Lesson 3:
Biocomplexity of small patterned-ground features

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Overview of talk

Introduction:

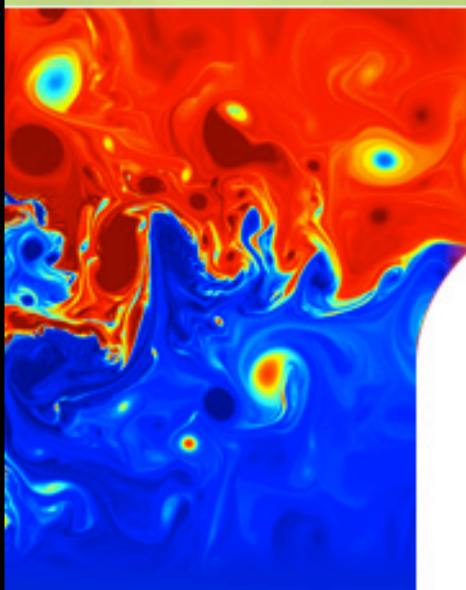
- What is biocomplexity?
- What are patterned-ground features?
- Why is this an important topic?
- Conceptual models of patterned ground formation.

Overview of results from project components:

- Climate and permafrost
- Soils and biogeochemistry
- Vegetation
- Modeling
- Education

NSF-Wide Investment

Biocomplexity in the Environment



The image above is from a numerical simulation of an idealized wind-driven ocean basin. Such computations allow a better understanding of the Earth's climate system.
Credit: Jeffrey B. Weiss, University of Colorado at Boulder

> More NSF-Wide Investments

Purpose
To understand complex environmental systems in which the dynamic behavior of living organisms is linked to the physical and chemical processes of the environment.

Background
The world faces significant scientific and societal challenges, including the prospect of rapid environmental and climatic change, and the complicated question of long-term environmental security. The integrity of ecosystems is inextricably linked to human well-being. Fundamental study of complex environmental systems is critical to developing new ways to anticipate environmental conditions and improve environmental decision-making.

Potential Impact

- A better understanding of natural processes, human behaviors and decisions in the natural world, and ways to use new technology effectively for environmental sustainability
- Improved forecasting capabilities
- Enhanced understanding of environmental decision-making
- Novel sensor systems and instrumentation
- A more comprehensive understanding of the ecology of infectious diseases
- Improved environmental education

Goal of the Biocomplexity of Patterned-Ground Project

To better understand the complex linkages between frost heave, frost cracking, 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


Why focus on small patterned-ground ecosystems?

BECAUSE:

- **The processes involved in the formation of patterned-ground landscapes are not well understood.**
- **The importance of patterned ground with respect to biogeochemical cycling, carbon sequestration and other ecosystem processes is poorly known.**
- **They are an ideal natural system to to help predict the consequences of climate change of disturbed and undisturbed tundra across the full Arctic climate gradient.**

Frost-heave Complexity Questions

Self organization

- How do frost-heave features self-organize themselves?
- How is vegetation involved in this process?

Complex adaptive systems

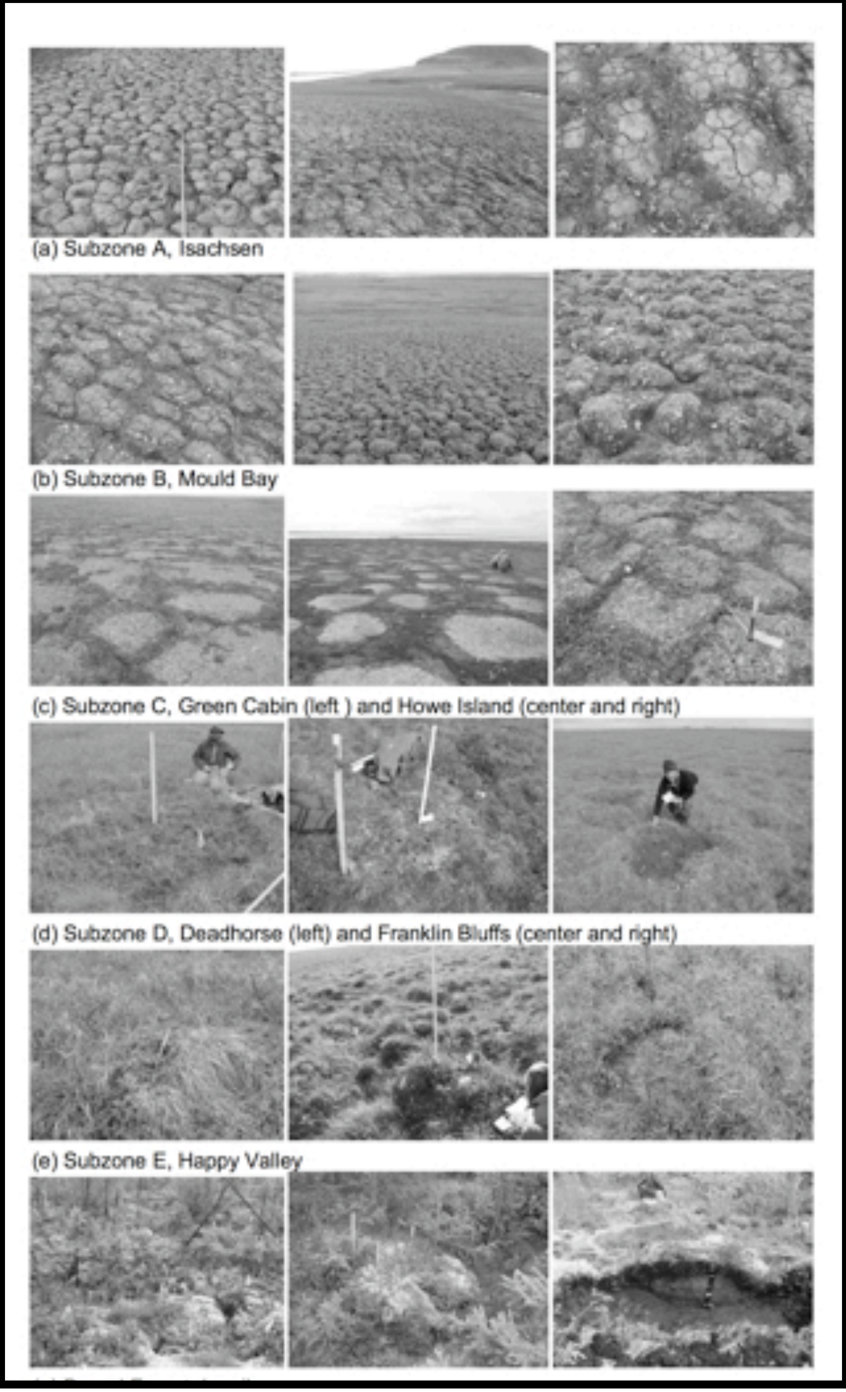
- How do frost-heave and associated ecosystems change along the arctic climate gradient?
- How does the vegetation affect the microclimate, ground ice, disturbance, and soils of frost-heave features along the Arctic climate gradient?

Scaling issues

- What are the emergent properties of frost-heave systems at different scales?
- How do frost-heave features affect trace gas fluxes, hydrological systems, and patterns of wildlife at large spatial scales?

Variety of frost-boil and earth hummock forms along the Arctic climate gradient

- **Subzone A and B: Mainly small polygons with vegetation concentrated in the cracks.**
- **Subzone C: Larger polygons, and frost-boils (nonsorted circles) with vegetation in the cracks and margins of circles and mostly barren frost boils.**
- **Subzone D: Partially vegetated circles with well-vegetated inter-circle areas with thick moss mats.**
- **Subzone E: Mainly small circles and earth hummocks thickly covered in vegetation.**



Some forms caused by differential frost heave

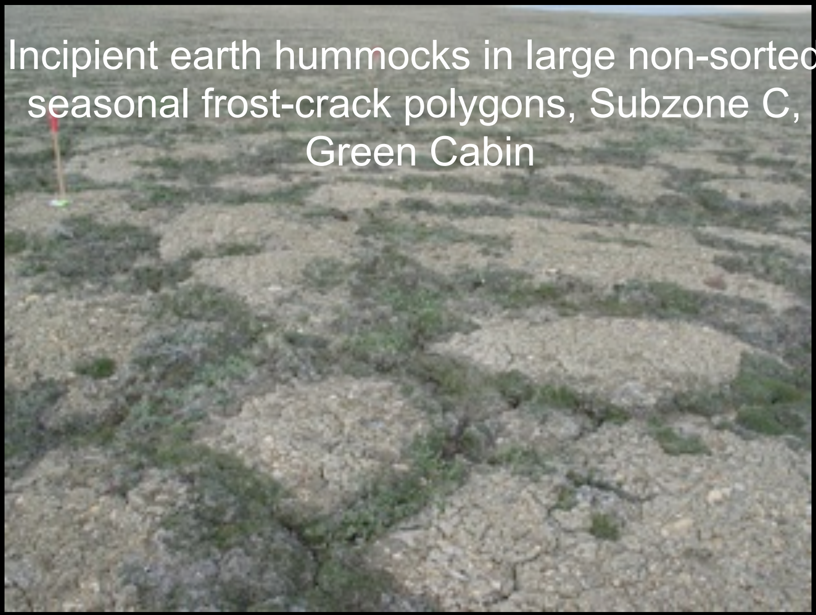
- **Frost-heave non-sorted circles**
- **Earth hummocks**

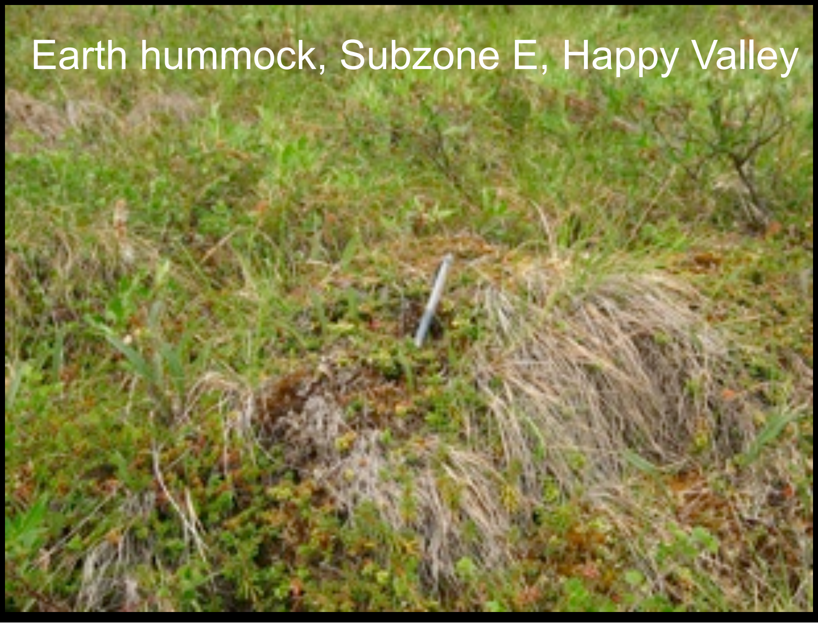
Non-sorted circles, Howe Island, AK, Subzone E.

Non-sorted circles, Franklin Bluffs, AK, Subzone D.

Earth hummock, Inuvik, NWT, Canada,, Northern Boreal Forest.
Photos: D.A. Walker

Earth hummocks caused by differential frost heave





Complexities caused by slope, soil moisture and rocky soils

- Stripes on slopes
- Very large non-sorted circles in wet sites.
- Sorted circles in rocky soils.

Non-sorted stripes, Subzone C, Green Cabin.

Large non-sorted circles in wet soils, Green Cabin.

Sorted Circles at Mould Bay, Canada, Elevation Belt A. Photos: D.A. Walker

Contraction Cracking

Mould Bay, Prince Patrick Island, Elevation, Belt A.

Contraction cracks in a drained lake basin, Prudhoe Bay, Alaska, Subzone D.

Green Cabin, Banks Island, Bioclimate Subzone C.

Howe Island, northern Alaska, southern Bioclimate Subzone C.

Photos: D.A. Walker

- **Small non-sorted polygons (Washburn 1980).**
- **Occur on most sandy to clayey soils in the High Arctic (Subzones A, B, C).**
- **Seasonal frost cracking (Washburn 1980).**
- **Can be confused with desiccation cracking.**

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

In the High Arctic, small contraction-crack polygons are the dominant patterned-ground features.

Isachsen, Ellef Ringnes I.

Mould Bay, Prince Patrick I.

Howe Island, northern Alaska

- **Small non-sorted polygons (Washburn 1980).**
- **Occur on soils of all textures in the High Arctic.**
- **May be caused by either desiccation cracking or seasonal frost cracking (Washburn 1980).**

Photos: D.A. Walker

Desiccation cracking vs. seasonal frost cracking

Desiccation cracks.
Mould Bay.

Desiccation cracks.
Dinosaur Provincial Park, Alberta.

Green Cabin, small non-sorted polygons

Green Cabin, polygon removed from soil.

Desiccation cracking:

- Washburn (1980) and Tricart (1967) attributed most fine-scale (<1-m diameter polygons) to desiccation cracking.

Seasonal frost cracking:

- Ubiquitous on most High Arctic surfaces.
- All soil textures.
- Deeper cracking.
- Experiments and models are needed to determine conditions for seasonal frost cracking.

Frost cracking occurs at many scales

Permafrost crack nonsorted polygons, Kuparuk R., Alaska

Small seasonal frost-crack non-sorted polygons, Green Cabin.

Frost cracking within small polygons, Mould Bay.

Frost cracking within *Dryas* hummock, Green Cabin.

Role of soil texture

Rocky soils: sorted circles and polygons, Mould Bay, Prince Patrick I.

Sandy soils: no circles nor hummocks Atkasuk, AK

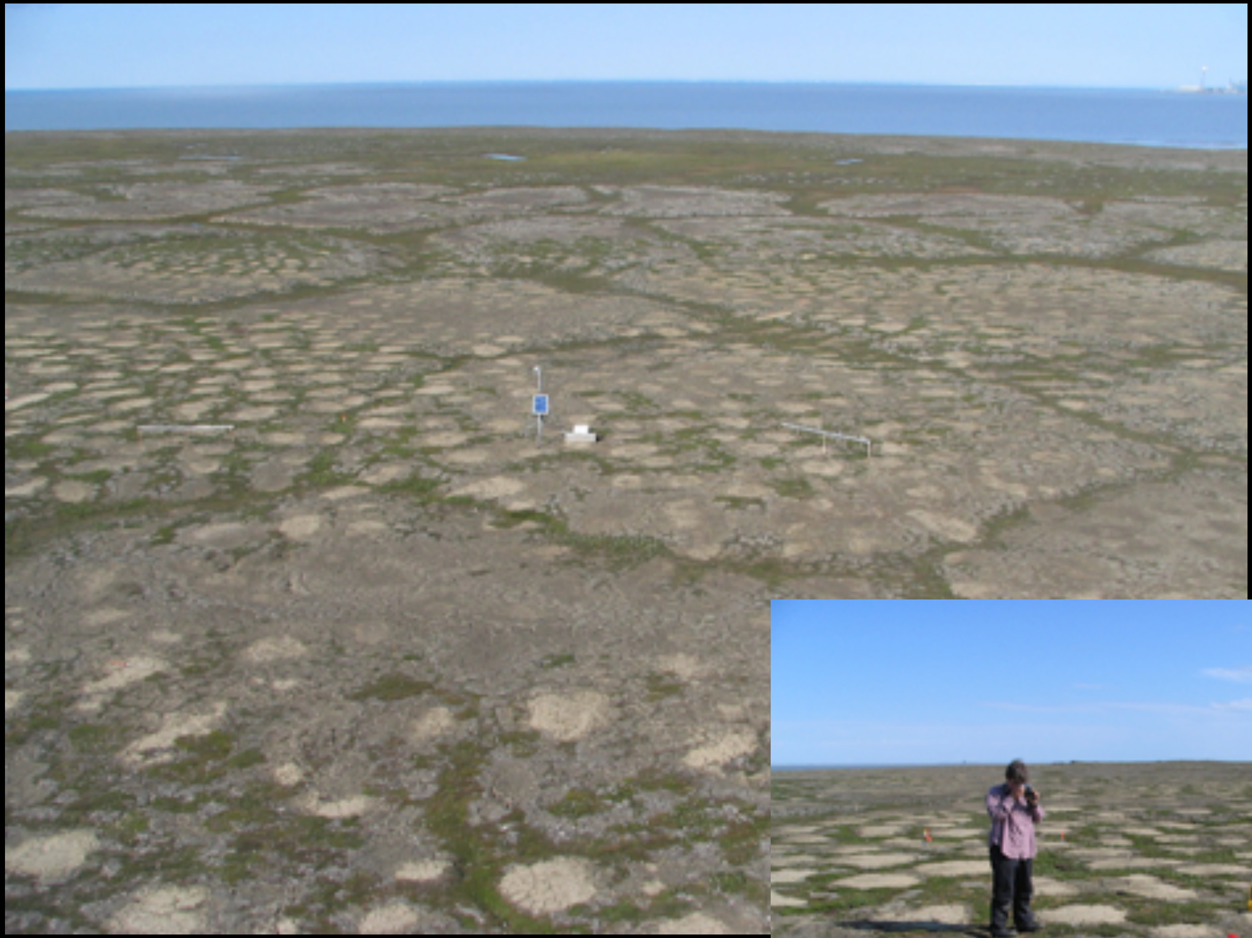
Silty soils: sorted circles without earth hummocks Prudhoe Bay, AK

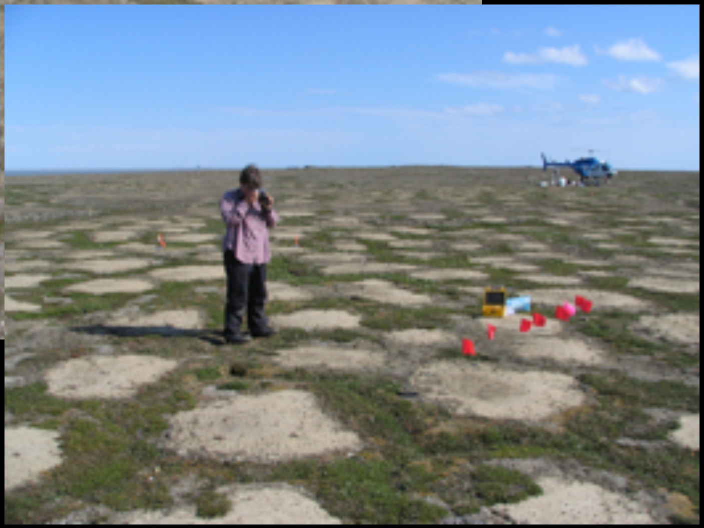
Clayey soils: earth hummocks, Inuvik, NWT

Variety of forms on different substrates

Stoney substrates:
Mould Bay, Prince Patrick I.

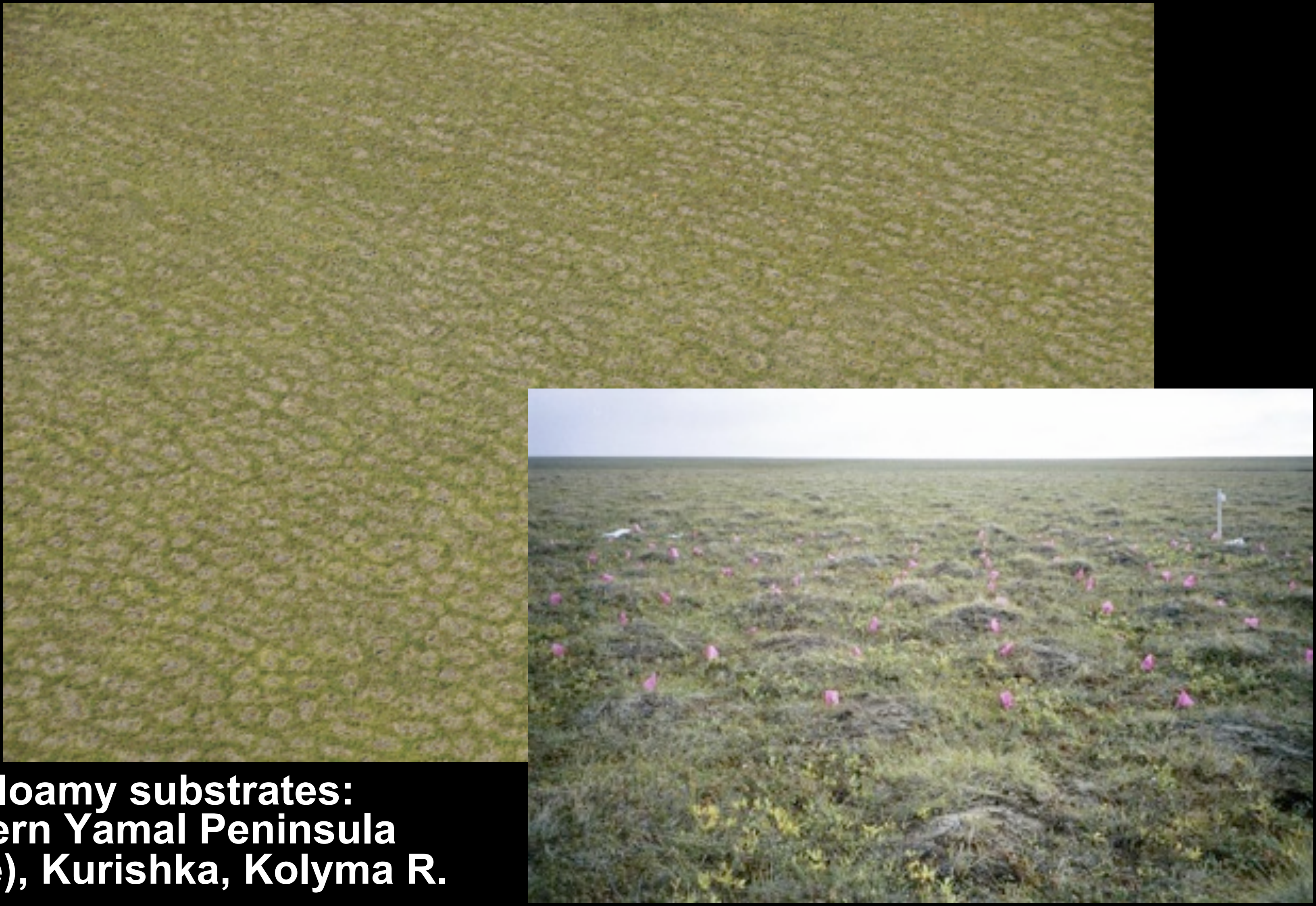
Variety of forms on different substrates





Saline sandy loam substrate:
Howe Island, Alaska

Variety of forms on different substrates



Mesic loamy substrates: Southern Yamal Peninsula (above), Kurishka, Kolyma R. (right)

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 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 soil texture and 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).

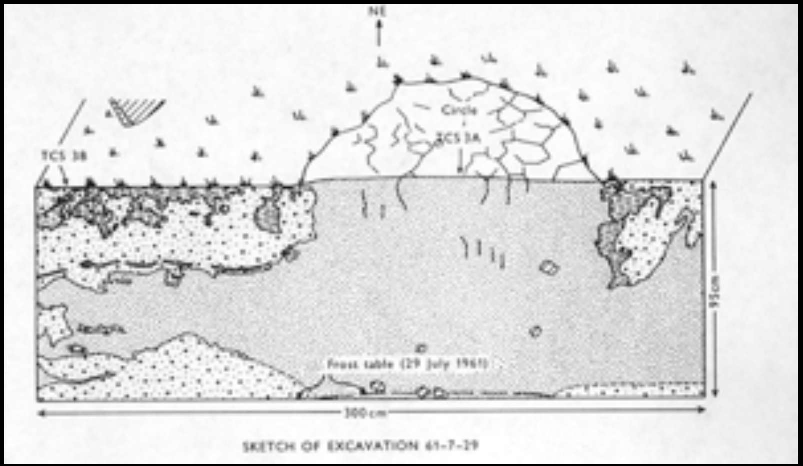
Project initially focused on “frost boils”

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

- **Caused principally by differential frost heave (Peterson and Krantz 2003).**

- **Also called:**
- Non-sorted circles (Washburn 1980)
- ‘Frost medalllions’ (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).

What are non-sorted circles?



