The role of snow in structuring the forest-shrub-tundra ecotones: (up)scaling in subarctic mountains

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and:
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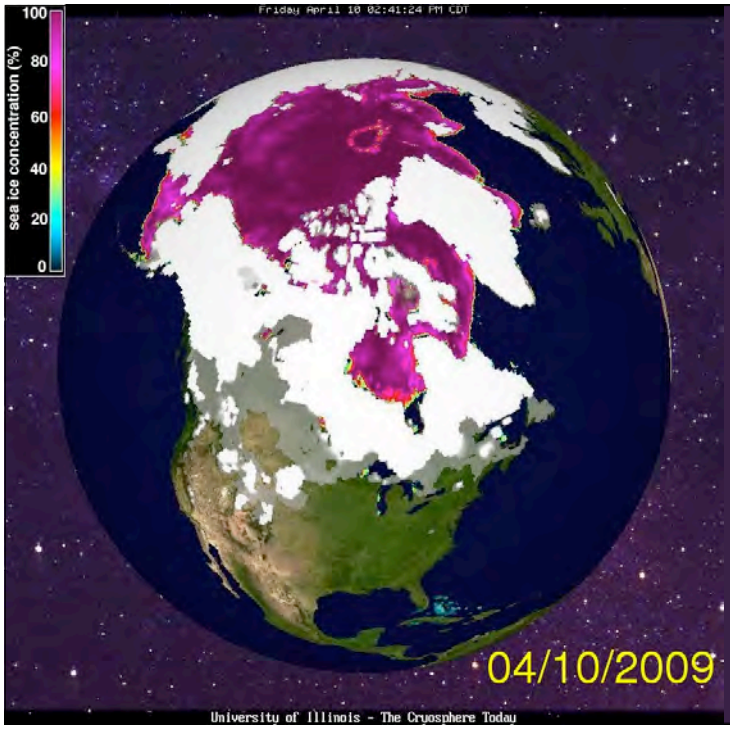
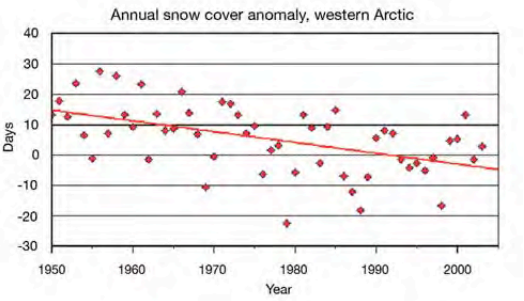
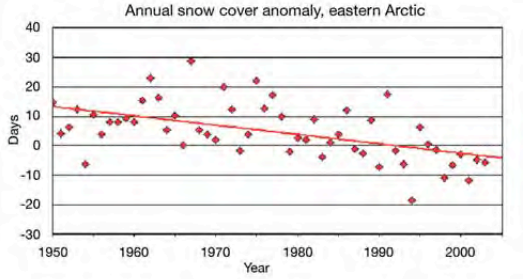
Ryan Danby - Queen's University
Alex Jarosch, Garry Clarke - University of British Columbia

Seasonal snow cover is a dominating feature of northern ecosystems



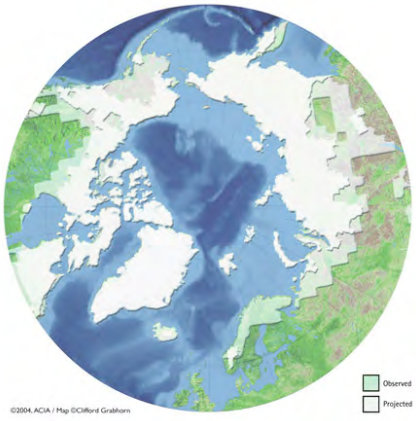
At a coarse scale we can measure snow cover, but not so easy at finer scales

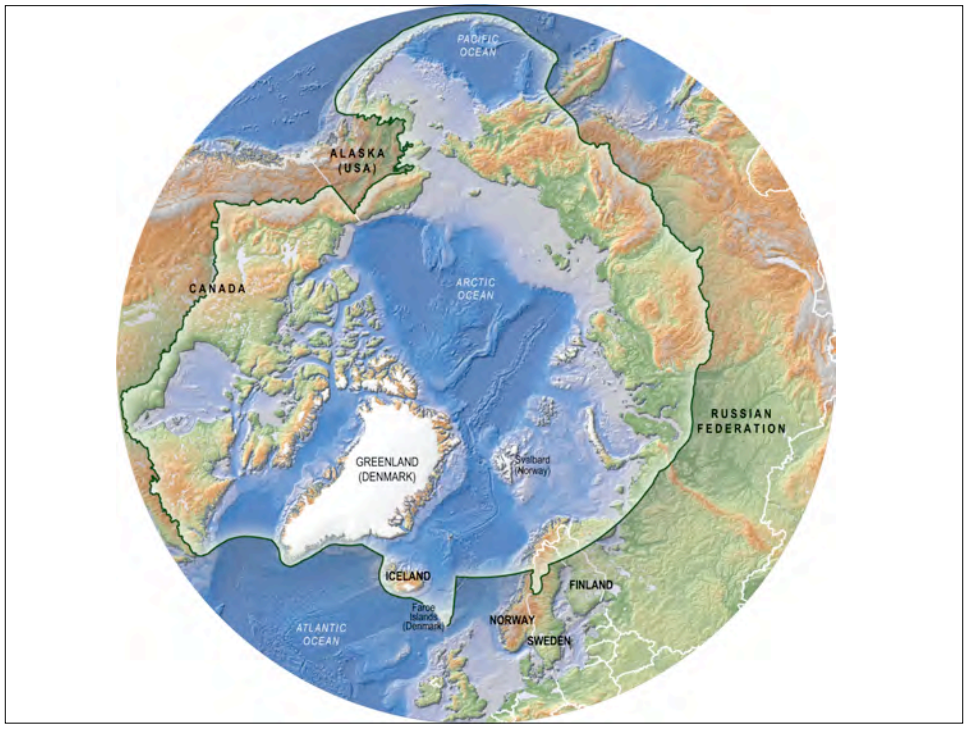




(Natural Resources Canada, 2007: change relative to 1990)

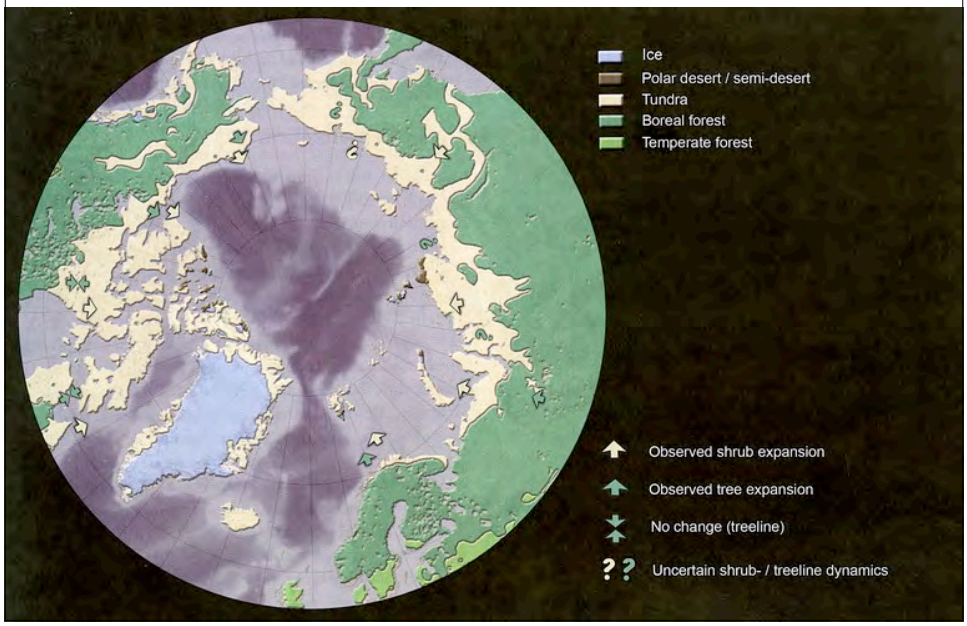
In many parts of the Arctic snow cover is decreasing and projected to decrease even more in coming decades.





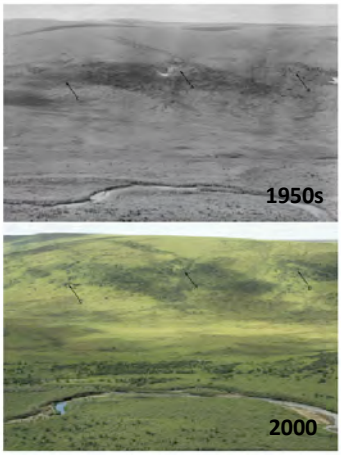
Summary of recent changes from 2008 NOAA Arctic Report Card

Van Bogaert et al.



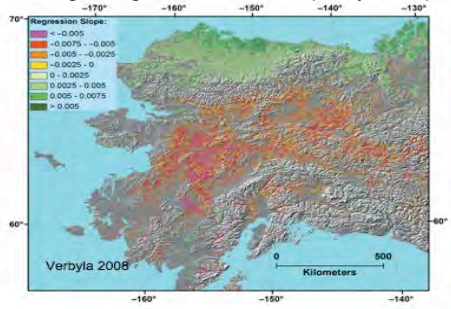
Repeat photography

North Slope of Alaska (Sturm *et al.* 2001, Tape *et al.* 2006)



Remote Sensing

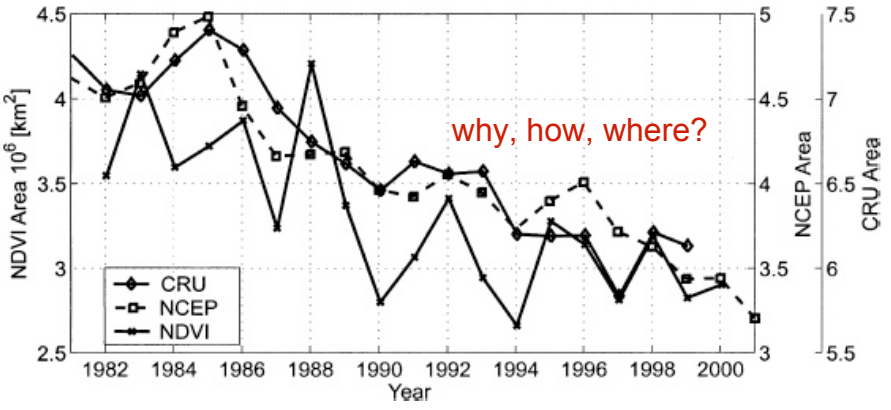
NDVI greening of the arctic tundra (Verbyla 2008)



Plot based studies

ITEX experiment (Walker et al. 2006), Toolik Lake - nutrient addition and warming experiment (Mack et al. 2004)

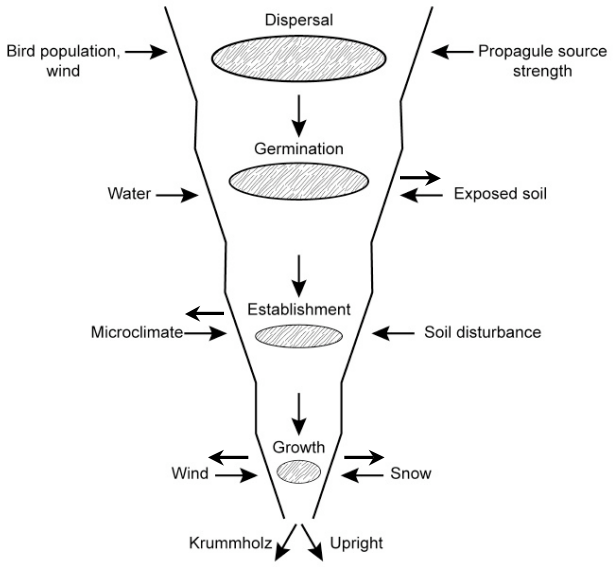
Arctic tundra is being replaced by forest-tundra



(estimates based on NDVI and Köppen Climate Classification)

(Wang & Overland. 2004. Climatic Change 67:43-62)

Snow and treeline?

