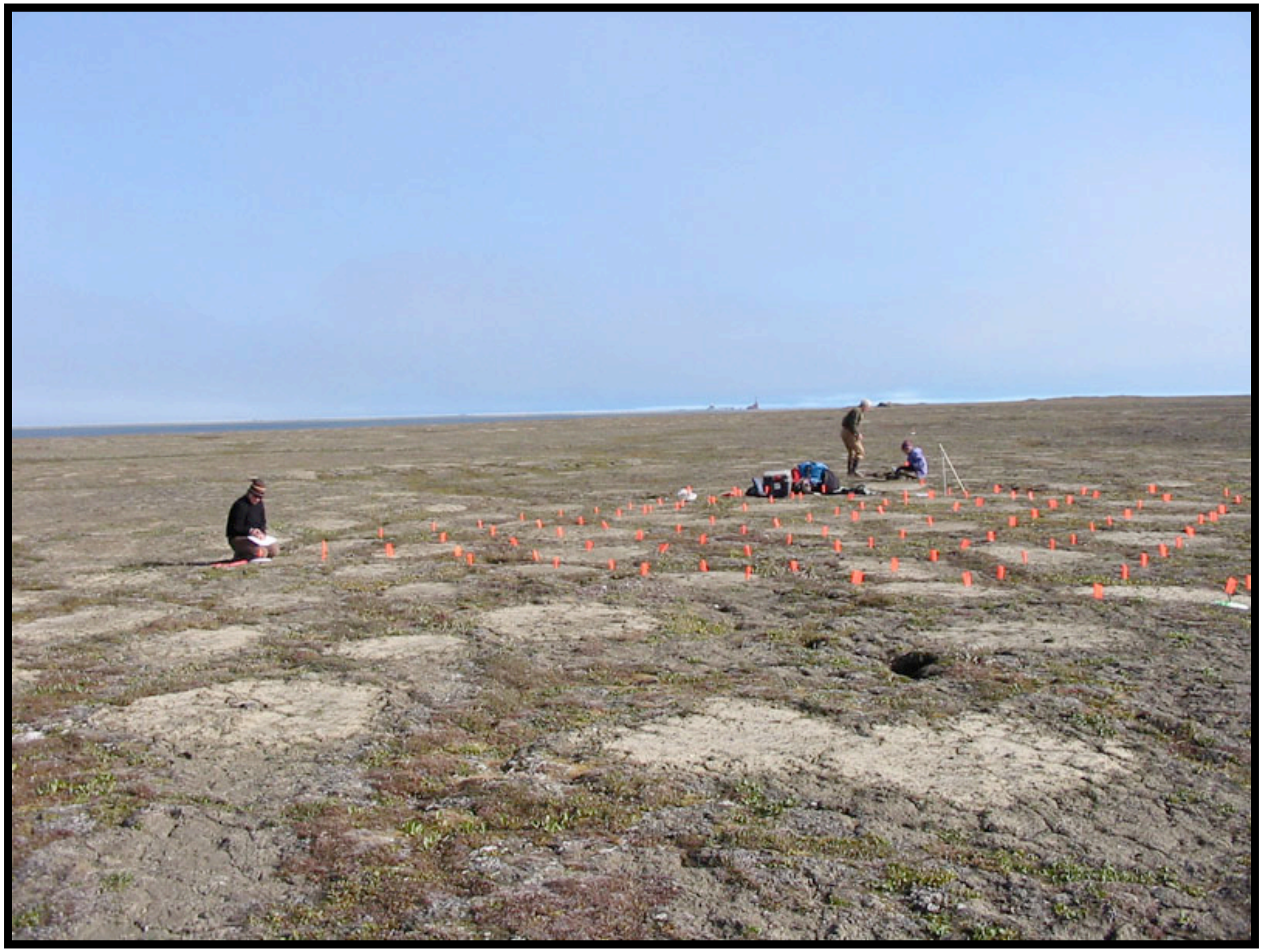
Biocomplexity of Frost-boil Ecosystems

Presented at the Arctic Forum
Washington, D.C.
May 16-17, 2002

Alaska Geobotany Center Home Page
http://www.geobotany.uaf.edu

Biocomplexity of frost-boil ecosystems



Frost boils on Howe Island, AK

Principal investigators:

Donald A. (Skip) Walker, *University of Alaska Fairbanks*

Howard E. Epstein, *University of Virginia*

William A. Gould, *International Institute of Tropical Forestry, San Juan, PR*

William B. Krantz, *University of Cincinnati*

Genadiy Tipenko, *Univeristy of Alaska Fairbanks*

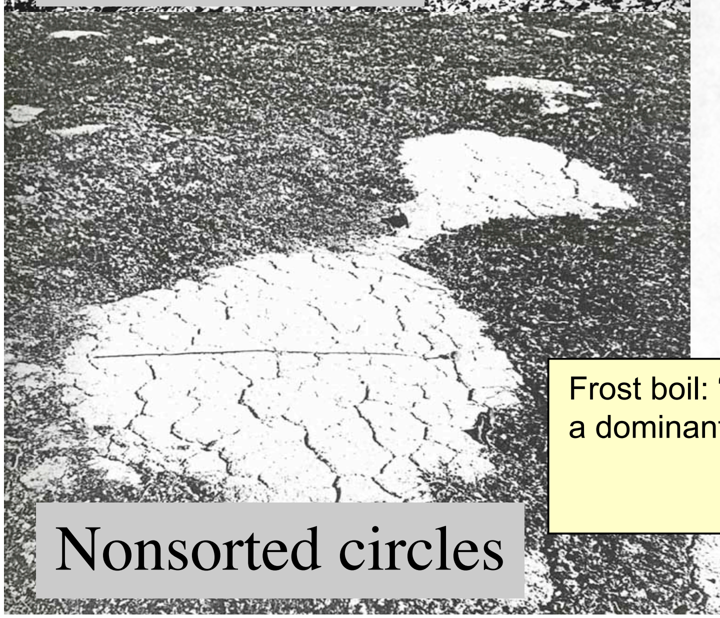
Chien-Lu Ping, *Uinversity of Alaska Fairbanks*

Vladimir Romanovsky, *University of Alaska Fairbanks*

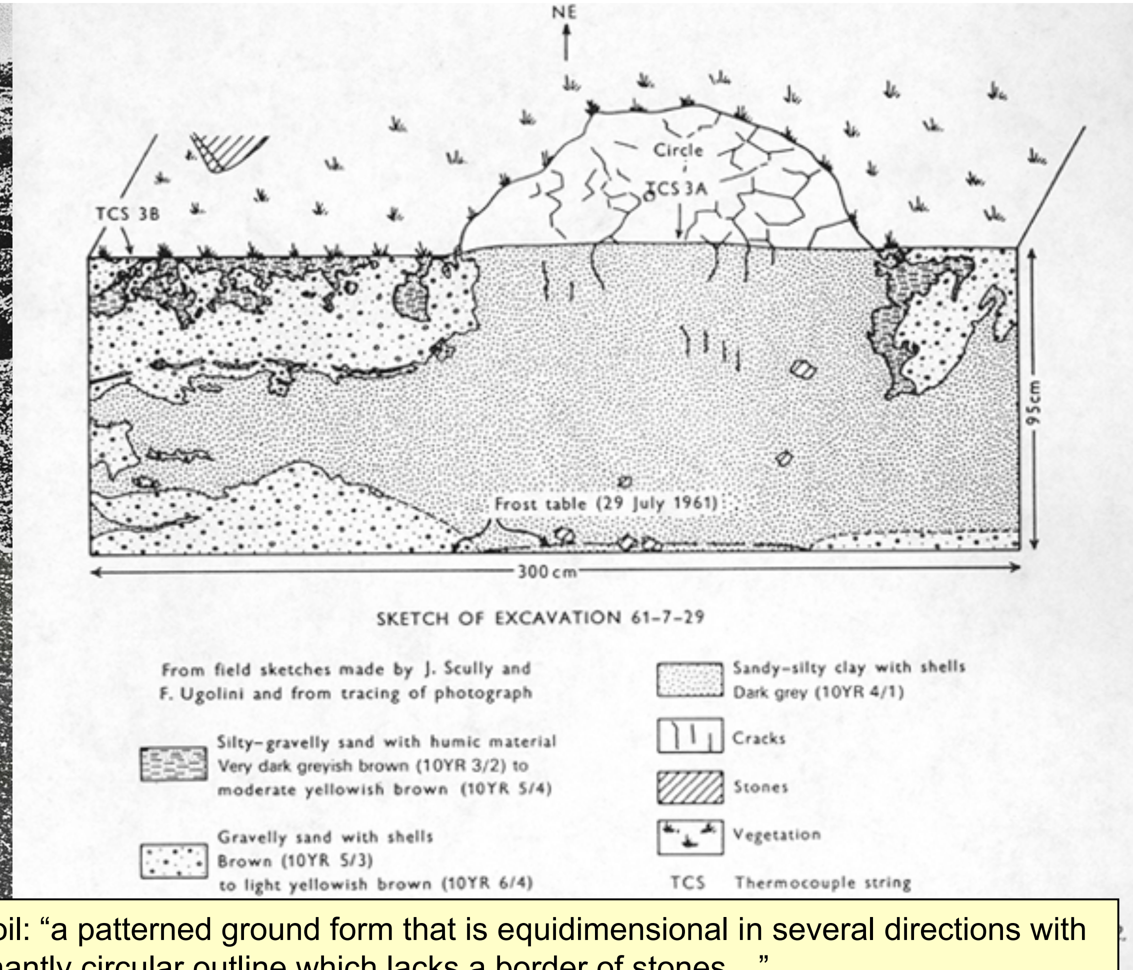
Marilyn D. Walker, *University of Alaska Fairbanks*

Geomorphology of frost-heave patterned ground forms

Sorted circles



Nonsorted circles



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

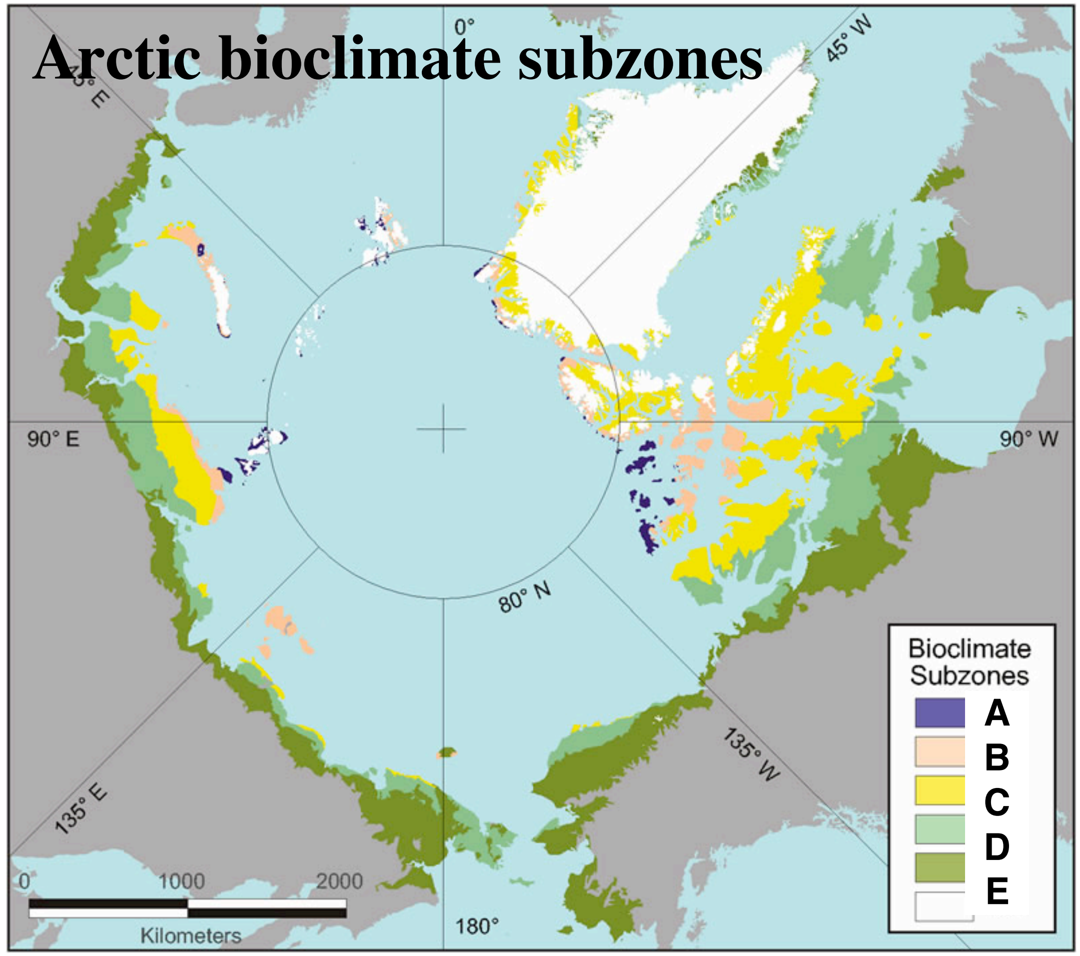
van Everdingen 1998

.

Figures from Washburn 1980

How do frost boils change across the arctic temperature 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

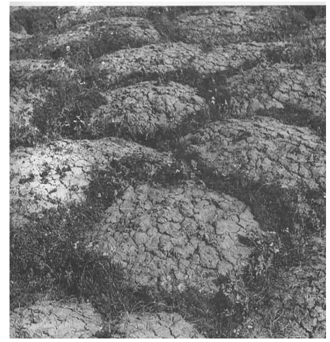


Circumpolar Arctic Vegetation Map, in prep.

Hypothetical series of “frost-boil” forms along the arctic bioclimate gradient

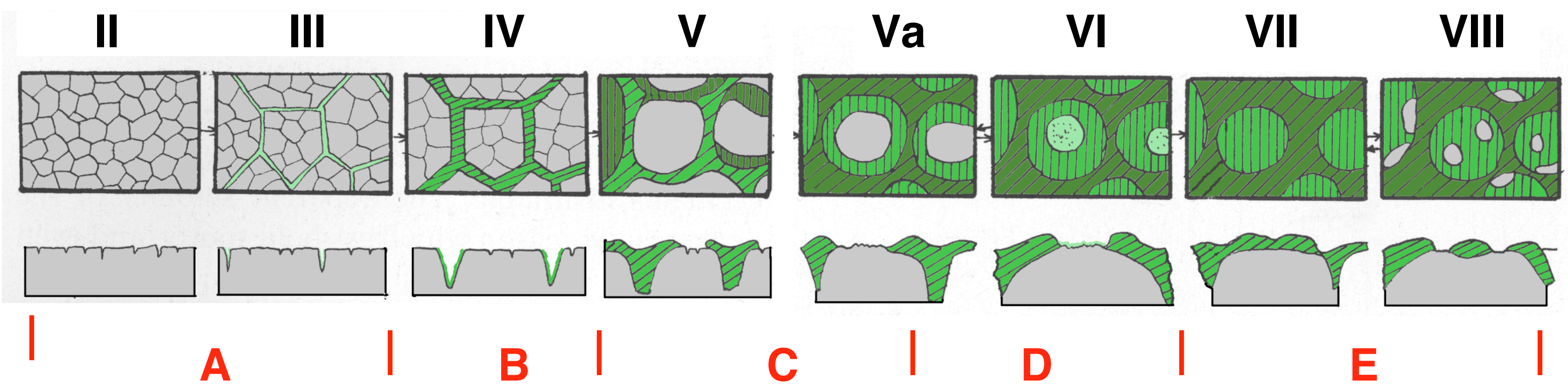

Subzone A


Subzone B


Subzone C


Subzone D

Frost-boil forms



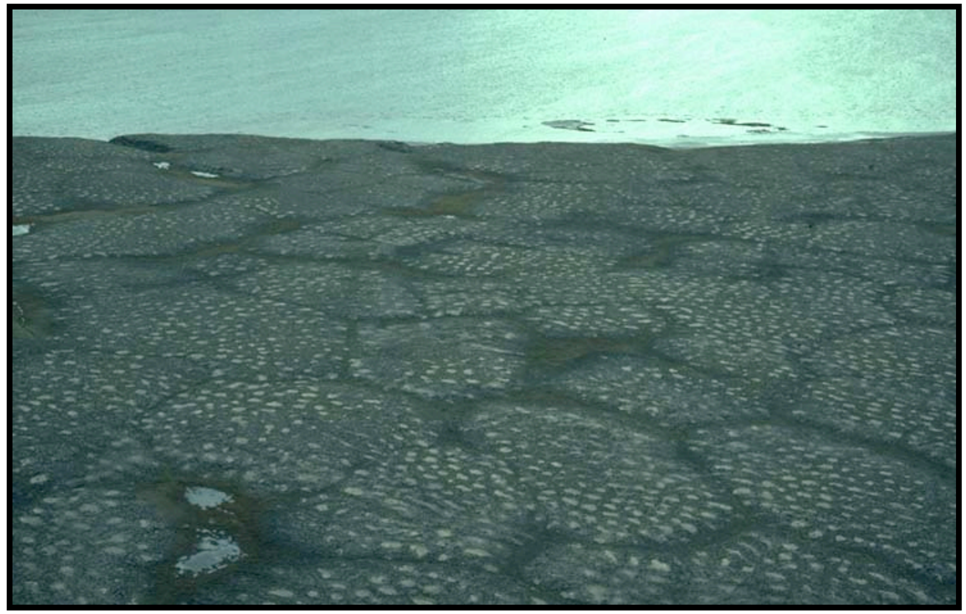
Bioclimate subzones

- Increased size of frost-boil polygons toward the south.
- Greater contrast between the frost-boil and inter-boil areas toward the south.