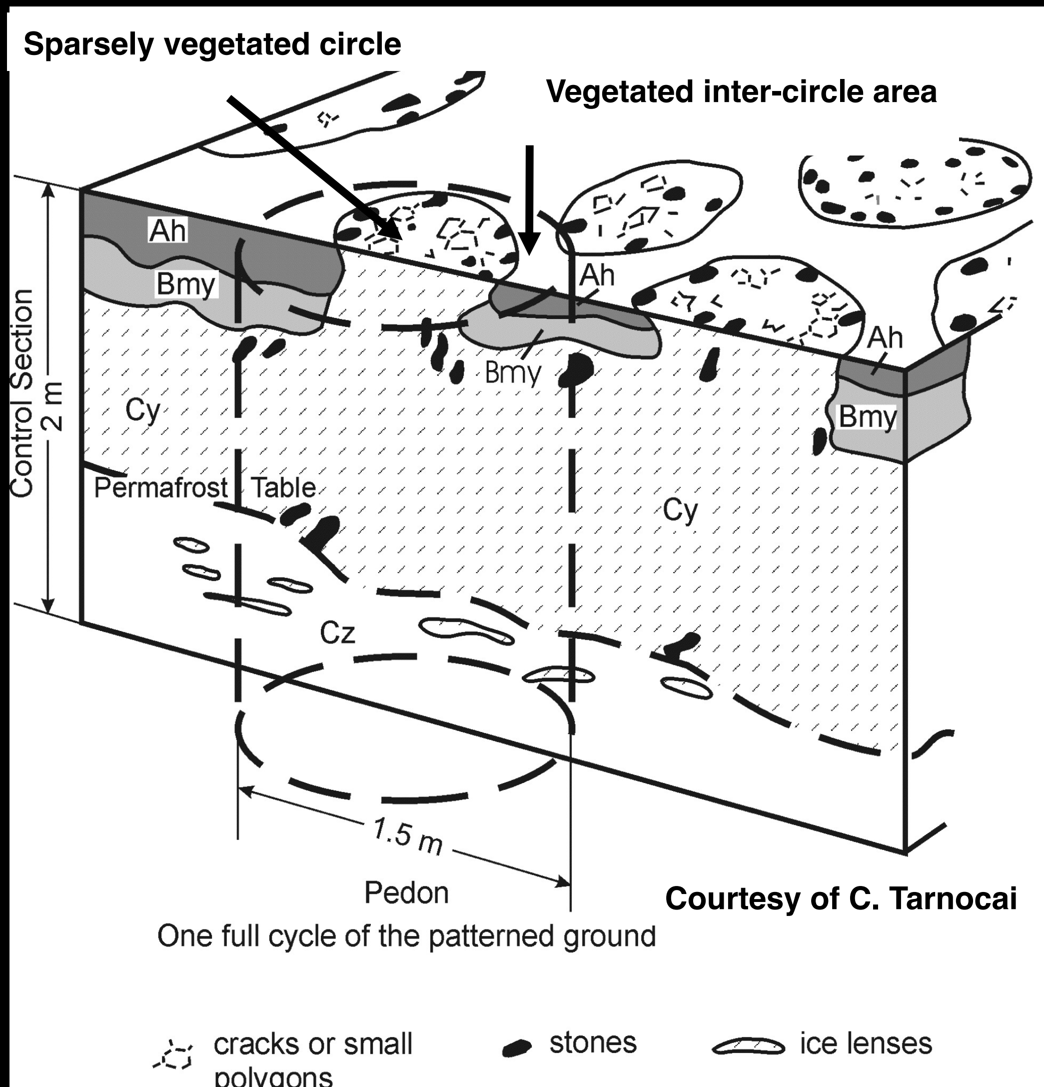
= Frost boil: “a patterned ground form that is equidimensional in several directions with a dominantly circular outline which lacks a border of stones…”

van Everdingen 1998

- Frost “boil” is a misnomer because no “boiling” is involved.
- Closest term in Russian is Piyatnoe medalion - “frost medallion”
- Moroznoe kepenie - frost churning due to needle-ice formation.
- Pyatneestaya tundra: “spotted tundra” in Russian

Figures from Washburn 1980

The non-sorted circle system

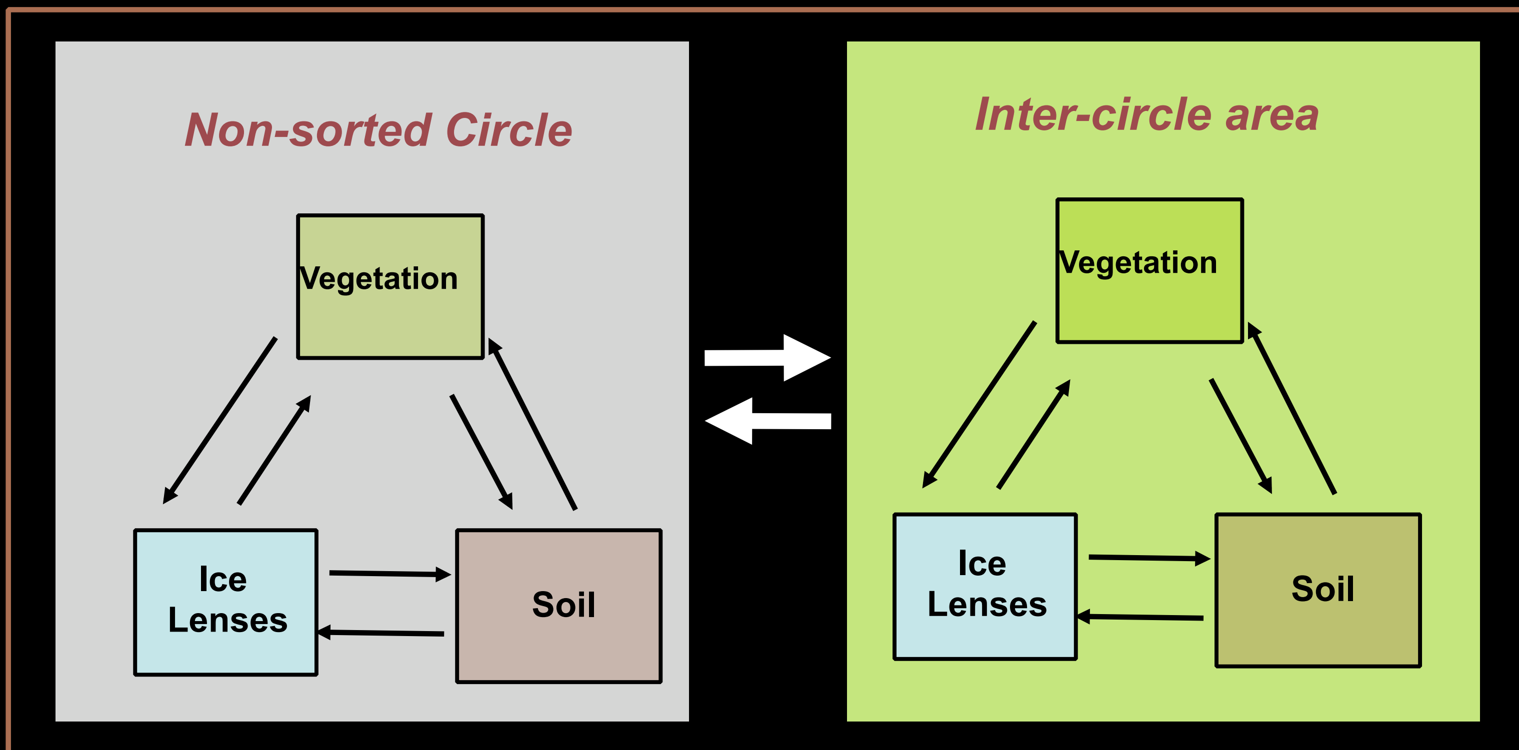


Central Questions

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?

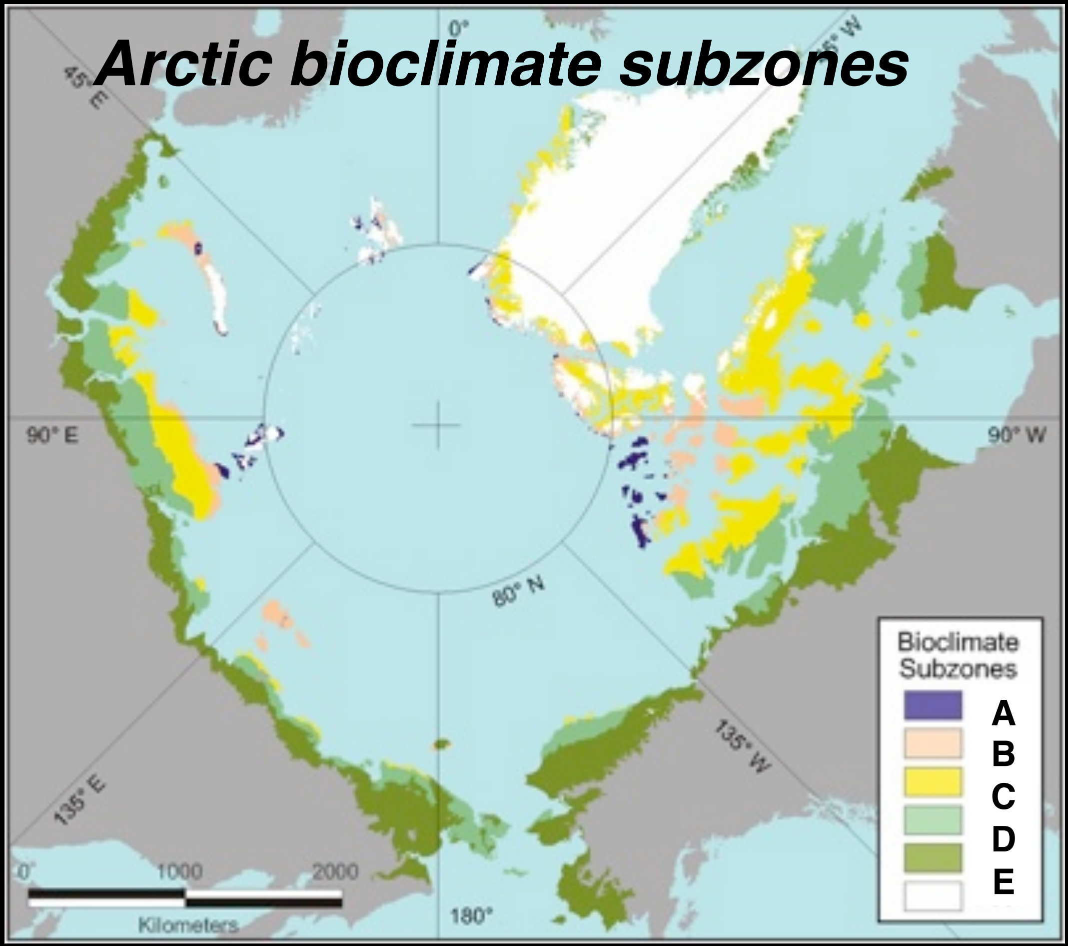
Conceptual model of the non-sorted circle system



The white arrows indicate interactions and feedbacks between **elements** (frost boils and inter frost boils), and black arrows between **components** of each element (ice lenses, soils, and vegetation).

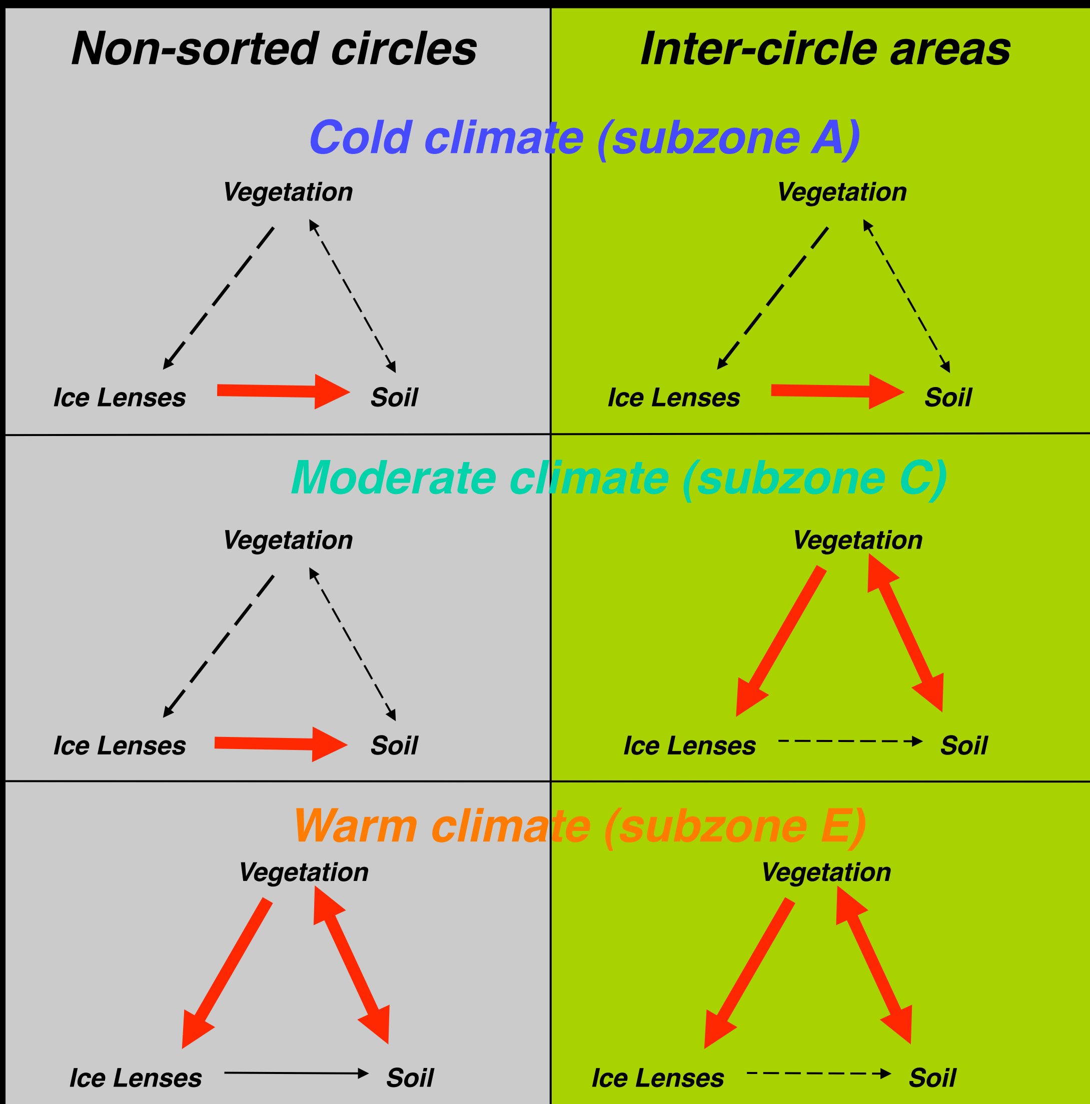
Examination of frost heave features across the Arctic bioclimate gradient

Sub-zone	*Mean July tempera-ture (˚C)*	*Dominant plant growth forms*
A	2-3	Cushion forbs, mosses, lichens
B	3-5	Prostrate dwarf shrubs
C	5-7	Hemi-prostrate dwarf shrub, sedges
D	7-9	Erect dwarf shrubs, sedges mosses
E	9-12	Low shrubs, tussock sedges, mosses



From the *Circumpolar Arctic Vegetation Map*, 2003.

Dominant drivers of patterned-ground formation across the Arctic bioclimate gradient



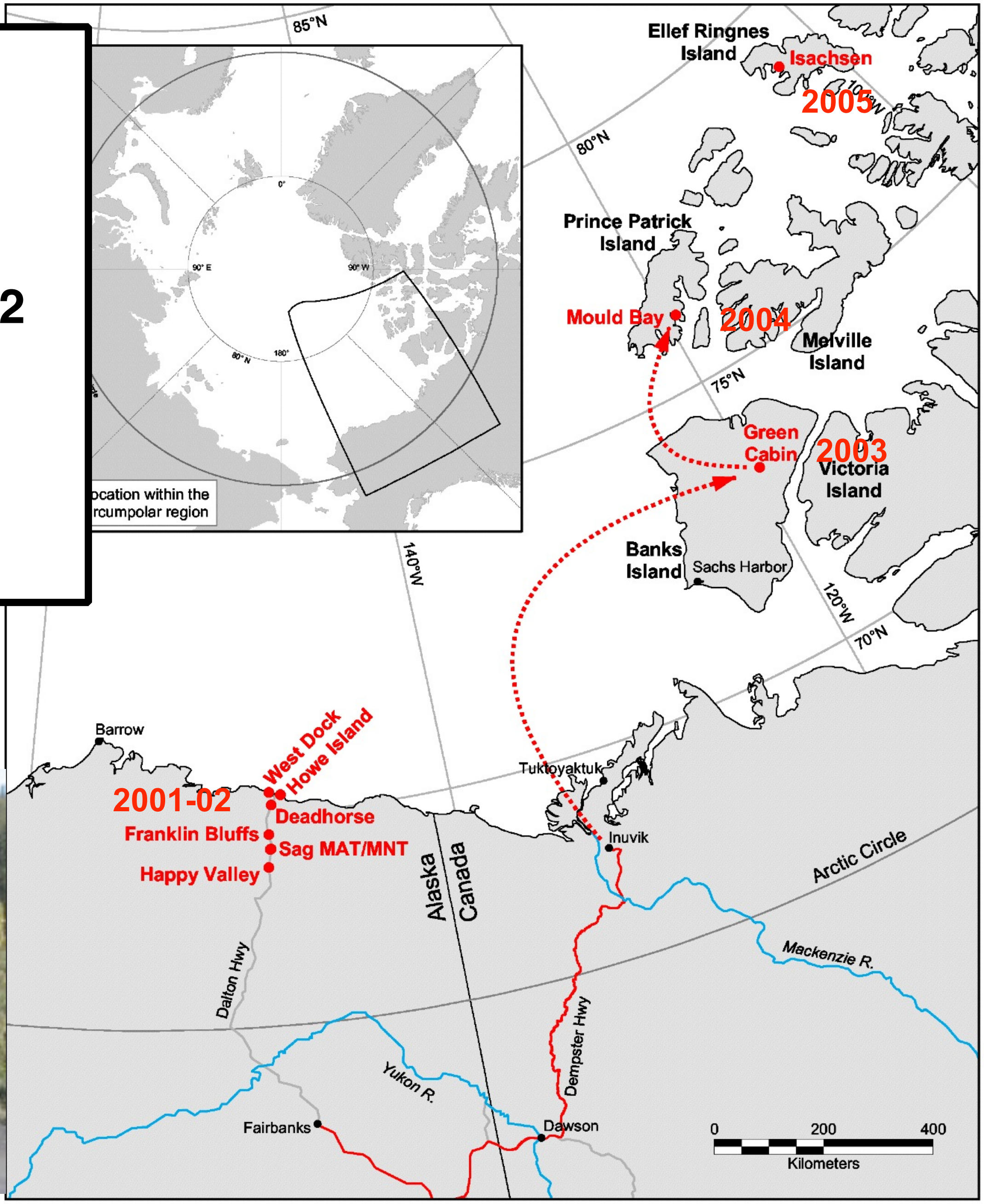
Dominantly physical processes on both circles and inter-circle areas

Dominantly physical processes on circles and biological processes in inter-circle areas

Dominantly biological processes on both circles and inter-circle areas

Expeditions and Timeline:

Dalton Highway: 2001-2002
Green Cabin: 2003
Mould Bay: 2004
Isachsen: 2005
Synthesis: 2006-2008



Ken Borak air support in the Canadian Arctic

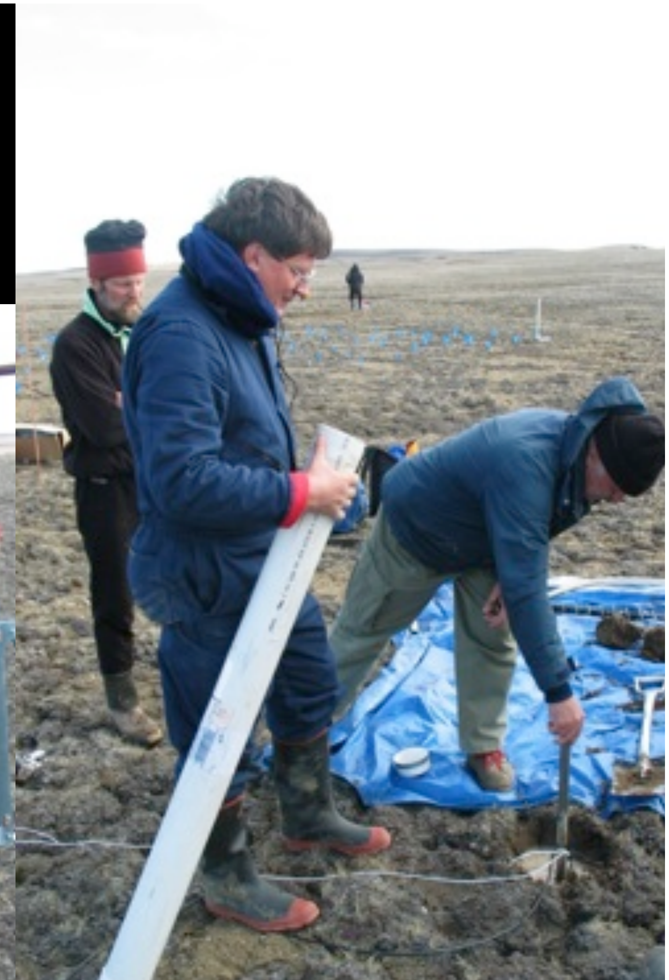

Low point of the
6-year project
Stuck in the mud!!

Field Camp at Green Cabin, Banks Island

Project components

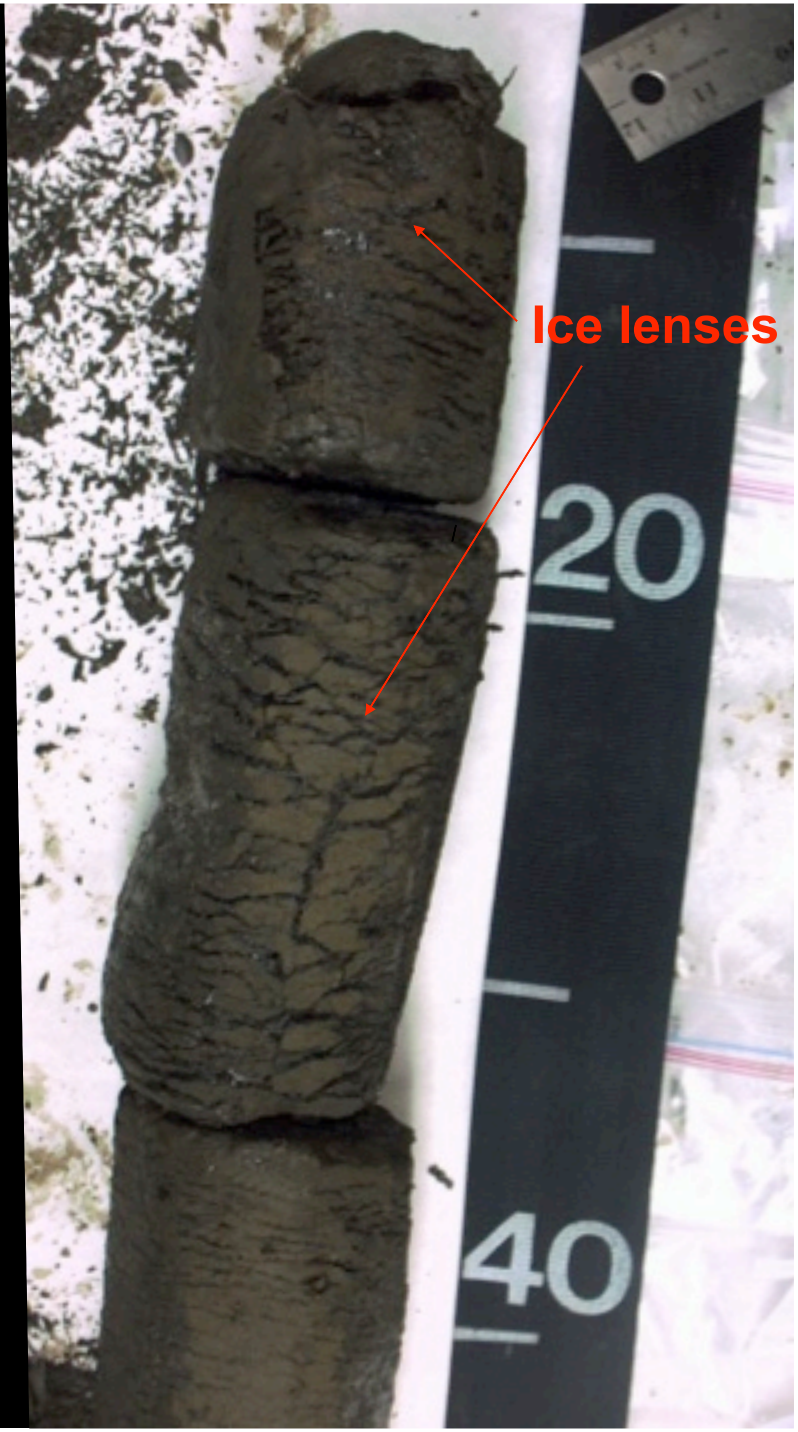
- **Climate and permafrost:** Vladimir Romanovsky, Ronnie Daanen, Yuri Shur
- **Soils and biogeochemistry:** Chien-Lu Ping, Gary Michaelson, Howie Epstein, Alexia Kelley
- **Vegetation:** Skip Walker, Anja Kade, Patrick Kuss, Martha Raynolds, Corinne Vonlanthen
- **Modeling:** Ronnie Daanen, Howie Epstein, Bill Krantz, Dmitri Nikolsky , Rorik Peterson, Vladimir Romanovsky
- **Education:** Bill Gould, Grizelle Gonzalez
- **Coordination and management:** Skip Walker

Climate and permafrost component



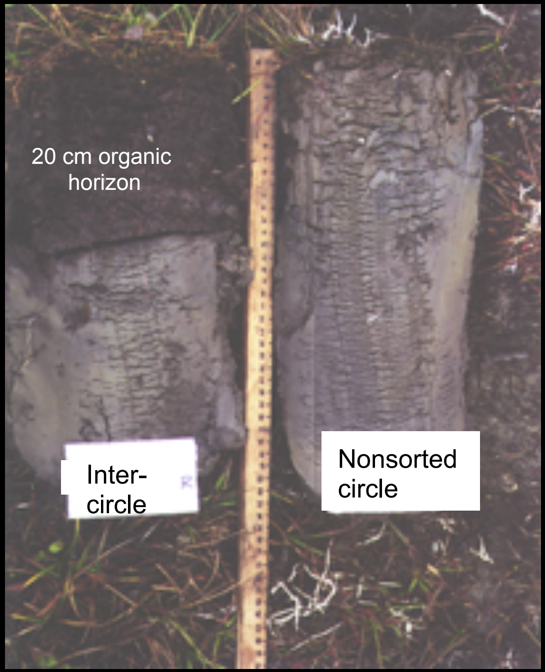
The ice-lens part of the nonsorted-circle system

- **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 formation of ice at the bottom of the active layer as the soil freezes upward.**



Frozen soil core from a frost boil
Photo Julia Boike

These processes are described in three models of differential frost heave (Peterson and Krantz 2003, Daanen et al. 2008, Nickolsky et al. 2008).



