

Overview of climate and land-cover change in the Arctic

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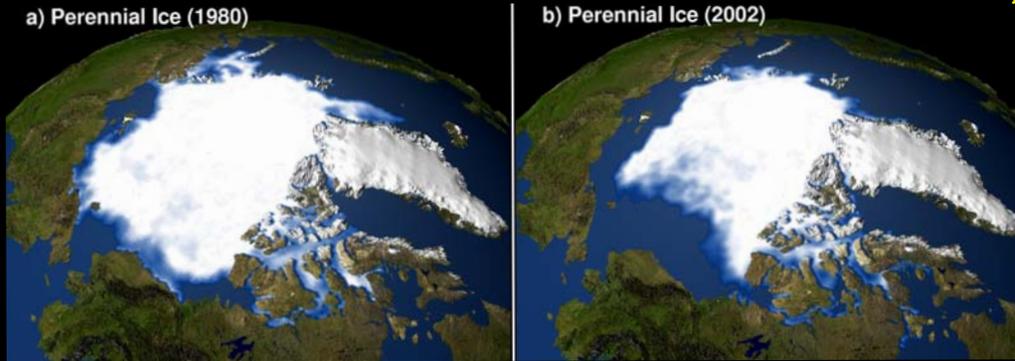
□ Photo courtesy of Bryan and Cherry Alexander

□ Talk given at the NASA Land-Cover and Land-Use Change Science Team Meeting, University of Maryland, 4-6 April 2007

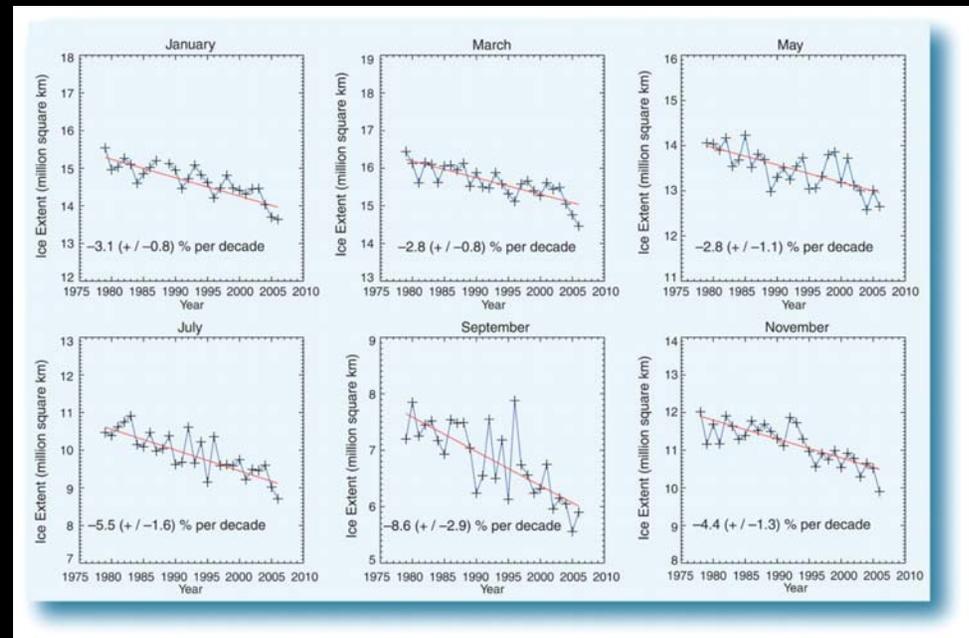
Outline

- Overview of the Arctic.
- Evidence for climate and LCLUC in the Arctic.
- Overview of Yamal LCLUC project.

The big story in the Arctic is the dramatic changes to sea ice during the past 30 years.



- Since 1975, perennial September sea ice extent has declined $8.6 \pm 2.6\%$ per decade.
- Total reduction of 21%.
- 40% of models predict complete loss of Arctic sea ice in September by 2100.



What are the implications of these trends to terrestrial ecosystems?

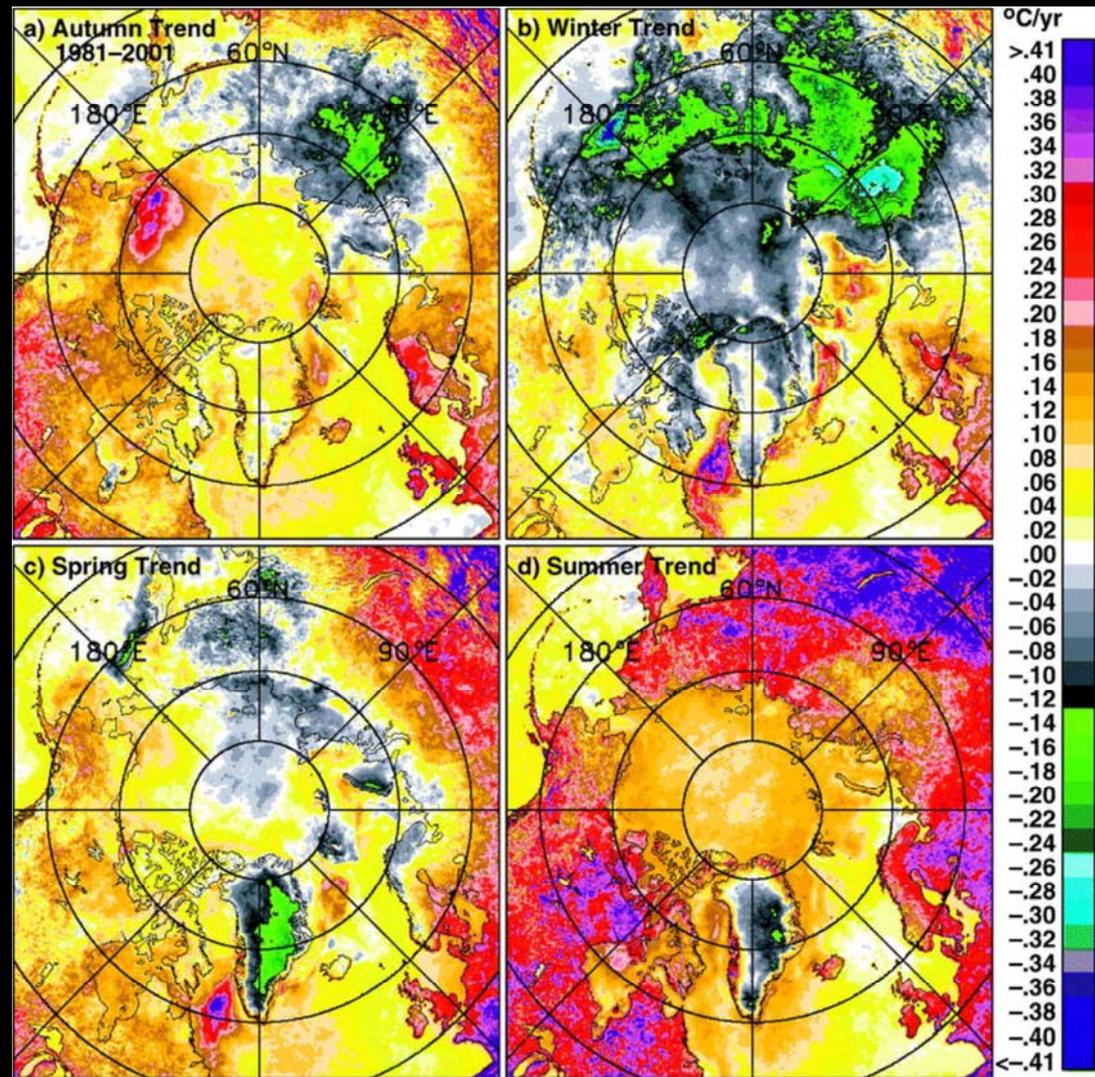
Courtesy of National Snow and Ice Data Center, http://nsidc.org/news/press/20050928_trendscontinue.html#fig1
Serreze et al. *Science* Mar 16, 2007.

The Arctic is not warming uniformly.

Different story coming from the station data and the the satellite LST data.

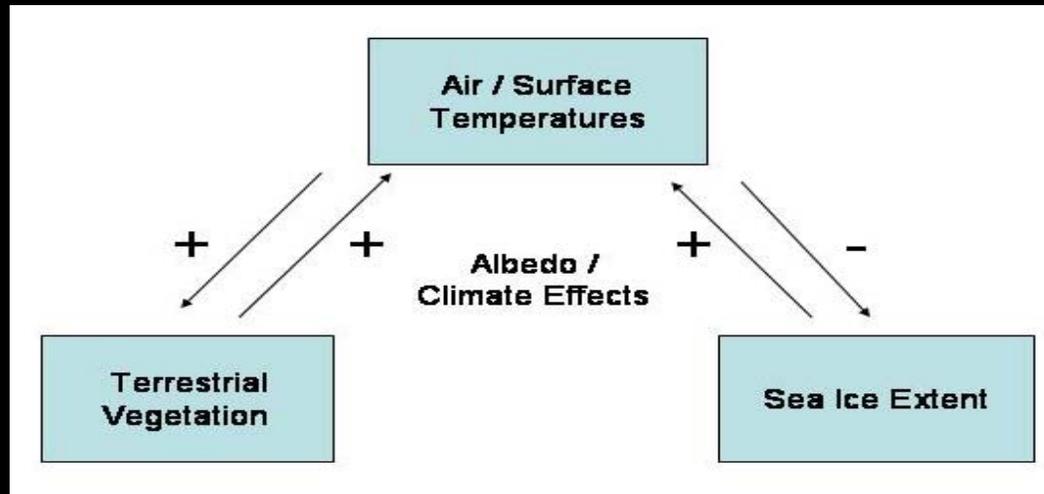
- Fall and spring: Warming in Beaufort Sea area and N. Canada, cooling over central Siberia and Yamal.
- Summer: General Arctic-wide warming in summer.
- Winter: Strong cooling in Siberia, warming in N. Canada.
- Is there a linkage between sea-ice patterns, land-surface temperatures, and land-cover change?

AVHRR thermal data



Comiso, 2003. Warming trends in the Arctic from clear sky satellite observations, *Journal of Climate*. 16: 3498-3510,

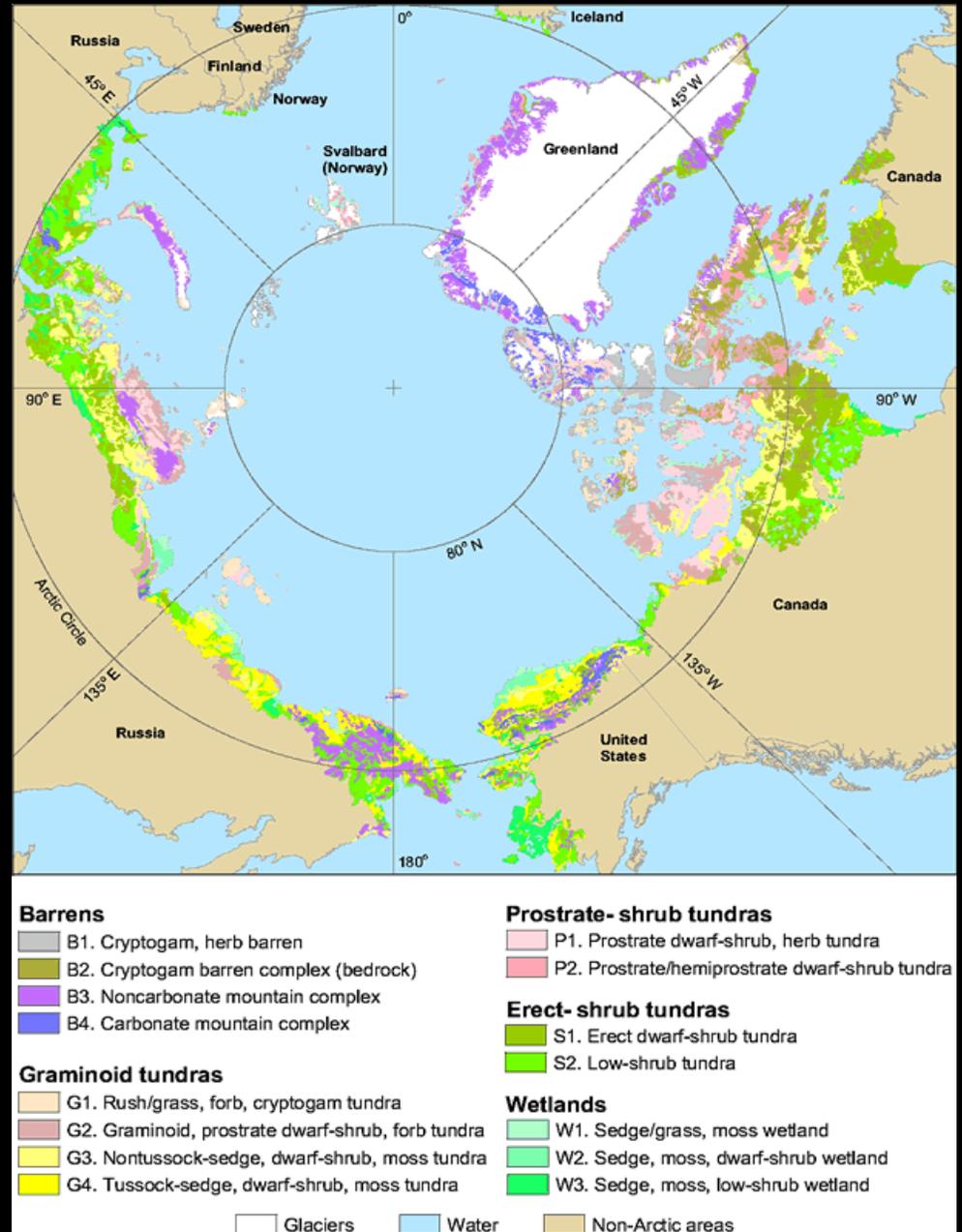
Land - Sea-ice Linkages



Linkages between sea ice and terrestrial vegetation are indirect – through albedo/climate feedbacks to the atmosphere.

