Dynamics of Vegetation and Soils in Arctic Tundra Ecosystems

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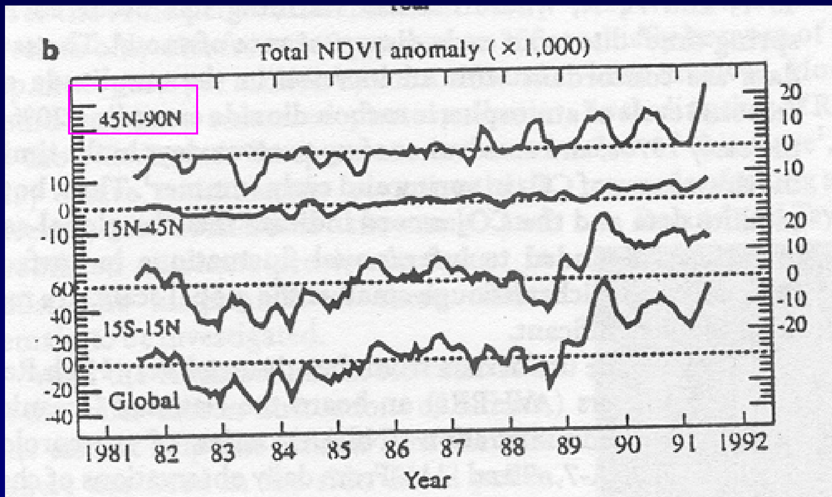
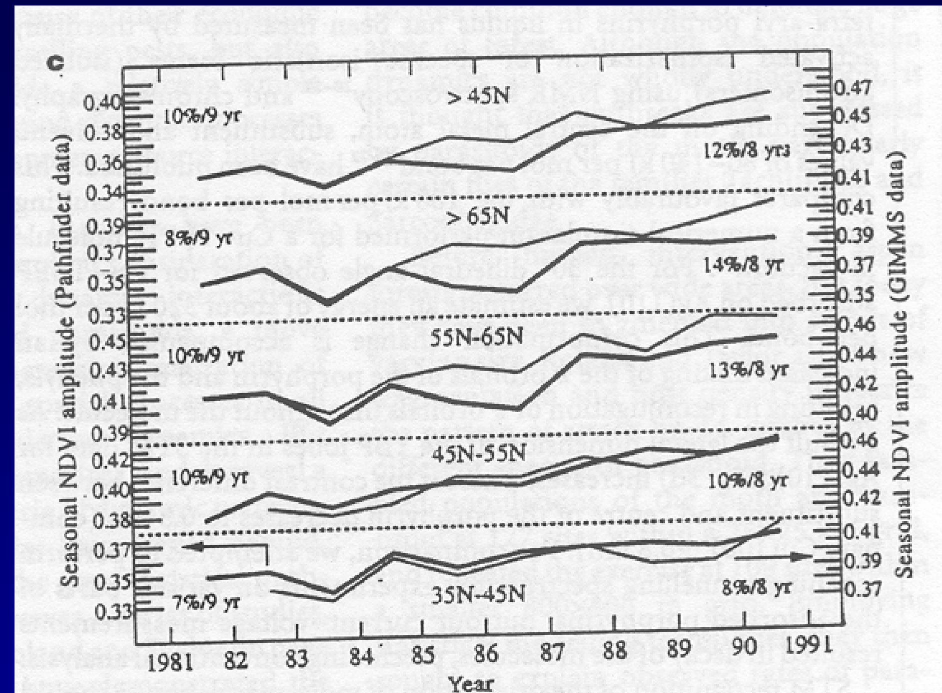
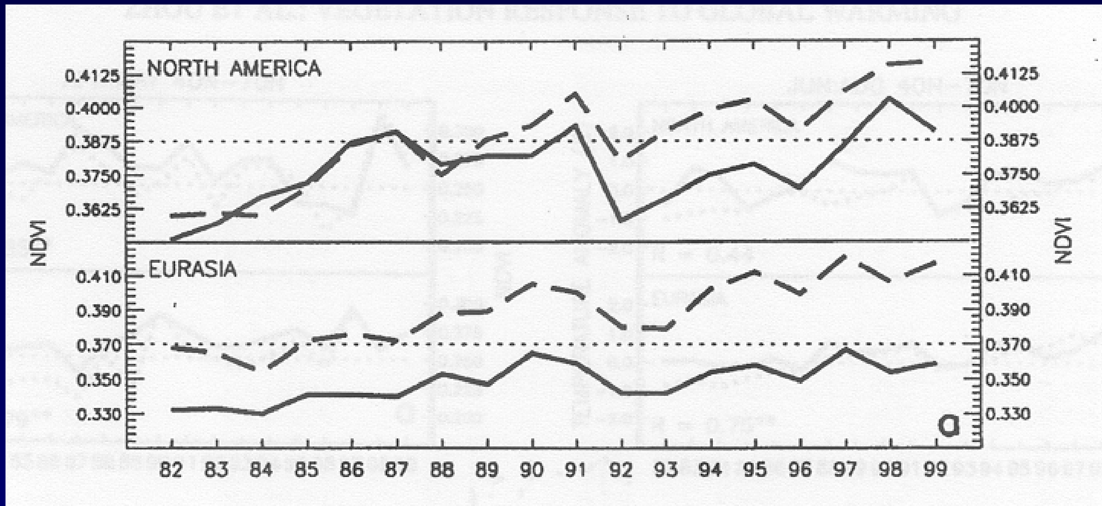
Temporal Dynamics of Vegetation at High Latitudes

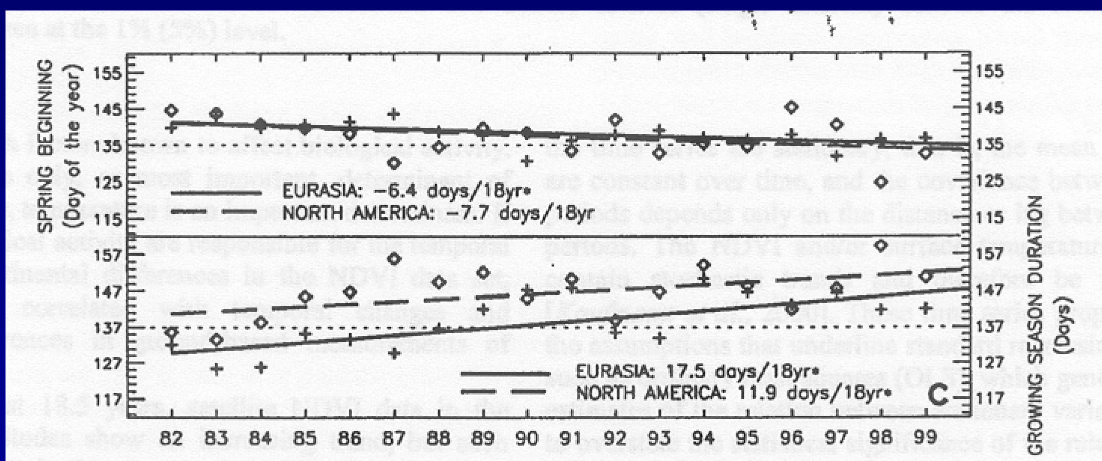




Myneni et al. 1997 *Nature*

- 10-14% increase in seasonal amplitude of NDVI above 45 °N from 1981 to 1991
- advance in the start of the growing season by up to 7 days



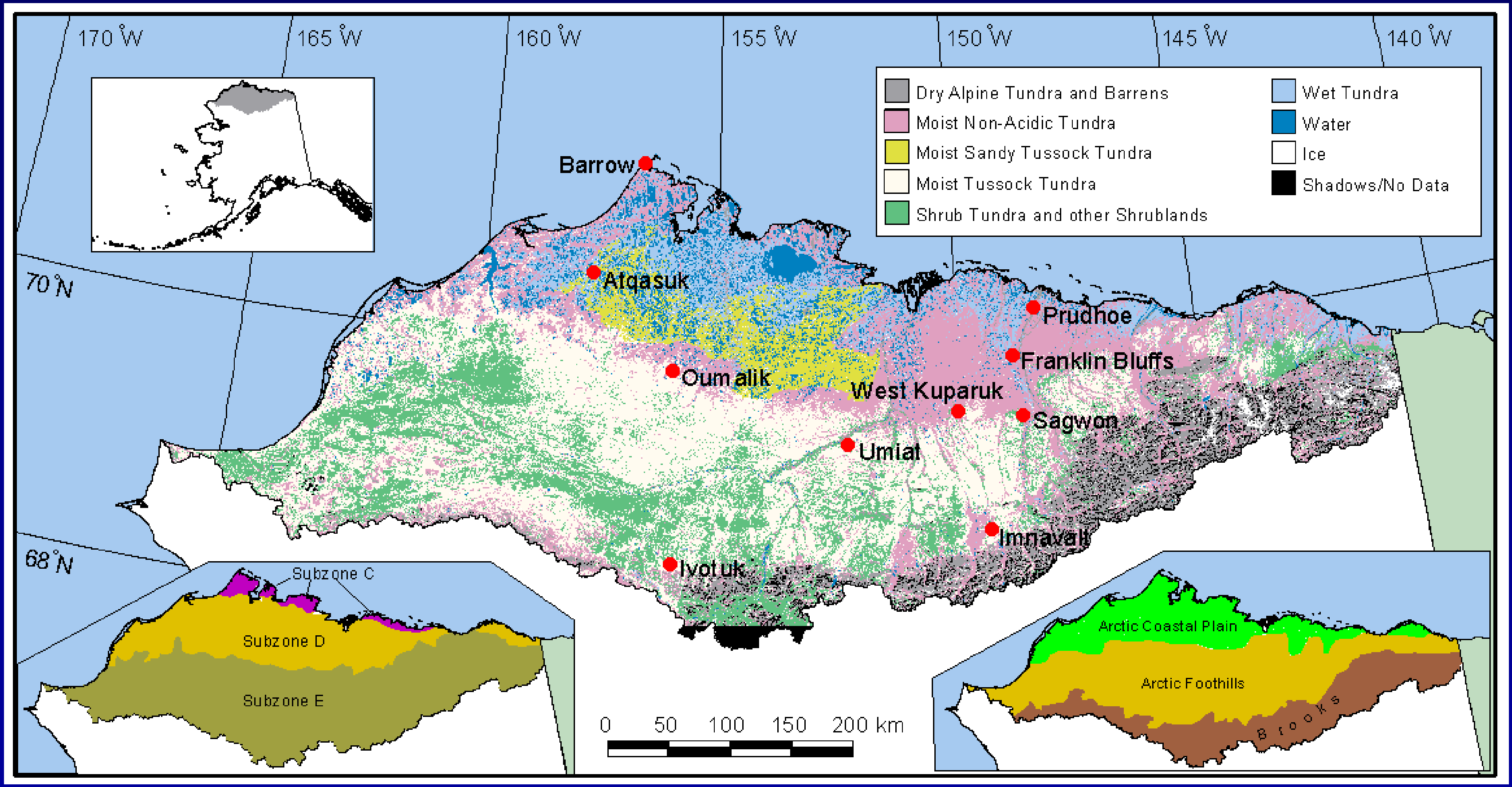


Zhou et al. 2001 *JGR*

- mean NDVI increase of 10% between 40 °N and 70 °N
  from 1981 to 1999
- mean increase of 15 days in the length of the growing season

However, temperature trends at northern latitudes over the past few decades are highly variable spatially, and therefore the circumpolar results are not necessarily applicable at the regional scale.

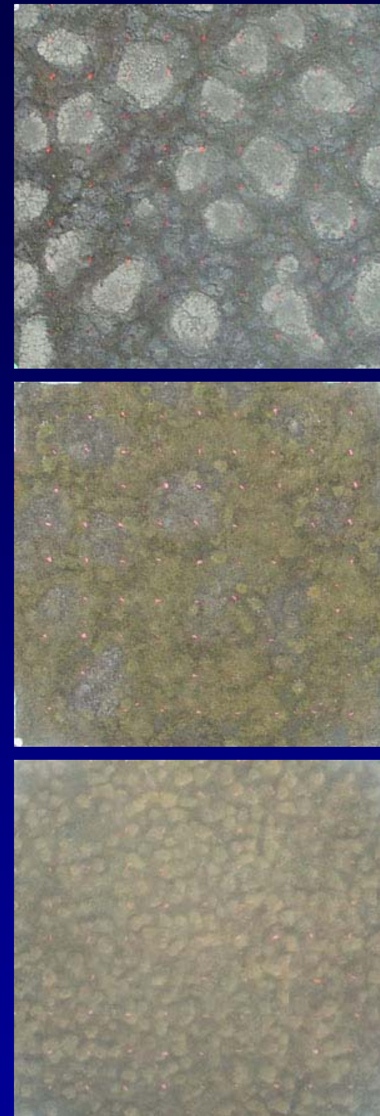
Our objective was to evaluate the temperature and NDVI trends over the past decade throughout the Arctic Slope, a region of heterogeneous tundra that encompasses over 100,000 km² from 68.0 °N to 71.4 °N.