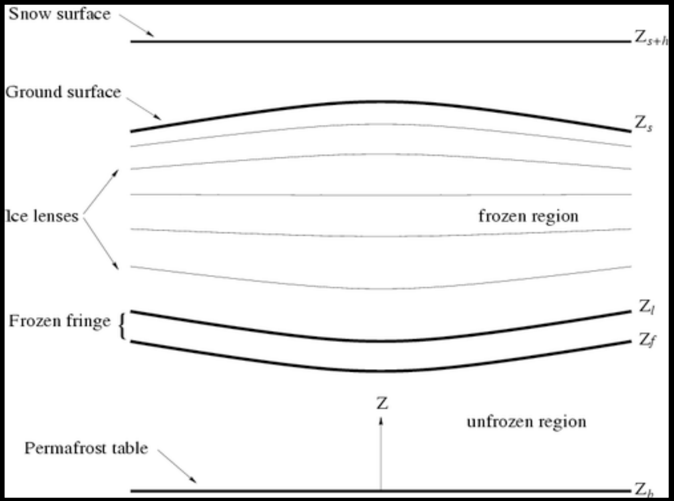
Lenticular voids in soil in summer created by ice lenses.

Briefly:

• Heat preferentially escapes from the surface at high points of small irregularities in the surface.

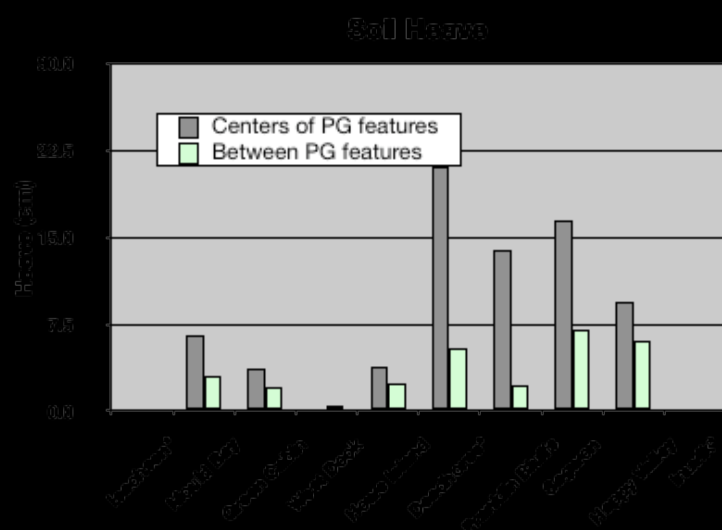
• These high points self-organize into patterns controlled by mechanical properties of the soil (e.g., texture) and active layer thickness.

• These high points are sites of increased heat and water flux, ice-lens development, and more heave. Water is pulled to the site of freezing by cryostatic suction.



Schematic of soil undergoing top-down freezing. Ice lenses exist in the frozen region and permafrost underlies the active layer.

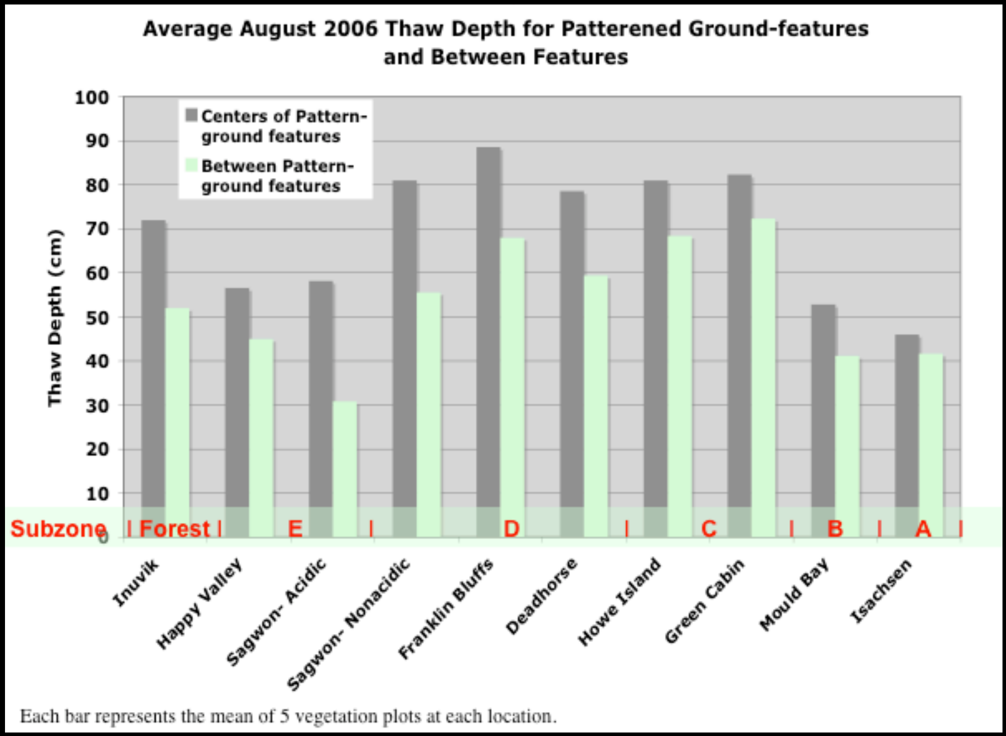
Frost heave measurements



- Differential heave is the greatest in subzone D, where centers are unvegetated but areas between features are well-vegetated.
- Heave greatest in northern Alaska on silty soils

Active Layer depth

Thaw probe and prober.




Soils component
20
40
60
80

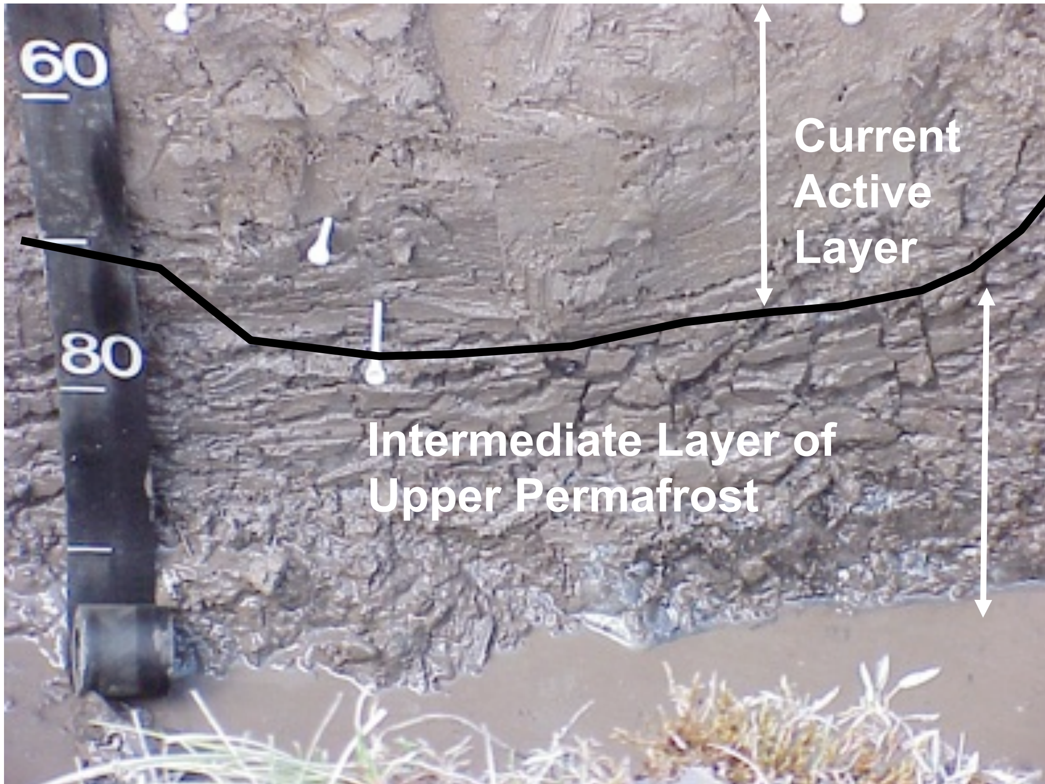
Chien-Lu Ping and Gary Michaelson

Charles Tarnocai

Complete characterization of soils

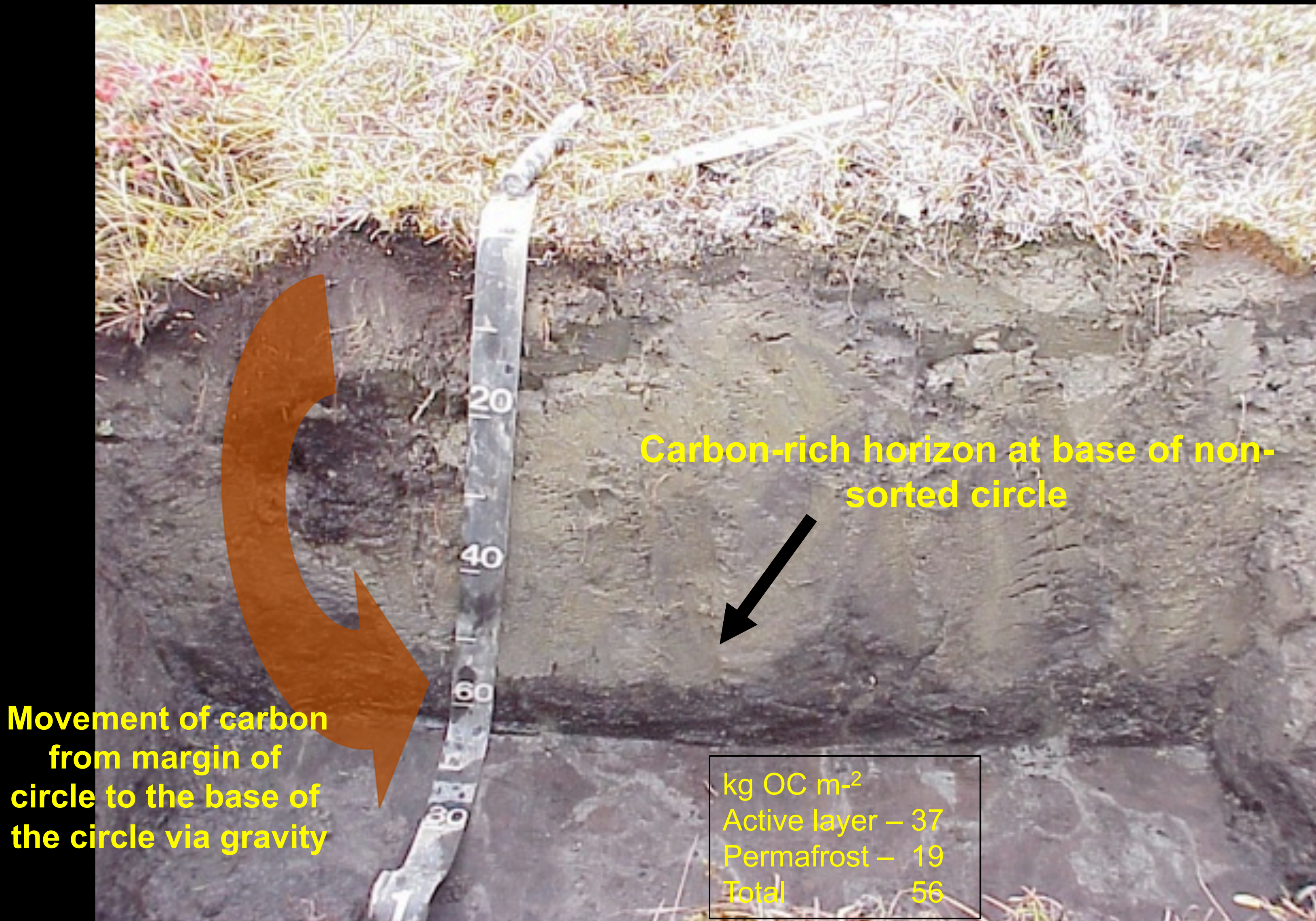
- Large soil pits across full patterned ground cycle.
- Lots of student help.

Buried carbon in the intermediate layer of permafrost table



Courtesy of Gary Michaelson

Sequestered carbon beneath frost boils



Carbon is concentrated in the cracks between small polygons.

Nonsorted circles, Ostrov Belyy, Russia.

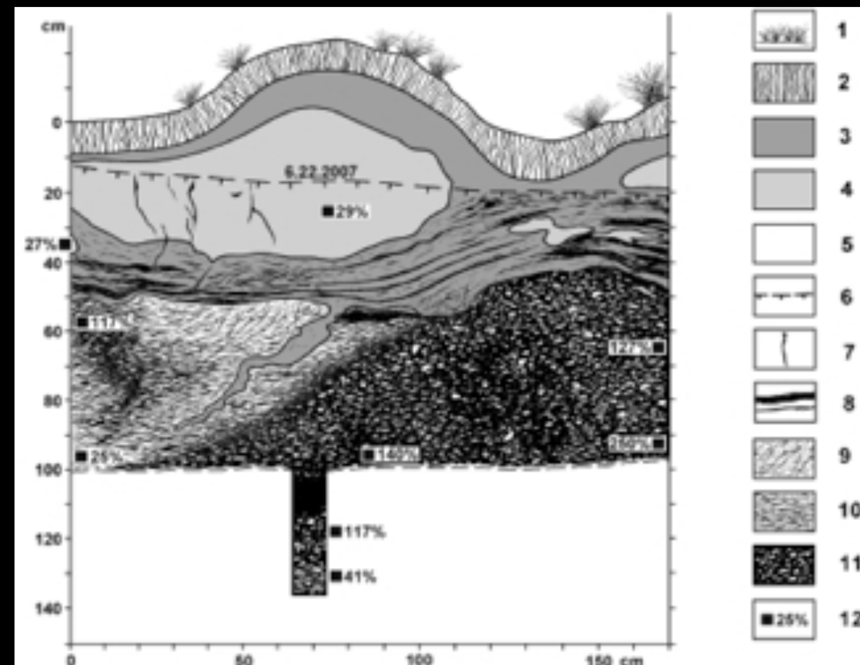
After removal of top 10 cm of soil.

Circles are situated in the centers of 60-90-cm diameter <u>nonsorted polygons with cracks.</u>

Movement of organic material along thermal cracks to the base of the active layer.

Photos: Left and center: Laborovaya, Russia; right: Mould Bay, Canada

Large amounts of carbon are sequestered at the top of the permafrost table in the intermediate layer.

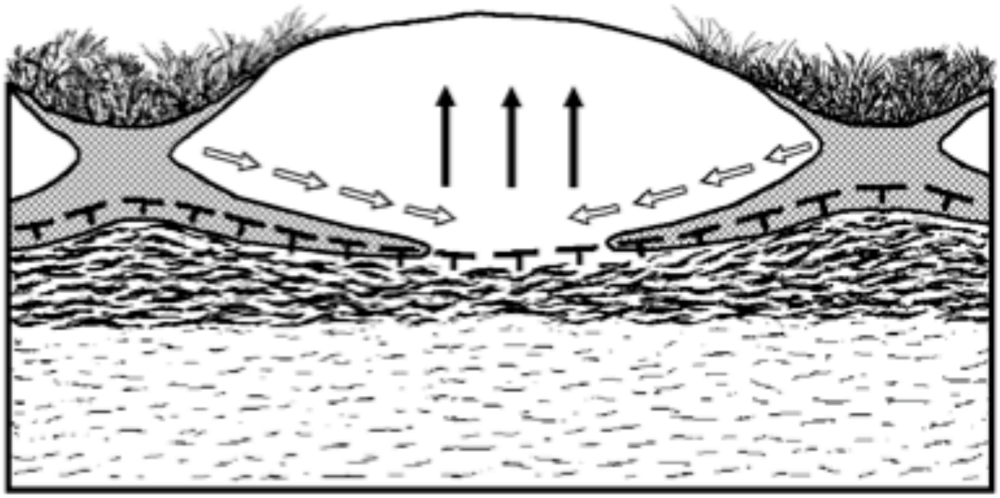


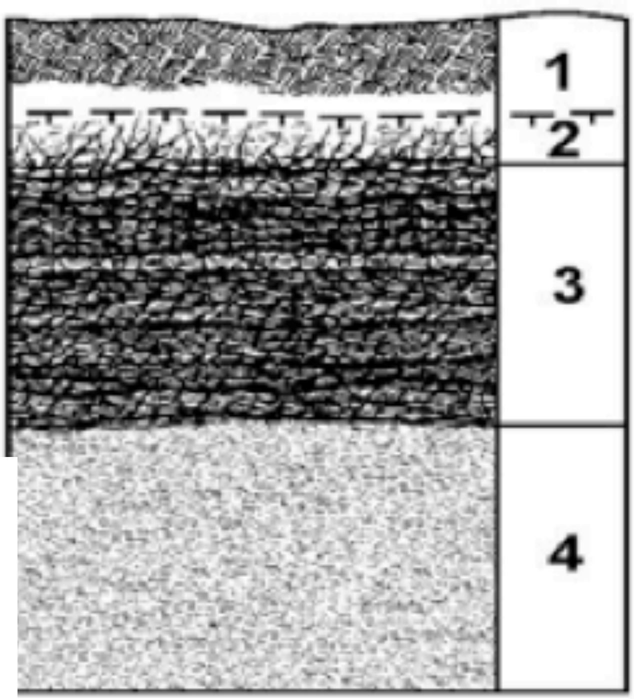
Courtesy of Misha Kenevskiy & Yuri Shur

Major questions:

How old is the carbon?
How stable is the carbon?
Is it susceptible to decomposition if the active layer becomes deeper?

Structure of active layer and top permafrost layers beneath a nonsorted circle.





1 – Active layer (zone of annually thawed soil).
2 – Transient layer (frozen in some summers and thawed in).
3 – Intermediate layer).
4 – Original permafrost.
Arrows denote hypothesized movement of organic material.

¶

Ice-rich intermediate layer in the upper permafrost

Courtesy of Yuri Shur and Misha Kanevsky

Needle-ice (Pipkrakes)

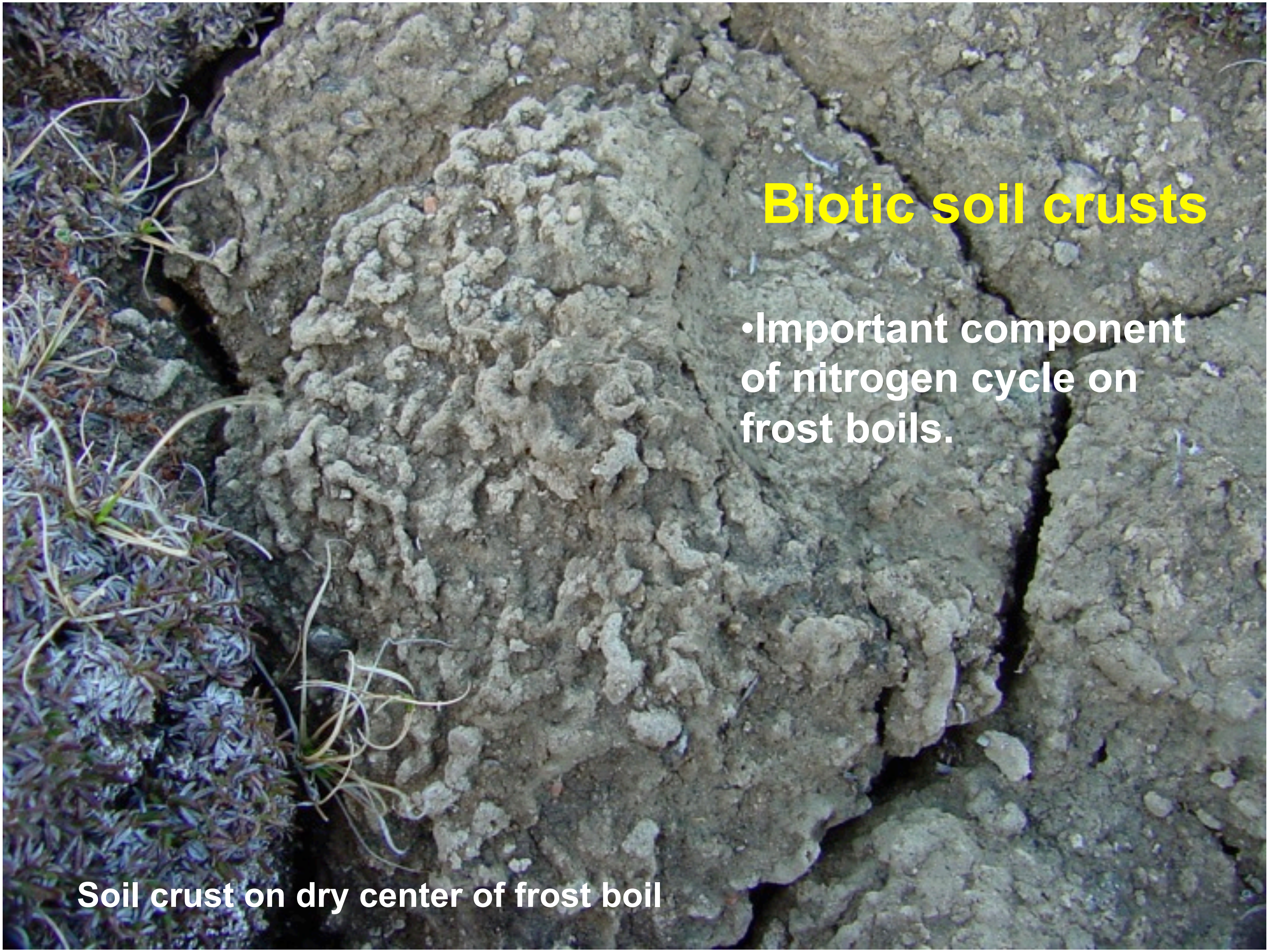
Soil surface is lifted by ice crystals during diurnal freeze-thaw cycles.

Photos: Outcalt 1971; Davies 2001

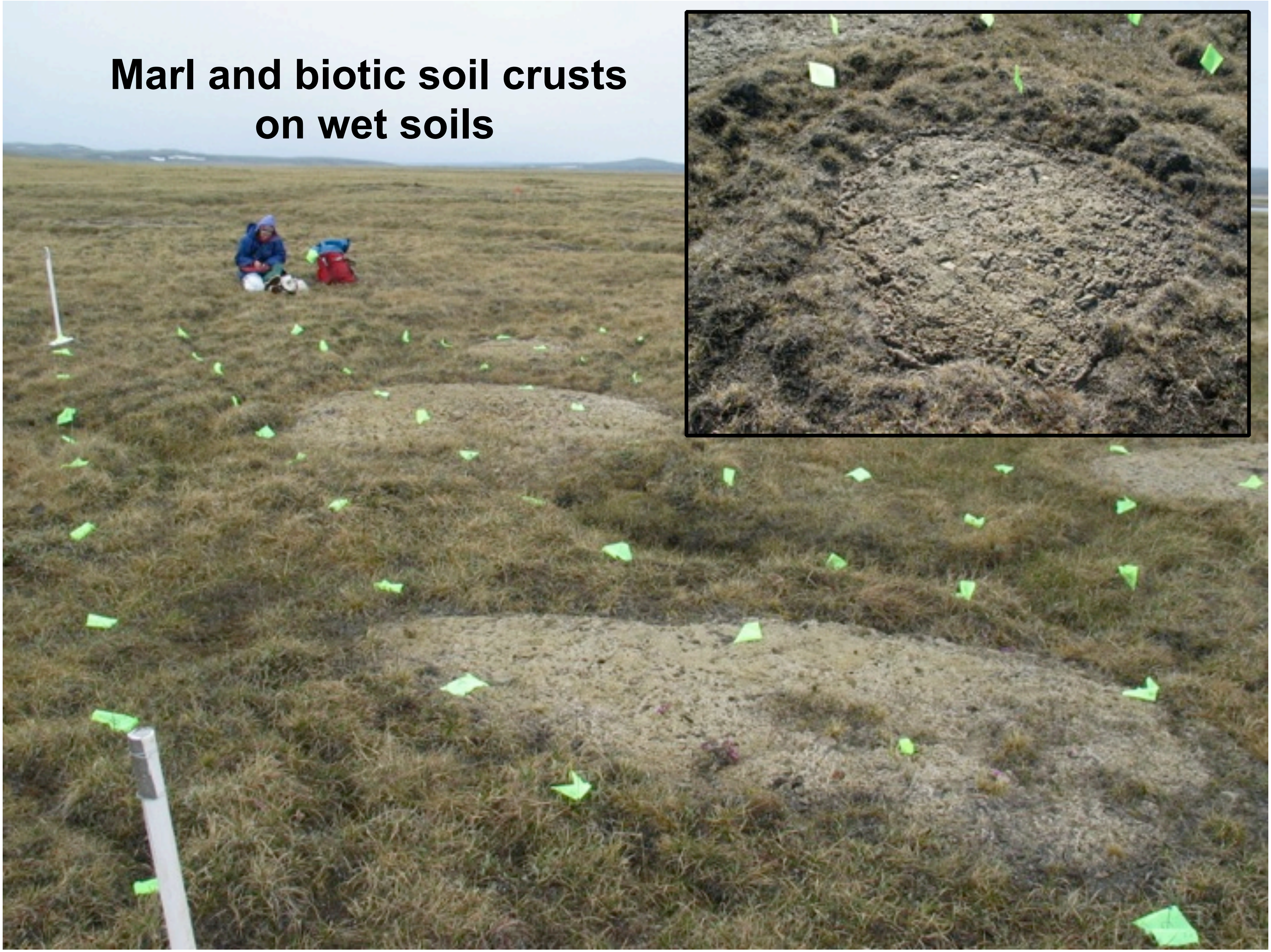
Needle-ice consequences

Cottage-cheese soil

Braya bartlettiana and root


Biotic soil crusts
•Important component of nitrogen cycle on frost boils.
Soil crust on dry center of frost boil