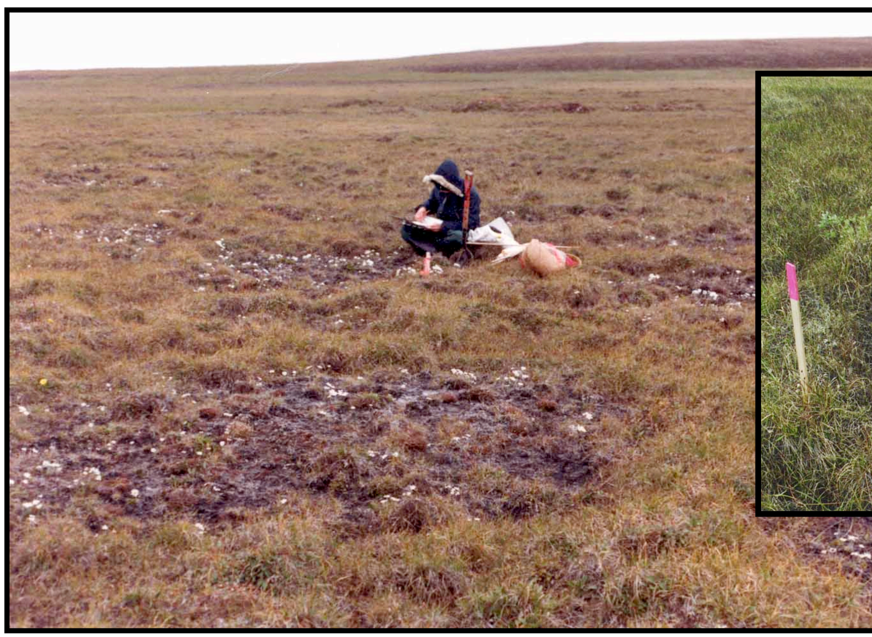
Modified from Chernov and Matveyeva 1997

“Spotted” tundra of Subzones C and D

- These features are best developed in silty soils.
- 1-3 m diameter circles.
- 20-30 frost boils/ 100 m^2
- Best developed where the mean July temperature is 5-9° C.
- 50-80% cover of plants on zonal surfaces, with thin peat development.
- 150-250 plant species in local floras.



Subzone C, Howe Island, Ak



Subzone D, Kuparuk oil field, Arctic Coastal Plain, Alaska

Frost boil soils

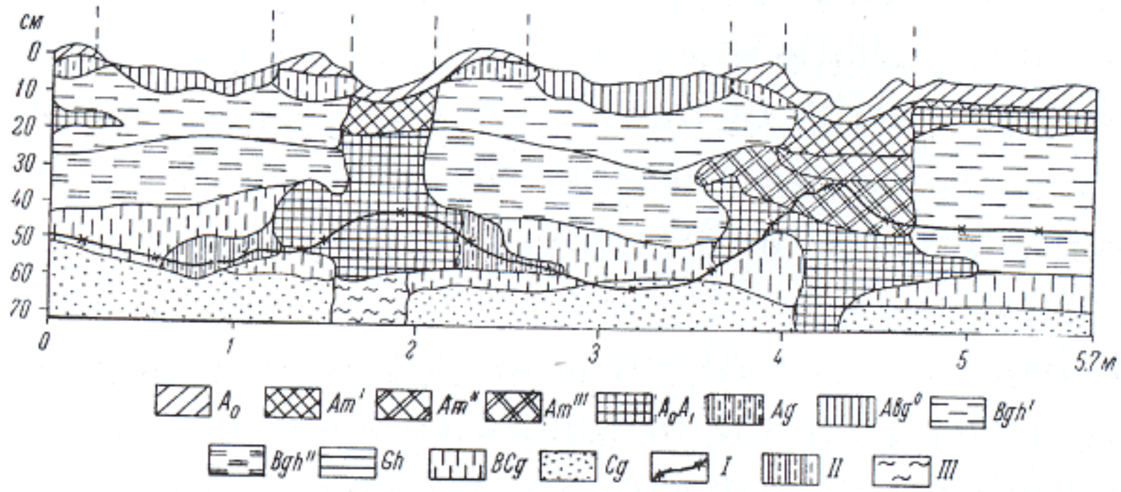
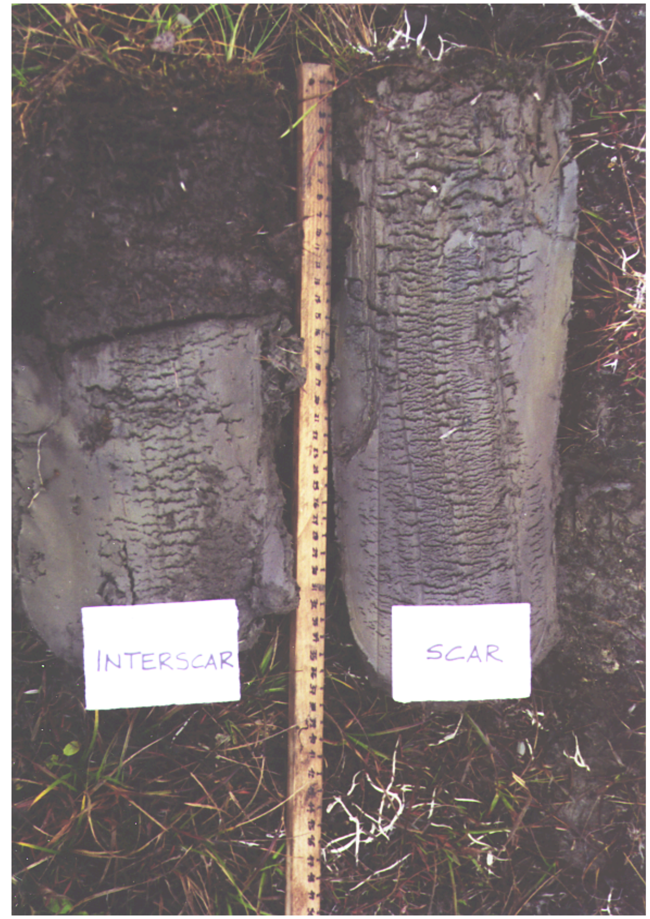


Fig. 16.42. Structure of a soil profile in a frost-boil *Dryas*–sedge–moss community in the typical tundra subzone at Tareya, Taymyr. Letter designations are soil horizons. I, permafrost level in August; II, humus streaks; III, ice wedge. From Ignatenko (1971).



Vegetation on frost boils

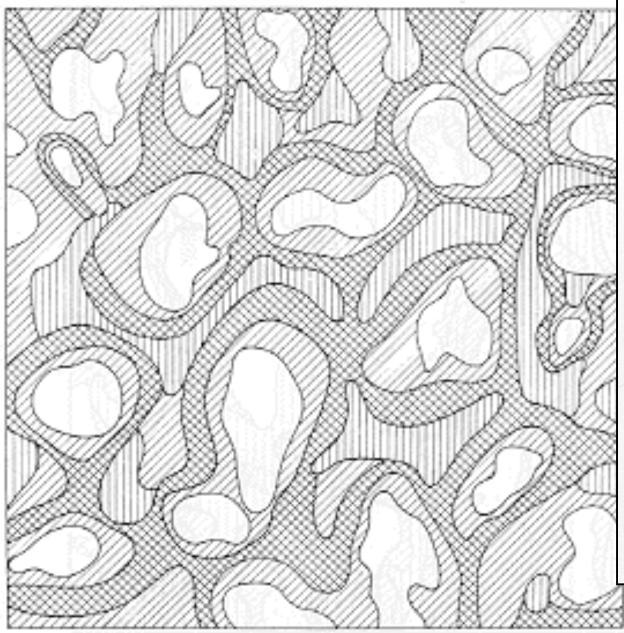


Fig. 16.36. Regular cyclic type of horizontal structure (first variant on a flat surface) in a frost-boil community at Kresty, Taymyr. 1, patches of bare ground in different successional stages; 2, *Hylocomium alaskanum* + *Aulacomnium turgidum* + *Carex ensifolia* ssp. *arctisibirica* + *Dryas punctata*; 3, *Tomenthypnum nitens* + *Betula nana* + *Vaccinium uligonosum* var. *microphyllum*; 4, *Tomenthypnum nitens* + *Aulacomnium turgidum*. Sample plot 10 × 10 m.

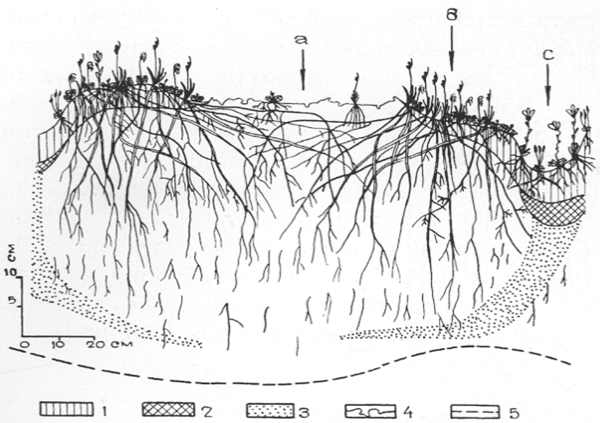


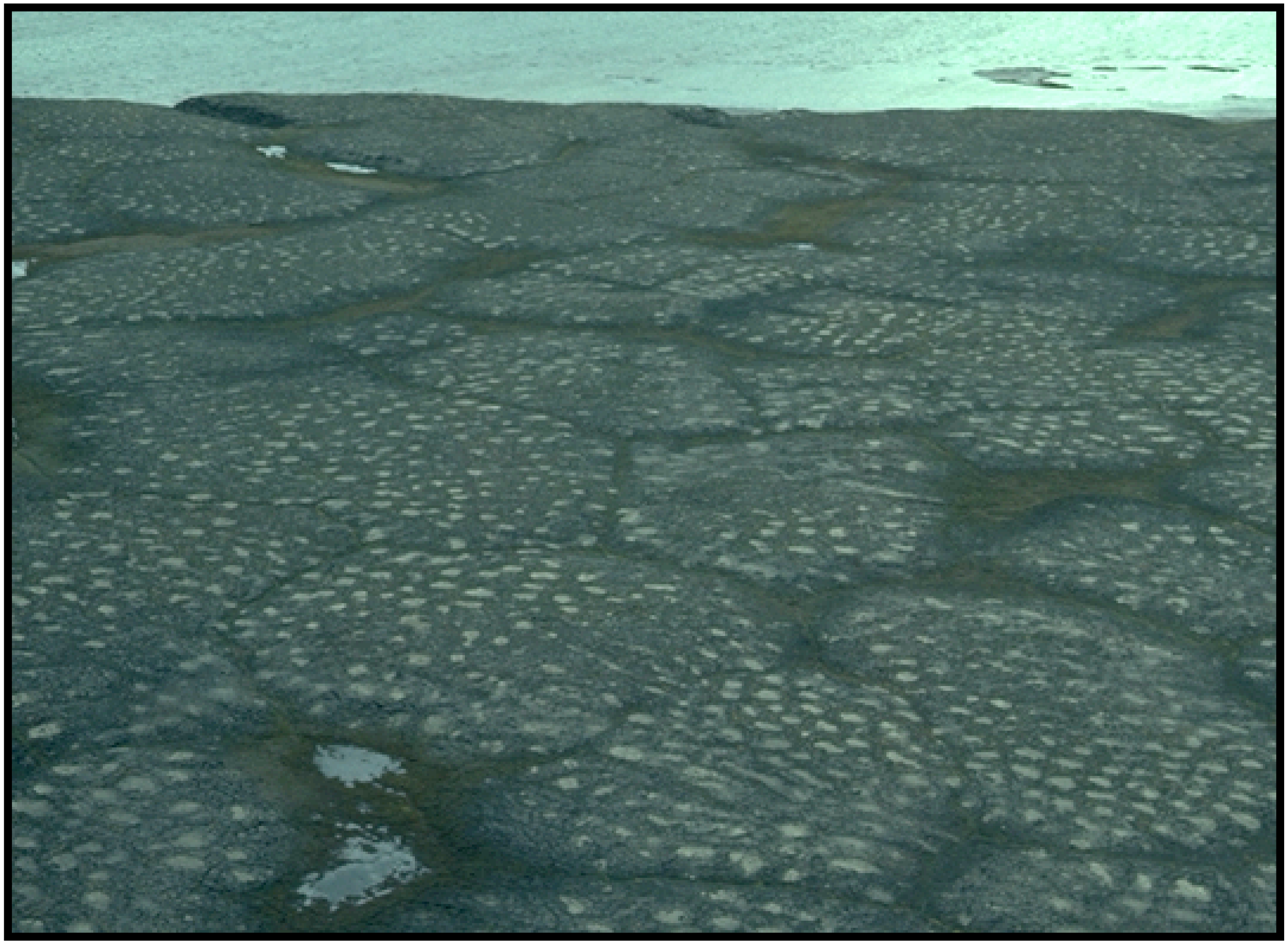
Fig. 16.44. Vertical section in a frost-boil *Dryas*–sedge–moss community in the arctic tundra subzone at Dikson, Taymyr. a, patch of bare ground; b, rim; c, trough; *alaskanum*; 2, dead part of moss turf; 3, peat; 4 ground; 5, level of permafrost.

Nadya Matveyeva's vegetation maps and descriptions of frost-boil vegetation from the Taimyr Peninsula, Russia, 1970s.

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

Frost boil ecosystems: central goal

To better understand the complex linkages between biogeochemical cycles, vegetation, disturbance, and climate across the full summer temperature gradient in the Arctic in order to better predict ecosystem responses to changing climate and land use.