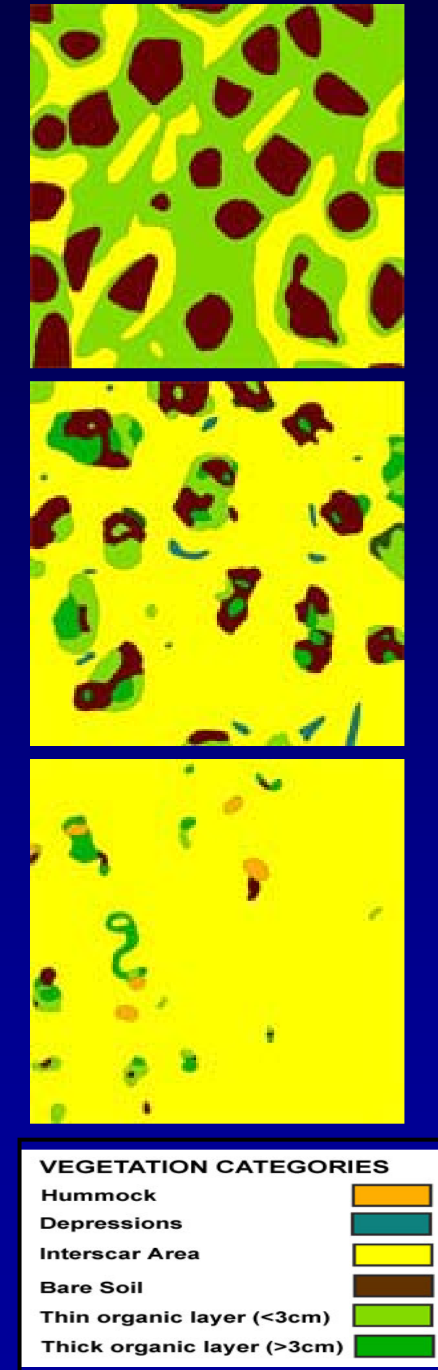
Prostrate dwarf shrub

Erect dwarf shrub

Low shrub



Aerial photos of 10 x 10 m grids




Howe Island bluff
In Subzone C


Subzone D


Subzone E
Hinzman
2 23 1999 17 49

Dominant Tundra Types

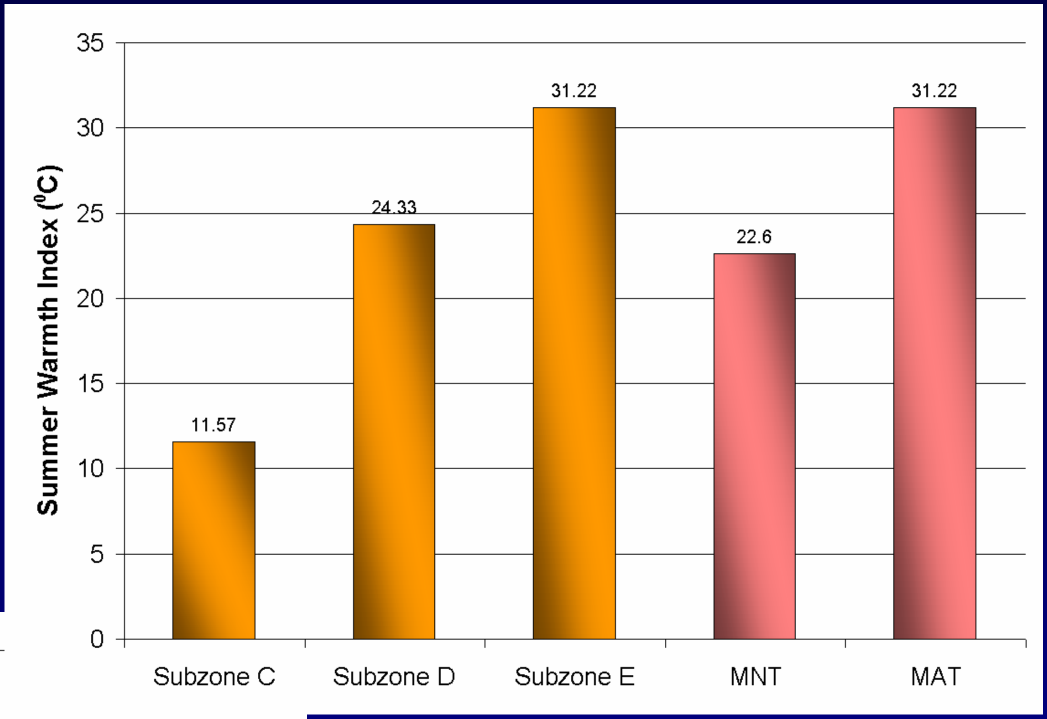
Sandy Tundra - found mainly in Subzone D in the western portion of the Arctic Slope; dominated by tussock graminoids and dwarf shrubs with lichen patches

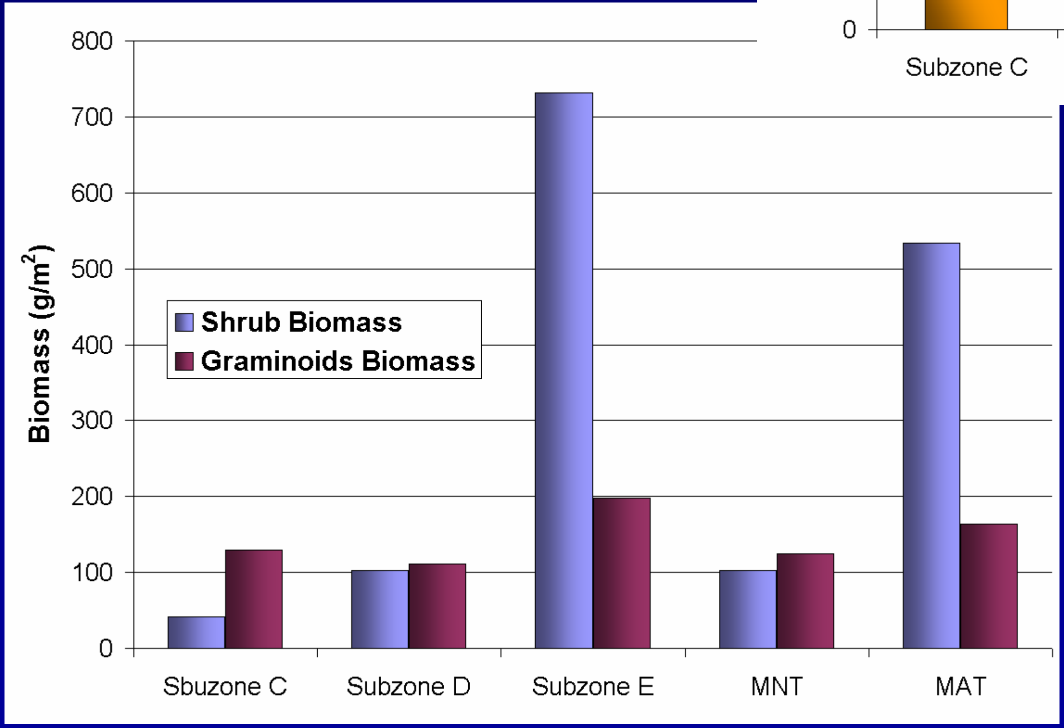
Moist Non-Acidic Tundra (MNT) - found throughout Subzones C and D; dominated by non-tussock graminoids, prostrate dwarf shrubs and mosses

Moist Acidic Tundra (MAT) - found throughout Subzone E; dominated by tussock graminoids (*Eriophorum vaginatum*), dwarf and erect shrubs and *Sphagnum* mosses

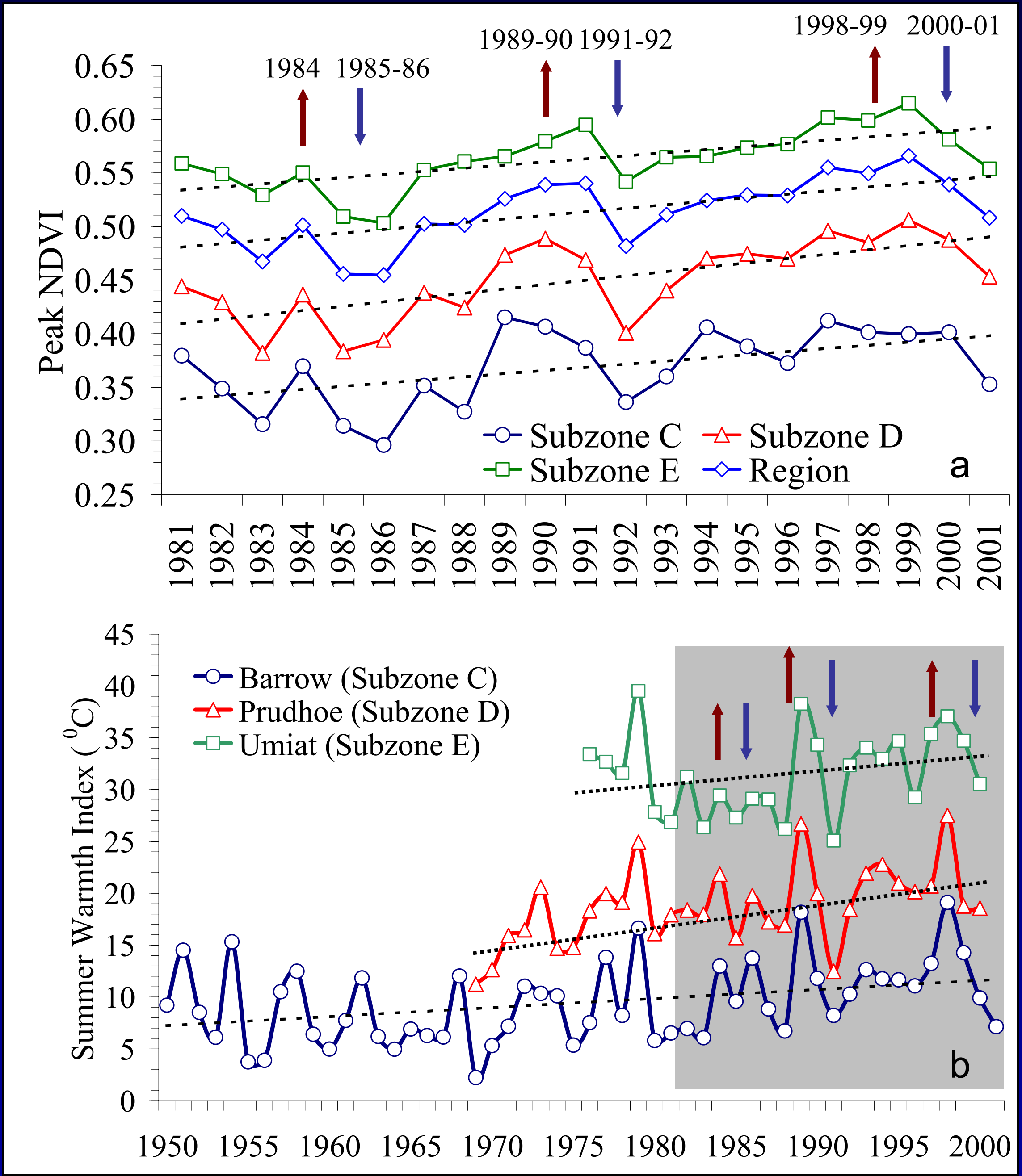
Shrub Tundra - found in the southern part of Subzone E; dominated by low shrubs (*Salix spp., Betula spp. and Alnus spp*.)

Summer Warmth Index
- sum of monthly mean temperatures > 0°C





Aboveground Live Biomass (g/m^2)



NDVI Increases with Warming, 1981-2001

- Peak greenness increased by 13-19% in two decades.

- This increase is higher than that in high-latitude N America

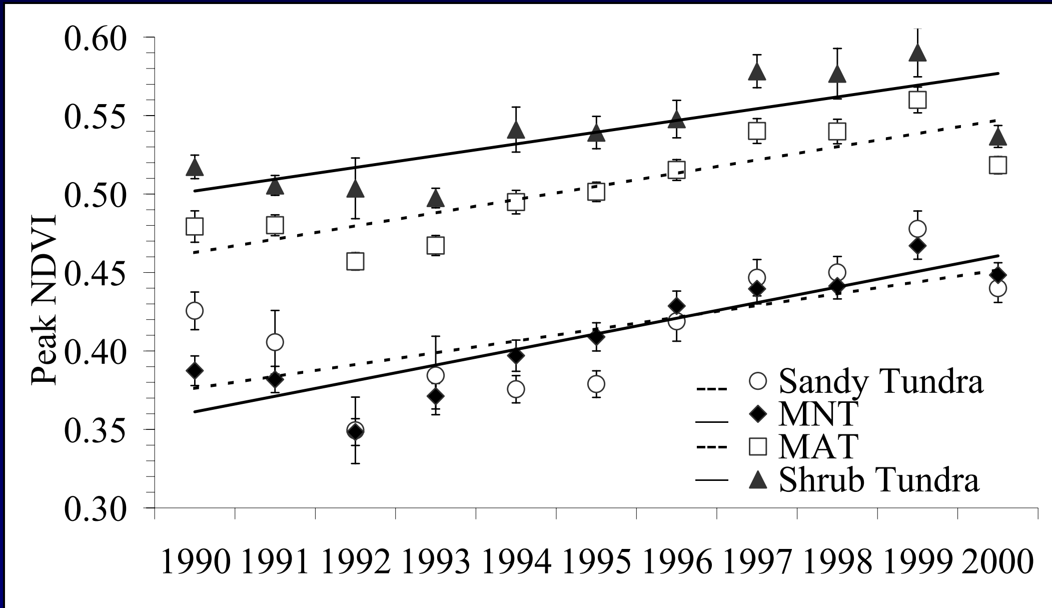
- Brief declines in 1985-86, 1992, and 2000-01

- Greatest increase in Subzone D

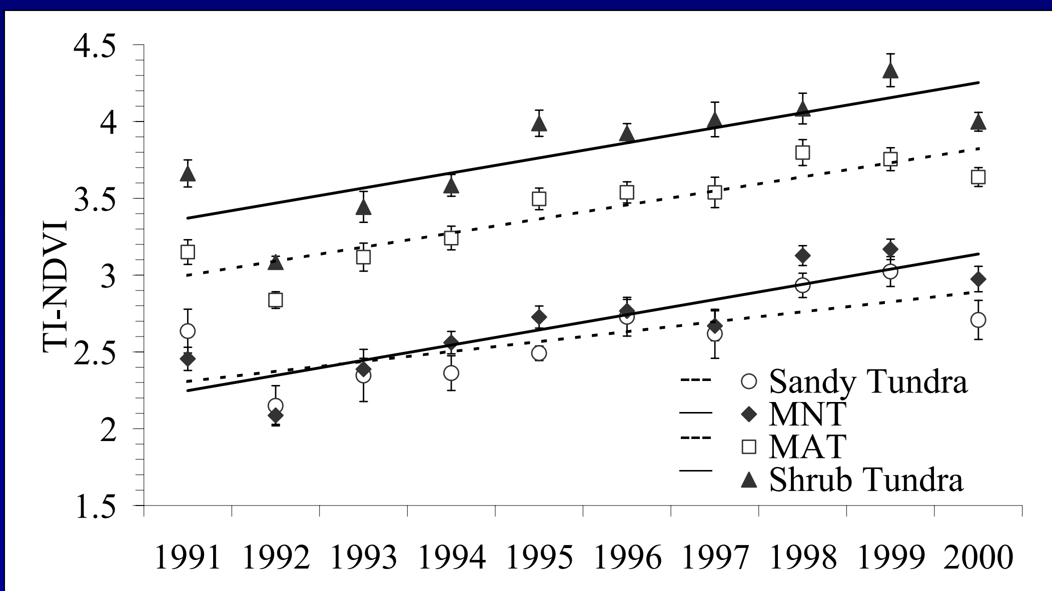
- Similar peaks and declines in SWI as arrows show

- The increase is likely responsive to SWI rise of 0.16-0.34 °C/yr.