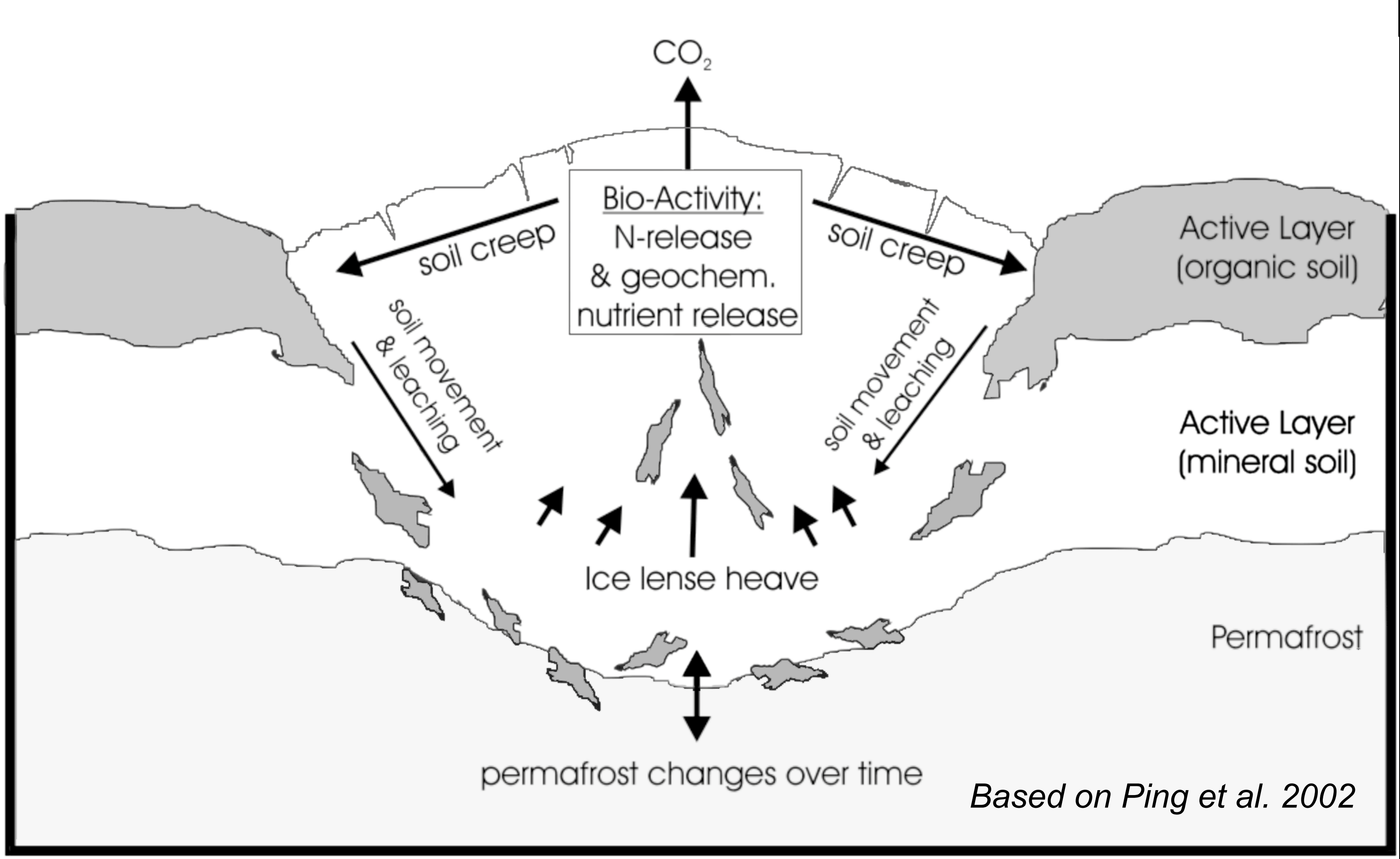
Marl and biotic soil crusts on wet soils



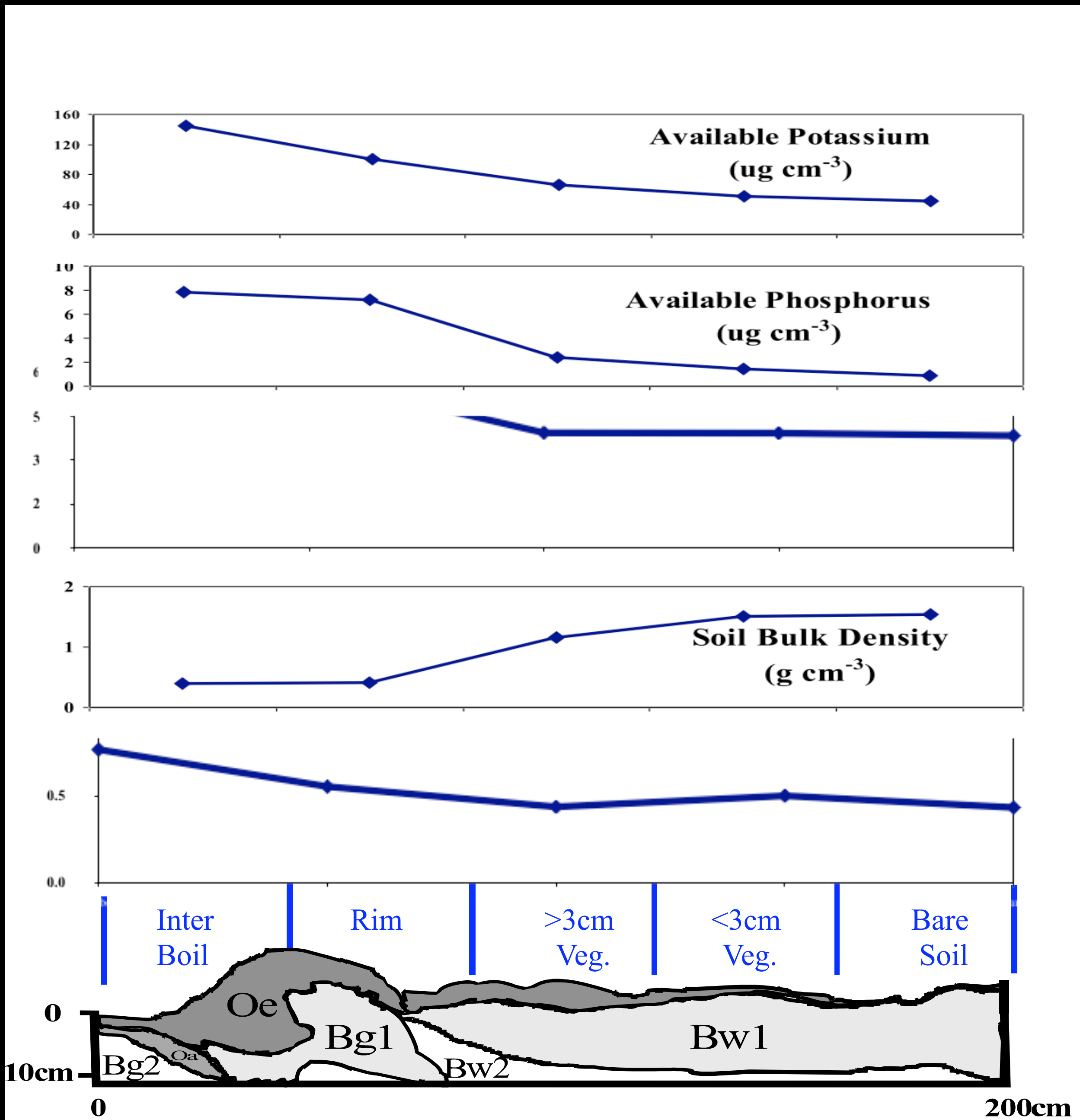

Marl with interior lining
of algae and fungal
hyphae

Nitrogen Mineralization studies

Biogeochemical cycling and carbon sequestration within frost heave features



Based on Ping et al. 2002



Spatial variation in soil properties across a non-sorted circle

Michaelson, G.J., Ping, C.L., Epstein, H., et al. 2008. Soils and frost boil ecosystems across the North American Arctic Transect. *Journal of Geophysical Research - Biogeosciences*. 113:1-11.

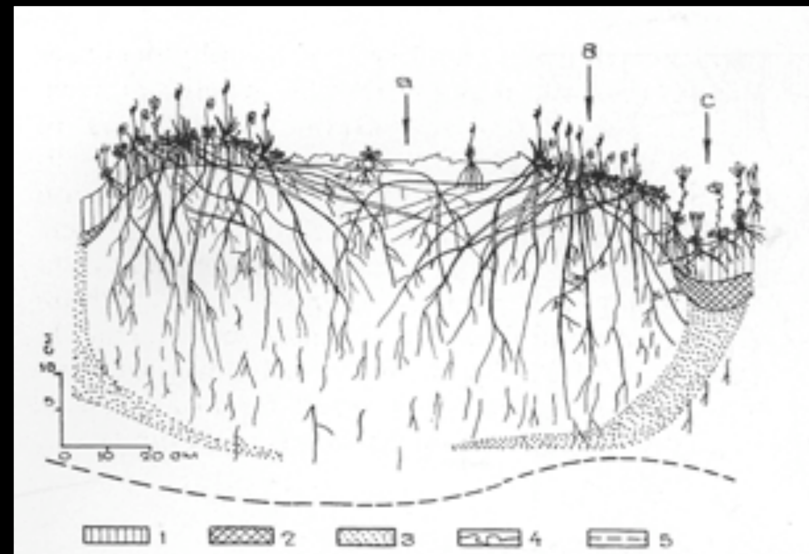
Ping, C.L., Michaelson, G.J., Kimble, J.M., et al. 2008. Cryogenesis and soil formation along a bioclimate gradient in Arctic North America. Journal of Geophysical Research - Biogeosciences. 113:G03S12.


Vegetation component

The added roles of vegetation

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.**



N. Matveyeva - Map and drawing of frost boil vegetation on the Taimyr Peninsula, Russia.

Bill Steere collecting *Bryum wrightii* on a frost boil at Prudhoe Bay, July, 1971.

Approach: Measurements along the NAAT

Measurements

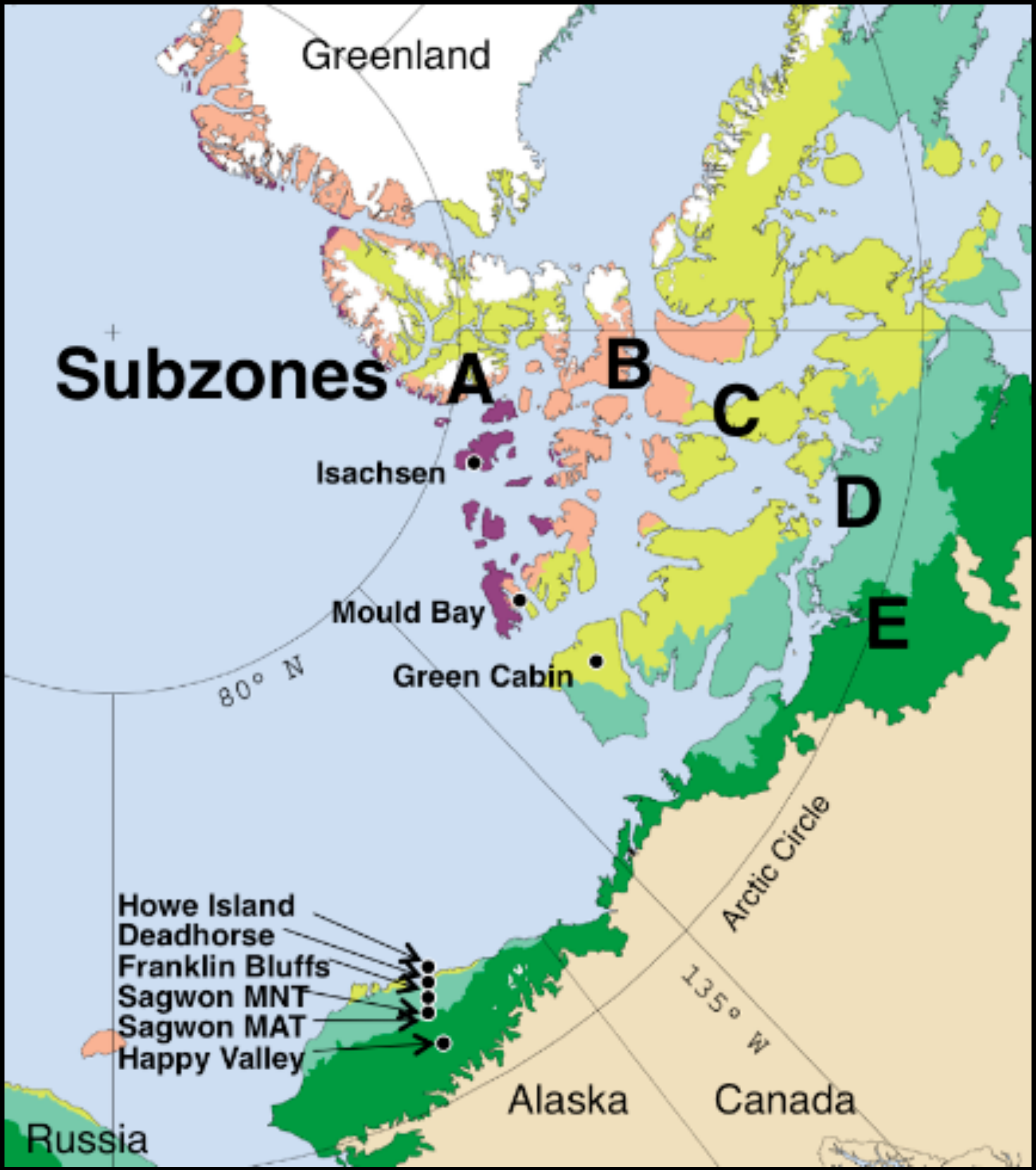
- 21 Grids and maps
  - Active layer
  - Vegetation
  - Snow
- Climate /permafrost
  - Met station
  - Soil temperatures
  - Frost heave
- Soils
  - Characterization
  - Nitrogen mineralization
  - Decomposition
- Remote sensing
  - NDVI
  - Biomass

10 x 10 m grid at Isachsen

North American Arctic Transect

Arctic Bioclimate Subzones

Sub-zone	MJT (˚C)	SWI (˚C mo)
A	<3	<6
B	3-5	6-9
C	5-7	9-12
D	7-9	12-20
E	9-12	20-35
Forest	>12	>35



Biocomplexity grids

Subzone A:
- Satellite Bay, Canada – 1
- Isachsen, Canada - 3 planned

Subzone B:
- Mould Bay, Canada - 2

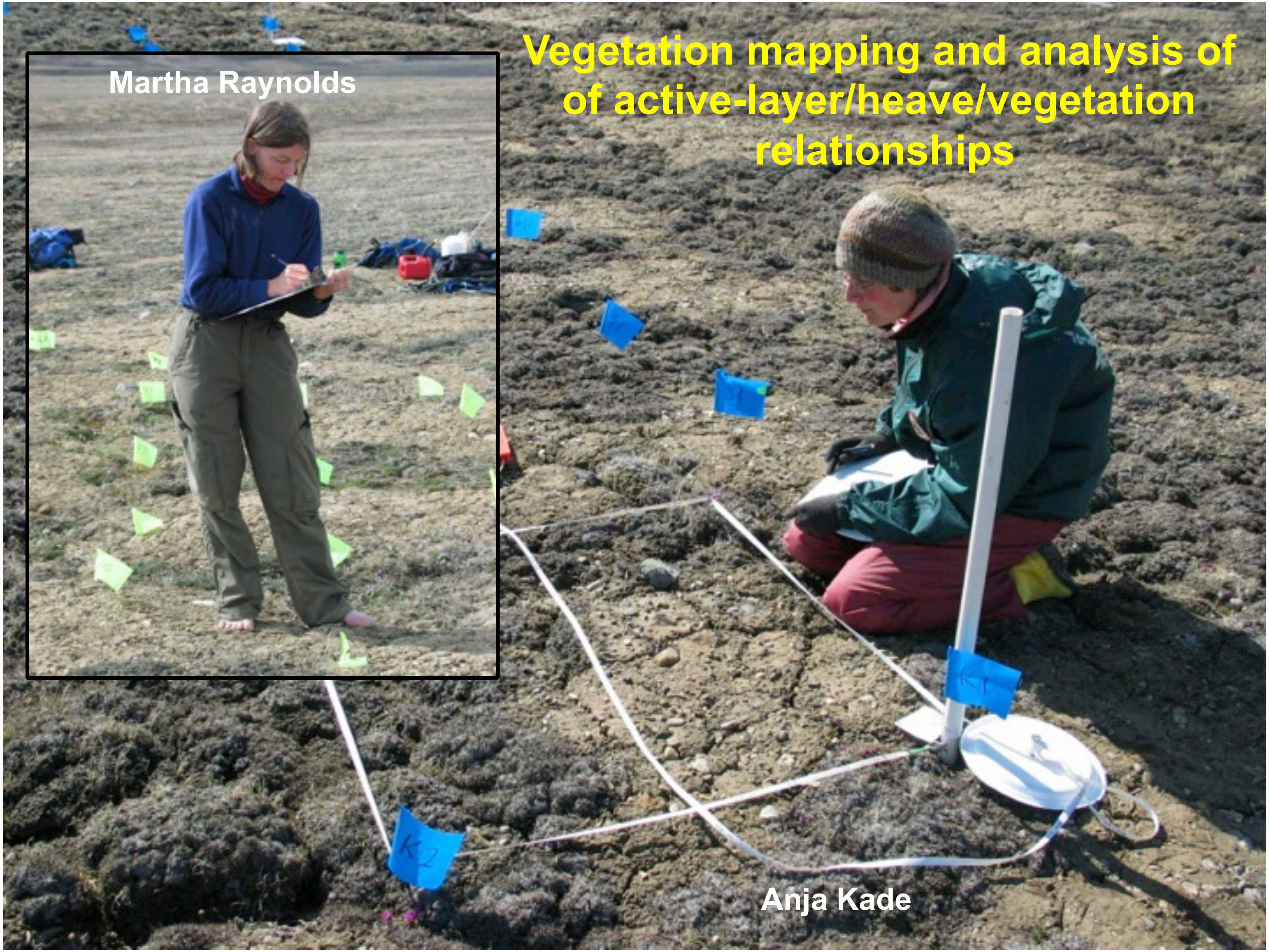
Subzone C:
- Howe Island, Alaska – 1
- West Dock, Alaska – 1
- Green Cabin, Canada - 3

Subzone D:
- Deadhorse, Alaska - 1
- Franklin Bluffs, Alaska - 3
- Sagwon MNT, Alaska- 2
- Ambarchik, Russian - 1

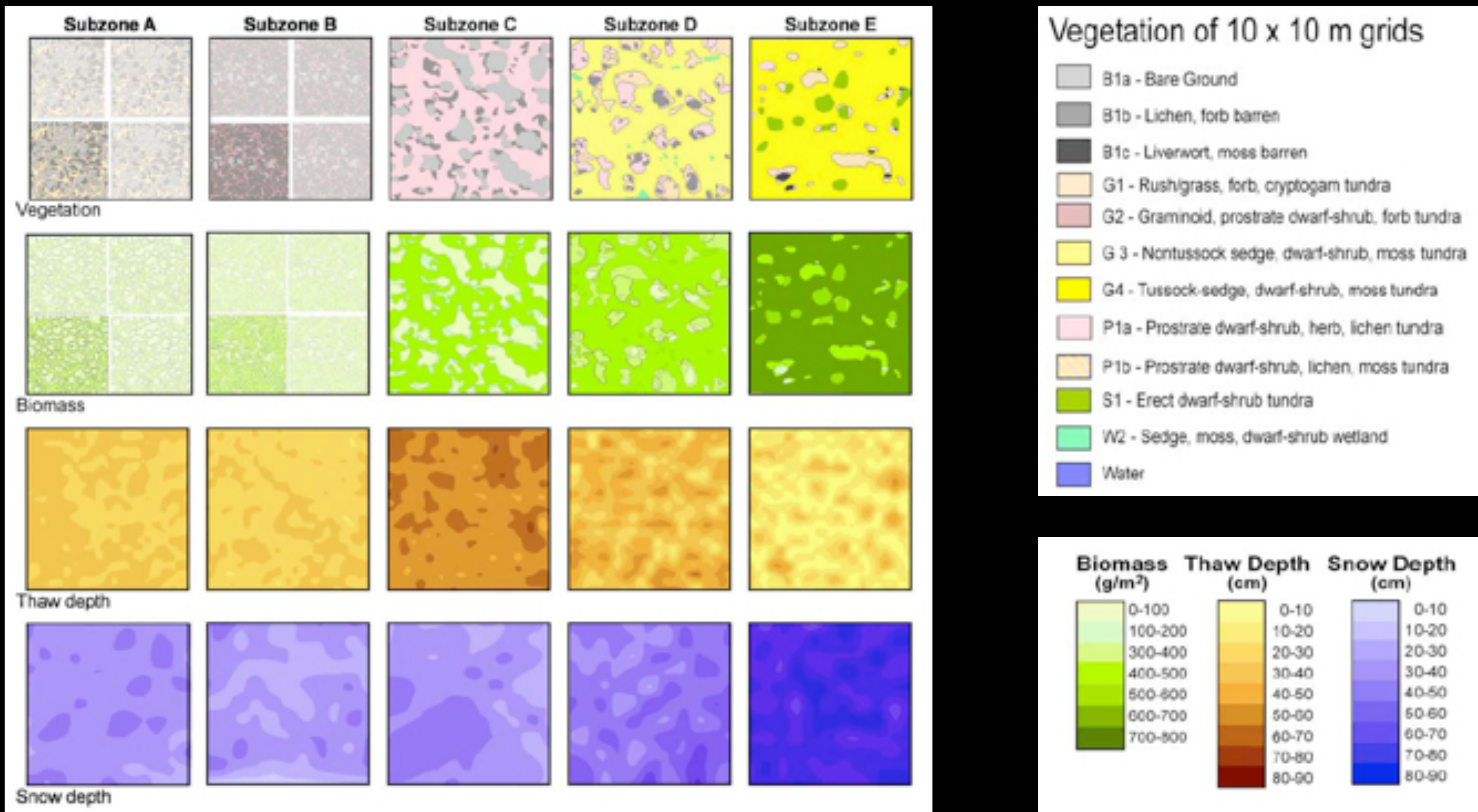
Subzone E:
- Sagwon MAT, Alaska - 1
- Happy Valley, Alaska - 3
- Kurishka, Russia - 1

TOTAL 20 + (3 planned) = 23

Happy Valley Grid

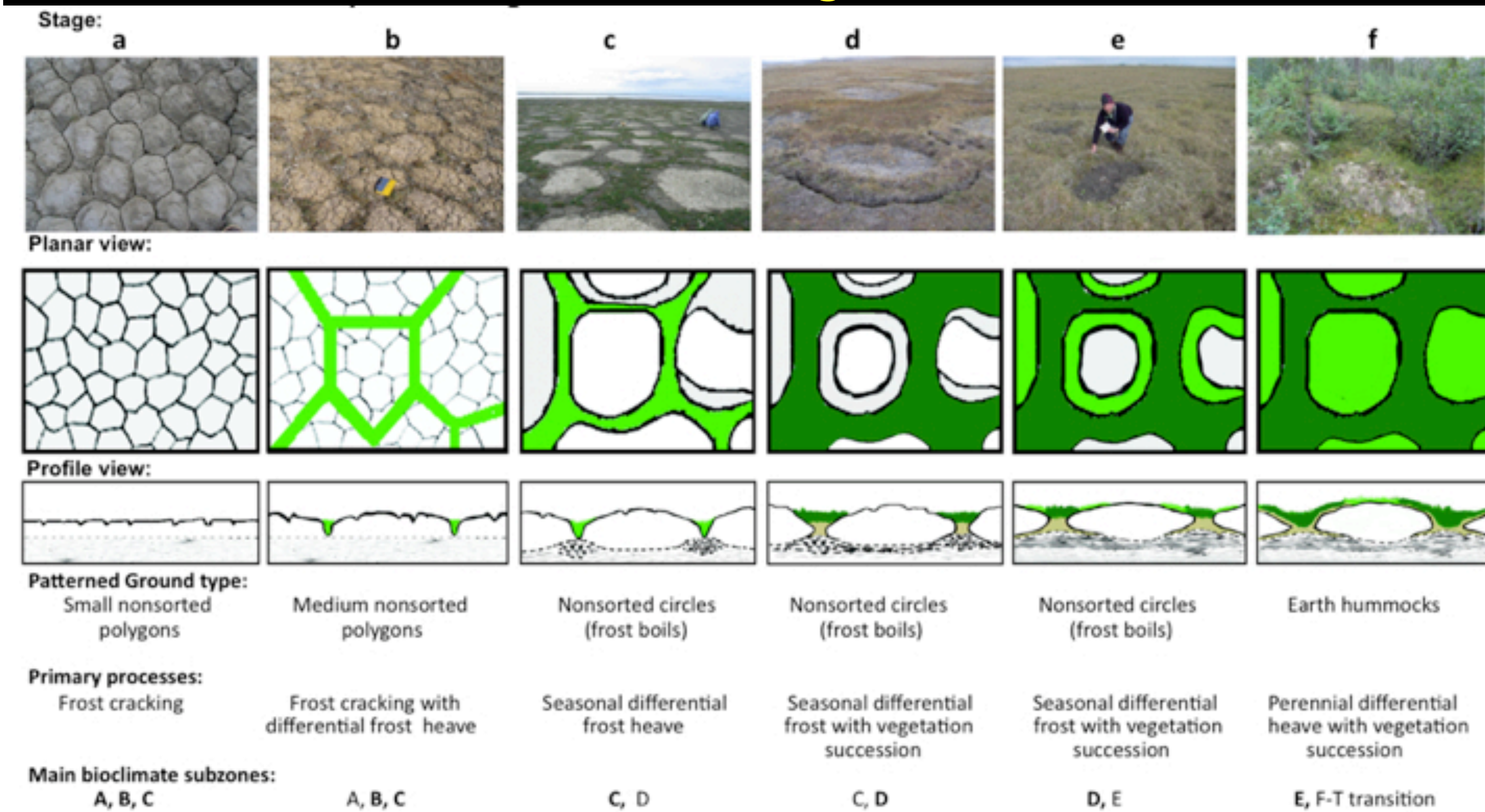

Vegetation mapping and analysis of
of active-layer/heave/vegetation
relationships
Martha Raynolds
Anja Kade

Small landscape maps along climate gradient: 10 x 10 grids

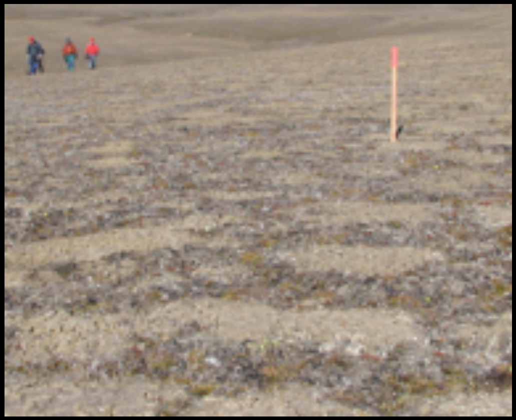


Raynolds, M.K., Walker, D.A., Munger, C.A., et al. 2008. A map analysis of patterned-ground along a North American Arctic Transect. *Journal of Geophysical Research - Biogeosciences*. 113:1-18

Trends in patterned-ground morphology and vegetation on zonal sites across the Arctic bioclimate gradient



Subzone A



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

Subzone C

Howe Island, Ak and Green Cabin, Banks Island, MJT, 8 ˚C, SWI = 16 ˚C mo

Subzone E

Tuktuyaktuk, NWT, Happy Valley, AK, MJT = 12 ˚C, SWI = 30 ˚C mo

Classification of patterned-ground vegetation along the NAAT

Phytocoenologia, 38 (1-2), 23-63
Berlin-Stuttgart, August 22, 2008

Patterned-Ground Plant Communities along a bioclimate gradient in the High Arctic, Canada

by Corinne M. Vonlanthen, Donald A. Walker, Martha K. Raynolds, Anja Kade, Patrick Kuss (Fairbanks, Alaska, USA), Fred J. A. Daniëls (Münster, Germany), and Nadezhda V. Matveyeva (St. Petersburg, Russia)

with 16 figures, 14 tables and 1 appendix

Phytocoenologia	35 (4)	761–820	Berlin–Stuttgart, December 13, 2005

Plant communities and soils in cryoturbated tundra along a bioclimate gradient in the Low Arctic, Alaska

by Anja Kade, Donald A. Walker and Martha K. Raynolds, Fairbanks, Alaska

with 24 figures, 12 tables and 1 appendix

Abstract. Nonsorted circles and earth hummocks are important landscape components of the arctic tundra. Here we describe the vegetation on these frost-heave features at seven study sites along a N-S-transect from the Arctic Ocean to the Arctic Foothills, Alaska. We established 117 relevés in frost-heave features and surrounding tundra and classified the vegetation according to the Braun-Blanquet sorted-table method. We used Detrended Correspondence Analysis to analyze relationships between vegetation and environmental variables. We identified nine communities: *Braya purpurascens-Puccinellia angustata* community (dry nonsorted circles, subzone C); *Dryas integrifolia-Salix arctica* community (dry tundra, subzone C); Salici rotundifoliae-Caricetum aquatilis ass. nov. (moist coastal tundra, subzone C); Junco biglumis-Dryadetum integrifoliae ass. nov. (moist nonsorted circles, subzone D); Dryado integrifoliae-Caricetum bigelowii Walker et al. 1994 (moist tundra, subzone D); *Scorpidium scorpioides-Carex aquatilis* community (wet tundra, subzone D); Cladino-Vaccinietum vitis-idaeae ass. nov. (dry nonsorted circles and earth hummocks, subzone E); Sphagno-Eriophoretum vaginati Walker et al. 1994 (moist tundra, subzone E); and *Anthelia juratzkana-Juncus biglumis* community (wet nonsorted circles, subzone E).

