Changing Views of a Changing Arctic Carbon Balance

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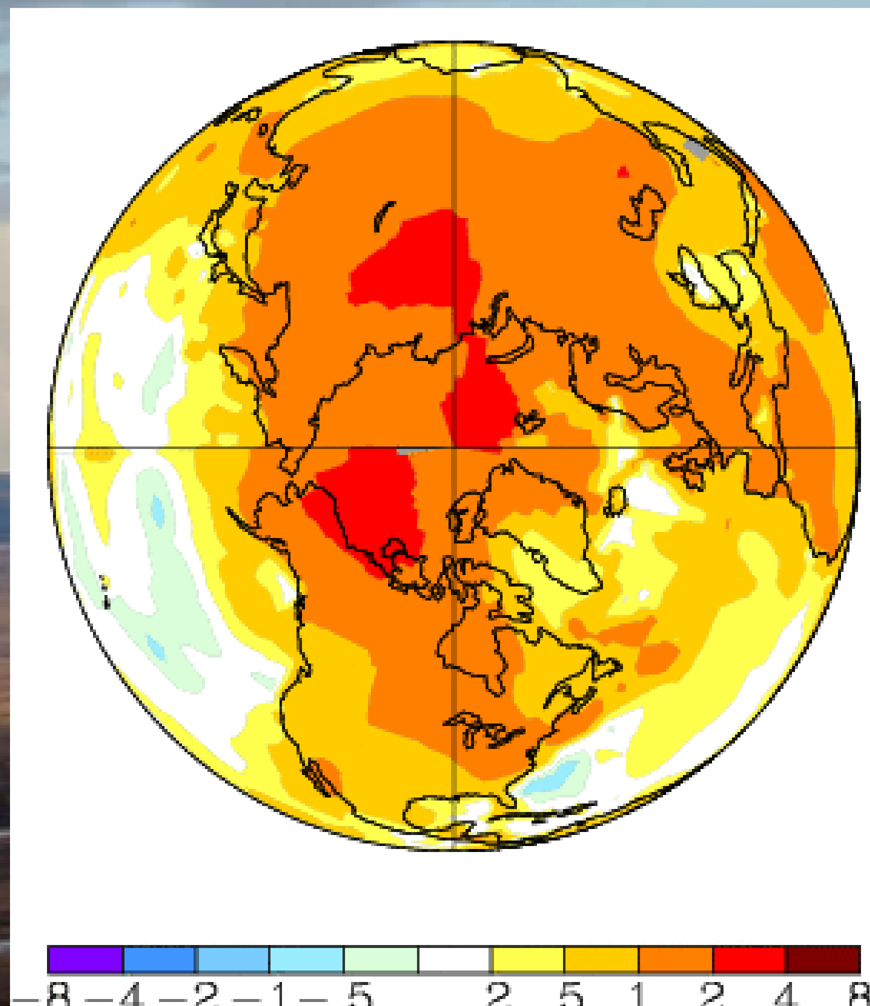
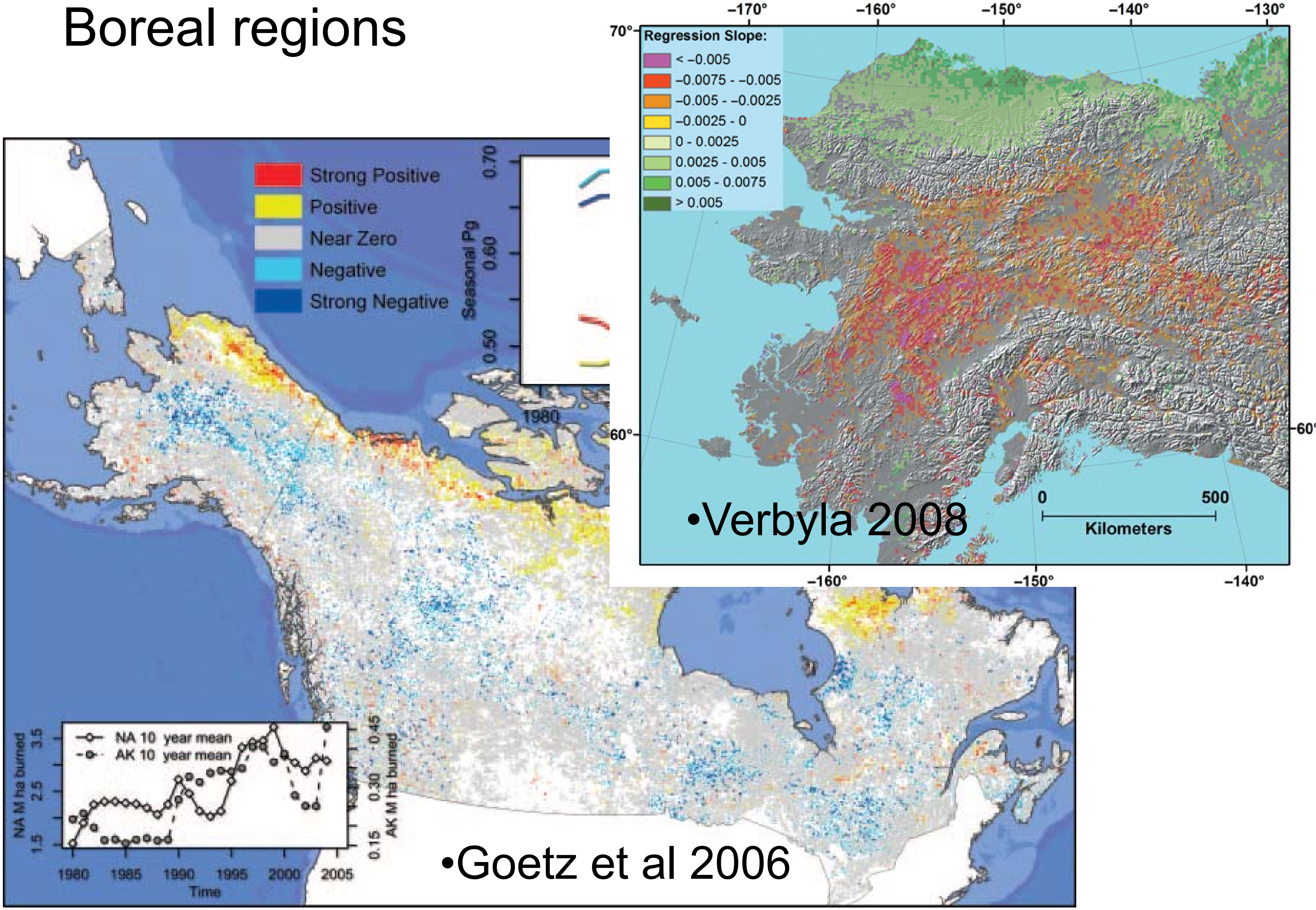
The heat is on!