Jia et al. GRL, submitted



NDVI Increases for all tundra types in 90s



Peak NDVI and TI-NDVI sampling categorized by tundra types.

Both indices increased for all tundra types: averagely 13.6% for peak NDVI and 17.7% for TI-NDVI.

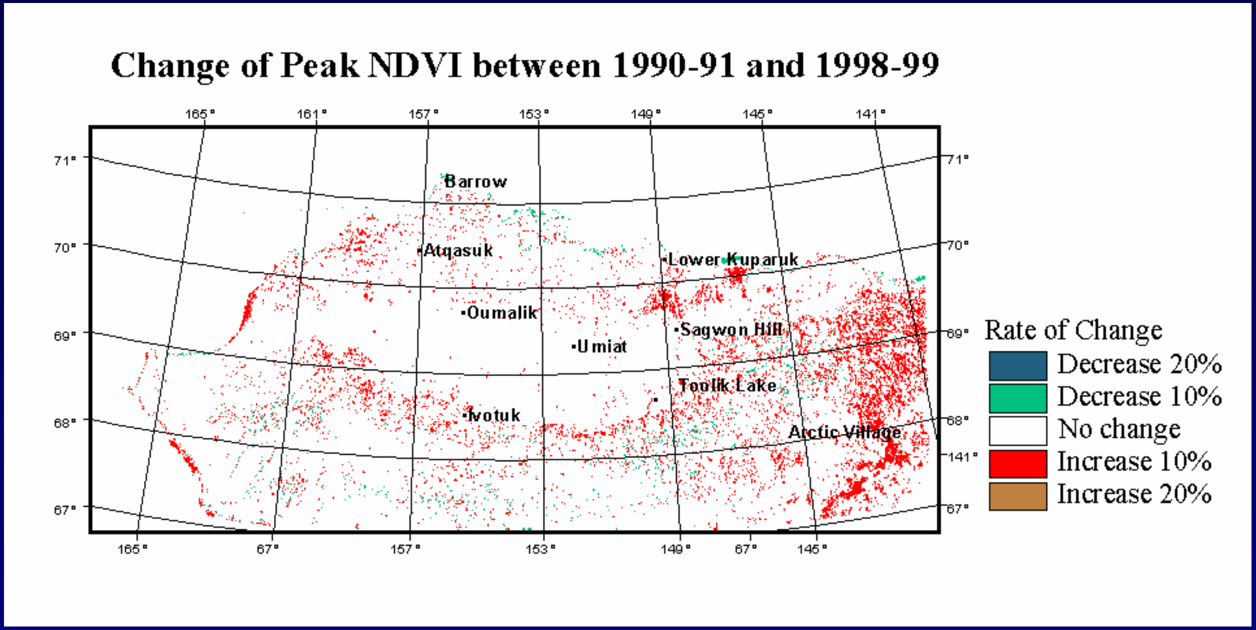
Mosit nonacidic tundra has the Greatest decadal increase in NDVI

Higher TI-NDVI increased were found in southern types.

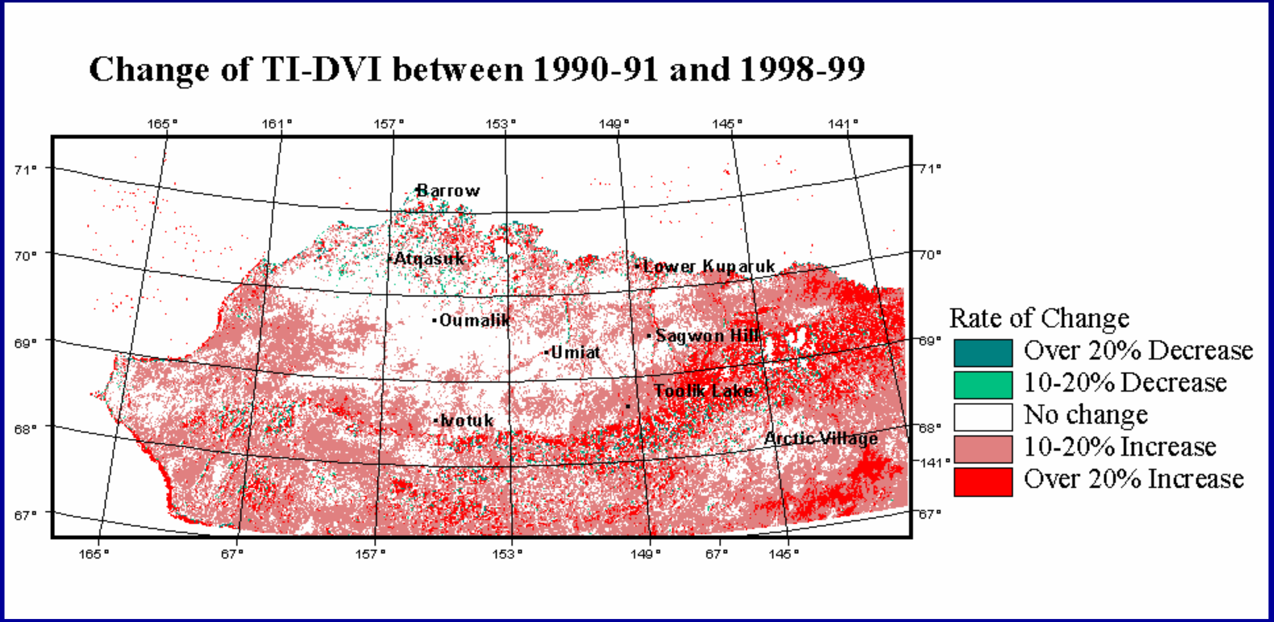
NDVI decline in 1992 after Mt Pinatubo eruption occurred for all tundra types.

Jia et al. GRL, submitted

Regional Temporal Changes in NDVI

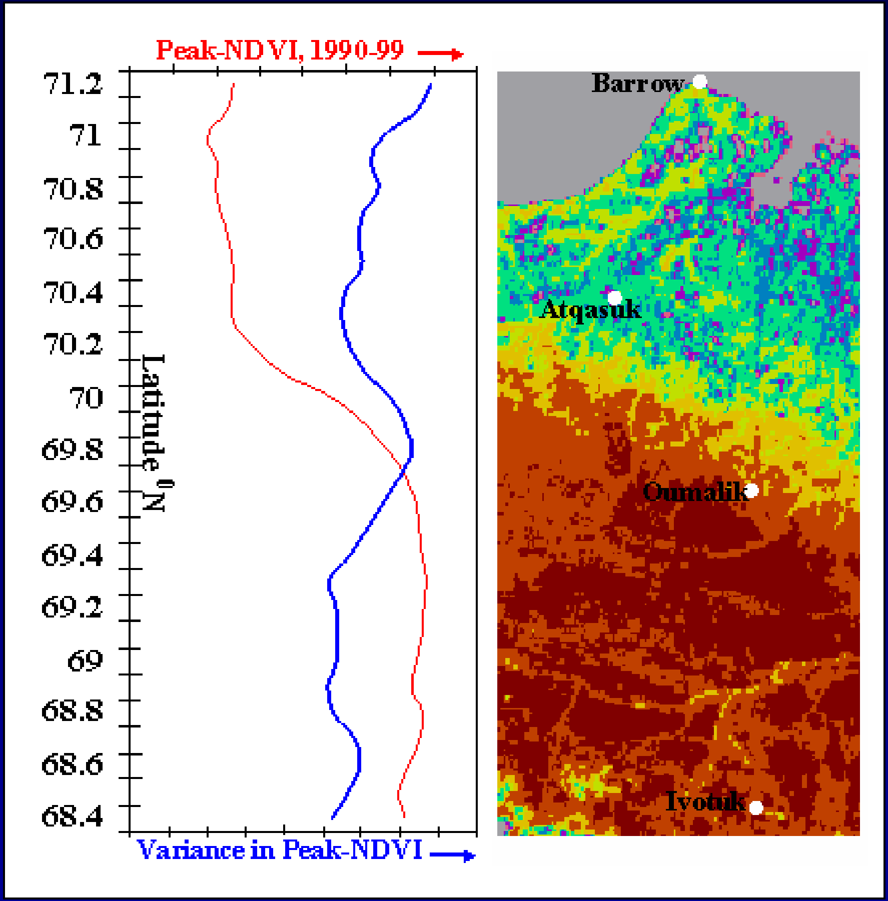


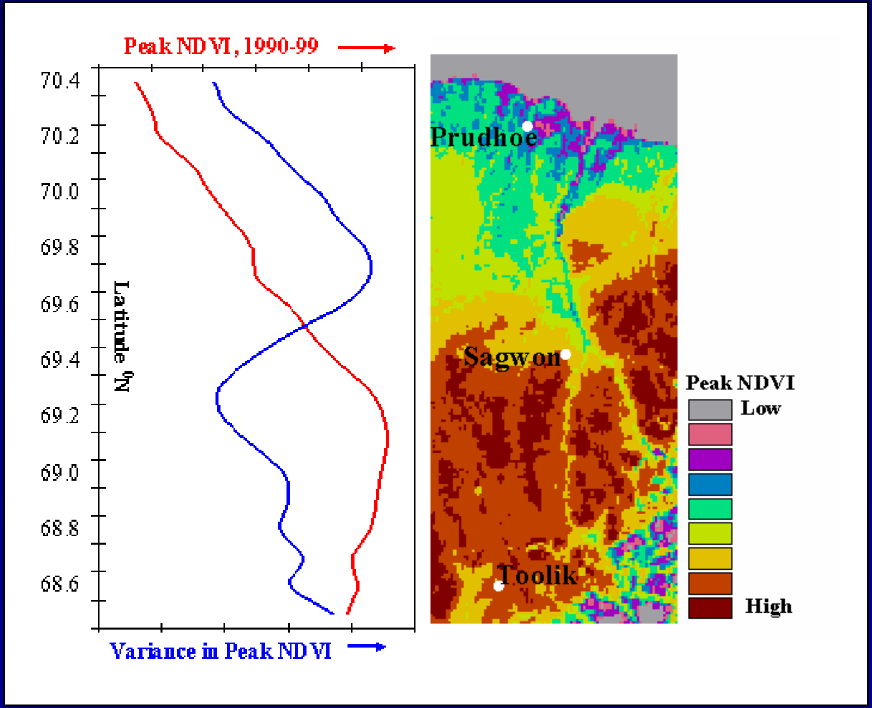
Peak NDVI



Temporally- Integrated (TI) NDVI

Mean and Temporal Variance of Peak NDVI along Western and Eastern Transects





- Transition zone in mean Peak NDVI between 69.4 °N and 70.2 °N for both transects
- Maximum variance in Peak NDVI falls within the transition zone

Where are the changes most pronounced?

		MEAN	STD	Increase	Slope vs. SWI	R^2
Peak NDVI						
	Subzone C	0.357	0.045	0.058	0.0034	0.19
	Subzone D	0.441	0.037	**0.069**	**0.0061**	**0.38**
	Subzone E	0.518	0.035	0.055	0.0052	0.37
	Sandy Tundra	0.415	0.042	0.043		
	MNT	0.411	0.038	**0.073**	**0.0029**	**0.29**
	MAT	0.505	0.036	0.060	0.0020	0.07
	Shrub Tundra	0.540	0.035	0.052		
TI NDVI						
	Subzone C	2.01	0.206	0.442	0.0437	0.49
	Subzone D	2.81	0.223	**0.511**	**0.0695**	**0.51**
	Subzone E	3.59	0.332	0.504	0.0568	0.40
	Sandy Tundra	2.60	0.194	0.231		
	MNT	2.67	0.221	0.497	0.0380	**0.54**
	MAT	3.40	0.293	**0.546**	**0.0548**	0.37
	Shrub Tundra	3.80	0.428	0.504		

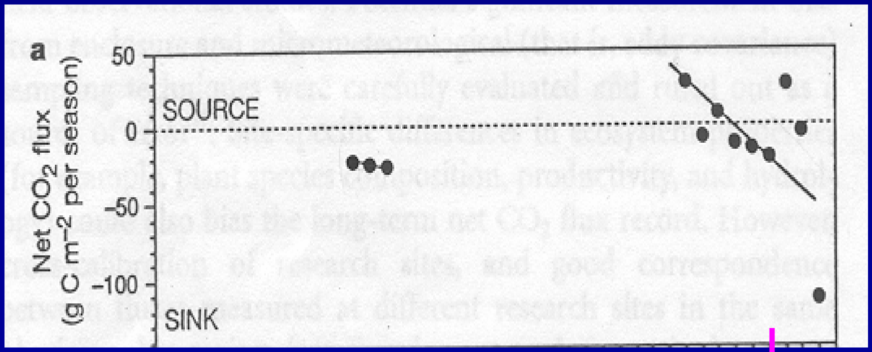
- Peak NDVI clearly most responsive in Subzone D and MNT (transition)
- TI NDVI shows more of a response toward the south compared to Peak

Possible Explanations and Supporting Evidence for Change

- Hope et al. (in press) suggest that increases in stratospheric optical depth following the eruption of Mt. Pinatubo in 1991 are largely responsible for the drop in NDVI in 1992 and the subsequent increase through 1996.

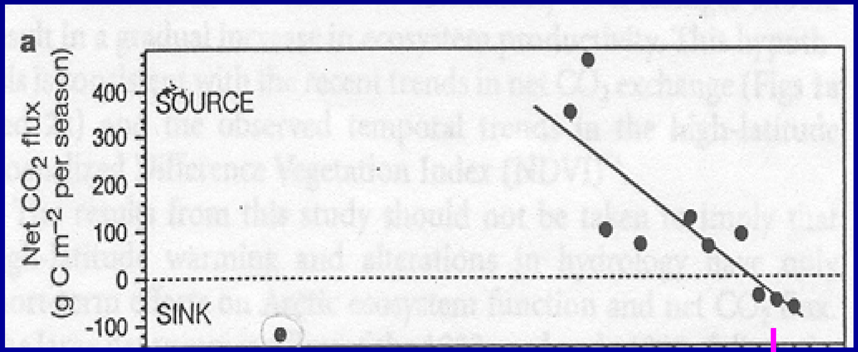
- Lucht et al. (2002), however, using a biogeochemical model of vegetation dynamics (LPJ-DGVM) infer that satellite-derived leaf area index was largely controlled by changes in temperature; the vegetation decline following Pinatubo was a result of decreased temperatures.

