A photograph of an Arctic landscape. In the foreground, there is a dense field of low-lying green vegetation, possibly shrubs or grasses. A winding river or stream flows through the middle ground, surrounded by more greenery. In the background, there are rolling hills and a rocky, light-colored slope. The sky is a pale blue with some light clouds.

The “greening” of the Arctic  
seen through the lens of satellites,  
field research, and local observations

*Gerald “J.J.” Frost*



ARCUS Webinar  
29 May 2020



# Road Map for Today

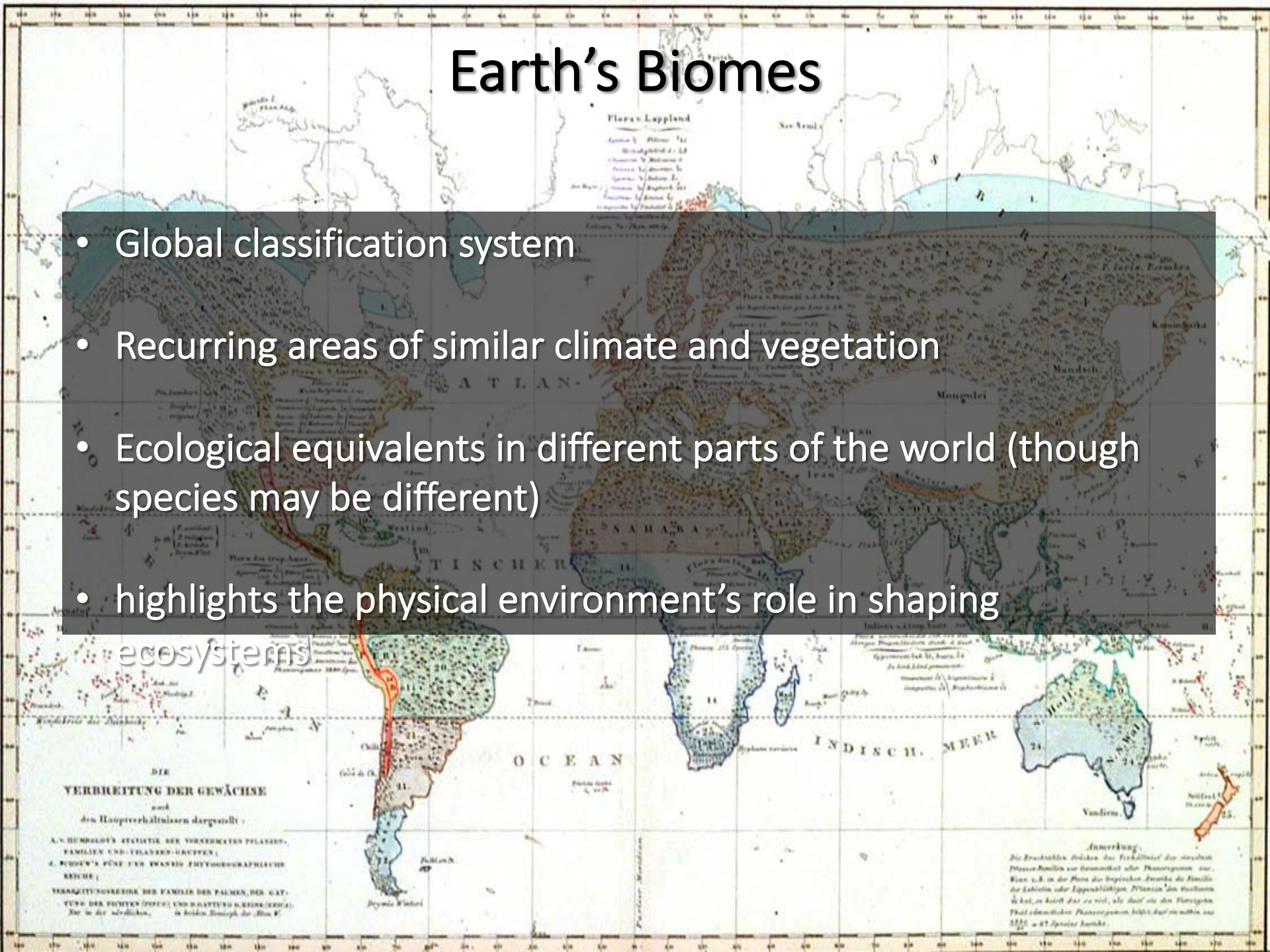
1. Earth's biomes and Arctic tundra 101
2. The view from space
3. The view on the ground
4. Observations and concerns of Arctic people





# Earth's Biomes

- Global classification system
- Recurring areas of similar climate and vegetation
- Ecological equivalents in different parts of the world (though species may be different)
- highlights the physical environment's role in shaping ecosystems





**Alexander von Humboldt pioneered the study of biogeography.**

**He noticed recurring patterns between local climate (temperature, precipitation) and vegetation as he traveled up and down the Andes Mountains.**













# Earth's northern biomes



Boreal forest – or, the “emerald wreath”

18 million square kilometers



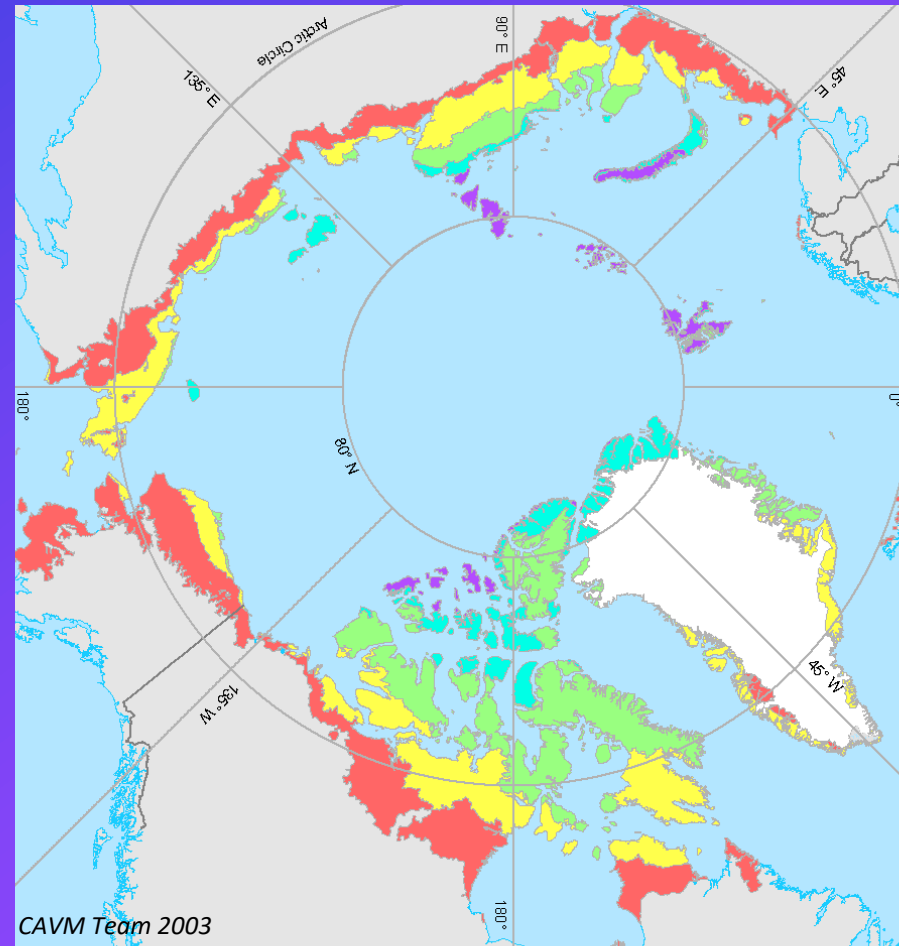
“The power and enchantment of the taiga lie not in giant trees or silence...but in the fact that only birds of passage know where it ends.”

- Anton Chekhov, *Across Siberia* (1890)





# Earth's northern biomes

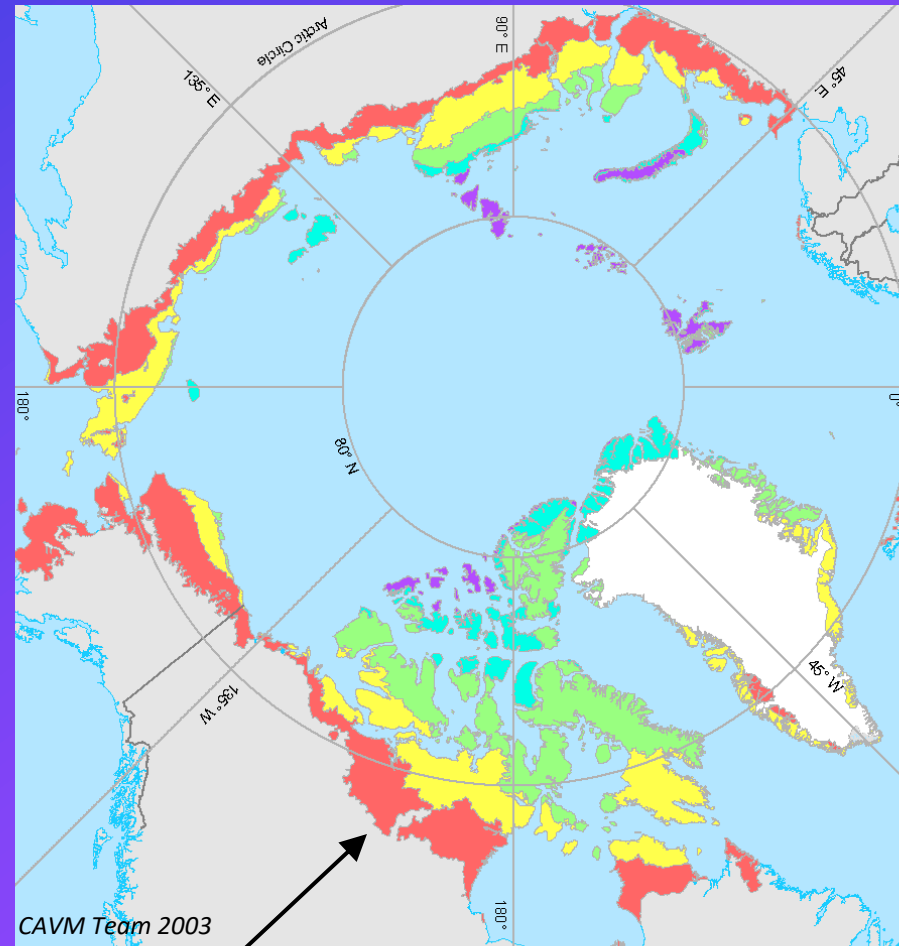


Arctic tundra

5 million square kilometers



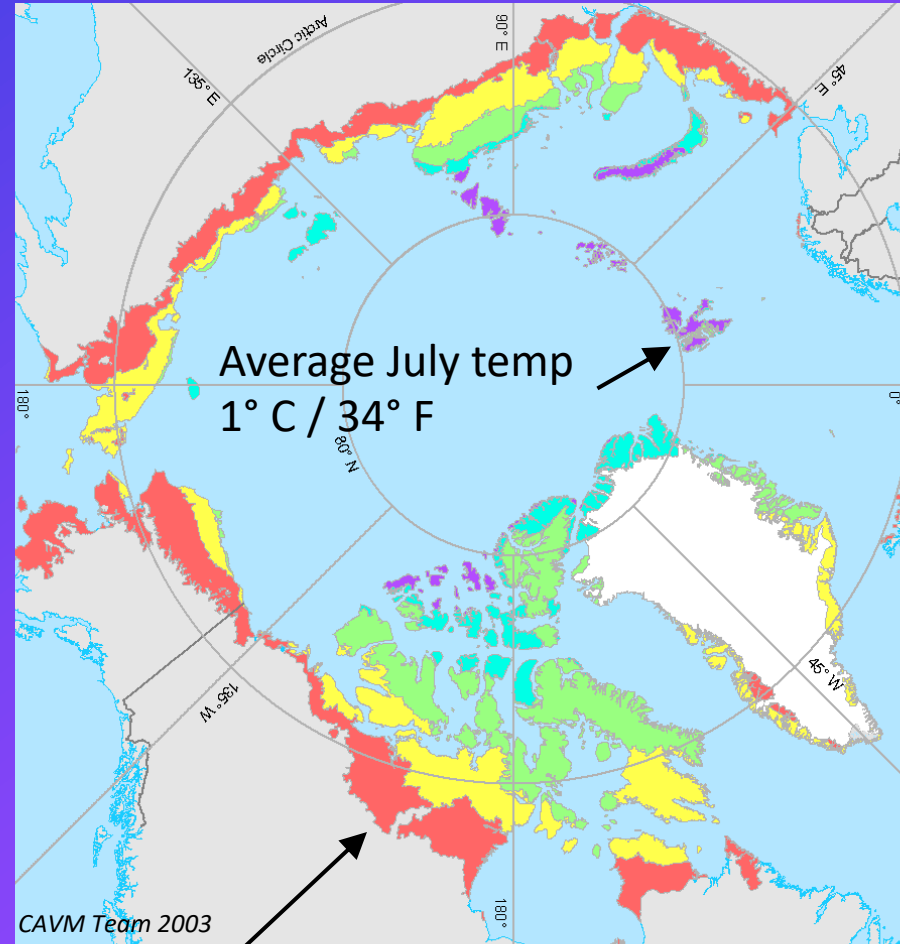
# Earth's northern biomes



Average July temperature 10° C / 50° F



# Earth's northern biomes



Average July temp  $10^{\circ}\text{C} / 50^{\circ}\text{F}$



# Polar Ural Mountains, Russia



*G. Frost photo*



Lake Iliamna area, Alaska



*G. Frost photo*



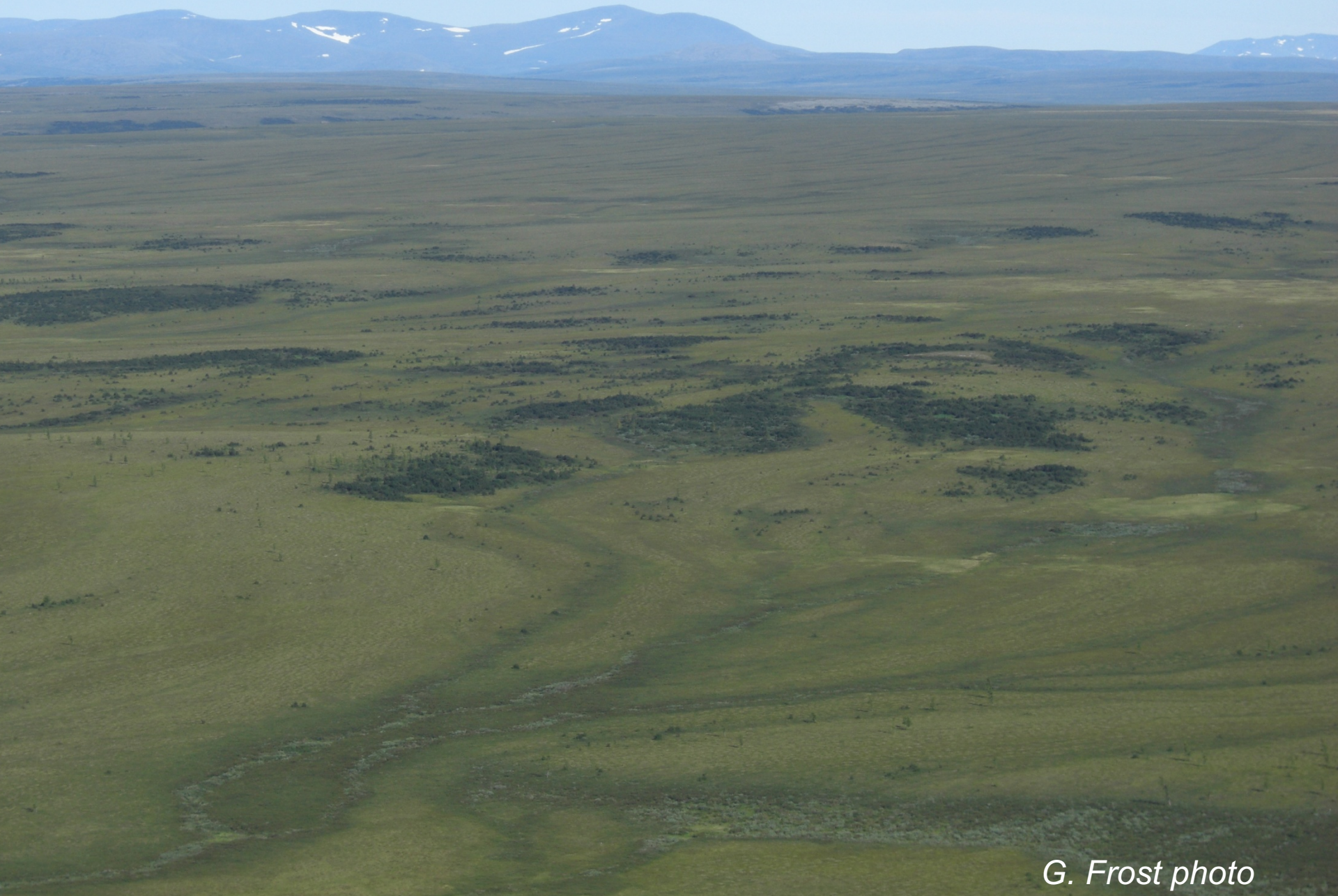
# Yamal Peninsula, Russia



*D. Walker photo*



Yamal Peninsula, Russia



*G. Frost photo*



Yamal Peninsula, Russia



*D.A. Walker photo*



Mean July temp 1°C



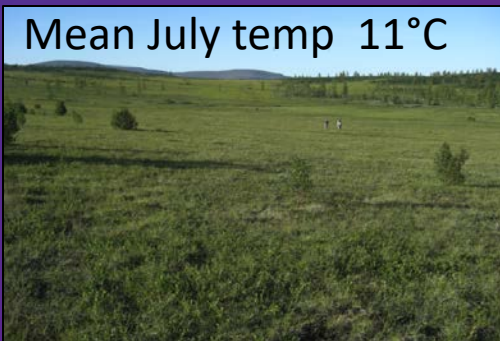
Mean July temp 4°C



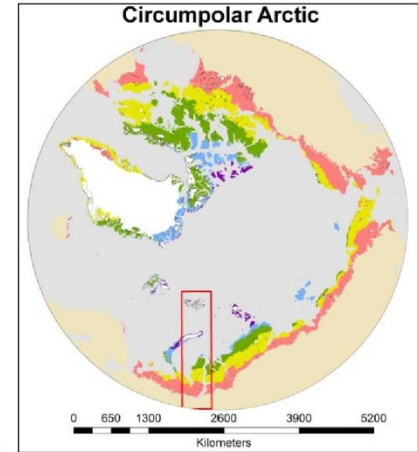
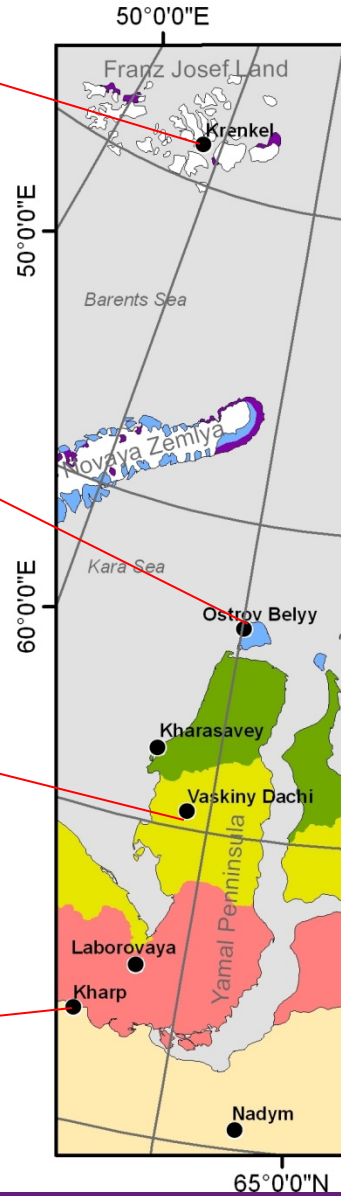
Mean July temp 8°C