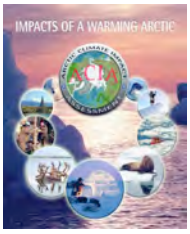


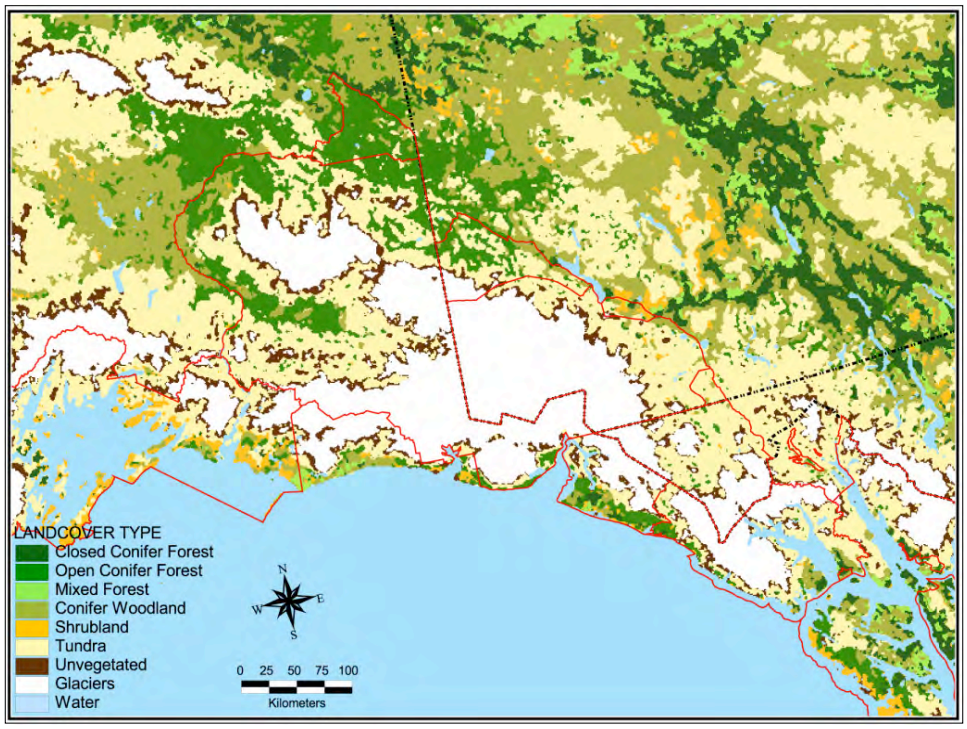
An example of an environmental sieve for sequence of processes influencing establishment of forest-tundra ecotone

(from Malanson et al. 2007, Physical Geography)

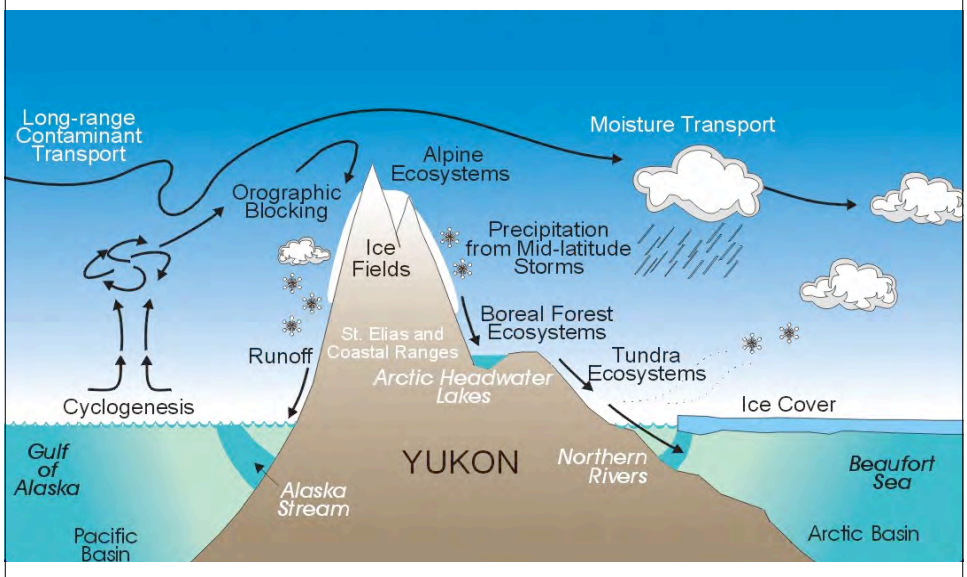
Of the 4 circumpolar sub-regions defined in the 2004 *Arctic Climate Impact Assessment*, the assessment concluded that -

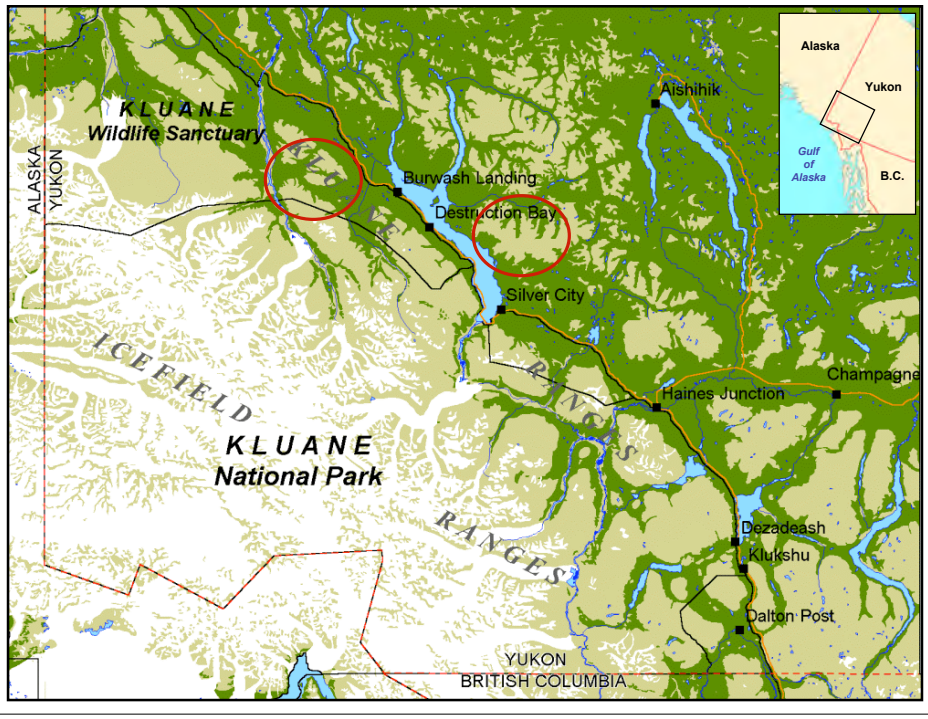
"Alaska and the Canadian Yukon have experienced the most dramatic warming, resulting in major ecological impacts…these trends are projected to increase."





The St. Elias Mountains are a significant obstacle for Pacific air-masses moving into the Arctic





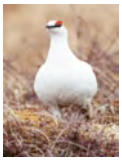
Effects of climate change in northern alpine and tundra environments

temperature, precipitation, phenology

Composition and production of vegetation

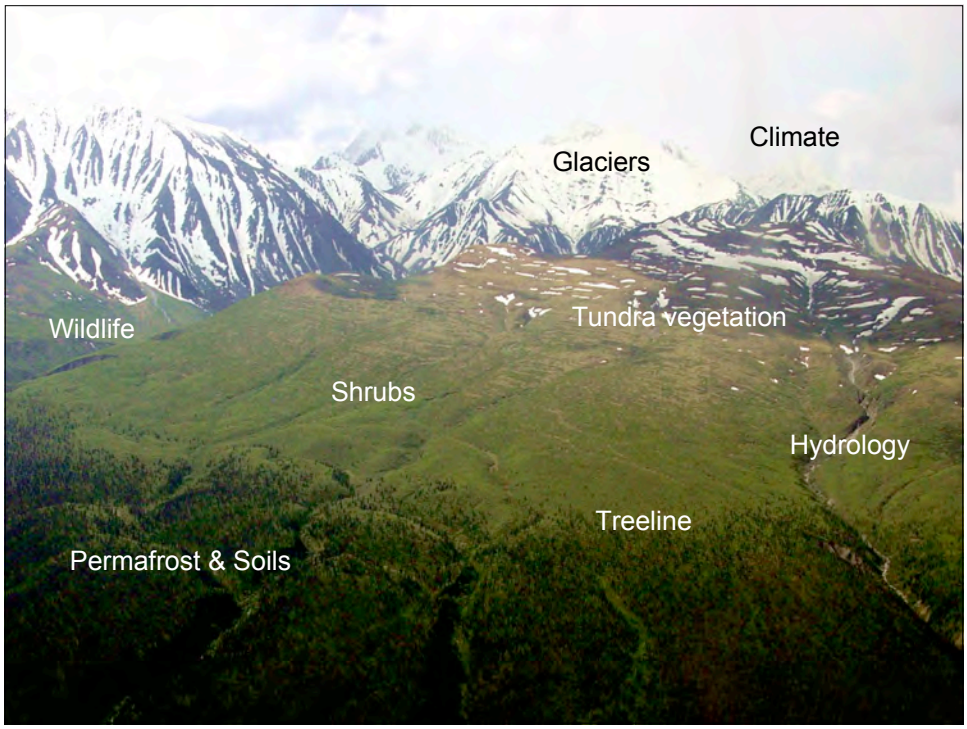
Ecotones ("tree-line" & "shrub-line")