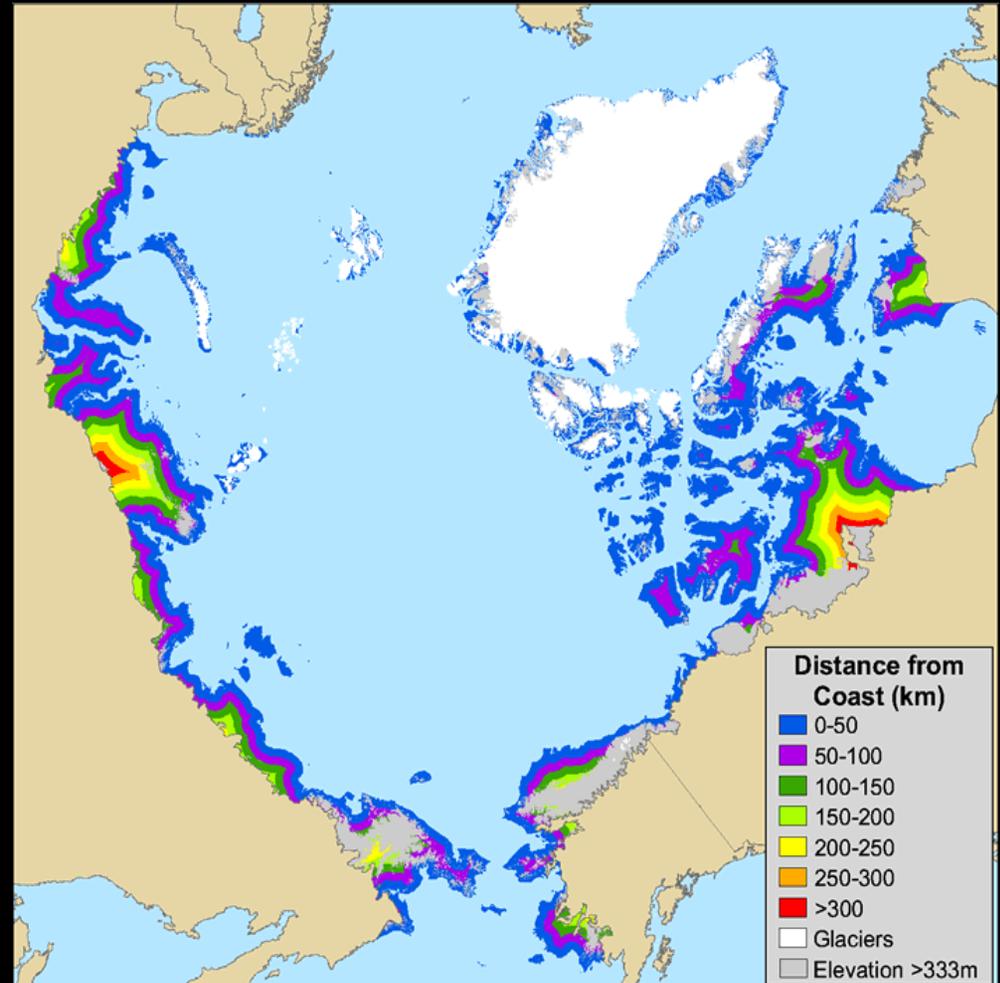
The Arctic tundra is a maritime biome.

- Vegetatively the Arctic is defined as the area that has an Arctic climate, an Arctic flora, and contains tundra vegetation.
- Southern boundary is tree line.
- Cool summer temperatures (MJT $<10^{\circ}\text{C}$) is the critical factor for tundra and this occurs at low elevations only in close proximity to the sea...
- ...but cold winter temperatures are also needed (hence the oceanic Aleutians and much of Iceland are outside the Arctic).

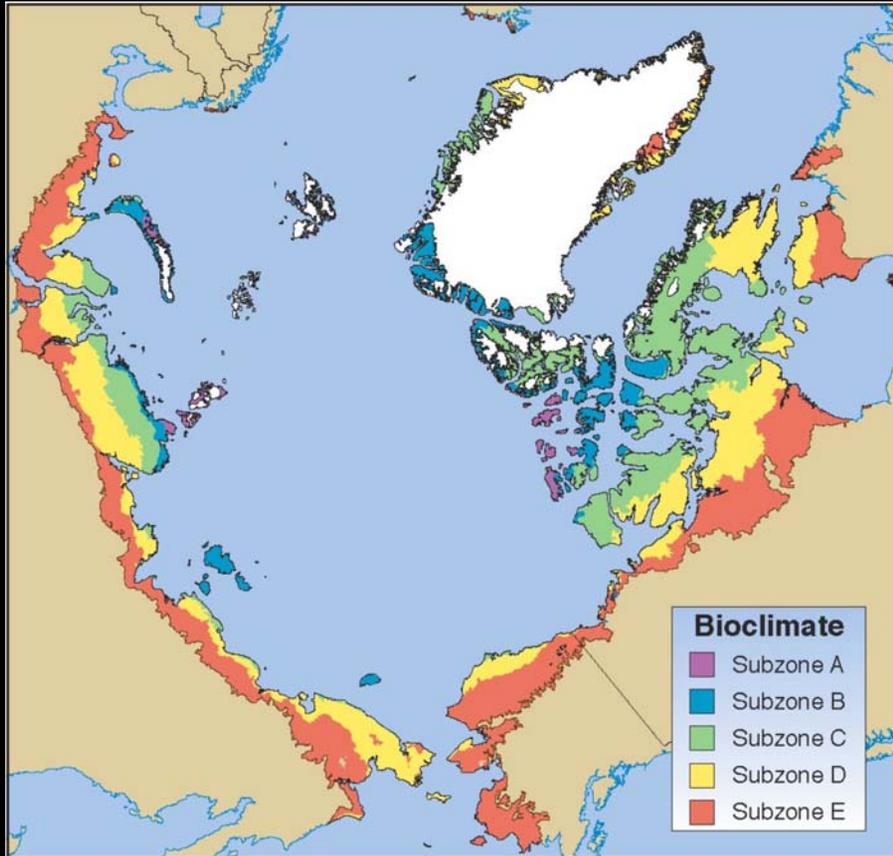


Changes in sea-ice concentrations could strongly affect the tundra.

- 61% of lowland tundra is within 50 km of sea ice (blue buffer),
- 80% is within 100 km (magenta and blue buffers),
- 100% is within 350 km.
- Changes in the Arctic ocean sea ice will very likely affect terrestrial ecosystems by affecting summer-time land-surface temperatures.



Zonation in the Arctic is largely a function of distance from the ice-covered ocean (not latitude).



Sub-zone	Mean Jul Temp (°C)
----------	--------------------

A	< 3
---	-----

B	3-5
---	-----

C	5-7
---	-----

D	7-9
---	-----

E	9-12
---	------

High, Middle and Low Arctic



Subzone A



Subzone C
E



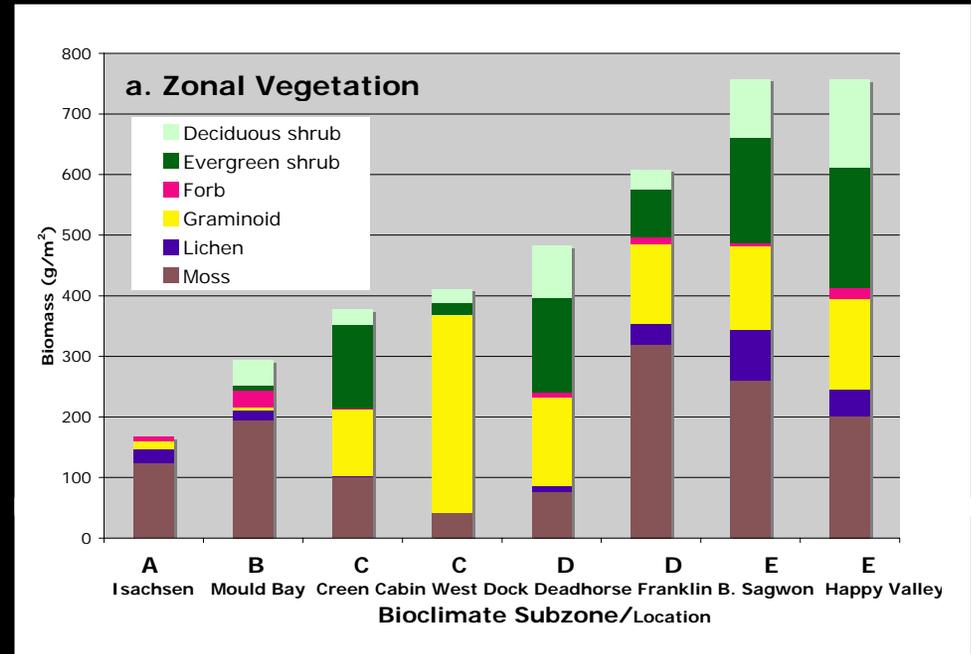
Subzone E

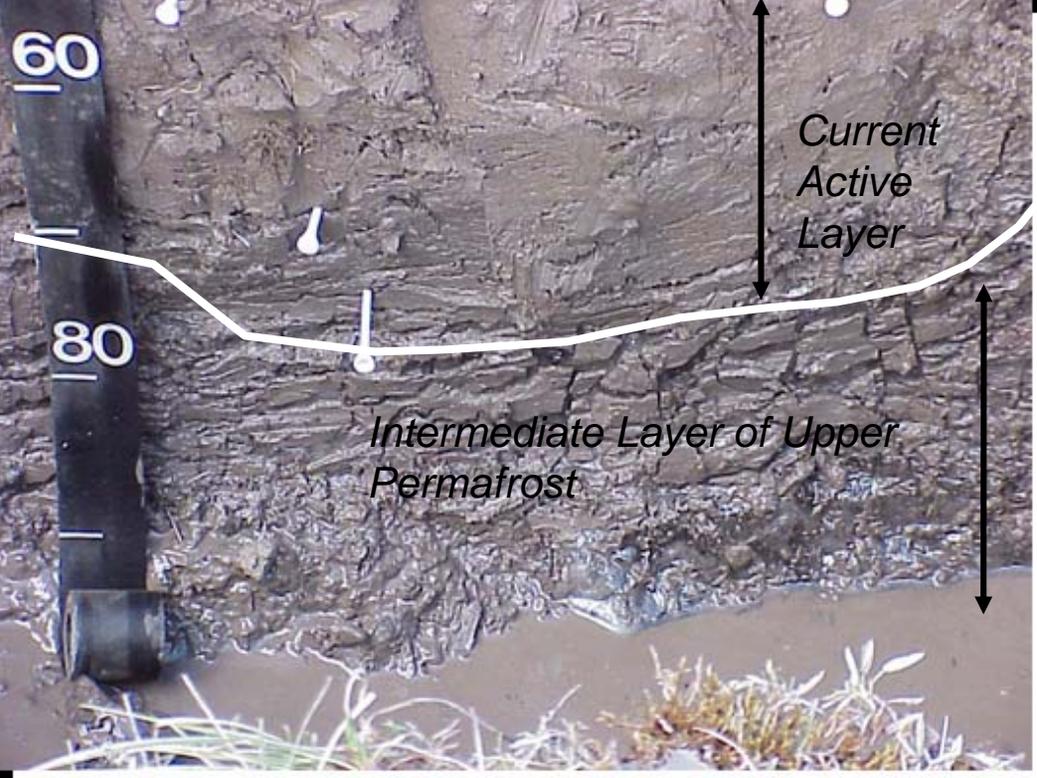
Across the Arctic there is a:

- 10 °C difference in mean July temperature,
- 5-10-x increase in biomass,
- 10-x increase in primary production,
- 25-x increase in plant canopy height,
- 5-x increase in vascular plant diversity,
- and similar major differences in number of invertebrate and vertebrate taxa.

Above-ground biomass on zonal sites increase about 5-10-fold along the North American Arctic Transect.

- The average aboveground biomass per unit area of tundra (the standing crop) is estimated to be about 550 g m⁻². This compares to about 9500 g m⁻² in the boreal forest and 7150 g m⁻² for global terrestrial ecosystems.
- Large variation in dominant plant growth forms.
- The major differences in biomass and dominant plant functional types have major implications for many ecosystem functions.





The big carbon story in the Arctic is below ground.