Mean July temp 11°C



# Eurasia Arctic Transect



## Bioclimate Subzones

- Glaciated
- Subzone A
- Subzone B
- Subzone C
- Subzone D
- Subzone E
- Non-Arctic

Study Location





# Arctic ecosystems in transition

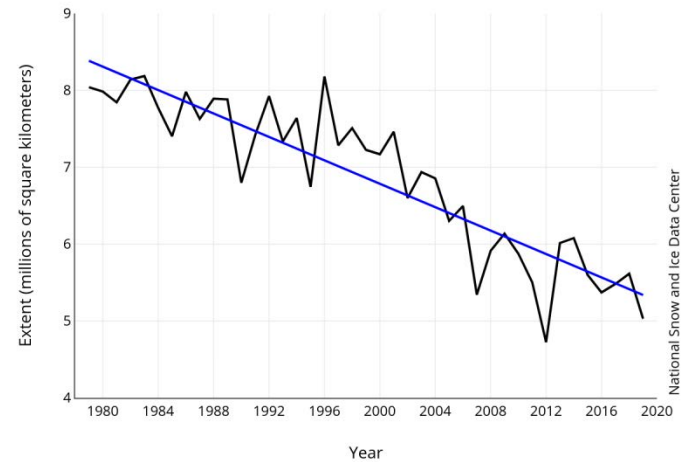
Sea Ice Extent, 16 Sep 2019



National Snow & Ice Data Center

The dramatic loss of Arctic sea ice has received widespread attention...

Average Monthly Arctic Sea Ice Extent  
August 1979 - 2019

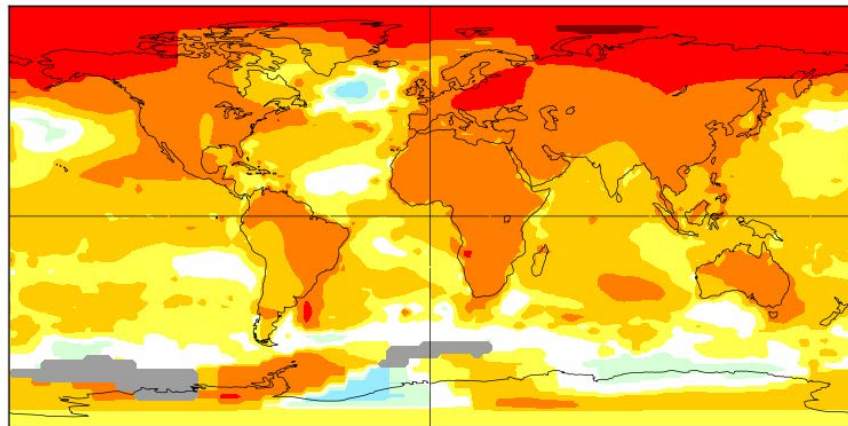


National Snow & Ice Data Center



# Arctic ecosystems in transition

## 2015-2019 temperatures compared to 1951-1980

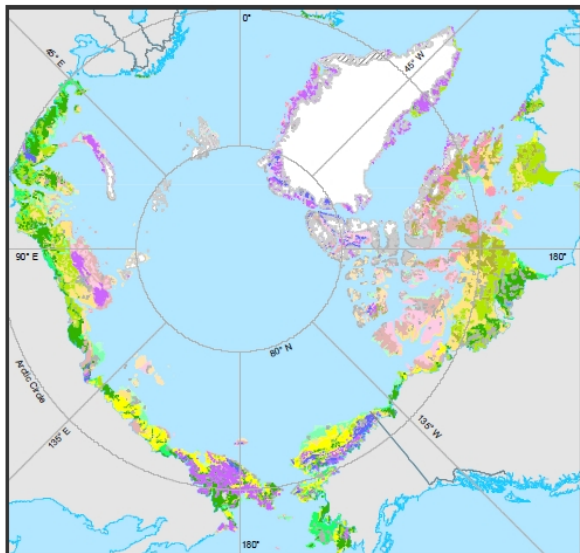


NASA - GISS -4.1 -4.0 -2.0 -1.0 -0.5 -0.2 0.2 0.5 1.0 2.0 4.0 4.2

...but changes on land are also occurring, with implications from local to global scales.

- “Arctic greening”
- permafrost thaw
- carbon release

## Circumpolar Arctic Region Vegetation



- Cryptogam, herb barren
- Cryptogam barren complex (bedrock)
- Noncarbonate mountain complex
- Carbonate mountain complex
- Prostrate dwarf-shrub, herb tundra
- Prostrate/Hemiprostrate dwarf-shrub tundra
- Rush/grass, forb, cryptogam tundra
- Graminoid, prostrate dwarf-shrub, forb tundra
- Nontussock sedge, dwarf-shrub, moss tundra
- Tussock sedge, dwarf-shrub, moss tundra
- Erect dwarf-shrub tundra
- Low-shrub tundra
- Sedge/grass, moss wetland
- Sedge, moss, dwarf-shrub wetland
- Sedge, moss, low-shrub wetland
- Nunatak complex
- Glaciers
- Water
- Lagoon
- Non-Arctic Areas

0 250 500 750 1000  
Kilometers

Lambert Azimuthal Equal Area Projection  
Longitude of origin: -180°, Latitude of origin: 90°

Derived from: CAVM Team, 2003. Circumpolar Arctic Vegetation Map (1:7,500,000 scale). Conservation of Arctic Flora and Fauna (CAFF) Map No. 1. U.S. Fish and Wildlife Service, Anchorage, Alaska.

<http://www.Arctic-Atlas.org/>

Distribution of Arctic tundra is linked to summer temperature and the nearby ice-covered ocean.

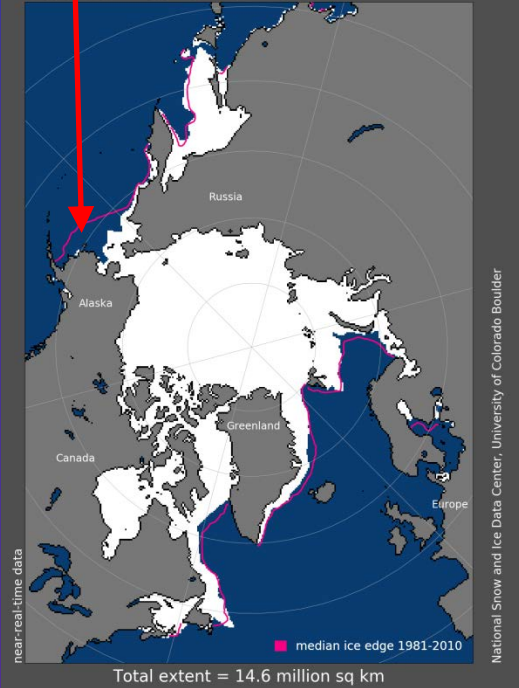
Models project the (slow) northward movement of boreal forest vegetation. But a lot is happening *within* the tundra in the meantime.



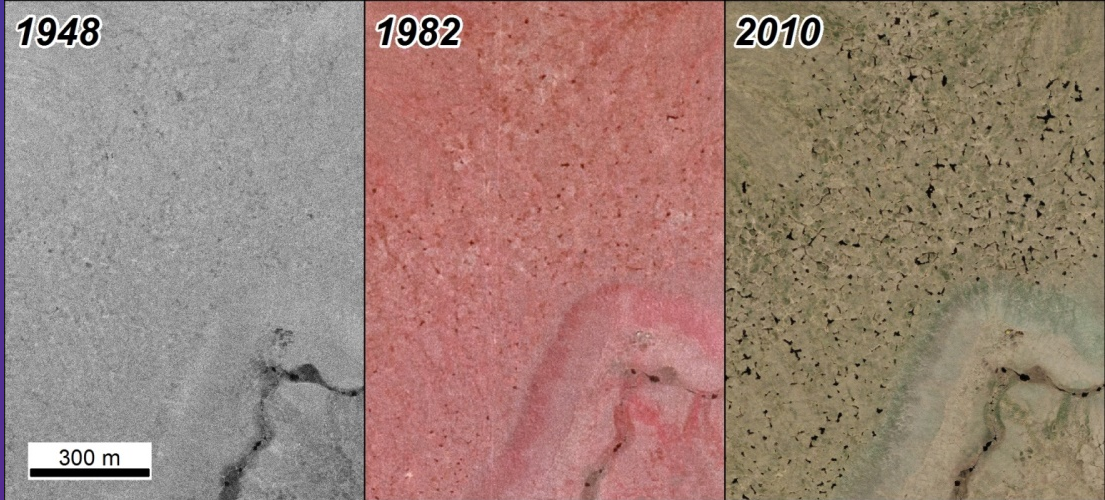
# “The map is changing”



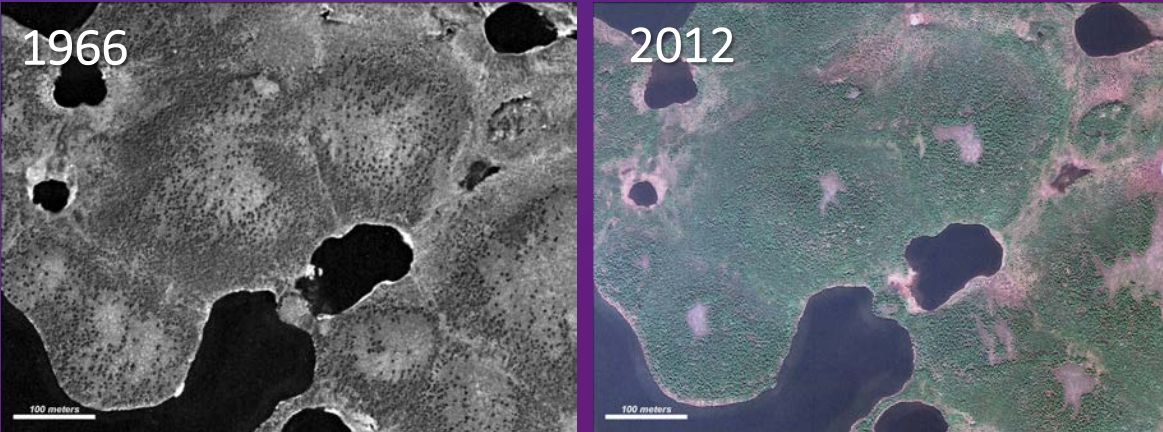
Sea Ice Extent, Mar 2019



Sea-ice decline



Permafrost thaw  
*Frost et al. 2018*



Shrub expansion  
*Frost & Epstein 2014*



# Vegetation & water





# Permafrost



ground-ice exposure at Amderma, Russia (Barents Sea coast)



# Geomorphology





# Soils



patterned-ground at forest-tundra transition, northwestern Siberia



Sea-ice





Animals and insects





# Disturbances





Tundra ecotone near King Salmon, Alaska, 1918.  
P. Hagelbarger photo © National Geographic Society.





Today, birch shrubs and spruce are much more extensive.  
G. Frost photo.





**1953**

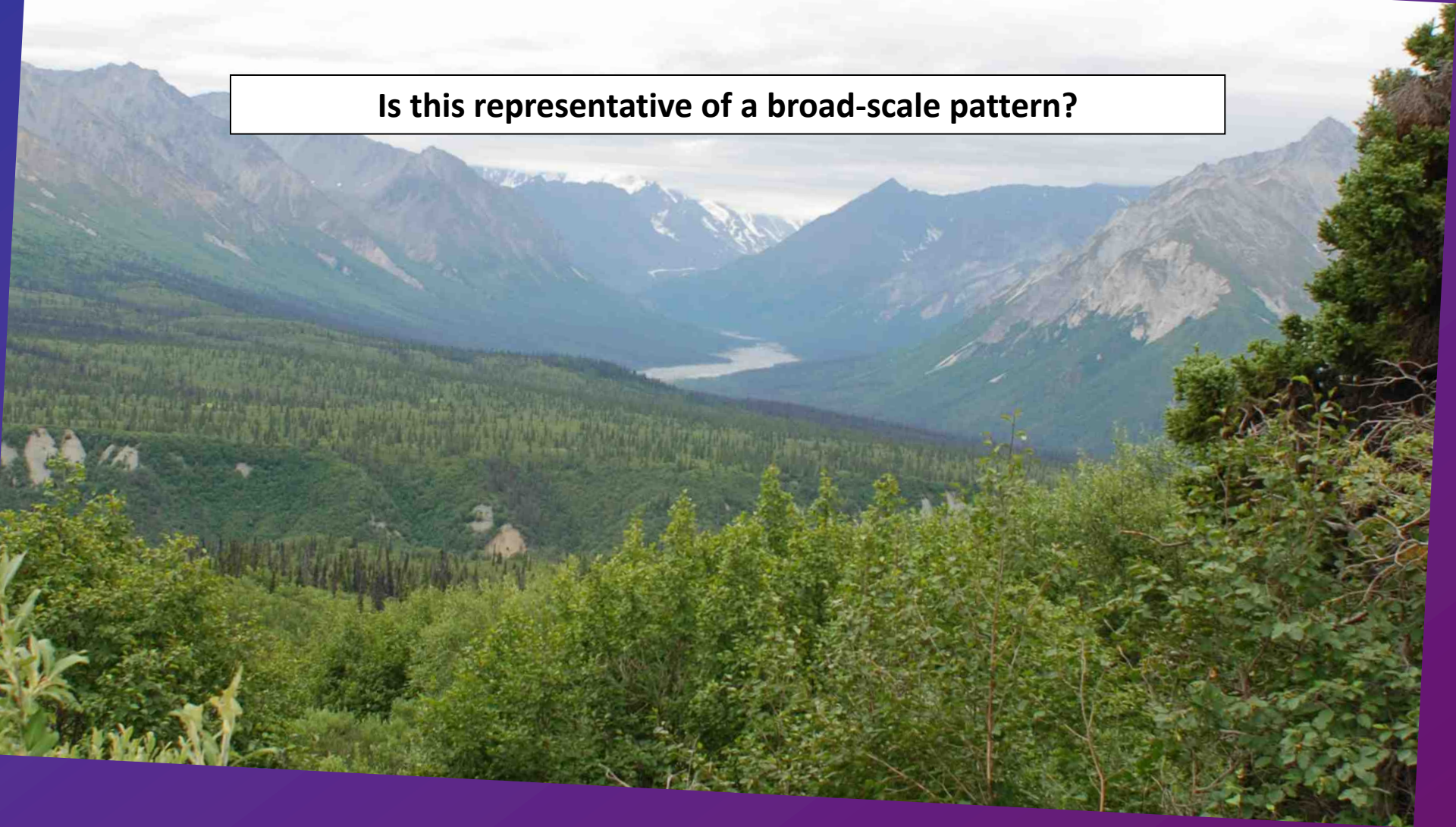


Upper Matanuska Valley, Alaska  
(USGS photo)



2007

Is this representative of a broad-scale pattern?