Total change in annual mean surface air temperature (°C), 1958-2007 ***[from J. Walsh]***



The Greening and the Browning of the Arctic and Boreal regions



•Goetz et al 2006

•Verbyla 2008

How can we evaluate these changes against a background of much greater variability in C stocks and turnover?

Productivity, for example, varies by 3 orders of magnitude among arctic ecosystems

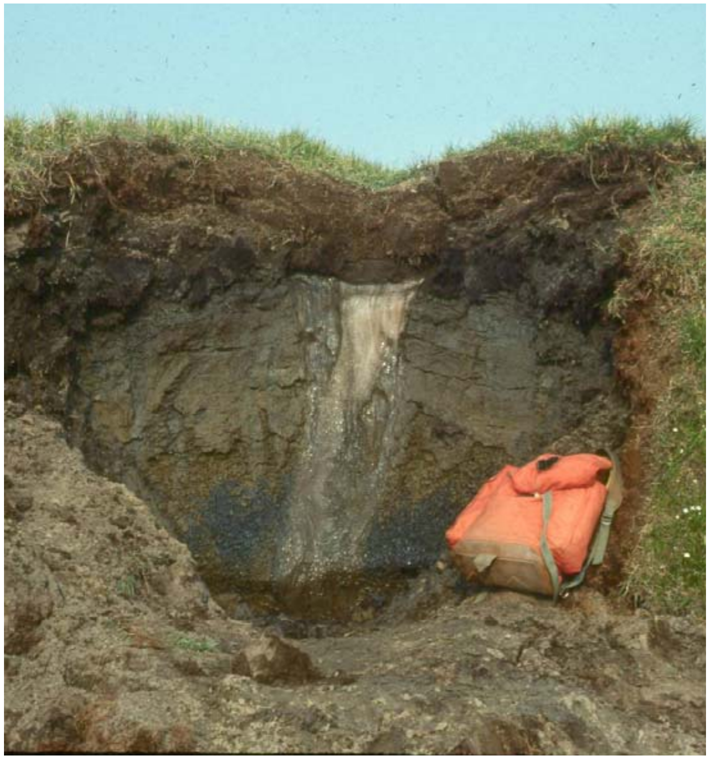
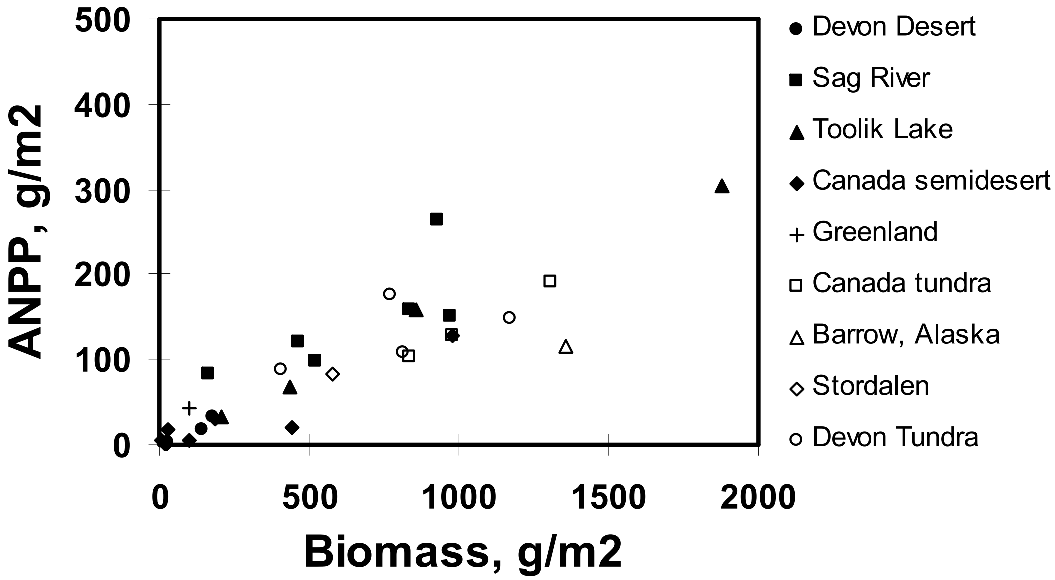
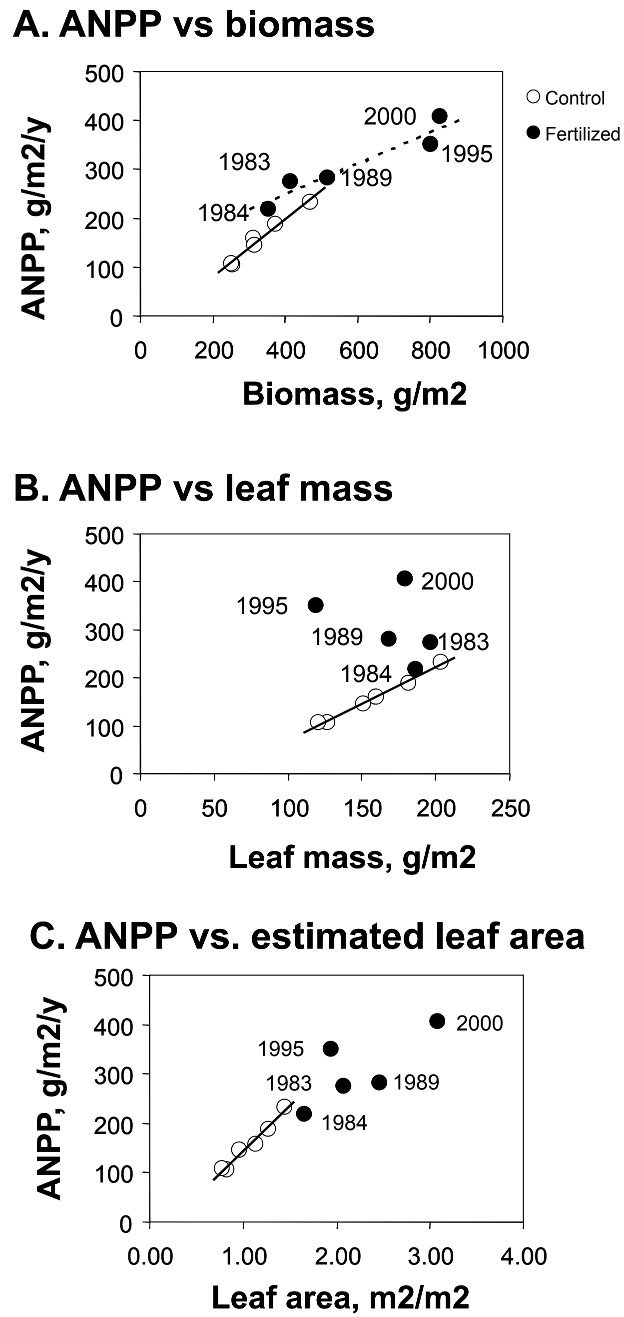