The DCA 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. Thawing of permafrost and a possible shift in plant community composition due to global warming could lead to a decline in frost-heave features and result in the loss of landscape heterogeneity.

Keywords: biocomplexity, Braun-Blanquet classification, Detrended Correspondence Analysis, earth hummocks, frost heave, nonsorted circles.

1 Introduction

The vegetation and soil patterns in many arctic tundra regions are influenced by the distribution of frost-heave features such as nonsorted circles and earth hummocks (Washburn 1980). Nonsorted circles and earth hummocks form

- **Used the Braun-Blanquet appraoch.**
- **Low Arctic: Kade, A., Walker, D.A., and Raynolds, M.K., 2005, Plant communities and soils in cryoturbated tundra along a bioclimate gradient in the Low Arctic, Alaska: Phytocoenologia, v. 35, p. 761-820.**
- **High Arctic: Vonlanthen, C.M., Walker, D.A., Raynolds, M.K., Kade, A., Kuss, H.P., Daniëls, F.J.A., and Matveyeva, N.V., 2008, Patterned-ground plant communities along a bioclimate gradient in the High Arctic, Canada: Phytocoenologia, v. 38, p. 23-63.**

Plant species and cover information for each plant community

Table 4. Community table of the *Braya purpurascens-Puccinellia angustata* community.

	typicum					Mycobilimbia lobulata var.				
Relevé No.	113	114	110	24	21	25	26	115	111	23
Altitude (m.a.s.l.)	4	6	6	12	15	10	13	6	5	7
Number of vascular taxa	3	2	2	3	2	10	9	9	11	3
Number of nonvascular taxa	2	2	1	2	0	17	18	17	16	10
Total number of taxa	5	4	3	5	2	27	27	26	27	13
Ch/D: Community										
Braya glabella ssp. purpurascens	1	+	+	1	+	+	1	1	+	+
Puccinellia angustata	+	+	+	1	+	+	+	1	+	+
Polyblastia sendtneri	+	+	+	.	.	1	2	2	1	2
D: Mycobilimbia lobulata var.										
Mycobilimbia lobulata	+	+	.	.	.	3	3	3	3	4
Lecanora epibryon	.	.	.	.	.	1	1	1	2	+
Salix ovalifolia	.	.	.	.	.	1	+	+	+	+
Fulgensia bracteata	.	.	.	r	.	+	+	+	+	+
Distichium inclinatum	.	.	.	.	.	+	1	1	1	.
Chrysanthemum integrifolium	.	.	.	.	.	+	+	+	+	.
Collema sp.	.	.	.	.	.	+	+	+	+	.
Polyblastia bryophila	.	.	.	.	.	2	2	1	.	+
Hennediella heimii var. arctica	.	.	.	.	.	1	1	1	.	+
Ctenidium procerrimum	.	.	.	.	.	+	+	.	+	.
Thamnolia subuliformis	.	.	.	.	.	+	r	.	+	.
Orthothecium varia	.	.	.	.	.	+	.	+	+	.
Bryum sp.	.	.	.	.	.	.	+	+	+	.
Cerastium beeringianum	.	.	.	.	.	.	+	+	r	.
Tortula ruralis	.	.	.	r	.	.	+	+	.	+
Draba cinerea	.	.	.	.	.	r	+	.	.	.
Potentilla uniflora	.	.	.	.	.	+	.	+	.	.
Encalypta alpina	.	.	.	.	.	.	+	.	1	.
Megaspora verrucosa	.	.	.	.	.	.	+	.	+	.
Pertusaria dactylina	.	.	.	.	.	+	.	.	+	.
Cirriphyllum cirrosum	.	.	.	.	.	+	.	.	.	+
Pedicularis capitata	.	.	.	.	.	r	r	.	.	.
Cephaloziella arctica	.	.	.	.	.	+	.	+	.	.
Lophozia collaris	.	.	.	.	.	+	.	.	+	.
Artemisia campestris ssp. borealis var. borealis	.	.	.	.	.	r	.	.	r	.
Campylium stellatum	.	.	.	.	.	.	+	+	.	.
Draba sp.	.	.	.	.	.	.	.	+	+	.
Bryoerythrophyllum recurvirostre	.	.	.	.	.	.	.	+	+	.
Encalypta sp.	.	.	.	.	.	.	.	+	.	1
Others										
Androsace chamaejasme	+	.	.	.	.	r	.	.	+	.
Cochlearia groenlandica	.	.	.	+	.	+	.	+	.	.

Single occurrences: Amblystegium serpens (rel. 25: +), Rinodina roscida (25: +), Salix arctica (26: +), Aloina brevirostris (26: +), Encalypta rhaptocarpa (26: +), Arctagrostis latifolia (26: r), Ochrolechia frigida (26: r), Juncus biglumis (115: +), Didymodon rigidulus var. icmadophilus (115: +), Ditrichum flexicaule (115: +), Dryas integrifolia (111: +), Polygonum viviparum (111: +), Saxifraga oppositifolia (111: +), Didymodon sp. (111: +), Distichium capillaceum (23: +).

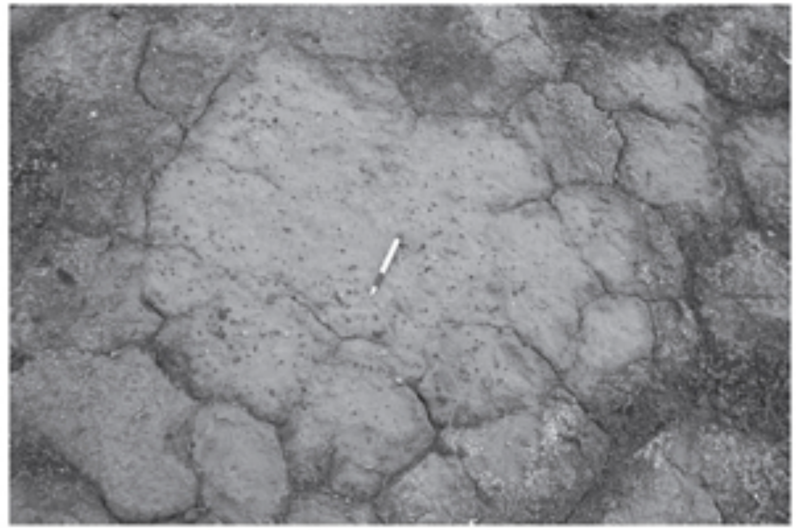


Fig. 6. *Braya purpurascens-Puccinellia angustata* community, with the typicum variant occurring on the dry nonacidic nonsorted circles and the *Mycobilimbia lobulata* variant occurring on the small polygons surrounding the central bare area. Subzone C, Howe Island, Alaska.

Classification according to Braun-Blanquet approach

Kade et al. 2005, Plant communities and soils in cryoturbated tundra along a bioclimate gradient in the Low Arctic, Alaska. *Phytocoenologia*, 35: 761-820.

Frost-boil plant communities, soil and site information

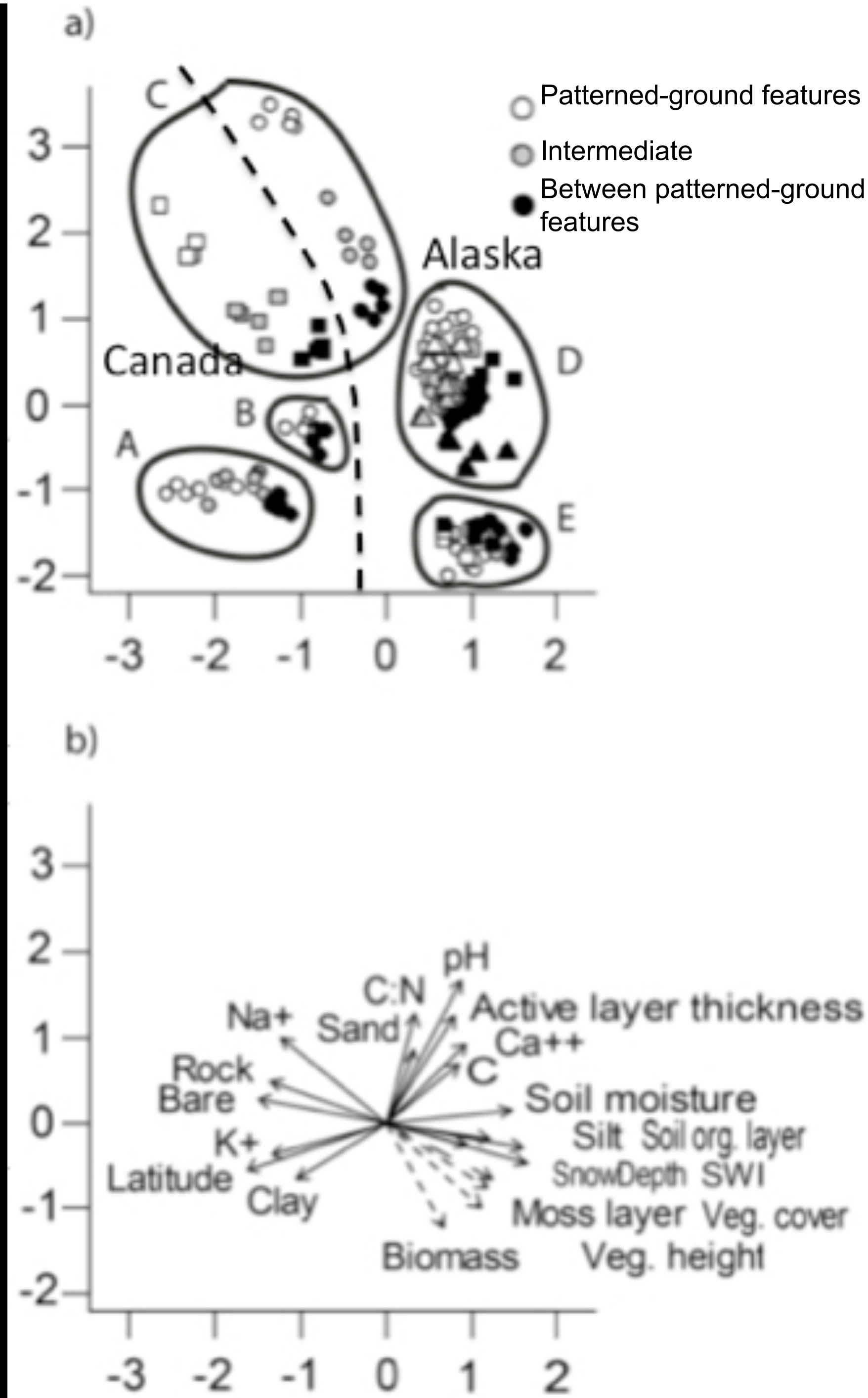
Table 3. Class, order, alliance and association or community names and habitats of the cryoturbated tundra in the Alaskan Low Arctic.

Undescribed unit
Braya purpurascens-Puccinellia angustata comm.
Nonsorted circles and small polygons; dry nonacidic tundra; subzone C
C. Carici rupestris-Kobresietea bellardii Ohba 1974
O. Kobresio-Dryadetalia (Br.-Bl.1948) Ohba 1974
A. Dryadion integrifoliae Ohba ex Daniëls 1982
Dryas integrifolia-Salix arctica comm.
Stable, dry nonacidic tundra; subzone C
Junco biglumis-Dryadetum integrifoliae ass. nov.
Nonsorted circles; moist nonacidic tundra; subzone D
Dryado integrifoliae-Caricetum bigelowii Walker et al. 1994
Stable, moist nonacidic tundra; subzone D
C. Scheuchzerio-Caricetea nigrae (Nordh. 1936) Tx. 1937
O. Scheuchzerietalia palustris Nordh. 1936
A. Caricion lasiocarpae Vanden Berghen ap. Lebrun et al. 1949
Salici rotundifoliae-Caricetum aquatilis ass. nov.
Stable, moist nonacidic coastal tundra; subzone C
Scorpidium scorpioides-Carex aquatilis comm.
Stable, wet nonacidic tundra; subzone D
C. Loiseleurio-Vaccinietea Eggler 1952
O. Rhododendro-Vaccinietalia Br.-Bl. ap. Br.-Bl. & Jenny 1926
(A. Loiseleurio-Diapension (Br.-Bl. Et al. 1939) Daniëls 1982?)
Cladino-Vaccinietum vitis-idaeae ass. nov.
Nonsorted circles and earth hummocks; moist acidic tundra; subzone E
Sphagno-Eriophoretum vaginati Walker et al. 1994
Stable, moist acidic tundra; subzone E
C. Salicetea herbaceae Br.-Bl. 1947
O. Salicetalia herbaceae Br.-Bl. 1926
A. Saxifrago-Ranunculion nivalis Nordh. 1943 emend. Dierß. 1984
Anthelia juratzkana-Juncus biglumis comm.
Nonsorted circles; moist acidic tundra; subzone E

Table 1. Environmental variables and soil physical and chemical properties for the plant associations and communities of the cryoturbated tundra. Mean with standard error in parentheses.

	Braya purpurascens-Puccinellia angustata comm.	Dryas integrifolia-Salix arctica comm.	Salici rotundifoliae-Caricetum aquatilis ass.	Junco biglumis-Dryadetum integrifoliae ass.	Dryado integrifoliae-Caricetum bigelowii ass.	Scorpidium scorpioides-Carex aquatilis comm.	Cladino-Vaccinietum vitis-idaeae ass.	Sphagno-Eriophoretum vaginati ass.	Anthelia juratzkana-Juncus biglumis comm.
Thaw depth (cm)	79.4 (1.1)	65.0 (1.4)	28.0 (0.3)	88.1 (1.4)	64.9 (1.9)	70.0 (1.8)	60.3 (0.9)	33.6 (1.6)	59.8 (1.9)
Snow depth (cm)	8.1 (2.0)	13.3 (2.7)	19.2 (2.6)	27.0 (1.9)	39.8 (2.5)	58.6 (7.4)	39.7 (4.6)	60.1 (4.4)	63.2 (0.9)
O-horizon depth (cm)	0.0 (0.0)	0.4 (0.2)	26.8 (1.2)	0.2 (0.1)	15.3 (1.5)	25.4 (0.9)	6.4 (1.6)	11.9 (1.0)	0.0 (0.0)
Bare soil (%)	55.0 (11.8)	0.0 (0.3)	0.1 (0.1)	26.3 (4.8)	0.3 (0.2)	2.4 (1.1)	0.0 (0.0)	0.0 (0.0)	10.6 (4.2)
Soil moisture (vol.-%)	28.3 (2.9)	37.3 (2.6)	47.1 (0.4)	39.2 (0.9)	45.2 (2.5)	49.0 (1.9)	35.8 (1.6)	44.1 (1.3)	41.8 (3.3)
Bulk density (g/cm^3)	1.11 (0.04)	0.79 (0.03)	0.82 (0.02)	1.35 (0.04)	1.23 (0.07)	1.34 (0.04)	0.95 (0.05)	1.07 (0.04)	1.13 (0.04)
Sand content (%)	52.1 (3.3)	65.3 (2.3)	36.8 (1.6)	44.9 (2.7)	45.3 (3.3)	43.3 (2.7)	29.8 (1.4)	33.4 (1.9)	28.6 (1.9)
Silt content (%)	31.8 (2.3)	30.1 (2.6)	45.7 (2.0)	34.9 (2.6)	40.8 (3.0)	46.6 (5.8)	44.4 (1.1)	44.9 (1.1)	43.6 (1.5)
Clay content (%)	16.1 (3.9)	4.6 (0.8)	17.5 (2.2)	20.2 (0.6)	13.9 (1.2)	10.1 (3.2)	25.8 (0.8)	21.7 (1.8)	27.8 (1.8)
Soil pH	8.3 (0.1)	7.9 (0.1)	6.5 (0.1)	8.1 (0.1)	7.9 (0.1)	7.7 (0.1)	5.0 (0.1)	5.3 (0.1)	5.2 (0.1)
Total C (%)	4.77 (0.31)	6.30 (0.24)	5.34 (0.11)	5.1 (0.21)	5.78 (0.26)	5.42 (0.83)	3.73 (0.39)	3.46 (0.28)	2.68 (0.55)
Total N (%)	0.11 (0.01)	0.18 (0.03)	0.19 (0.02)	0.18 (0.01)	0.29 (0.03)	0.26 (0.05)	0.21 (0.02)	0.21 (0.02)	0.15 (0.04)
Available Ca^{2+} (me/100g)	39.8 (1.4)	48.3 (1.8)	22.0 (0.8)	67.3 (6.7)	53.2 (2.7)	40.6 (8.3)	5.4 (0.9)	9.2 (0.5)	6.0 (0.9)
Available Mg^{2+} (me/100g)	2.35 (0.12)	1.78 (0.15)	1.14 (0.08)	1.7 (0.18)	1.86 (0.21)	1.20 (0.12)	0.76 (0.10)	1.59 (0.07)	1.07 (0.11)
Available K^{+} (me/100g)	0.18 (0.01)	0.14 (0.02)	0.11 (0.01)	0.12 (0.01)	0.18 (0.02)	0.18 (0.02)	0.10 (0.01)	0.07 (0.01)	0.08 (0.01)
Available Na^{+} (me/100g)	3.18 (0.61)	0.32 (0.14)	1.42 (0.10)	0.05 (0.01)	0.06 (0.01)	0.06 (0.01)	0.02 (0.01)	0.02 (0.01)	0.02 (0.01)

Kade et al. 2005, Plant communities and soils in cryoturbated tundra along a bioclimate gradient in the Low Arctic, Alaska. Phytocoenologia, 35: 761-820.



Ordination of zonal patterned ground vegetation: controlling environmental gradients

- NMDS ordination.
- Clear gradient of vegetation response to cryoturbation within each subzone and clear floristic separation between subzones.
- But no clear overall controlling factors for the whole data set.
- Floristic separation between Alaska and Canada portions of the gradient due to different floristic provinces, and substrate differences.

Walker, D.A., Kuss, P., et al., 2011 (in revision), Vegetation and patterned-ground relationships along the Arctic bioclimate gradient in North America Applied Vegetation Science.

Biomass for each relevé was used to develop landscape-level biomass for each grid.

Table 4. Aboveground Plant Biomass Sampled Along a North American Arctic Transect[a]

Grid	Grid Biomass, kg/100 m^2	Biomass of Individual Vegetation Types, kg/100 m^2										
		B1a	B1b	B1c	G1	G2	G3	G4	P1a	P1b	S1	W2
is-d	1.25	0	0.9		36.9							
is-z	17.13	0	3.9		36.9							
is-m	23.17	1.9	16.6		36.8							
mb-d	9.17	0.7	10.7						22.5			
mb-z	14.99	0	5.8			31.2						
gc-d	14.25	0.4	6.6						46.8			
gc-z	30.28	0.4	6.6						46.8			
gc-m	27.08	0.1	6.6				41.2					29.1
hi-z	33.33	0.2	0.2						80.9			
wd-z	61.82						61.8					
dh-z	33.17		9.5				41.6		18.5	18.5		41.6
fb-d	48.96		4.8				62.8		36.2			
fb-z	43.40		4.8				48.3		36.2	36.3		42.1
fb-w	40.39		11.5				48.3		36.3			42.1
sn-z1	44.19		3.7				60.9		41.1	41.1		
sn-z2	56.30		3.7				60.9			41.1		60.9
sa-z	75.10			10.0				75.8		48.1	73.4	
hv-d	73.54			10.0				75.6		48.1	61.1	
hv-z	72.08			10.0				75.6		48.1	61.1	
hv-m	73.44			10.0				75.6		48.1	61.1	

[a]Grid biomass for 10 × 10-m grids (kg/100 m^2) are based on relevé biomass of vegetation types multiplied by proportion of vegetation types within each grid (see Figure 7), and biomass density (kg/100 m^2) of individual vegetation types on each grid. See Figure 5 and Table 3 for description of vegetation type codes.

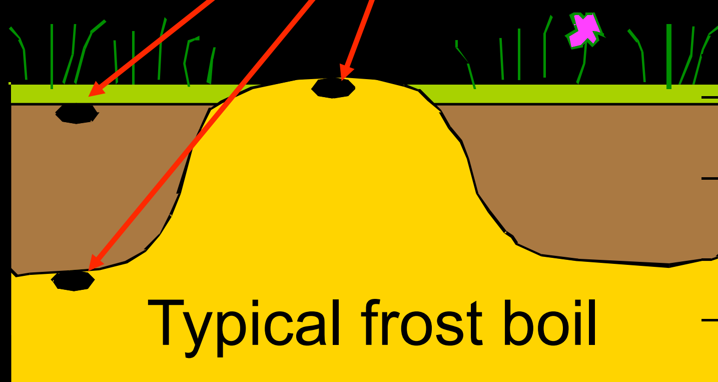
Raynolds, M.K., Walker, D.A., Munger, C.A., Vonlanthen, C.M., and Kade, A.N.a., 2008, A map analysis of patterned-ground along a North American Arctic Transect: Journal of Geophysical Research - Biogeosciences, v. 113, p. 1-18.

To examine the insulative effect of vegetation: *n*-factor was determined for each vegetation type.

i-button data loggers

Loggers:

1. base of live vegetation
2. base of organic horizons
3. center of circle



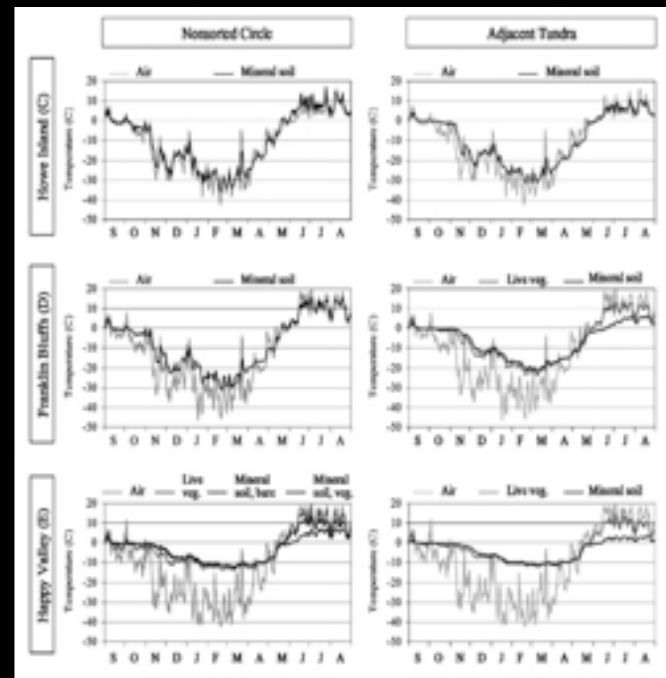


Figure 4 Daily mean temperatures from 1 September 2003 to 31 August 2004 for air (2 m height), under live vegetation and at the surface of the mineral soil for nonsorted circles and adjacent tundra at the three study sites.