Upper Matanuska Valley, Alaska  
(Frost photo)



# Arctic change: the view from space

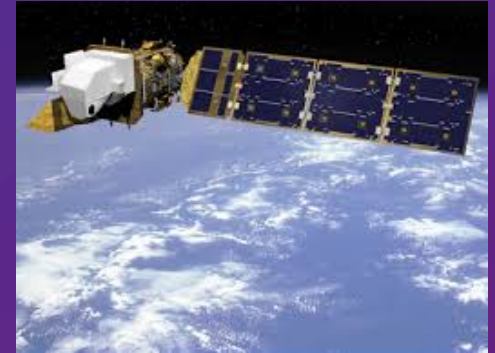


*Launch of Landsat 8, Vandenberg Air Force Base, February 2013*



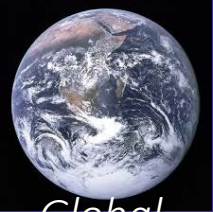
# Remote sensing in the Arctic

- Lots of challenges for observation
  - short summer
  - often cloudy
  - permafrost is a critical feature...but subsurface!
- Many legacy tools, and many new ones
  - can now monitor change over 50+ year period
  - new tools provide monitoring in near real-time





# Earth-observing satellites

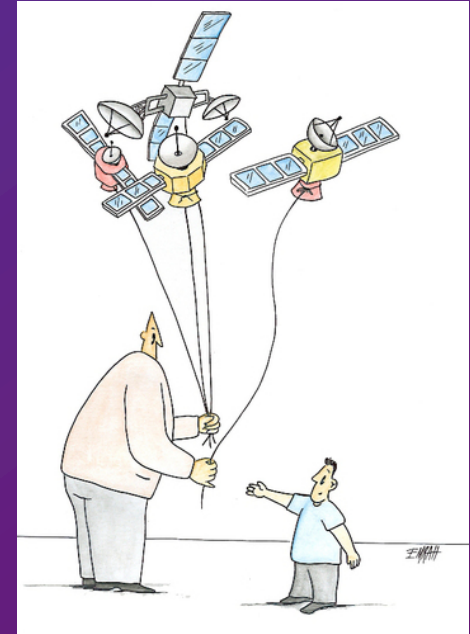


*Global*



*Local*

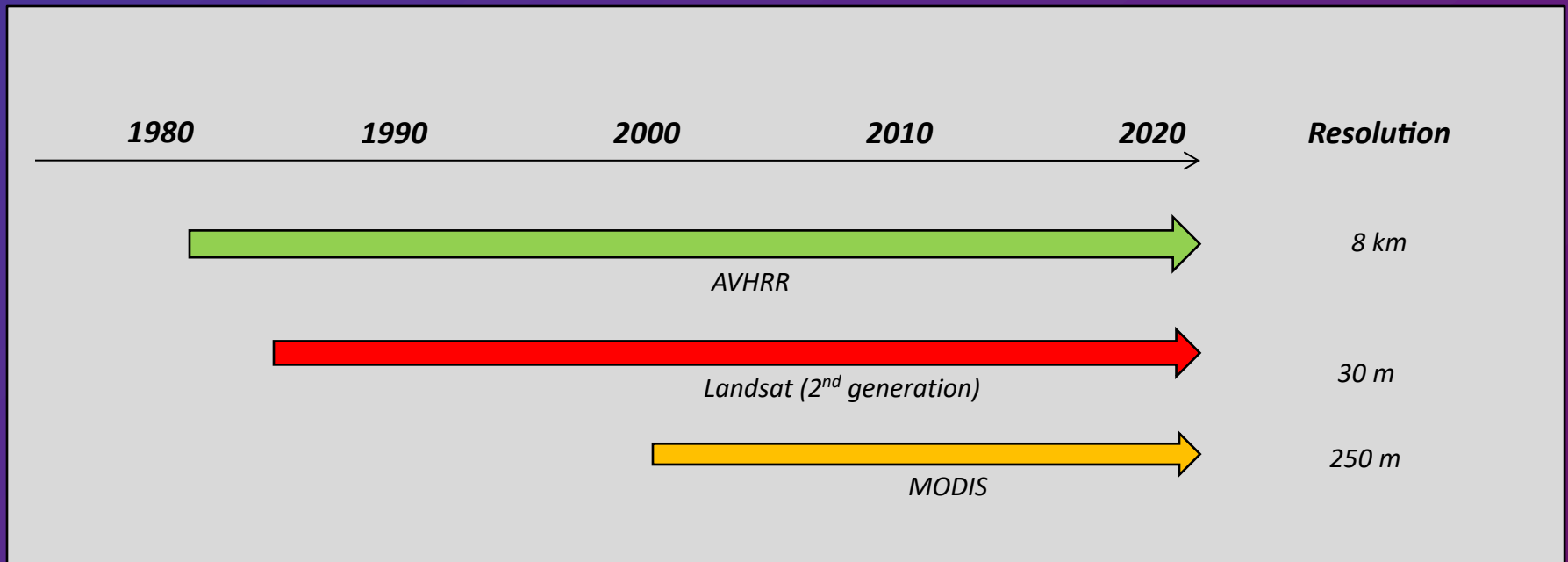
- AVHRR - 7 km
- MODIS - 240 m
- Landsat - 30 m
- High-res satellites – 1 m





# Satellite timeline

- Useful greenness observations began in 1982
- Each sensor has its own strengths (and weaknesses)
- Some observe entire Earth every day, but with lower resolution
- Others get “close looks,” but not every day





*How do we monitor “greenness” from space?*





# *Electromagnetic spectrum*





# *Electromagnetic spectrum*





# *Electromagnetic spectrum*





# "NDVI"







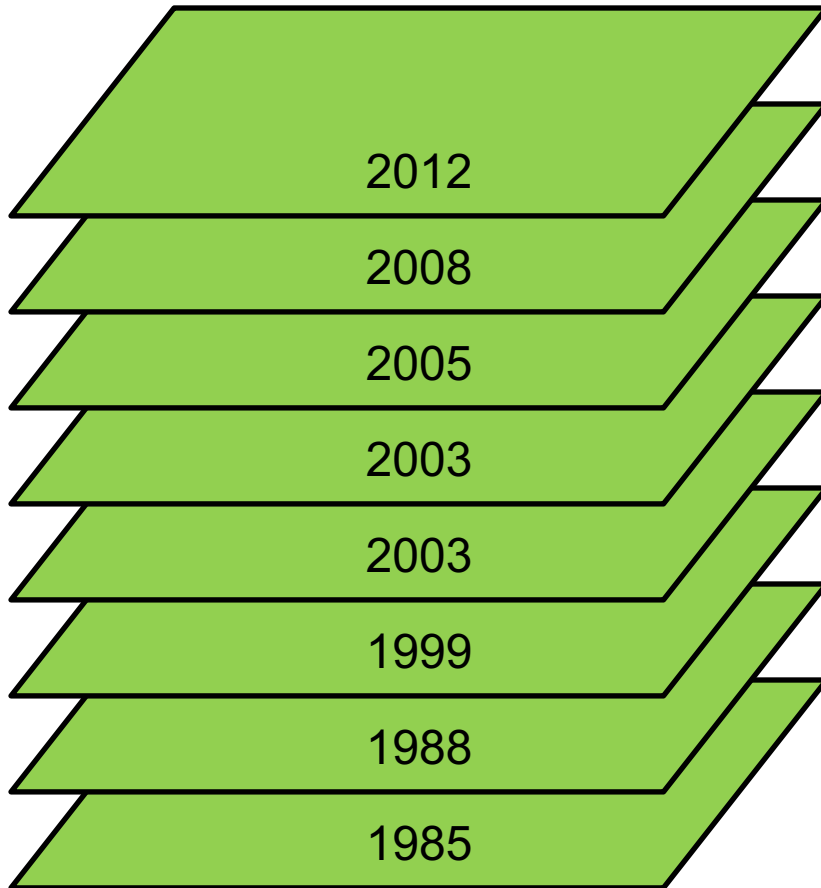
$NDVI =$   
*Normalized Difference Vegetation Index*



(NASA Global NDVI animation)

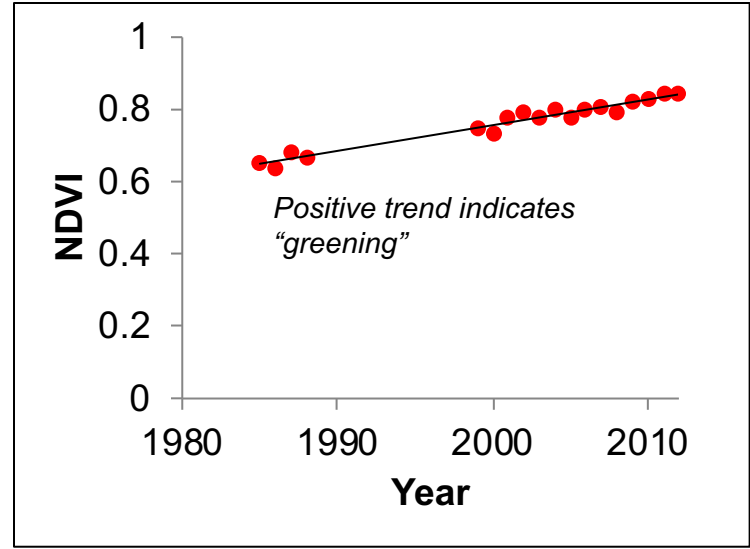
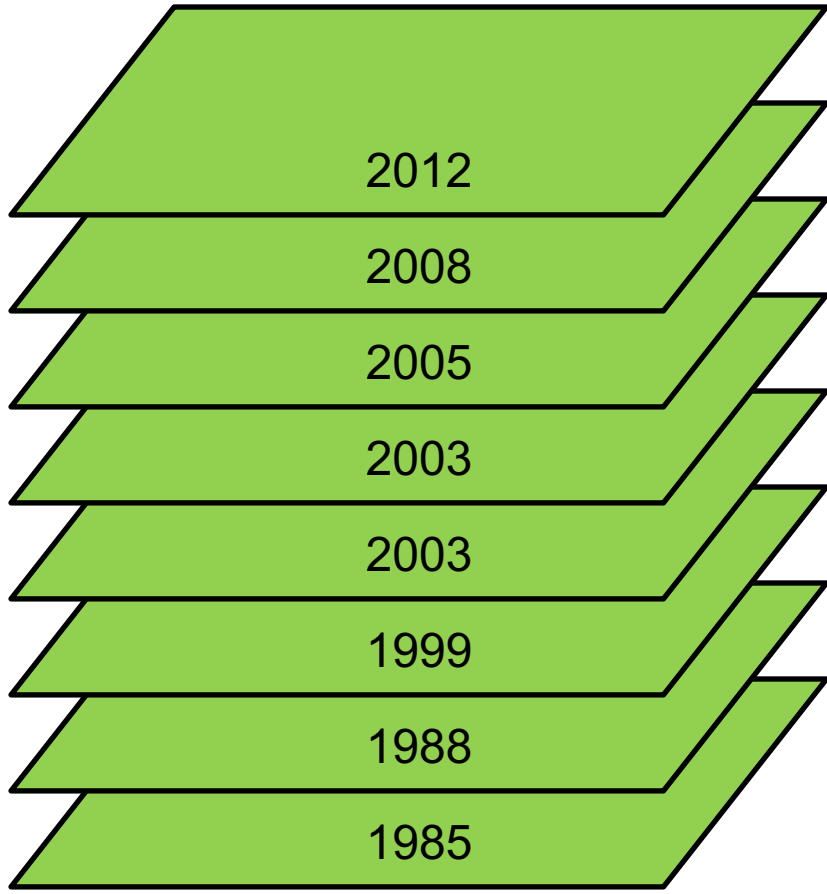


# Time-series analysis





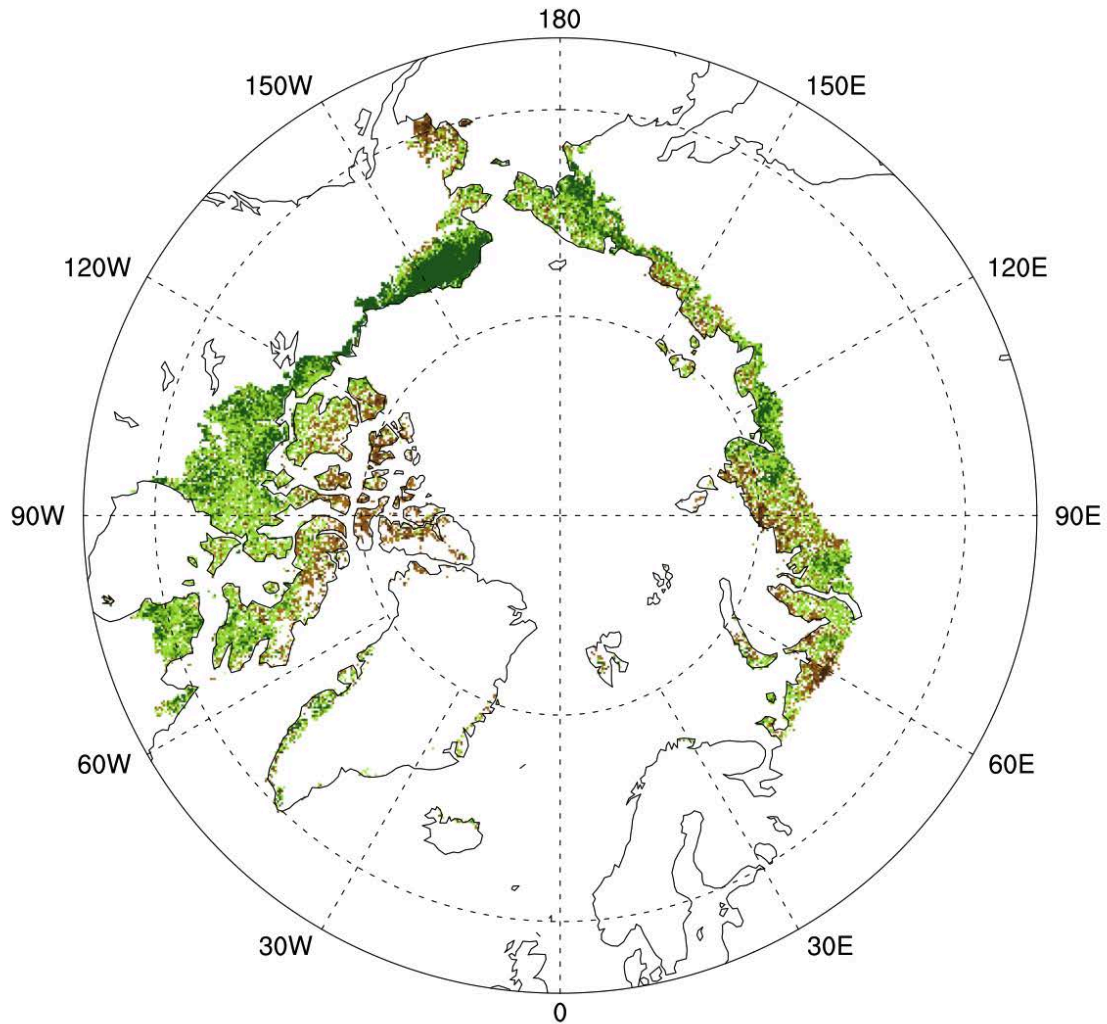
# Time-series analysis



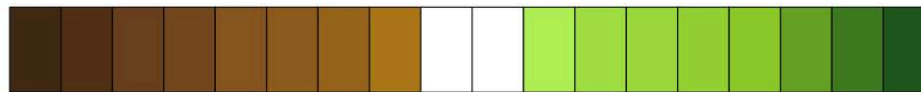
Scenes selected from 4-week period in mid-summer, when biomass is at its peak



# Greenness trends – seasonal peak (1982–2019)



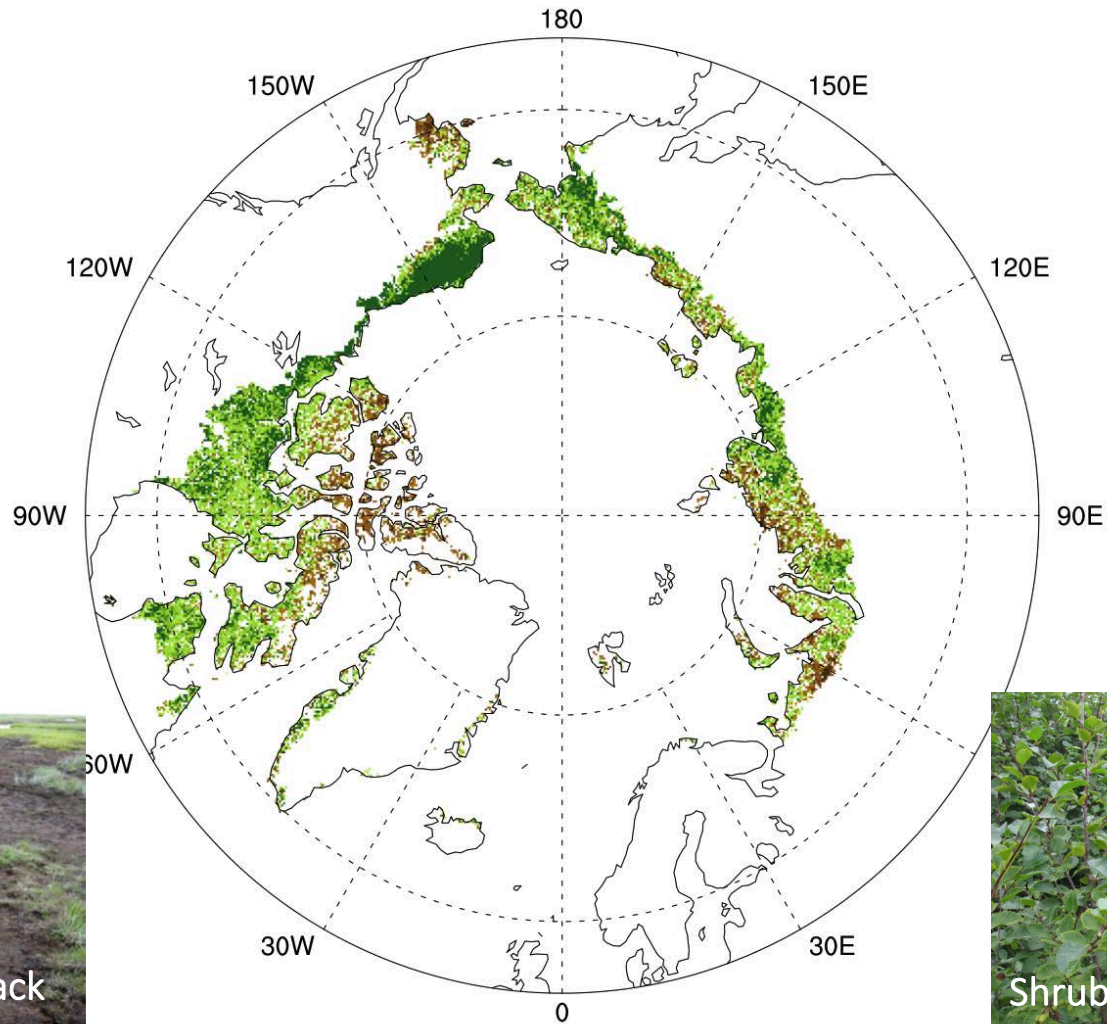
*“browning”*



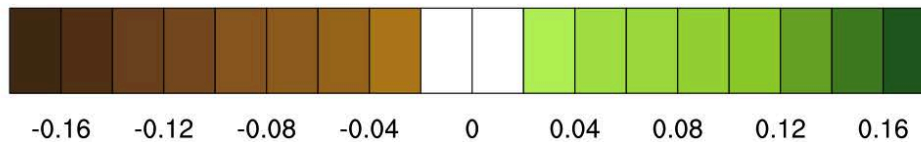
-0.16 -0.12 -0.08 -0.04 0 0.04 0.08 0.12 0.16