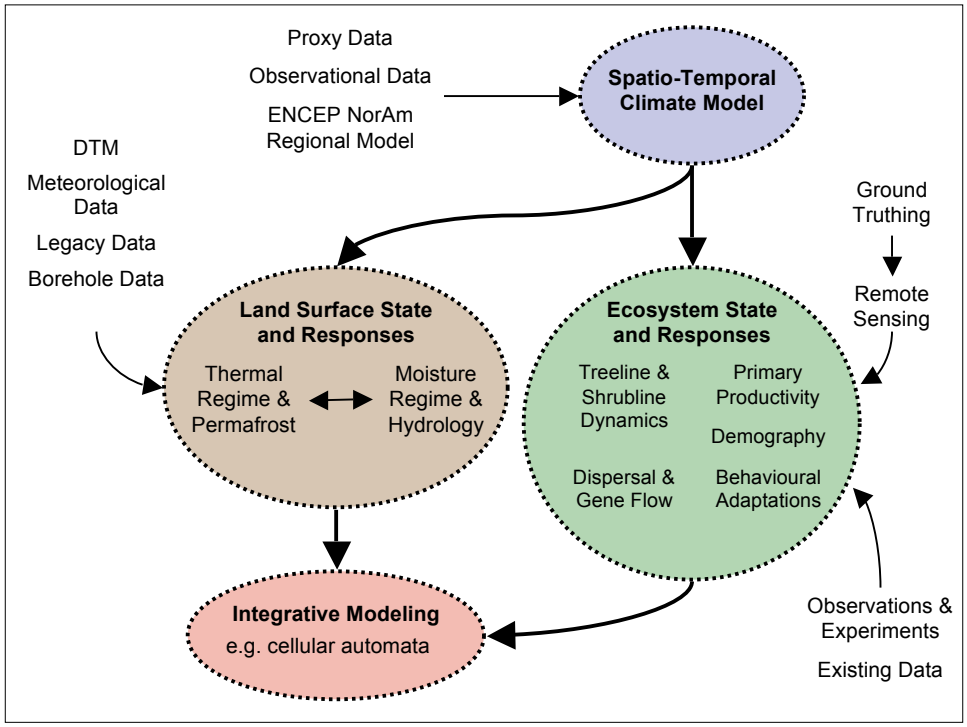
Survival, reproduction, behaviour

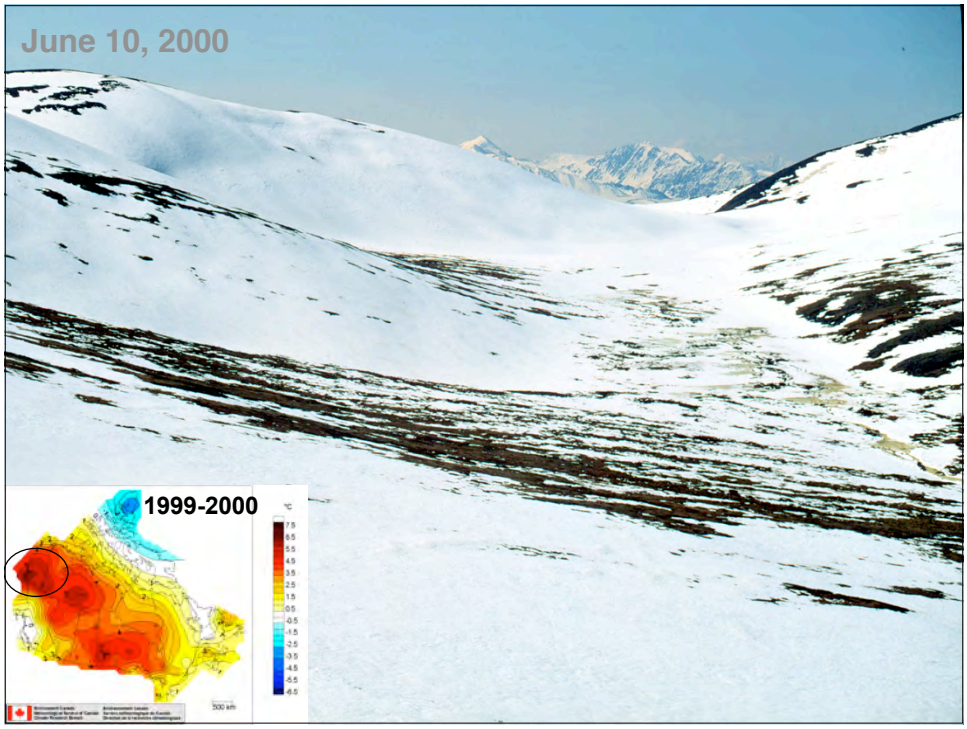


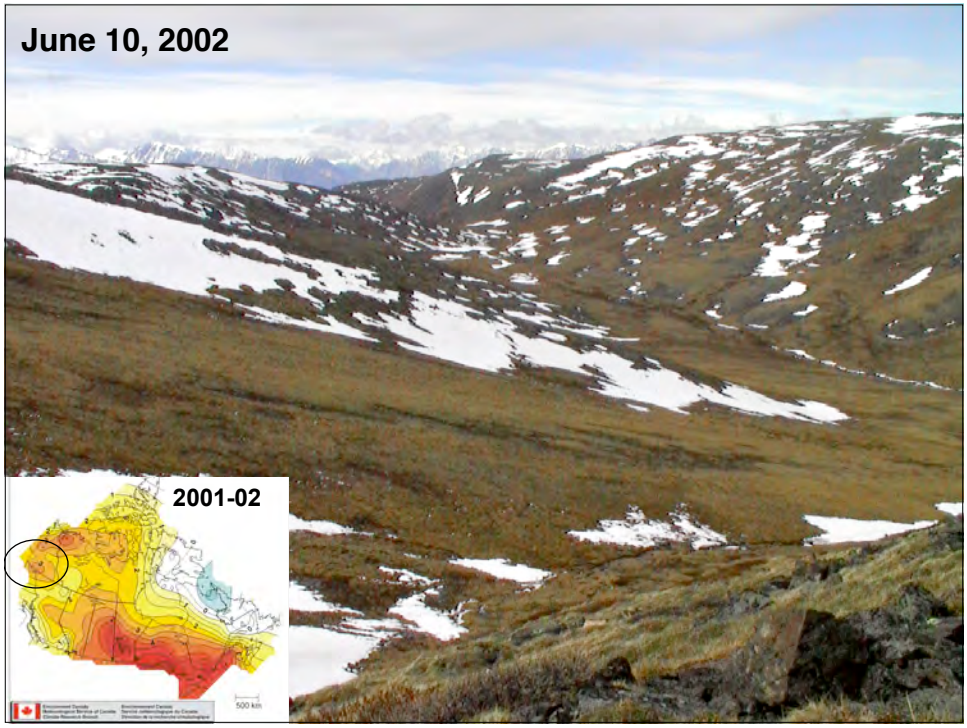
Distribution

??


Climate
Glaciers
Wildlife
Tundra vegetation
Shrubs
Hydrology
Treeline
Permafrost & Soils


Proxy Data
Observational Data
ENCEP NorAm Regional Model
Spatio-Temporal Climate Model
DTM
Meteorological Data
Legacy Data
Borehole Data
Ground Truthing
Remote Sensing
Land Surface State and Responses
Thermal Regime & Permafrost
Moisture Regime & Hydrology
Ecosystem State and Responses
Treeline & Shrubline Dynamics
Primary Productivity
Demography
Dispersal & Gene Flow
Behavioural Adaptations
Integrative Modeling
e.g. cellular automata
Observations & Experiments
Existing Data


June 10, 2000
1999-2000


June 10, 2002
2001-02

Mammalian herbivores and snow

Collared pika

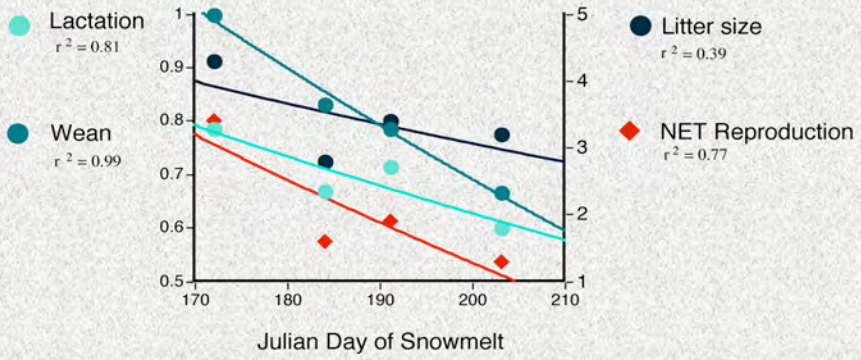
Arctic ground squirrel

Hoary marmot

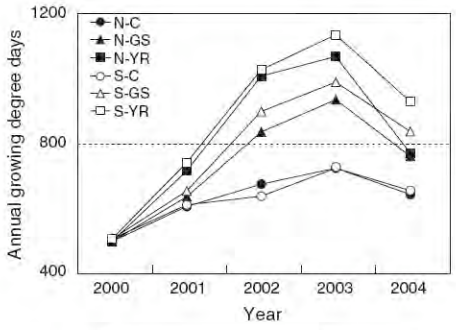
Dall sheep

Annual Life Cycle of Hoary Marmots

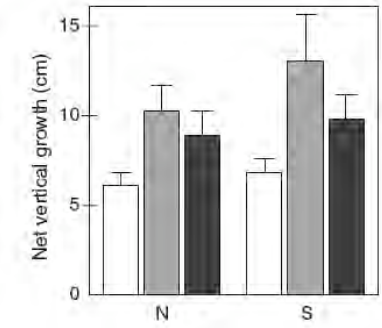
Effect of Timing of Snowmelt on Rates of Reproduction for Marmots



Karels & Hik, MS



Less snow = more growing degree days

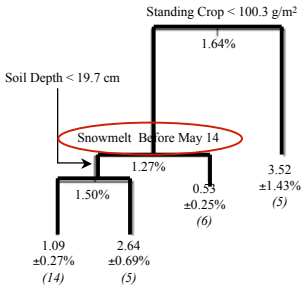


More growing degree days = more growth

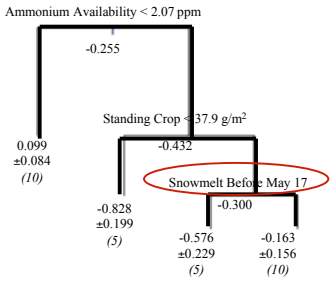
(Danby & Hik, Global Change Biology, 2007)

In other experimental studies, both abiotic and biotic variables can control the balance between competition and facilitation - but timing of melt always important.

Species abundances

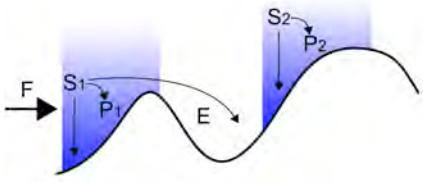


Competitive response

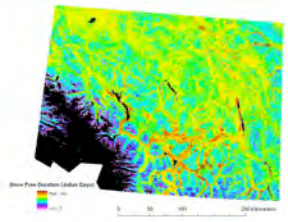


(Mitchell, Cahill & Hik, 2009, Ecology)

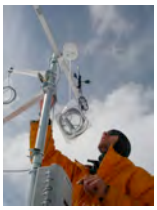
Three approaches for determining precipitation



1. Downscaling NARR



2. Remote Sensing: MODIS fractional snowcover

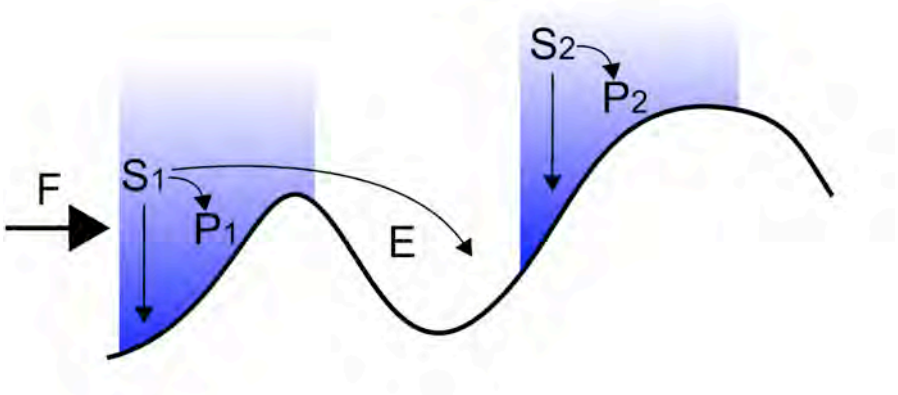


3. Better & more instrumentation

Downscaling NARR Techniques: Precipitation

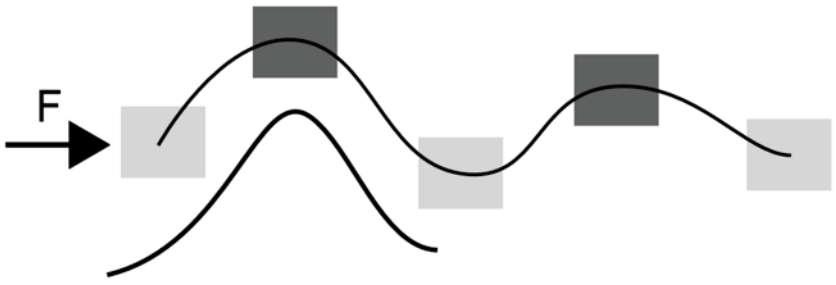
- Takes all input variables (state of the atmosphere) from the NARR dataset.
- Rely on a linear model for orographic precipitation (LOP) [Smith, RB and Barstad, I. J. Atmos. Sci. (2004)] to achieve spatial complexity.
- **Our approach:**
  - Calculate the state of the atmosphere (moisture, wind, etc.) from NARR.
  - Estimate the low res. orographic precip. field of NARR
  - Replace the low res. orographic precip. with the high res. precip. from the LOP model.

Orographic Precipitation

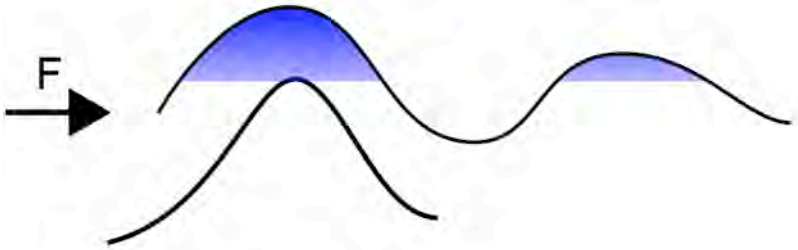


Smith, RB and Barstad, I. J. Atmos. Sci. (2004)

