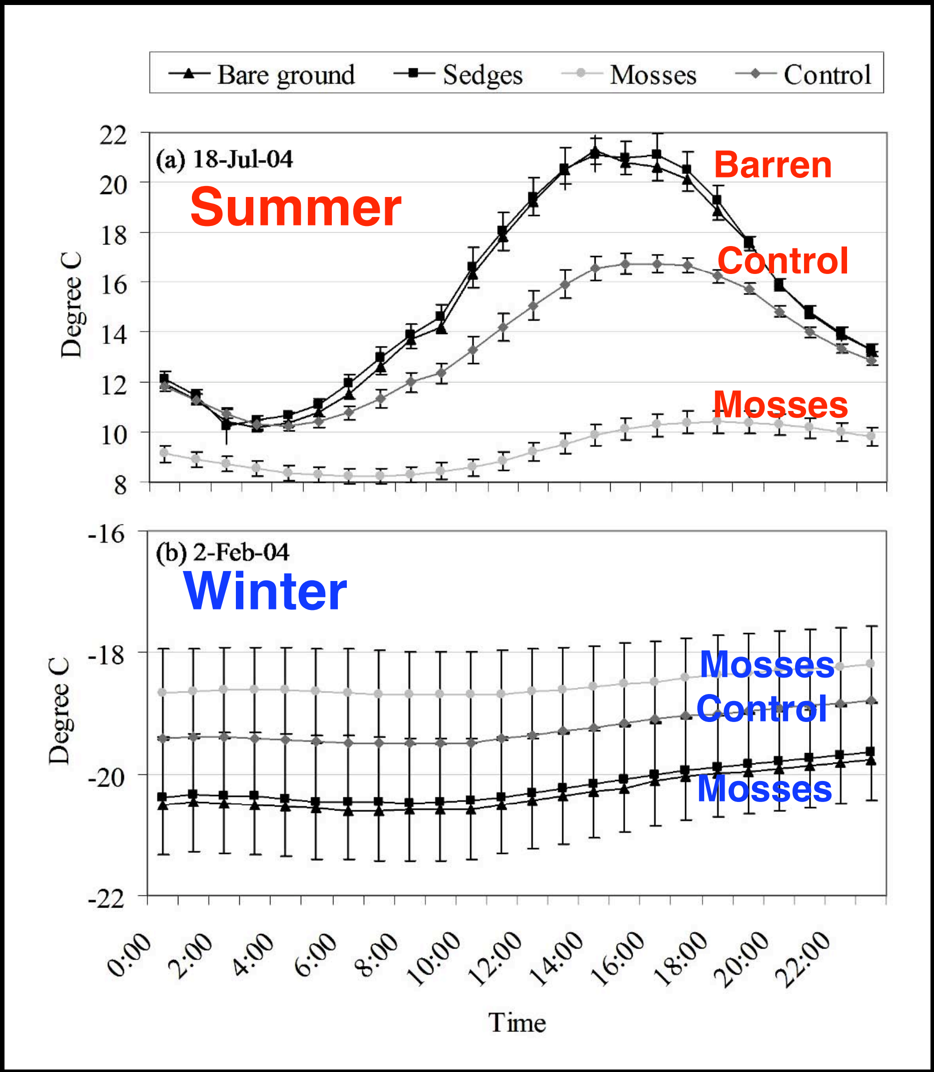
Vegetation removal (barren)

Transplant sedges

Transplant moss carpet

Kade and Walker, 2008, *Arctic, Alpine and Antarctic Research*

Effects of vegetation on summer and winter soil surface temperatures.



Mean Summer Temperature:

Vegetation removal: +1.5˚C (+22%)

Moss addition: -2.8 ˚C (-42%)

Mean Winter Temperature:

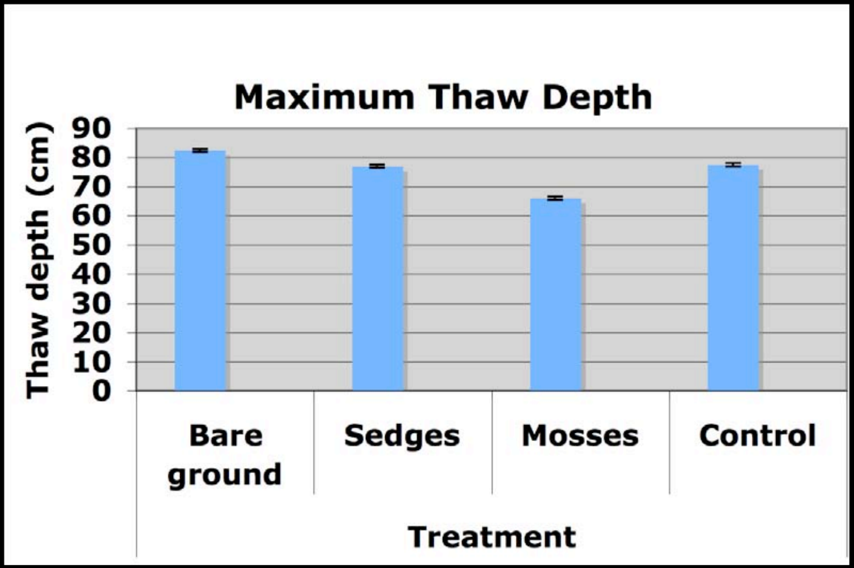
Vegetation removal: -0.9˚C (-6%)

Moss addition: +1.3˚C (+7%)

- The sedge treatment had a similar response as the barren treatment.