*“greening”*

# Greenness trends – seasonal peak (1982–2019)



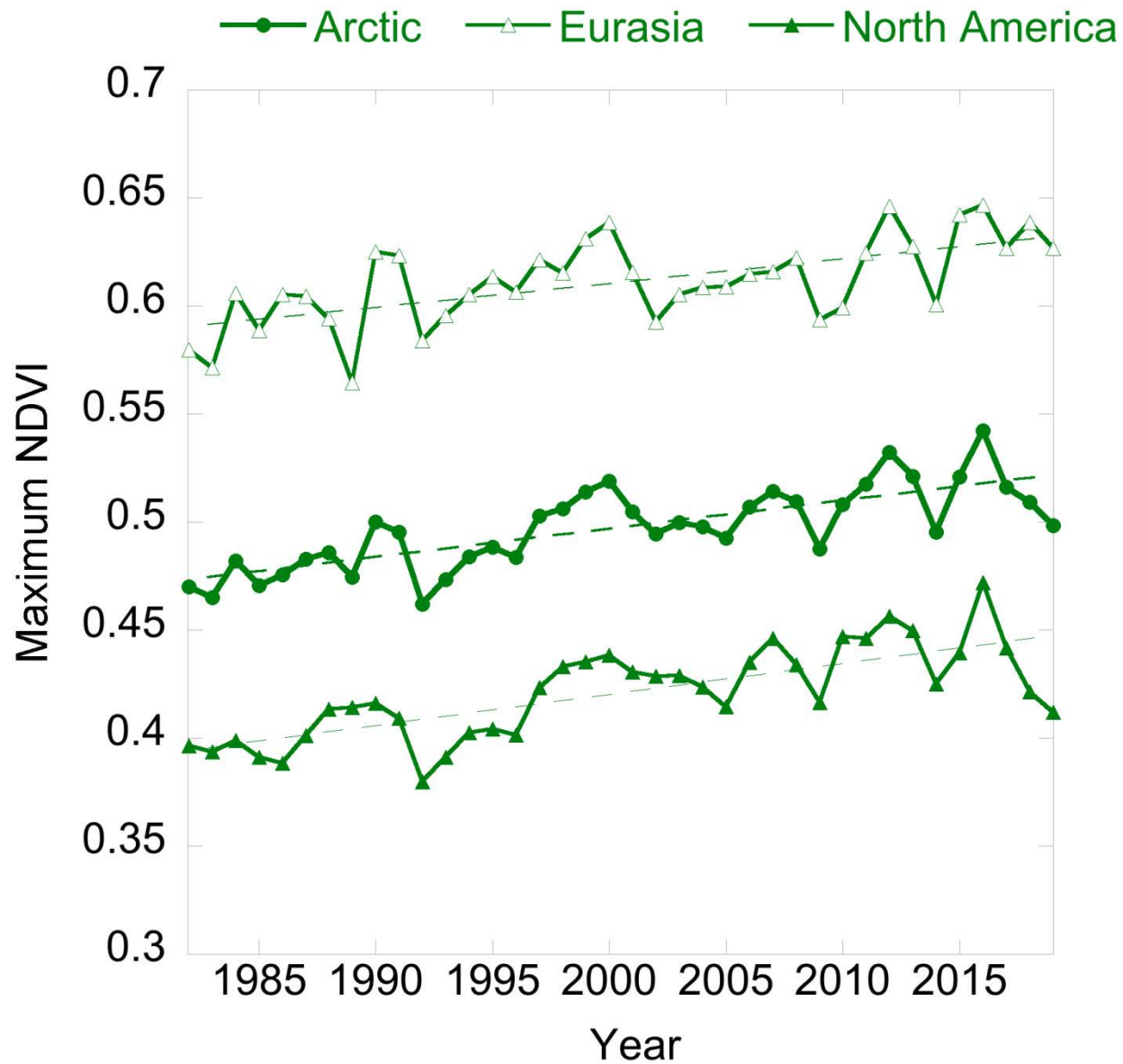
*“browning”*



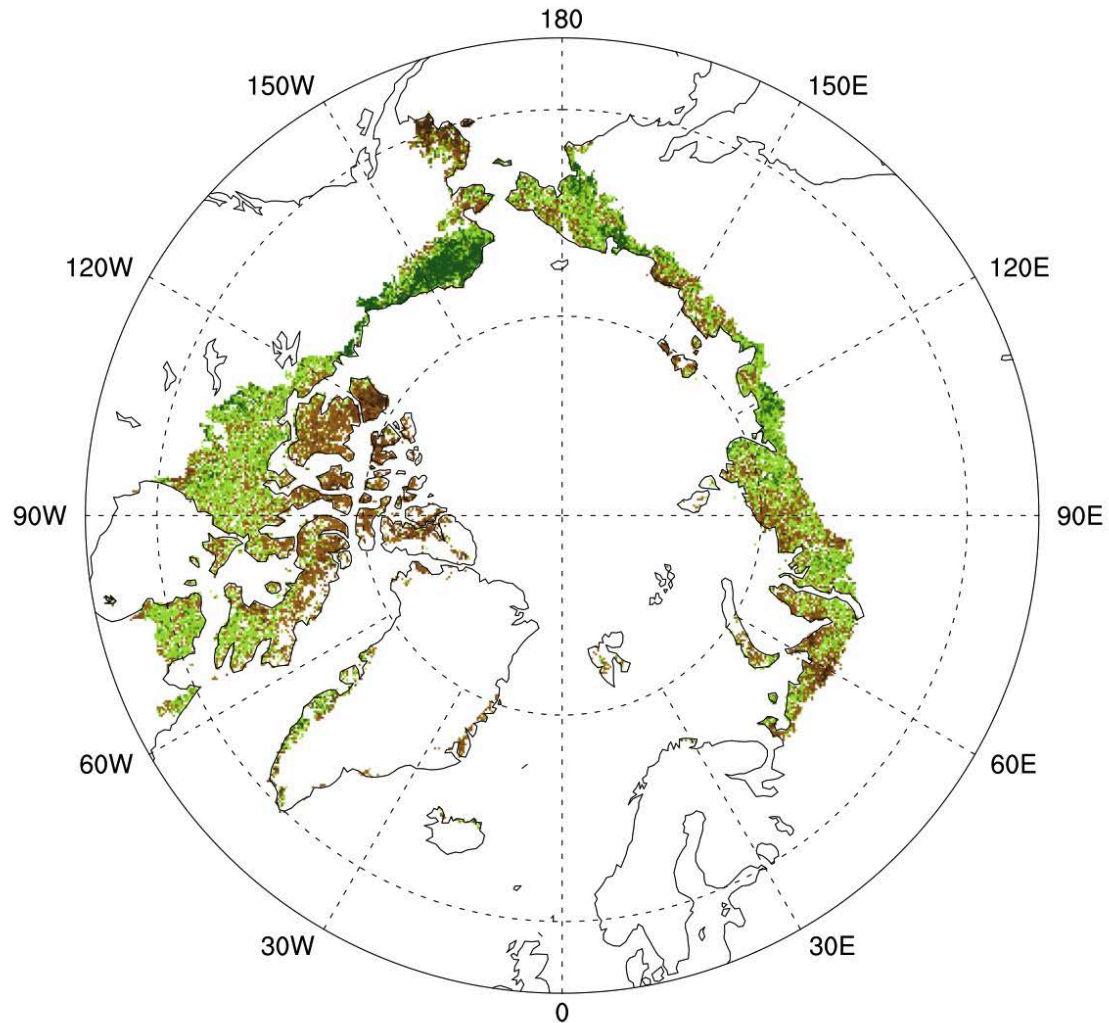
*“greening”*



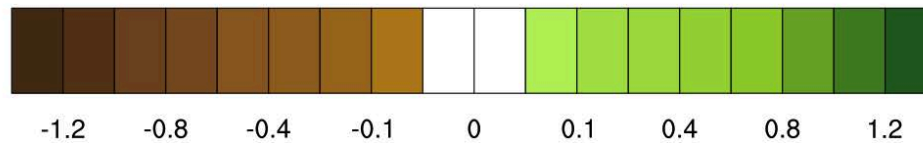
# Greenness trends – seasonal peak (1982–2019)



# Greenness trends – full season (1982–2019)



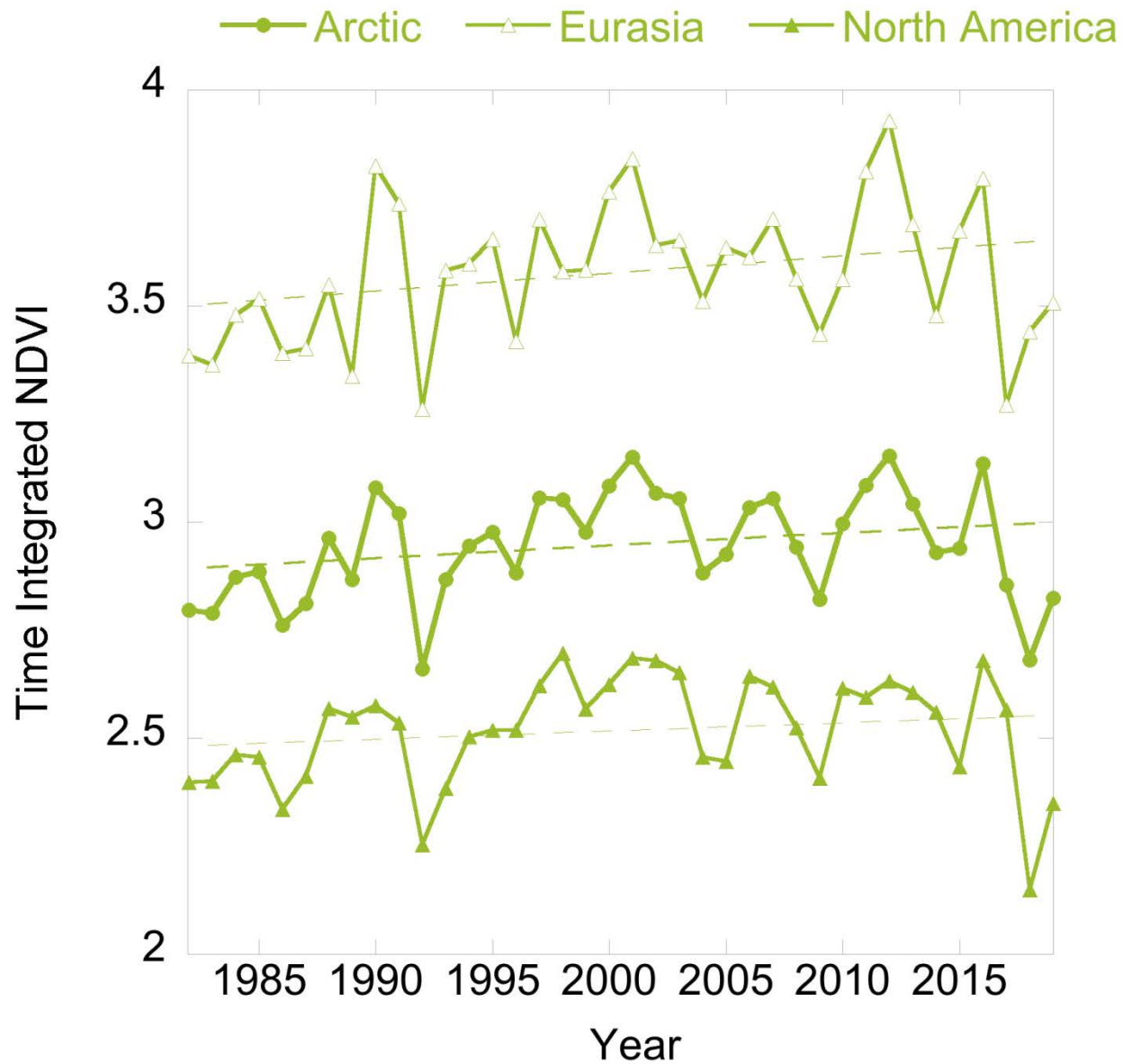
*“browning”*



*“greening”*



# Greenness trends – full season (1982–2019)



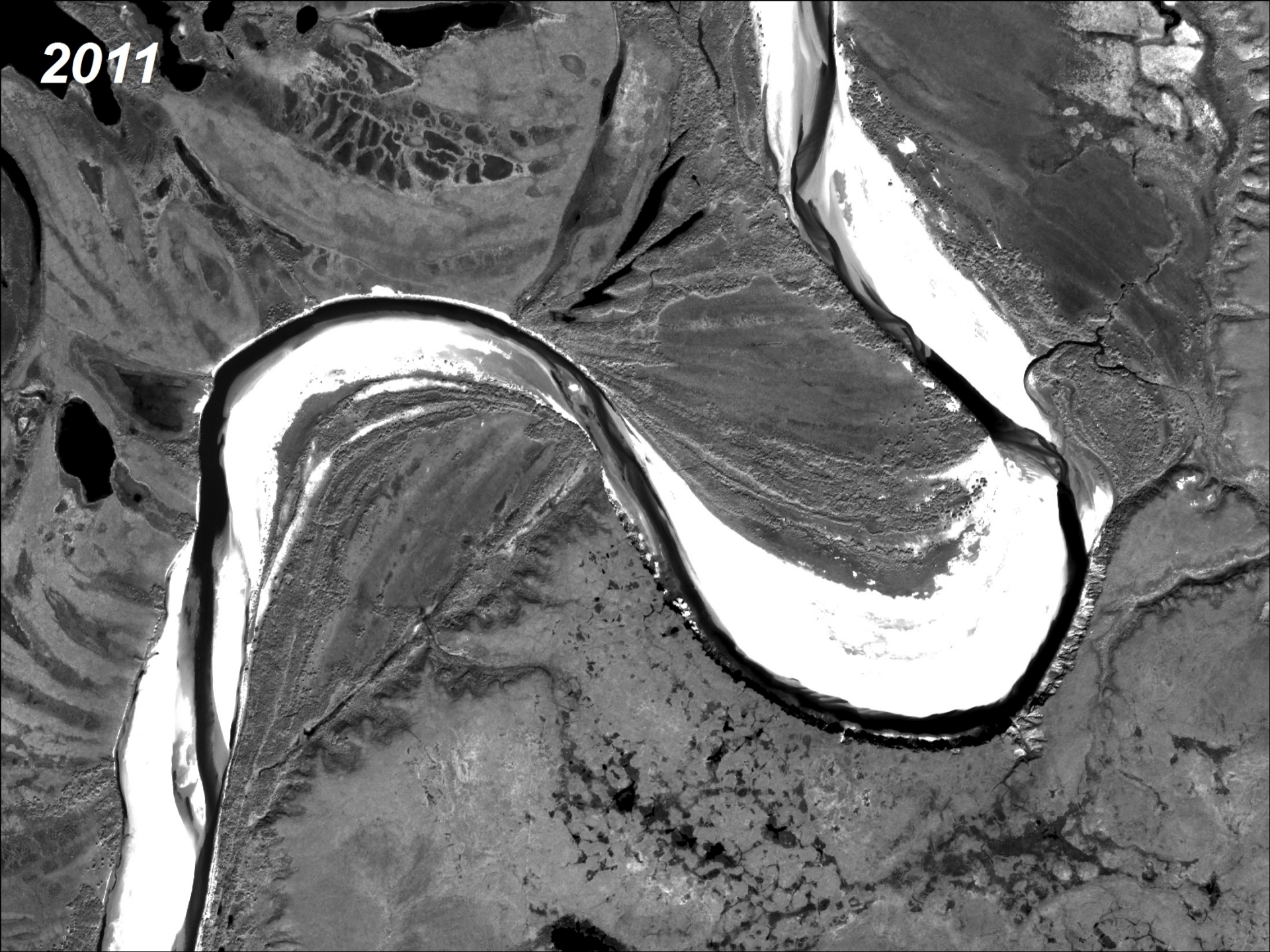
1968



How do NDVI trends relate to changes on the ground?