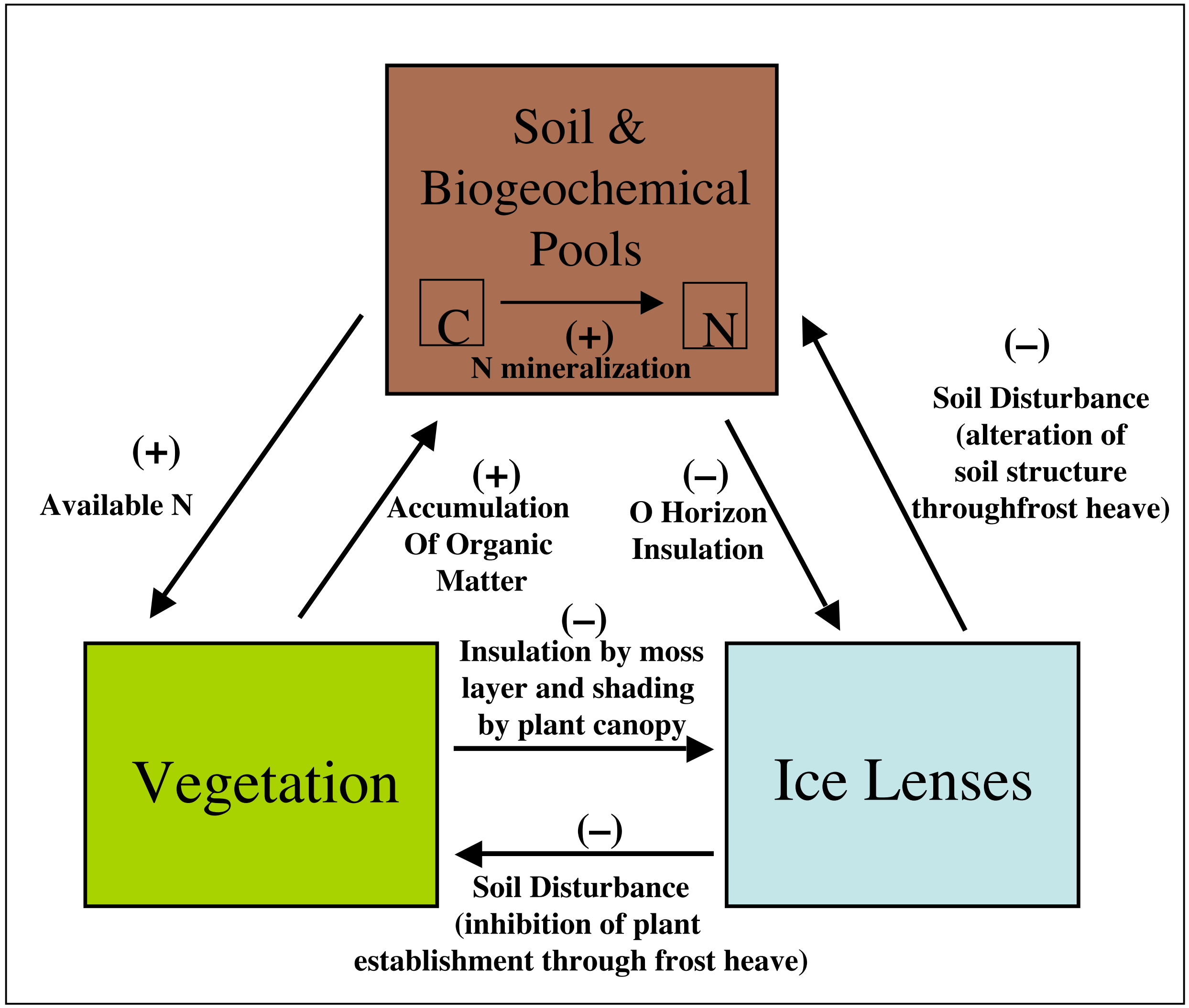


Frost boils in a network of ice-wedge polygons
Howe Island, Alaska

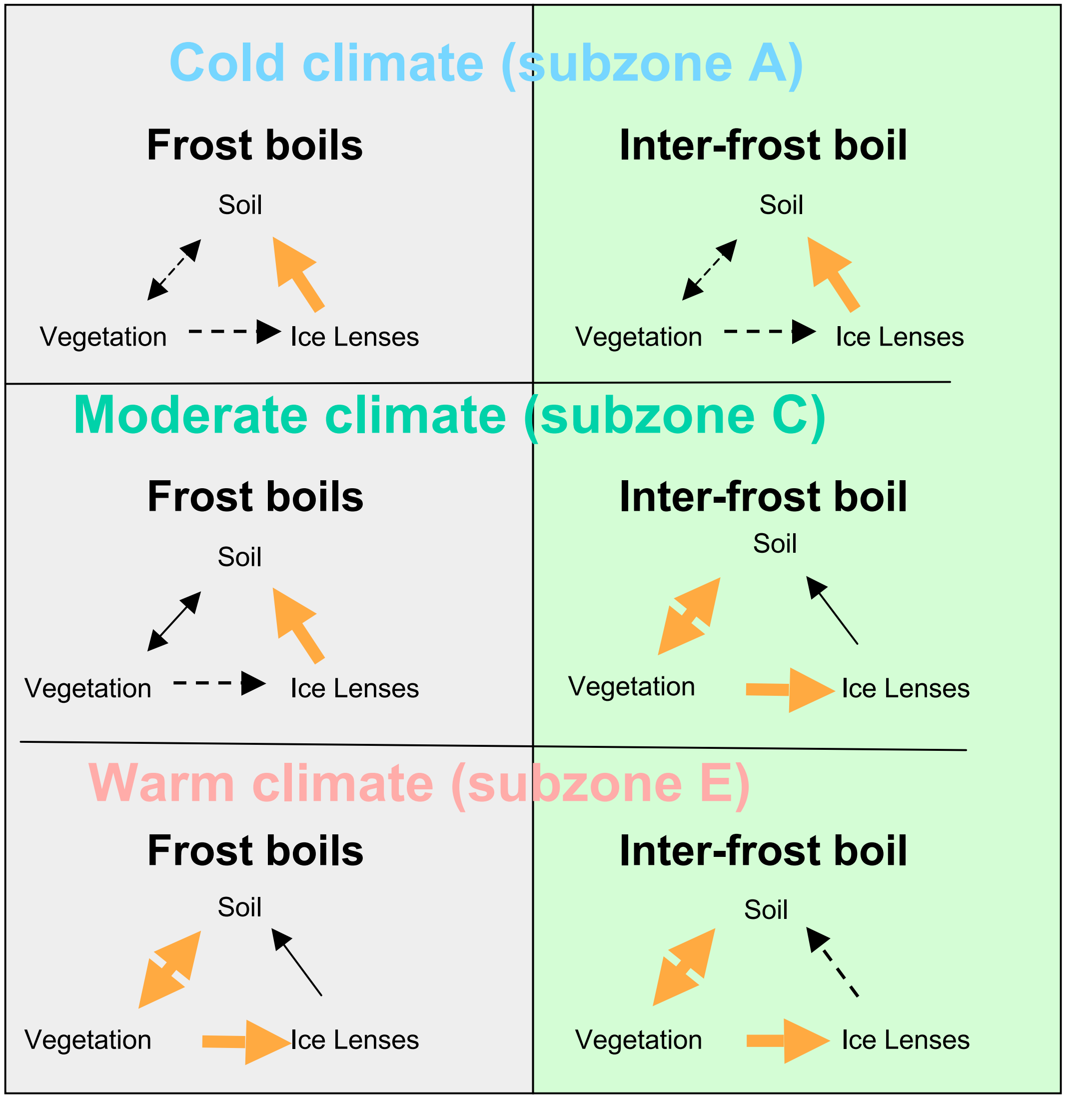
The Frost-Boil System

Central questions:

1. How does the process of frost heave affect soil biogeochemical processes and vegetation?
2. What are the feedbacks between these components?



3. How are these components and linkages affected by the prevailing climate?



Hypothesized response

Subzone A: Physical processes dominate in both microsites (low cover of plants on frost boils and inter-frost-boil areas)

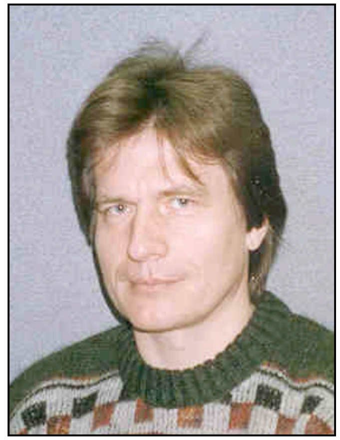
Subzone C: Physical processes dominate on frost boils, biological processes dominate inter-boil areas (maximum contrast between boils and inter-boil)

Subzone E: Biological processes dominate in both microsites (plants cover both frost boils and inter-boil areas)

Component 1, Frost-boil dynamics and climate

William Krantz U. Cincinnati

Rorik Peterson U. Alaska Fairbanks



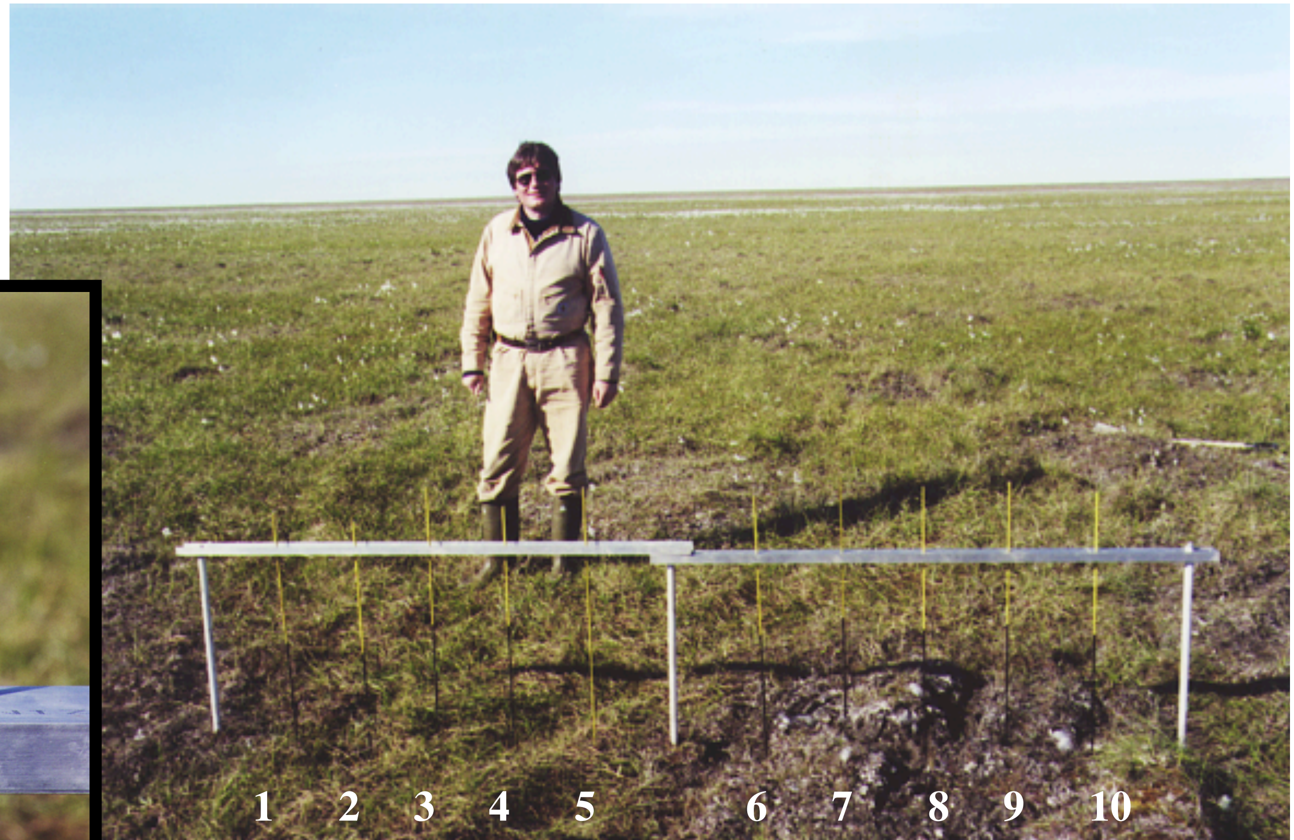
Vladimir Romanovsky U. Alaska Fairbanks

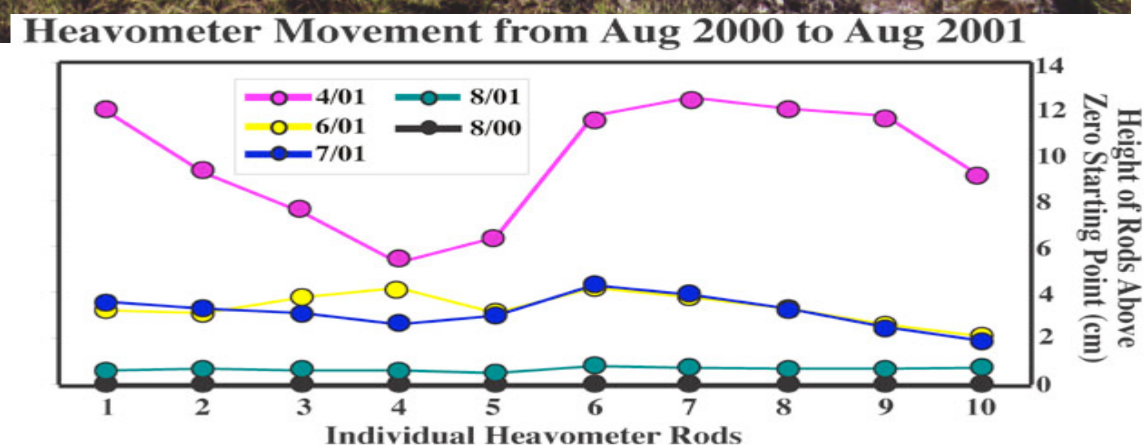
Gennadiy Tipenko U. Alaska Fairbanks

Frost heave follows physical laws that drive the self-organization of frost boils. This in turn drives biogeochemical cycling and vegetation succession of the frost-boil system. ***Our first task is to develop a physically-based model of frost-boil formation.***

Measuring frost heave

Vlad Romanovsky: Proud inventor of heavometer





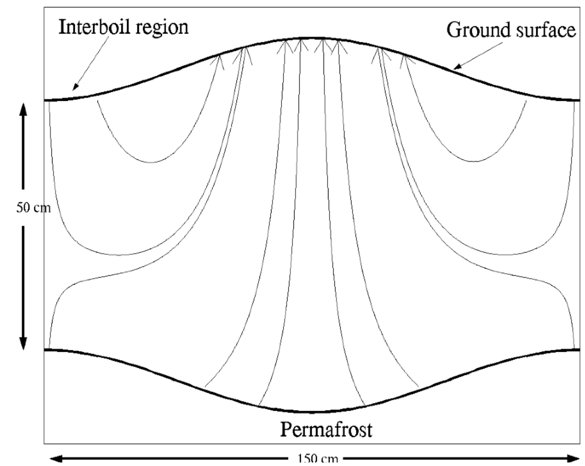
Differential Frost Heave (DFH) models the self-organization of frost boils (Peterson and Krantz 1998)