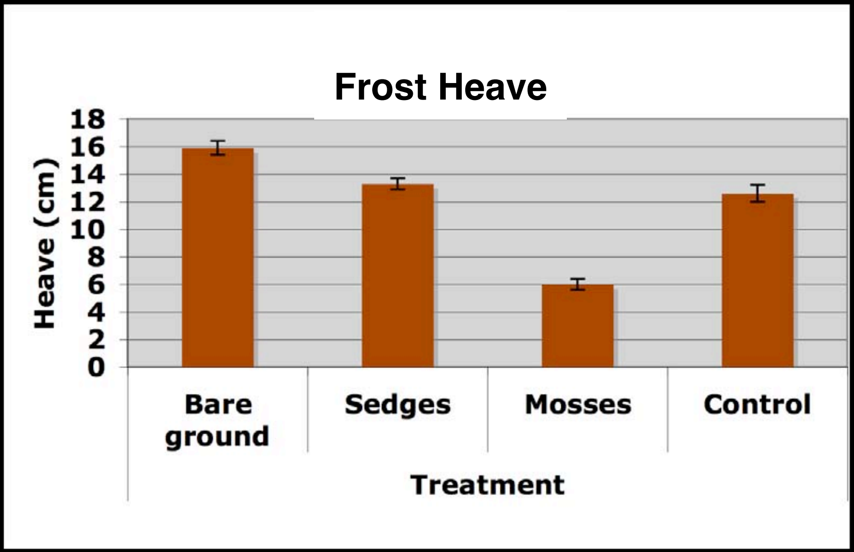
Kade and Walker, 2008, *Arctic, Alpine and Antarctic Research*

Effects of vegetation on thaw depth and heave



Thaw:

Vegetation removal: +5 cm (+6%)
Moss addition: -11 cm (-14%)

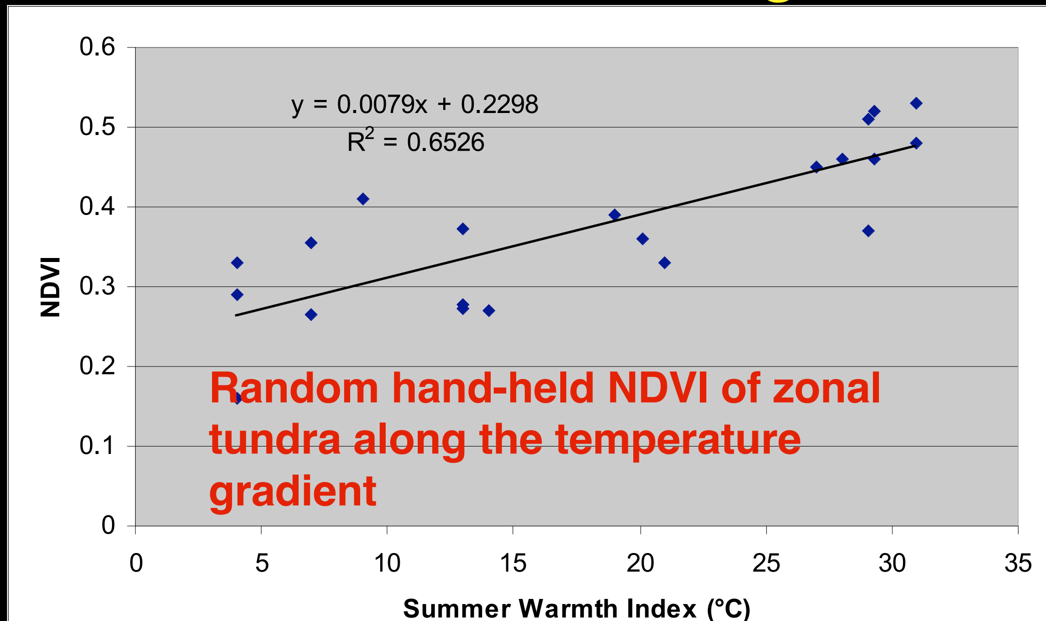


Heave:

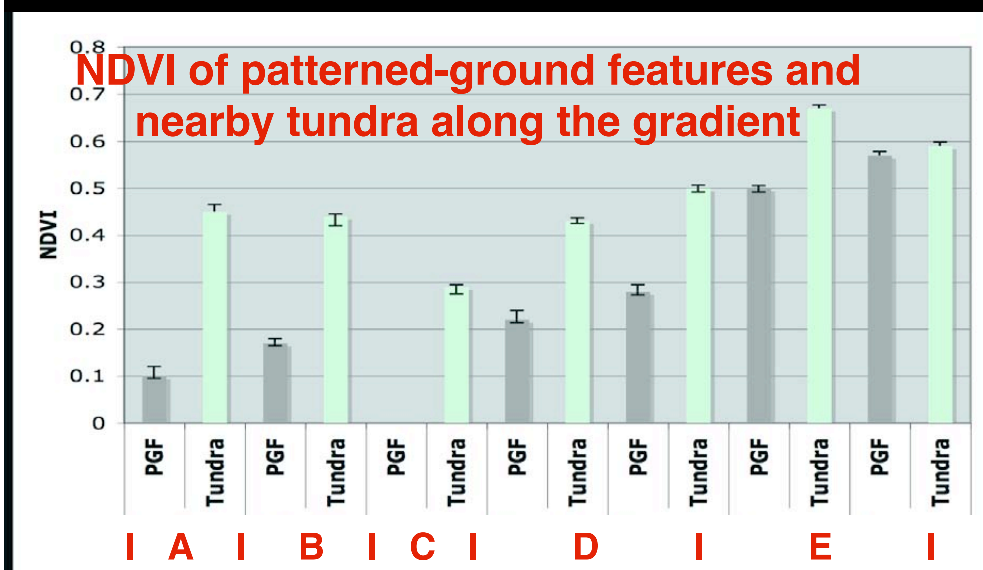
Vegetation removal: +3 cm (+24%)
Moss addition: -5 cm (-40%)