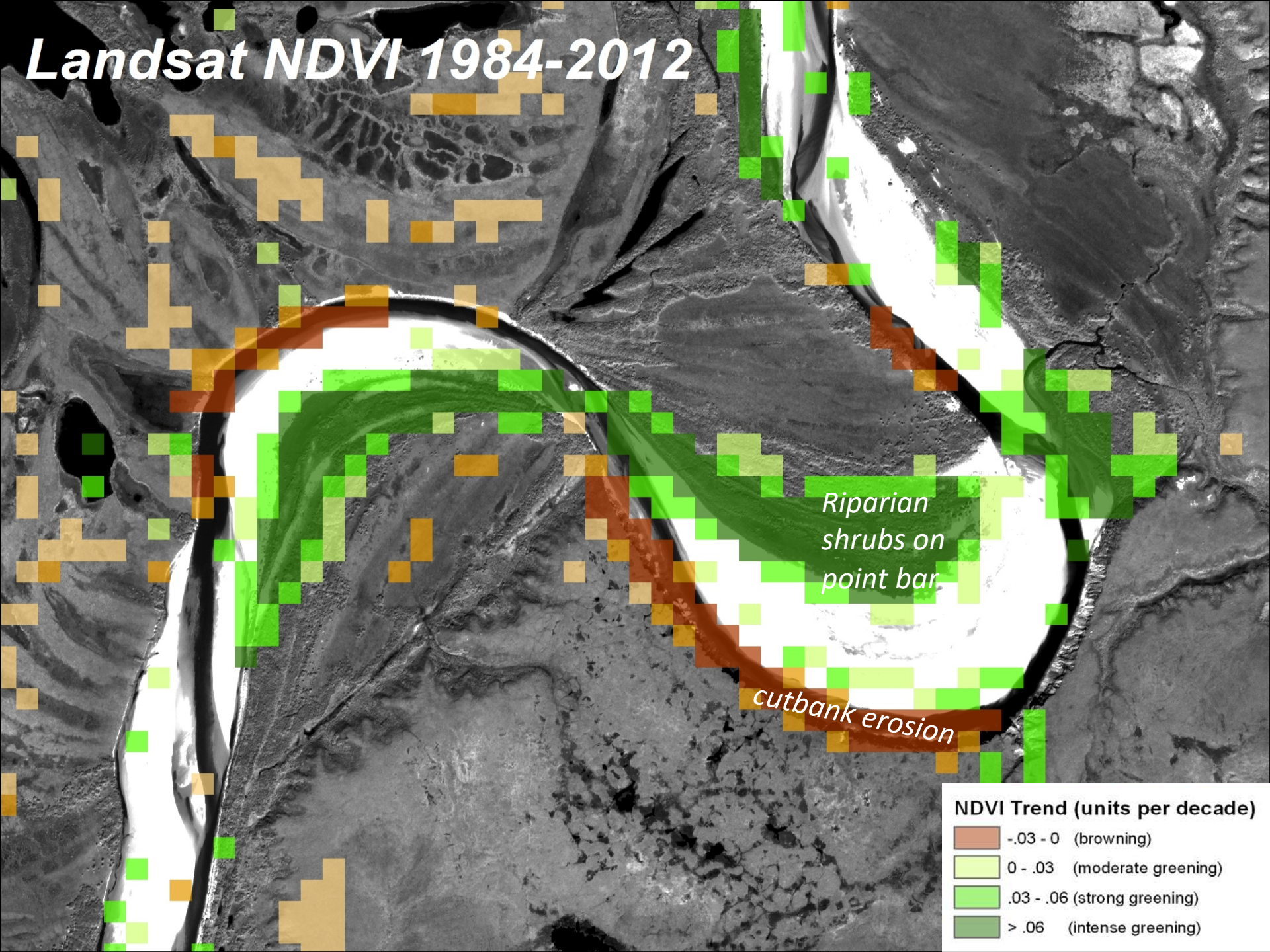


2011









# Landsat NDVI 1984-2012



*Riparian shrubs on point bar*

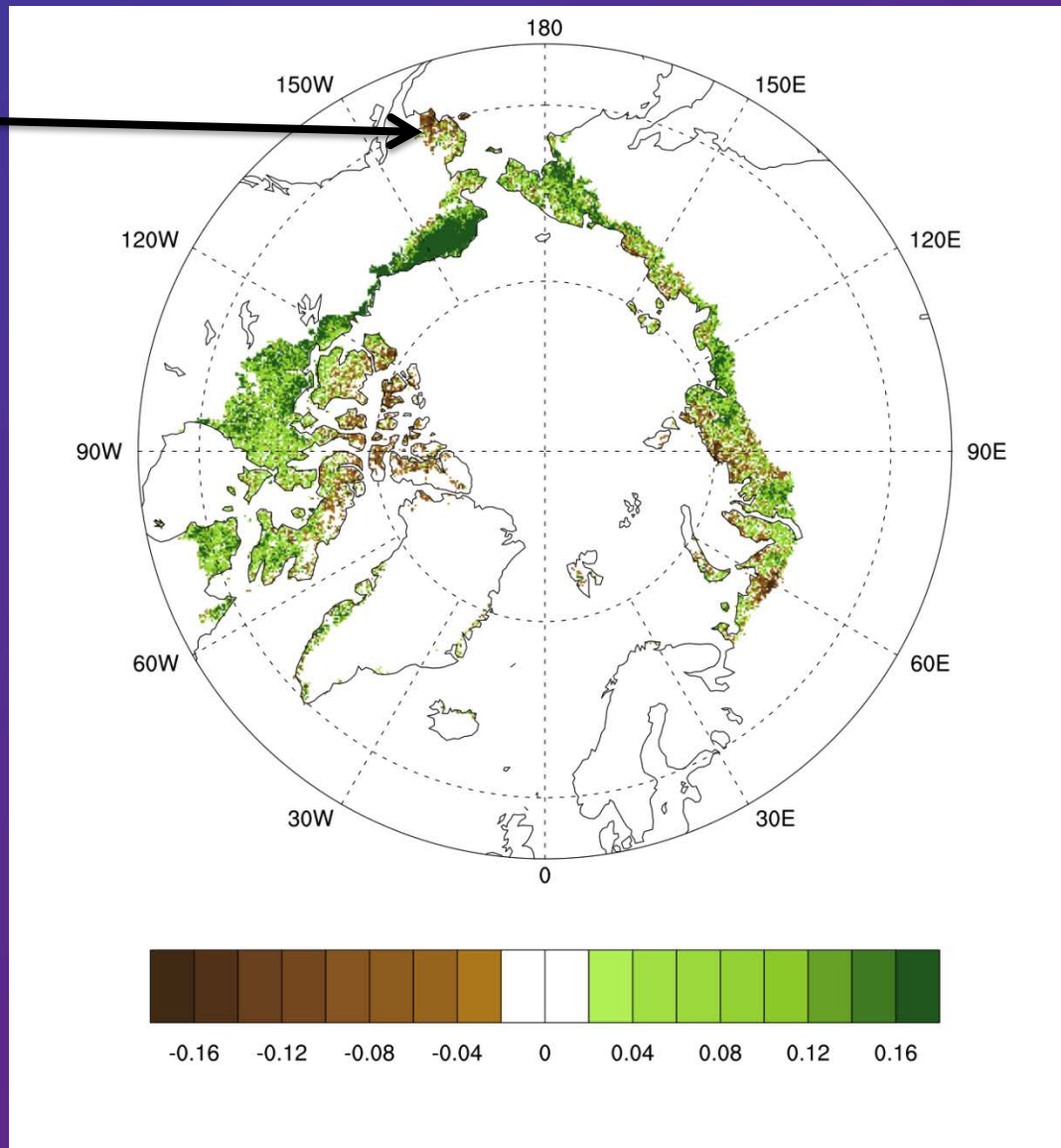
*cutbank erosion*

## NDVI Trend (units per decade)

-  -.03 - 0 (browning)
-  0 - .03 (moderate greening)
-  .03 - .06 (strong greening)
-  > .06 (intense greening)

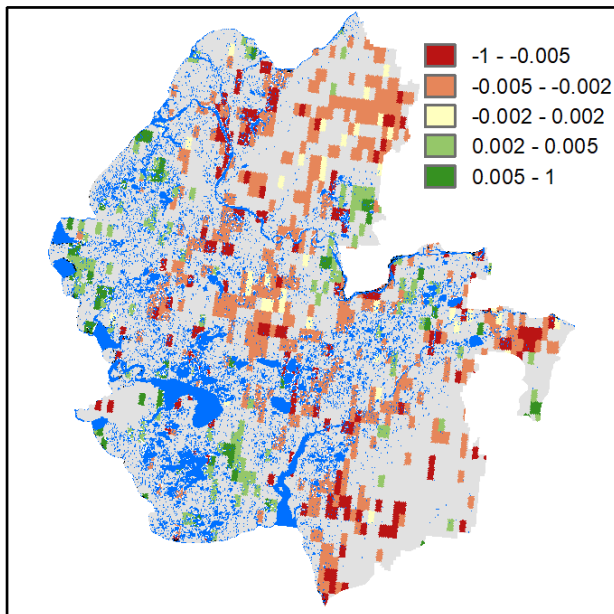


# How do satellite records compare?



# Comparison of peak greenness, YK Delta (2000–2018)

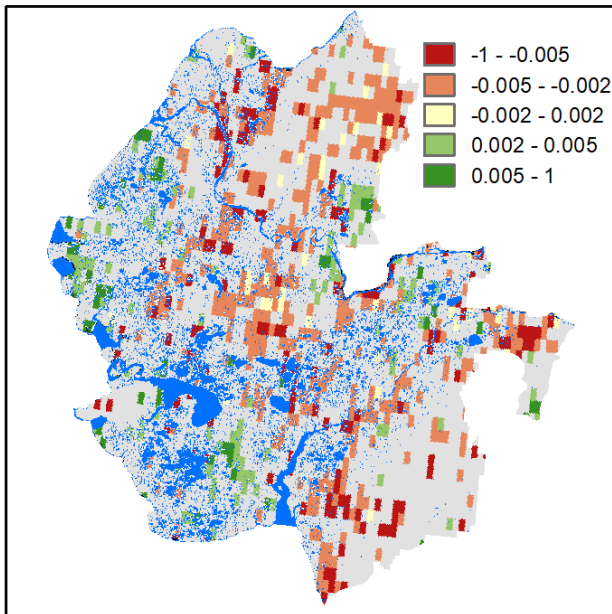
AVHRR GIMMS-3g+ MaxNDVI (~7 km)



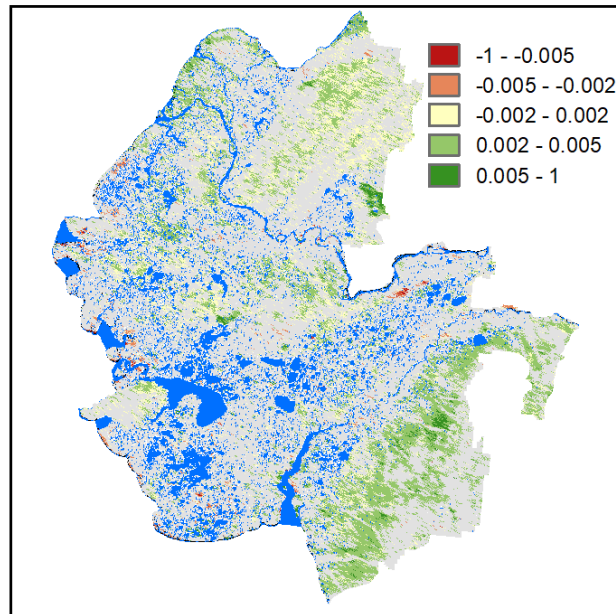


# Comparison of peak greenness, YK Delta (2000–2018)

AVHRR GIMMS-3g+ MaxNDVI (~7 km)

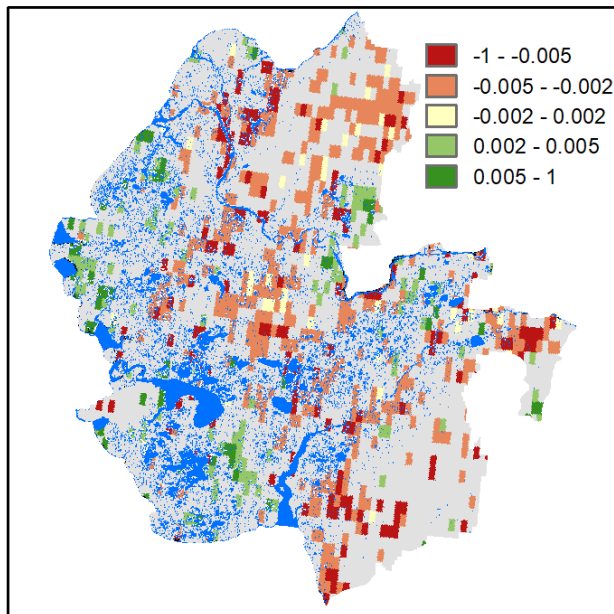


MODIS MCD43A4 MaxNDVI (480 m)

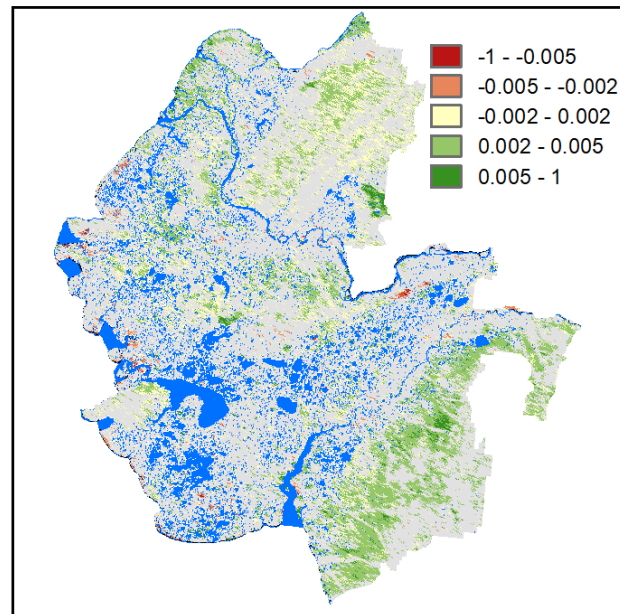


# Comparison of peak greenness, YK Delta (2000–2018)

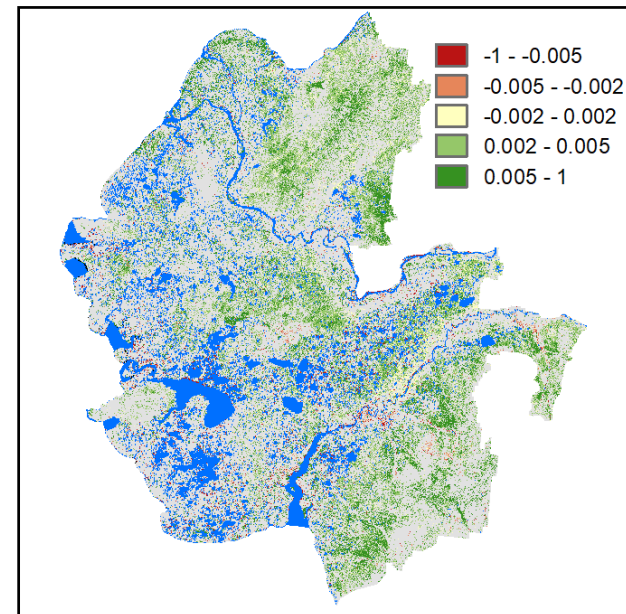
AVHRR GIMMS-3g+ MaxNDVI (~7 km)



MODIS MCD43A4 MaxNDVI (480 m)



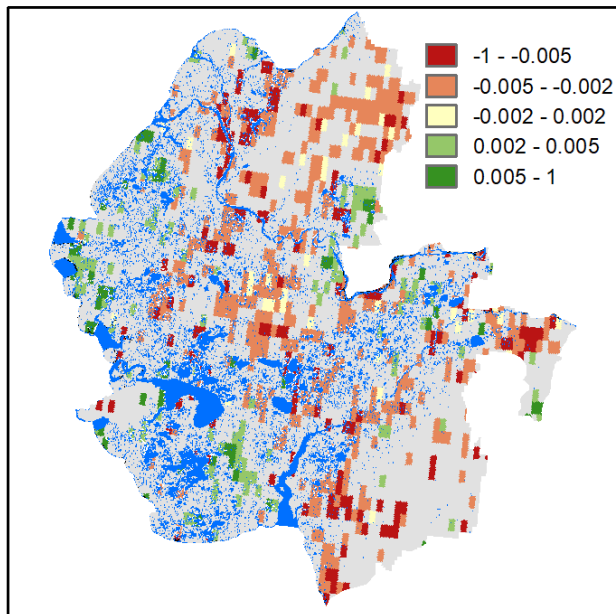
Landsat MaxNDVI (30 m)



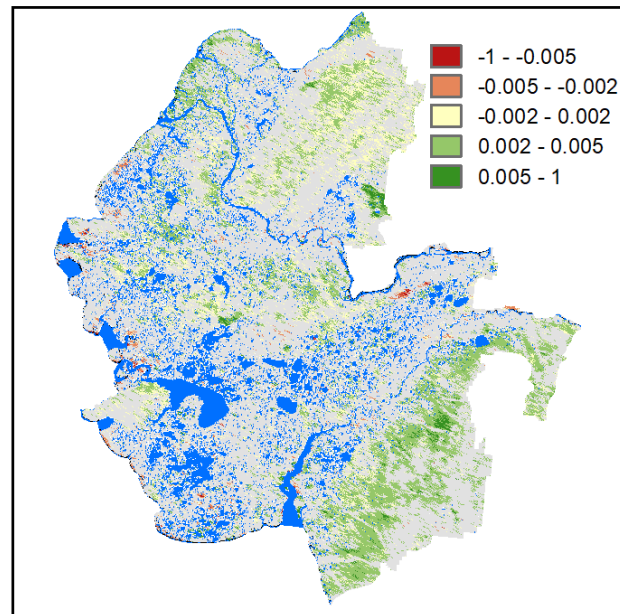


# Comparison of peak greenness, YK Delta (2000–2018)

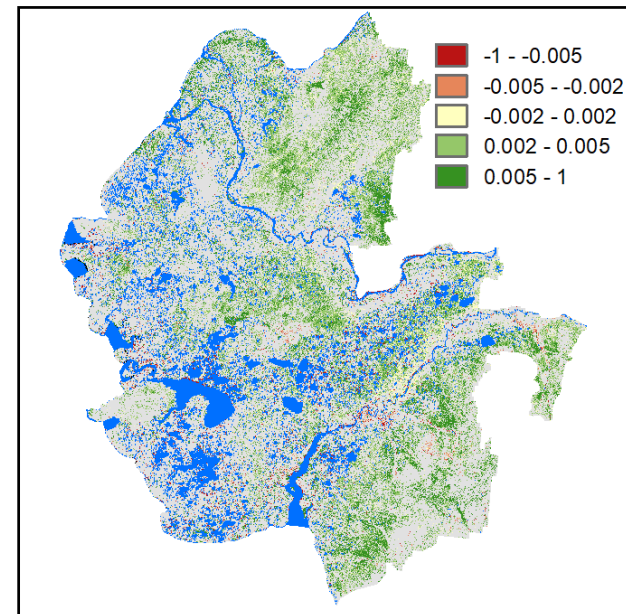
AVHRR GIMMS-3g+ MaxNDVI (~7 km)



MODIS MCD43A4 MaxNDVI (480 m)



Landsat MaxNDVI (30 m)



- More recent sensors suggest Arctic “greening” may be even more widespread than the AVHRR record indicates
- High-resolution remote sensing and field studies needed to identify landscape drivers

# High-resolution satellite observation

1990                      2000                      2010                      2020  
→

Proliferation of commercial  
satellites began in 1999...