Kade, A., Romanovsky, V.E., and Walker, D.A., 2006, The N-factor of nonsorted circles along a climate gradient in Arctic Alaska: Permafrost and Periglacial Processes, v. 17, p. 279-289.

n-factor:

–Ratio of the degree-day total at the soil surface to the degree-day total of the air.

– Summer n factor uses thawing-degree days.

– Winter n factor uses freezing-degree days.

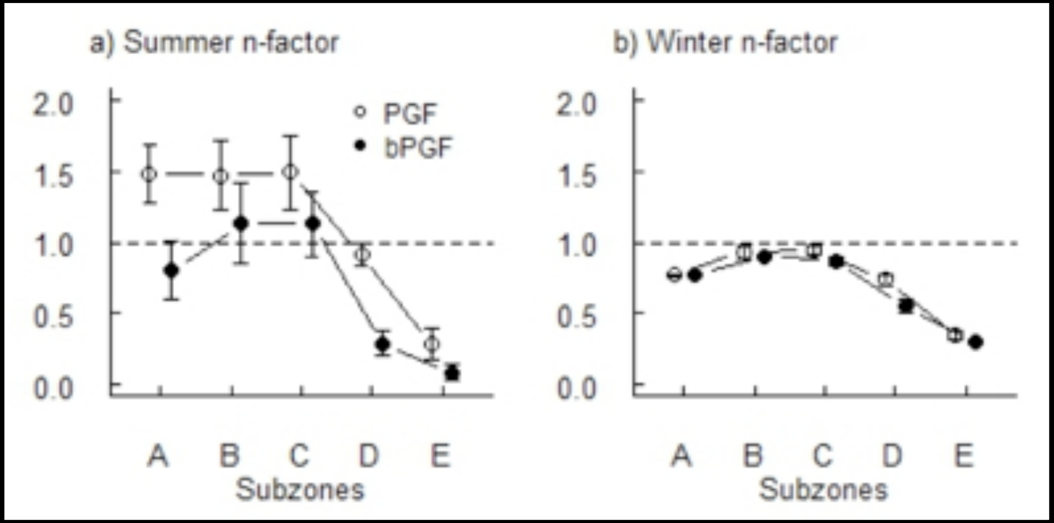
High Arctic: Mineral soil temperature warmer than air temperature because of radiative warming of the soil surface.

Low Arctic: Interboil mineral-soil temperatures are colder than air temperatures because of insulation of vegetation and organic soil.

Winter: Soil temperatures much warmer than air temperature, particularly in Low Arctic because of snow insulation.

n-factors for patterned- ground features along the NAAT

$$n = DDT_{soil} / DDT_{air}$$



Walker, D.A., Kuss, P., et al., 2011 (in revision), Vegetation and patterned-ground relationships along the Arctic bioclimate gradient in North America Applied Vegetation Science.

Experimental alteration of vegetation canopy to examine effects of vegetation on active layer and frost heave

Ph.D. project of Anja Kade

Control

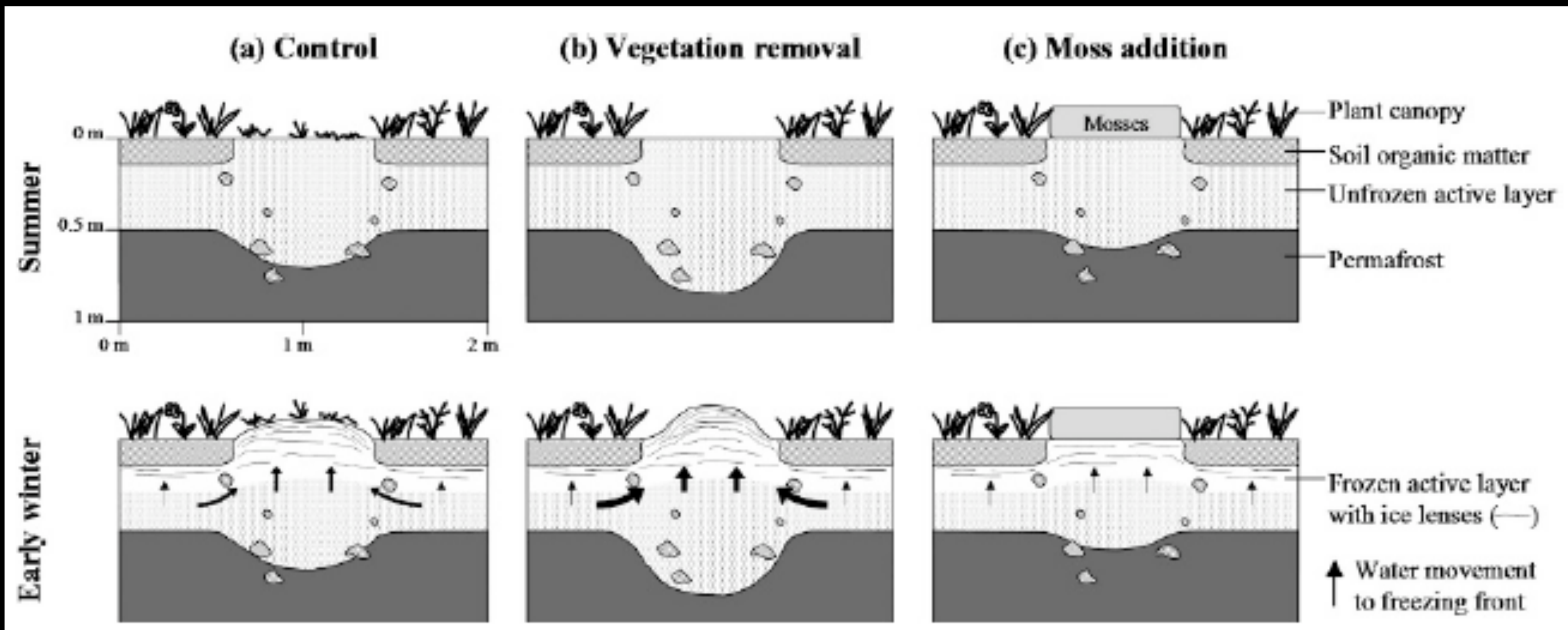
Vegetation Removal

Graminoid Transplants

Moss Carpet Transplants

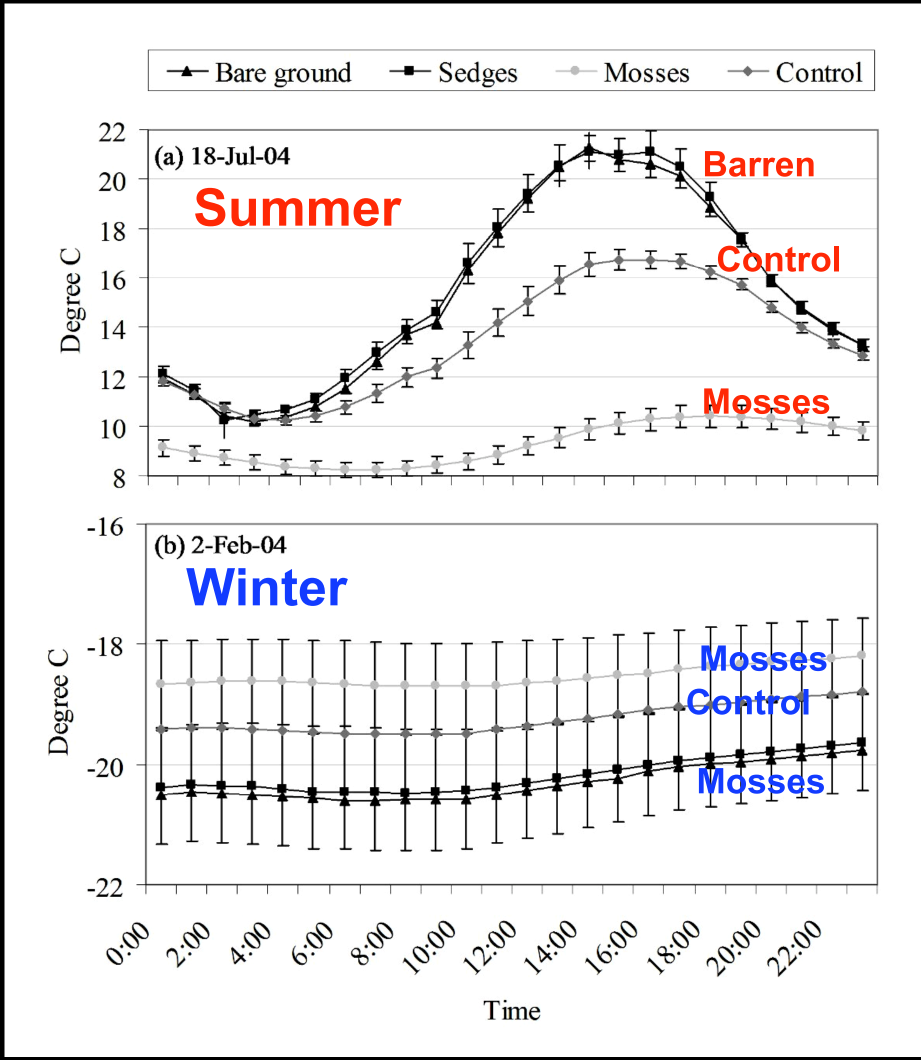
Response Variables: Frost Heave, Thaw Depth, Soil Moisture, Soil Temperature

Hypothesized effects of Kade experiment



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:

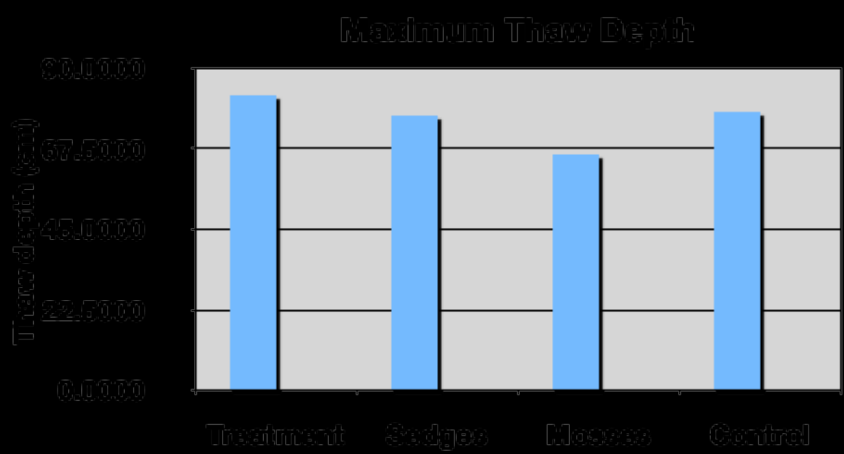
Vegetation removal: -0.9˚C (-6%)

Moss addition: +1.3˚C (+7%)

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

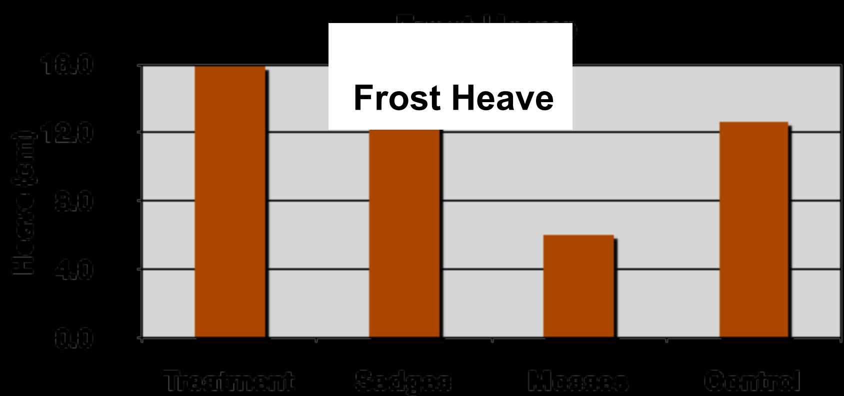
Kade and Walker, 2008, *Arctic, Alpine and Antarctic Research*

Effects vegetation on thaw depth and heave



Thaw:

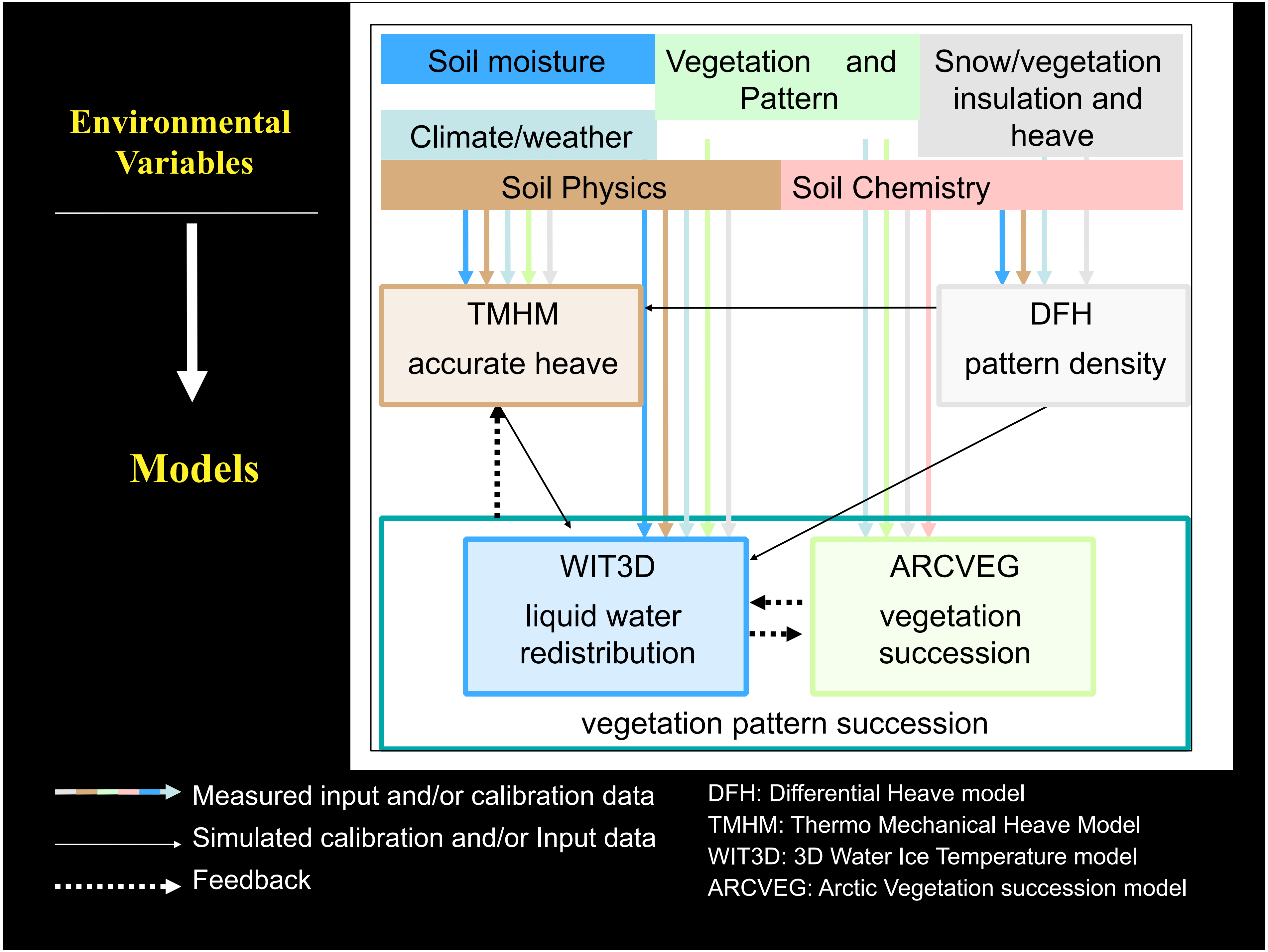
Vegetation removal: +5 cm (+6%)
Moss addition: -11 cm (-14%)



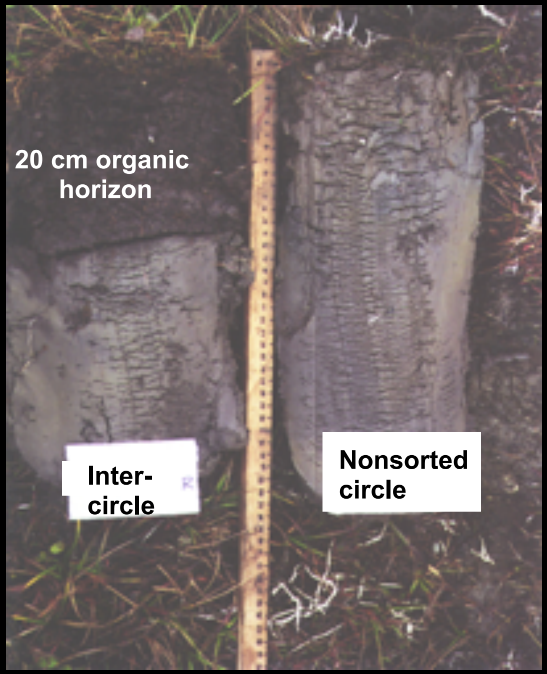
Heave:

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

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

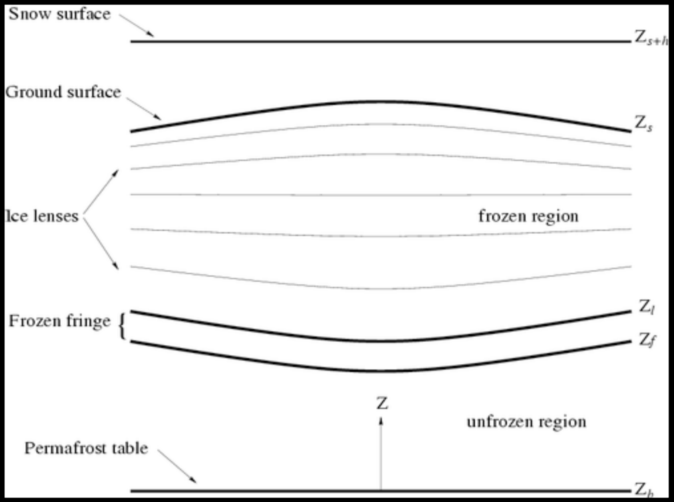

Environmental Variables
Models
Soil moisture
Vegetation and Pattern
Snow/vegetation insulation and heave
Climate/weather
Soil Physics
Soil Chemistry
TMHM
accurate heave
DFH
pattern density
WIT3D
liquid water redistribution
ARCVEG
vegetation succession
vegetation pattern succession
Measured input and/or calibration data
Simulated calibration and/or Input data
Feedback
DFH: Differential Heave model
TMHM: Thermo Mechanical Heave Model
WIT3D: 3D Water Ice Temperature model
ARCVEG: Arctic Vegetation succession model

Differential frost heave (DFH) model of frost-heave feature formation (Peterson and Krantz 2003)



Lenticular voids in soil created by ice lenses.

- Heat preferentially escapes from the surface at high points of small irregularities in the surface.
- These high points self-organize into patterns controlled by mechanical properties of the soil (e.g., texture) and active layer thickness.
- These high points are sites of increased ice-lens development, and more heave.
- Theoretically, non-sorted circles should be more closely spaced in shallowly thawed soils.



Schematic of soil undergoing top-down freezing. Ice lenses exist in the frozen region and permafrost underlies the active layer.

Modeling Components of the Project

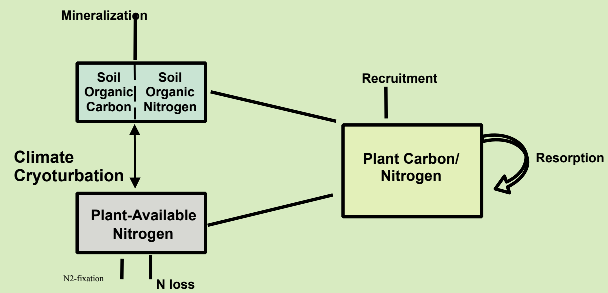
- Differential Frost Heave (DFH) model (Peterson & Krantz): Describes the self-organization of non-sorted circles in the absence of vegetation. Models the process of differential frost heave and spacing of frost features using linear instability analysis.

- Thermo-mechanical model (TMM) of frost heave (Nikolskiy et al.): Detailed simulation of heaving process within a non-sorted circle that includes mass, momentum and energy conservation laws for water, ice, and soil. Accounts for the observation that heave is considerably greater than can be accounted for by simply freezing the amount of the water in the soil.

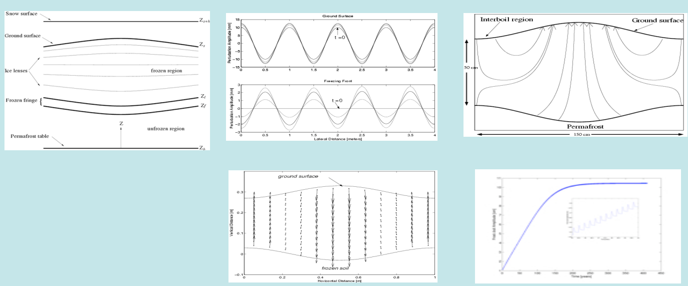
- WIT/ArcVeg (Daanen & Epstein): A 3-dimensional model of frost heave. Mainly a hydrology-heave model driven by temperature differentials and changes in vegetation patterns.

Linking modeling efforts

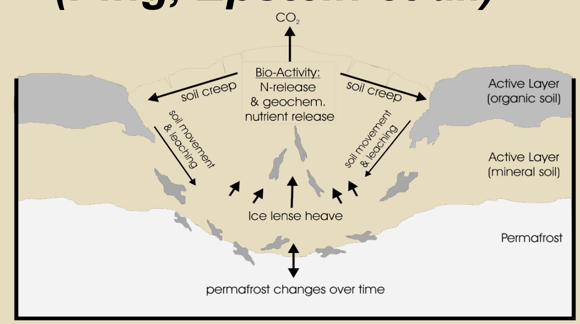
Vegetation Component (Epstein, Walker et al.)



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

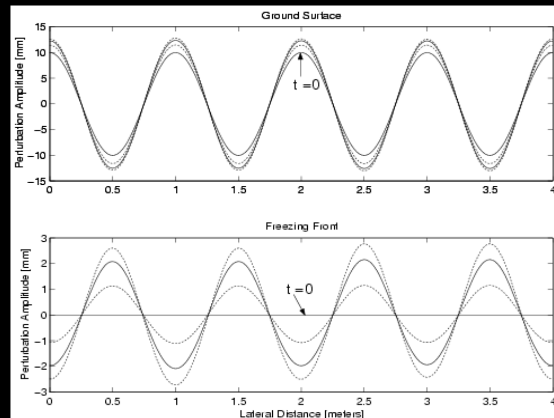


Soil Component (Ping, Epstein et al.)

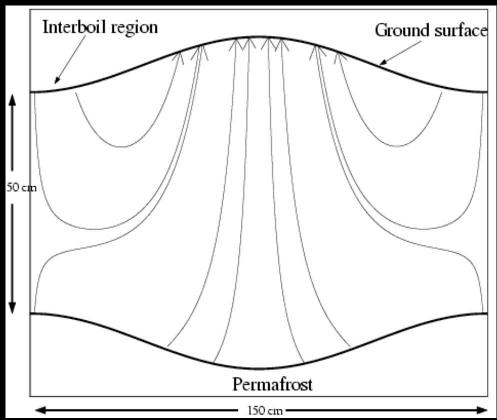


Differential Frost-Heave (DFH) Model

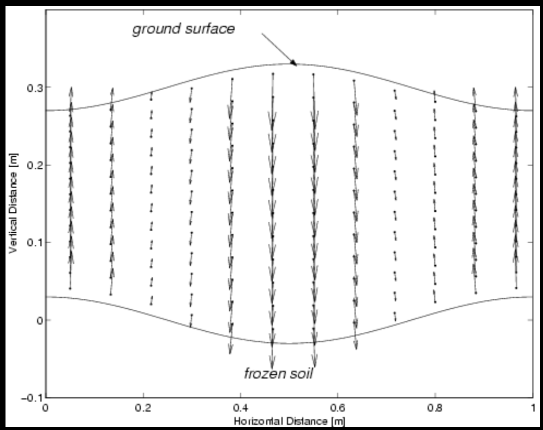
- The model successfully predicts order of magnitude heave and spacing of frost boils.
- Other predictions include effect of soil texture, air temperature, snow depth on magnitude of heave.