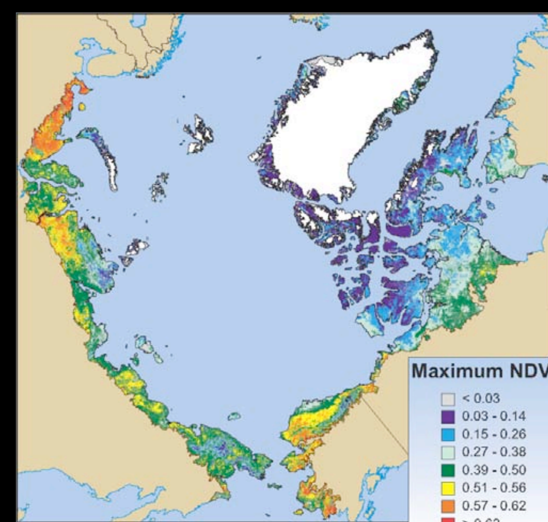
Kade and Walker, 2008, *Arctic, Alpine and Antarctic Research*

Ecosystem effects: Biomass affects greenness (NDVI) along the bioclimate gradient.



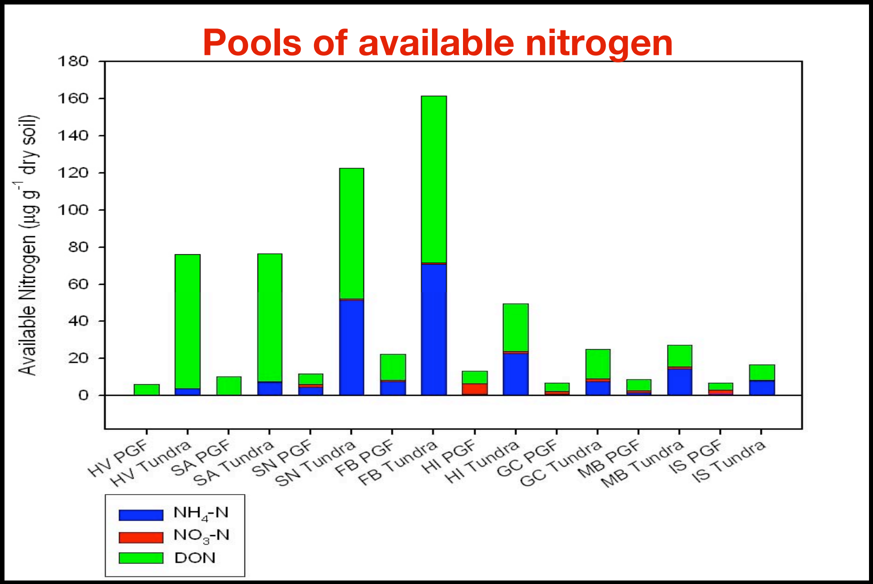
- 2-fold increase of the NDVI on zonal surfaces.
- NDVI of patterned-ground features increase more rapidly than that of the adjacent tundra areas.
- Important for many system processes such as fluxes of CO_2, H_2O, and heat.