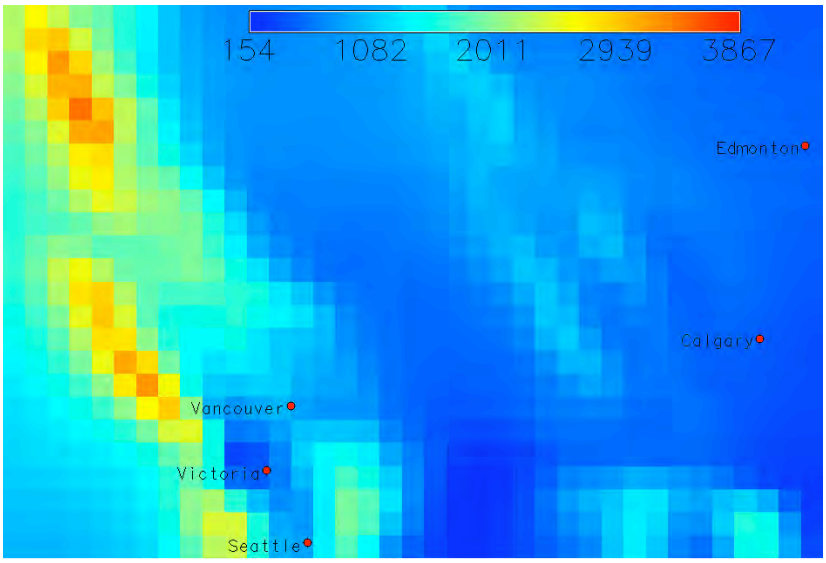
Mountain Wave Formation



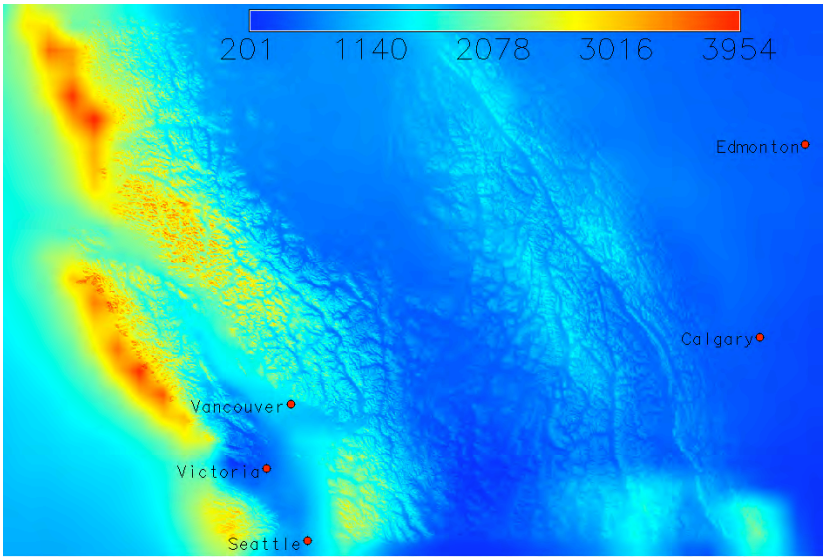
Mountain Wave Formation



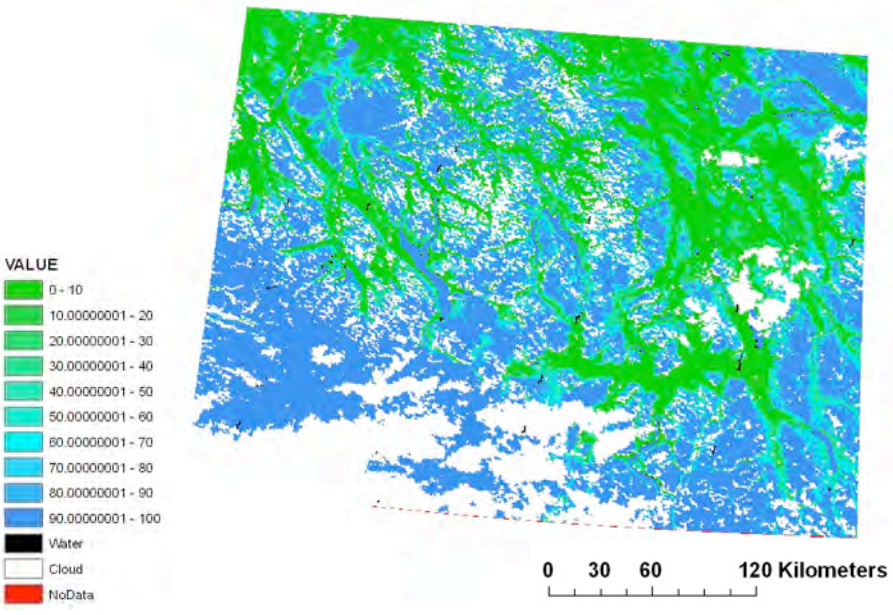
NARR Precip Field



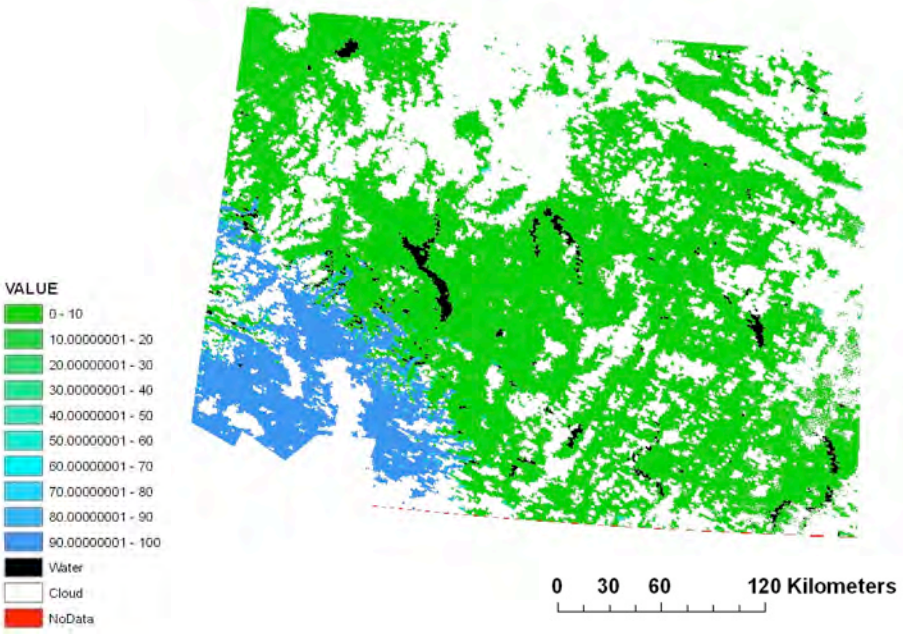
Downscaled Precip Field



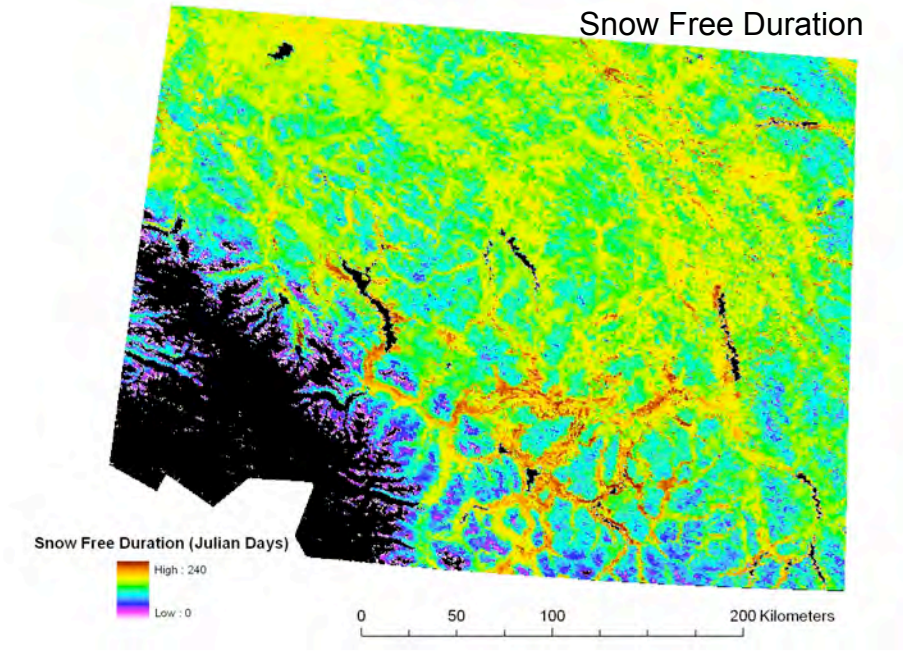
MODIS Fractional Snow Cover - 1 May 2007

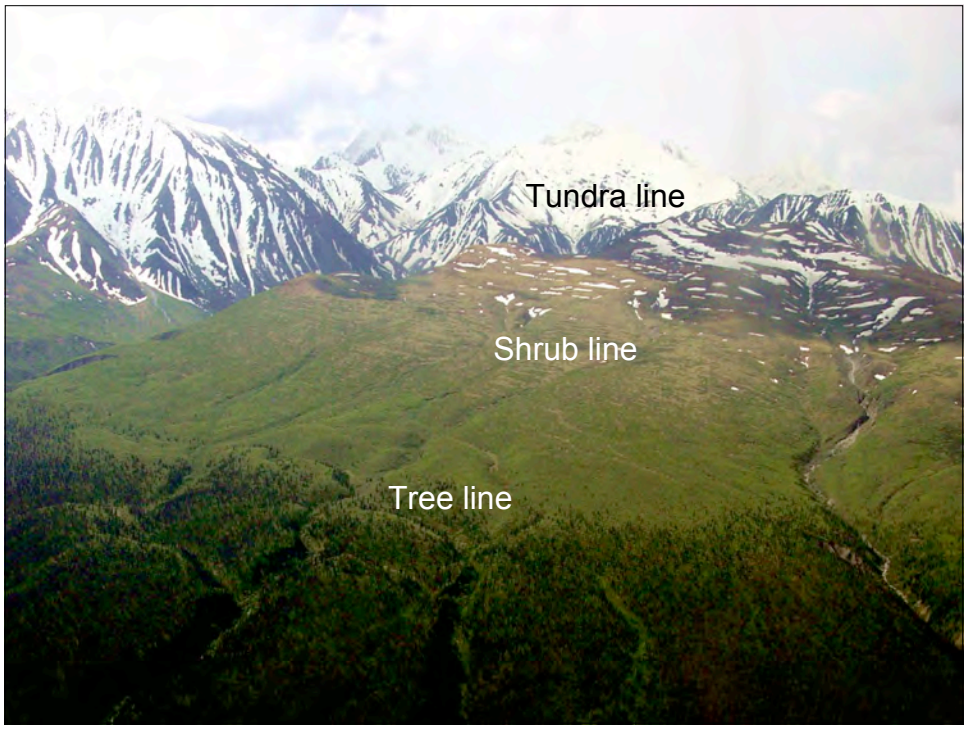


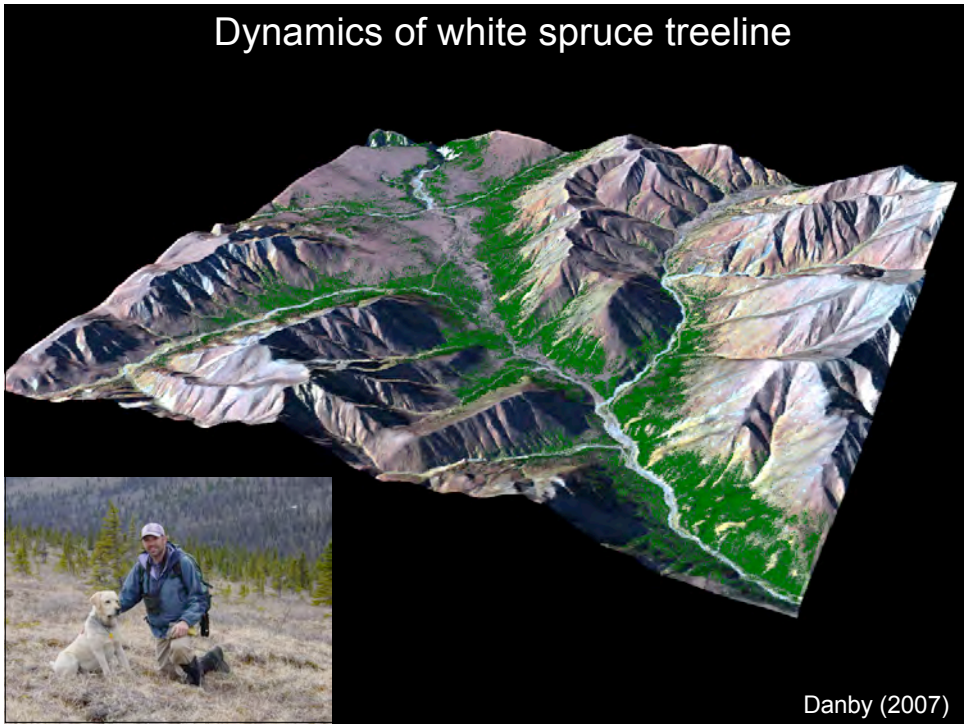
MODIS Fractional Snow Cover - 15 July 2007