Table 6.10. Soil organic matter, plant biomass, and net primary production (NPP) in the main Arctic ecosystem types. After Jonasson et al. (2001) based on data from Bliss and Matveyeva (1992) and Oechel and Billings (1992).

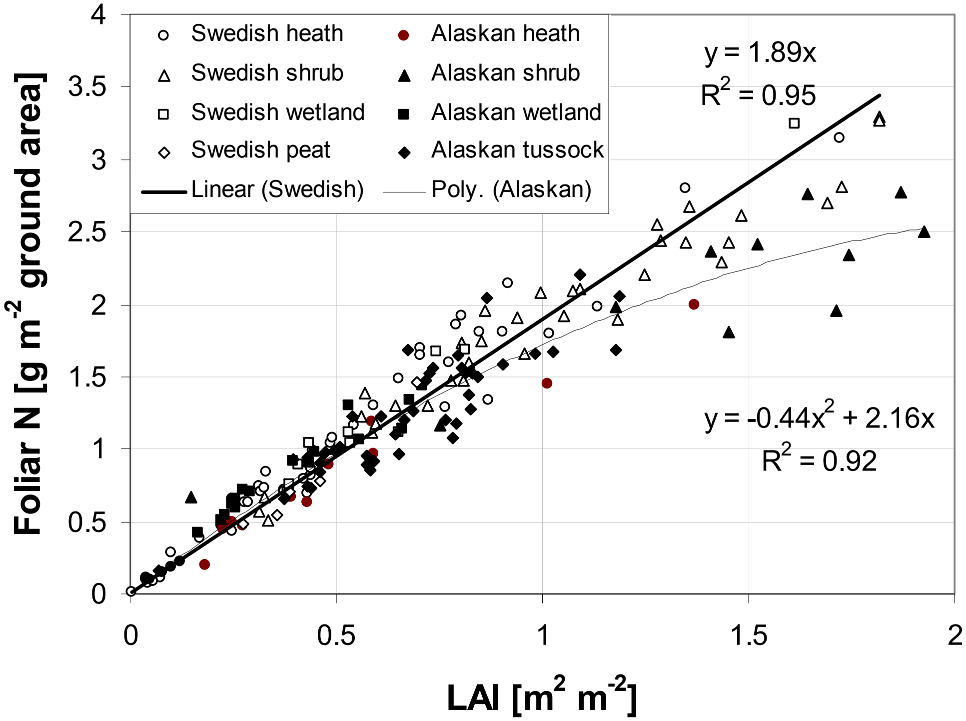
	Soil organic matter (g/m^2)	Vegetation biomass (g/m^2)	NPP ($g/m^2/y$)	Soil: Vegetation	Soil:NPP	Veg:NPP	% of total area
			High Arctic				
Polar desert	20	2	1	10	20	2.0	15
Semi-desert	1030	250	35	4.1	29	7.1	8
Wet sedge/mire	21000	750	140	28	150	5.4	2
			Low Arctic				
Semi-desert	9200	290	45	32	204	6.4	6
Low shrub	3800	770	375	4.9	10	2.1	23
Wet sedge/mire	38750	959	220	40	176	4.3	16
Tall shrub	400	2600	1000	0.2	0.4	2.6	3
Tussock/ sedge dwarf shrub	29000	3330	225	8.7	129	16	17





Production:Biomass relationships are continuous across a wide range of very different vegetation types, even under rapid change

Shaver et al. 1996, 2001



LAI-Canopy N relationship is constant across most vegetation types at Toolik Lake, Alaska, and Abisko, Sweden (van Wijk et al. 2005)

Observed LAI-N relationship optimizes GPP (Williams and Rastetter 1999)