- Oechel et al. (2000) observed (and Lucht et al. simulated) a switch in tundra ecosystem from a source to a sink of CO_2 in the early 1990s.



Coastal Tundra

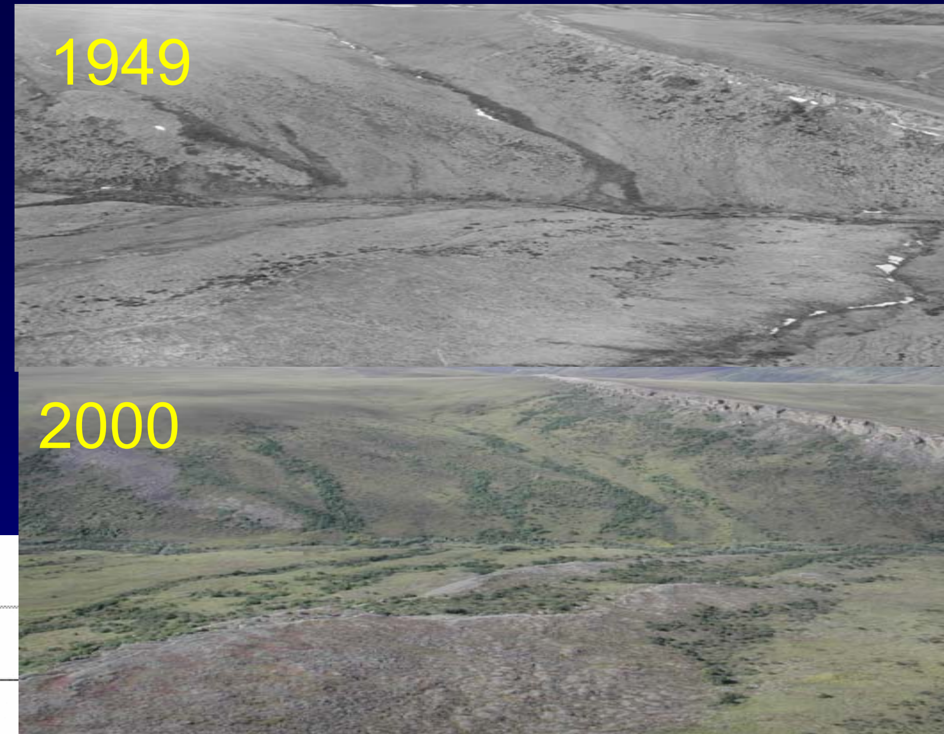
1995

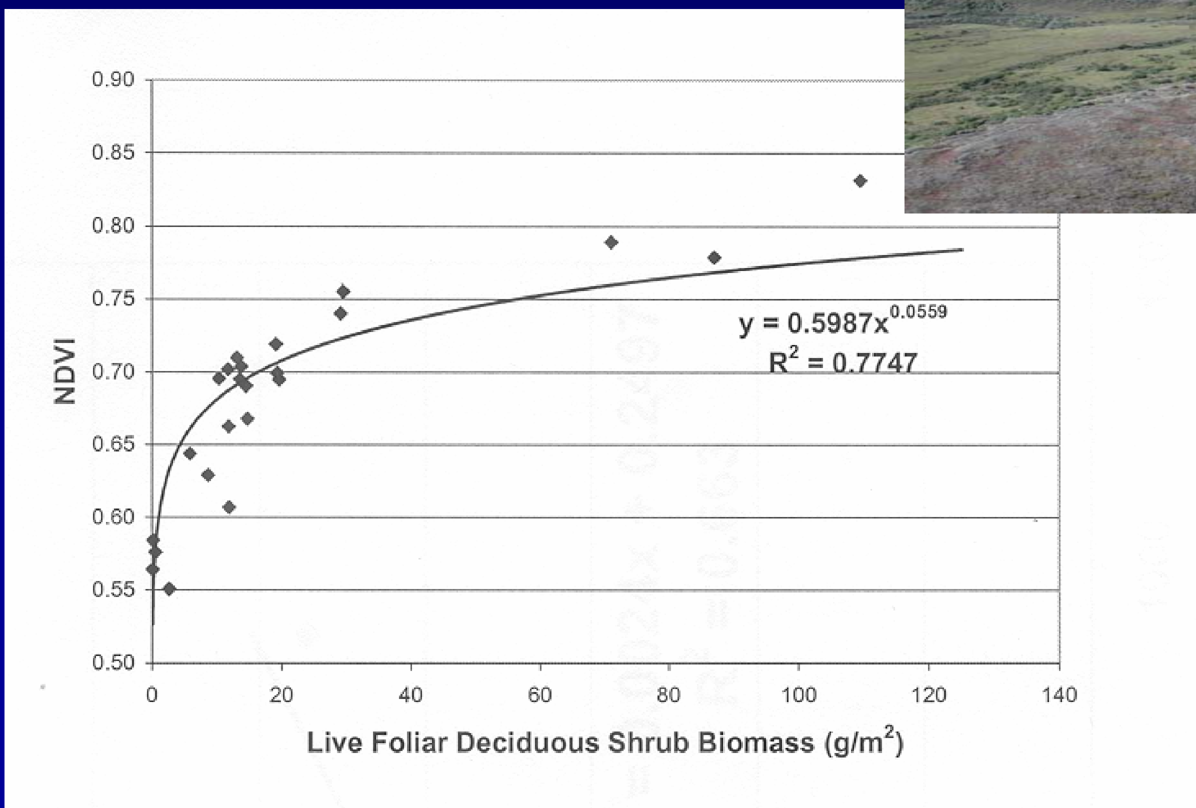


Interior Tundra

1995

- Sturm et al. (2001) show increases of shrubs over the past 50 years in aerial photographs

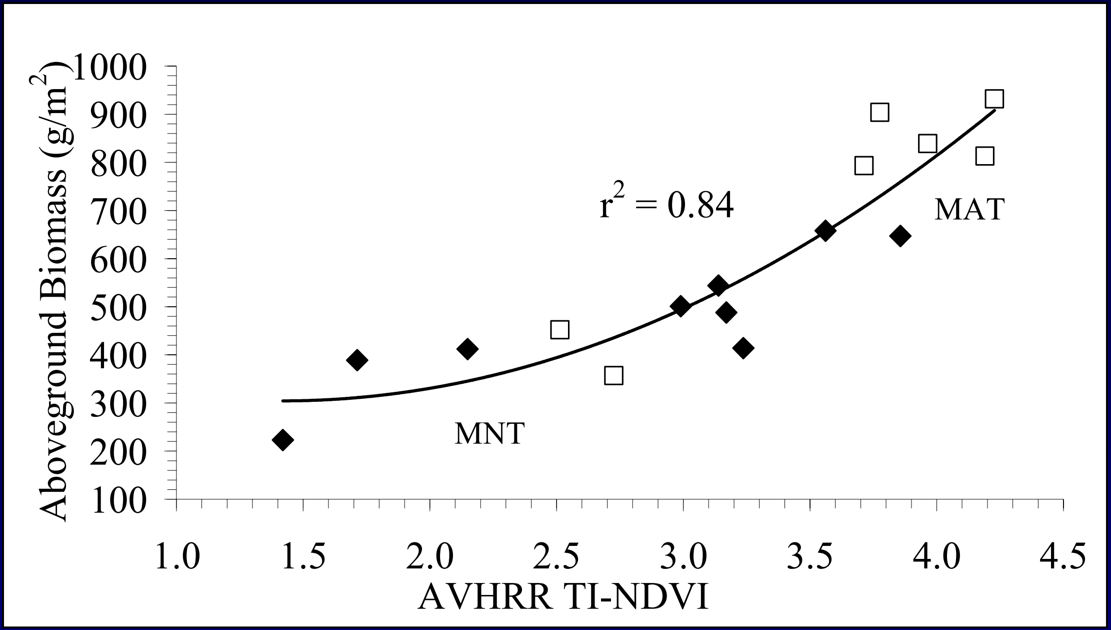


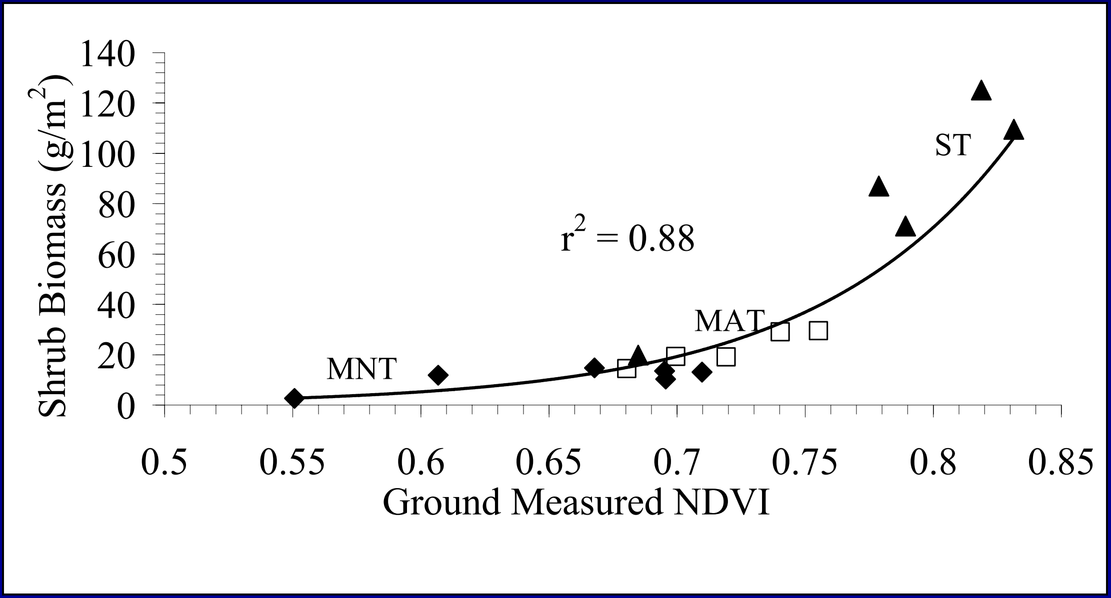


- Riedel et al. (submitted) and Hope et al. (1993) demonstrate that live deciduous shrub leaves exert a strong control on NDVI

- relationship nearly saturated for shrub tundra

NDVI vs. Biomass





- NDVI and aboveground plant biomass are positively correlated on both regional and local scales.

- NDVI explains 84-88% of the variance in plant biomass.

-NDVI increase corresponds to a ~20% (40-180 g/m^2) increase in plant biomass.

- Slight increase in biomass in MNT can greatly contribute to a higher NDVI

- Saturation of effect of biomass to NDVI is observed in shrub tundra.

Jia et al. GRL, submitted

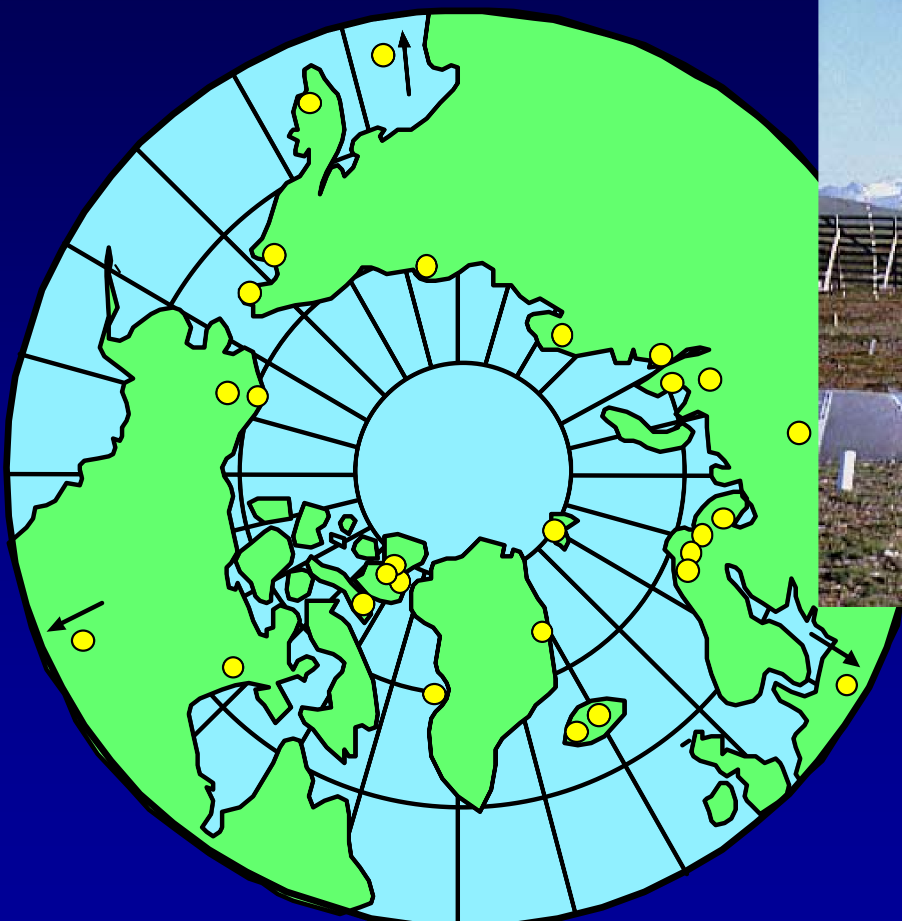
Summary

1) Peak NDVI increased from 10-19% for various Subzones and vegetation types on the Arctic Slope from 1990-2000; TI-NDVI increased from 8-25%.

2) Greatest response to temperature changes for Peak NDVI was found in moist non-acidic tundra (MNT) and generally in Subzone D; temporal increases in peak green vegetation were found in areas with high latitudinal variability in NDVI in the northern Arctic Slope.

3) Other evidence shows arctic tundra vegetation responding to temperature increases with increased leaf area, increased sinks of CO_2 and greater abundance of shrubs, which can lead directly to increases in NDVI.

Is plant community change detectable over time frames consistent with field experiments?