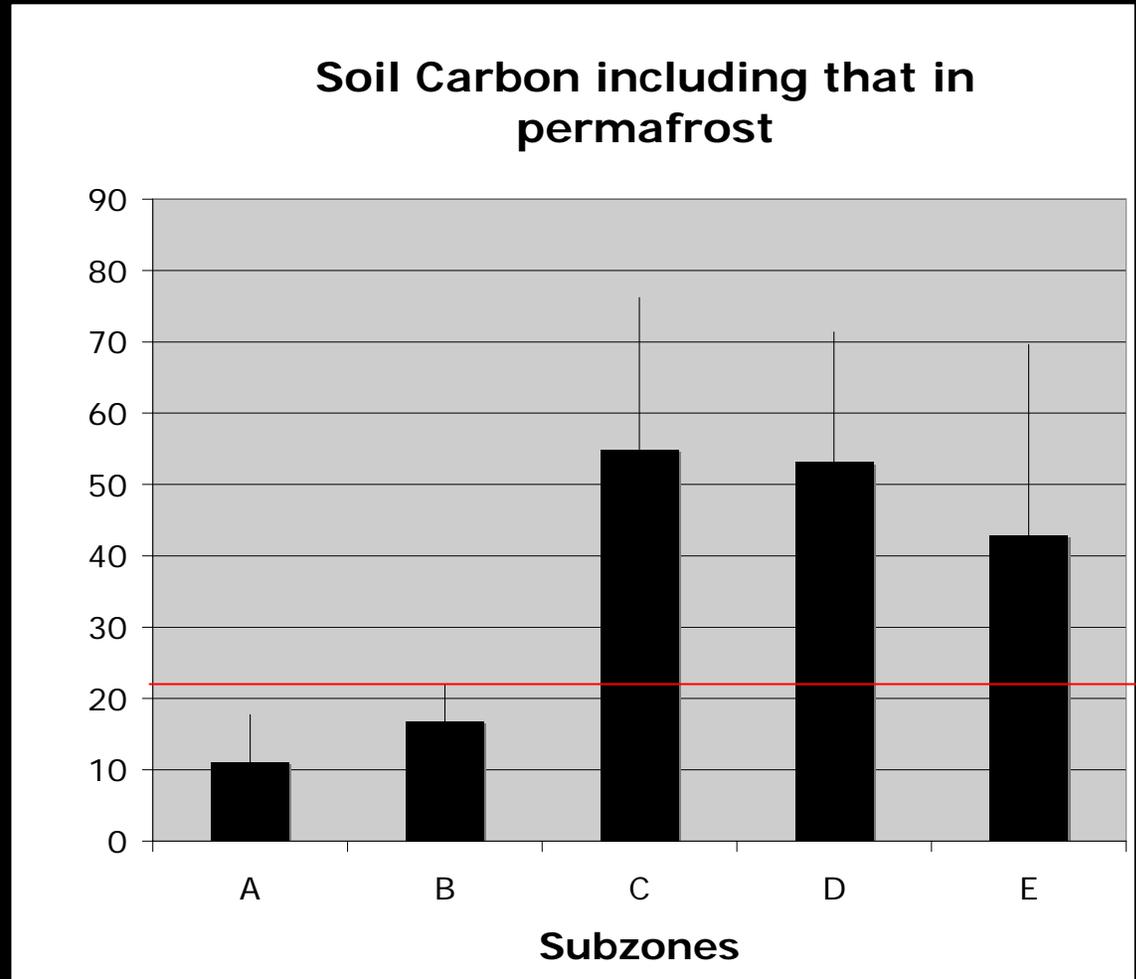


Buried carbon in the intermediate layer of permafrost table

Courtesy of Gary Michaelson

Below-ground Carbon

- A large amount of carbon accumulates in arctic soils due to slow decomposition rates and cryoturbation.
- Published soil:vegetation C ratios are estimated to be 13:1 in the Arctic compared to 1.2 in the boreal forest and 0.8 globally.
- The amount of carbon in arctic soils is estimated at about $21,800 \text{ g m}^{-2}$ (Post et al. 1982, red line in graph).
- Our data indicate this is a conservative estimate because it is based only on the carbon in the active layer. Values shown here are average carbon to 1 m depth along the North America Arctic Transect.
- There is much more carbon deeper.



Courtesy of Chien Lu Ping 2007 in prep.

Tree-line is advancing from the south.



Photo P. Kuhry, <http://www.ulapland.fi/home/arktinen/tundra/tu-taig.htm>

- Treeline advance is not a matter of gradual response to temperature.
- Threshold responses suggest that pattern and timing of change is contingent on local, landscape, and regional-scale factors, as well as species' biology (Danby and Hik 2007).
- Response in Arctic is strongly related to permafrost and local hydrology.

Changes to the above-ground carbon pool will have profound effects on nearly all Arctic-system properties.

Greater above-ground plant biomass will affect:

Heat budgets: insulative value of vegetation and soil, active-layer depths, permafrost temperatures (Nelson et al. 1987, Walker et al. 2003, Romanovsky),

Carbon budgets: Increase above and below-ground carbon reserves (McGuire et al. 2000, Shaver et al. 2000, 2001; Oechel et al. 2000),

Trace-gas fluxes: CO₂, CH₄, H₂O (Oechel et al, 2000, 2001; Reeburg et al. 1998; Eugster et al. 2005),

Water budgets: Changes of flux of moisture to the atmosphere and runoff of water to the Arctic Ocean and snow distribution (Hinzman et al. 2005; Sturm et al. 2001),

Albedo feedbacks to the climate system: decreased albedo of trees of trees and shrubs (Chapin et al. 2005),

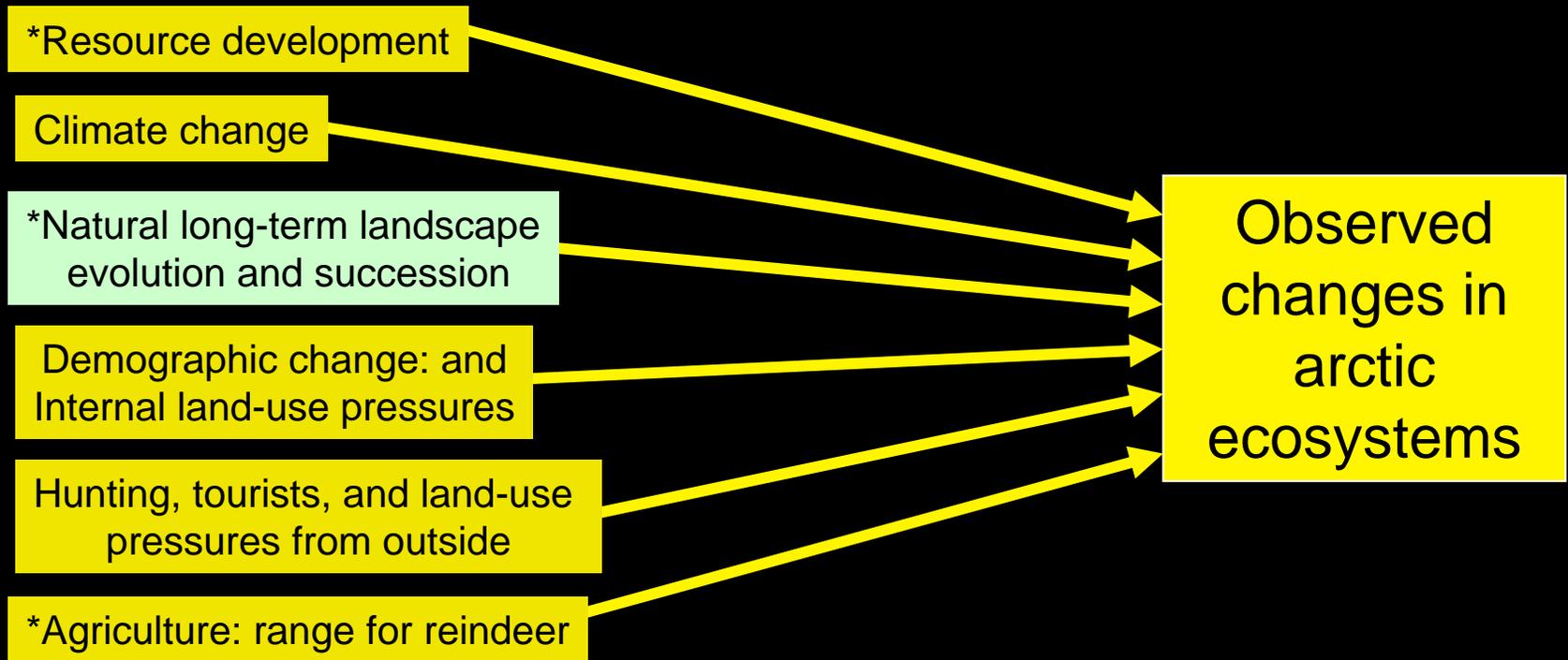
Wildlife: e.g. caribou forages (Griffith et al. 2003),

...ultimately people living in the Arctic and to the planet as a whole (ACIA, 2004, Sturm et al. 2003; Serreze et al. 2000; Overland et al. 2004, Overpeck et al. 2005, Hinzman et al, 2005).

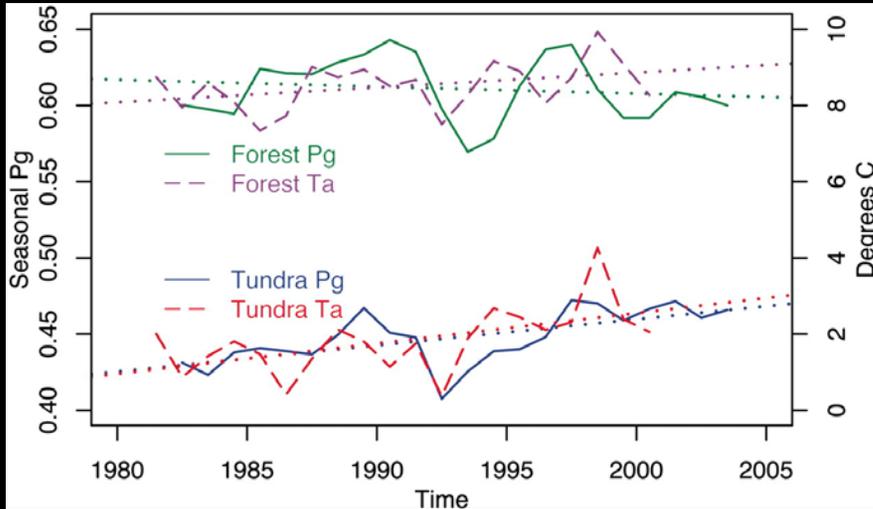
Take home points regarding Arctic tundra systems.

- Tundra is a one large transition zone, strongly affected by Arctic Ocean and sea-ice on the north and treeline to the south.
- Permafrost plays a major role in controlling hydrology, soil temperatures, carbon dynamics.
- Most of carbon is concentrated in the soils, much of it locked in permafrost.
- Changes in biomass will affect nearly all aspects of the tundra system.

Observed land-cover changes are the result of the convergence of multiple factors.

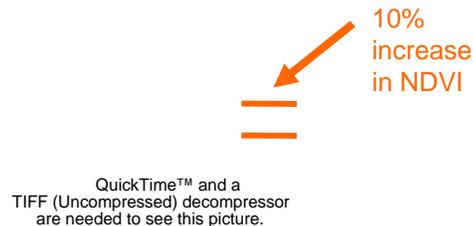


Evidence of change: NDVI in North America

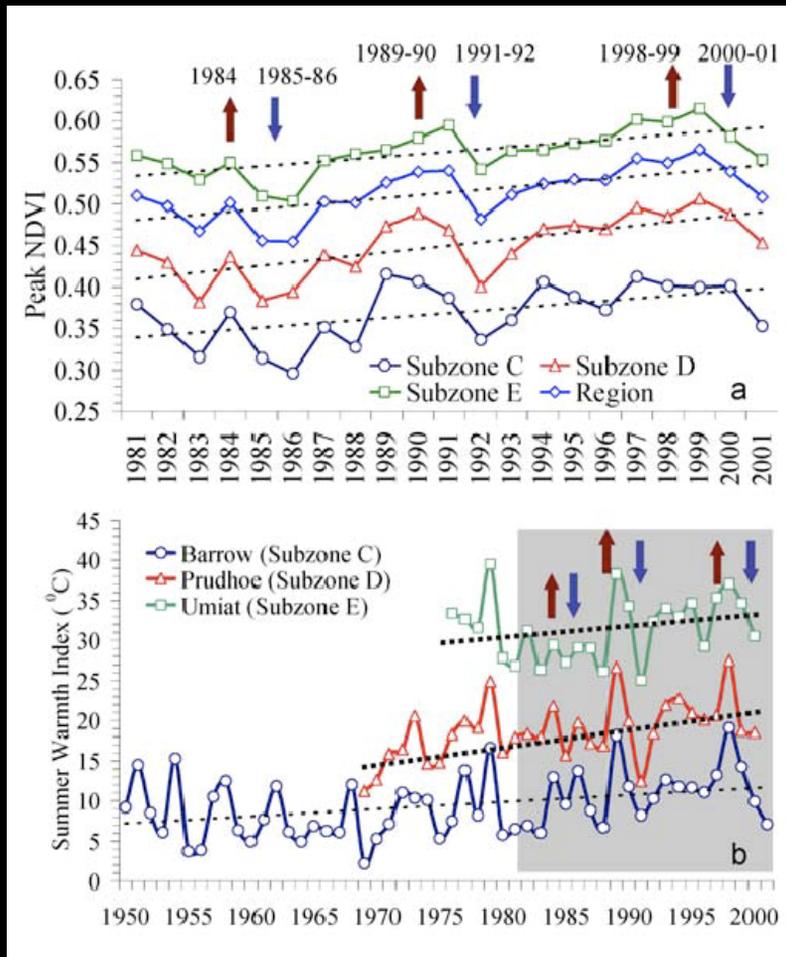


- Temperature has increased in both the forest areas and the tundra.
- NDVI has declined in the forest and increased in the tundra following the Pinatubo eruption in 1991.
- Decline in the forests may be due to drought stress.
- Tundra regions have shown a continued increase in Pg (10% total increase) and a marked 10-day shift toward earlier onset of greening.

Seasonal trend in NDVI



NDVI in northern Alaska increased 10-20% from 1982-2001.