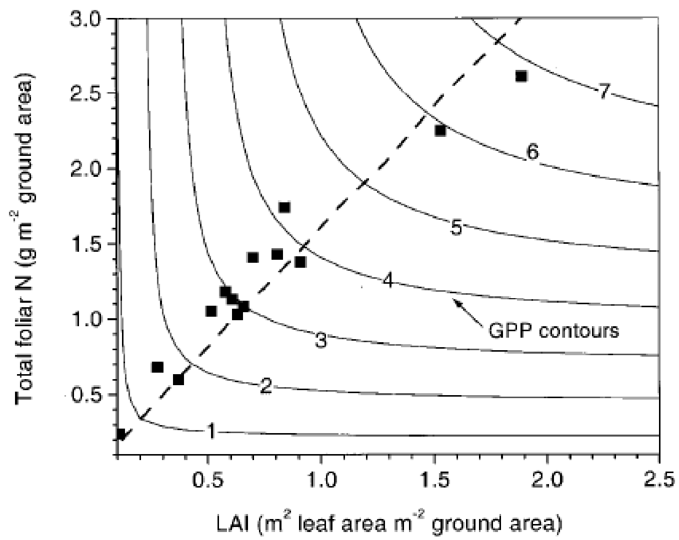
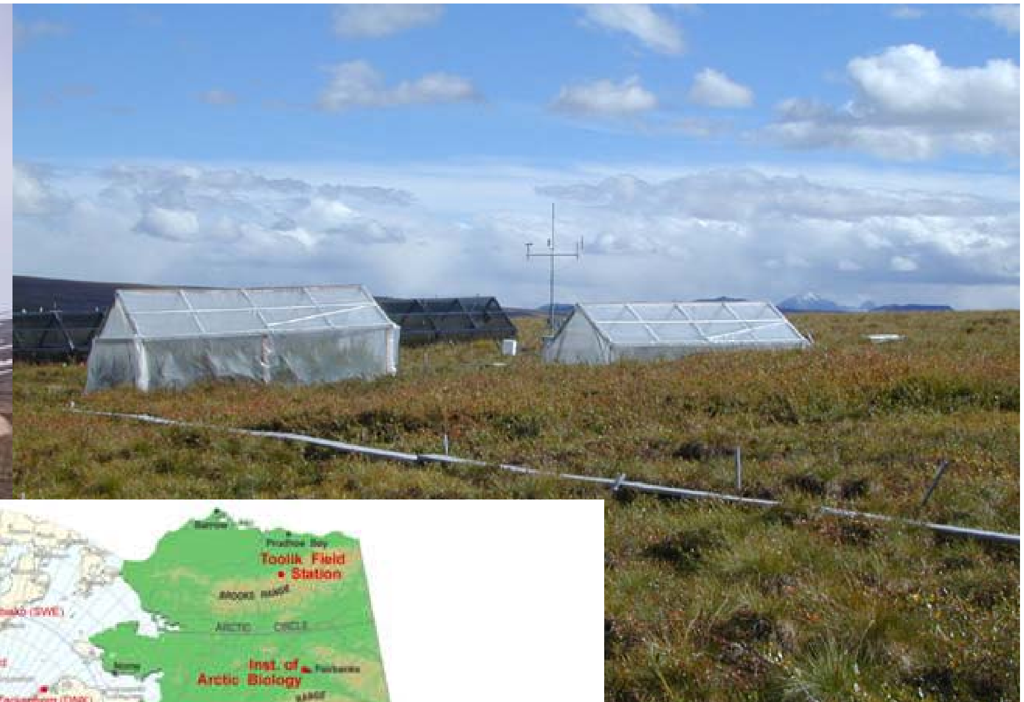
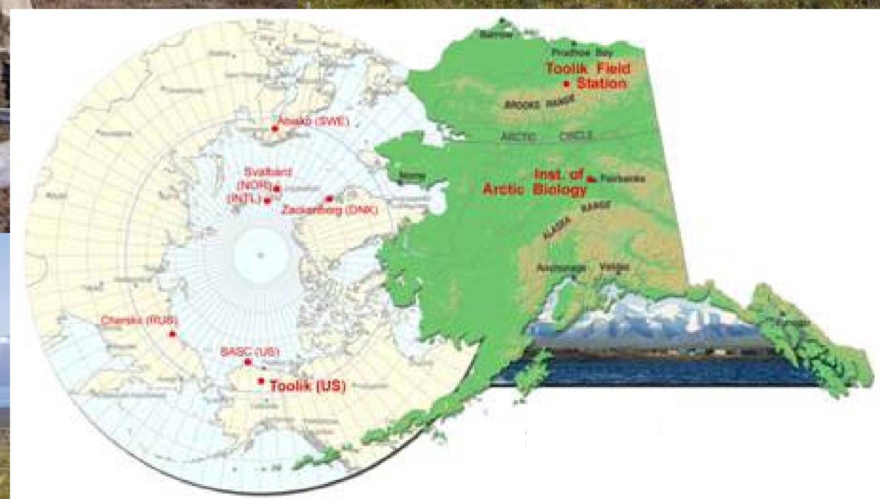