ITEX - the International Tundra Experiment

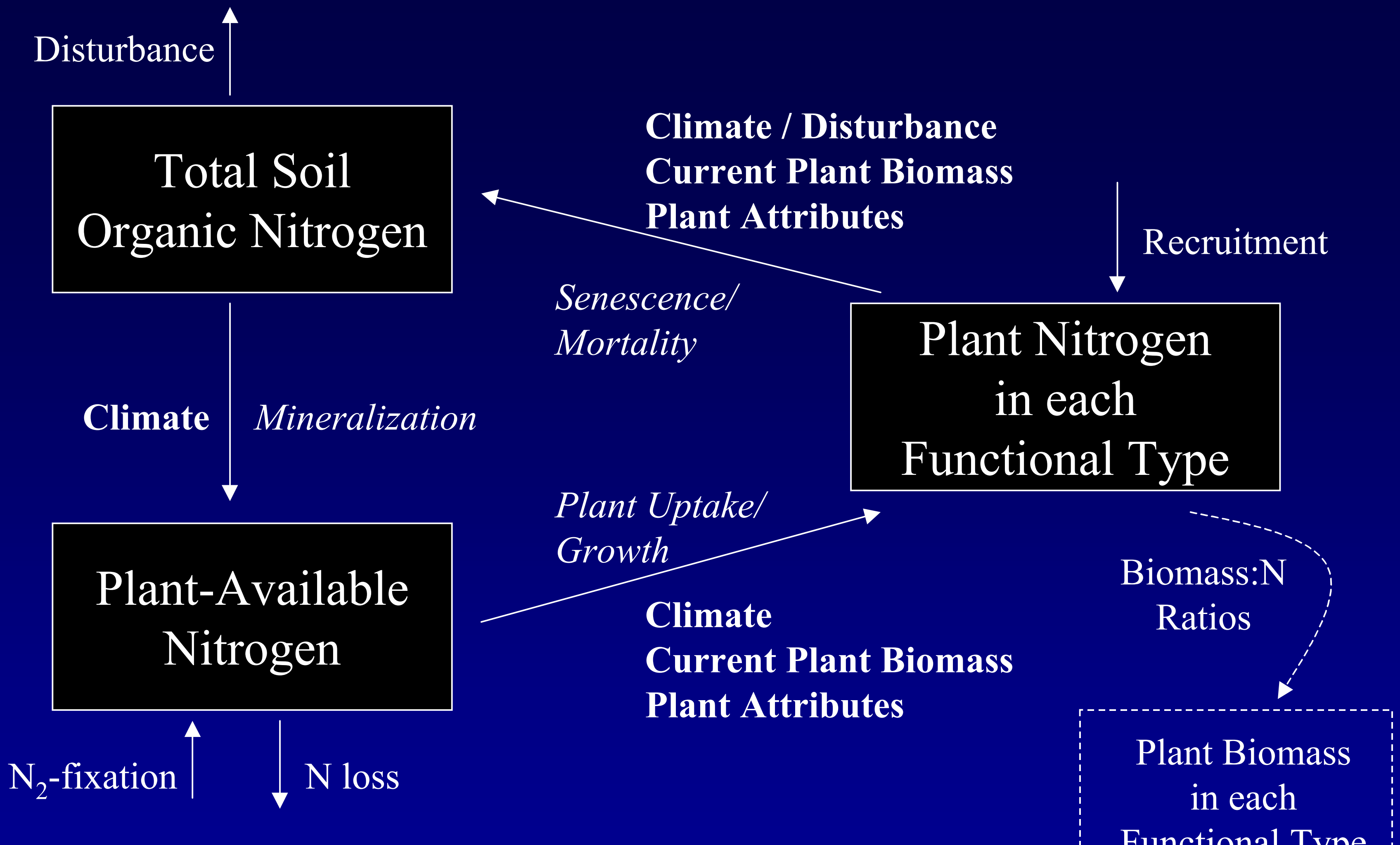
Assessing the Variability of Moist Acidic Tundra Vegetation

Spatial Variability

- Aboveground vegetation harvests at Ivotuk, AK (1999)
- Analysis of patch heterogeneity simulated by ArcVeg

Temporal Variability

- Control and manipulated plots in field warming experiments
  (e.g. Chapin et al. 1995, Hobbie and Chapin 1998)
- Simulating warming for 20 years using the ArcVeg model



ArcVeg – spatial variability

- single execution (500 years to equilibrate)
- single year of data
- variability across 10 1m² patches with different disturbance regimes and seedling establishment probabilities

Spatial Heterogeneity

Mean and CV of Plant Functional Type Biomass Across Patches

	Moss	Dec. Shrub	Ev. Shrub	Gram.	Lichen	Forb
IVOTUK						
Mean (g/m²)	208	166	178	71	40	3
CV	**84**	**41**	**90**	**80**	**235**	**251**
ARCVEG	271	117	129	22	37	3
Mean (g/m²)	**64**	**50**	**70**	**70**	**100**	**90**
CV						

- Favorable comparison between field and model data
- High spatial variability within a single hectare particularly for lichen and forbs

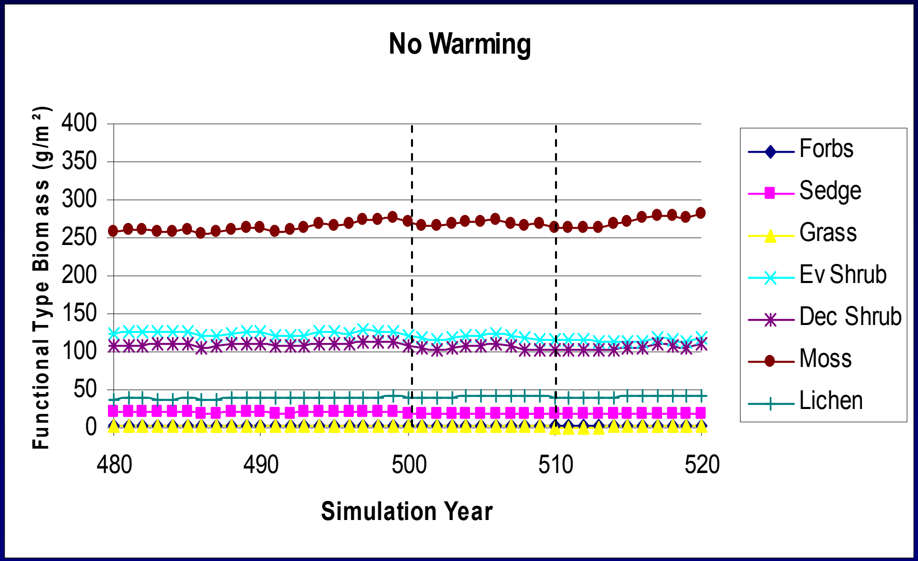
Temporal Heterogeneity

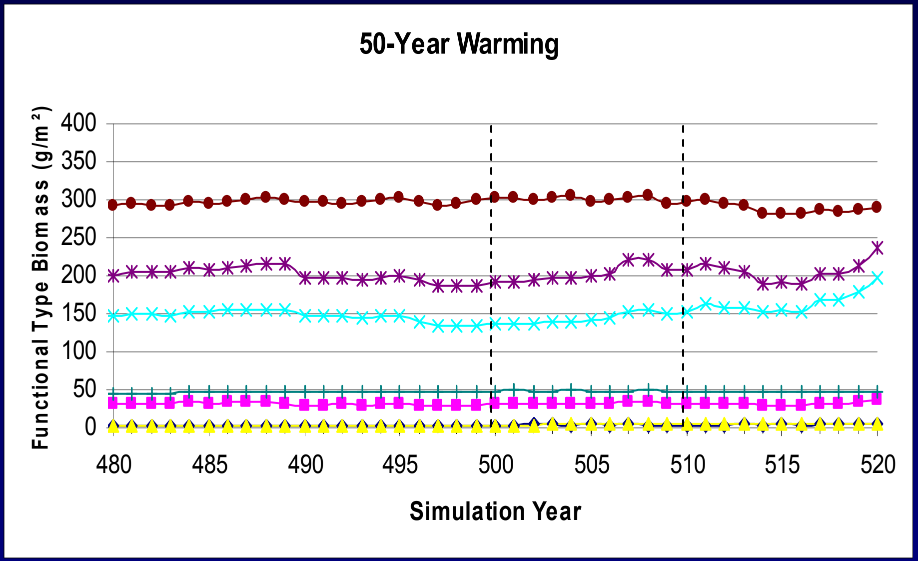
Warming Experiments (using in situ greenhouses)

	Moss		Dec. Shrub		Ev. Shrub		Gram.	
	CTL	WRM	CTL	WRM	CTL	WRM	CTL	WRM
Chapin et al. (1995)								
Mean (g/m^2) - 3yr	213	244	183	150	312	292	188	217
Mean (g/m^2) - 9yr			281	307	314	431	105	123
% diff. from CTL (3yr)		**+15**		**-18**		**-6**		**+15**
% diff. from CTL (9yr)				**+9**		**+37**		**+17**
Hobbie & Chapin (1998)								
Mean (g/m^2) - 3yr	265	290	72	115	193	169	52	45
% diff. from CTL (3yr)		**+13**		**+60**		**-12**		**-13**

- % differences between warming and control plots are small
- exceptions are evergreen shrubs (9yrs) and deciduous shrubs
- deciduous shrubs in control plots increased strongly

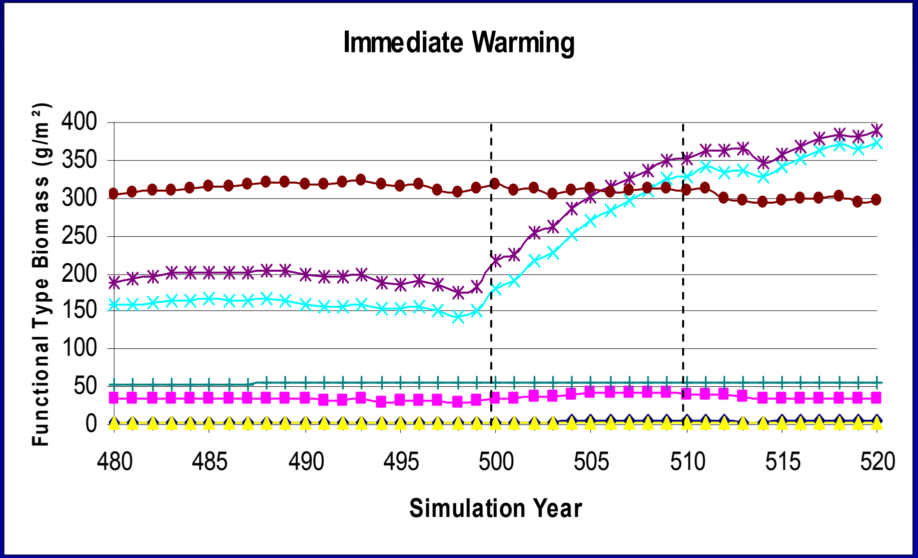
Dynamics of Plant Functional Type Biomass (ArcVeg model)



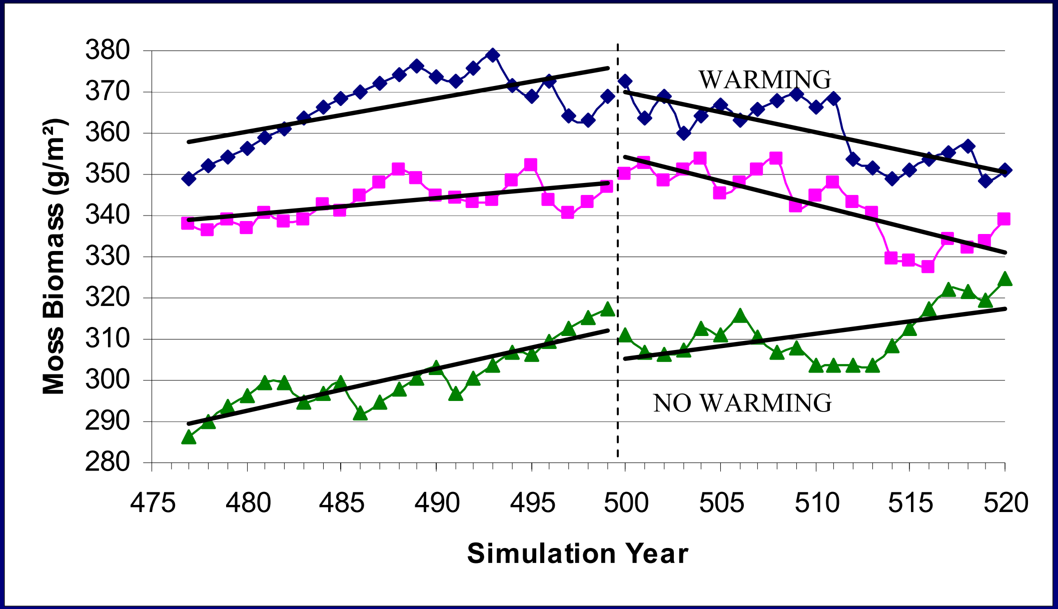


Detectable change in shrub components after 10 years under immediate warming scenario.

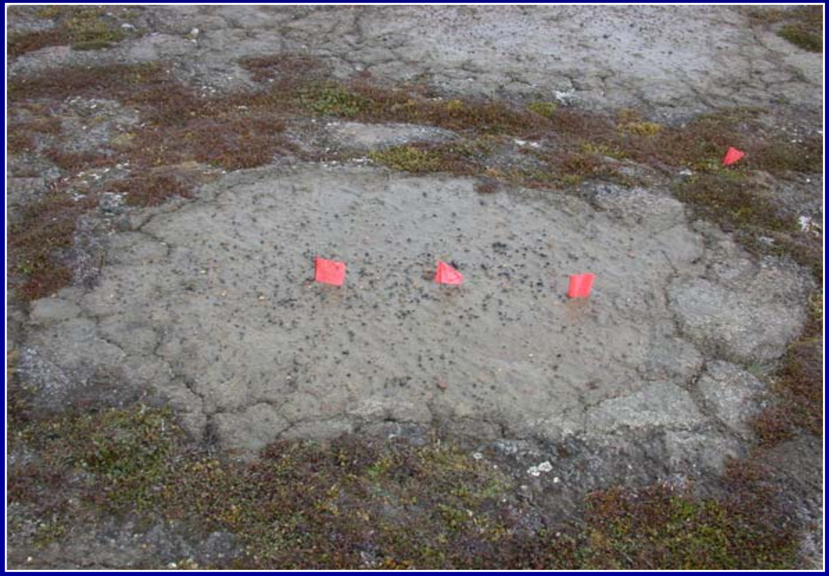
Potentially detectable shrub change in 50-year ramped warming scenario after 20 years.