- Average $17 \pm 6\%$ increase in peak NDVI.
- Changes in NDVI follow annual changes and long-term trend in temperature.
- Does this correspond to about an 170 g m^{-2} average increase in biomass?

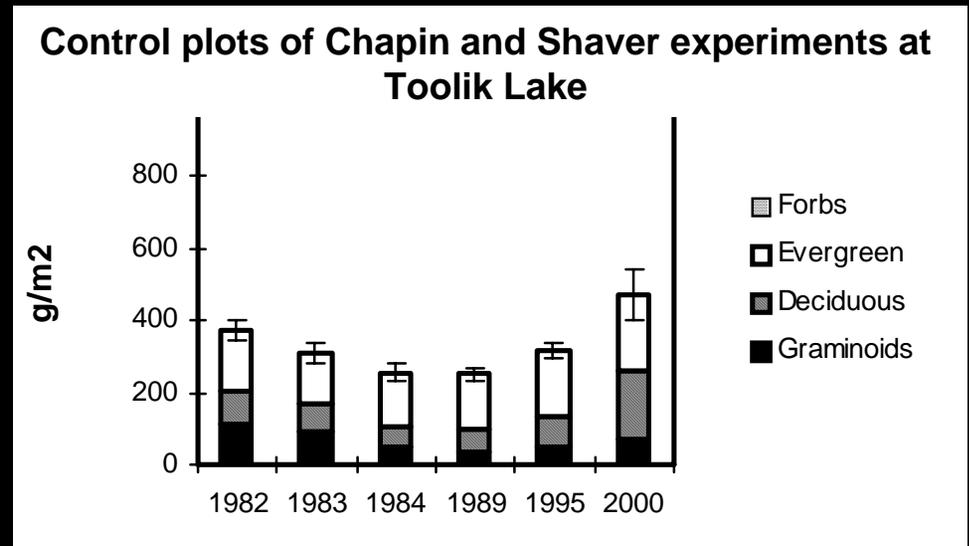
Scepticism regarding magnitude of greening trends

“Should we believe in the NDVI trend? There are no “ground truth” measurements of photosynthesis at northern high latitudes over the same period, and so the accuracy of the trend cannot be established unambiguously.... It will be a challenge for ecologists to explain how photosynthesis could possibly have increased by approximately 10% from 1981 to 1991.”

(Inez Fung 1997.)

There are very few long-term biomass studies and many problems with existing data.

- Most existing data were collected during the 1970s as part of the International Biological Programme.
- Major methodological problems:
 - Vegetation type at harvest site poorly documented.
 - No site or soil information.
 - Harvest and sorting methods not documented.
 - Harvest sites not geo-referenced or marked.
 - Little or no replication.
 - The definition of the soil surface is not recorded – a particularly important issue for the moss component of the biomass.
 - Belowground biomass rarely collected.
 - No NDVI, leaf area index (LAI), or cover data.
- Virtually no time series data.



(Shaver et al. 2001. *Ecology* 82: 3163-3181).

For purposes of monitoring change to circum-Arctic vegetation, it is essential to have replicated sampling of biomass in conjunction with NDVI measurements using standard protocols for collecting and reporting biomass data.

Direct evidence for Change in Arctic Vegetation

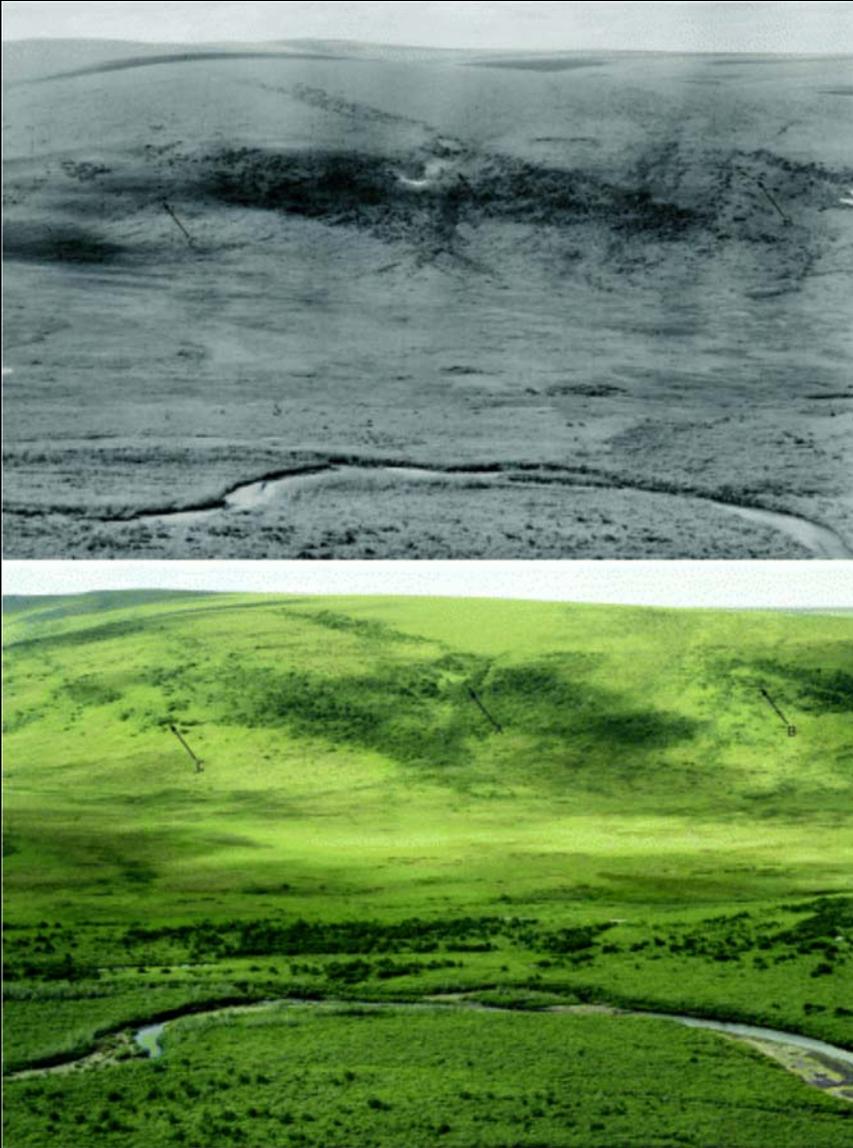


Photo record of shrub cover change (Tape, et al. 2006; Sturm et al. 2001):

- Over 30% increase in alders on some stable valley slopes in Subzone E.
- Dramatic increase in shrub cover on river terraces.
- More vegetation and less sand and gravel in river floodplains.
- Difficult to make quantitative regional extrapolations from these data because of the oblique view angle of the photographs and their limited geographic extent.
- Images taken from satellites with near vertical view angles provide more quantifiable information over broader areas and at regular time intervals.

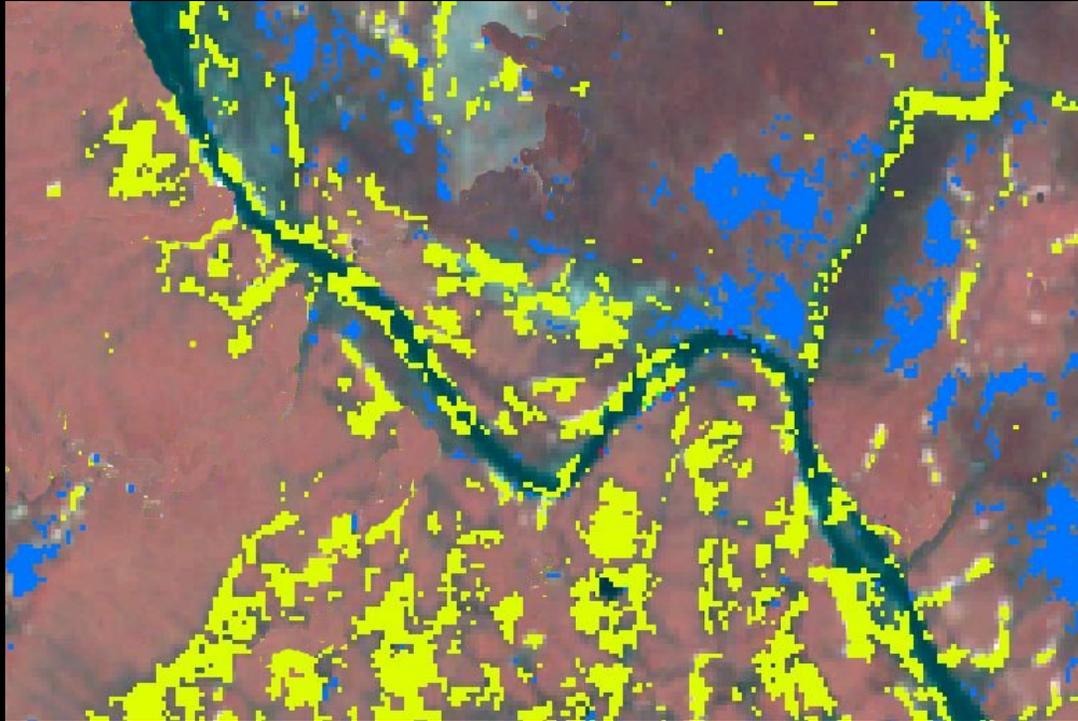
Change after 27 years at the former IBP microtopographic grid at Barrow



- Dramatic changes that are consistent with a drying of the tundra.
- Three wettest vegetation communities classified in 1973 have almost entirely disappeared.

Land Cover Change Detection on the Seward Peninsula, AK

Difference from 1986-1992 in TM imagery of Council, AK

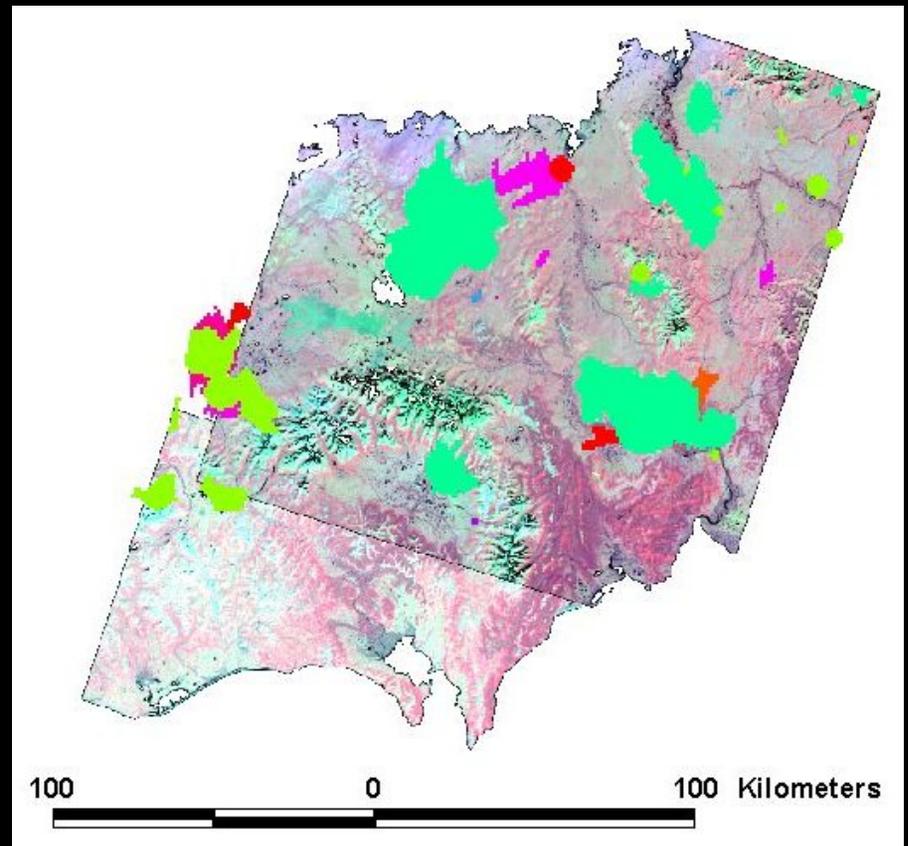


- Yellow areas: potential increases in leaf area and canopy density.
- Changes mostly in shrubby areas along riparian corridors and along mountain valleys.

Based on Silapaswan, Verbyla, and McGuire, *Canadian Journal of Remote Sensing*, 2004.)

Fire on the Seward Peninsula

Since the 1950's, there have been 35 large tundra fires recorded on the Seward Peninsula (Alaska Fire Service).



Based on Silapaswan, Verbyla, and McGuire, *Canadian Journal of Remote Sensing*, 2004.)