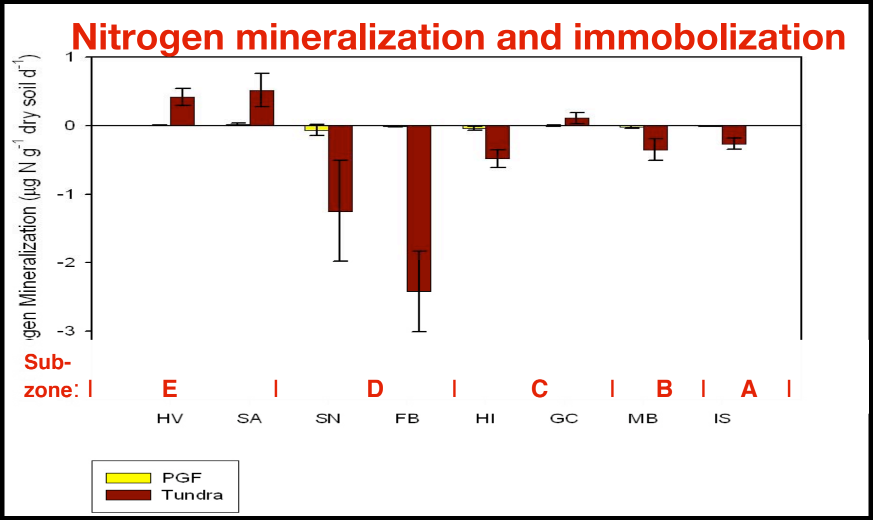




Modified from Epstein et al. 2008, JGR-Biogeosciences

Ecosytem consequences: Effects on soil nitrogen

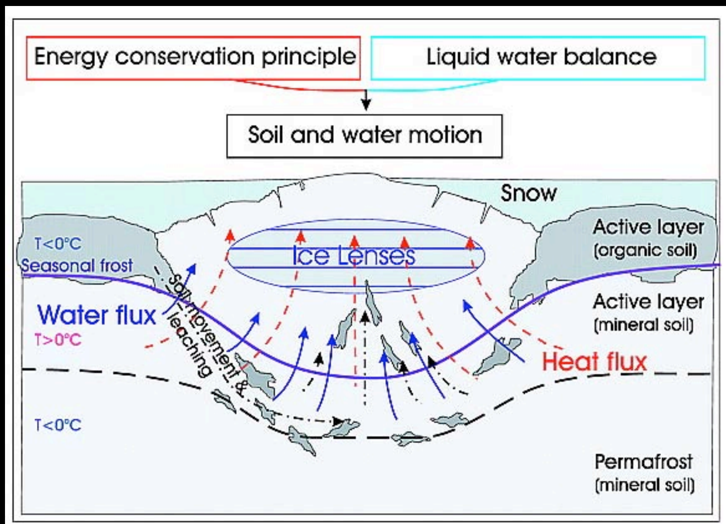




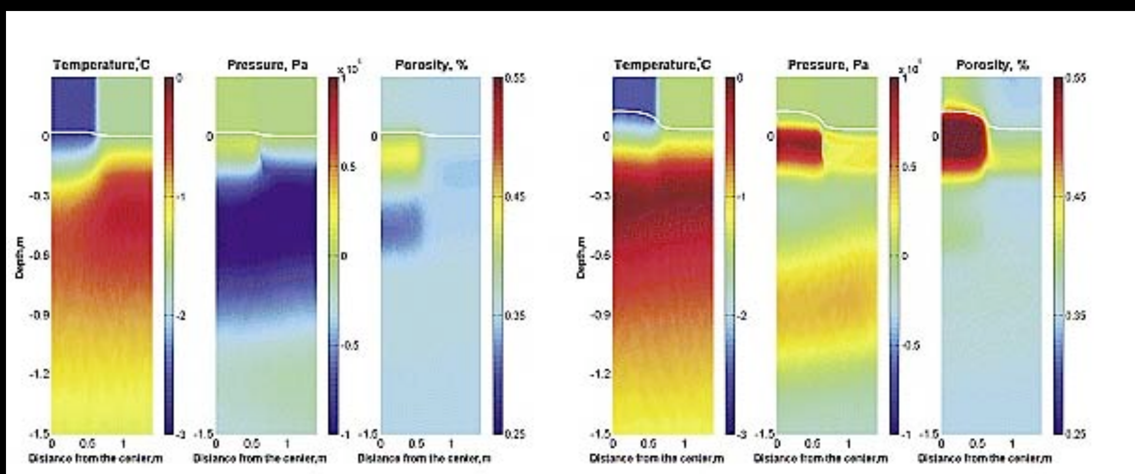
Courtesy of Alexia Kelley, in prep.

- Strong differences in nutrient pools between patterned ground features (short bars) and the surrounding tundra (long bars).
- Nutrient pools and N-immobilization are greatest in subzone D, the region with the warmest soil temperatures.
- Major implication for landscape-scale productivity and biodiversity patterns.

Modeling approaches (1): Thermo-mechanical model of frost-heave and vegetation interactions

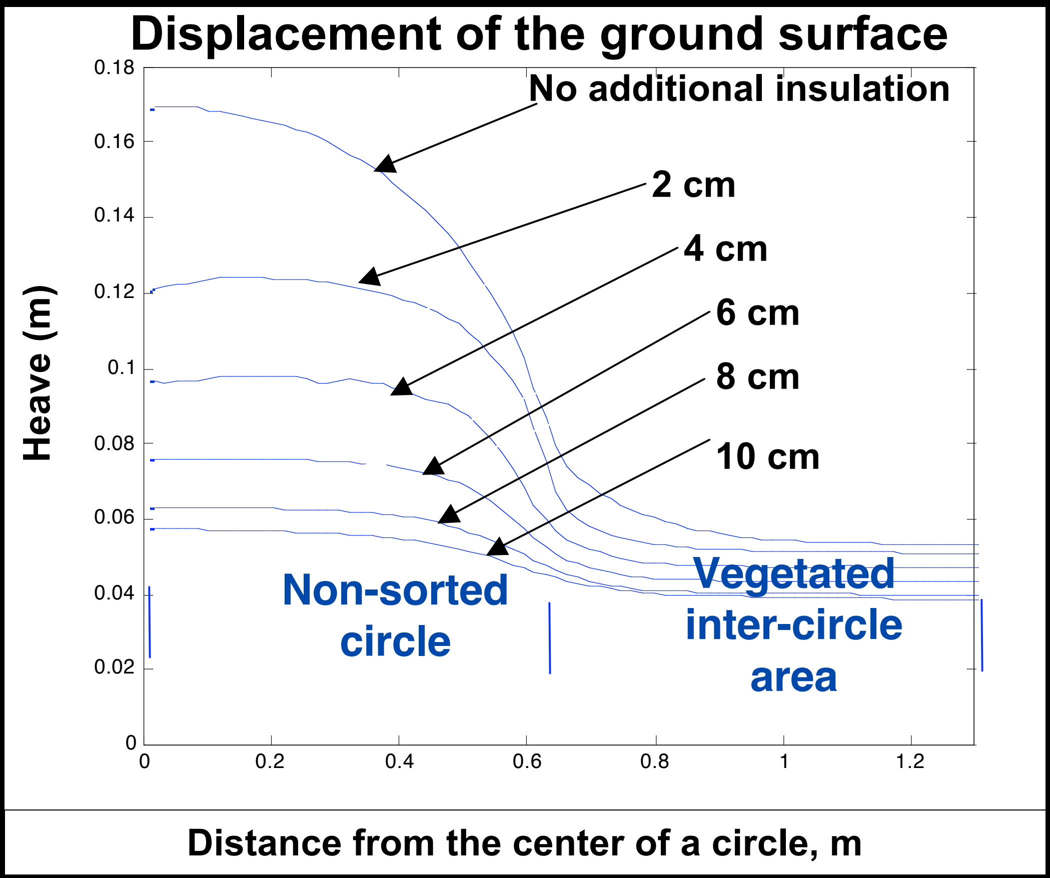


- *Differences in heat flux drive the movement of water necessary for differential heave.*
- **This creates vertical and horizontal gradients of temperature, pressure and porosity within the system.**