Fig. 6 The modelled response surface of GPP of vascular plants (contour lines, g C m^{-2} day^{-1}) to combined variations in LAI (L; m^2 leaf area m^{-2} ground area) and total foliar N (N; g N m^{-2} ground area). Also shown (symbols) are the LAI–N relationships for the sites along the transect, and the line that connects points on the surface where $\partial P/\partial L = 1.48\ \partial P/\partial N$, where P = GPP.





Prudhoe Bay
Toolik Field Station
BROOKS RANGE
ARCTIC CIRCLE
Inst. of Arctic Biology
Fairbanks
ALASKA RANGE
Anchorage
Valdez
Abisko (SWE)
Svalbard
(NOR)
(INTL)
Zackenberg (DNK)
Cherskii (RUS)
BASC (US)
Toolik (US)

The data base: CO_2 fluxes and light response were measured on a total of 79 plots in 32 different site/vegetation combinations (1454 flux measurements in 125 light response curves). About half of these were in Sweden and half in Alaska.

Abisko, Sweden 2004 (68º 10-20'N, 18 º 45-55' E)

Latnjajaure (elevation 975-1000 m):
12 plots in 6 vegetation types (Dryas, heath, mesic meadow, snowbed, tussock, wet meadow)

Paddus (elevation 580-600 m):
13 plots in 6 vegetation types (Betula, wet fen, heath, rocky, Salix, wet sedge)

STEP site (elevation 725-750 m):
11 plots in 5 vegetation types (Betula, heath, rocky, Salix, wet sedge)

Toolik Lake and Imnavait Creek, Alaska 2003 and 2004 (68° 35-45'N, 149° 35-45'W)

Imnavait Creek 2003 (elevation 875-945 m)
8 plots in 5 vegetation types (Betula, Salix, tussock, heath, wet sedge)

Imnavait Creek 2004 (elevation 875-945 m):
15 plots in 5 vegetation types (Betula, Rubus/Sphagnum, wet sedge, tussock, Salix)

Toolik Lake 2004 (elevation 760-800 m):
20 plots in 5 vegetation types (moist acidic tussock, moist nonacidic tussock, nonacidic nontussock, heath, wet sedge)

….and similar surveys of CO_2 flux at Svalbard and Zackenberg in 2005-2006 and Barrow in 2009