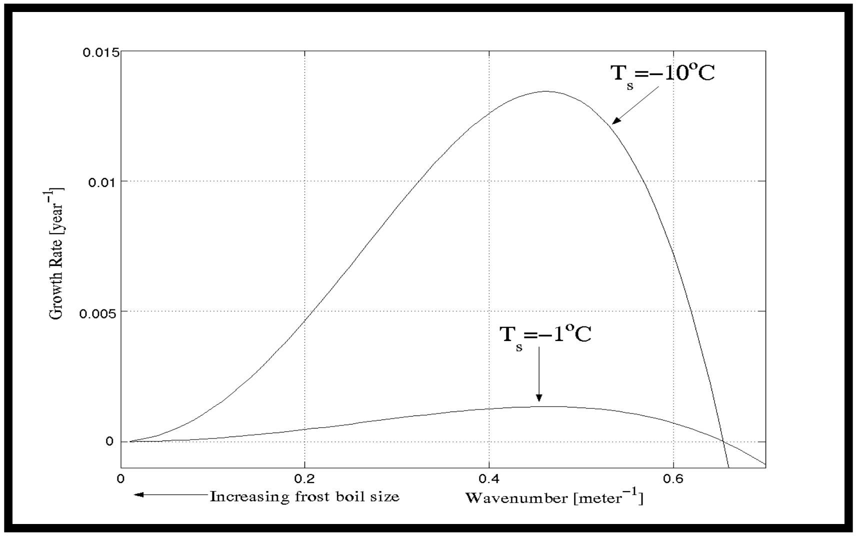
• *Physically based model that provides considerable insight to the self-organization processes in frost boils.*

• *Can predict many phenomena associated with frost boils including the amount of heave, spacing and size of the boils.*

• *Early model results suggest that soil texture, soil moisture, and* ***ground-surface temperature*** *are the primary controls of frost heave.*

•*Vegetation and/or snow cover can constrain the development of frost boils by insulating the soils.*



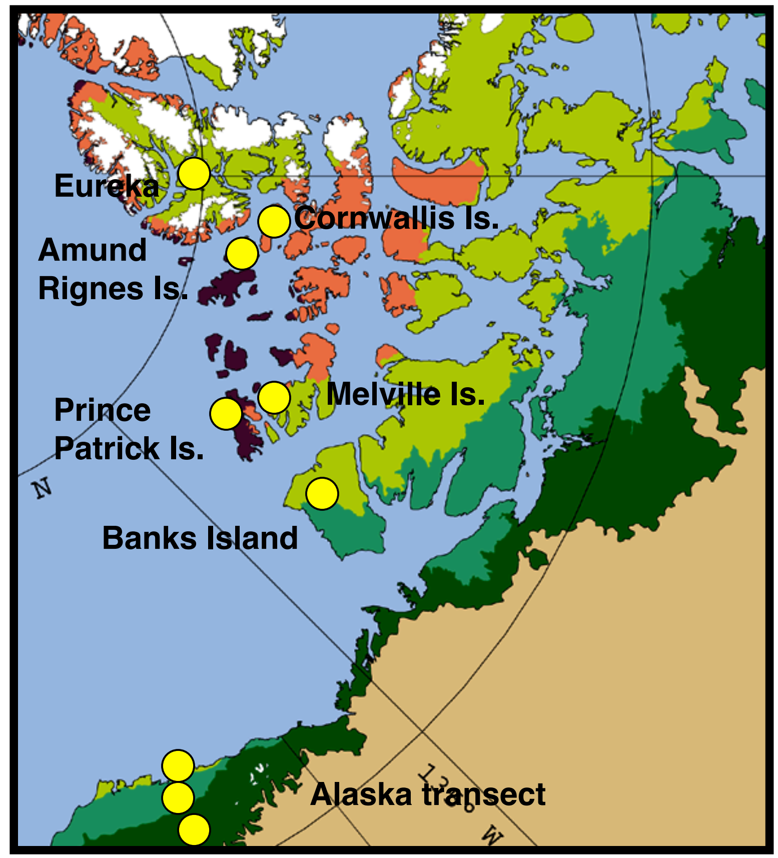


Ice lenses drive frost heave

• Large (>3mm) lenses in the upper 35 cm.
• About 40% ice by volume.
• Lenses are thinner in the middle portion of the core.
• Another thick ice lens occurs at the base of the active layer at about 1 m depth.

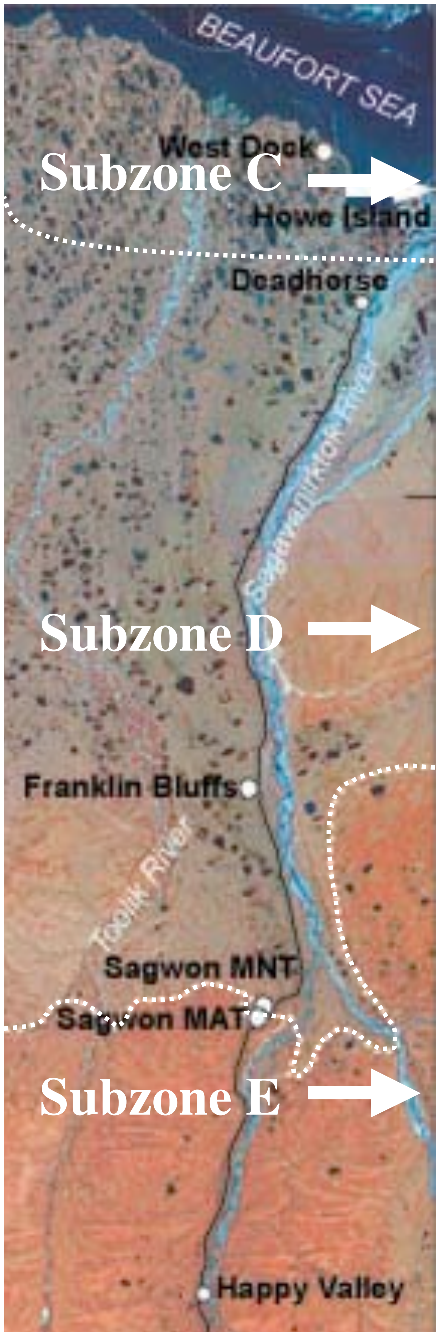
Proposed study sites in Alaska and Canada spanning all five bioclimate subzones

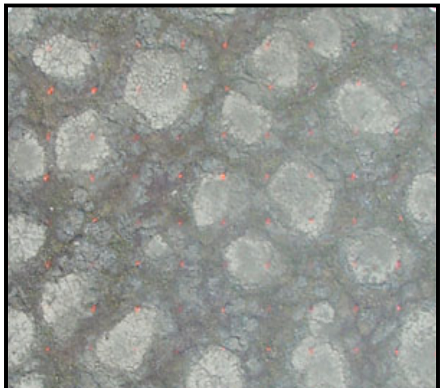
- Alaska transect along the Dalton Highway consists of six sites spanning three subzones.
- Six sites proposed in Canada.

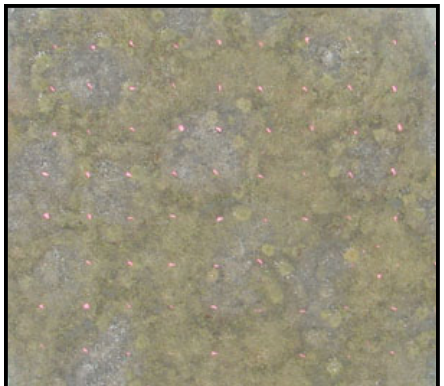


Mapping frost boil systems

Aerial Photos of
10 x 10 meter grids for Subzones
3, 4, and 5




Howe Island


Deadhorse

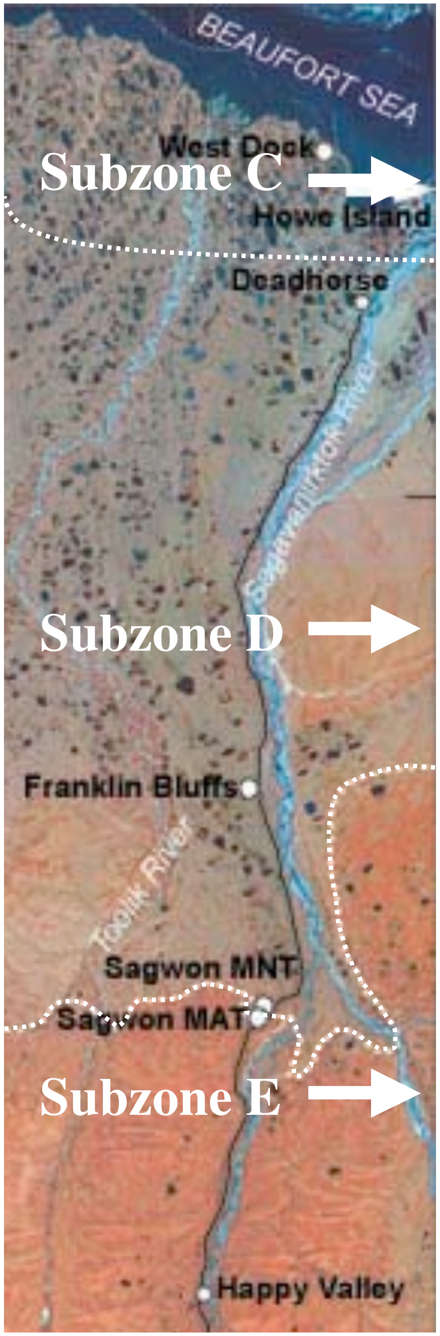

Franklin Bluffs


Sagwon MNT(2)