Nicolsky et al. 2008, *JGR—Biogeosciences*

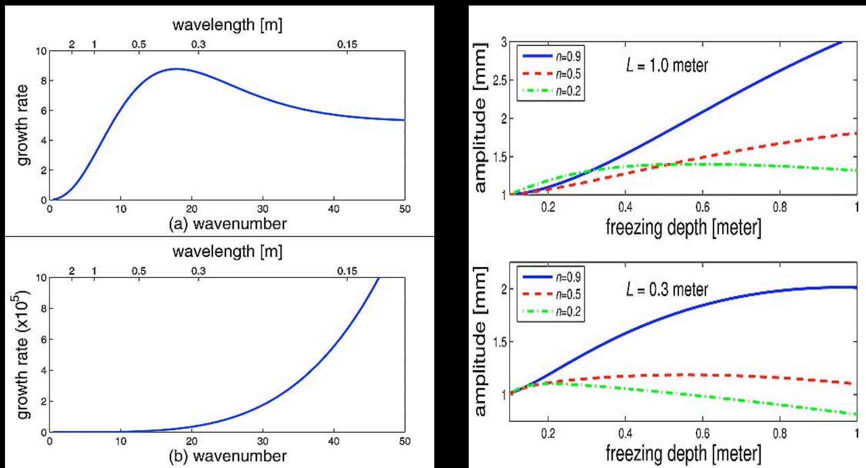
Modeling approaches (1): Thermo-mechanical model of frost-heave and vegetation interactions

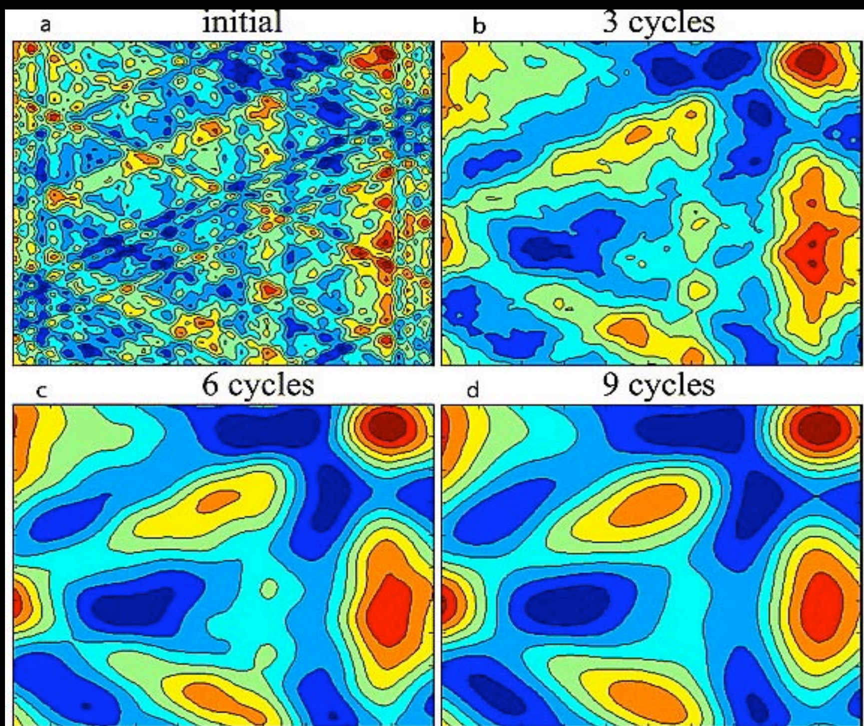


- Adding a thick vegetation mat, as occurs with vegetation succession, reduces frost heave and other cryogenic processes.
- Vegetation removal, as occurs with many types of disturbance, causes differential heave to increase.

Nicolsky et al. 2008, *JGR—Biogeosciences*

Modeling approaches (2): Differential frost heave model





Peterson and Krantz. 2008, *JGR—Biogeosciences*

Physically based model that explains initial self-organization of patterns non-sorted circles and other other heave forms <u>in the absence of vegetation</u>.

- One-dimensional frost heave can become unstable and evolve into multidimensional differential frost heave (DFH).
- Characteristic spacing of the patterns is a function of the soil thermal conditions during freezeup, and soil properties.
- Differential temperatures due to insulation from vegetation can create feedback that intensify the pattern.

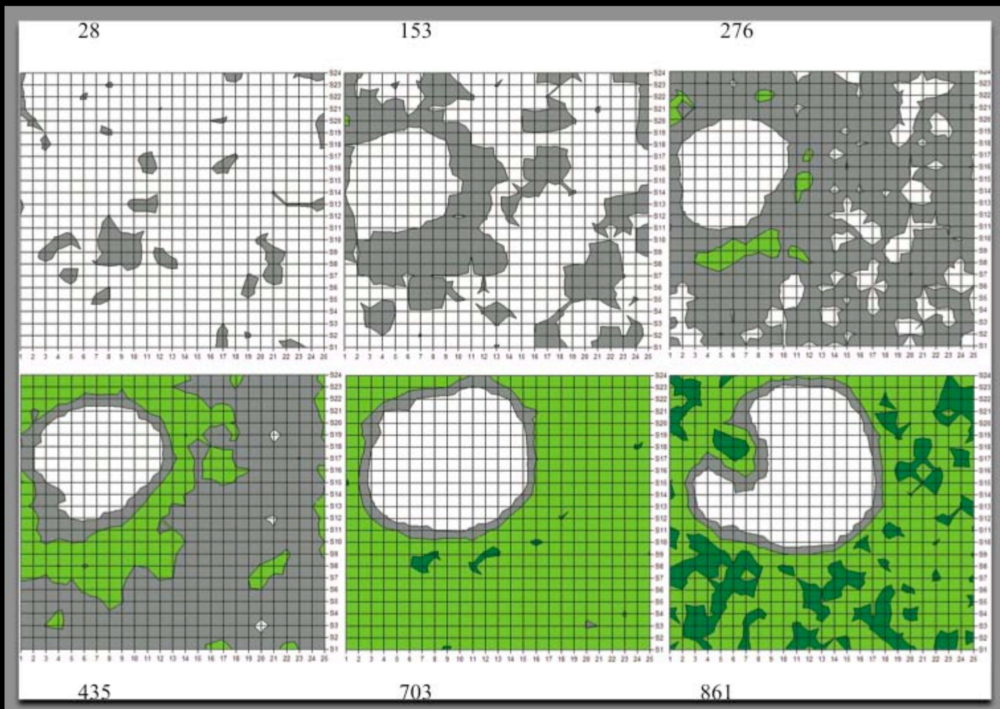
Modeling approaches (2): Differential frost heave model