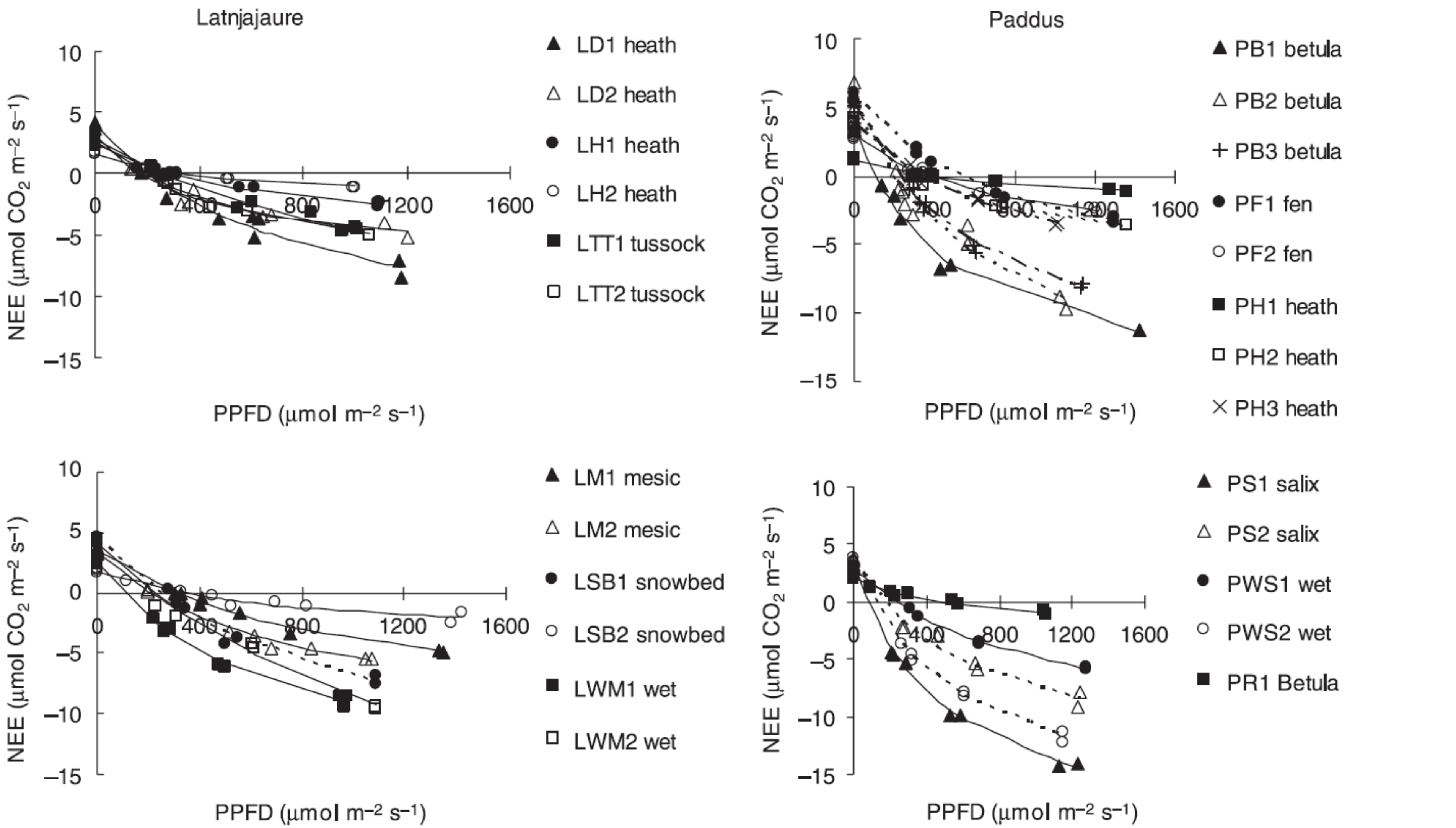
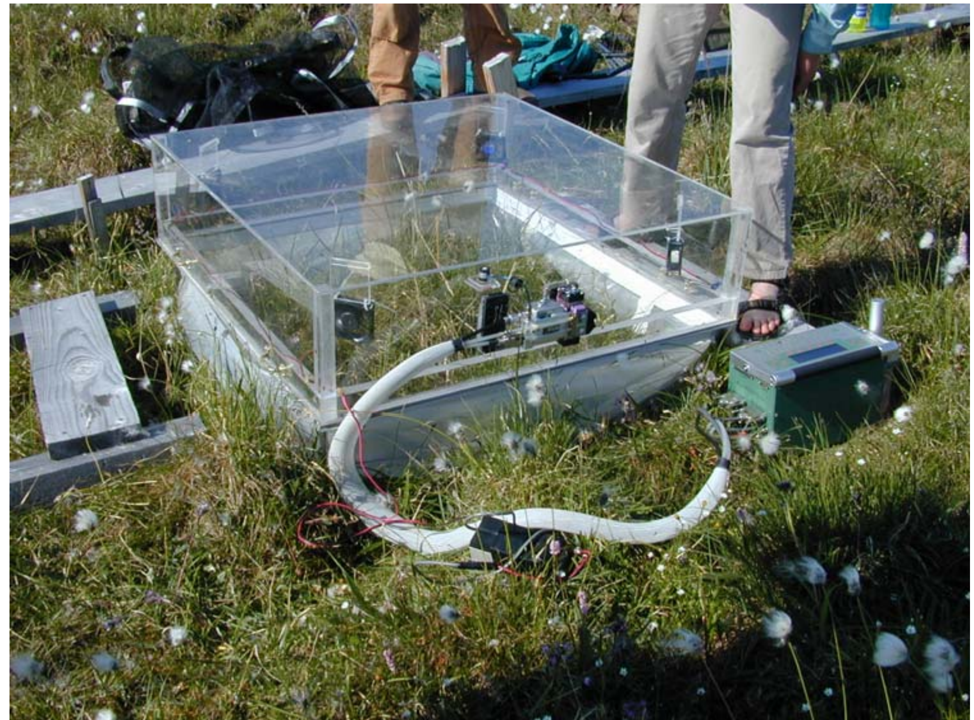


Fig. 1 NEE light response curves from the Latnjajaure and Paddus sites at Abisko, illustrating variation among and within contrasting vegetation types. Data points represent individual NEE and PPFD measurements; different symbols and lines represent data from a single plot.