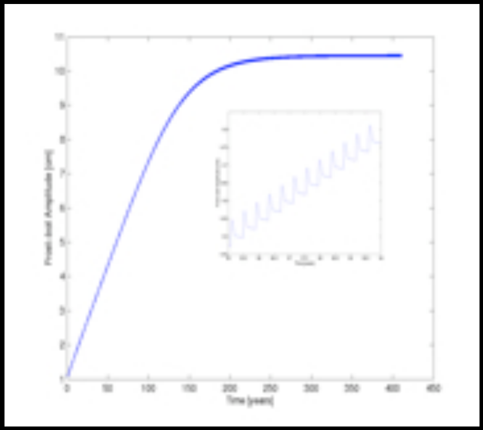
Position of ground surface and freezing fronts



Particle trajectories over several hundred years

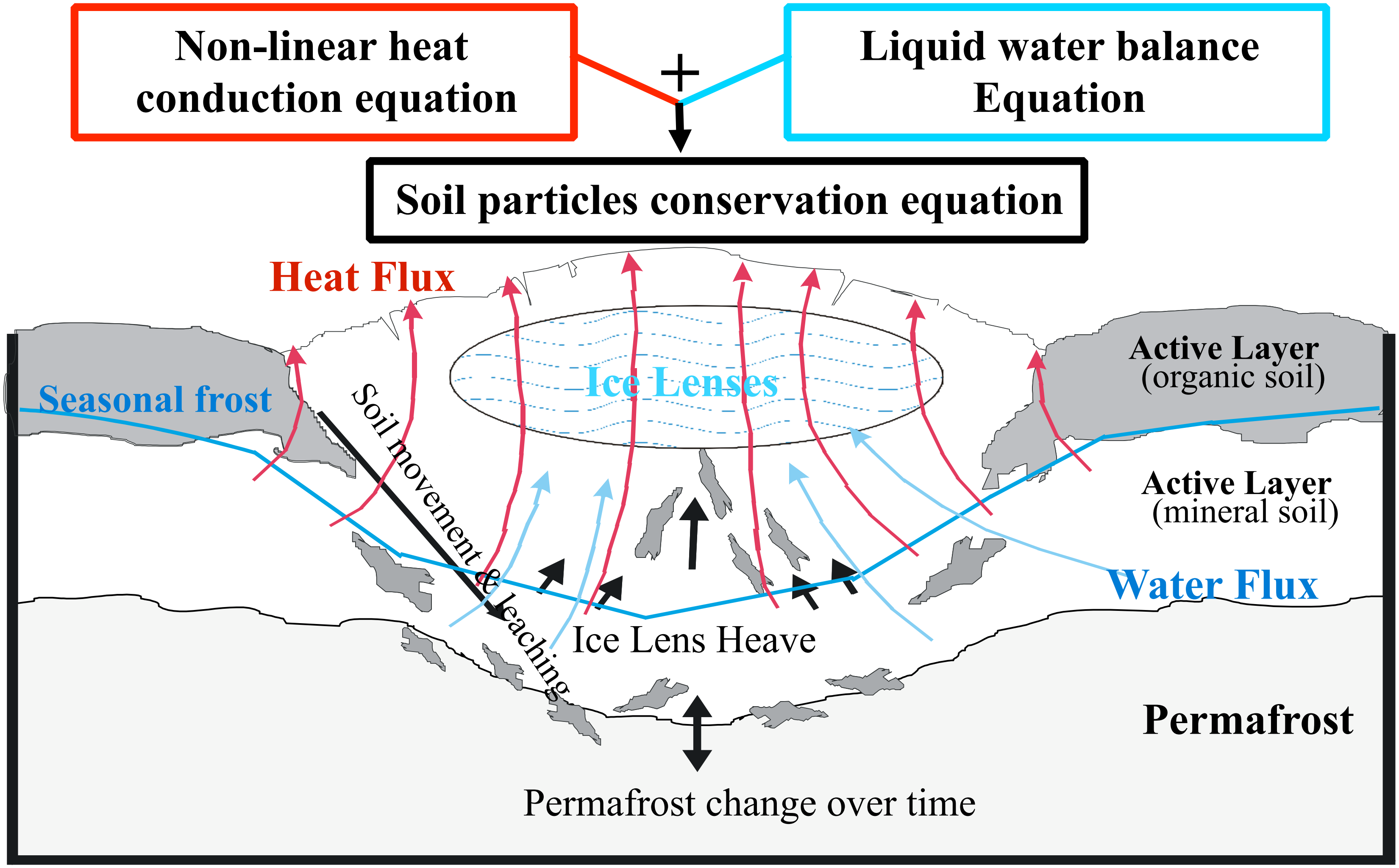


Soil creep



Time to stabilization

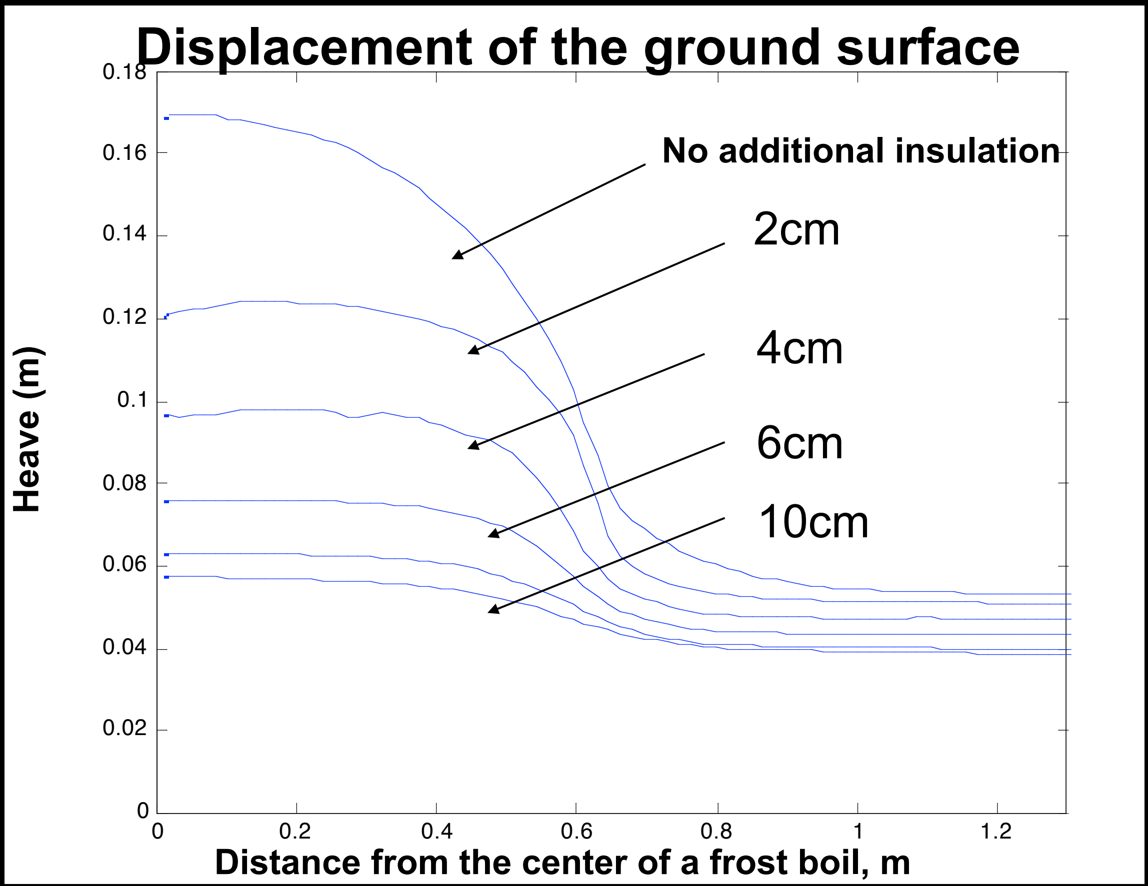
Thermo-Mechanical Model of Frost Heave



Nicolsky, D.J., Romanovsky, V.E., Tipenko, G.S., Walker, D.A. 2008. Modeling biogeophysical interactions in nonsorted circles in the Low Arctic. *Journal of Geophysical Research - Biogeosciences. 113:1-17.*

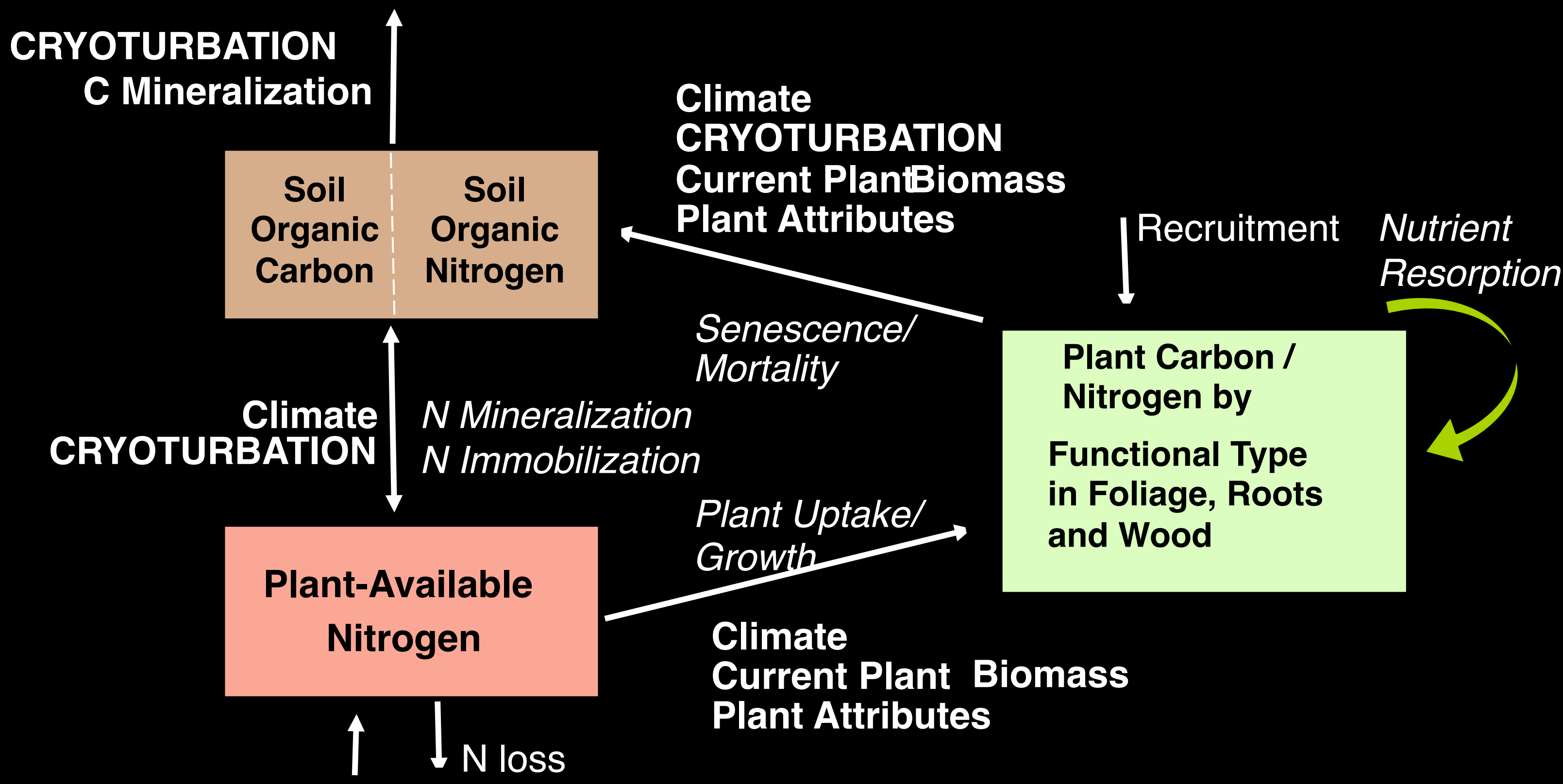
The effect of insulation:

Thermo-mechanical model of frost heave vegetation interactions



- Each blue line corresponds to the different depth of an additional insulation layer over boil.
- The insulation simulates the effect of vegetation cover on frost heave.
- Thicker vegetation layer causes better thermal insulation and lowers cryogenic suction, hence the smaller frost heave of the ground.

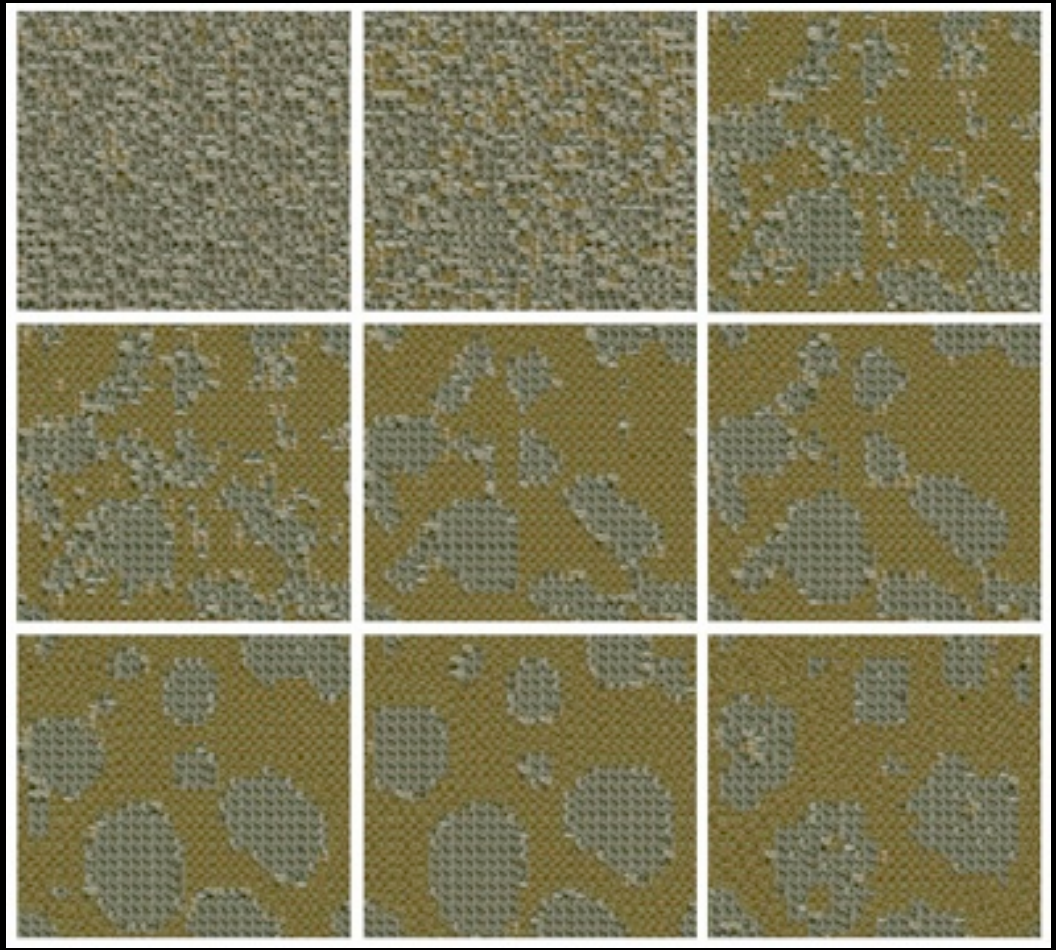
ArcVeg Model (Epstein et al. 2000)



- Simulates the interannual dynamics of tundra plant community composition and biomass.
- Parameterized for up to 20 plant growth forms.
- Based on nitrogen mass balance among pools of soil organic and inorganic nitrogen, and live plant nitrogen in live phytomass.
- Changes in temperature drive changes in net N mineralization and the length of the growing season and thereby alter the community biomass and composition.
- Climate and disturbance are stochastic forcing variables.

Modeling WIT-ArcVeg

Random vegetation
Year 1

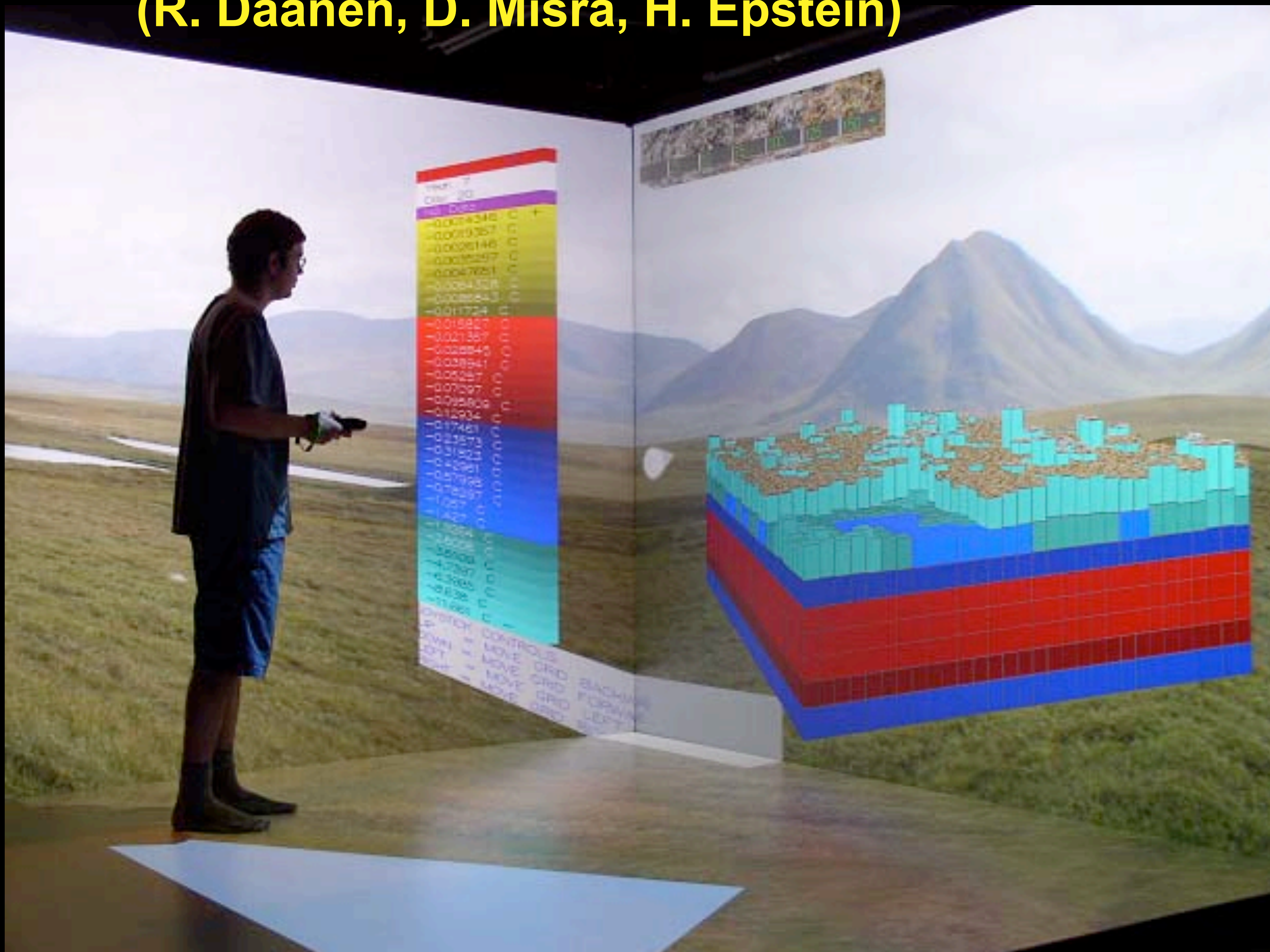


Organized vegetation
Year >1000

http://snowy.arsc.alaska.edu/WIT3D/

Daanen, R.P., Misra, D., Epstein, H., et al. 2008. Simulating nonsorted circle development in arctic tundra ecosystems. Journal of Geophysical Research - Biogeosciences. 113:1-10.

3-D Modeling of patterned-ground formation
(R. Daanen, D. Misra, H. Epstein)



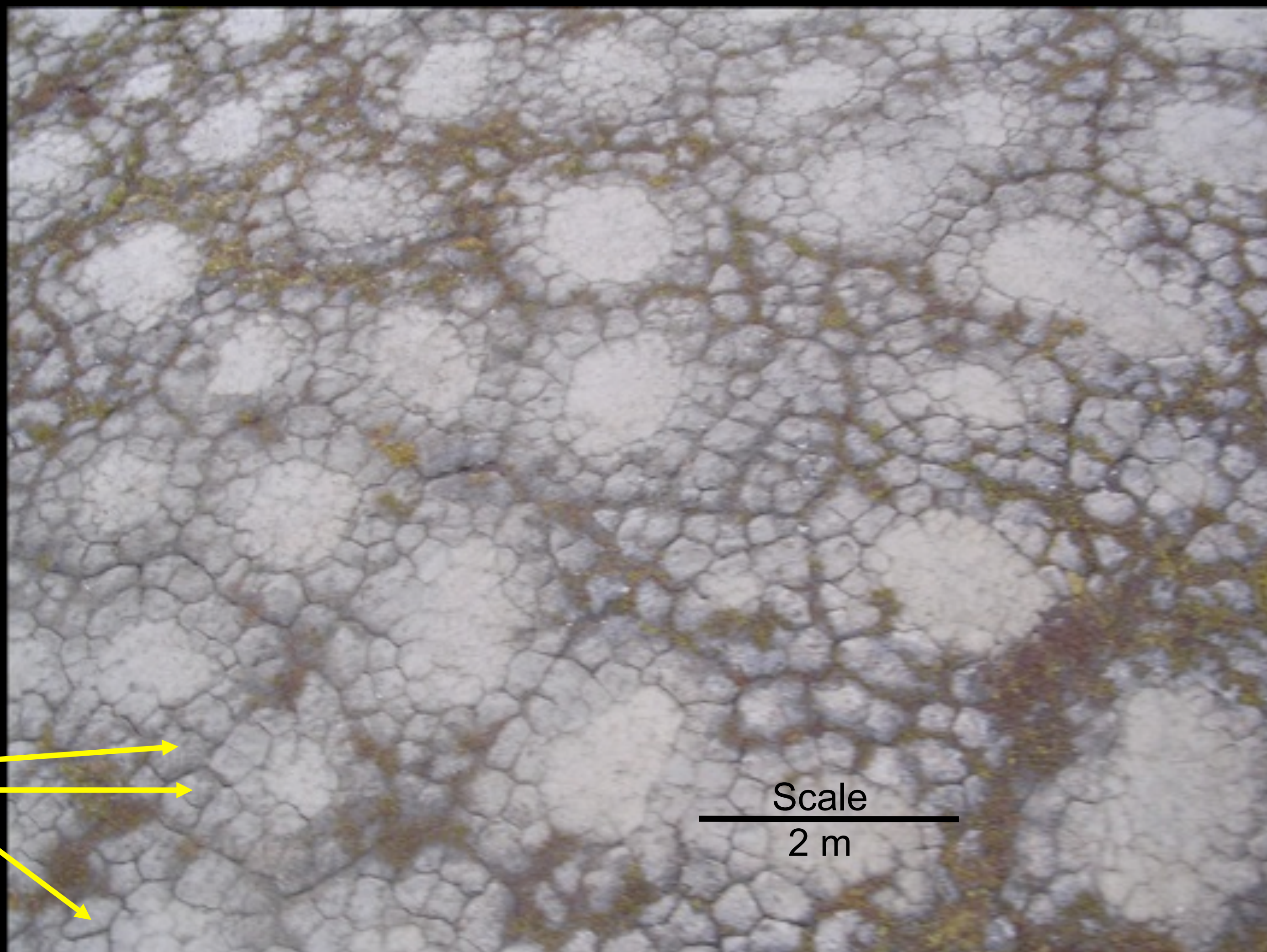
WIT3D/ArcVeg Model in ARSC Discovery Lab. Photo: Ronnie Daanen

Modeling did not address issue of cracking.