Linking Optical Signals to Functional Changes in Arctic Ecosystems

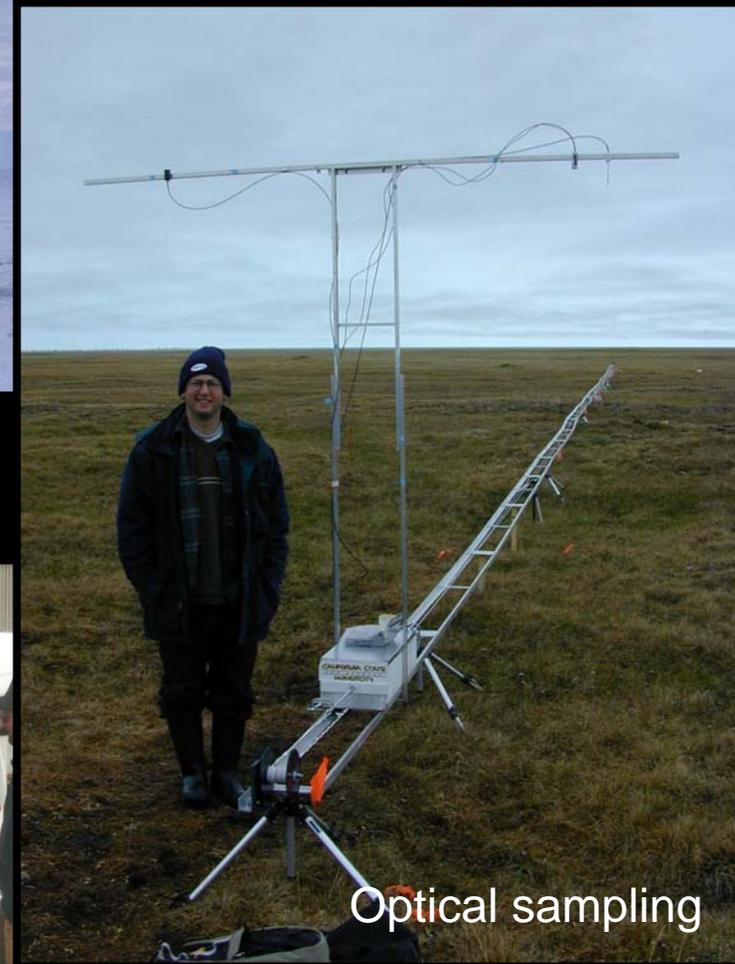
John A. Gamon (PI)
Fred Huemmrich (Co-PI)
Stan Houston & Erika Anderson

Walt Oechel
Hyojung Kwon
Rommel Zulueta
Joe Verfaillie
Glen Kinoshita

Craig Tweedy
Patrick Weber



Eddy Covariance

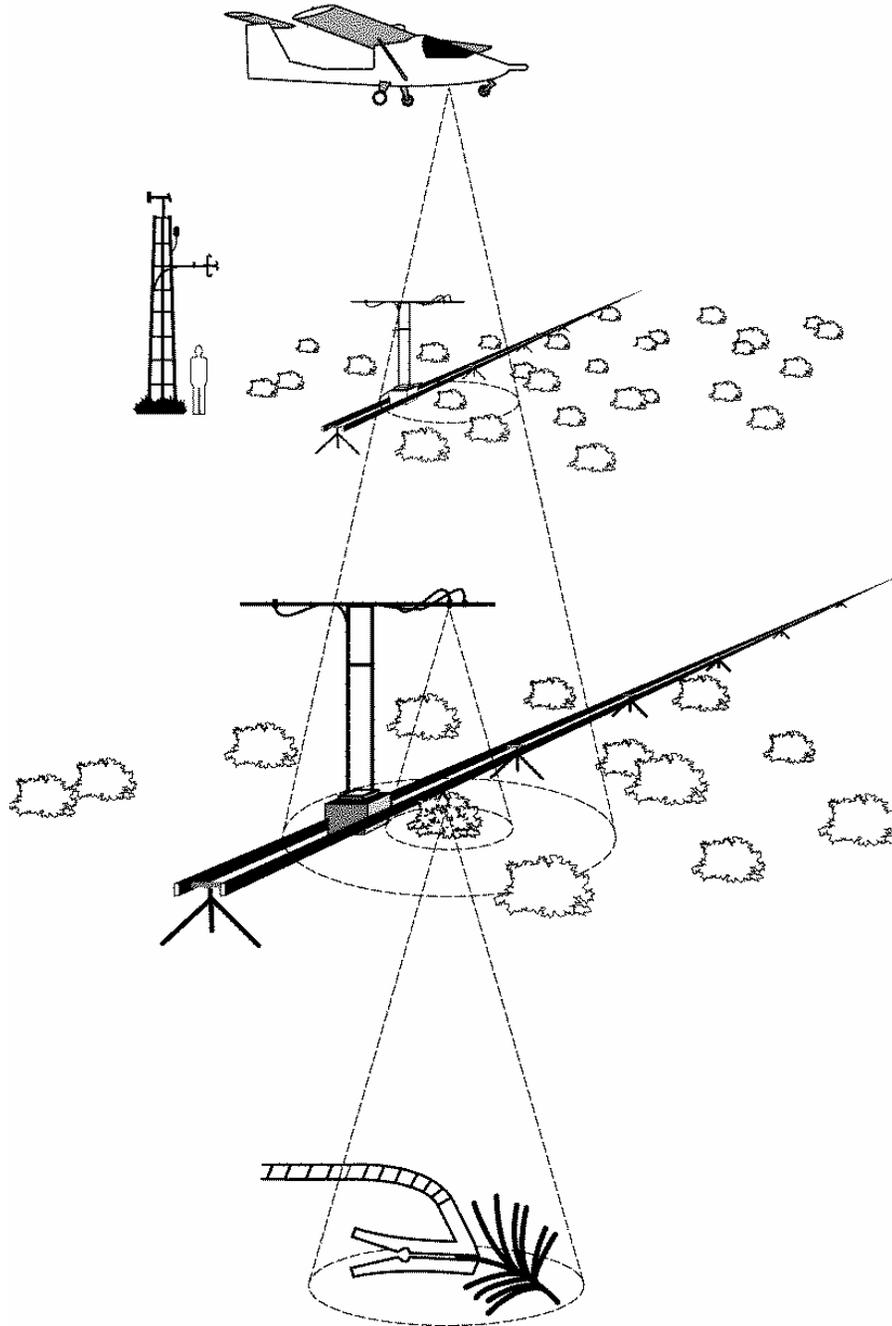


Optical sampling



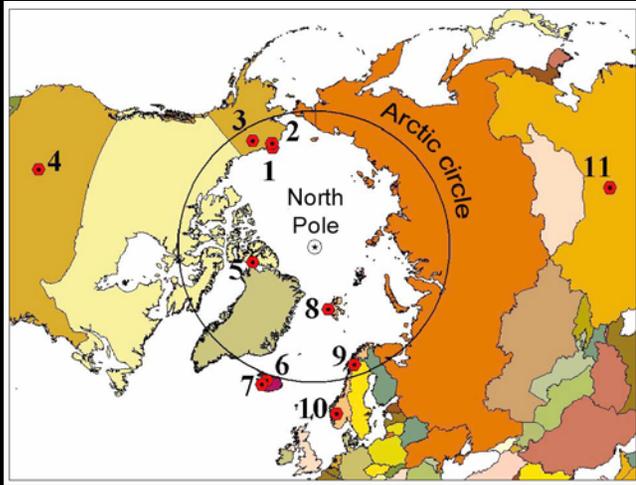
Aircraft remote sensing

Multi-scale
sampling



*Simultaneous
optical and
flux measurements
at multiple
spatial and
temporal scales.*

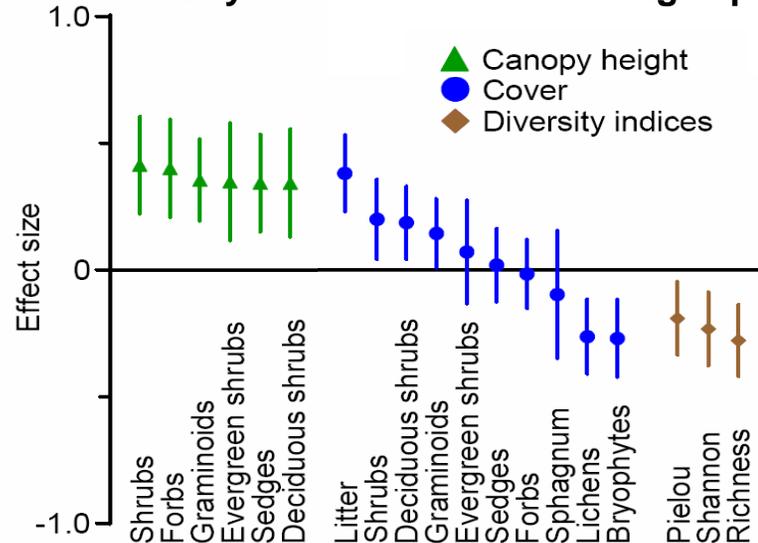
Experimental evidence: International Tundra Experiment (ITEX) synthesis



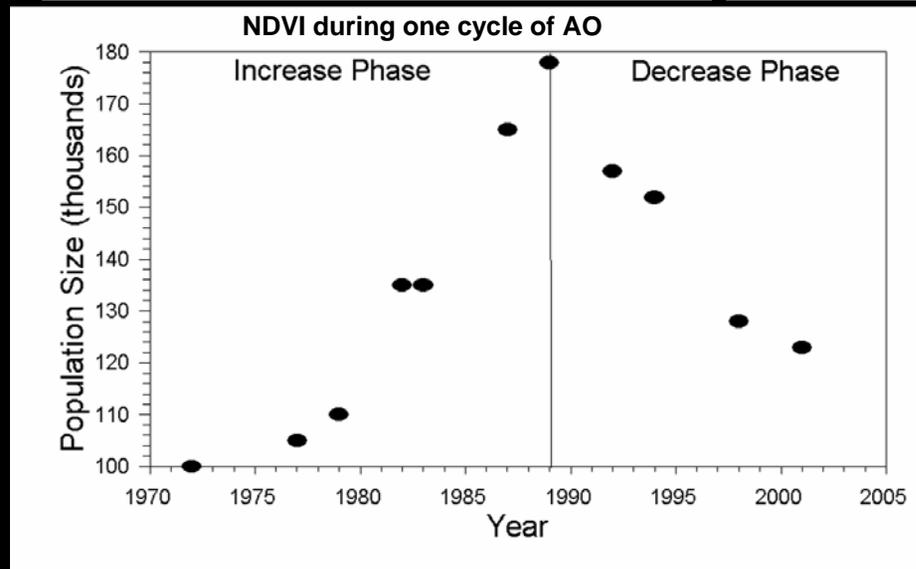
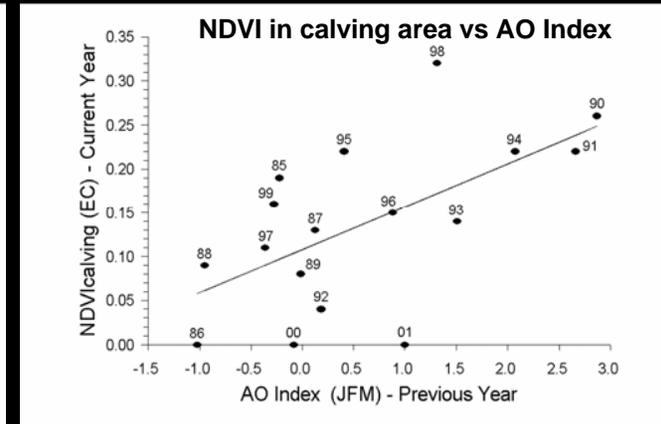
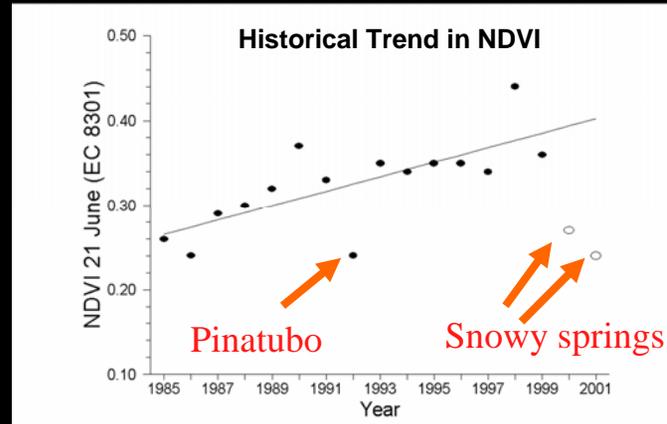
Warming:

- Increased shrubs, graminoids
- Decreased lichens, mosses, species diversity.

Meta-analysis of effects of warming experiment



Evidence for effects on wildlife: NDVI and Porcupine Caribou Herd population during one cycle of the Arctic Oscillation



The Nenets, reindeer and LCLUC



Vegetation change (shrubification):

Positive effects:

- Nenets collect willows for firewood, tools, etc.
- Important fodder species for the reindeer.

Negative effects:

- In the south, the willows have gotten so big that the reindeer can now disappear into them and get left behind during migration.



Other land-cover and land-use changes:

Interactions with extensive oil development infrastructure in the region.

Restriction of forage to smaller regions, overgrazing, desertification, grassification.

Photos: (top) Sven Haakanson,
(bottom) Bryan and Cherry Alexander(top)

1964



Population growth is a major factor of change in the Arctic.