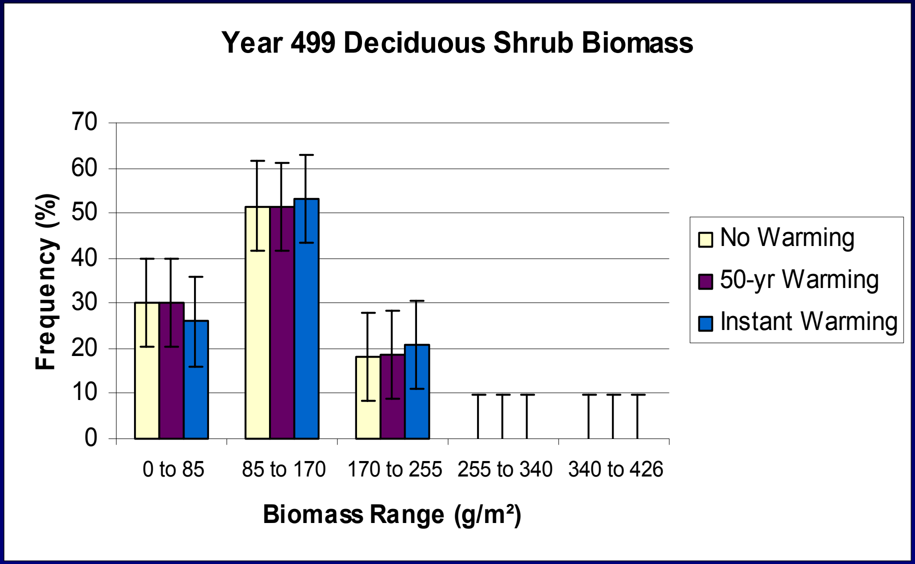
Dynamics of mosses

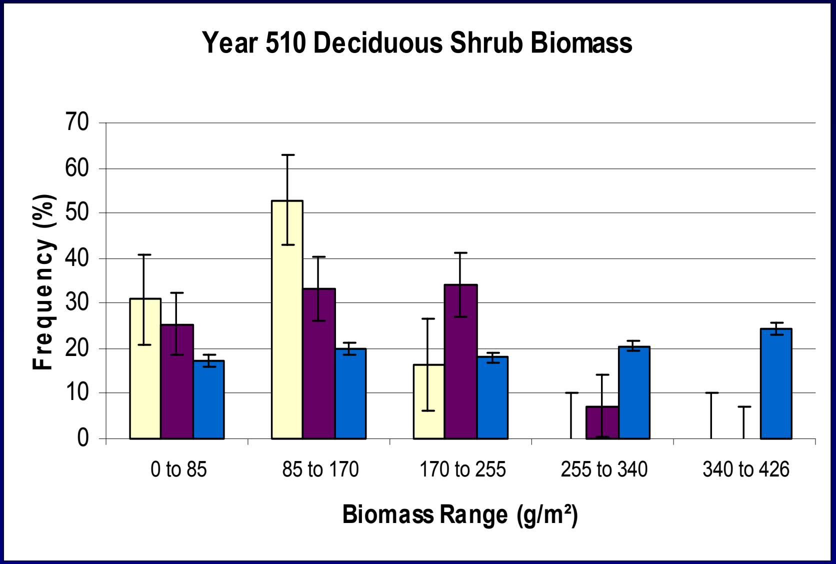


Mosses show directional, low magnitude change with warming over 20 years - no change in direction in absence of warming.

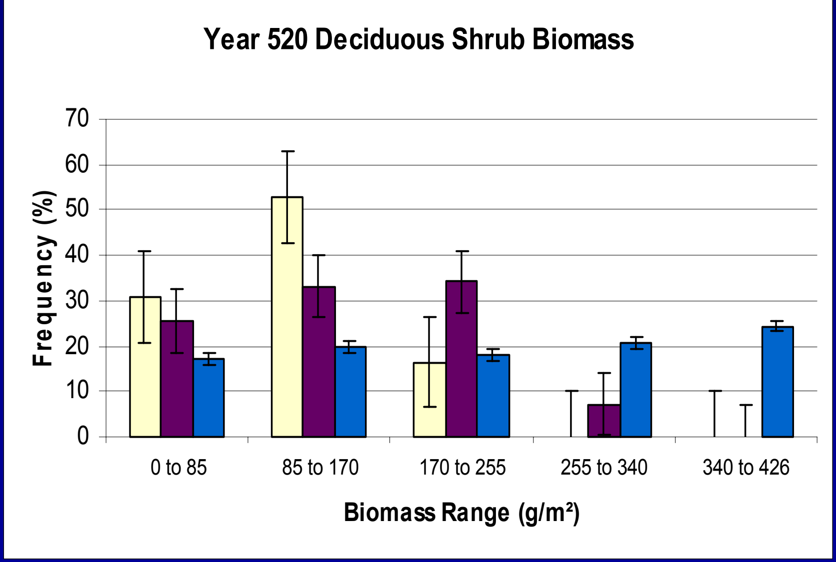


Effects of warming on spatial heterogeneity





- mean increases with warming
- variance also increases with warming, especially with immediate warming
- changes detectable after 10 years



Summary

1) Landscape scale heterogeneity (1 ha.) is high.

2) Effects of experimental warming over 3-9 years in most cases were small and no greater than observed spatial or control temporal variability.

3) There have been observations of shrub increases under controlled scenarios and with warming treatments (Chapin et al. 1995, Hobbie and Chapin 1998, Sturm et al. 2001).

4) Shrubs and mosses may be good indicators of community change, as demonstrated by both field and modeling studies.

5) Spatial heterogeneity may also change with warming, possibly increasing in the case of shrubs.

Biocomplexity associated with biogeochemical cycles in arctic frost-boil ecosystems

Investigators

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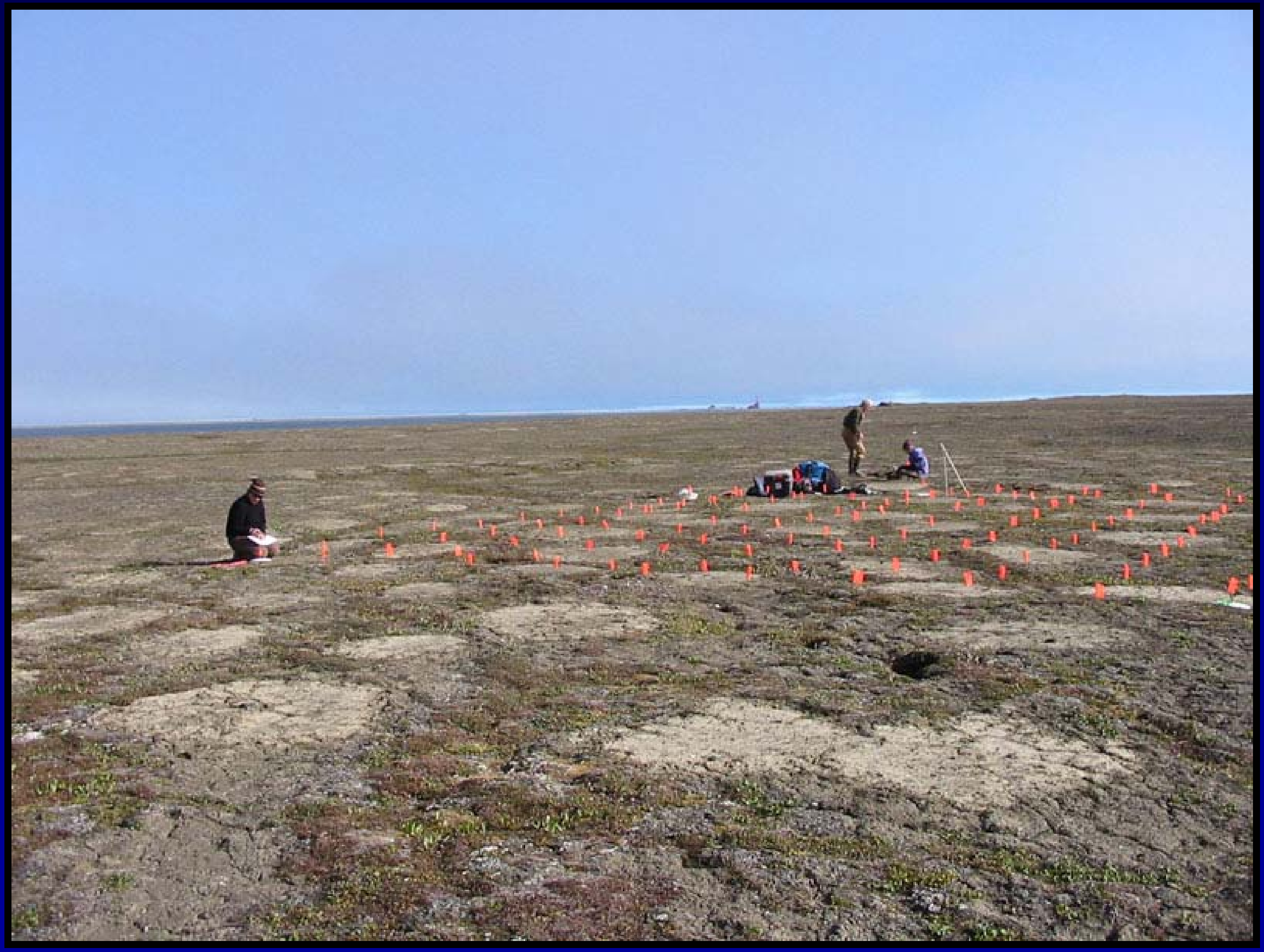
Marilyn D. Walker

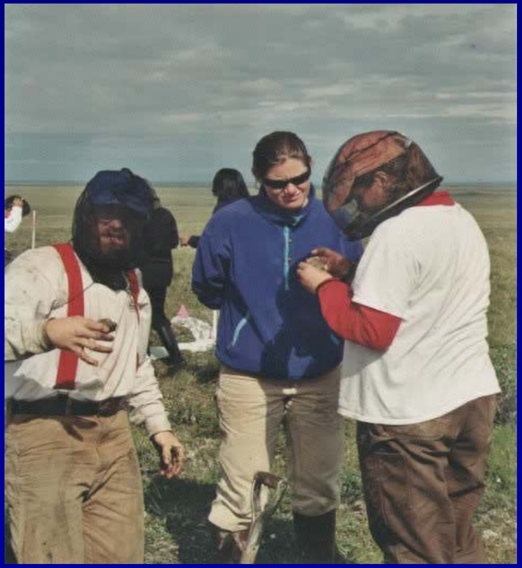


What is a frost boil (a.k.a non-sorted circle)?

- form of cryoturbation (disturbance associated with freezing and thawing)
- result from horizontal differences in soil heaving due to ice lens formation
- small circular forms, generally 0.5 to 3 m in diameter
- soil heaving prevents vegetation from colonizing – no insulation of soil
- cover between 5-73% of the ground in arctic Alaska

Central Goal

- *To understand the complex linkages among biogeochemical cycles, vegetation, cryoturbation, and climate across the full summer temperature gradient in the Arctic in order to better predict ecosystem responses to changing climate.*



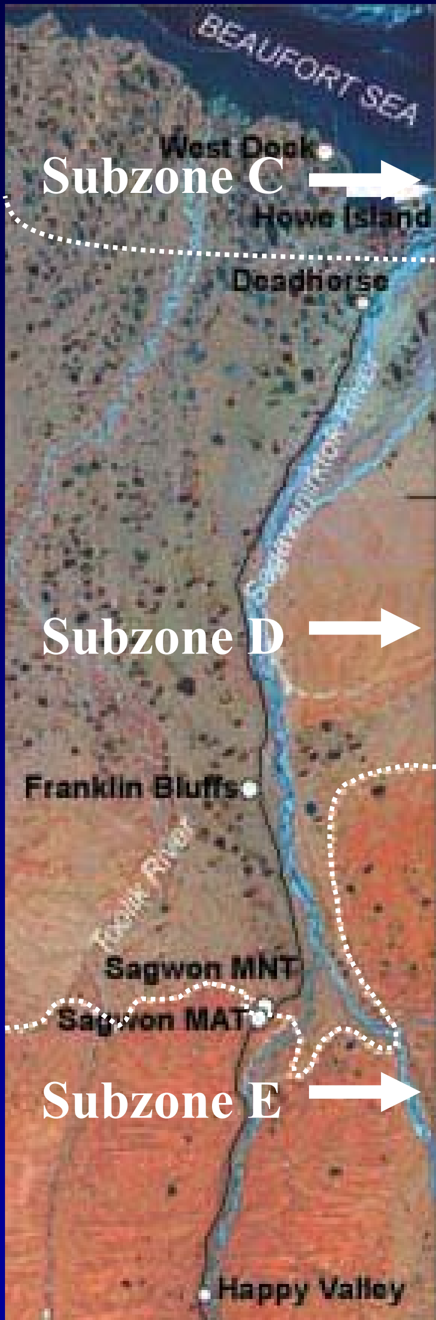
Why focus on frost boils?

(1) The processes that are involved in the self-organization of these landforms drive biogeochemical cycling and vegetation succession of extensive arctic ecosystems.

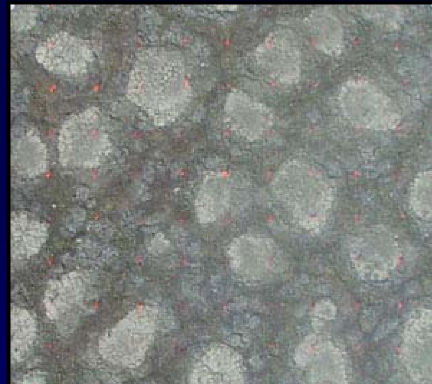
(2) These ecosystems contain perhaps the most diverse and ecologically important zonal ecosystems in the Arctic and are important to global carbon budgets.

(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.

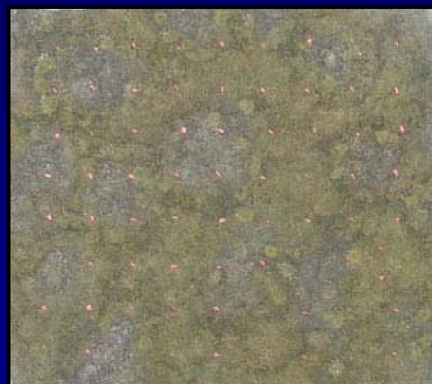
In a nutshell, frost boils form a large portion of the landscape, their abundance and properties vary with climate and other environmental factors, and they have a major influence on biogeochemical cycles, including regional budgets.