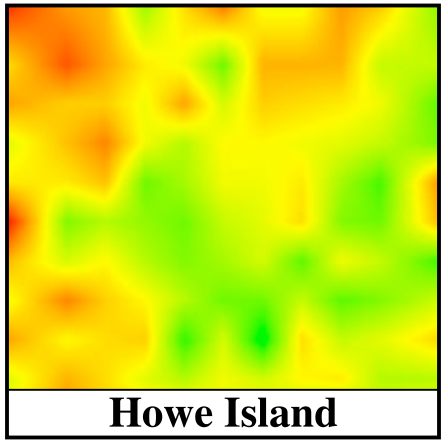

Sagwon MAT

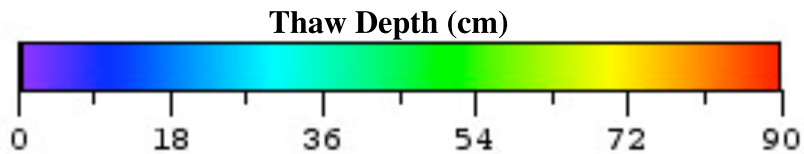

Happy Valley

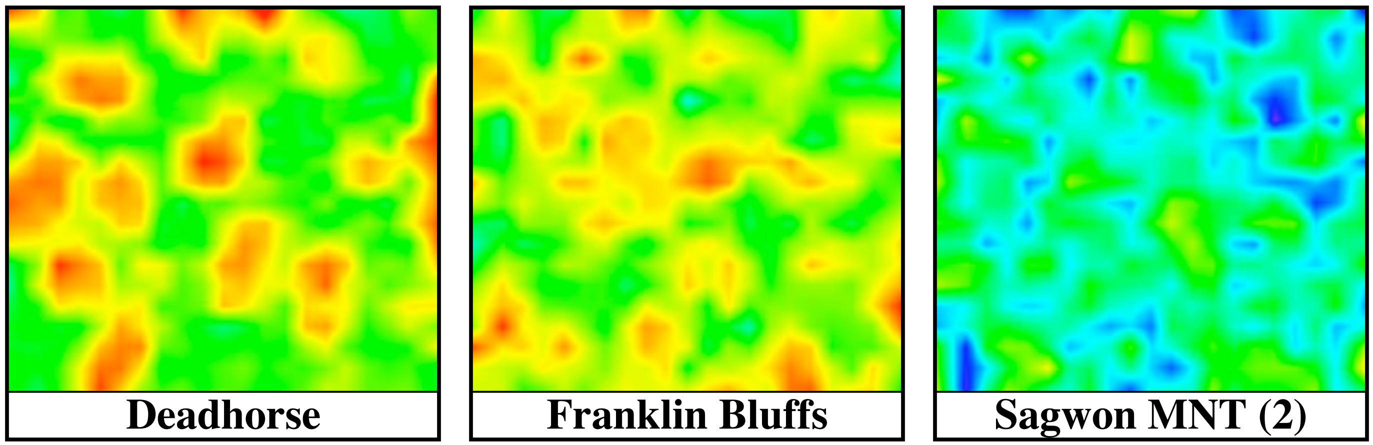
Arctic Slope,
Alaska

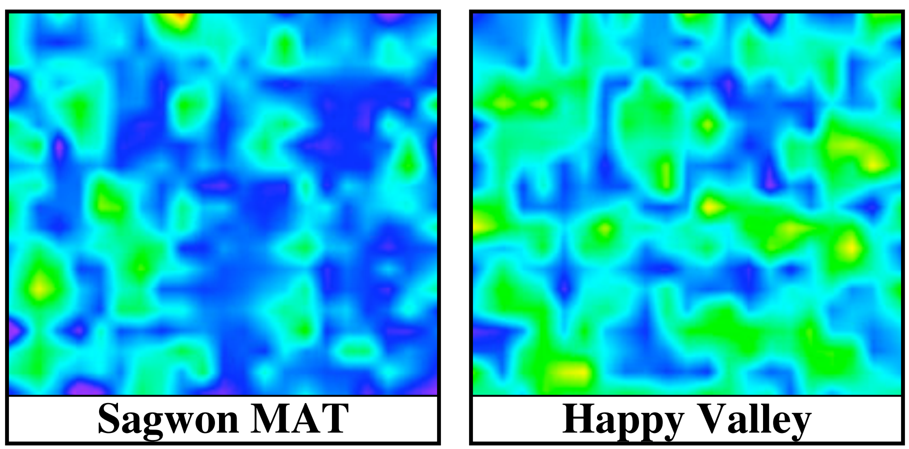


Active-layer Maps of 10 x 10 meter grids for Subzones 3, 4, and 5



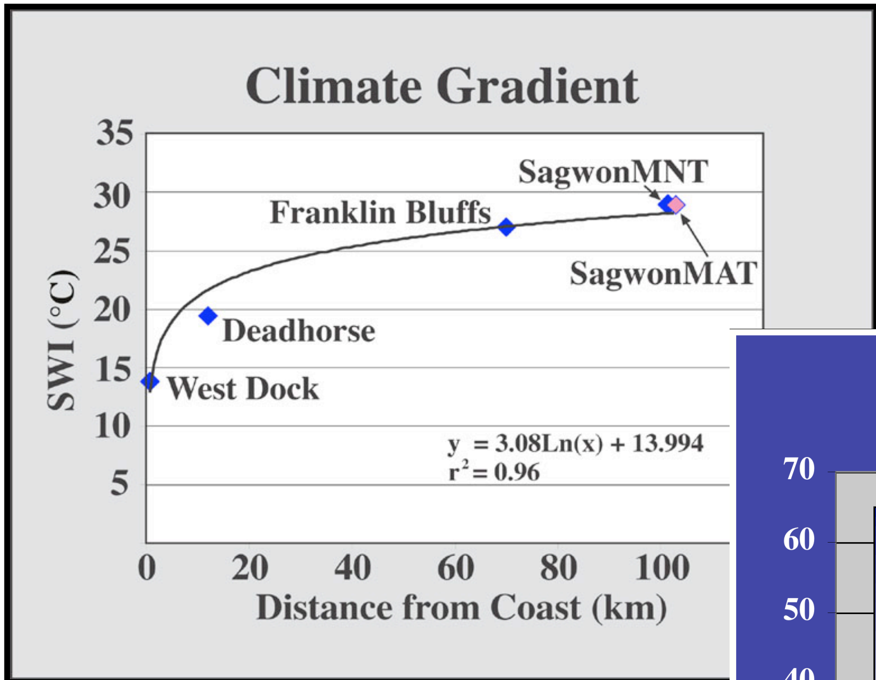


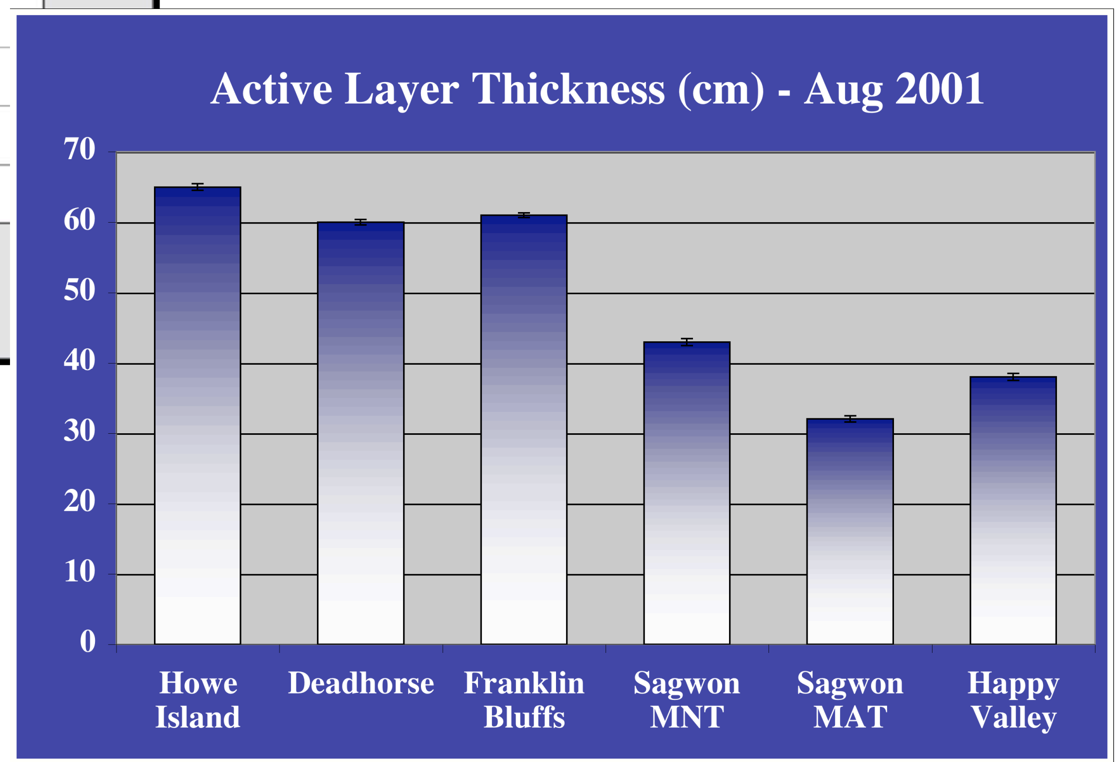




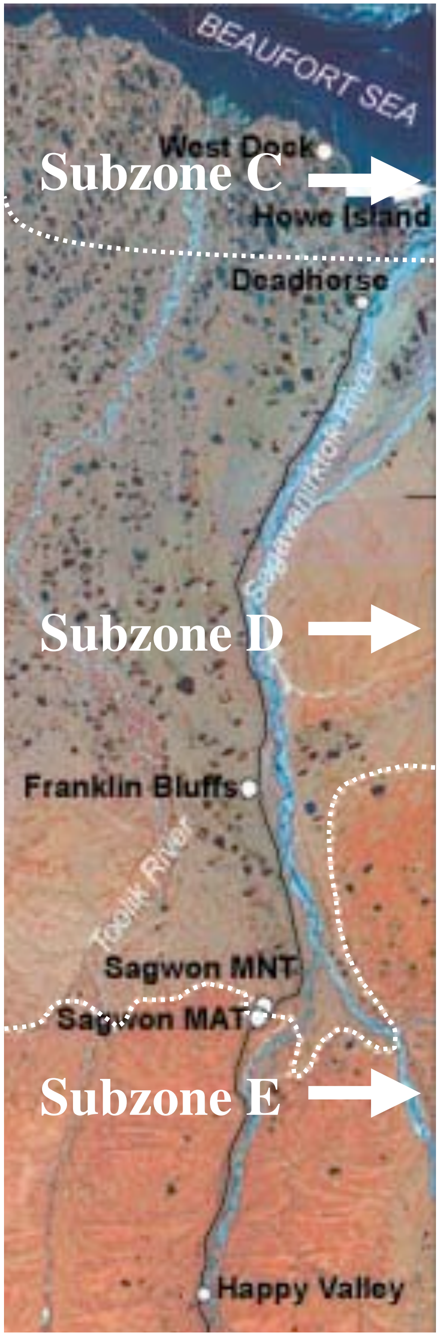
August 2001
Arctic Slope,
Alaska

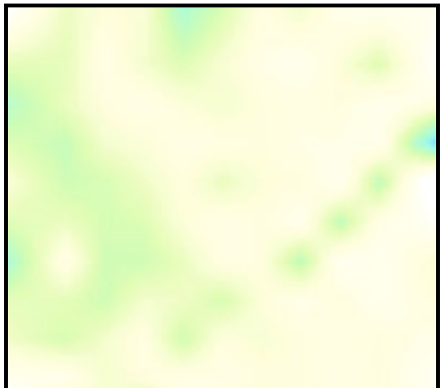
Active layer vs. air temperature





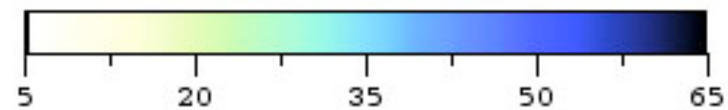
Active layer on zonal sites is inversely related to the summer air temperatures?

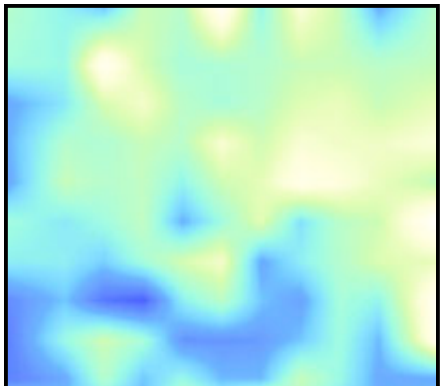




West Dock

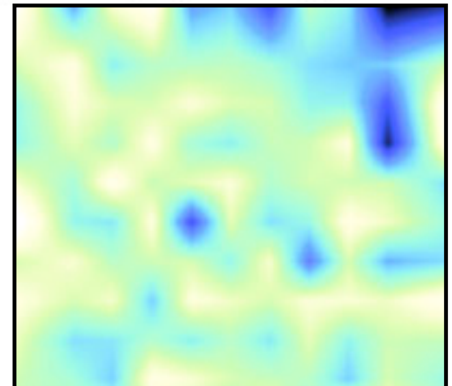
Snow Maps of 10 x 10 meter grids for Subzones 3, 4, and 5



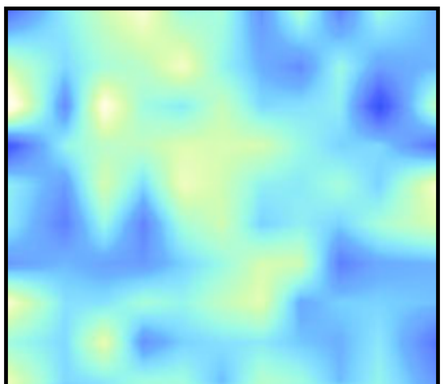


Deadhorse

Franklin Bluffs



Sagwon MNT (2)



Sagwon MAT

- **Snow has a major effect on winter soil surface temperature and hence on frost heave.**
- **The DFH model predicts an an optimal snow depth for frost heave (about 20 cm?)**

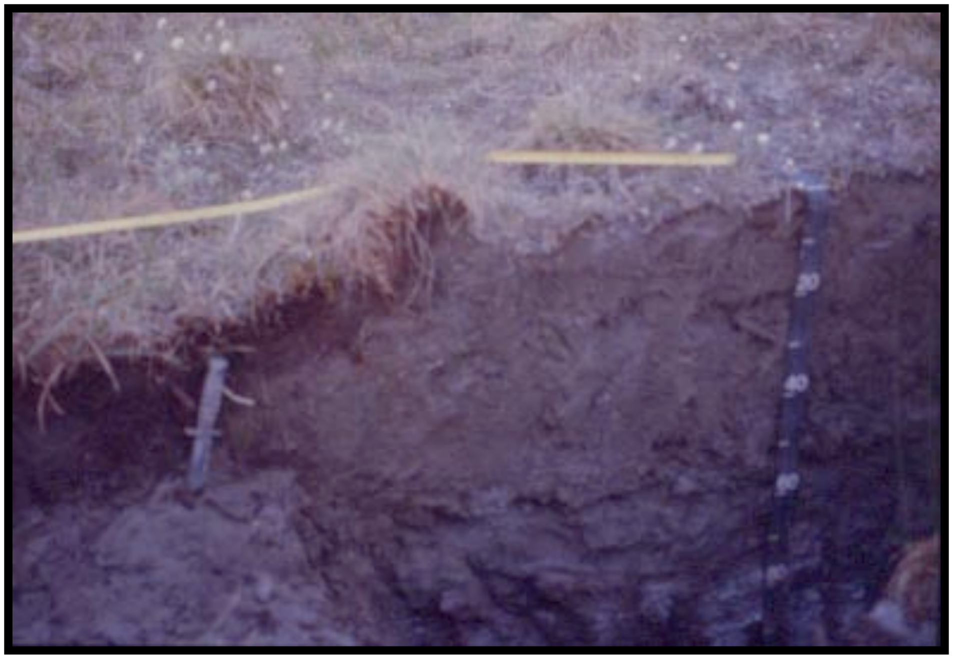
Component 2, Soils and biogeochemistry

Chien Lu Ping
U. Alaska Fairbanks

Gary Michaelsom
U. Alaska Fairbanks

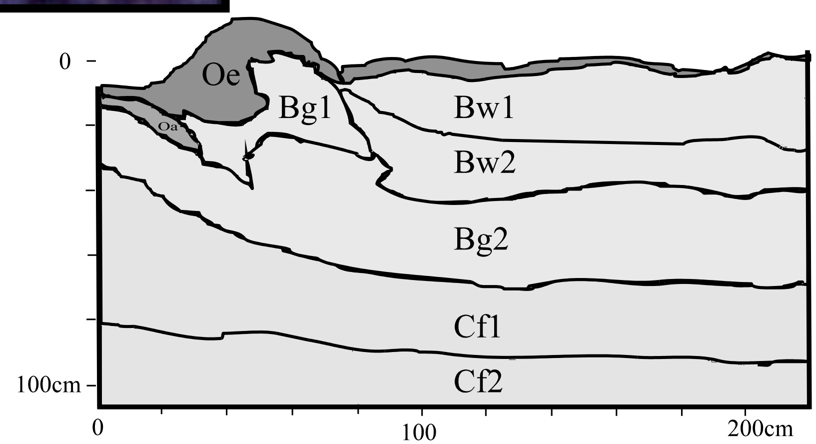
These are complex adaptive systems involving the coevolution of soils, vegetation, and complete ecosystems in response to variations in frost heave and climate. ***Our second task is to describe the variation in frost-boil soils and biogeochemistry along the arctic climate gradient.***

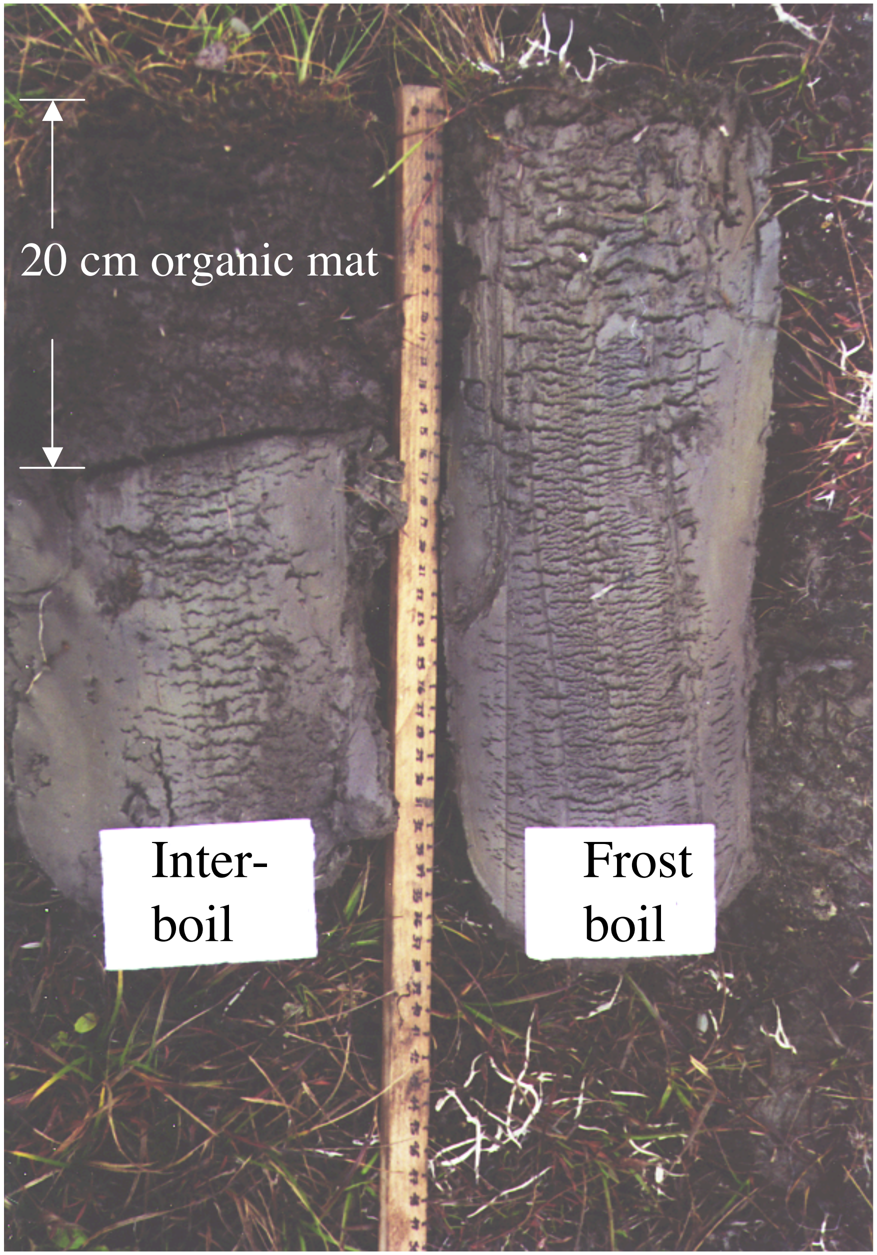
Soil related tasks



- Soil description and characterization
- Quantify key soil variables for the DFH model
- Soil coring during winter
- Spatial and temporal analysis of biogeochemistry
- Paleoanalysis of soils

Deadhorse Frost Boil Site
(7/18/01)