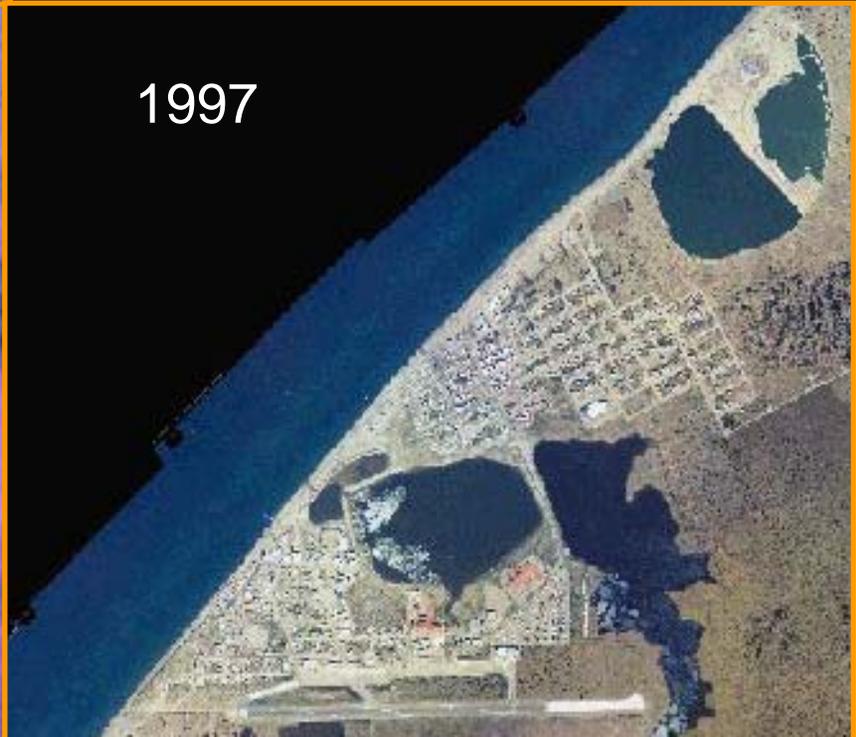
Courtesy of Pat Webber and Craig Tweedie



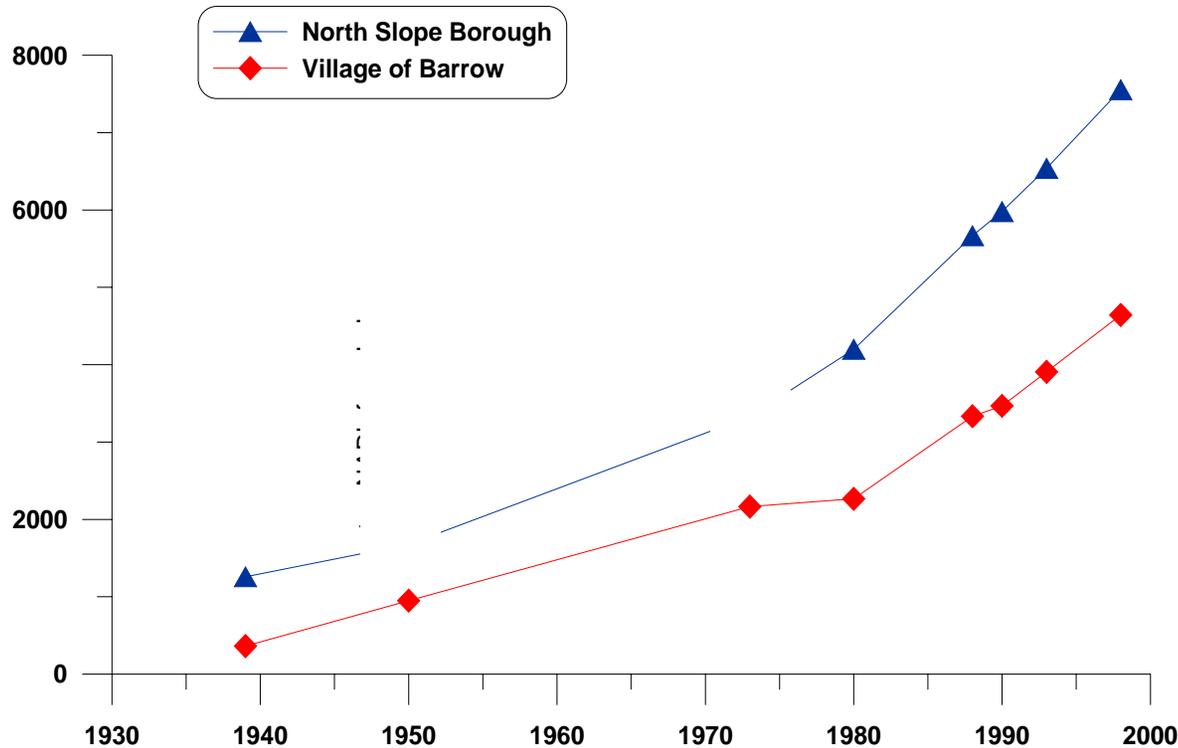
1979



1997



Population growth in Arctic Alaska



Courtesy of Ken Hinkle and Anna Klene

[Source: NSB GIS office, based on US Census data.]

- Barrow has greater than 20-fold increase in population in 60 yr.
- What are the effects on:
 - Land use
 - Subsistence resources
 - Off-road vehicle use
 - Long-term research sites
 - Local climate?

Cumulative impacts of resource development



- Developed oil fields cover about 3200 km²
- Over 600 km of roads in the Prudhoe Bay region
- 1760 km of aboveground pipelines
- 4311 ha of gravel placement and mines
- Another 4400 ha in the Dalton Highway

Off-road vehicles: 3-D seismic



1984-85 2-D
Seismic exploration of
the ANWR 1002 Area
2-D Sesmic Line
spacing, about 4-5 km
apart

3-D seismic Line
spacing, about 300 m
apart!



3-D seismic Line trails in the Kavik River
vicinity, AK, 2001



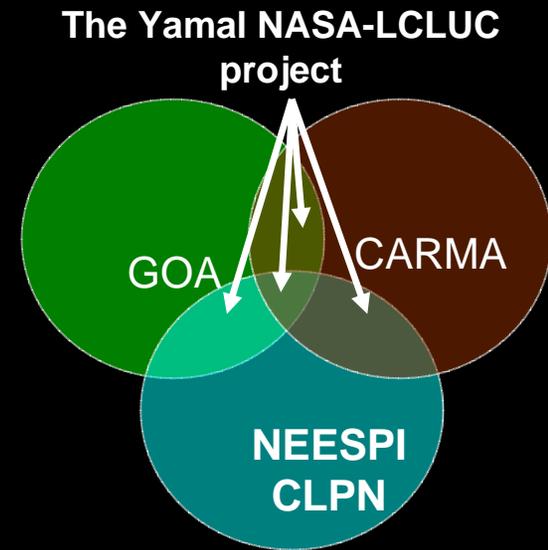
Take home points regarding Arctic Change

- **NDVI record indicates that the landscapes have greened considerably in the past 25 years.**
- **Direct evidence of changes in biomass is hard to come by.**
- **Industrial development and population growth have caused larger, more easily observed changes than changes from climate.**

NASA/NEESPI project is examining the interactions of climate change, industrial development, and humans on the Yamal Peninsula, Russia.



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Involves three International Polar Year initiatives:

- **GOA:** Greening of the Arctic
- **CARMA:** Circumpolar Arctic *Rangifer* Monitoring and Assessment.
- **CLPN:** Cold Land Process in NEESPI (CLPN). NEESPI = Northern Eurasia Earth Science Partnership Initiative.

Central land-cover/land-use change questions in Northwest Siberia

The Yamal region in northwest Siberia is a “hot spot” for climate change and land-use change. Large-scale oil and gas development is interacting with climate change, a sensitive landscape and nomadic reindeer herds to produce extensive land-cover changes.

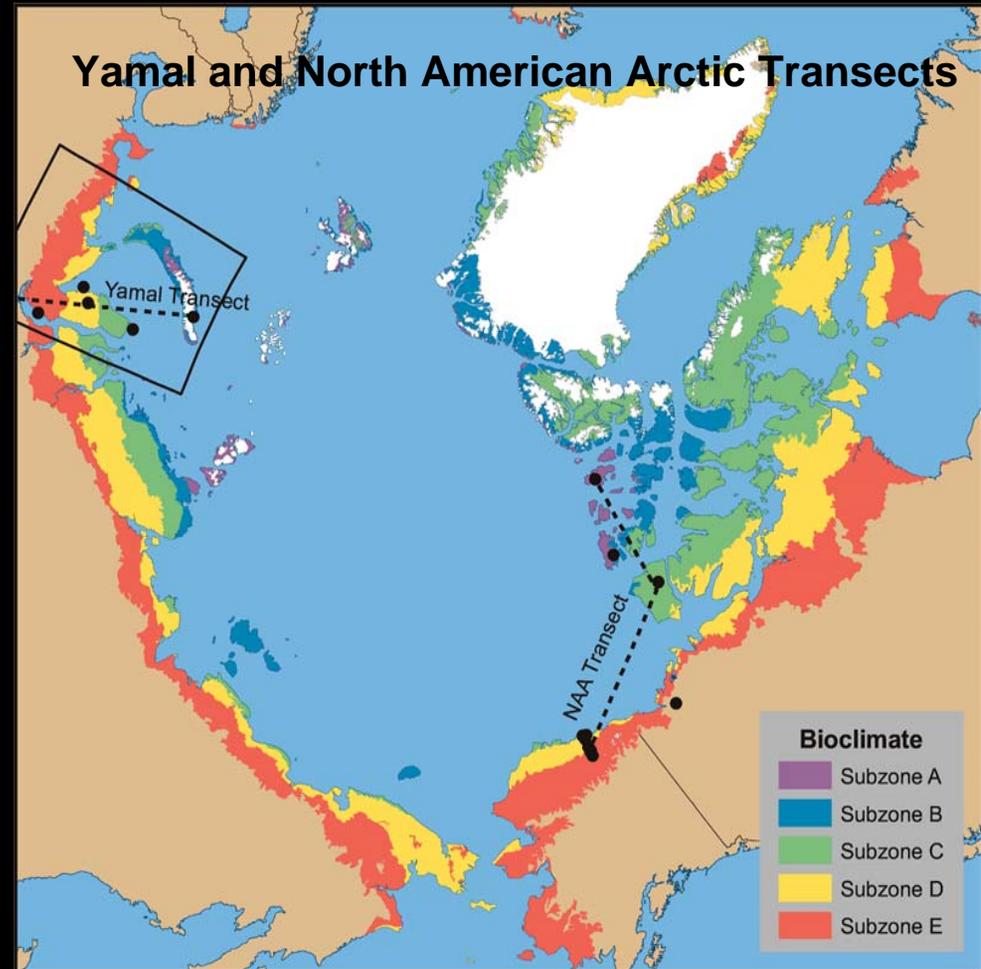
Questions:

- What will happen to the tundra regions as the climate warms and sea ice retreats?
- How are the Nenets and their reindeer responding to LCLUC on the Yamal Peninsula?



GOA studies are focused along North American and Yamal transects.

- Our umbrella question is, "How do different patterns of sea-ice distribution affect spatial and temporal patterns of the terrestrial vegetation change?"

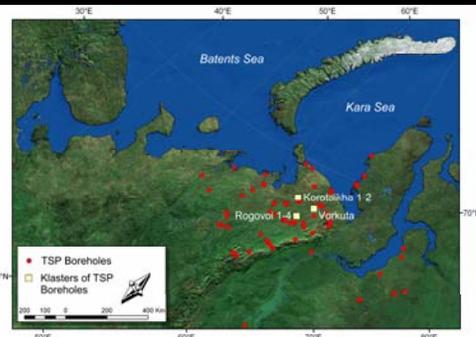


Early results: Permafrost temperatures northern Alaska and Yamal region

Northern Alaska



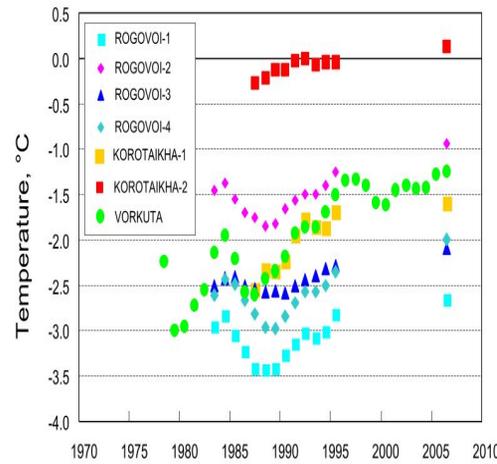
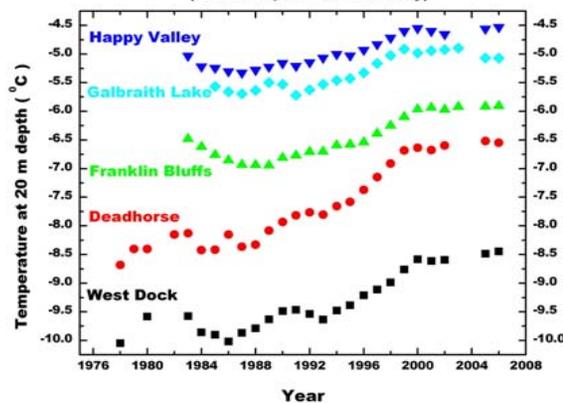
Yamal Region



Analysis:

- Thermal State of Permafrost (TSP) project is IPY and NEESPI project.
- Monitoring permafrost temperatures, active-layer depths, and geomorphic response (e.g., thermokarst, landslides) along NAAT and Yamal transects.

"TSP" Time Series - Northern Alaska (Osterkamp and Romanovsky)



Results:

Similar patterns of permafrost temperatures in Alaska and Yamal region:

- Cooling in early 1980s.
- Warming in 1990s.
- Little change since 2000.
- Surprisingly warm temperatures in some continuous permafrost areas.