Aerial Photos of 10 x 10 meter grids for Subzones C, D, and E



Howe Island



Deadhorse

Franklin Bluffs

Sagwon MNT

Sagwon MAT

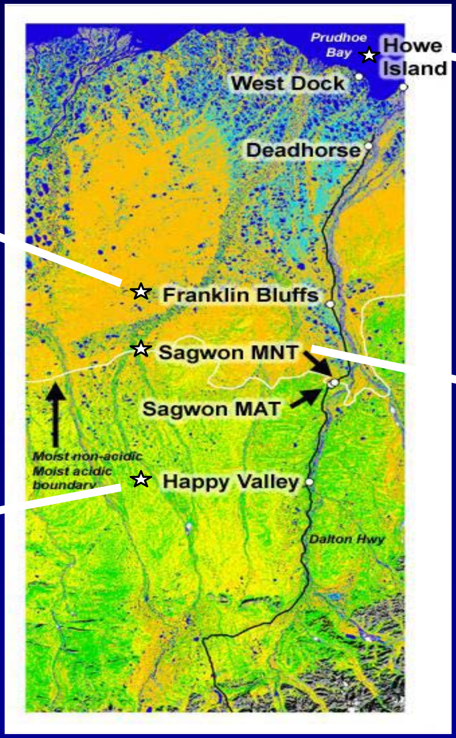
Happy Valley

Arctic Slope, Alaska

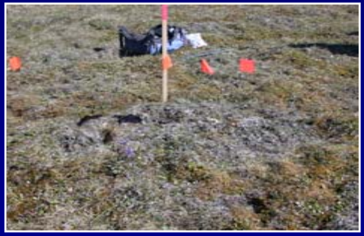
Studies sites along the temperature gradient

Franklin Bluffs
Subzone D
Area of ground covered by frost boils: 61%

Happy Valley
Subzone E
Area of ground covered by frost boils: 13%



Howe Island
Subzone C
Area of ground covered by frost boils: 73%

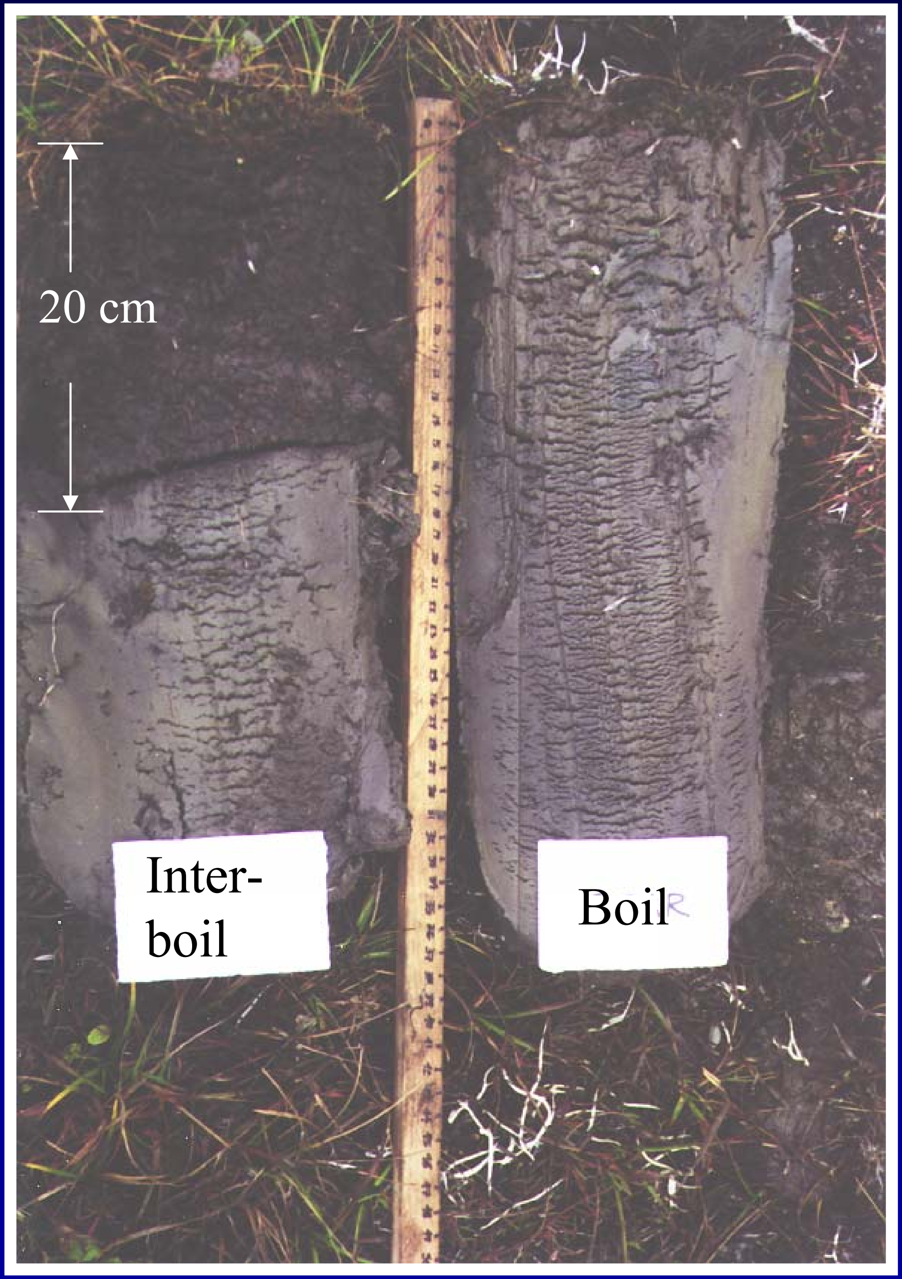


Sagwon MNT
Subzone D
Area of ground covered by frost boils: 17 - 37%

Frost boils are much more abundant in moist nonacidic tundra (MNT) and are thought to be a major control of its distribution

TABLE 1. COMPARISON OF ECOSYSTEM PROPERTIES OF MNT AND MAT (Walker et al. 1998)

Ecosystem Property	MNT	MAT
pH of top mineral horizon	6.9	5.2
Number of vascular plant species	26	14
Average height of plant canopy (cm)	3.9	6.5
Leaf area index (m^2 m^{-2})	0.50	0.84
Moss cover (%)	65	79
NDVI	0.28	0.41
O-horizon thickness (cm)	11	21
Bare soil (% cover)	7.5	0.8
Soil heat flux (MJ m^{-2} d^{-1})	3.13	1.83
Thaw depth (cm)	52	39
Gross primary production (mg CO_2-C m^{-2} d^{-1})	940	1820
Net CO_2 uptake	670	950
Respiration loss	270	870
Methane emission (mg CH_4 cm^{-2} y^{-1})	69	449
Soil organic carbon to 1 m depth (kg C m^{-3})	40	88

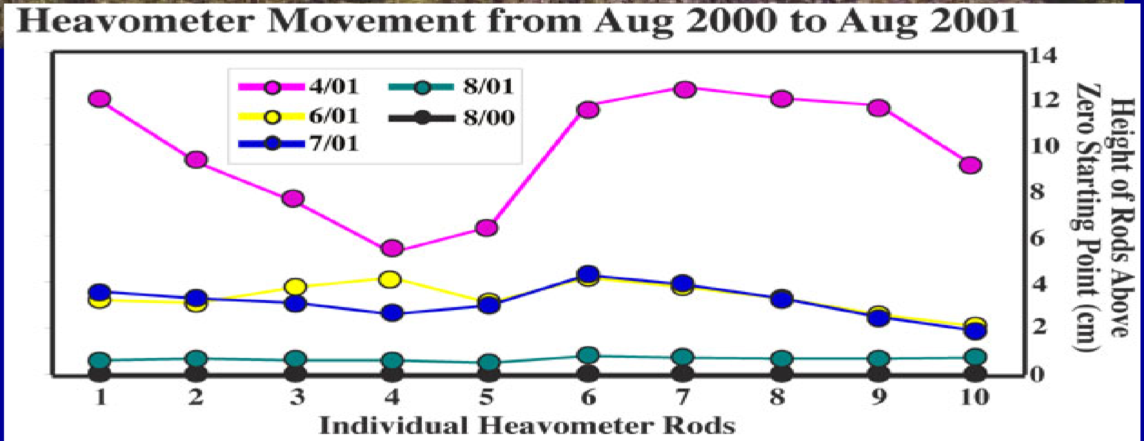


Ice lenses, active layers, and heave in frost boils

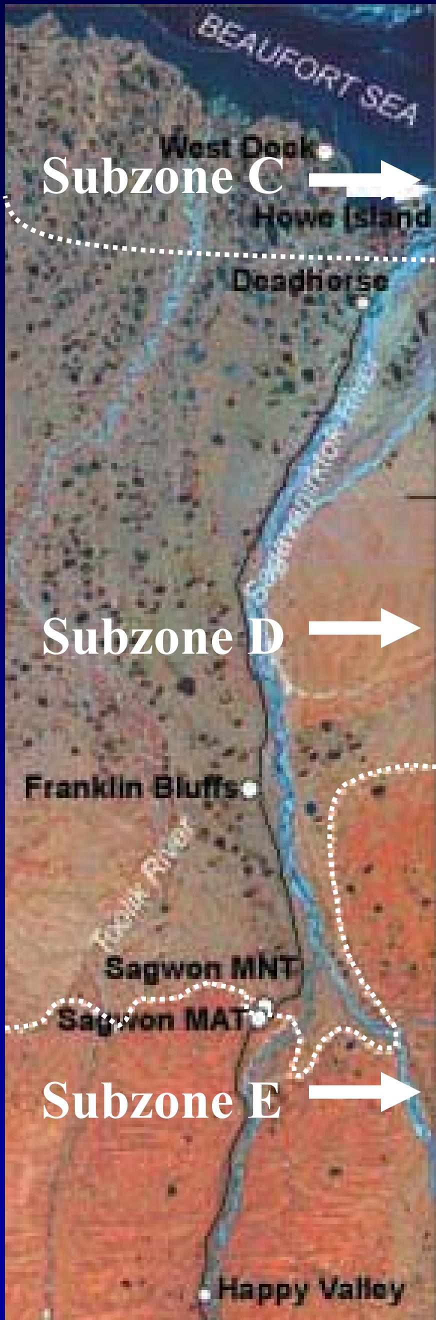
- Platey soil structure caused by ice lenses.
- Deep organic layer of inter-frost-boil areas insulates the soil reducing the active layer thickness and hence the number of active lenses and the amount of heave.

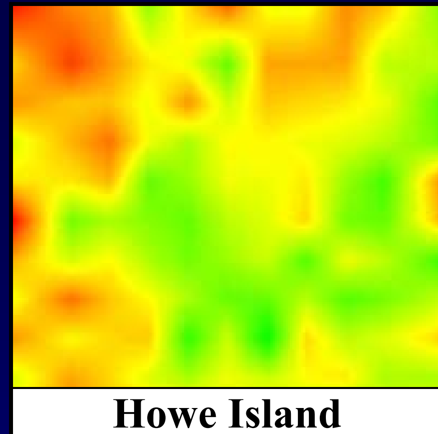
Measuring and modeling frost heave: 12 cm of heave on frost boils

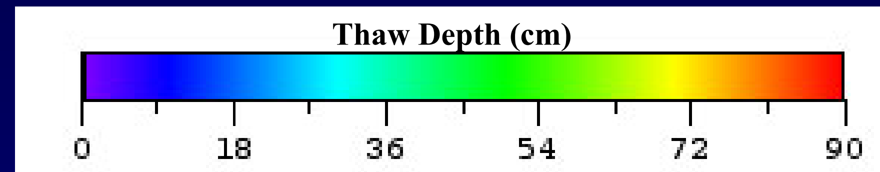
Vlad Romanovsky:
Proud inventor of
heavometer

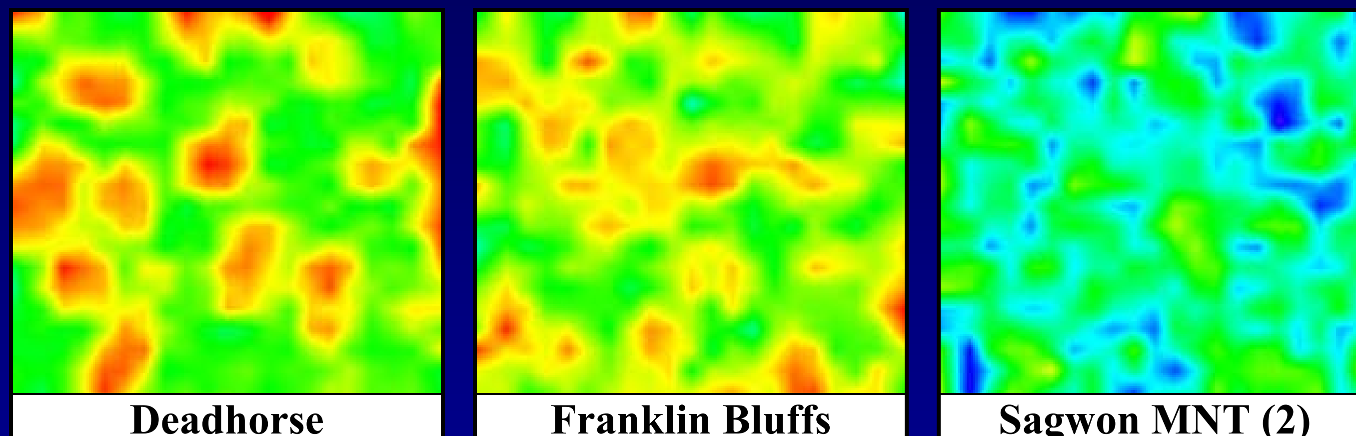


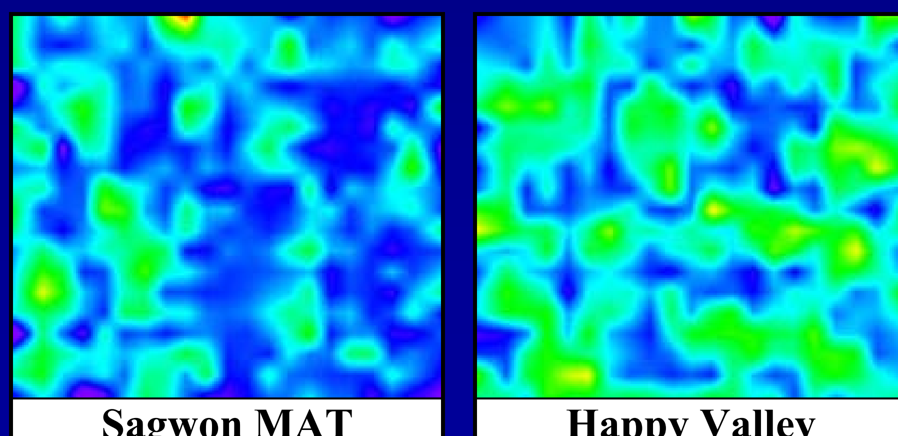
Thaw Maps of 10 x 10 meter grids for Subzones C, D, and E