Snow Free Duration

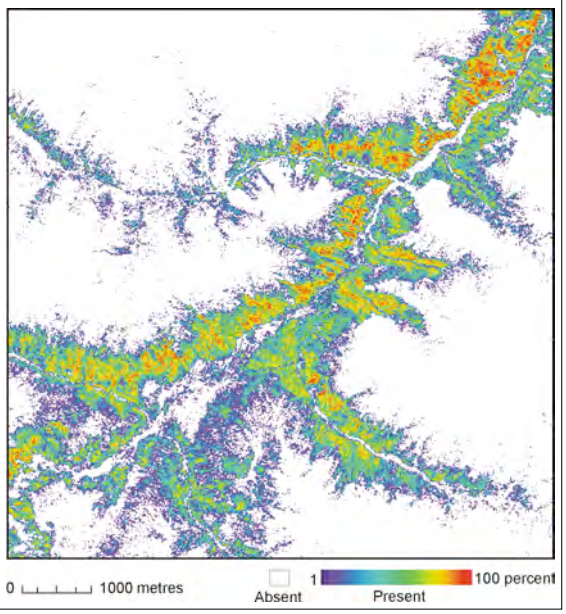


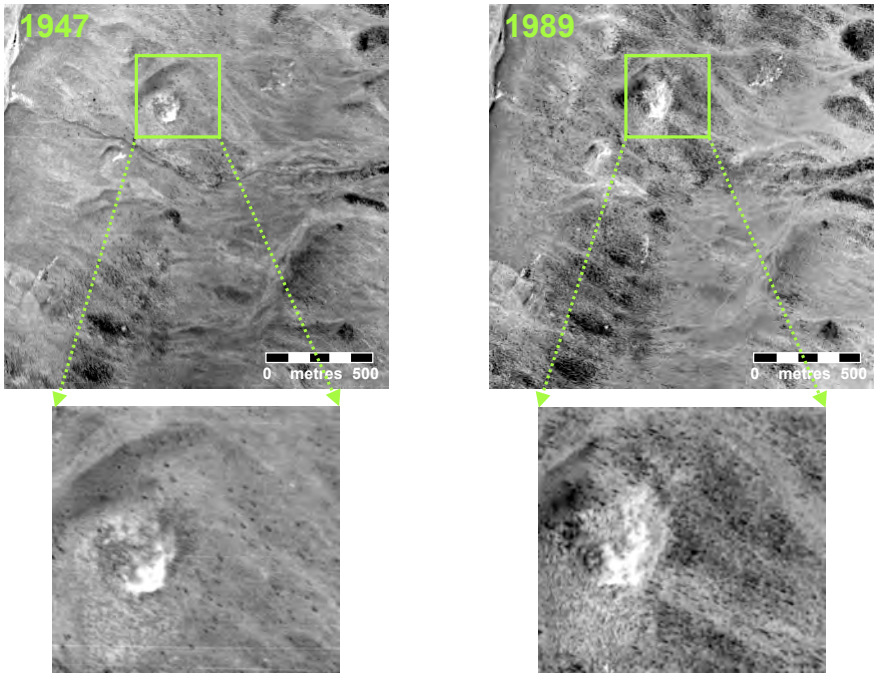

Tundra line
Shrub line
Tree line


Dynamics of white spruce treeline
Danby (2007)

Quickbird & Treeline

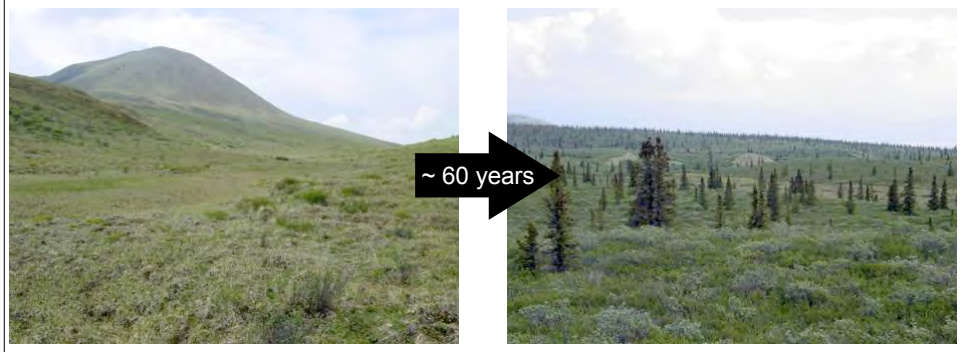
- Spruce class = 94% users accuracy
- C&RT analysis indicates significant terrain related affects on distribution and abundance



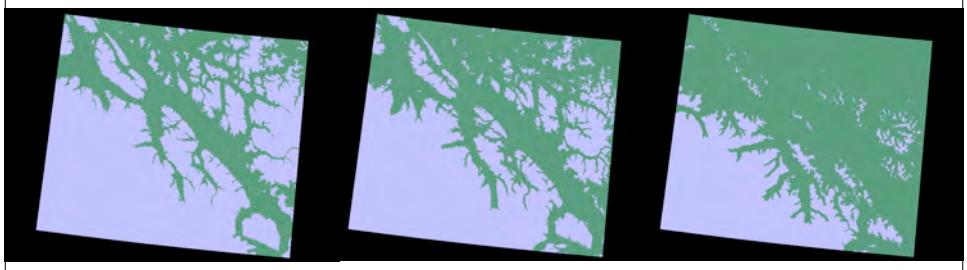


Danby and Hik (2007) Arctic

So we have some idea about how quickly treeline might change



Binary Model of Treeline Elevation Change



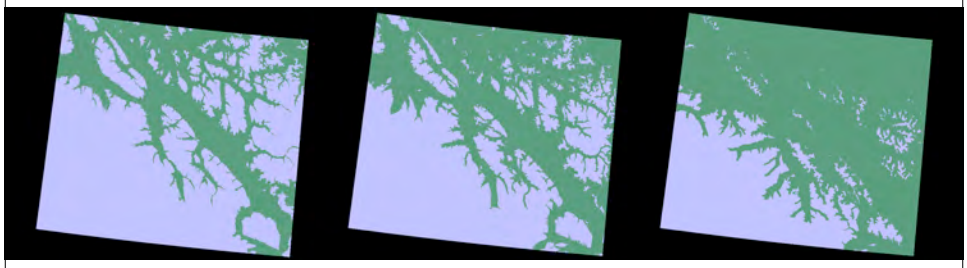
- Current
- Mapped using 1989 aerial photography
- Above = 14 333 km^2
- Below = 8 010 km^2

- 100 m rise
- Based on recent change
- Above = 11 823 km^2
- Below = 10 520 km^2
- **Alpine habitat fragmentation**

- 525 m rise
- CGCM2 CO_2 Scenario B (3.4°C warming by 2080)
- Field measured lapse rate of 0.65 C $^{-100m}$
- Above = 7 345 km^2
- Below = 14 998 km^2
- **Alpine habitat loss**

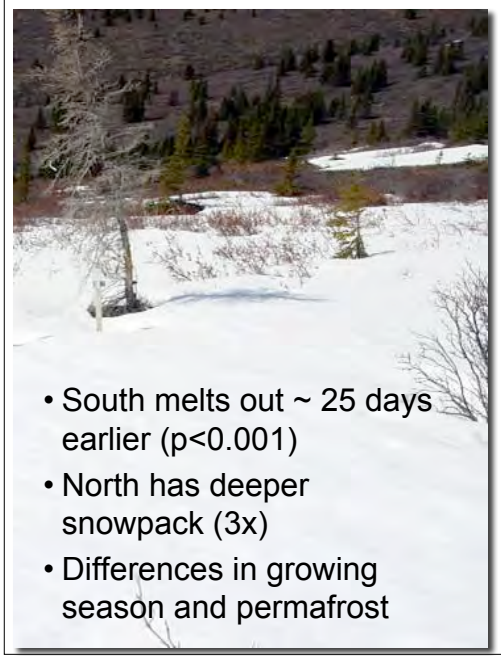
Danby (2007)

Binary Model of Treeline Elevation Change

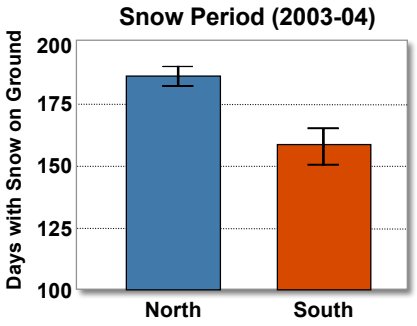


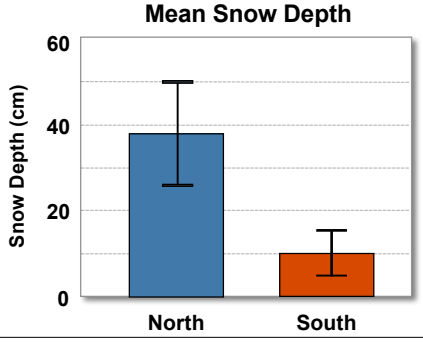
However, the dynamics of these sorts of models lack spatial, temporal and process detail

Snow and Aspect

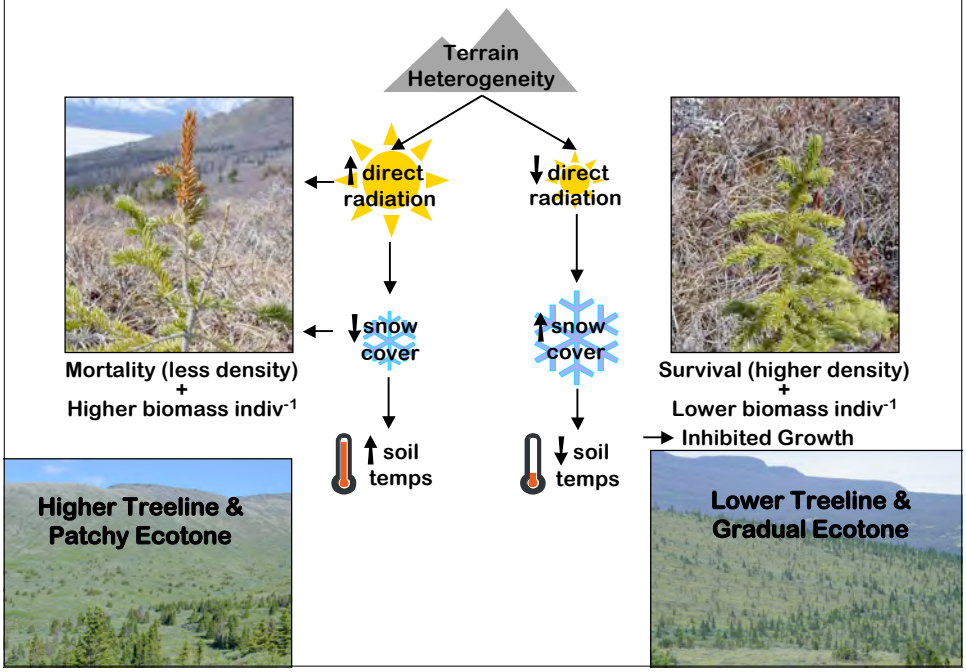


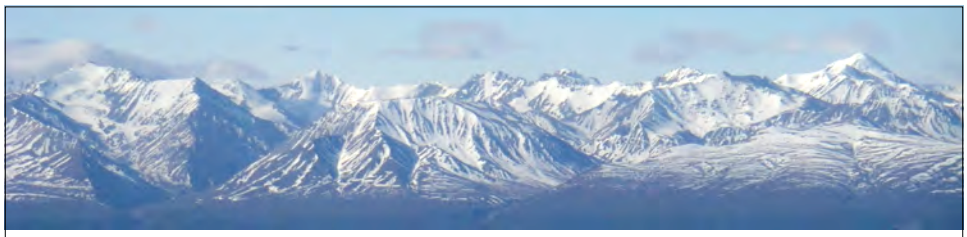
- South melts out ~ 25 days earlier ($p<0.001$)
- North has deeper snowpack (3x)
- Differences in growing season and permafrost





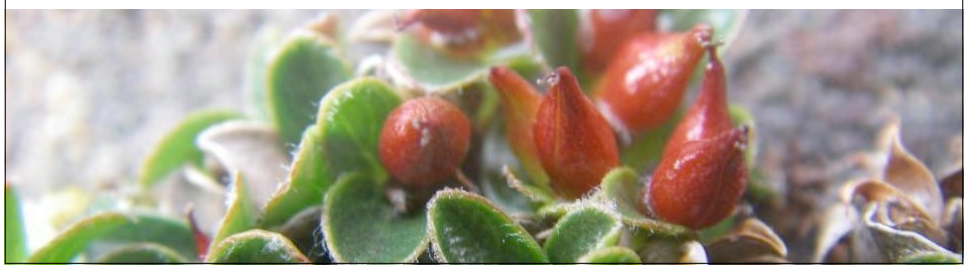
Scale-based, Pattern/Process Interactions at Treeline



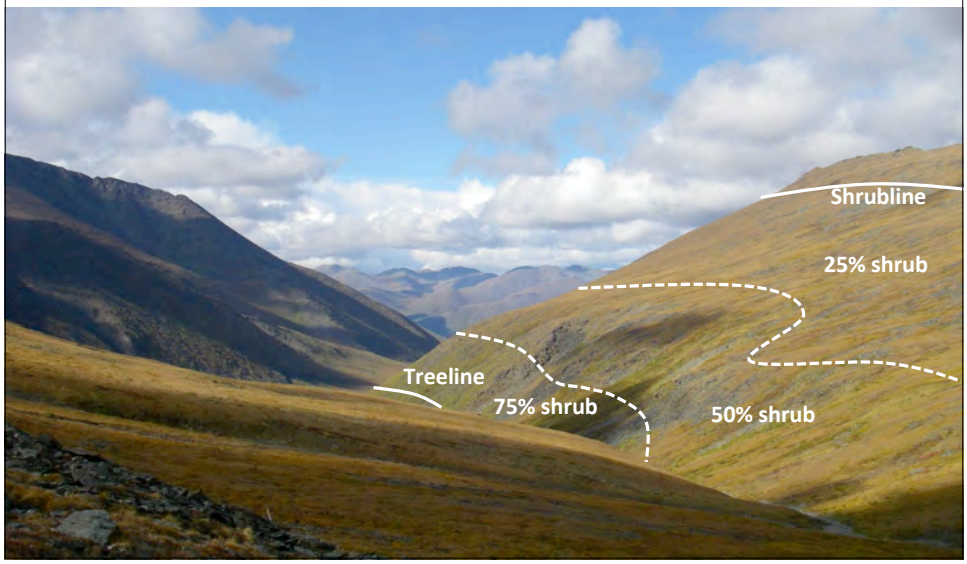


What about the shrubs?