Photo by Anja Kade

- Predicted pattern is hexagonal packing.
- Spacing is a function of the soil thermal conditions during freezeup, and soil properties.
- Aerial photo shows:
  - Small nonsorted polygons (gray areas, 20-50-cm diameter, due to cracking).
  - Nonsorted circles (white areas, 1-2 m diameter, due to frost heave).

Peterson and Krantz, 2008, *JGR—Biogeosciences*

Modeling approaches (3): Hydrology Vegetation Interactions Model (WIT/ArcVeg) Model



Daanen et al. 2008, *JGR—Biogeosciences*

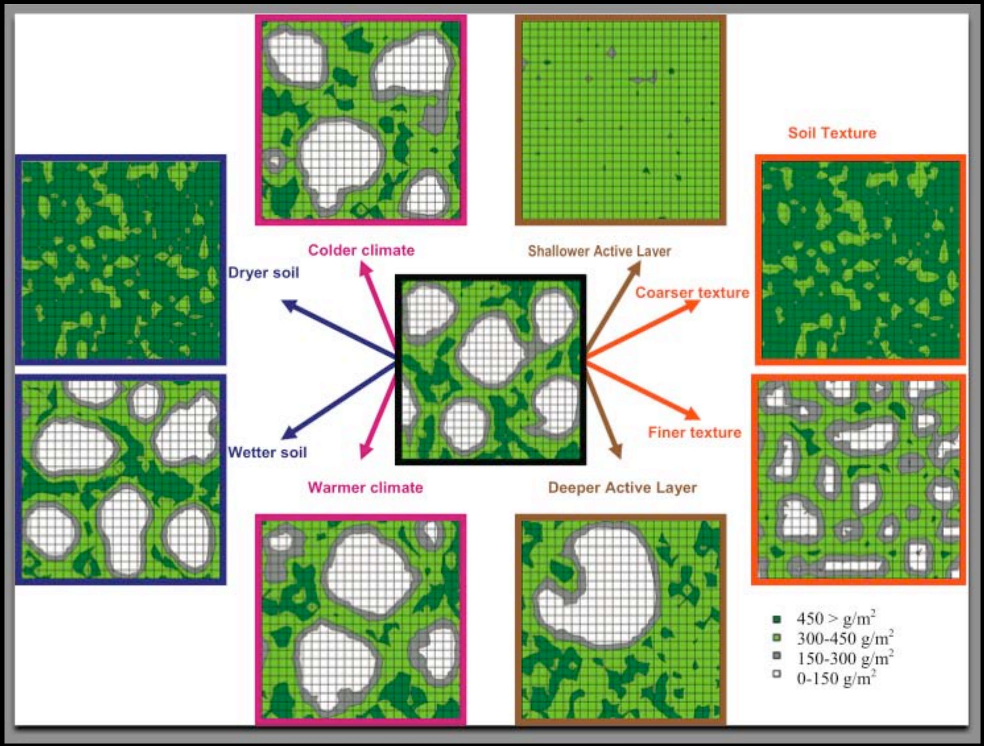
Coupled model:

ArcVeg: Vegetation dynamics

WIT: Heat and moisture transport with phase change (water - ice)

- Starts with random vegetation in 10-cm cells, providing heterogeneous insulation to the surface.
- With lack of disturbance vegetaton succession proceeds to regional zonal biomass.
- Ice preferentially accumulates in barren areas, which creates a feedback that keeps these areas free of vegetation due to frost heave disturbance.
- Pattern matured after 861 years in this run.

Modeling approaches (3): Sensitivity analyses with different soil moisture, climate, thaw-layer thicknesses and texture



Daanen et al. 2008, *JGR—Biogeosciences*

Soil moisture: Wet soils: larger circles, lots of heave.

Climate: Little effect.

Thaw layer depth: Shallow active layers prohibit the formation of circles.