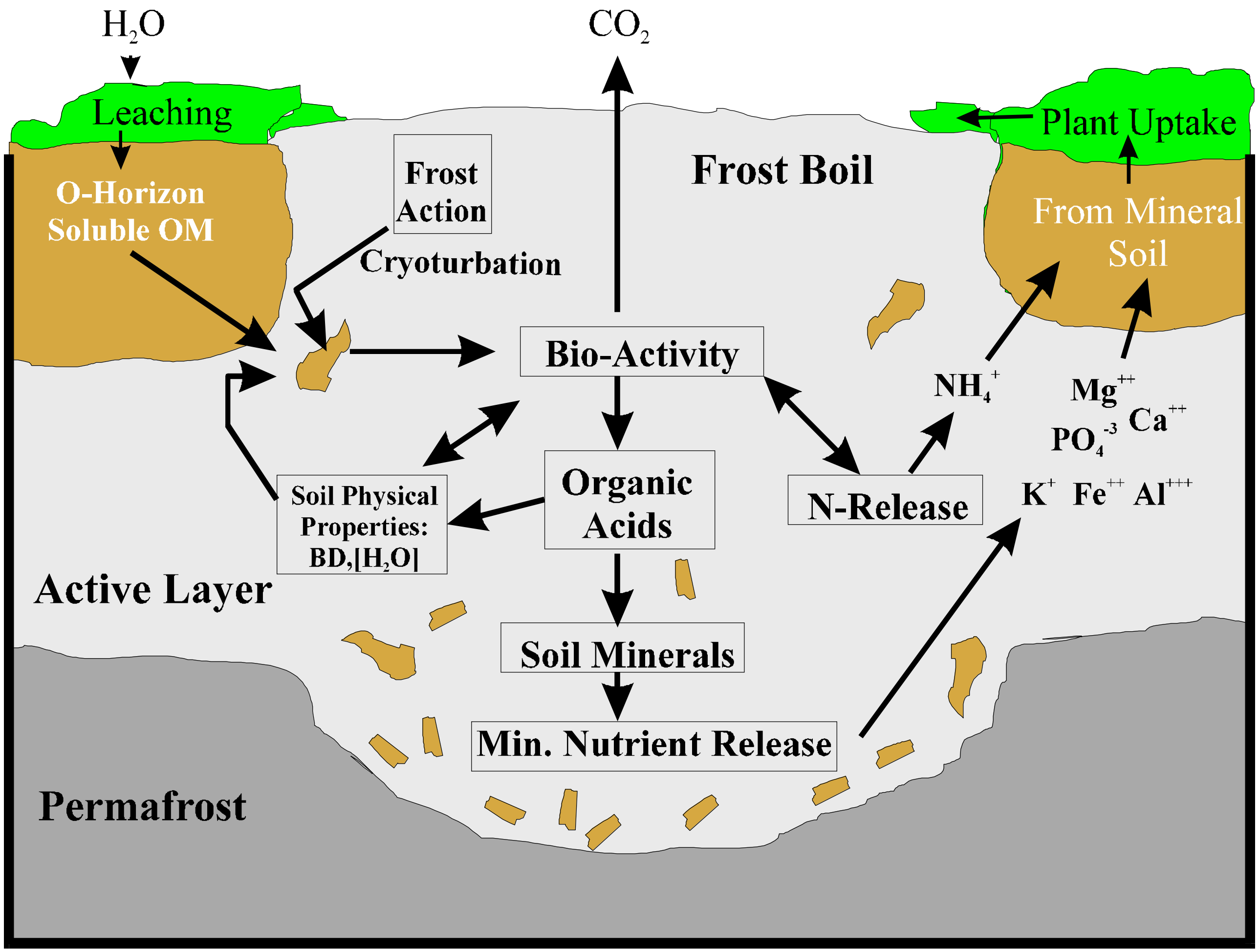




Soils of frost boil and the inter-boil area

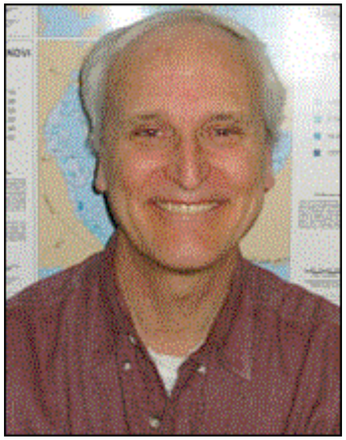
- Platey soil structure is caused by ice lenses.
- Deep organic layer of inter-frost-boil areas insulates the soil reducing the active layer thickness and hence the number of lenses and the amount of heave.

Generalized biogeochemical links within frost-boil soils



- C and N enter the center of the frost boil system from the margins of the boil through frost action. and
- Cryptogamic crusts (not shown) are important source of nitrogen fixation and provide substrate for other organisms in vegetation succession on frost boils.

Component 3, Vegetation



Skip Walker
U. Alaska
Fairbanks

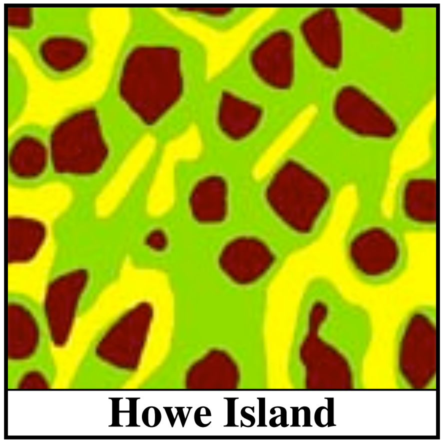
Martha Raynolds
U. Alaska
Fairbanks

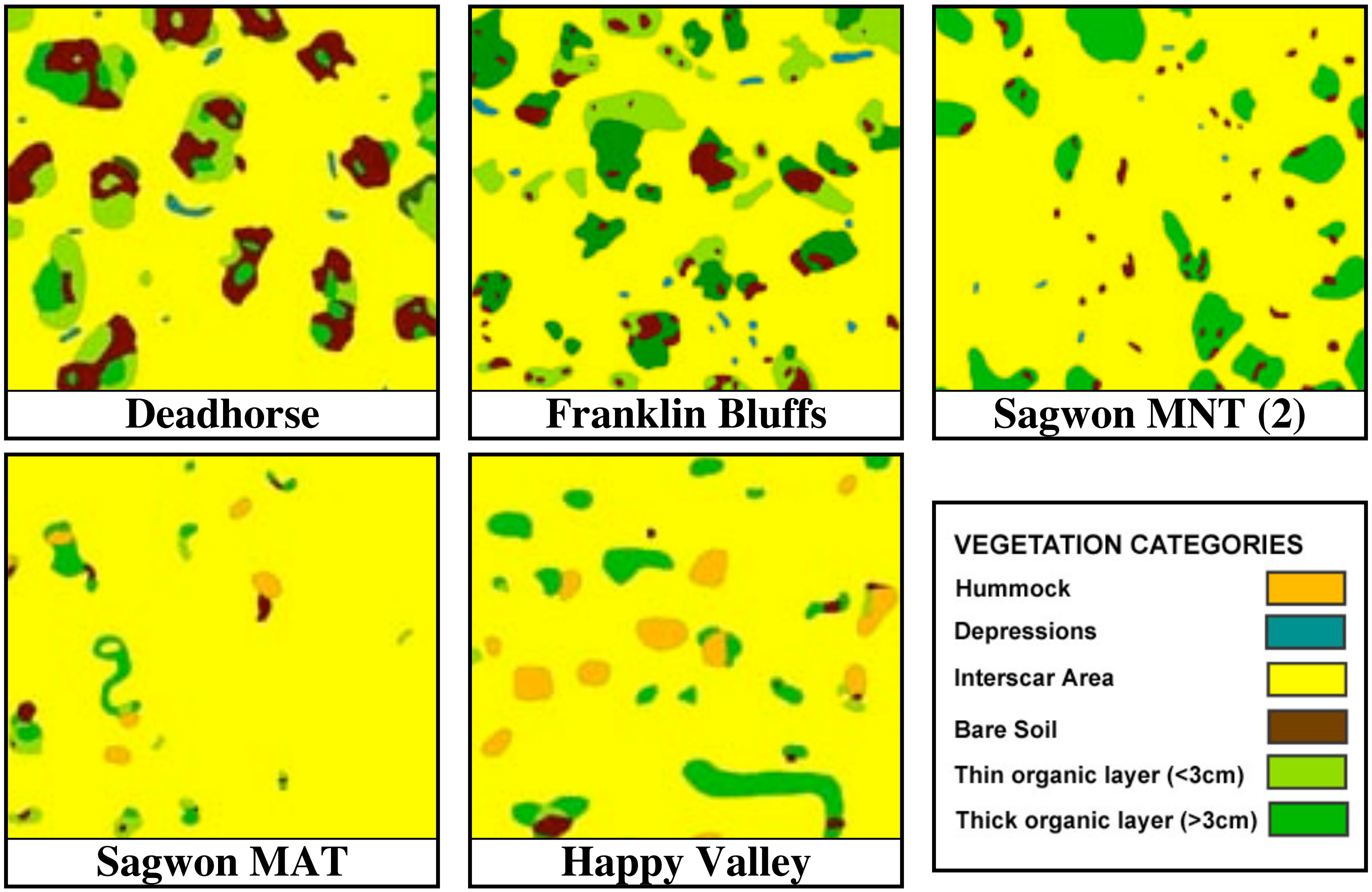
Anja Kade
U. Alaska
Fairbanks

Part of our third task is to describe the variation in vegetation along the arctic climate gradient at several scales and to examine the controls that vegetation has on frost boil formation.

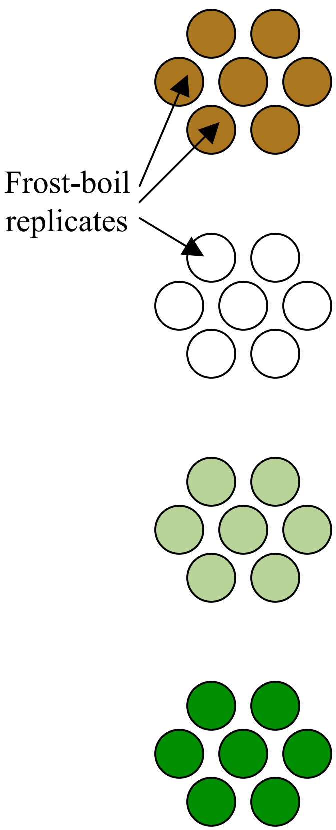
Vegetation Classification and Maps

- Braun-Blanquet approach to classification
- Vegetation mapping at four scales (plot, landscape, regional, circumpolar)





Frost-boil manipulation experiments: *Effects of vegetation on frost heave, Anja Kade*



Control

No manipulation

Removal of vegetation mat

What influence does the plant canopy have on thermal insulation and cryoturbation activity of frost boils?

Removal of vegetation & establishment of a cryptogam cover

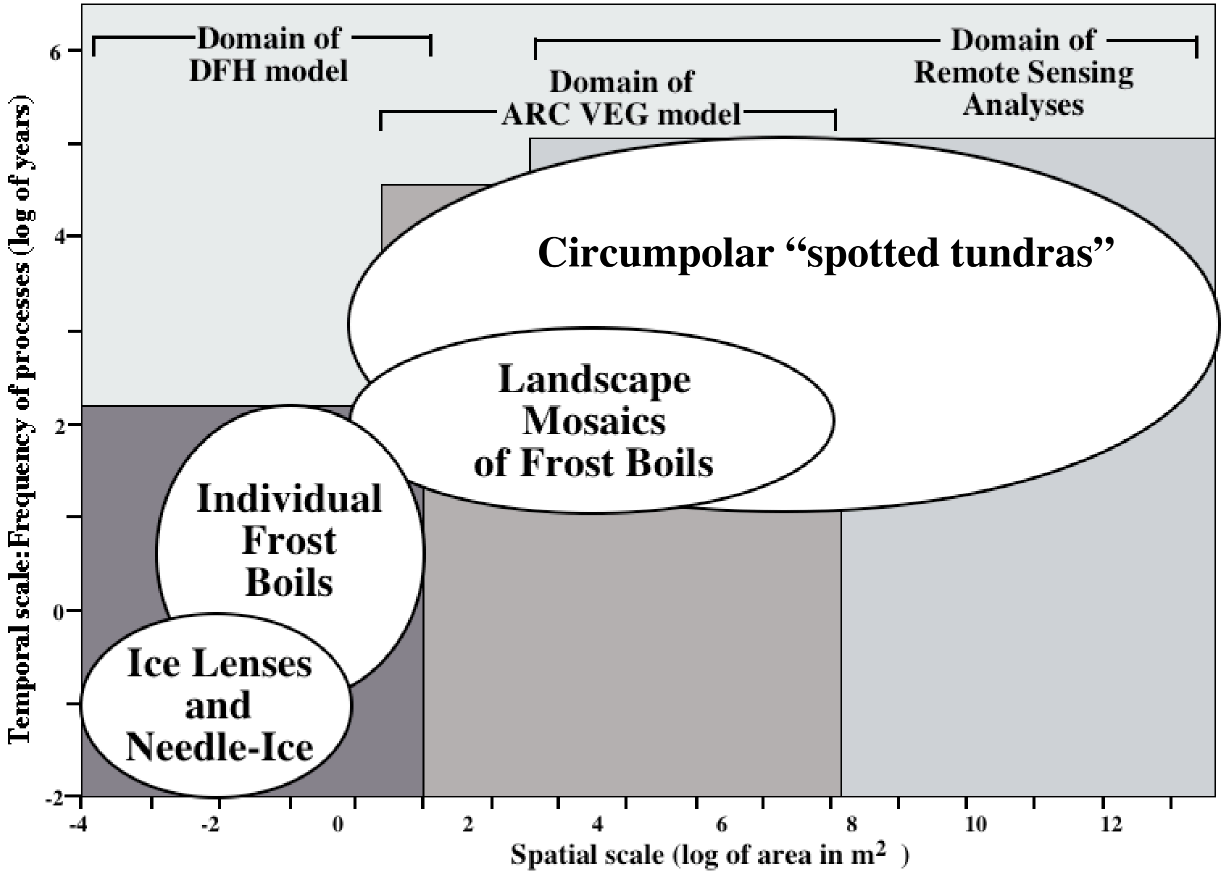
What effect does the initial stage of plant succession have on cryoturbation activity and soil-surface stability?

Removal of vegetation & transplanting graminoids

How does a late successional vegetation stage influence cryoturbation parameters?