Isla Myers-Smith, PhD student, University of Alberta



Mapping vegetation transitions



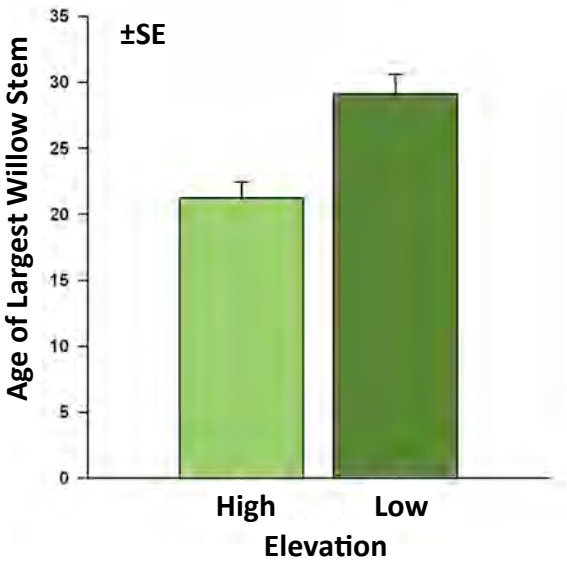
Willows

High diversity (with potential for hybridization)

Species differ in…

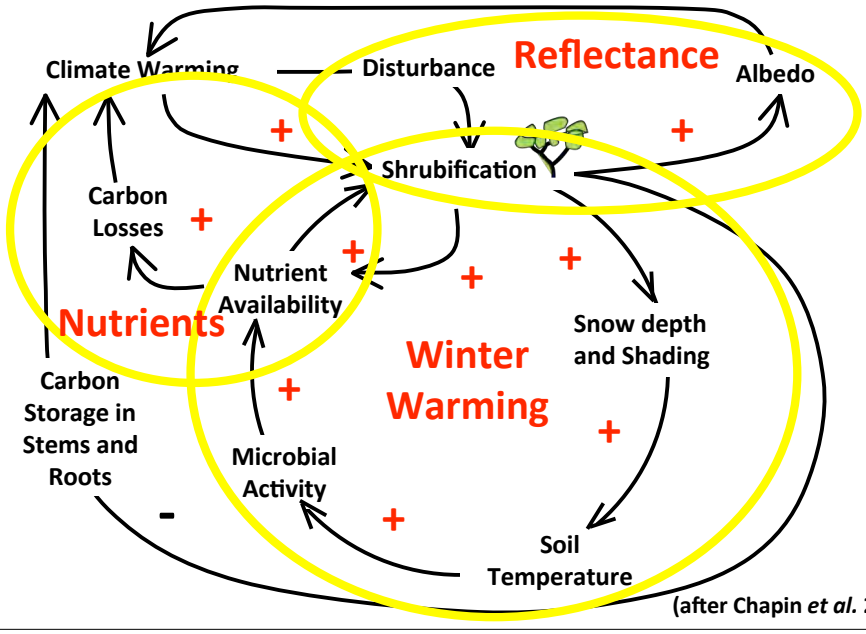
- **Phenology**
- **Microclimate preference**

Shrubline is advancing

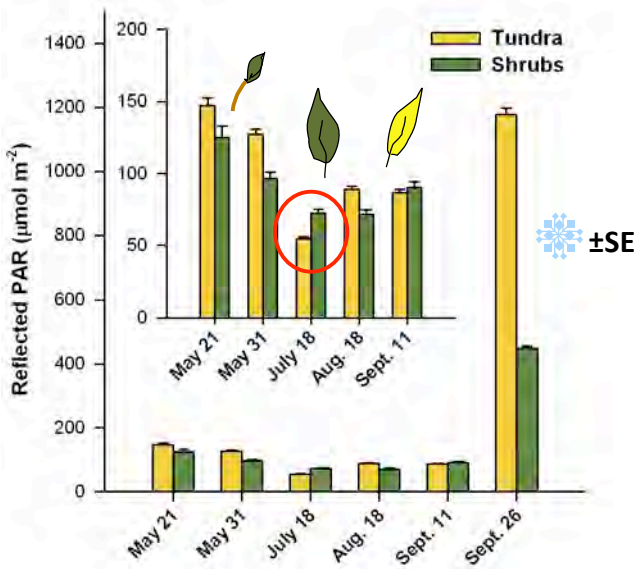


- Almost no observed mortalities

Ecosystem Feedbacks



Reflectance



Snow Trapping Hypothesis

Sturm et al. 2001 predicted that with increasing shrubs, greater trapping of snow in winter would warm soils and increase carbon release

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Snow–Shrub Interactions in Arctic Tundra: A Hypothesis with Climatic Implications

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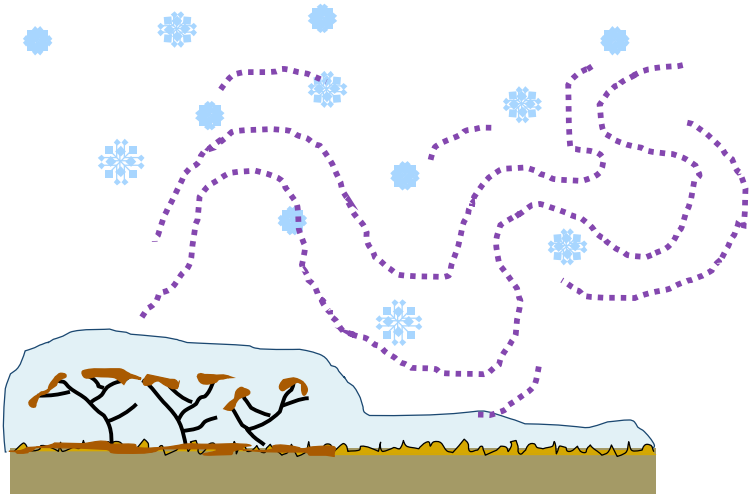
Wind Distribution of Snow



Shrub Manipulation

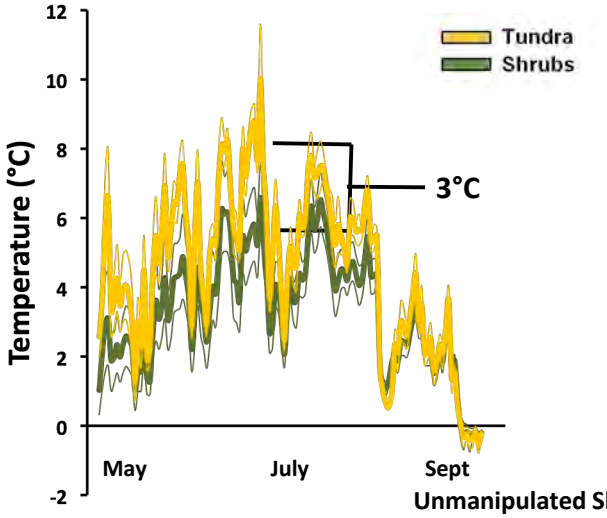
Shrubs

Artificial Shrubs

Tundra

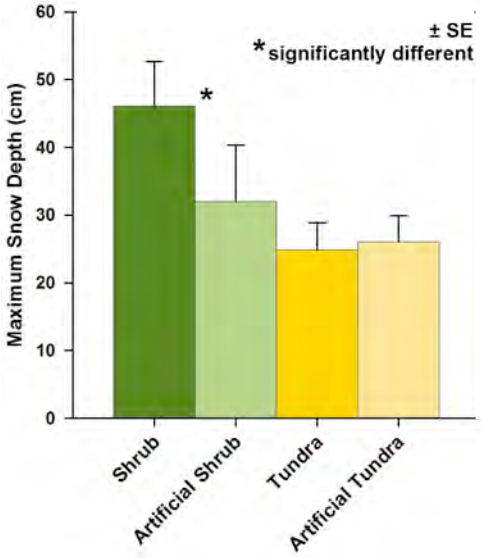
Artificial Tundra

In Summer…
Shrubby soils are cooler: shading?

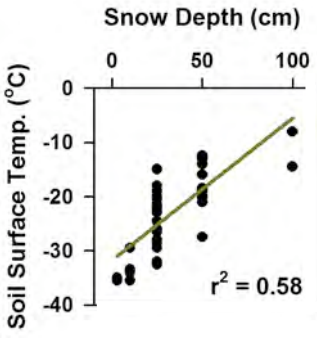


Unmanipulated Shrubs
Soil Temperature 2cm depth

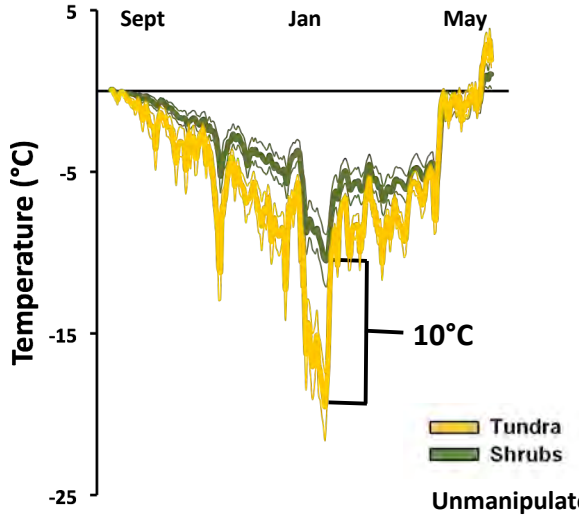
In Winter…
Shrubs trap snow



Max. January
Snow Depth



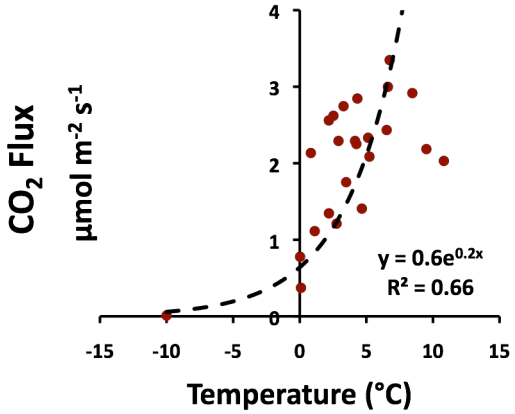
In Winter…
Shrubby soils are warmer: insulation?