- Courtesy Vladimir Romanovsky

Sea-ice concentration, LST, and NDVI within 50 km of coast

Beaufort Sea

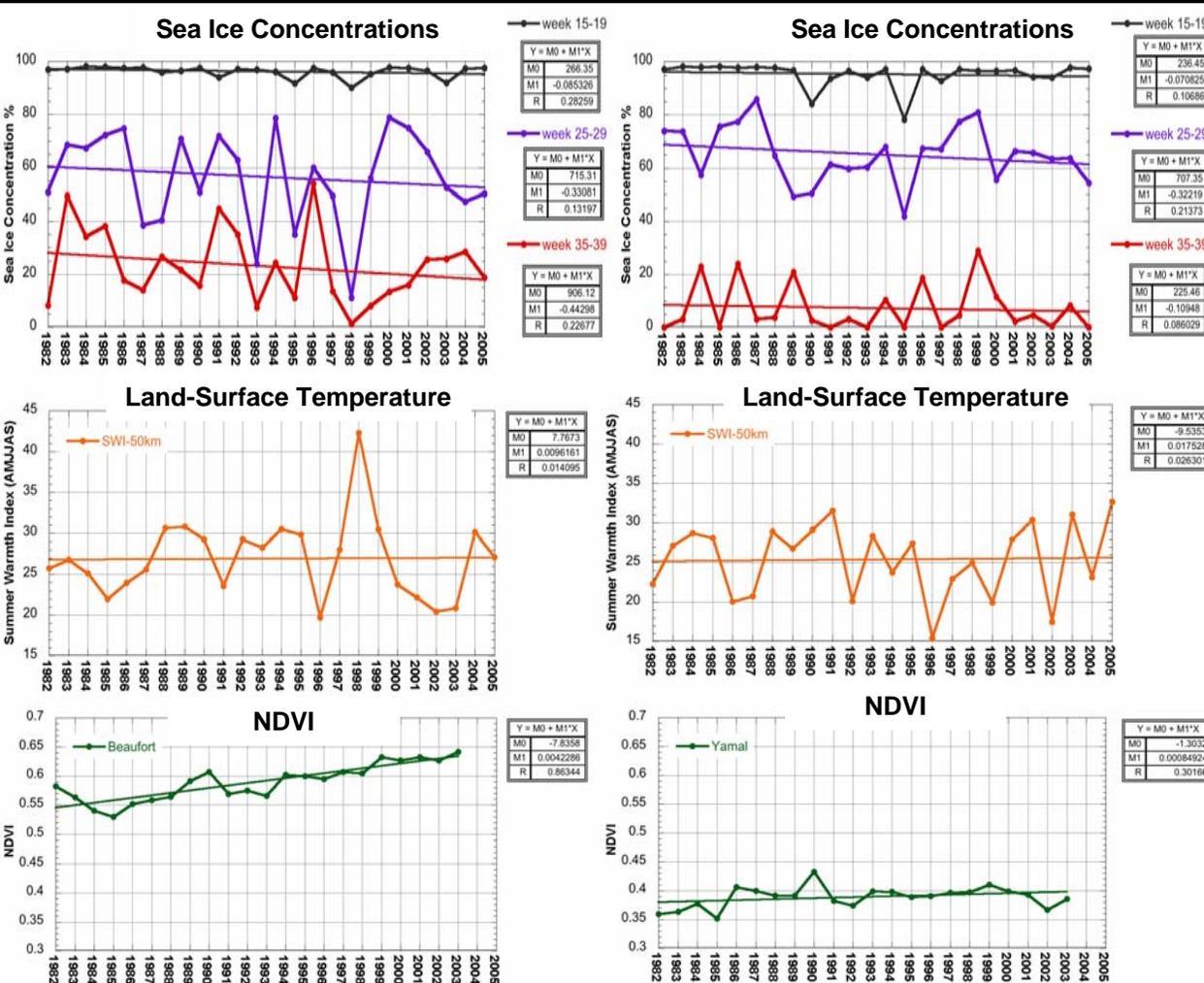
Kara Sea/Yamal

Analysis:

- AVHRR data
- 50-km buffer seaward for sea ice and inland for LST and NDVI.
- Examined coastal swath along coast of entire Beaufort and Kara (Yamal portion) seas.

Results:

- Weak negative trends in sea-ice concentrations within 50 km of coast with high year-to-year variation (same trend seen in all areas of the Arctic except N. Greenland-Ellesmere area where sea ice has increased).
- Kara is more icy in early summer but is generally ice free by late summer.
- No long term trend in LST.
- Strong increase in NDVI in Alaska, but weak trend in Russia.
- Much higher NDVI along the Beaufort coast compared to Kara.



Climate indices

- **NAO** - North Atlantic Oscillation
- **NAM** - Northern Annular Mode (= Arctic Oscillation or AO)
 - (Note: NAO and NAM are correlated at 0.81)
- **NPI** - North Pacific Index (Sea Level Pressure in N. Pacific)
- **ENSO** - El Nino Southern Oscillation
 - (Note: NPI and ENSO are negatively correlated at -0.55 because midlatitude atmosphere responds by strengthening the Aleutian low during ENSO.)
- **Siberian High** - Sea level pressure over 40-60°N & 70-120°E
 - (Note: Siberian High and NAM are negatively correlated (-0.56) because the during the positive phase of the NAM the Siberian N-S pressure gradient is weaker than normal.)
- **PDO** - Pacific Decadal Oscillation (Sea Surface Temperature Index over the North Pacific.)

Correlations between sea-ice, climate indices, LST, SWI, and NDVI

Beaufort Sea

DJFM indices	Sea ice Week 25-29 avg	LST	NDVI
NAO	-----	0.43 (95%)	-----
NAM	-----	0.30	0.30
NPI	-----	-----	0.12
ENSO	-0.51 (99%)	0.37	-0.12
Siberian High	0.23	-0.27	-0.43 (95%)
PDO	-0.26	-----	-0.33
Summer Indices			
SWI	-0.60 (99%)	X	
Ice	X		
NDVI	-----	-----	X

Kara Sea/Yamal

DJFM indices	Sea ice Week 25-29 avg	LST	NDVI
NAO	-0.50 (99%)	0.25	0.15
NAM	-0.56 (99%)	-----	0.23
NPI	-0.35	-----	-----
ENSO	0.13	-----	-0.16
Siberian High	-----	0.15	-0.24
PDO	0.48 (99%)?	-----	-0.12
Summer Indices			
SWI	-0.47 (98%)	X	
Ice	X		X
NDVI		-----	

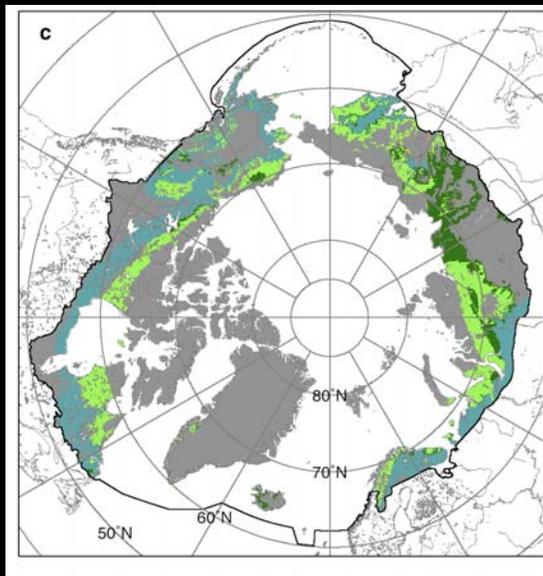
Results:

- The LST and sea ice in both regions are strongly correlated.
- The sea ice in the Beaufort is most strongly correlated with Pacific climate indices (ENSO and PDO).
- Sea ice in the Kara is more closely related to N. Atlantic indices, with the exception of the PDO (a bit surprising).

Modeling approach: 3 different models

BIOME4

- Global-scale dynamic vegetation change model.
- Uses a limited set of plant functional types, their physiological response (photosynthesis, transpiration), biogeography, and biogeochemistry in combination with GCM output to predict equilibrium vegetation types following climate change.



Results:

This output simulates the mean forest vegetation change for 2 °C warming (other scenarios showed cooler and warmer possibilities):

- Tundra extent reduced by 42%.
- Forests are “ultimately” replaced by parkland (lichen woodlands).



Courtesy of Jed Kaplan

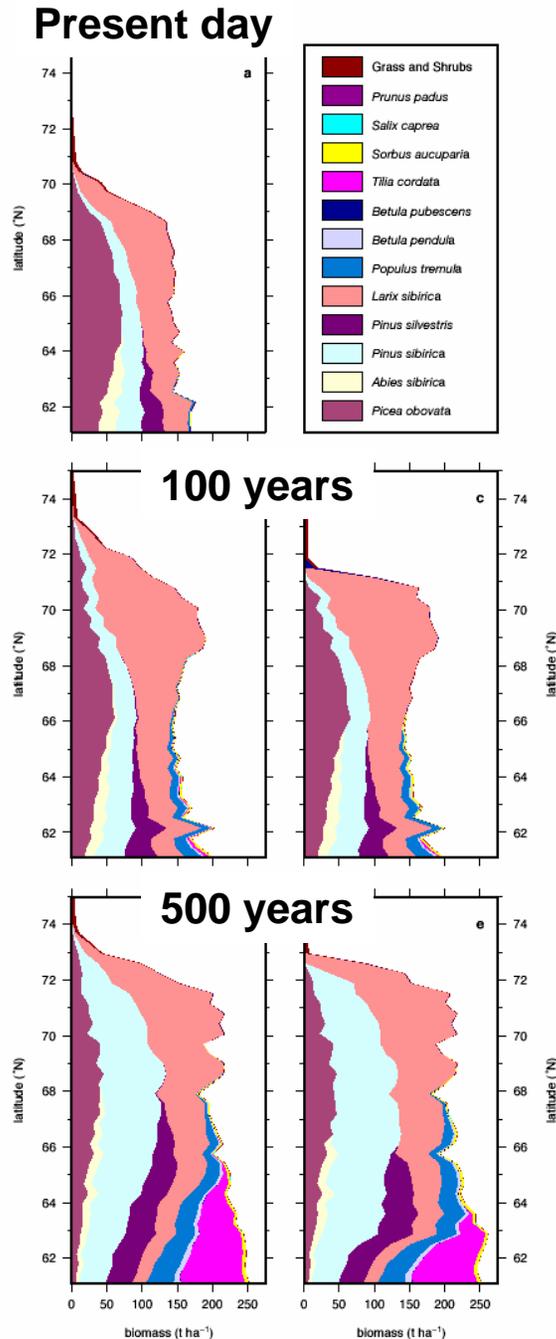
Forest transition model: TreeMig model to examine succession and migration of species

TreeMig (Lischke et al. 2007)

- Dynamic forest stand model that determines forest population dynamics at the species level.
- Including seed production, seed dispersal, seed bank dynamics, germination, growth, competition, and mortality.
- It runs at a 1 km grid cell size.

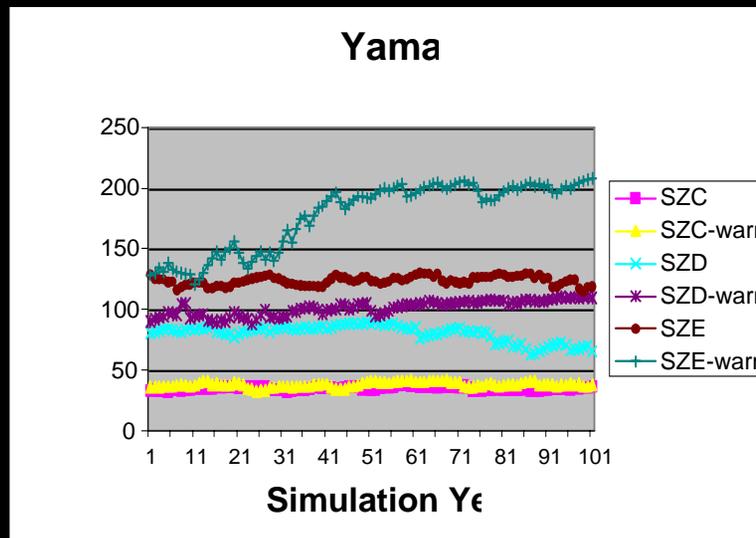
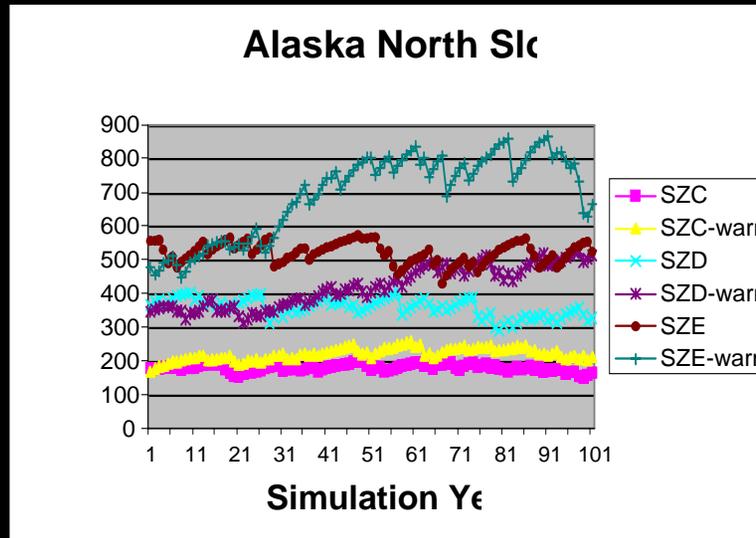
Results:

- With a 2.5°C summer warming, treeline advances rapidly northward.
- Succession only scenario (left hand column) 235 m yr⁻¹
- Succession + migration scenario (right column) 177 m yr⁻¹.
- Forest composition changes considerably with dominance of deciduous species (*Larix* in the north and *Populus*, *Prunus*, and *Tilia* in the south).



Lischke, H., T. J. Löffler, P. E. Thornton, and N. E. Zimmermann. 2007. Up-scaling of biological properties and models to the landscape level, in *A changing world: challenges for landscape research*, edited by F. Kienast, et al., pp. 259-282, Kluwer, Dordrecht.