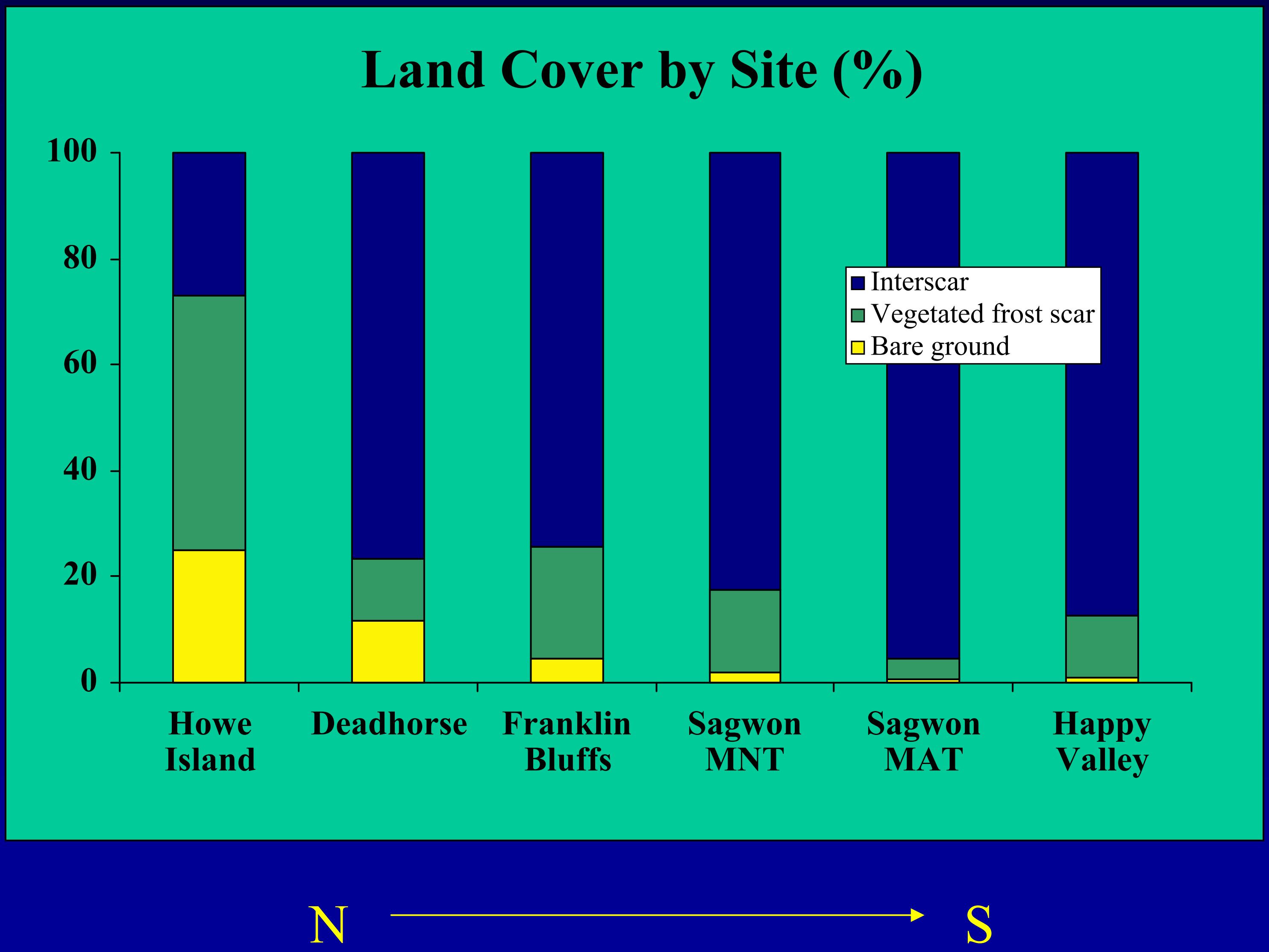






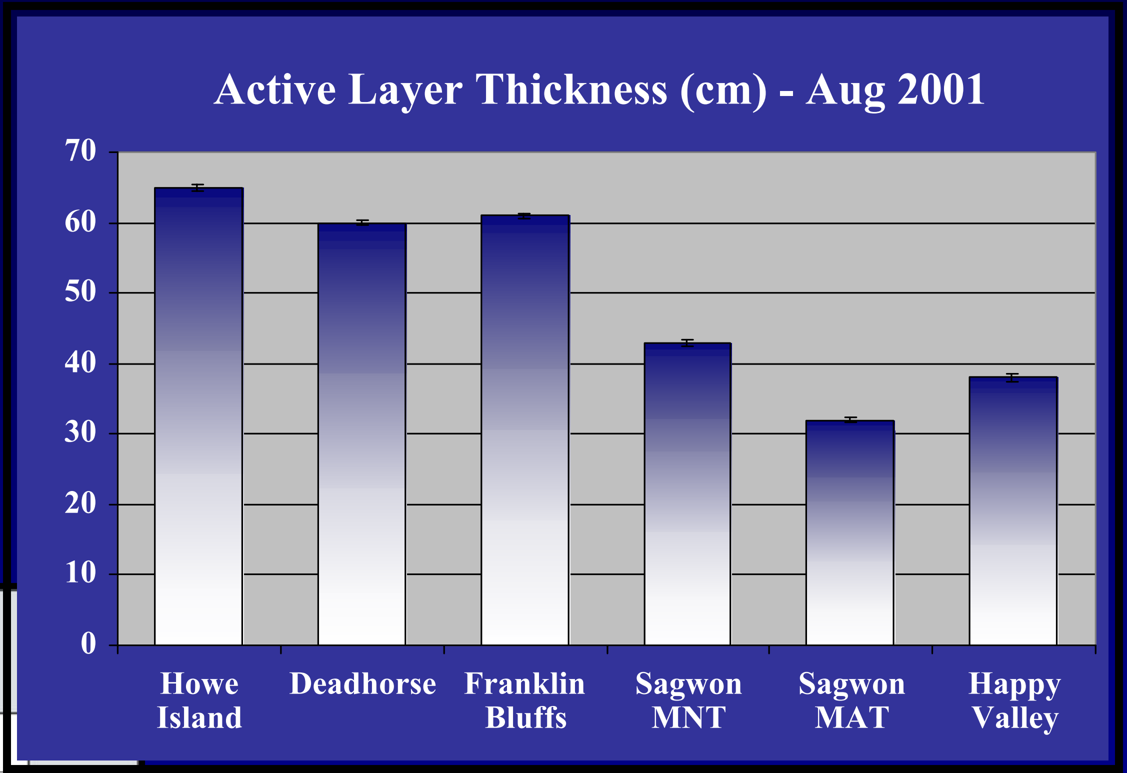


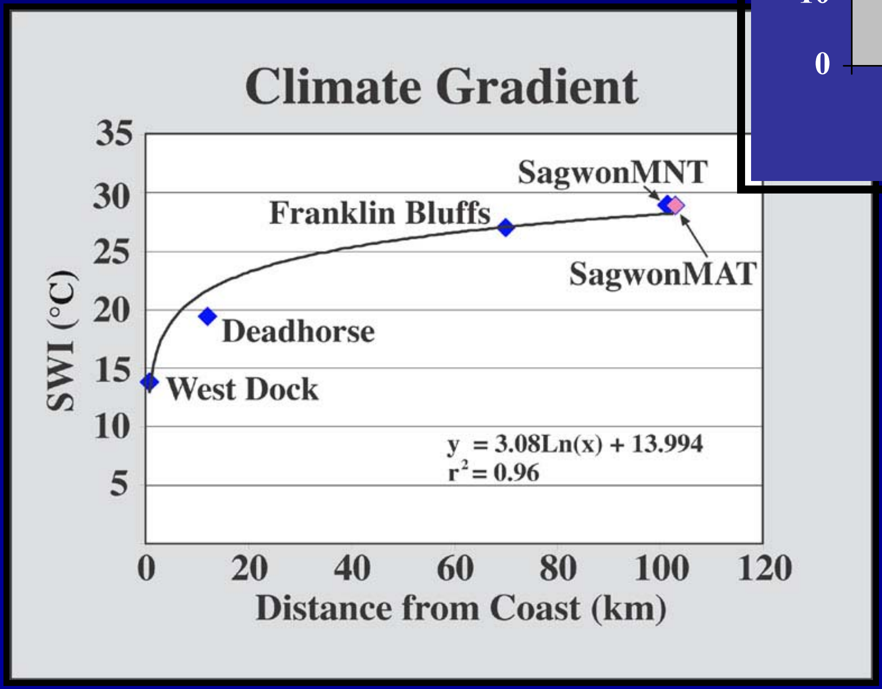
August 2001
Arctic Slope, Alaska


Land Cover by Site (%)
100
80
60
40
20
0
Interscar
Vegetated frost scar
Bare ground
Howe Island
Deadhorse
Franklin Bluffs
Sagwon MNT
Sagwon MAT
Happy Valley
N
S

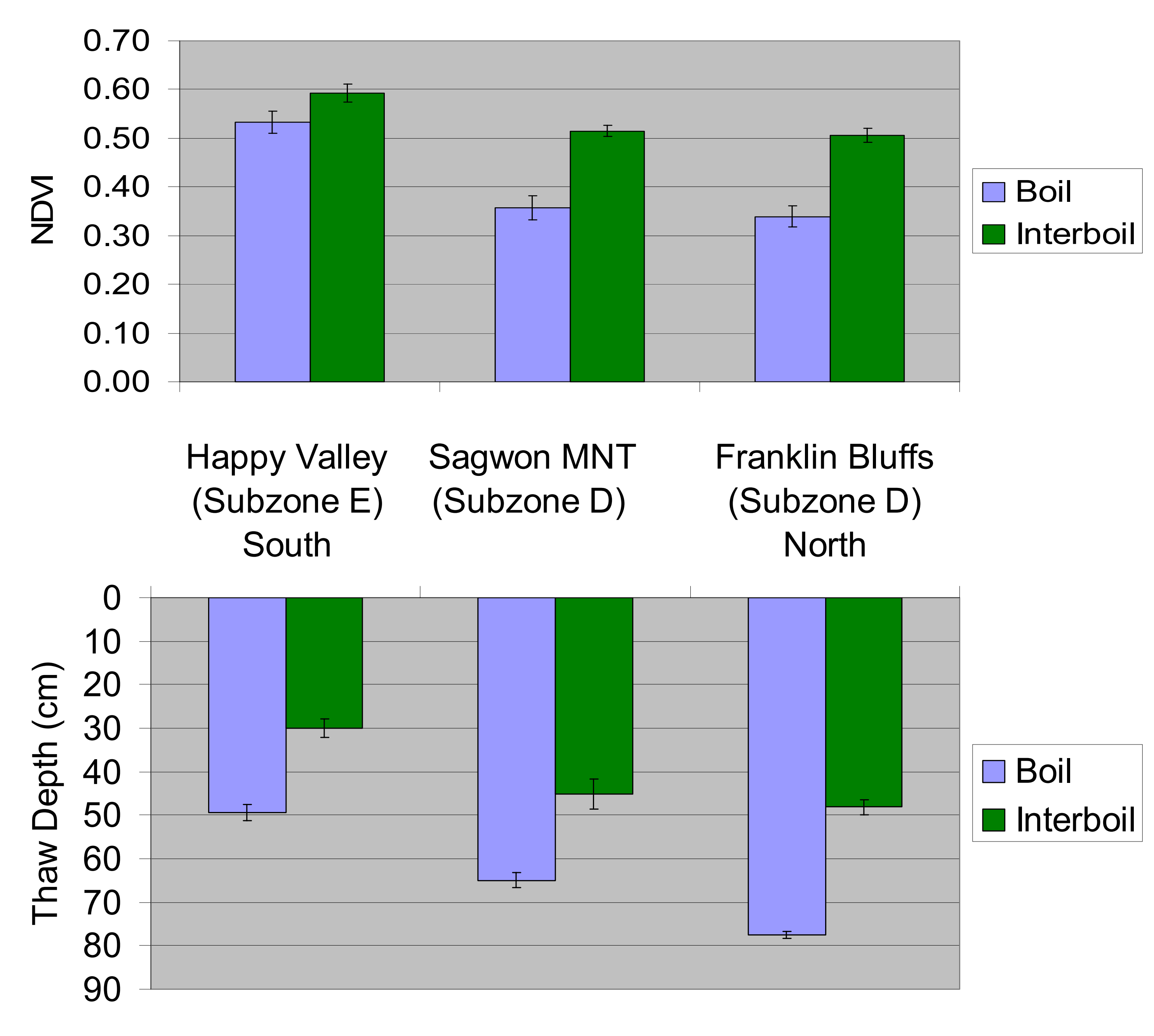
Active layer vs. Air temperature

Active layer on zonal sites is inversely related to the summer air temperatures, due to insulation effect of vegetation





N → S



NDVI
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Boil
Interboil
Happy Valley (Subzone E) South
Sagwon MNT (Subzone D)
Franklin Bluffs (Subzone D) North
Thaw Depth (cm)
0
10
20
30
40
50
60
70
80
90
Boil
Interboil

Major components of the study

- *Frost boil dynamics and climate (Krantz, Peterson, Romanovsky, Tipenko).*
- *Soils and biogeochemistry (Epstein, Michaelson, Ping, Romanovsy)*
- *Vegetation (Epstein, Gould, Walker)*
- *Modeling vegetation and nutrient dynamics (Epstein, Walker)*
- *Education (Gould)*

Summary

1) Frost boils are an important land cover component in arctic ecosystems.

2) Ecosystem properties and biogeochemical cycling are extremely different in frost boils compared to the surrounding vegetated, non-heaving areas.

3) Depth of thaw is related to summer temperatures as well as to the quantity of insulating vegetation on the land surface; therefore frost boils play a key role in active layer processes.

4) Understanding the nature of frost boil ecosystems, in addition to what drives changes in the abundance and distribution of frost boils is important for deriving regional scale estimates of vegetation, soil and nutrient dynamics.

Acknowledgements

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