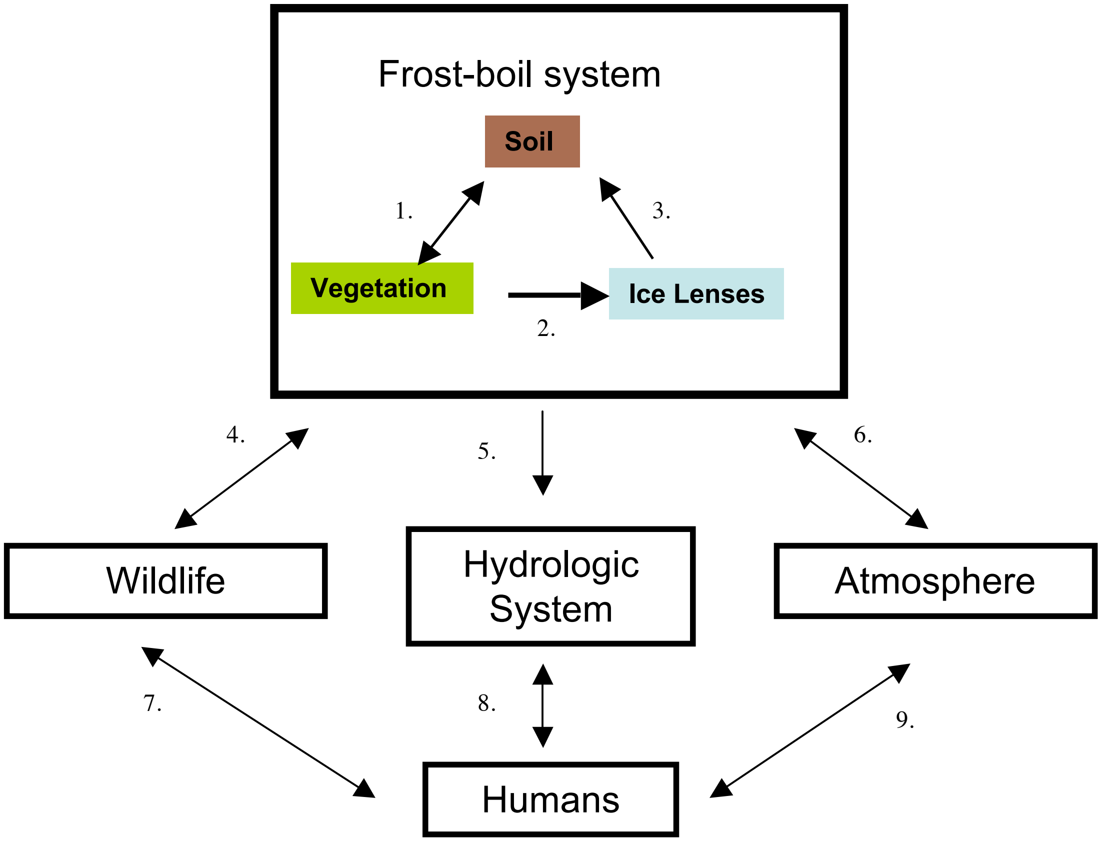
Variables to be measured		
Plant composition	Frost heave	Soil moisture
Plant cover	Thaw depth	Soil temperature
Plant biomass	Soil-surface stability	Soil carbon content

Manifestation of frost-boils at different spatial and temporal scales



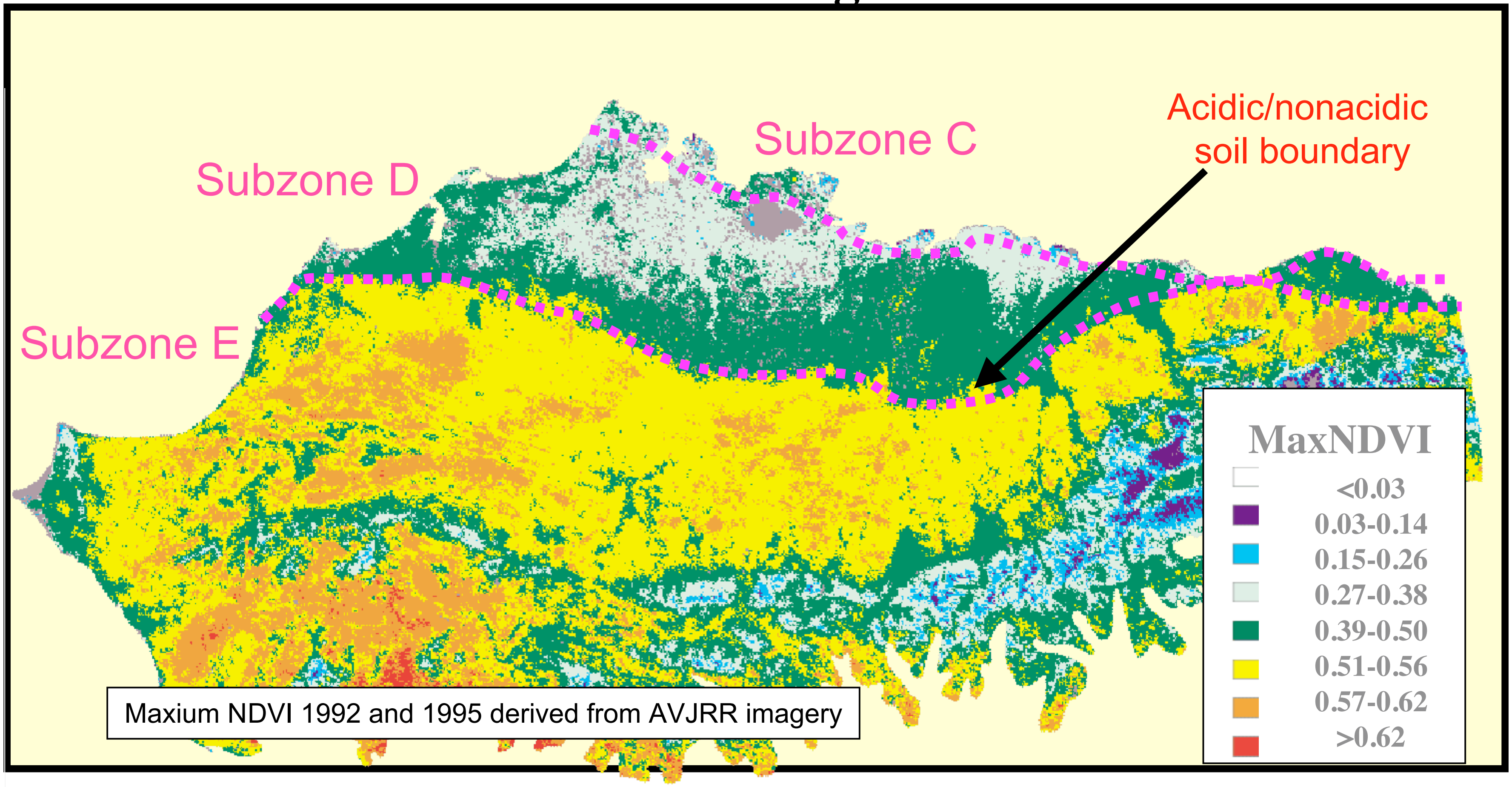
There are unpredictable emergent properties of the frost-boil systems at coarser spatial scales, which have important implications for higher trophic levels and land use of the these regions. ***Our fourth task is to examine frost-boil ecosystems at coarser spatial scales (landscape, regional and circumpolar scales) and collaborate with scientists working with animals in these systems to better understand how changes in frost boil systems manifest at coarser scales.***

Linkages between the frost-boil system and the greater arctic ecosystem and biosphere



- **Forage quality and wildlife habitat**
- **Water flux and water quality**
- **Fluxes of energy and trace gases to the atmosphere**

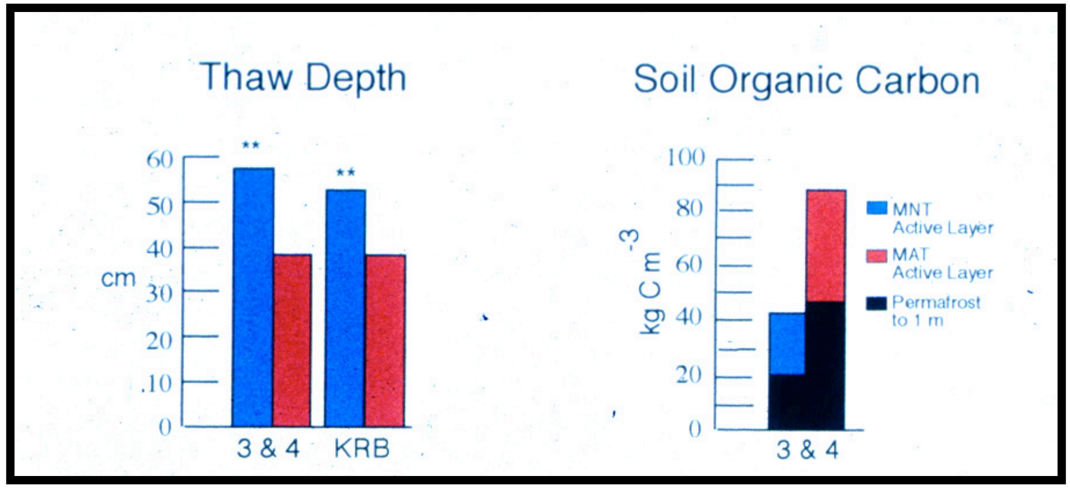
Manifestation at regional scales

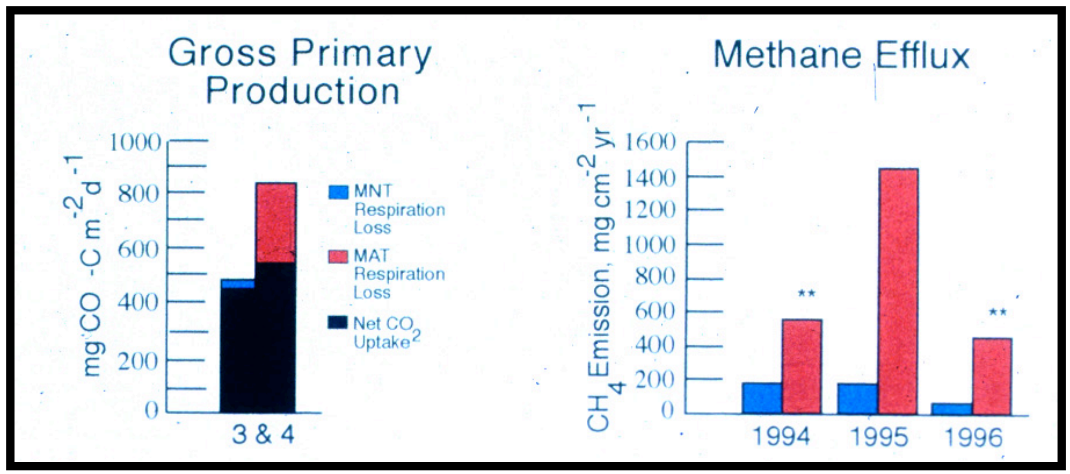


- Boundary between bioclimate subzones C and D corresponds to a major spectral boundary on remotely sensed images.
- North of the boundary:
    - Higher soil pH
    - More frost boils
    - Deeper, less dense snow cover
    - Fewer shrubs, and shorter plants

Effects of frost boils on ecosystem properties

- Compared to acidic tussock tundra, frost-boil ecosystems have:
  - 50% deeper active layers.
  - 28% greater heat flux.
  - Less than half the soil carbon in the upper 1 m.
  - 70% less net CO_2 uptake.
  - 15% of the methane flux.





Walker et al., 1998. Nature *394: 469-472.*)

Factors that could enhance animal use of frost-boil systems in subzones C and D

- Greater diversity of vascular plant species
- Greater diversity of microhabitats
- Plants have less secondary metabolites
- More nitrogen and calcium in plant tissues
- Warmer soils are better habitat for burrowing animals and insects
- Thinner moss carpets and fewer tussocks create better footing for migrating mammals

Walker, D.A et al.. 2001. Quaternary Science Reviews, 20: 149-163.

Vegetation modeling

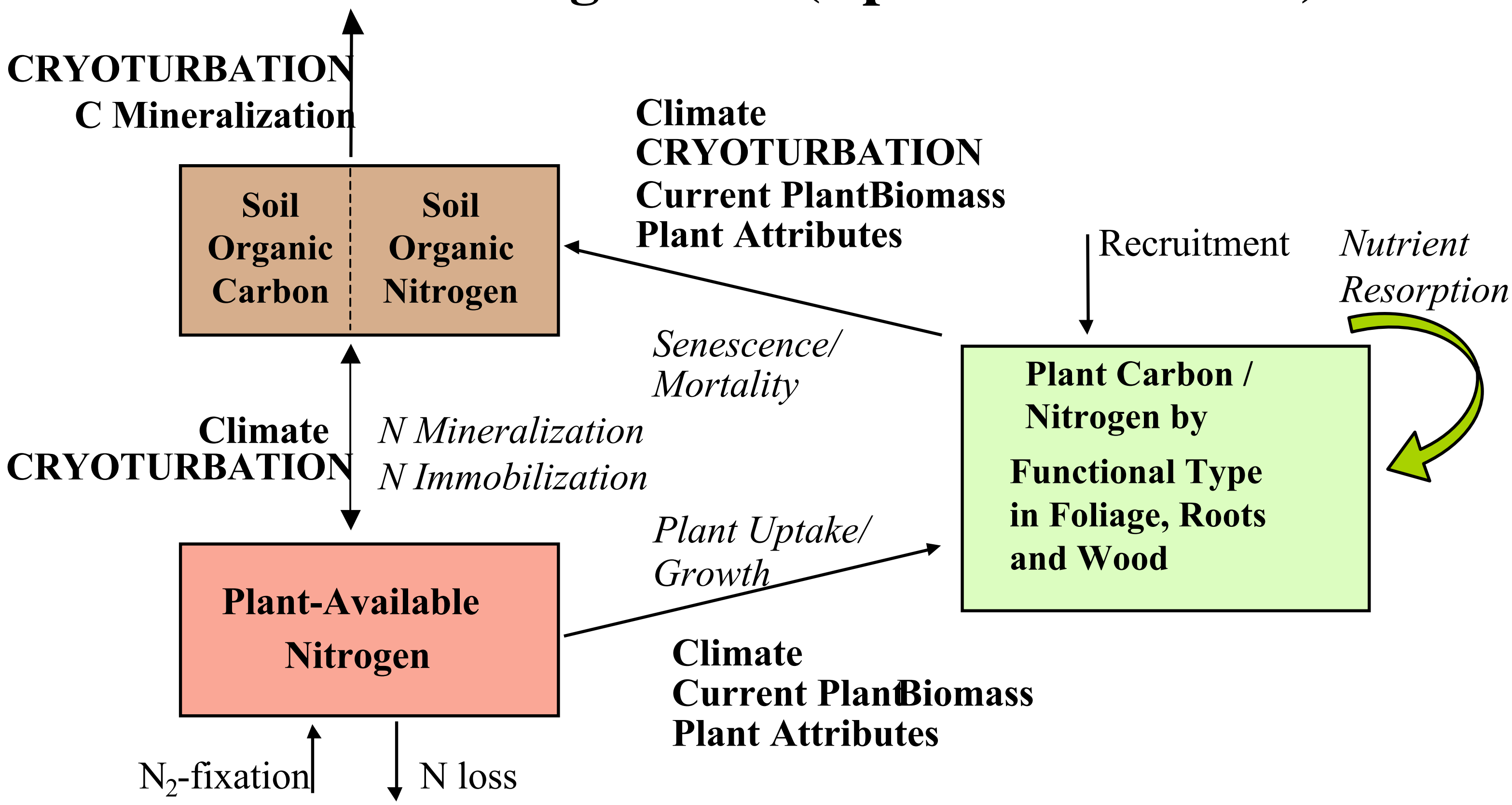
Howie Epstein
U. Virginia

Marilyn Walker
U. Alaska
Fairbanks

Alexei Kelly
U. Virginia

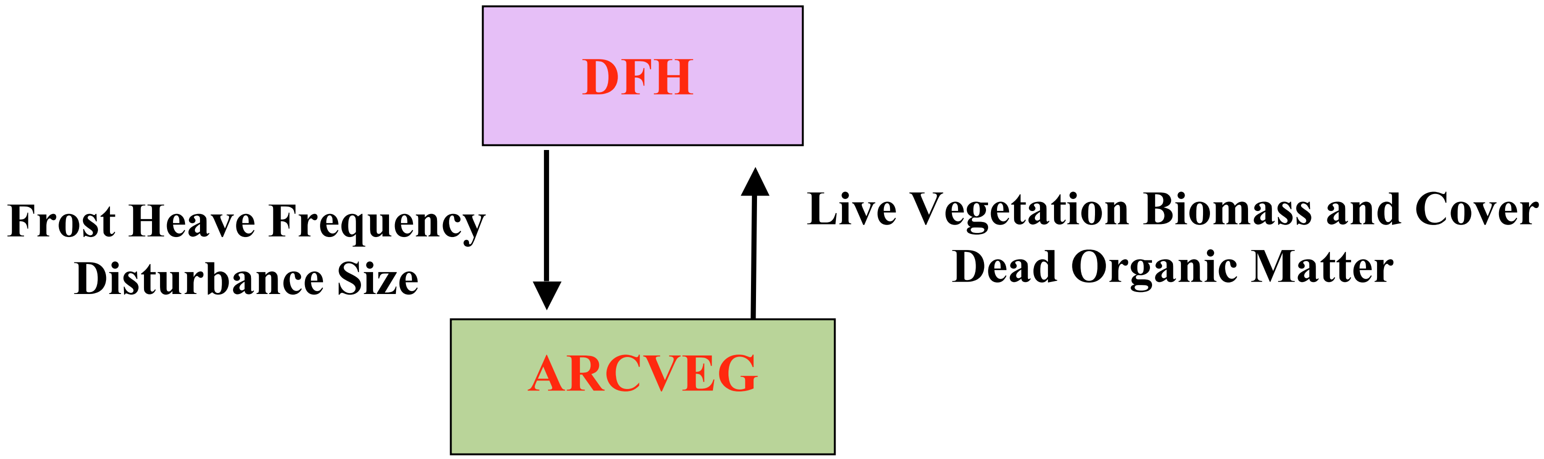
The responses of these systems to changes in temperature are likely to be nonlinear and unpredictable, but can be partially understood and modeled by examining the relative strengths of feedbacks between the components of the system at several sites along the natural arctic temperature gradient. ***Our fifth task is to develop a vegetation model of succession on frost boils that is linked to climate, biogeochemical cycling, and the differential frost-heave model.***