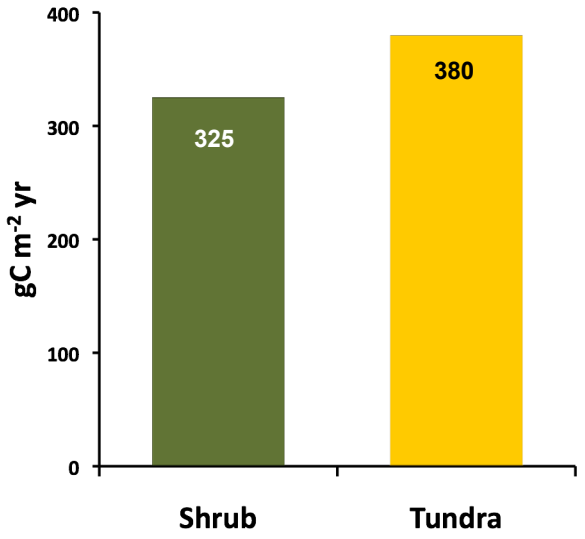
Unmanipulated Shrubs
Soil Temperature 2cm depth

Connecting Temperature to Carbon

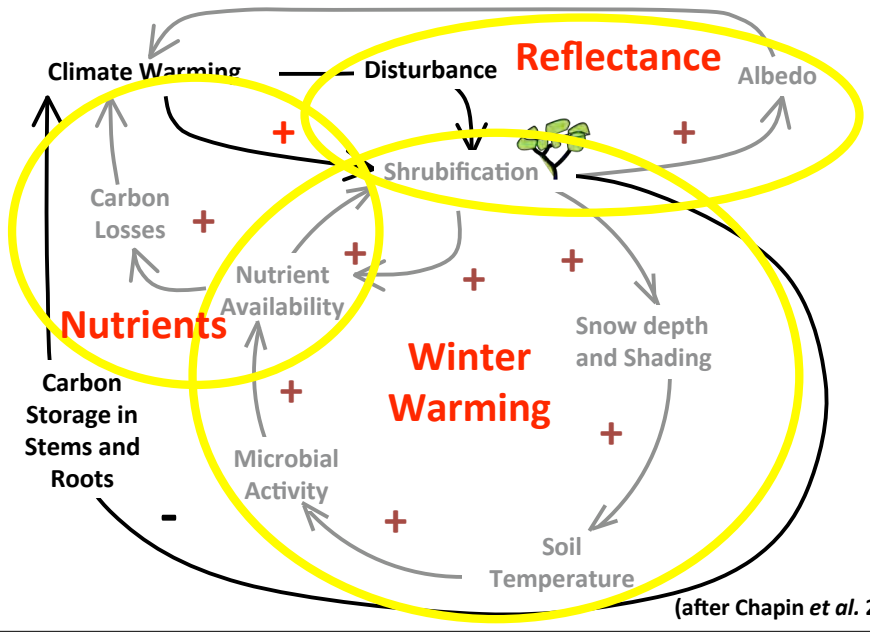
Soil CO_2 efflux data can be used to build a relationship between soil temperature and carbon release for this field site.



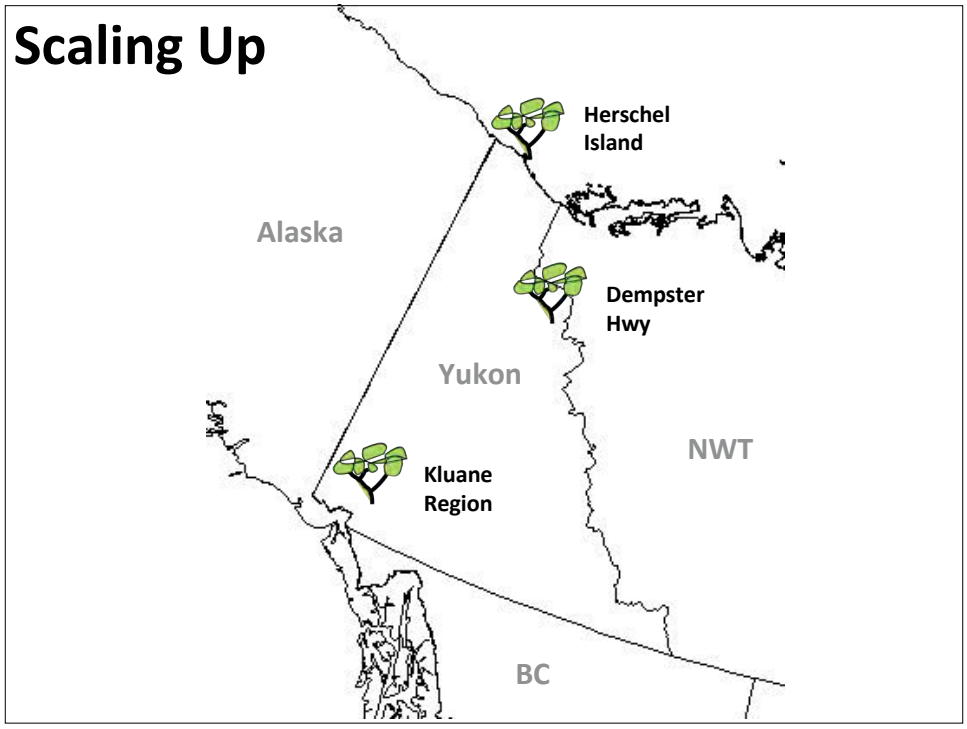
Annual Carbon Release



Ecosystem Feedbacks



(after Chapin *et al.* 2005)


Scaling Up
Herschel Island
Alaska
Dempster Hwy
Yukon
NWT
Kluane Region
BC


Herschel Island 2008

Herschel Island 2050?

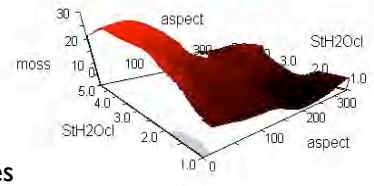
What about tundra transition?

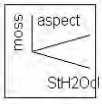
Bioclimate Envelope Models to Determine Species Distributions

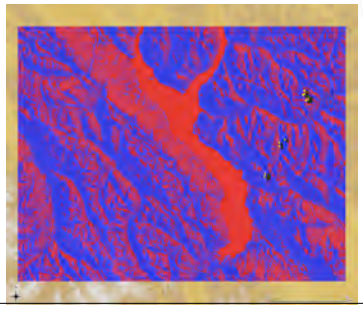
Nonparametric Multiplicative Regression Modelling

The observed abundances of a species in an "environmental neighbourhood" are used to predict spp. abundances at a new "target" site.

An environmental neighbourhood is made up of sites close in multidimensional environmental space made up of one or more predictor variables. e.g. elevation, aspect or duff layer depth



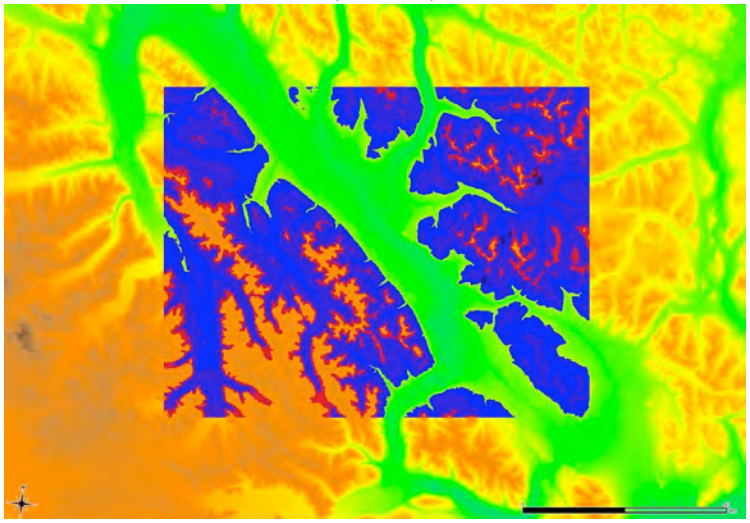




Total lichen (predicted)

Mapped on elevation

0%-34% (Blue to Red)



% cover

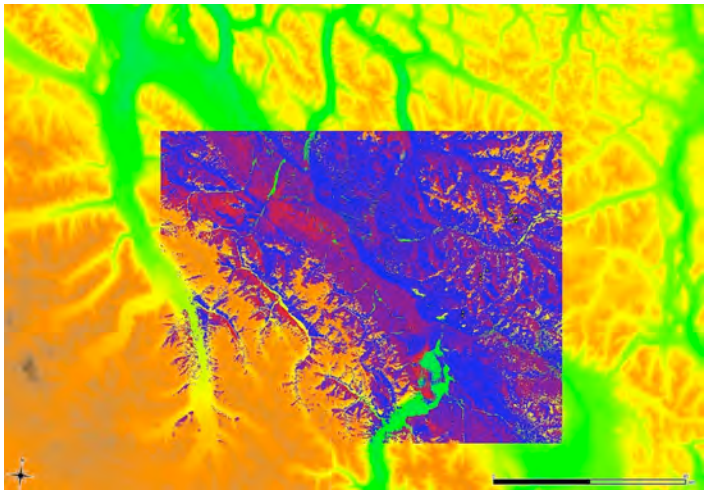
Actual 2008 Total Lichen	2008 Lichen Predicted
16.8	4
4.86	**8**
3.4	**3**
18	**6**
10	**6**
26.33	**11**
11.76	**8**
20.86	**20**
16.6	**19**
1.78	**4**
2.38	**3**

Wilcoxon p=0.09

Moss (predicted)

Mapped on aspect and Landsat 5 Band1

2%-14% (Blue to Red)



% cover

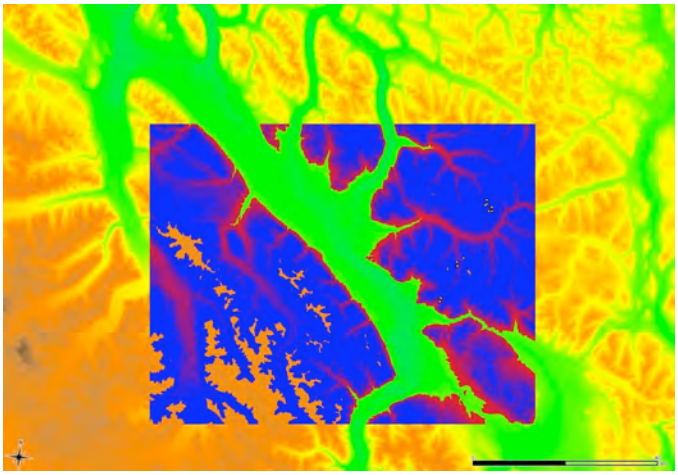
Actual 2008 Moss	Predicted 2008 Moss
8	**9**
3.16	**3**
11.4	**10**
2	**4**
14	**4**
1.6	11
7.3	4
0.48	3
0.78	**4**
1.78	**3**
13.8	4

Wilcoxon p=0.47

Deciduous Shrubs (predicted)

Mapped on Elevation

0% - 49% (Blue to Red)



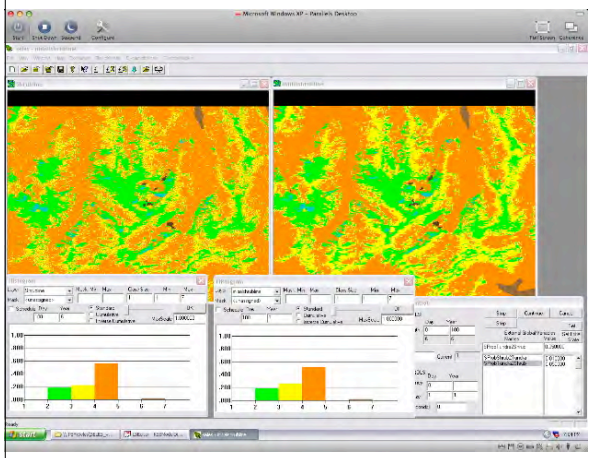
% cover

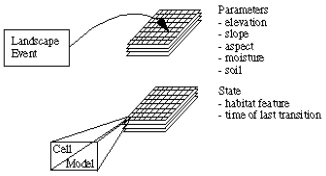
Actual 2008 Dec Shr	Predicted 2008 Dec Shrb
15.2	**16**
0	1
15.3	**17**
1	**4**
0.4	4
0	1
0	1
0	**0**
0	**0**
7.44	**15**
12.18	**22**

Wilcoxon p=0.18

Can we use our understanding to predict the future?