**IKONOS** →

**QuickBird** →

**WorldView-1** →

**GeoEye** →

**WorldView-2** →

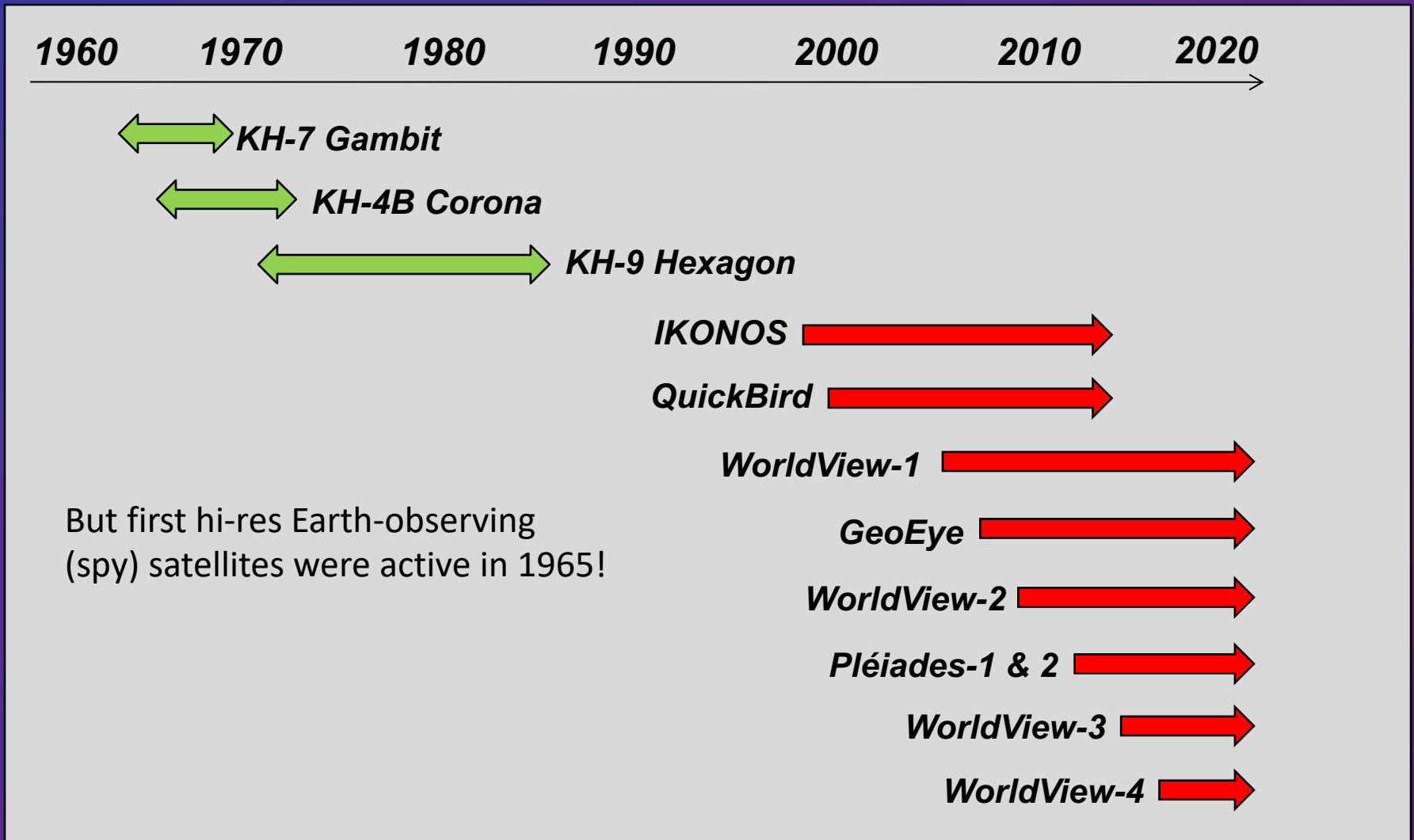
**Pléiades-1** →

**WorldView-3** →

**WorldView-4** →



# High-resolution spaceborne observations





- Cold War-era surveillance heralded beginning of modern remote sensing
- worldwide coverage
- high resolution (0.75 – 2 m)
- allows detection of land-cover change over last 55 years

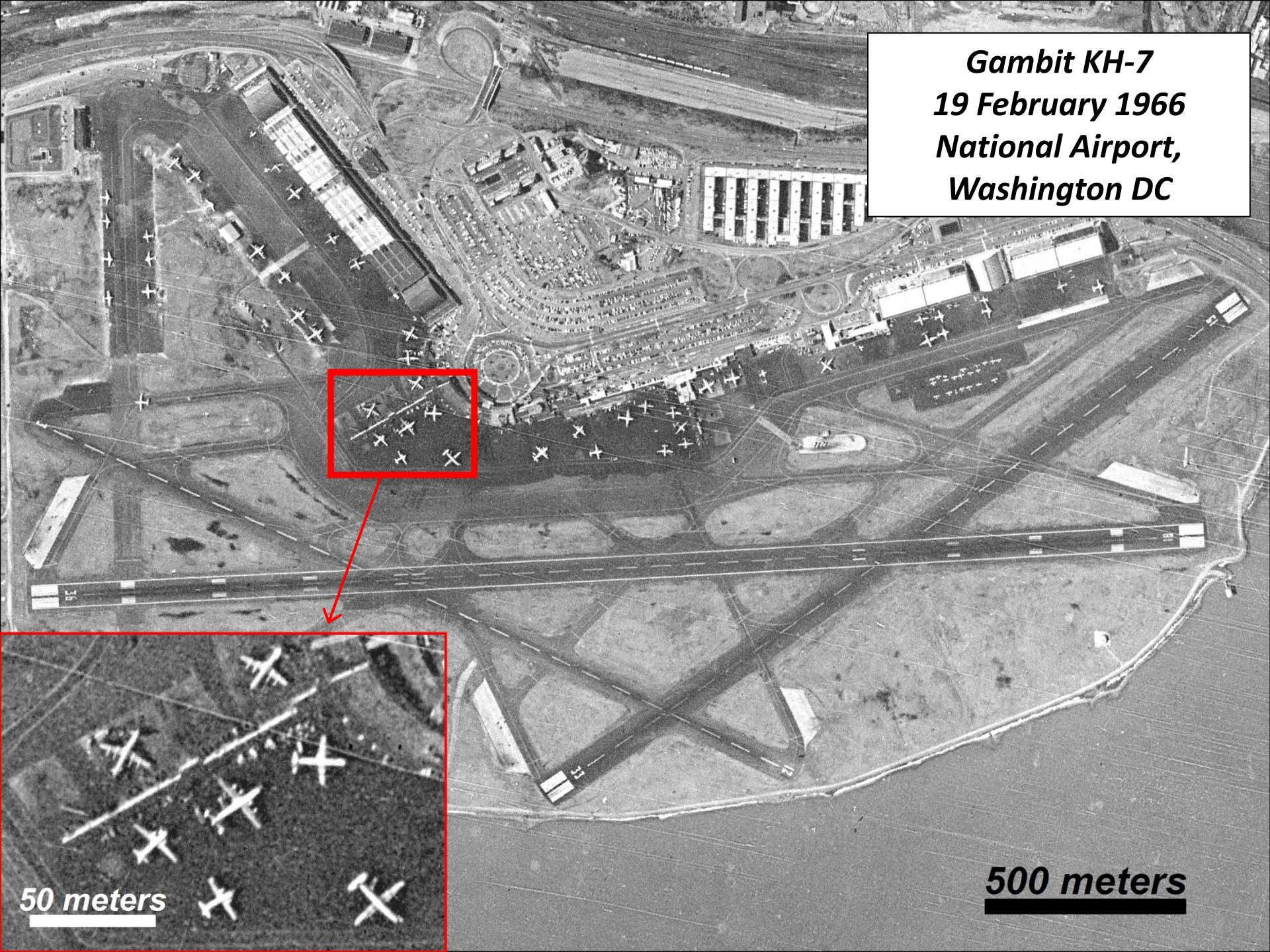
C  
O  
R  
O  
N  
A

LAUNCH & RECOVERY SEQUENCE





***Gambit KH-7  
19 February 1966  
National Airport,  
Washington DC***



**50 meters**

**500 meters**



***Gambit KH-7***  
***15 July 1966***



***100 meters***

***Frost and Epstein 2014, Global Change Biology***

***Western Taymyr Peninsula***





**GeoEye-1**  
**9 July 2009**

100 meters

*Frost and Epstein 2014, Global Change Biology*

**Western Taymyr Peninsula**



*Gambit KH-7*  
*15 July 1966*

100 meters

Western Taymyr Peninsula




***Corona KH-4B***  
***21 August 1968***

***250 meters***



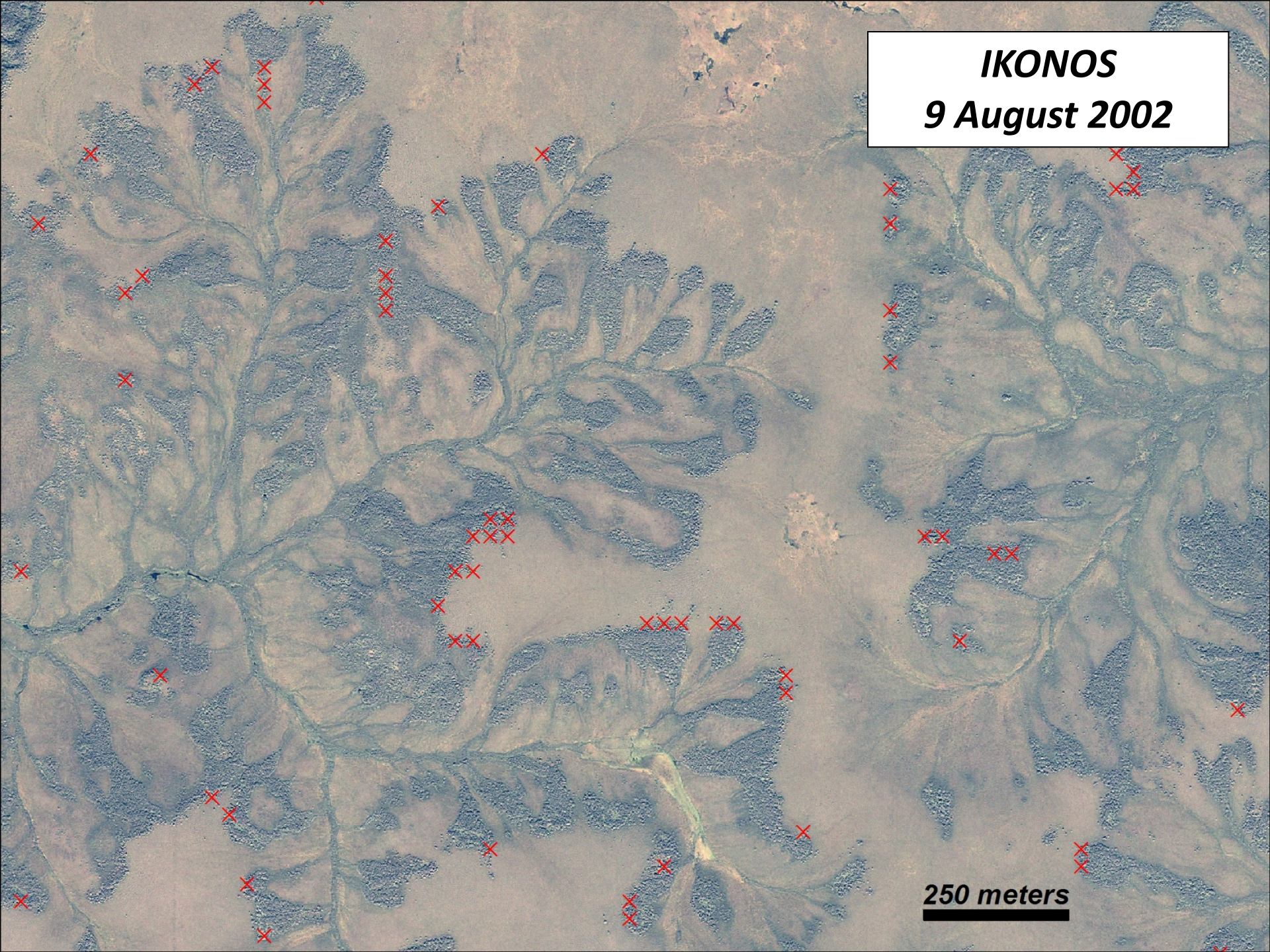
**IKONOS**  
**9 August 2002**

**250 meters**

This is a satellite image from the IKONOS mission, dated August 9, 2002. The image shows a complex river delta system with numerous channels and distributaries. The terrain is characterized by a mix of light brown and tan colors, suggesting a mix of soil types and vegetation. A prominent channel runs vertically down the left side of the image, branching out into a dense network of smaller channels. In the lower right quadrant, there is a distinct, bright green area, likely representing a wetland or a specific type of vegetation. A scale bar in the bottom right corner indicates a length of 250 meters.



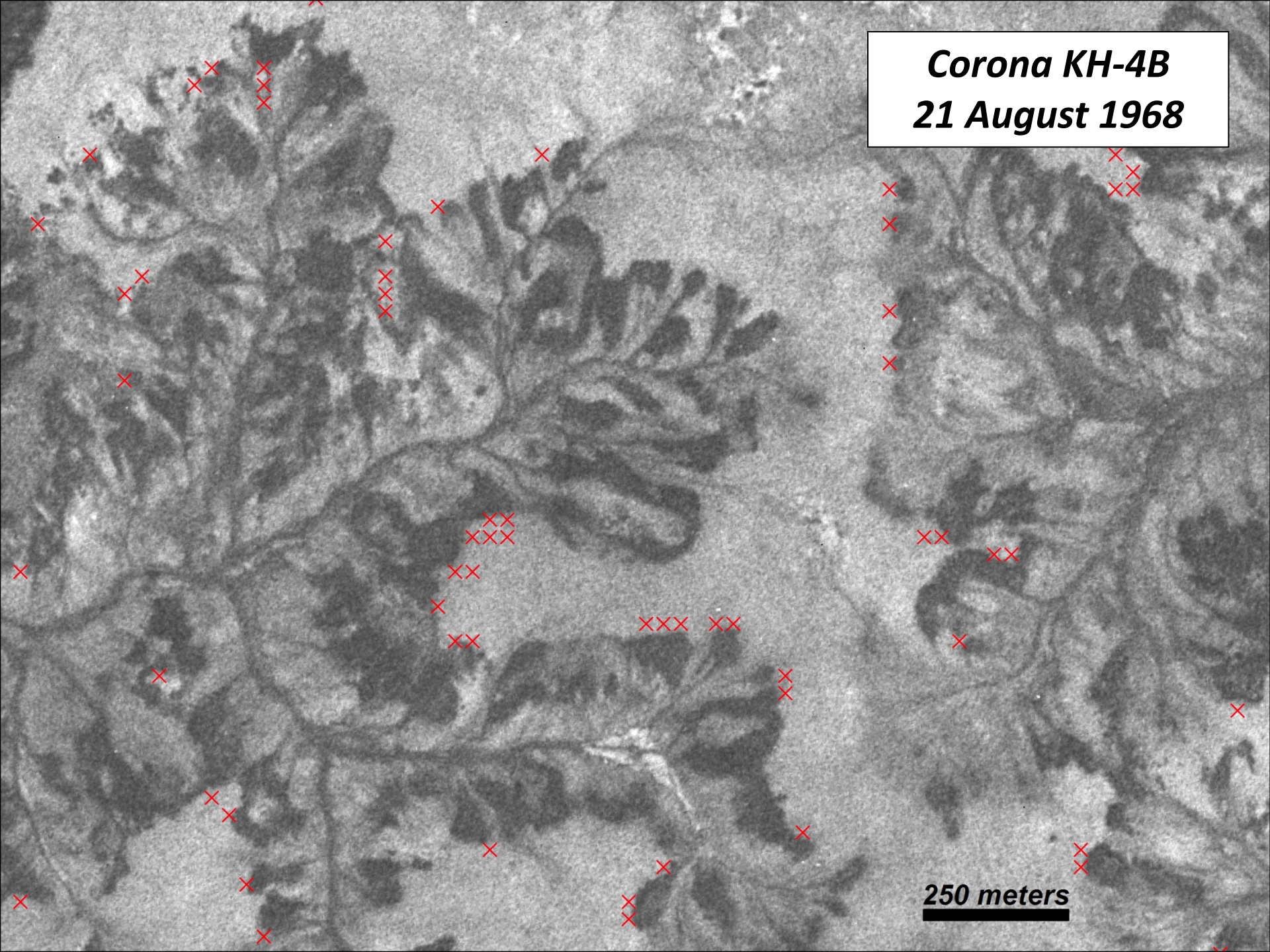
**IKONOS**  
**9 August 2002**



**250 meters**



**Corona KH-4B**  
**21 August 1968**



**250 meters**





# Scenes from the field







***Crossing the S'ob River***

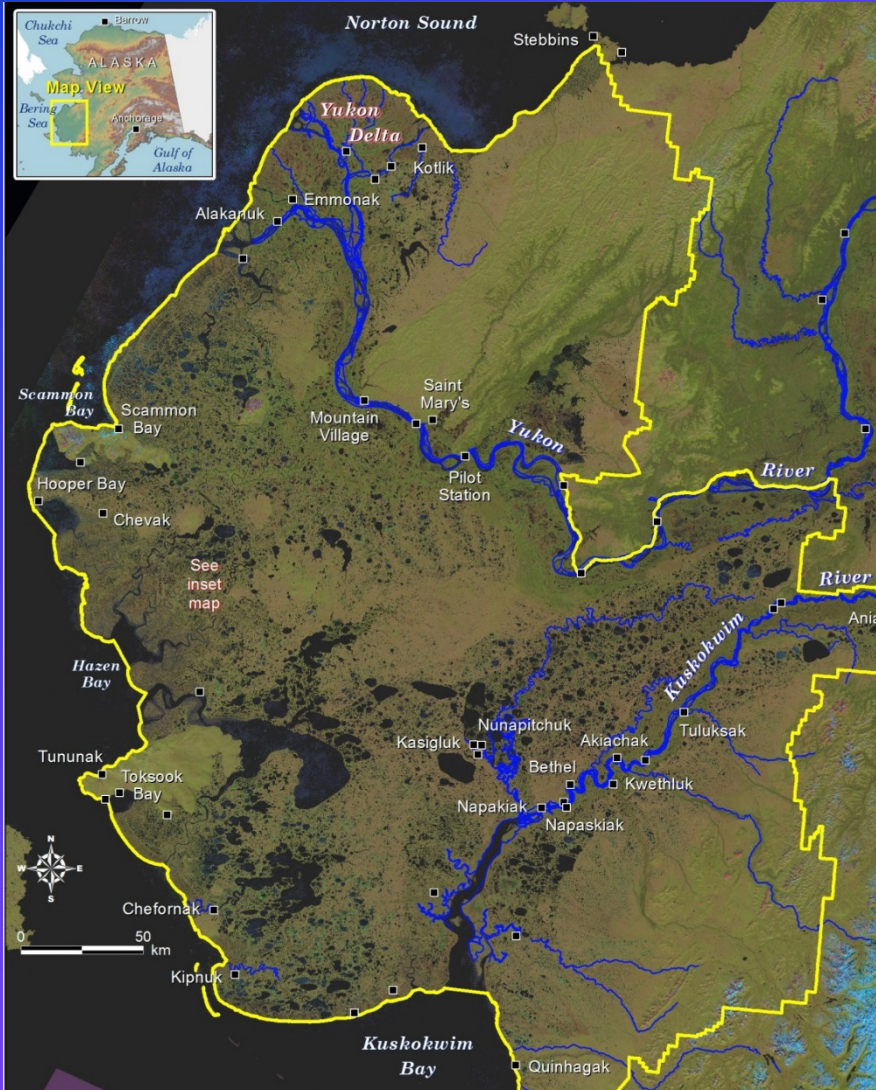




***Crossing the S'ob River***



# YK Delta region



- 35 villages
- ~30,000 Yup'ik people
- 70% below 30 m elevation
- Bethel mean annual temp = -2°C
- 19 million acre refuge

Circumpolar Arctic Region  
Bioclimate Subzones

- Zone A
- Zone B
- Zone C
- Zone D
- Zone E
- Non-Arctic  
Glaciers

180°

0 500 1000 1500 2000  
Kilometers

Lambert Azimuthal Equal Area Projection  
Longitude of origin: 2130°, Latitude of origin: 90°

Derived from: CAVM Team. 2003. Circumpolar Arctic Vegetation Map. (1:7,500,000 scale). Conservation of Arctic Flora and Fauna (CAFF) Map No. 1. U.S. Fish and Wildlife Service, Anchorage, Alaska.