Howe Island, AK

Photo by Anja Kade

Small non-sorted polygons



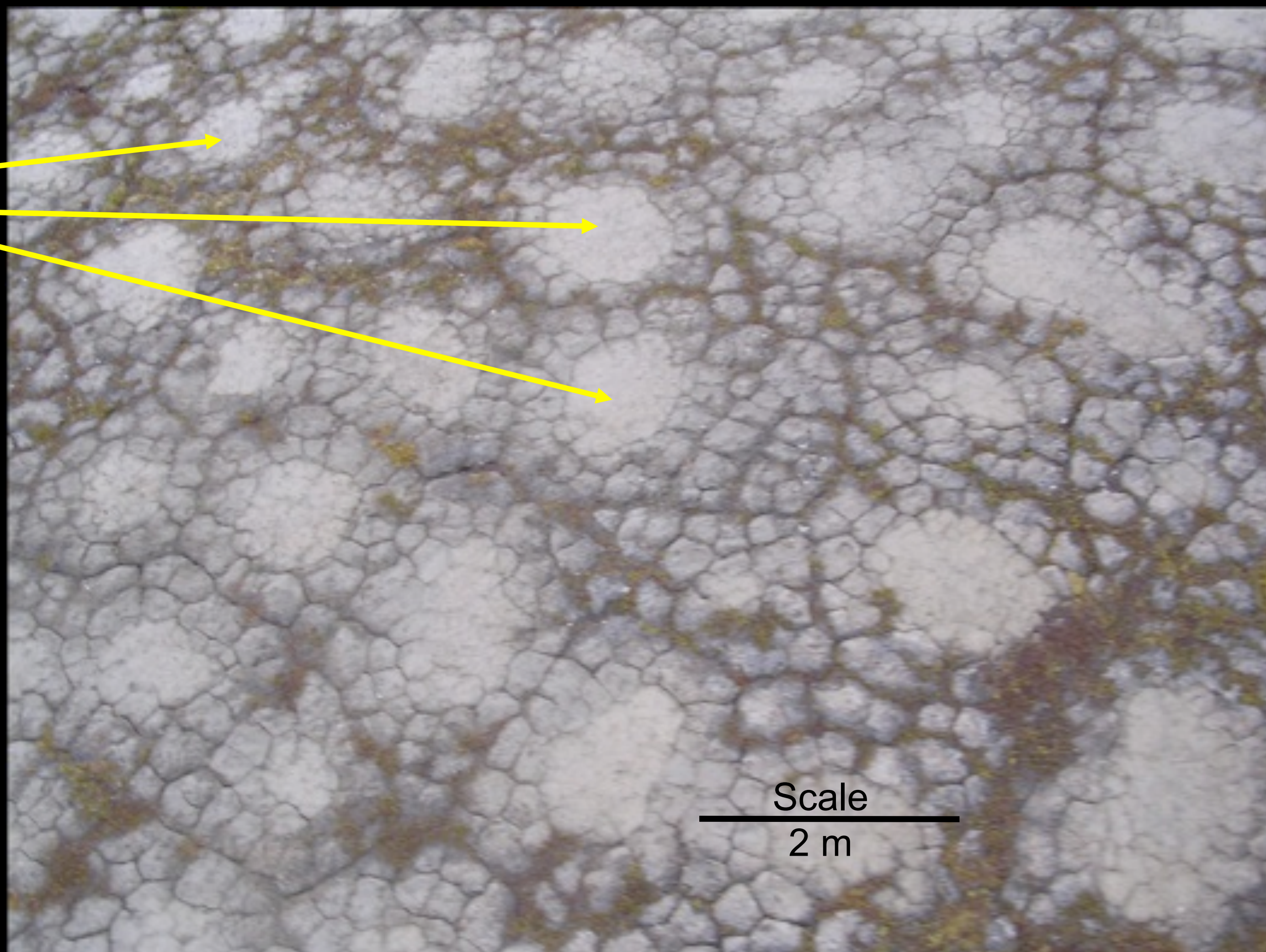
Small Non-sorted polygons (35-50 cm)

Howe Island, AK

Photo by Anja Kade

Non-sorted circles

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

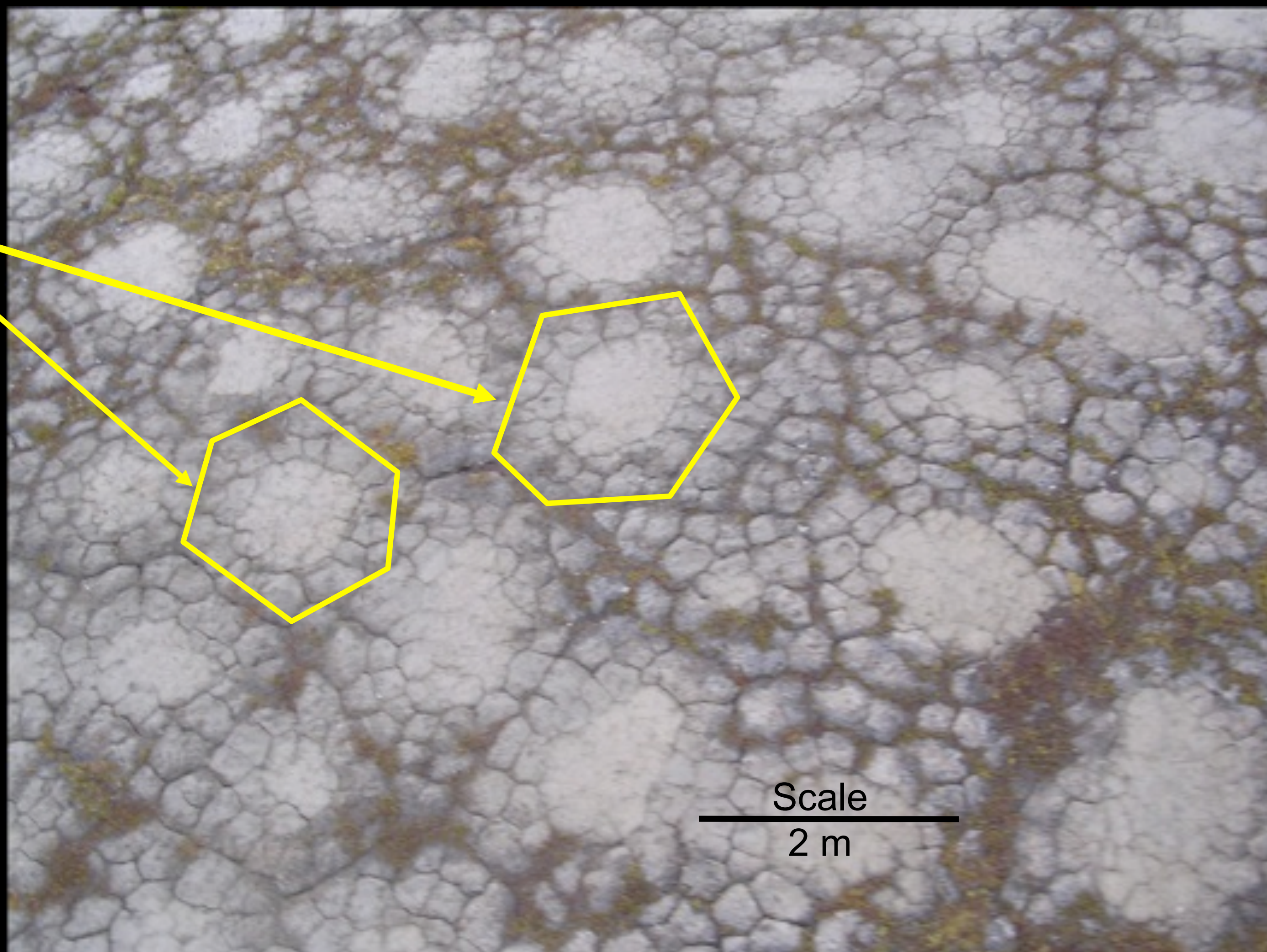


Howe Island, AK

Photo by Anja Kade

Medium-size non-sorted polygons

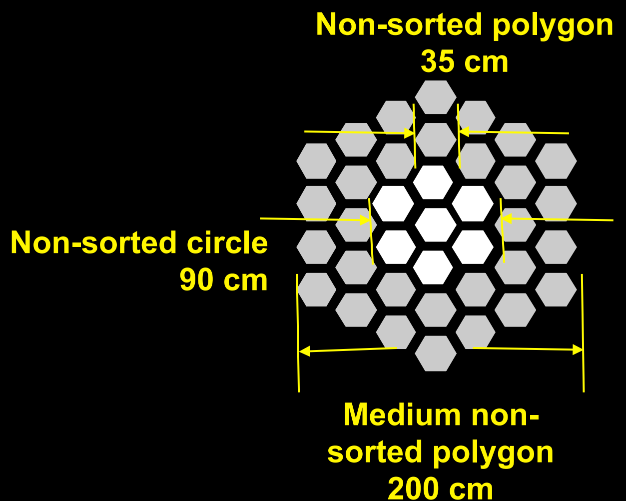
Medium non-sorted polygons (200-300 cm)

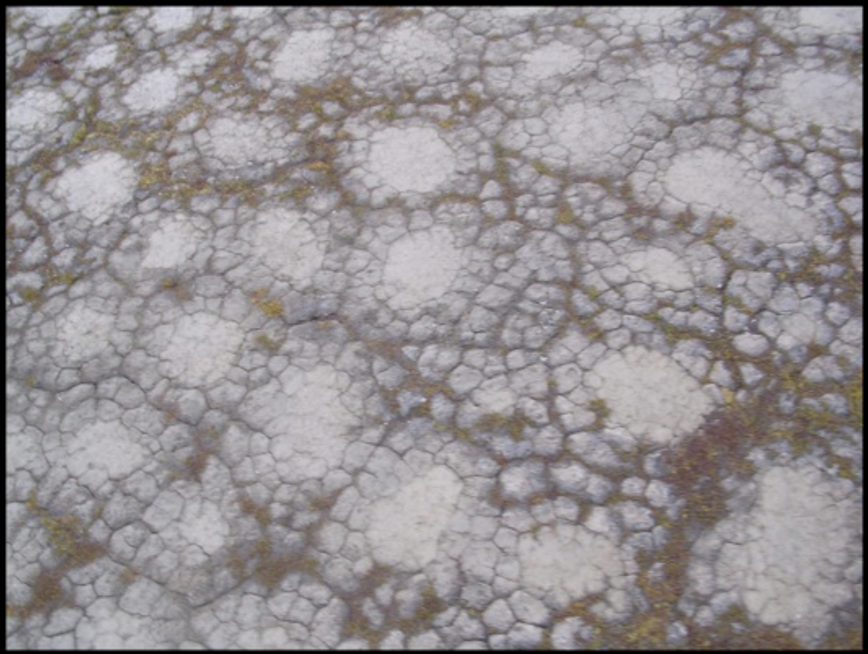


Howe Island, AK

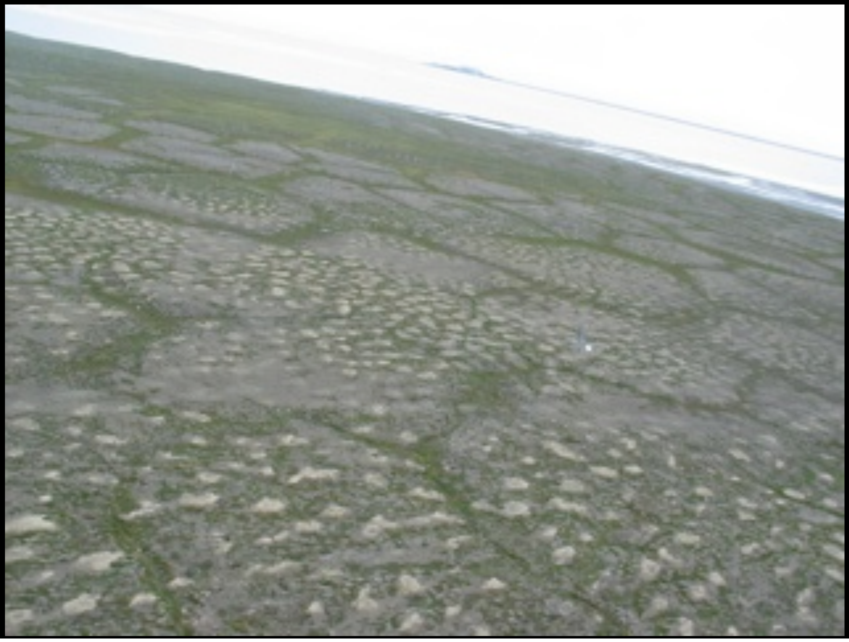
Photo by Anja Kade

Components of landscape modified by both cracking and differential heave



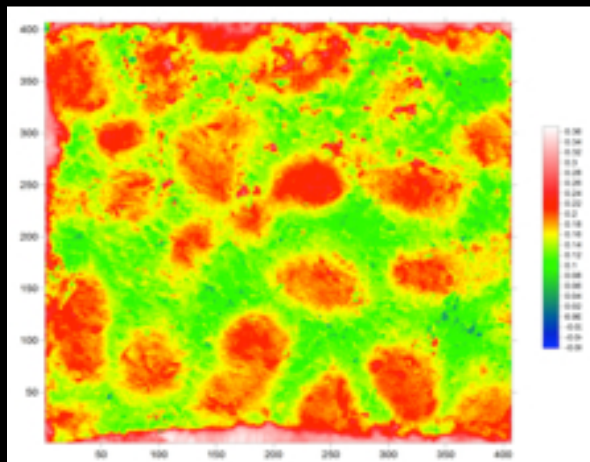


Large and small seasonal frost-crack non-sorted polygons, Howe Island. Photo: Anja Kade



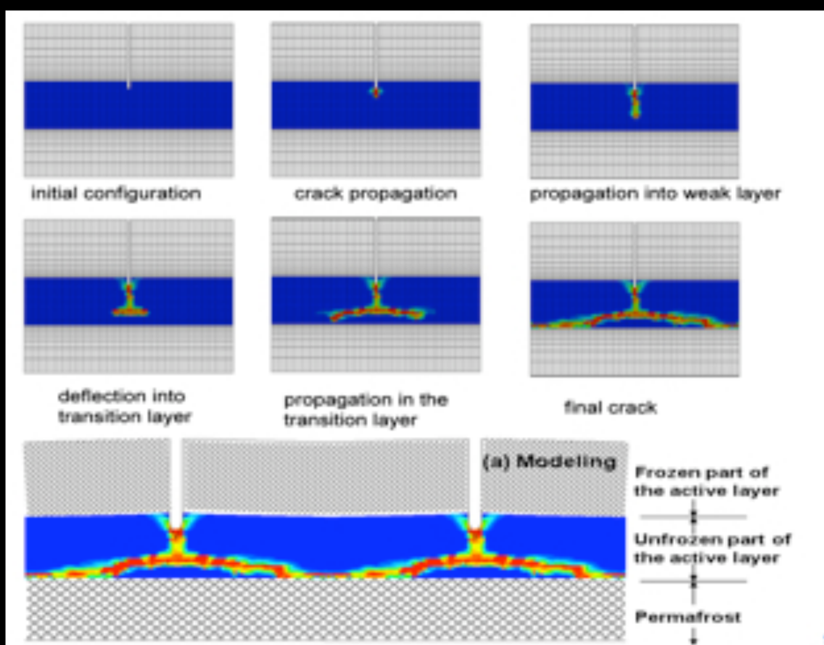
Large non-sorted permafrost crack polygons (20-30 m diameter), Howe Island
Photo: D.A. Walker

New tools for looking at complexity of patterned ground



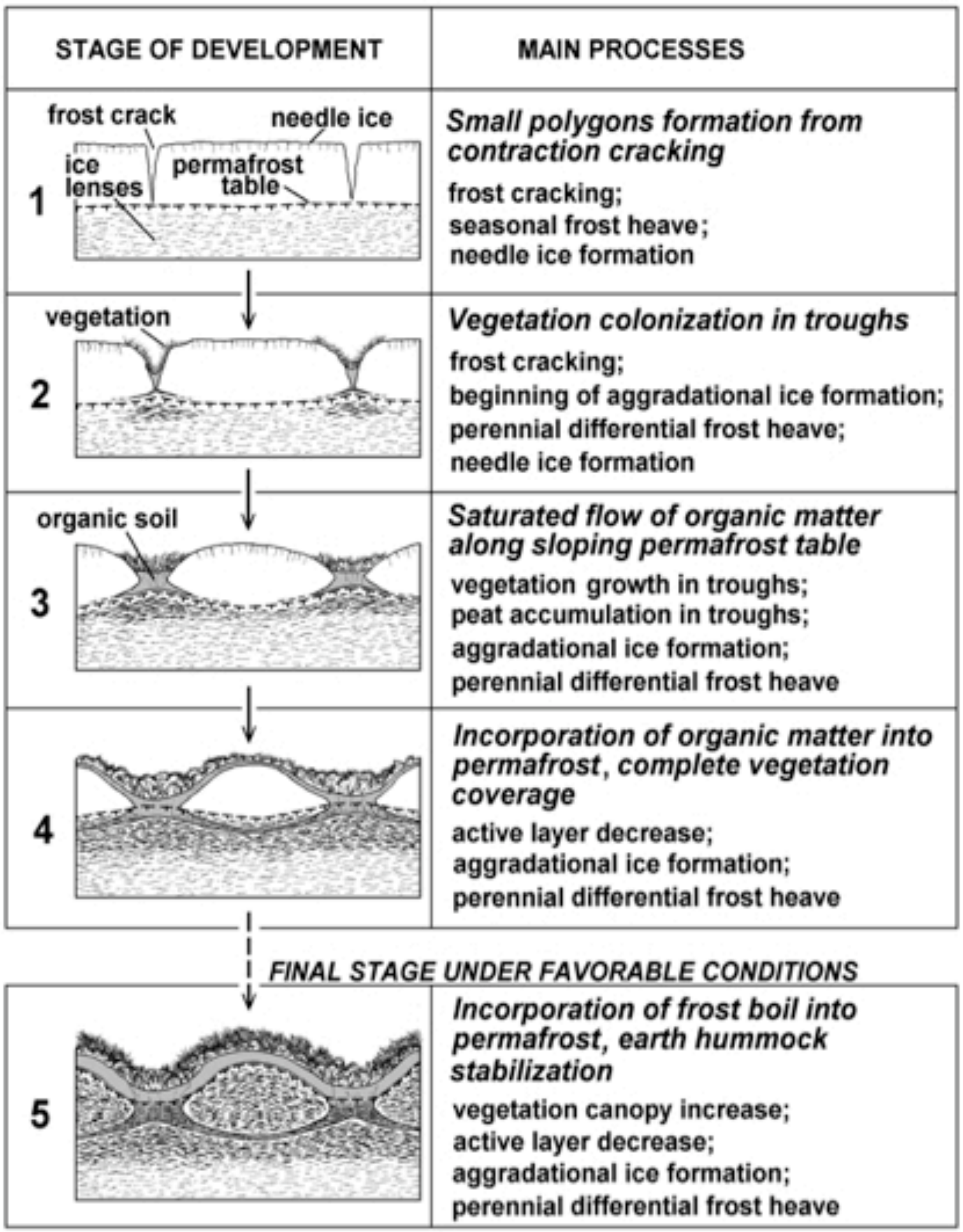
Ground-base LIDAR units for detailed 3-D views of frost heave: Daanen et al. 2010.

Has shown that the annual frost can exceed 25 cm!



Frost cracking model:
Zhang et al. (in progress):

Has replicated horizontal cracking observed at the top of the permafrost table and could help explain development of intermediate layer.



Conceptual model frost boils and earth hummock formation in relationship to permafrost dynamics

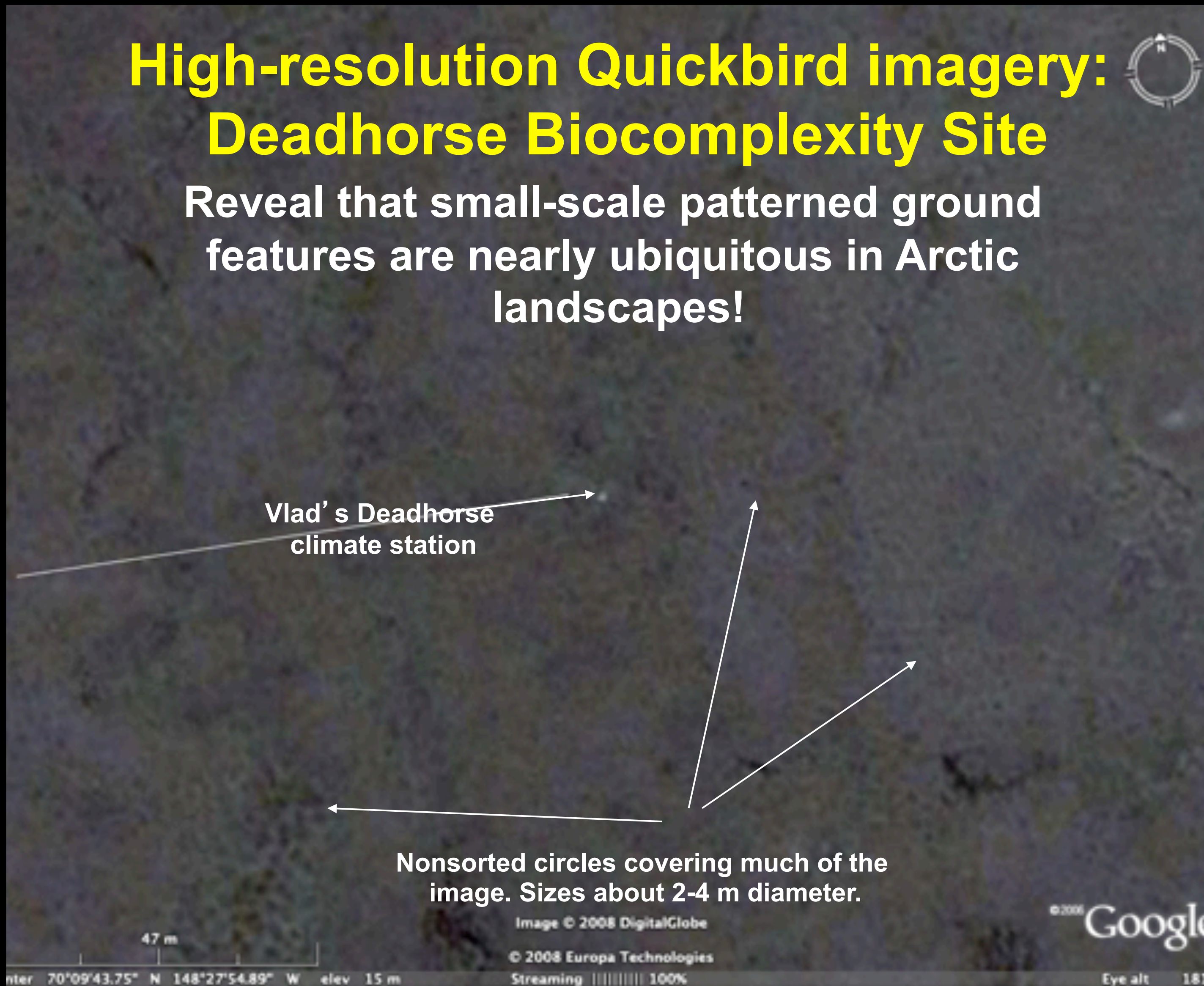
Only model that invokes the permafrost and cracking!

Others operate entirely in the active layer.

Shur, Y., Jorgenson, T., Kanevskiy, M., and Ping, C.-L., 2008, Formation of frost boils and earth hummocks, in Kane, D.I., and Hinkel, K.M., eds., Ninth Internaitonal Conference on Permaforst, Fairbanks, Institute of Northern Engineering, University of Alaska Fairbanks, p. 287-288.

High-resolution Quickbird imagery: Deadhorse Biocomplexity Site

Reveal that small-scale patterned ground features are nearly ubiquitous in Arctic landscapes!

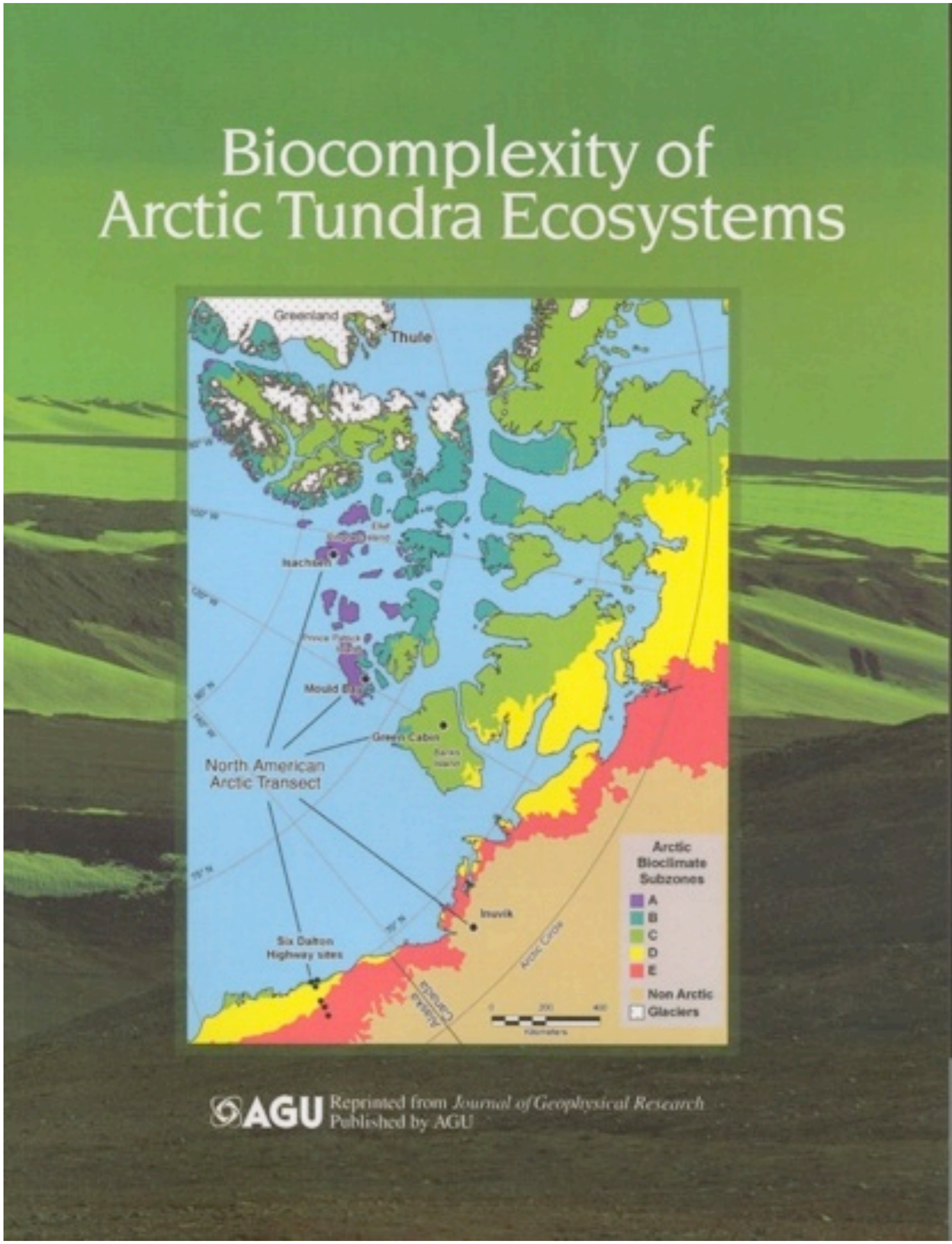


Education component


Students both learned through a course offered by Bill Gould and Grizelle Gonzalez and they worked with the research team providing labor and insights and their own research projects.
Photo: Heather Fuller

Conclusions

1. Patterned-ground morphology on zonal sites changes in predictable ways with differences in climate, soil-moisture, soil-texture, and the structure of the vegetation.
2. Contrasts in the vegetation on and between patterned-ground features is best developed in Subzones C and D. These differences drive the movement of heat and water and the development of frost heave.
3. Strong thermal, hydrological, and chemical gradients help to maintain the position of these features in the same locality over long time periods.
4. Cryoturbation of organic material and aggrading permafrost tables act to sequester large amounts of carbon within the permafrost of these ecosystems.
5. Models have replicated the patterns related to frost heave (non-sorted circles and earth hummocks). Contraction cracking will require new models.
6. The presence of non-sorted circles strongly affect a wide variety of ecosystem properties (soil temperatures, active-layer depths, carbon storage, flux rates, biodiversity, successional pathways) and determine how these systems respond to disturbances including climate change.



Synthesis of biocomplexity project

9 Articles from the North America transect:

Walker, D.A., Epstein, H.E., Romanovsky, V.E., Ping, C.L., Michaelson, G.J., Daanen, R.P., Shur, Y., Peterson, R.A., Krantz, W.B., Raynolds, M.K., Gould, W.A., Gonzalez, G., Nicolsky, D.J., Vonlanthen, C.M., Kade, A.N., Kuss, P., Kelley, A.M., Munger, C.A., Tarnocai, C.T., Matveyeva, N.V., and Daniëls, F.J.A., 2008, Arctic patterned-ground ecosystems: A synthesis of field studies and models along a North American Arctic Transect: Journal of Geophysical Research - Biogeosciences, v. 113, p. G03S01.

Photo courtesy of Martha Raynolds

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Aurora Institute
Parks Canada
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Institute of Arctic Biology, UAF

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