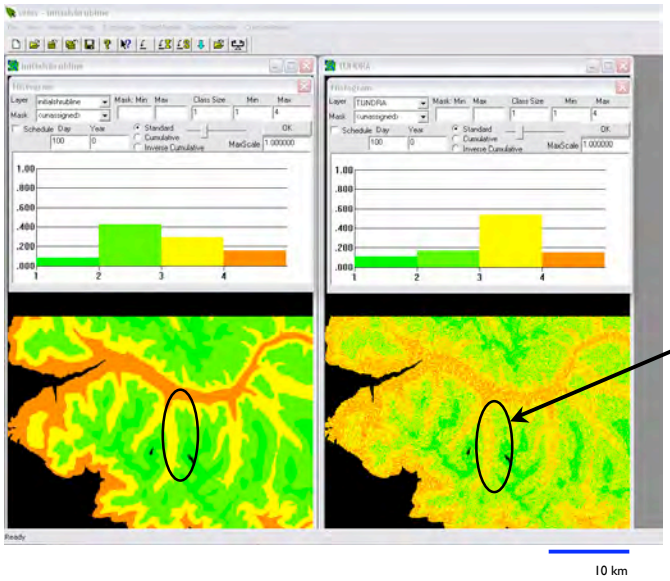
Spatially Explicit Landscape Event Simulator





Future climate - vegetation interaction scenarios can be modeled using predictive vegetation distribution models and high resolution models of climate data

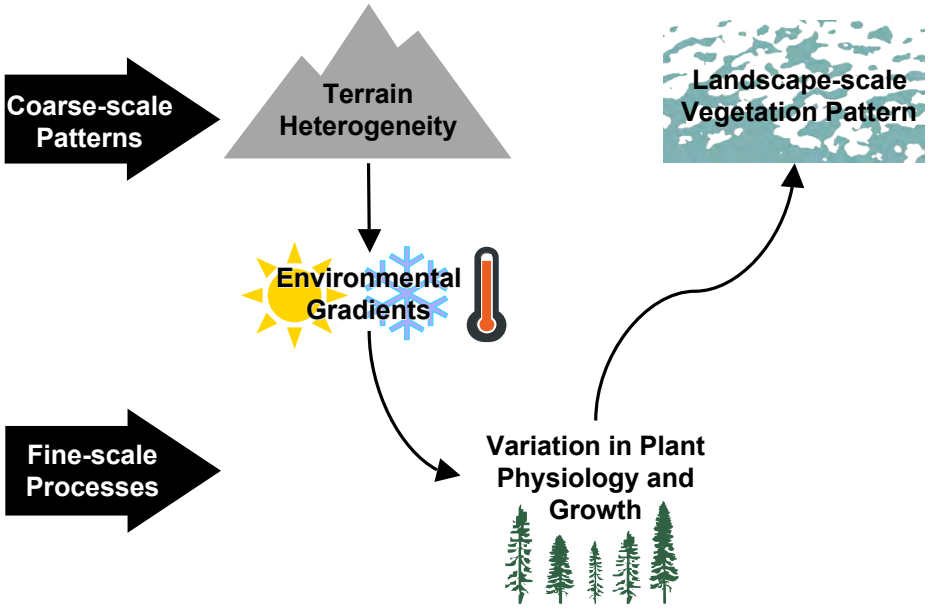
Histograms show the distribution of abundance classes before (initial shrubline) and after 10 years (tundra)

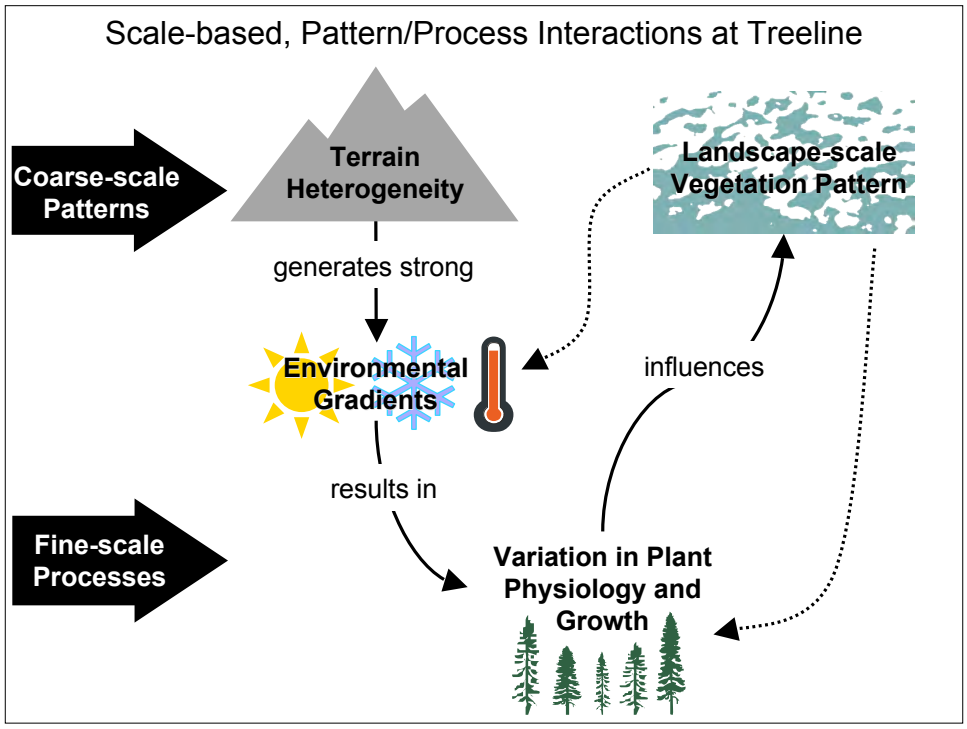


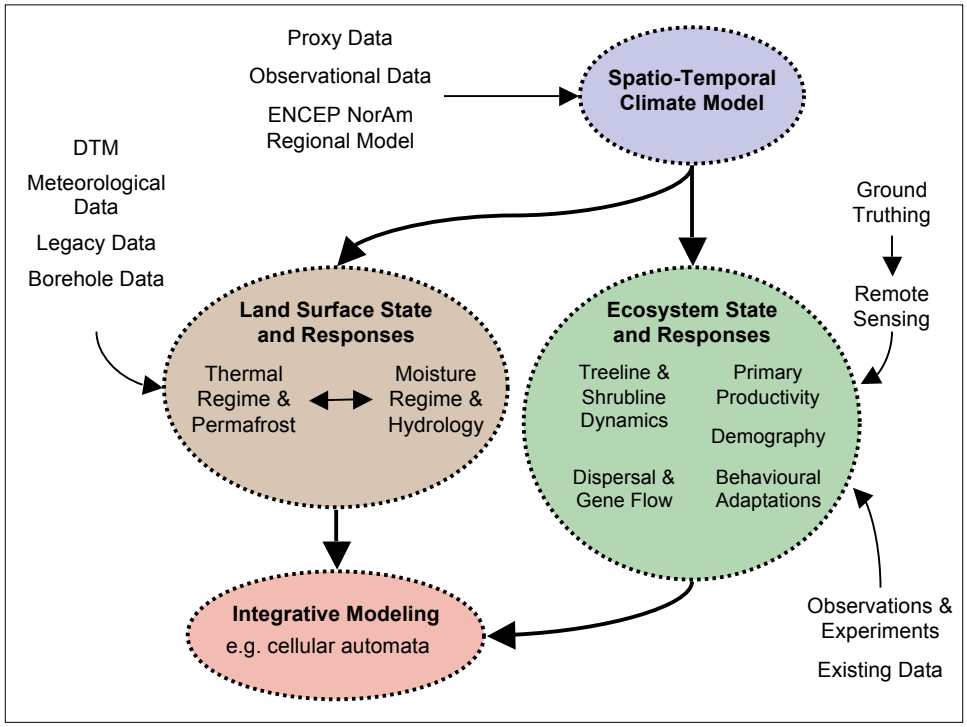
Cover Class
1 = 0% Dark green
2 = 1-15% Light green
3 = 16-50% Yellow
4 = > 50% Brown

Shows advance of shrubline up slope into areas where previously shrub densities were low or non-existent. (Green turns to yellow, yellow turns to brown).

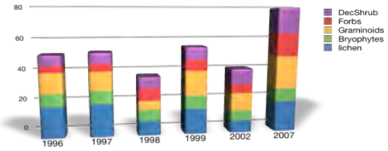
Scale-based, Pattern/Process Interactions



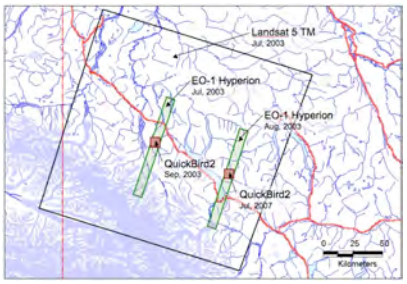

Scale-based, Pattern/Process Interactions at Treeline
Coarse-scale Patterns
Terrain Heterogeneity
Landscape-scale Vegetation Pattern
generates strong
Environmental Gradients
influences
results in
Fine-scale Processes
Variation in Plant Physiology and Growth


Proxy Data
Observational Data
ENCEP NorAm Regional Model
Spatio-Temporal Climate Model
DTM
Meteorological Data
Legacy Data
Borehole Data
Ground Truthing
Remote Sensing
Land Surface State and Responses
Thermal Regime & Permafrost
Moisture Regime & Hydrology
Ecosystem State and Responses
Treeline & Shrubline Dynamics
Primary Productivity
Demography
Dispersal & Gene Flow
Behavioural Adaptations
Integrative Modeling
e.g. cellular automata
Observations & Experiments
Existing Data

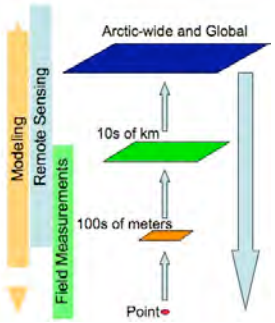
Next Steps



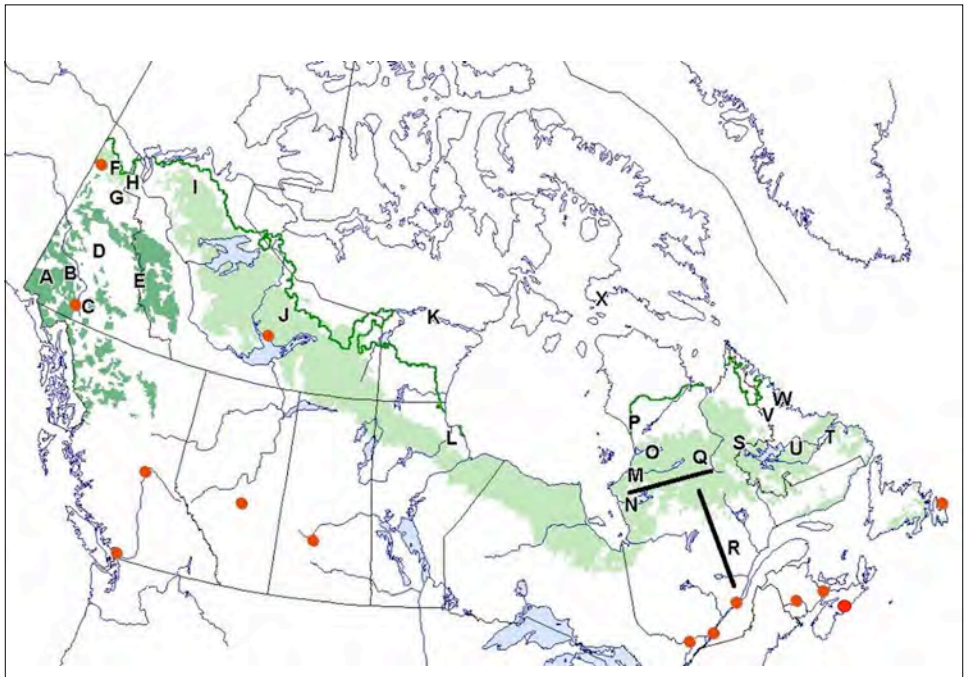
1. Additional parameterization by including other experimental results

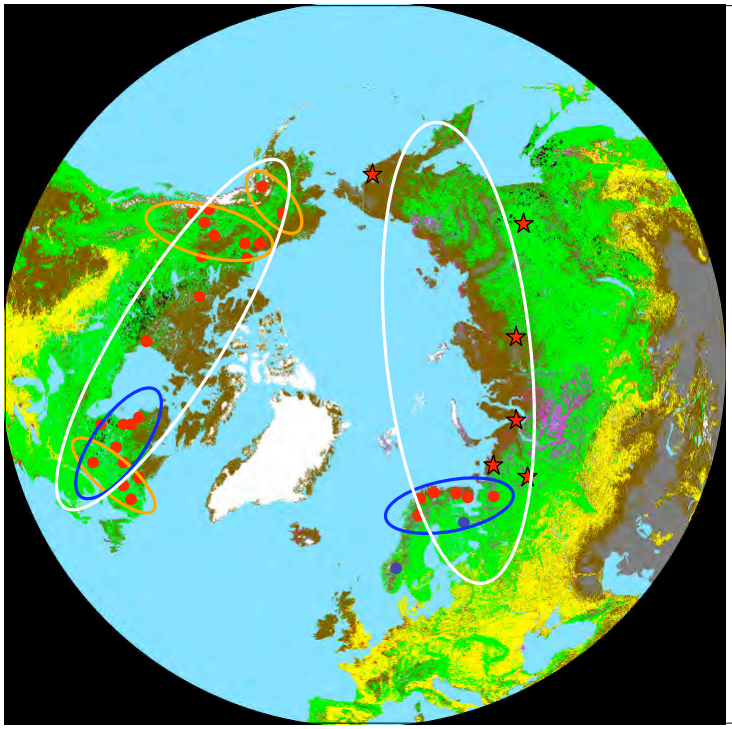


2. Evaluation of multispectral data (jointly with NASA)



3. Test predictive ability of models at other sites





PPS Arctic

- active/proposed
- links/proposed
- non arctic

Canada: 21

Barents region: 9

Alaska: 2

Russia: 4 + ?

Summary

Snow is a critical variable and we need better ways to measure it.

New predictive tools being developed to model species and communities at higher resolution.

Biotic interaction matter but need detailed process information to feed models (experiments).

Long-term observations are essential.