Plot-level model: ArcVeg to examine transient dynamics of tundra vegetation



ArcVeg model (Epstein et al. 2001, 2004):

- Simulates changes to plant functional types.
- Climate and N are the main drivers.
- Runs on at 1-m plot scale.

Results:

- This simulation shows response of total above-ground biomass after 100 years in Subzones C, D, and E on the Alaskan North Slope, vs the Yamal.
- Sandy nutrient-poor soils of the Yamal strongly constrain production.

Interviews with Nenets reindeer herders



- Researchers will travel with the nomadic Nentzy people during their annual migration
- Formal semi-structured interviews to see how LCLUC is affecting their reindeer and daily life.
- Recorded on film and digital tape.
- Medium- and/or very-high-resolution satellite imagery to focus on specific places and features that the herders can recognize easily.



Reindeer herd clustered together on lake shore

Reindeer sleds and chums for private herder on northern Yamal Peninsula

Quickbird panchromatic image, 0.63 m resolution, Yamal, July 2004

Courtesy of Bruce Forbes

Participants in the Yamal LCLUC project

Arctic Centre, Rovaniemi, Finland:

Bruce Forbes: Human dimensions of Yamal transect

Earth Cryosphere Institute, Moscow:

Marina Liebman: permafrost on Yamal transect

Natalia Moskolenko: vegetation on Yamal transect

Institute of Atmospheric Physics, Beijing:

Gensuo Jia: Temporal analysis of circumpolar NDVI

NASA-Goddard:

Joey Comiso: Circumpolar sea-ice and LST

Swiss Federal Institute of Forest Snow and Landscape Research:

Jed Kaplan: BIOME4 modeling

Heike Lischke: TreeMig modeling

University of Berne, Switzerland:

Patrick Kuss: Vegetation analysis

University of Alaska Fairbanks:

Uma Bhatt: Co-PI, Climate dynamics,

Gary Kofinas: Human dimensions of Yamal transect

Martha Reynolds: Spatial analysis of circumpolar NDVI,

Vlad Romanovsky: Co-PI, permafrost and climate,

Skip Walker: PI, vegetation analysis.

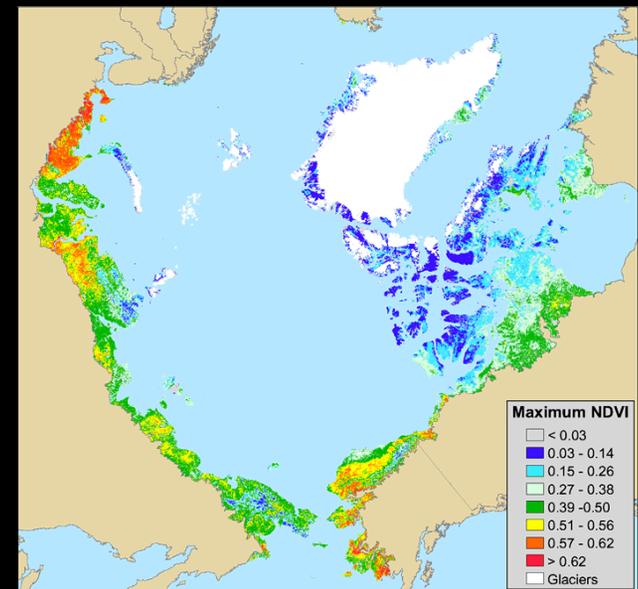
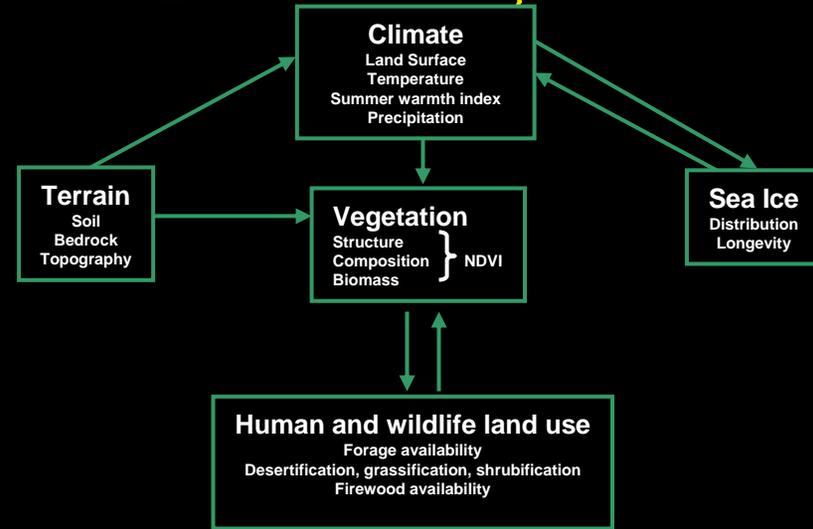
University of Virginia:

Howie Epstein: Co-PI, ArcVeg model, NDVI

Qin Yu: NDVI, ArcVeg Model

Unifying theme of GOA projects: Sea Ice ~ Land-surface-temperature ~ Greening relationships

- Detailed examination of the 25-year record of greenness across the entire circumpolar Arctic as measured by the normalized difference vegetation index (NDVI) using satellite imagery (AVHRR and MODIS).
- Will link trends in NDVI to changes in climate, sea-ice distribution, land-surface-temperatures (LSTs), snow-cover, bioclimate subzones, vegetation type, glacial history, and other variables in a circumpolar GIS database.
- Modeling studies will use the past trends in NDVI to predict future distribution of arctic vegetation.



Four components of the GOA study

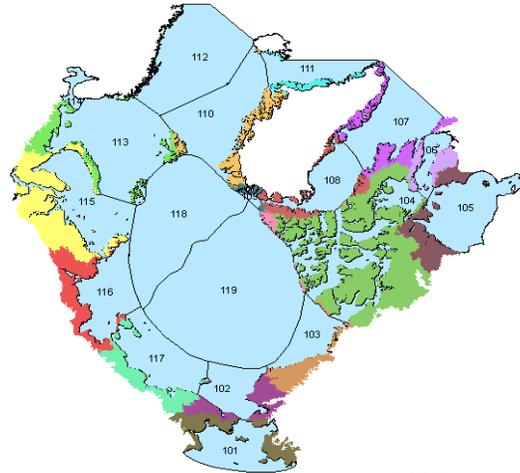
- I. Analysis of LCLUC and impacts to reindeer and the Nenets people on the Yamal Peninsula Russia: Funded by NASA
- II. Circumpolar spatial and temporal analysis of sea Ice – land-surface-temperature – terrain – NDVI relationships: Funded by NSF.
- III. Web-based *Arctic Geobotanical Atlas*: Funded by NSF.
- IV. Pan-Arctic vegetation change: A U.S. contribution to the Circumpolar Biodiversity Monitoring Program and Greening of the Arctic initiative. Proposal submitted to NSF.

Next steps:

Legend

Ocean Basins and Associated Tundra

	Ice Cap & Non-Arctic
	Ocean
	101 Bering Sea
	102 Chukchi Sea
	103 Beaufort Sea
	104 Canadian Arch.Straits
	105 Hudson Bay
	106 Hudson Strait
	107 Davis Strait
	108 Baffin Sea
	109 Lincoln Sea
	110 Greenland Sea
	111 Denmark Strait
	112 Norwegian Sea
	113 Barents Sea
	114 White Sea
	115 Kara Sea
	116 Laptev Sea
	117 E.Siberian Sea
	118 Russian Arctic Basin
	119 American Arctic Basin



Modified from Treshnikov et al. (ed.) 1985. *Arctic Atlas*, Russian Academy of Science.

- Historical differences in sea-ice concentration in all Arctic ocean regions (Treshnikov 1985) in relationship to climate drivers, LST, and NDVI.

- NDVI variation with respect to geobotanical factors (e.g., soils, climate subzones, glacial history, topography, hydrology).

Plan for Yamal field work

2007:

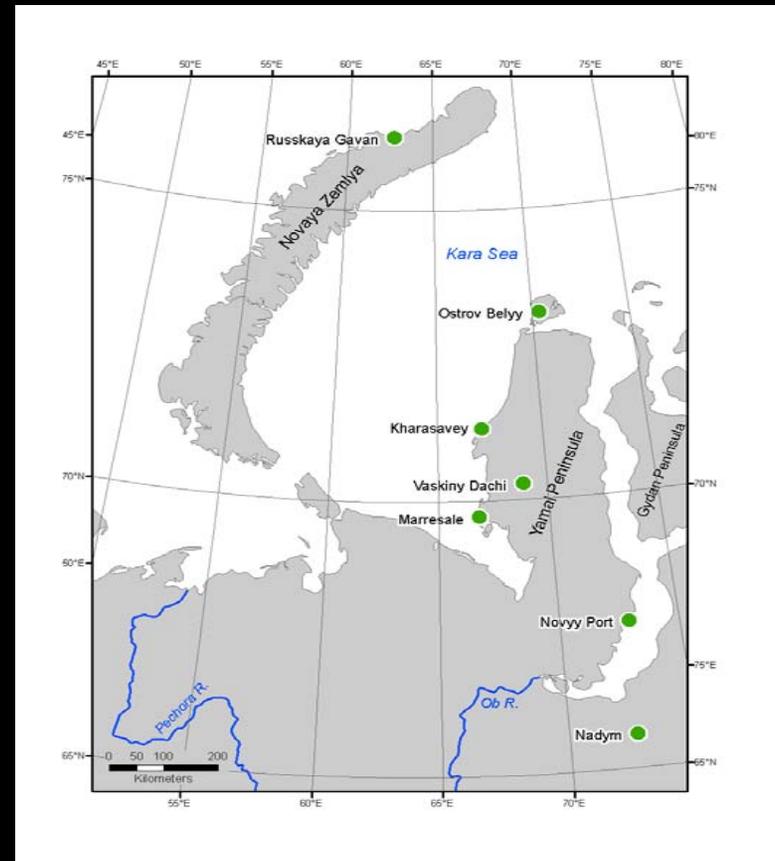
- Jun 30 to Jul 26 Field work at Nadym, Km 143, and Vaskiny Dacha.

2008:

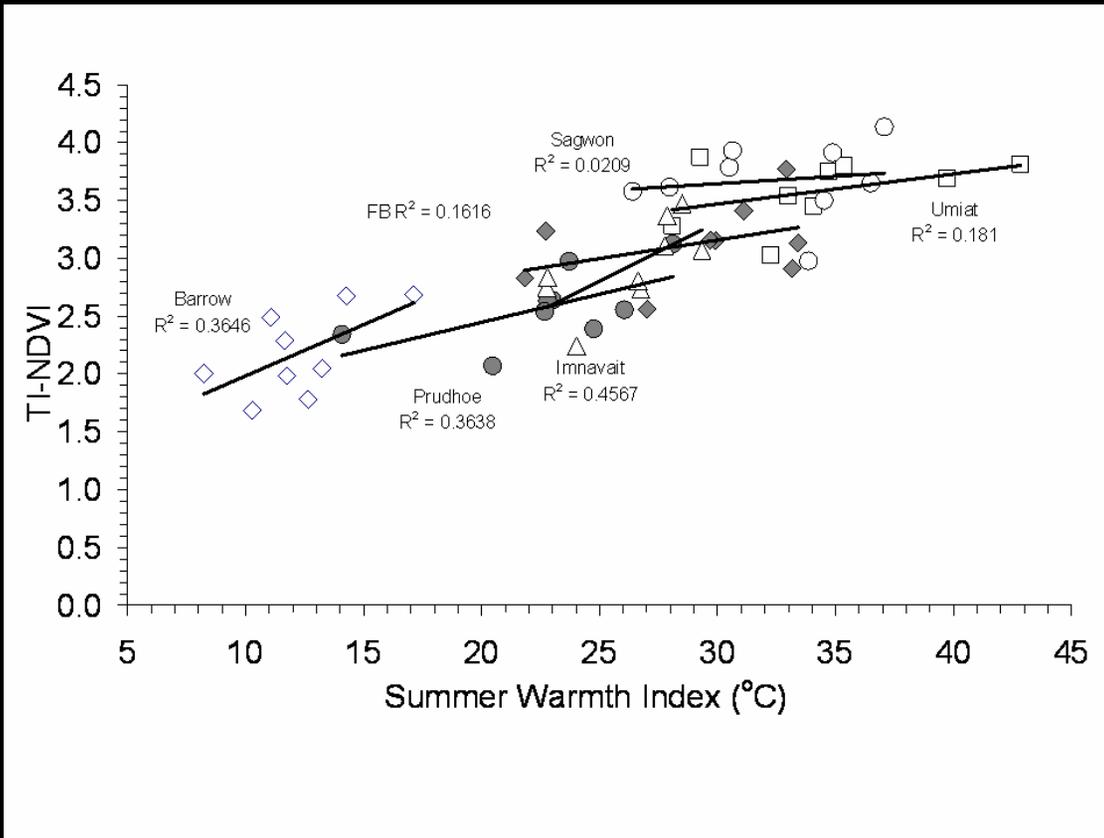
- Field work at Marrasale, Kharasavey, and Ostrov Belyy

2009?:

- Field work at either Svalbard, Franz Josef Land, or Novaya Zemlya



Correlations between summer air temperature and NDVI in Alaska



Modified from Jia et al. 2006. *Global Change Biology*. 12: 42-55.

- LST, NDVI, and sea-ice data show average conditions along long coastal stretches with high spatial variability in climate, topography, and vegetation.
- LST data also are collected only during clear-sky conditions, so consistent cloudy conditions near coast may affect the trends.
- Correlations between station climate data and NDVI of 9-pixel areas at each station show consistent positive correlations.
- LST data may show similar correlations with NDVI if smaller areas are examined.