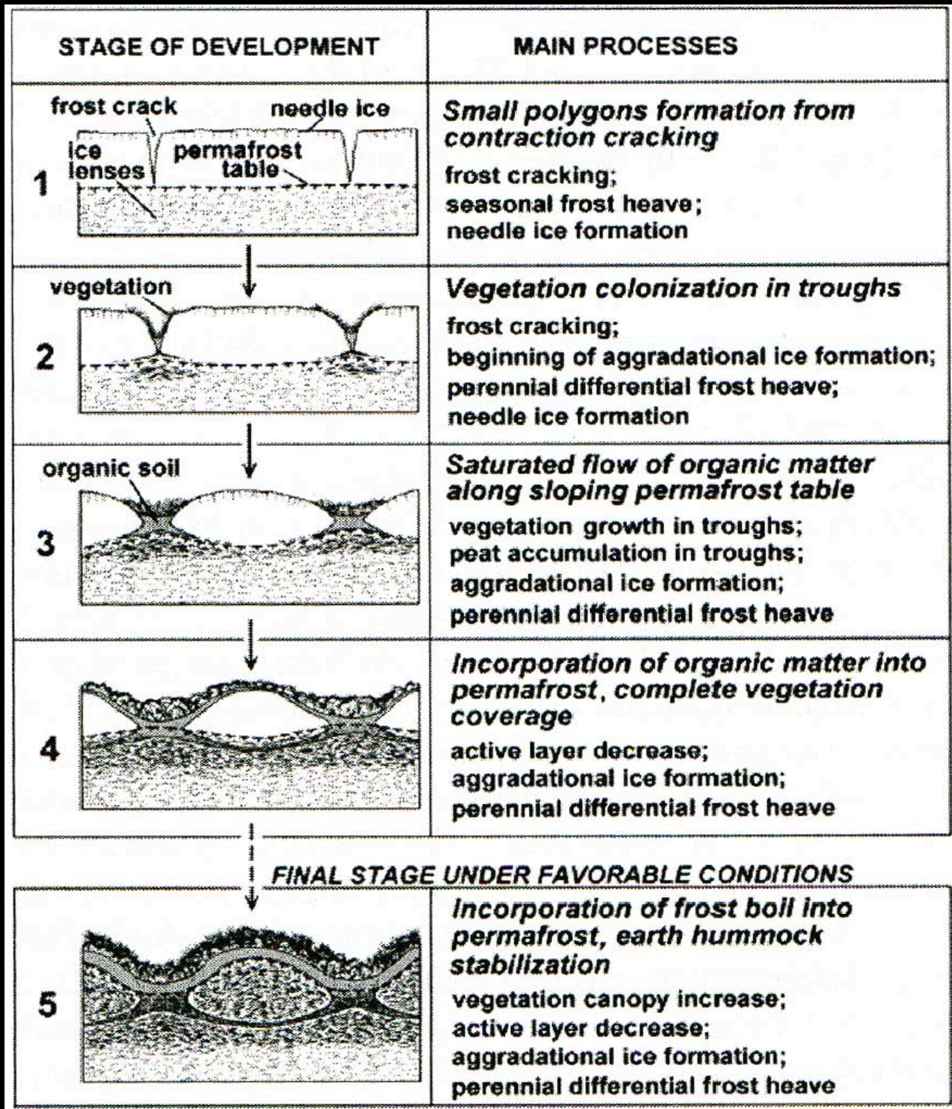
Soil texture: Determines the freezing characteristics curve and the hydraulic conductivity.

Sandy: No nonsorted circles

Clayey: Many small circles.

Silty: Largest patterns.

Modeling approaches (4): Shur permafrost model



Shur et al. 2008, *NICOP Proceedings*

Conceptual model. Thermal cracking initiates the pattern, which creates microenvironments for plant colonization that changes the thermal regime of the soil and causes differential frost heave, and an aggrading permafrost table.

- Causes major changes in the structure of the upper layer of the permafrost, including formation of very-ice-rich carbon-rich layer at the top of the permafrost.

Excavation of earth hummock

After removal of thaw layer:

- Bowl shaped depression in permafrost table.
- Deepest thaw in center of feature with thinnest soil-organic layer.

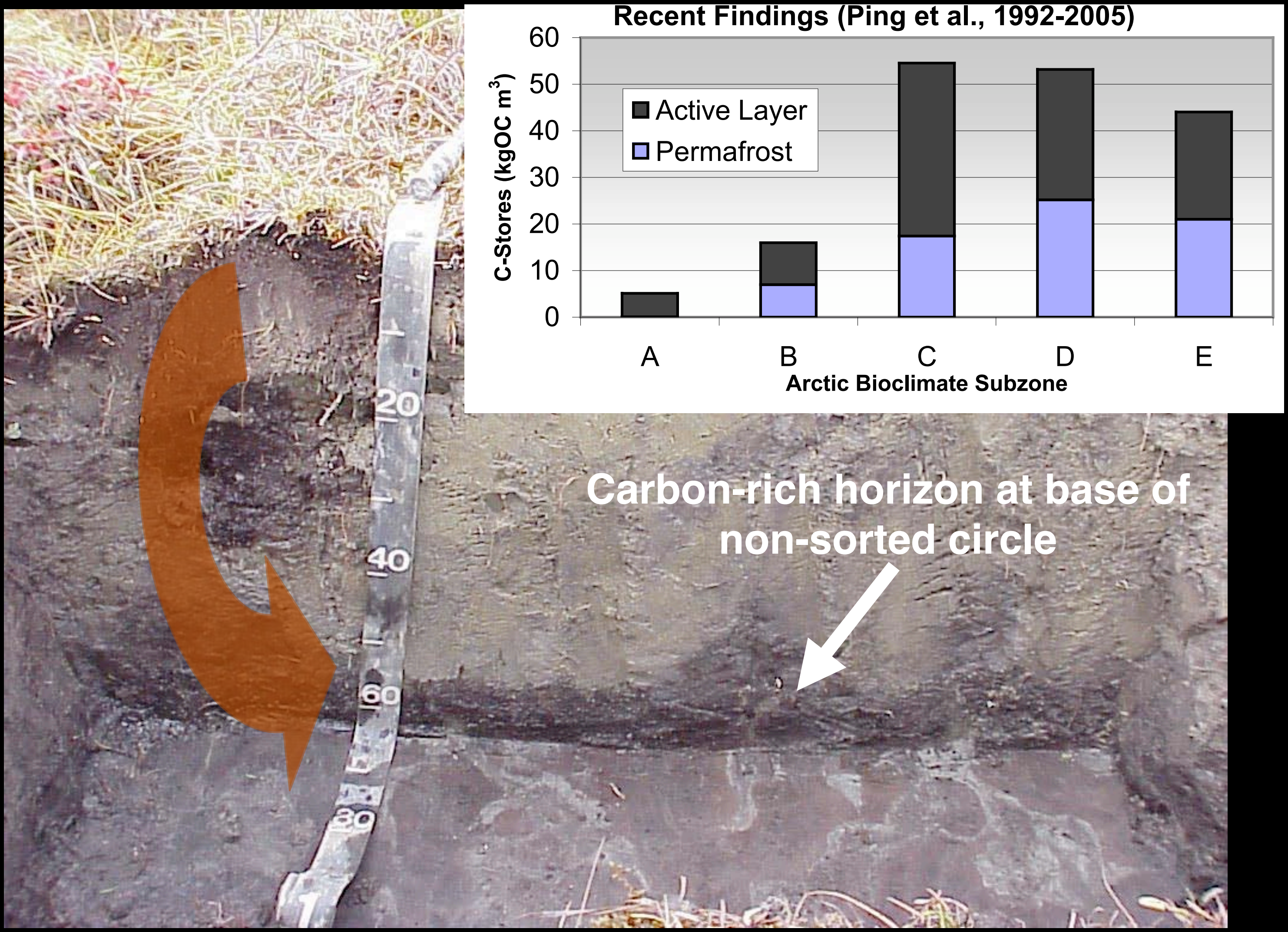
After removal of all soil to 1 meter depth (including frozen soil):