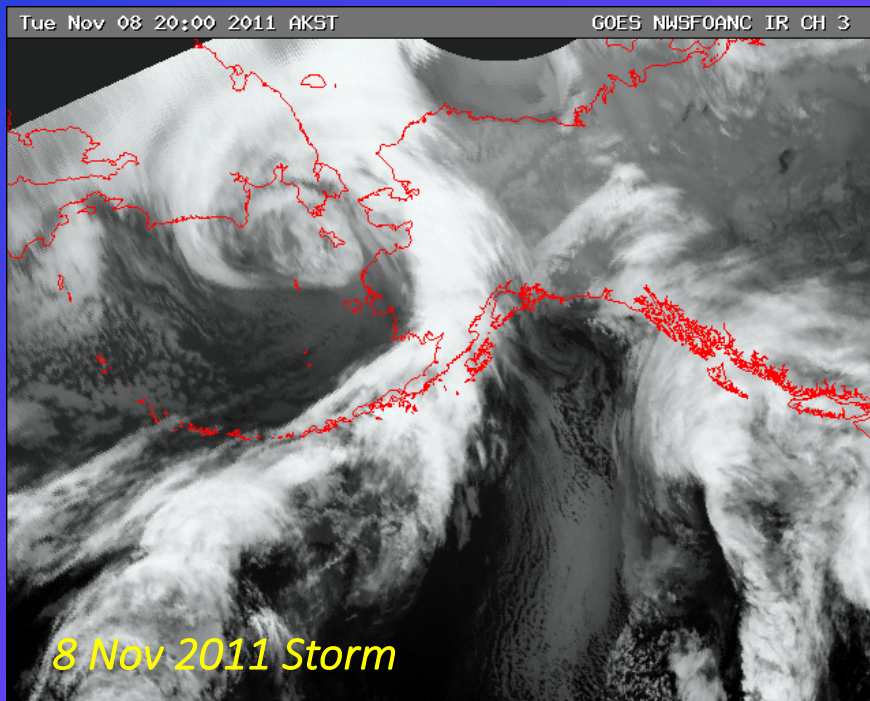
Northwest Arctic Borough

“...the delta is the most important shorebird nesting area in the country...[and the] most important wetland for post-breeders shorebirds on the west coast of North America” - USFWS



# Vulnerability to Climate Change

## Storms and Sea Level Rise



## Permafrost Thaw



YKD especially vulnerable to “tipping points” around elevation and temperature thresholds.



# Communities & Infrastructure



*Kasigluk, AK*



*Newtok, AK*

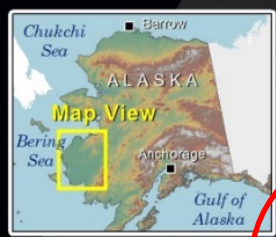
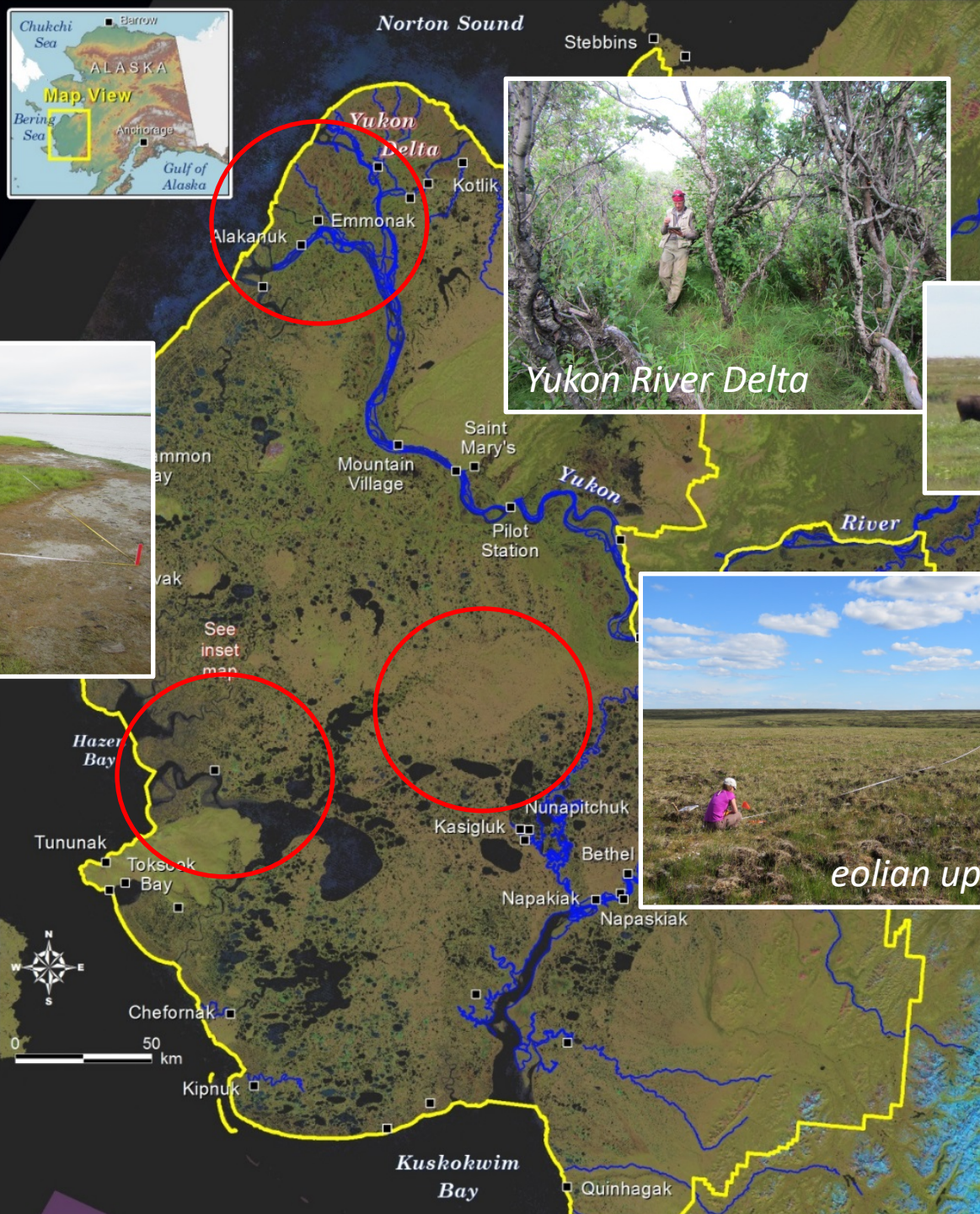


*Bethel, AK*

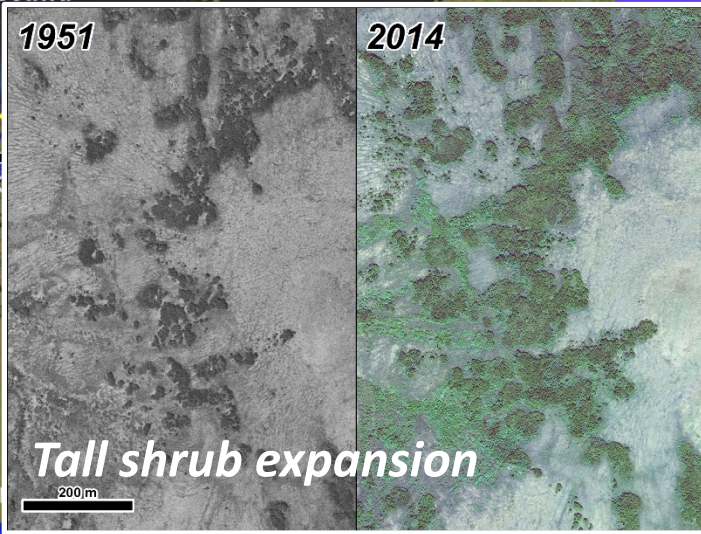
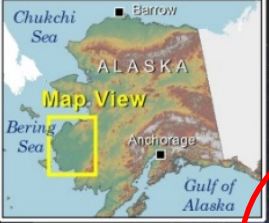
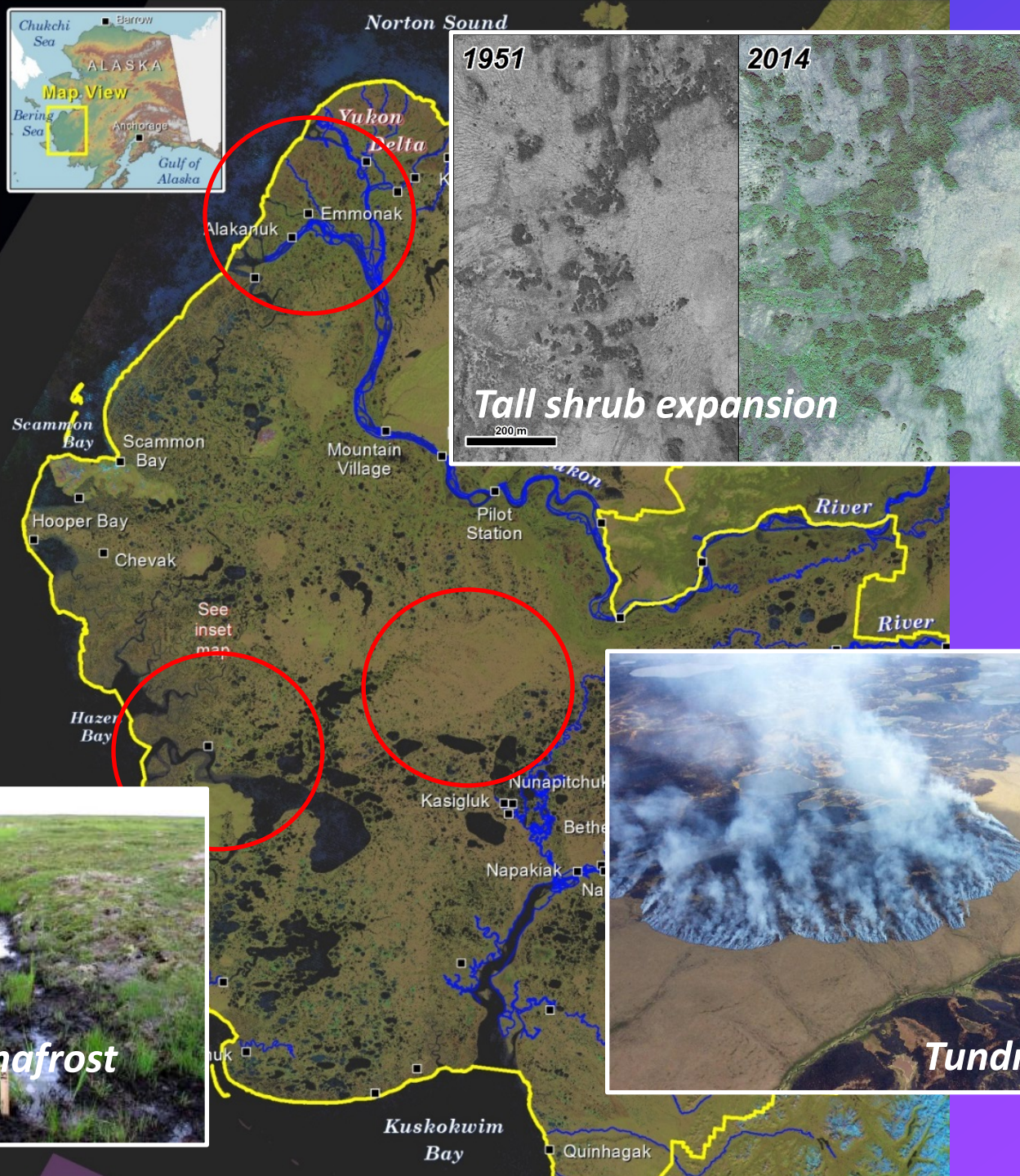


Ten villages on Alaska's Y-K Delta face "imminent threat from flooding and erosion" (GAO 2009)







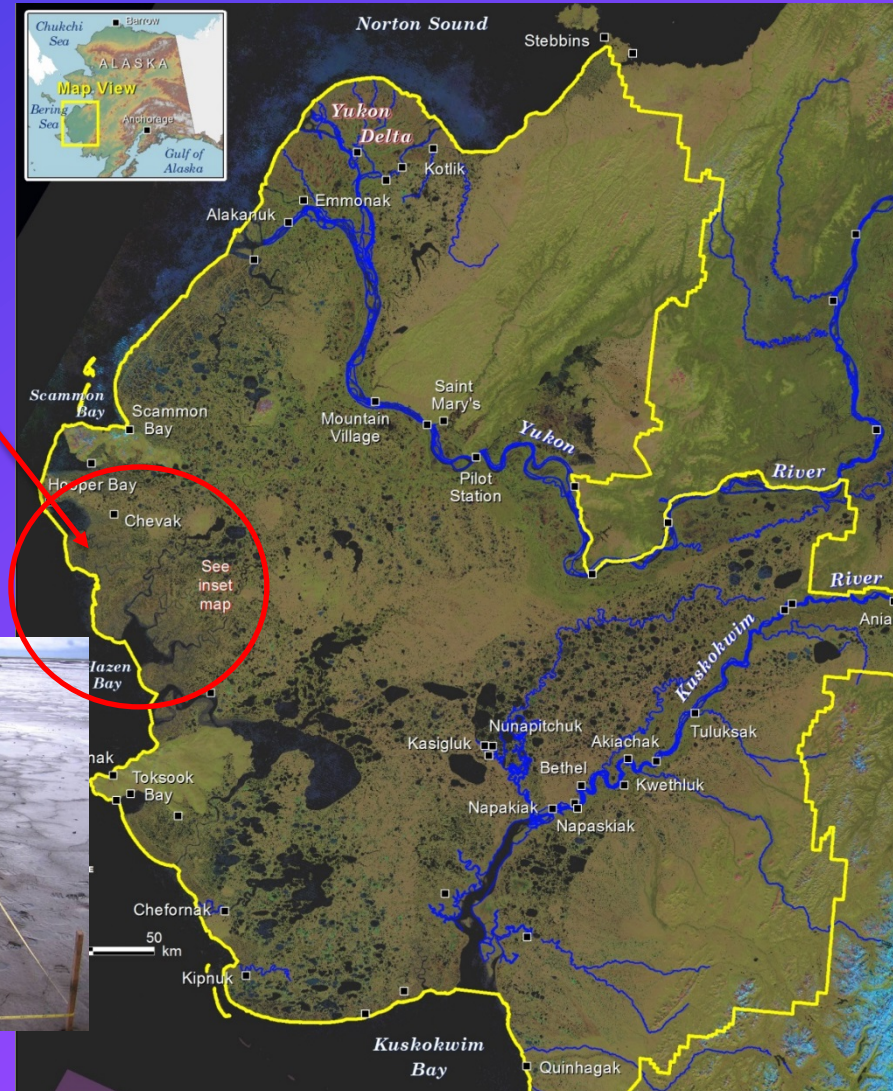




# Field Studies: from pixels to plants

Long-term monitoring transects (1994, 2005, 2016)

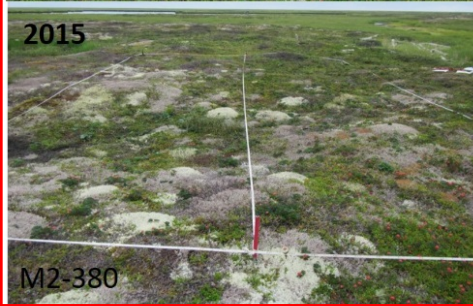
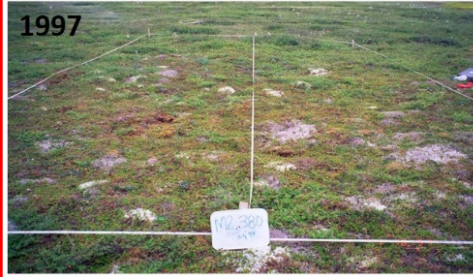
- Vegetation point-intercept
- Surface elevation
- Soils
- Thaw depth





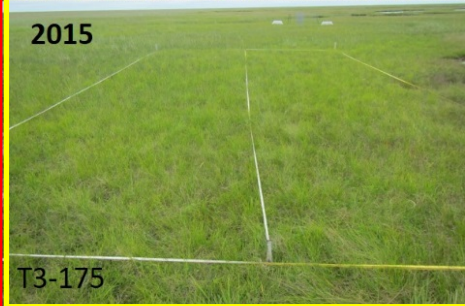
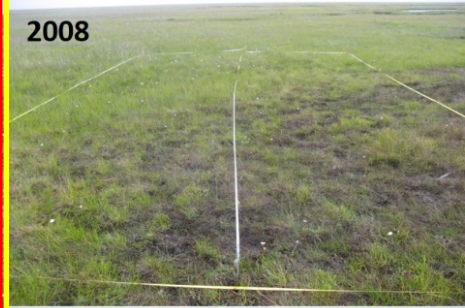
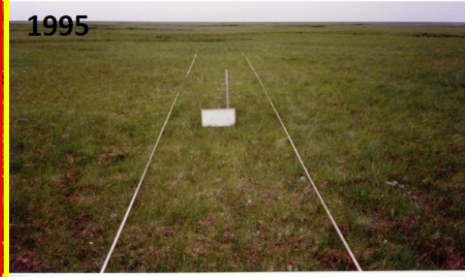
# Field Studies