ArcVeg Model (Epstein et al. 2000)



- **Smulates 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.**

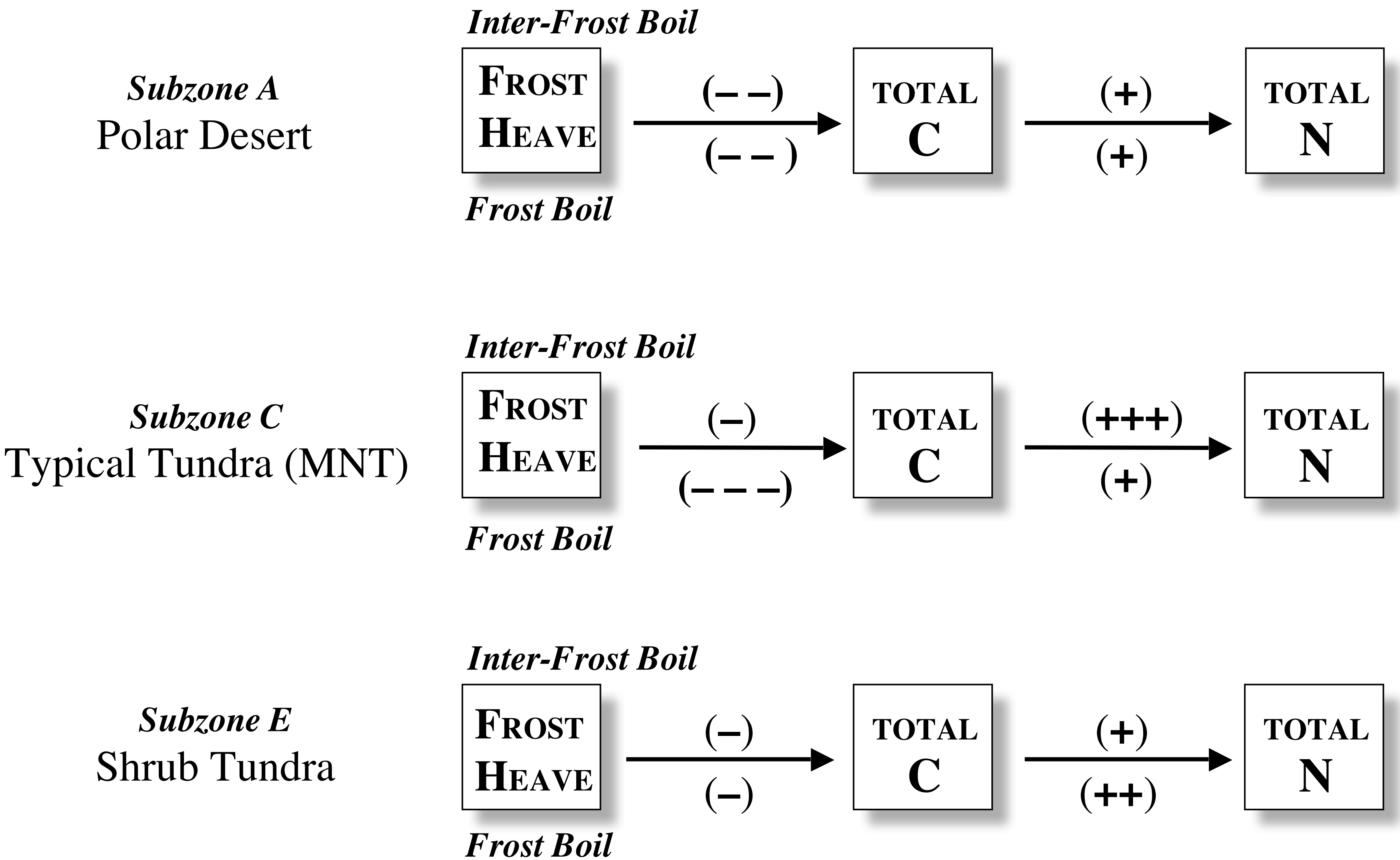
Linkages between ArcVeg and DFH models



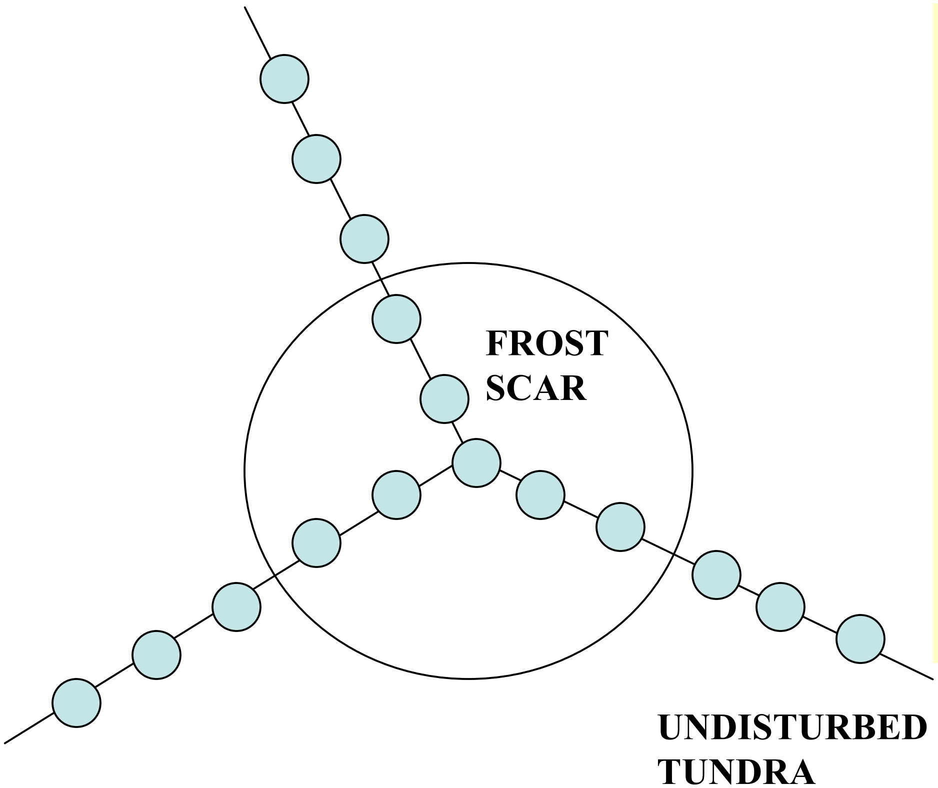
- The DFH model will provide for ArcVeg the spatial frequencies of frost boil disturbances.
- The ArcVeg model will pass to the DFH model the total live phytomass by plant type and the total soil organic matter.

Dissolving complex nonlinear responses into a series of simpler relationships along the climate gradient

Example: Soil carbon and nitrogen of frost boils along the climate gradient

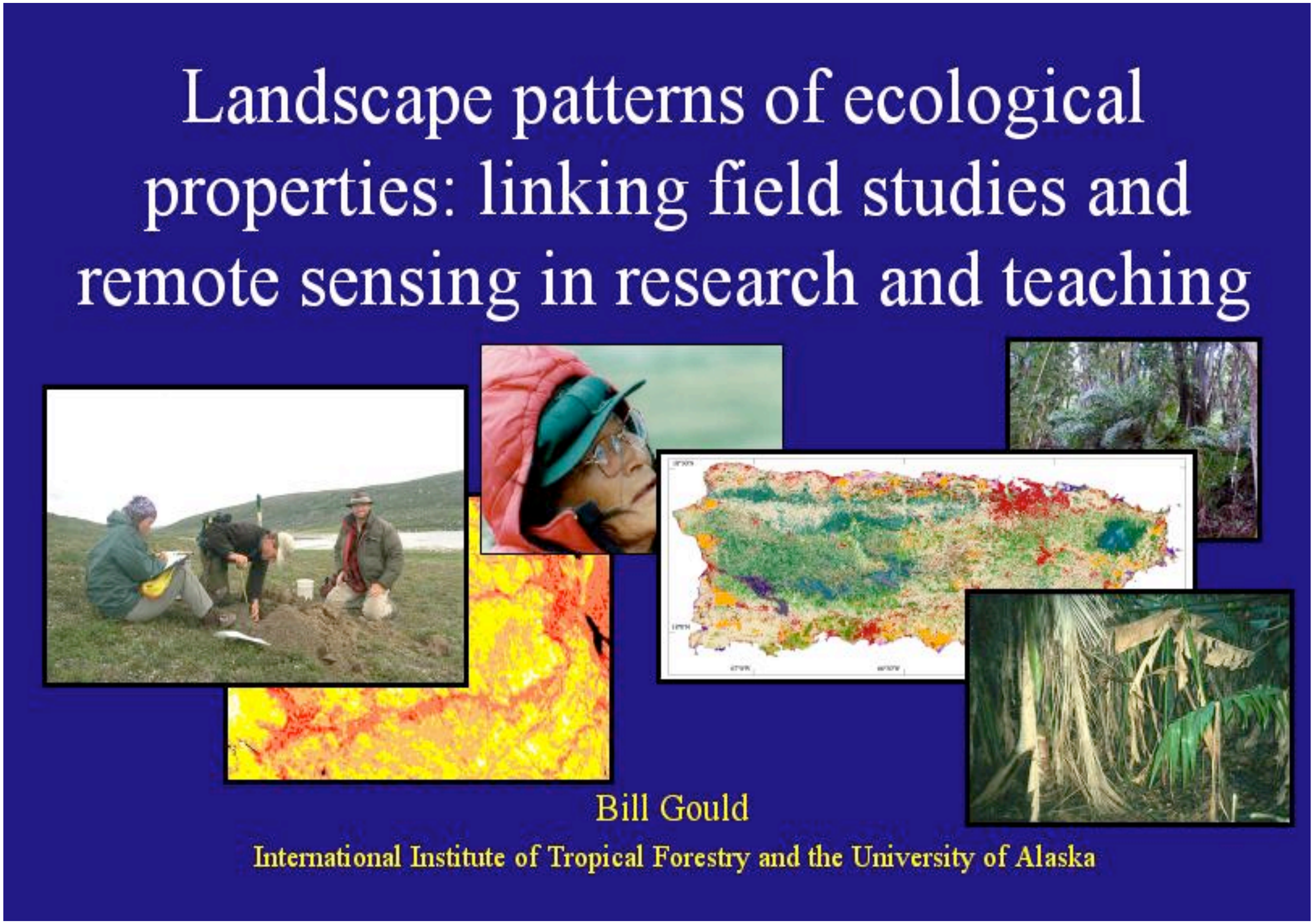


Temporal and spatial variation of biogeochemistry across successional gradients: *Alexia Kelly's Ph.D. project*



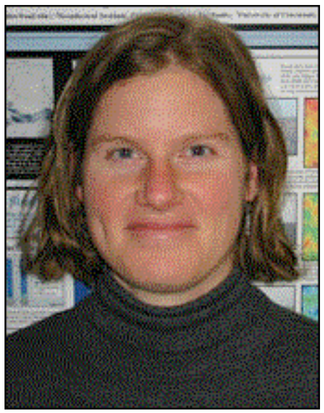
- **Series of micro-transects on replicate frost scars at each of several locations along the climate gradient.**
- **Soil organic C and N, NH_4, NO_3, pH, cations, soil respiration.**
- **Samples across the frost boils in areas with differing stability.**
- **Biweekly sampling.**

Component 4, Education



Our sixth task is to involve students and native people in our biocomplexity research through field study programs.

Component 5, Coordination and data management



Julie Knudson
U. Alaska
Fairbanks

Hilmar Maier
U. Alaska
Fairbanks

Jiong Jia
U. Virginia

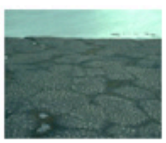
Our seventh task is to coordinate the various components of the project and make the data available to all project members, the scientific community, and the public.

http://www.geobotany.uaf.edu/cryoturbation/

ALASKA GEOBOTANY CENTER: BIOCOMPLEXITY PROJECT







Biocomplexity of Frost-Boil Ecosystems

Project Summary

This project seeks to understand the complex linkages between biogeochemical cycles, vegetation, disturbance, and climate across the full summer temperature gradient in the Arctic in order to better predict ecosystem responses to changing climate. We focus on frost-boils because: (1) The processes that are involved in the self-organization of these landforms drive biogeochemical cycling and vegetation succession of extensive arctic ecosystems. (2) These ecosystems contain perhaps the most diverse and ecologically important zonal ecosystems in the Arctic and are important to global carbon budgets. (3) The complex ecological relationships between patterned-ground formation, biogeochemical cycles, and vegetation and the significance of these relationships at multiple scales have not been studied. (4) The responses of the system to changes in temperature are likely to be nonlinear, but can be understood and modeled by examining the relative strengths of feedbacks between the components of the system at several sites along the natural arctic temperature gradient.

We examine three aspects of biocomplexity associated with frost-boil ecosystems. They are: complexity associated with self-organization in frost-boil; complexity associated with interactions between biogeochemical cycles, cryoturbation, and vegetation; biocomplexity across spatial-temporal scales.

We propose to answer six questions related to the biocomplexity of frost-boil ecosystems: (1) How does the self-organization associated with frost boils occur? (2) How does the frost heave affect the soil biogeochemical processes within and between the frost boils? (3) How do frost heave and biogeochemical processes affect plant communities? (4) How do the biological processes in turn feed back to control frost heave? (5) How do interactions between biogeochemistry, cryotrubation and vegetation change along the existing arctic climate gradient? (6) How do the complex patterns associated with frost boils affect the tundra systems in a hierarchy of spatial-temporal scales?

Full text of Biocomplexity of Frost-boil Ecosystem project proposal (in PDF, 328K)
VECO field arrangement and schedule (in PDF, 90K)
Project budget (in PDF, 48K)

[Biocomplexity Home] [Objectives] [Components] [Logistic] [Study Sites] [Preliminary Results] [Photo Gallery]

Alaska Geobotany Center [AGC]
Institute of Arctic Biology
University of Alaska Fairbanks
Fairbanks, Alaska
Update: 4/4/2002

Thoughts on biocomplexity

- Conceptualize the system in terms of specific questions, (e.g., three element diagram of the frost-boil system).
- The questions and the system change with scale (e.g., relationship of the frost boil system to the bioclimate gradient, and to regional arctic ecosystems).
- Complex systems involving physical components follow physical laws that lend themselves to mathematical solutions or groups of solutions, (e.g., self organization of frost heave features in the absence of vegetation).
- The components of complex systems involving living or conscious components (biocomplex systems) are constantly coadapting, evolving, are full surprises, and are unpredictable, (e.g., how frost boil ecosystems respond to climate change).
- Dissolving very complex relationships into simpler systems may help in the analysis, (e.g., examining the frost-heave/nitrogen relationships at discreet points along the bioclimate gradient).

Biocomplexity of Frost-boil Ecosystems

Presented at the Arctic Forum
Washington, D.C.
May 16-17, 2002

Return to:

Alaska Geobotany Center Home Page
http://www.geobotany.uaf.edu

Biocomplexity Home Page
http://www.geobotany.uaf.edu/cryoturbation/