- Organic-rich and ice-rich zone at top of permafrost table below the hummock is revealed.

Photos: D.A. Walker

Ecosystem consequences: Sequestered carbon at depth

- Movement of carbon from margin of circle to the base of circle via cryoturbation.
- 2x previous estimates of soil carbon in subzones D and E.

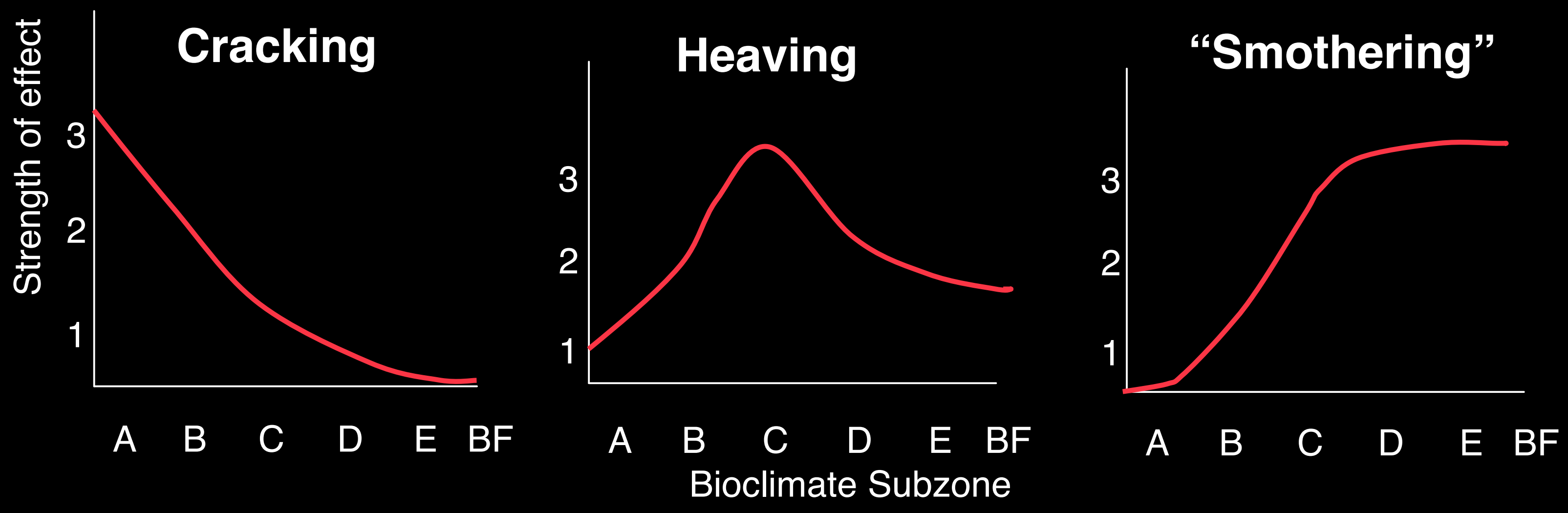


Ping et al. 2008 in press, *Nature-Geoscience*

Photo courtesy of Gary Michaelson.

Conclusions:

1. Cracking, differential heave and vegetation succession all interact to affect pattern-ground morphology along the Arctic climate gradient. Each of these processes has its dominant effect in a different part of the climate gradient.



Conclusions

2. Our study and models focused on the combined effects of differential heave and vegetation succession. New models will be needed to incorporate cracking.
3. Strong thermal contrasts between the centers and margins of heave features drive the movement of water and the development of frost heave.
4. The presence of patterned ground affects most ecosystem processes at small spatial scales. How these small-scale processes scale up to large regions still needs to be described.
5. Experimental manipulation of small-patterned ground features, such as that of Anja Kade help elucidate the response of these features to disturbance.

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Introduction to special section

Arens, S. J. T., P. F. Sullivan, and J. M. Welker (2008), Nonlinear responses to nitrogen and strong interactions with nitrogen and phosphorus additions drastically alter the structure and function of a high arctic ecosystem, *J. Geophys. Res., 113,* G03S09, doi:10.1029/2007JG000508
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