Lowland Moist Birch-  
Ericaceous Low Shrub



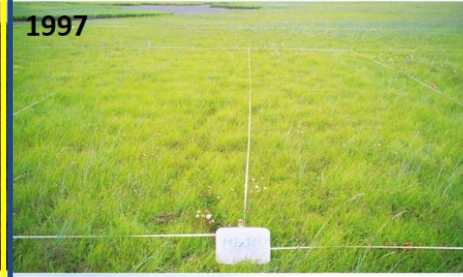
Salt-killed dwarf birch after  
2005 storm, later lichen  
expansion

Coastal Brackish Wet  
Sedge-Shrub Meadow



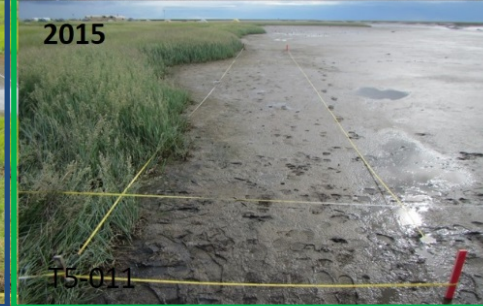
Salt-killed meadow after  
2005 storm, later *Carex  
ramenskii* sedge  
expansion

Coastal Saline Wet  
Sedge Meadow



Bank erosion along the  
Manokinak tidal river

Coastal Saline Fringe Wet  
Graminoid Meadow



Smothering of halophytic  
sedges after 2005 storm, no  
recovery



# Permafrost on the Delta

- Segregation ice in the soil raises ground surface enough to support mesic vegetation
- Positive feedback loop between elevation, vegetation cover, and permafrost
- Permafrost creates elevated plateaus



*after Whitley et al., 2018*





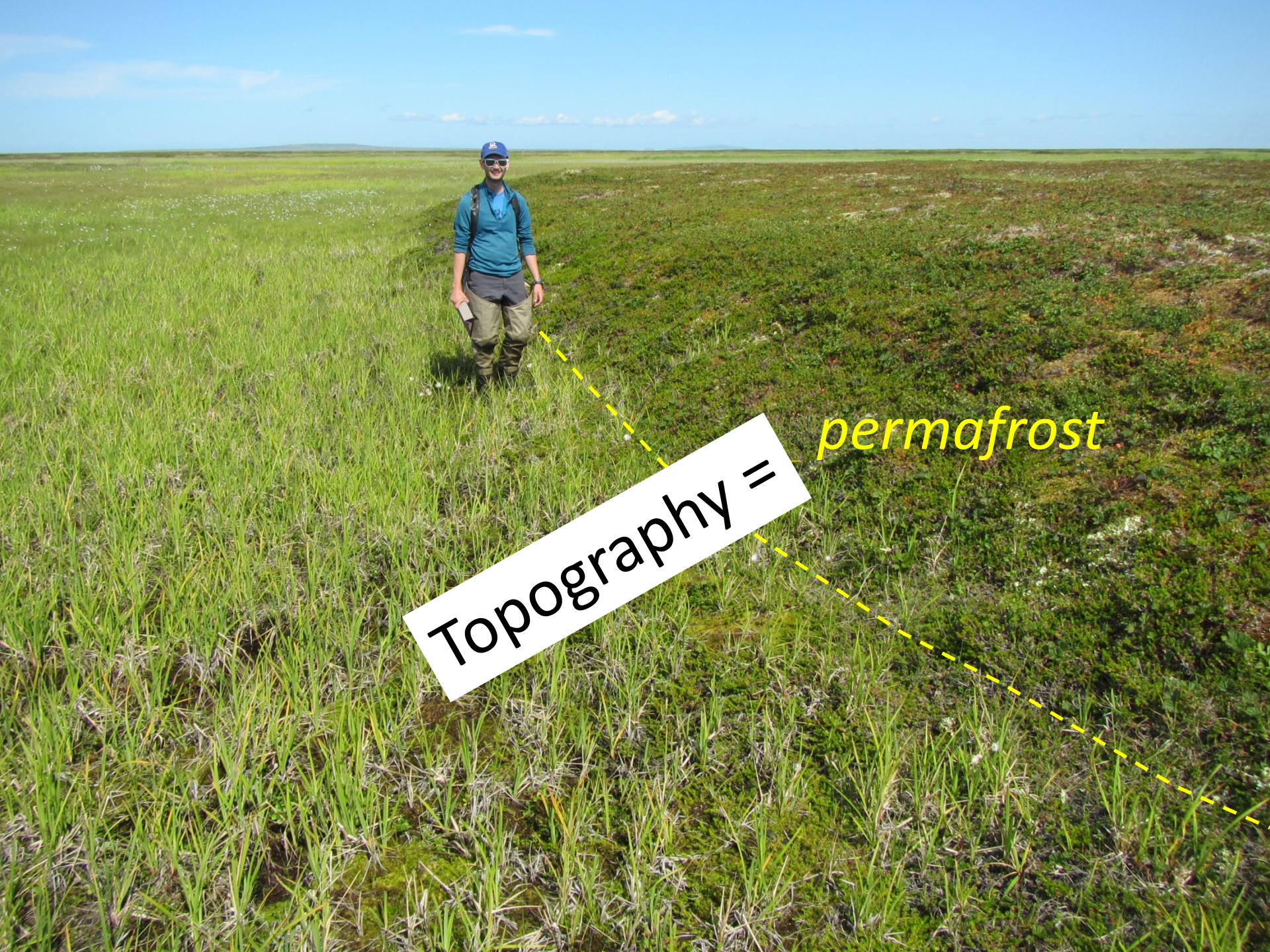




*non-permafrost*

*permafrost*





Topography =

*permafrost*

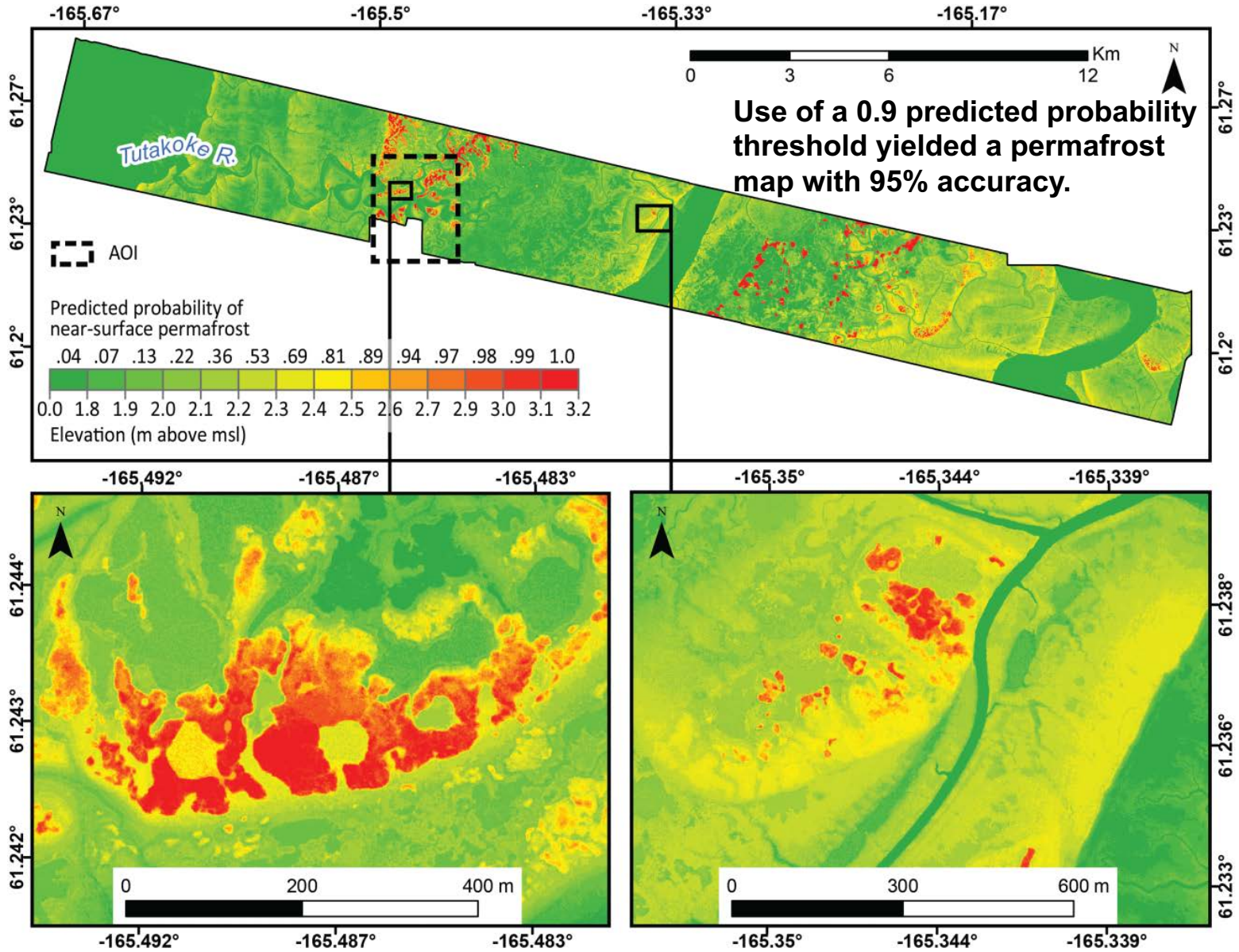


1. Field data collection
2. Extract elevations from remote sensing data
3. Make a map!
4. Validate the map using the field data.





# Probability of permafrost occurrence





# Impacts to People

- Berry crop
  - *Rubus chamaemorus*  
(Cloudberry)
  - *Empetrum nigrum*  
(Crowberry)
- Access to fresh water
- Loss of seasonal camps
- Loss of cultural sites





# Impacts on animals

- Bristle-thighed Curlew (*Numenius tahitiensis*)
- Entire global population uses YKD for staging prior to 6,000 km nonstop transpacific migration
- Stage on YKD permafrost plateaus to fatten up on berries





# Societal Impacts of Change



*NASA YK Delta Knowledge Exchange Meeting, Bethel, AK 16 November 2018*



# Societal Impacts of Change

“One change doesn’t make things harder. Many together will.”  
- James Ayuluk, Chevak

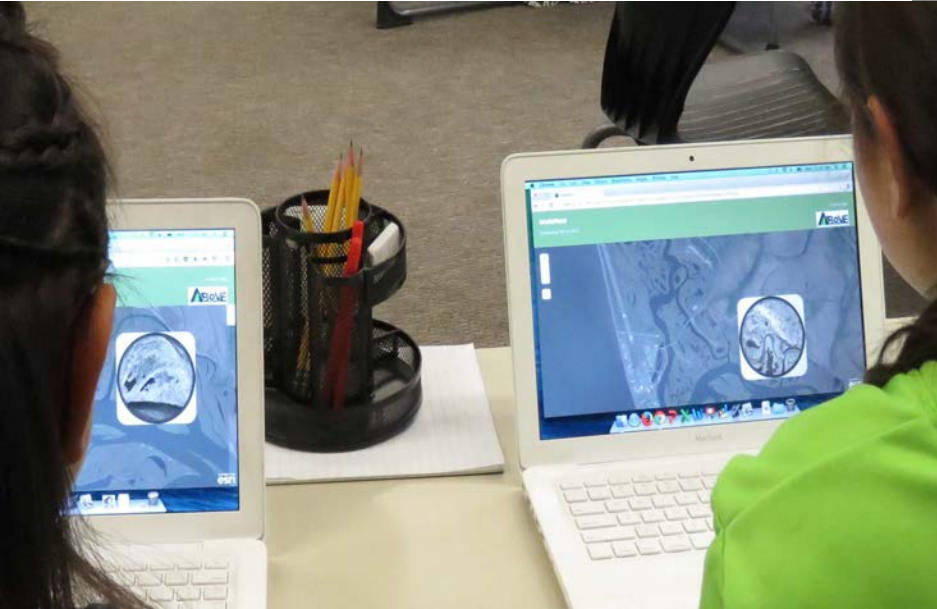




# 1 - Field research with Arctic people



# 2 - "Story Maps" and interactive tools for village science classes





# 65 Years of Landscape Change at Unalakleet, Alaska

Sally Kieper (UAF) and Gerald "JJ" Frost (ABR)  
REACH Project: Raising Educational Achievement through Cultural Heritage



By comparing photographs from aircraft and modern satellites, we can see a 65-year record of changes that have happened in Unalakleet and the surrounding landscape. A lot has happened in the last 65 years along the shores and in the hills:  
what kinds of changes can you find? Use a dry-erase marker to highlight interesting features and make notes.

Questions?  
We'd love to hear from you. Email us at:  
  
Sally Kieper  
sakieper@alaska.edu  
  
Gerald "JJ" Frost  
jfrost@abrinc.com

**July 1, 1951**

**August 31, 2015**

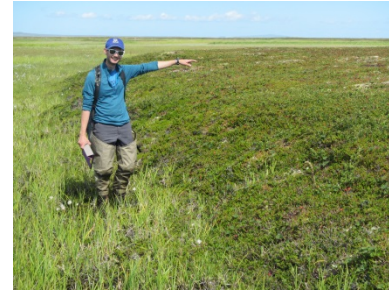


# Socio-ecological implications of change: Yukon Delta, Alaska

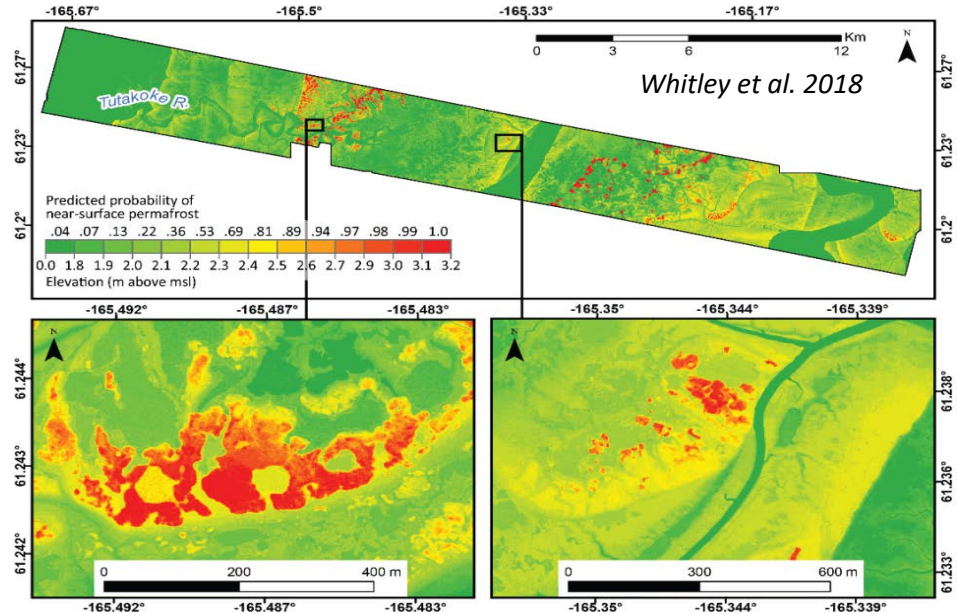
*Local observations, concerns, adaptations*



*Science community*



*Thawing permafrost*



*Hi-res maps of permafrost extent & change*



# Socio-ecological implications of change: Yukon Delta, Alaska

*Local observations, concerns, adaptations*



*Science community*

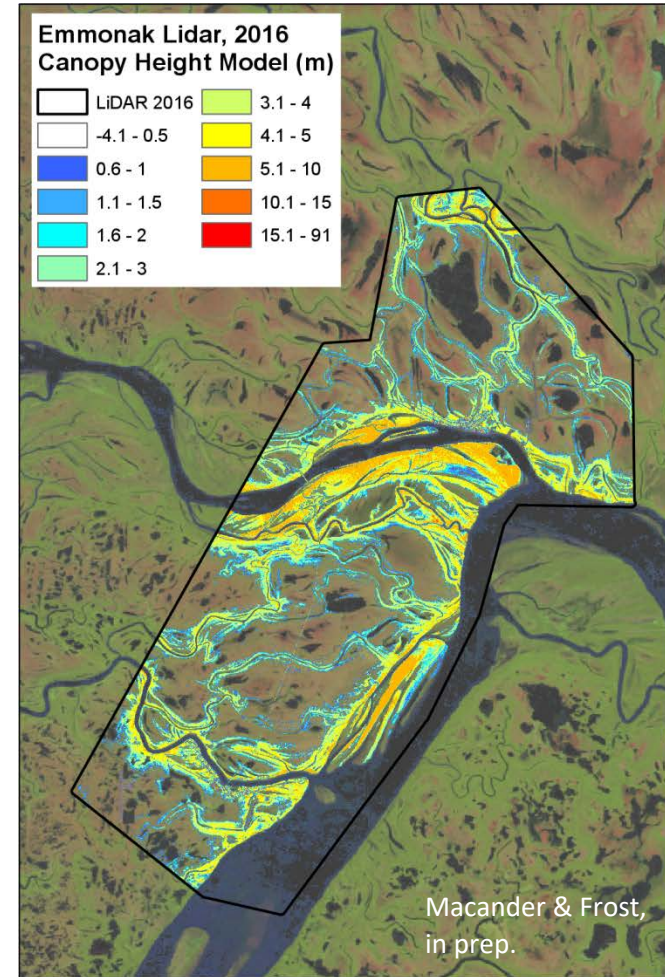
***Tundra shrub expansion***



*Loss of visibility, landmarks, "sense of place"*



*Hunting opportunities*



*Shrub height mapping*



# Conclusions

- Arctic greening is an evolving story. Stay tuned!
- Changing environment challenges our concept of “what is Arctic.”
  - Loss of sea ice
  - Loss of permafrost
- None of these distinctions matter for Arctic people. Big social, political challenges.
- Integrity and continuity of satellite and field observation are critical
- Arctic residents provide a frame of reference that predates the satellite record









Rachel Loehman  
USGS

Jesse Rochester  
Univ. of Maine

David Paradis  
Univ. of Maine

Tawna Morgan  
ABR

Peter Nelson  
Univ. of Maine

Lisa Saperstein  
USFWS



Uma S. Bhatt  
UAF



Matt Macander  
ABR



Torre Jorgenson  
Alaska Ecoscience



Peter A. Bieniek  
UAF



Brian McCaffery  
YDNWR



Ann Fienup-Riordan  
Cultural Anthropologist



Matthew Whitley  
UAF M.S. student



Amy Hendricks<sup>95</sup>  
UAF Ph.D. student



# Quyana! Questions...?