Controls on NEE

Two approaches:

1. The Arctic as a mosaic of patches with different properties
2. The Arctic as a continuously-varying system



The PIRT model

(Williams et al. 2006)

$$\mathrm{NEE} = R_{\mathrm{b}}\mathrm{e}^{\beta T} - \frac{P_{\max} I}{k + I}$$

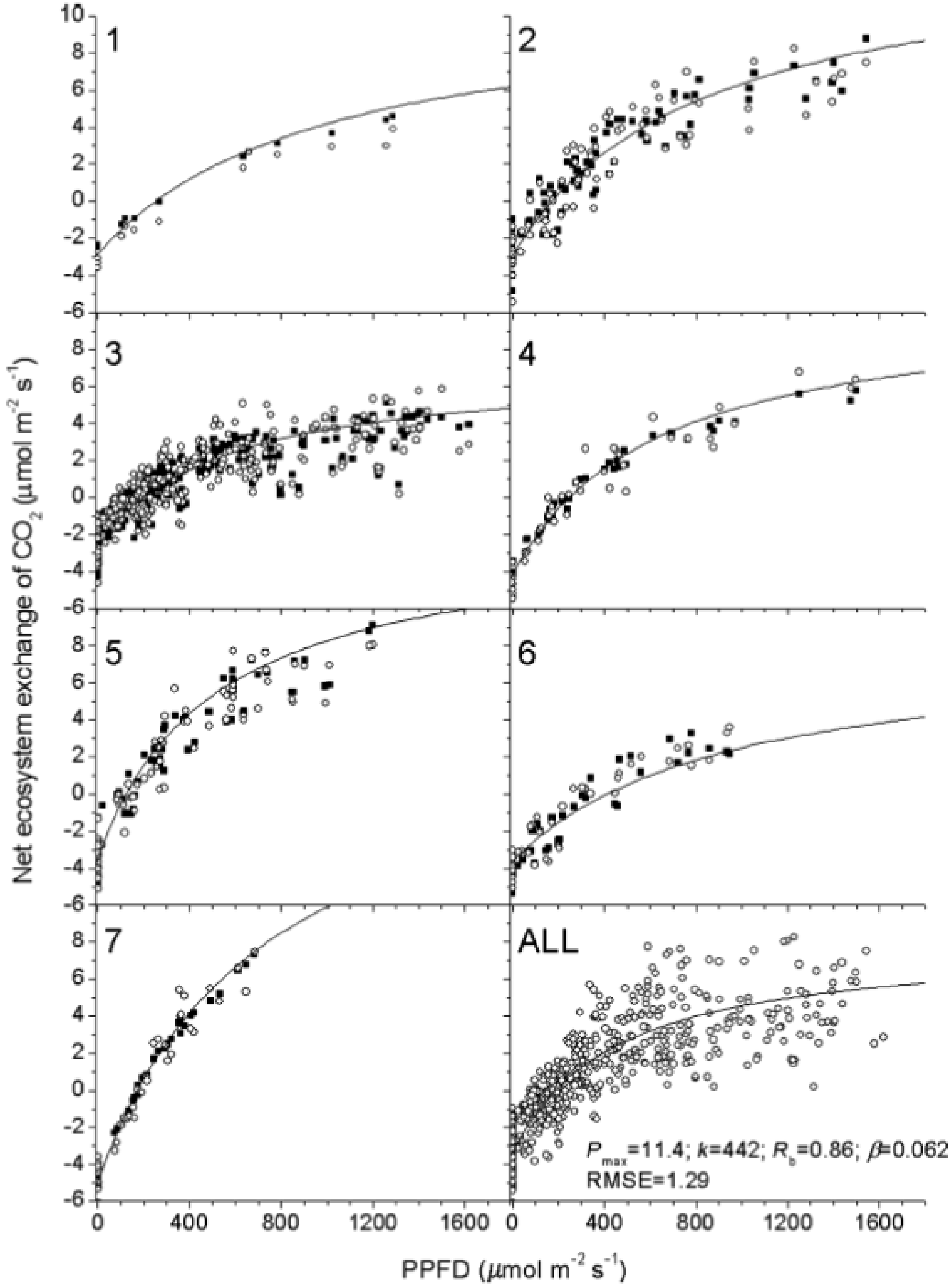
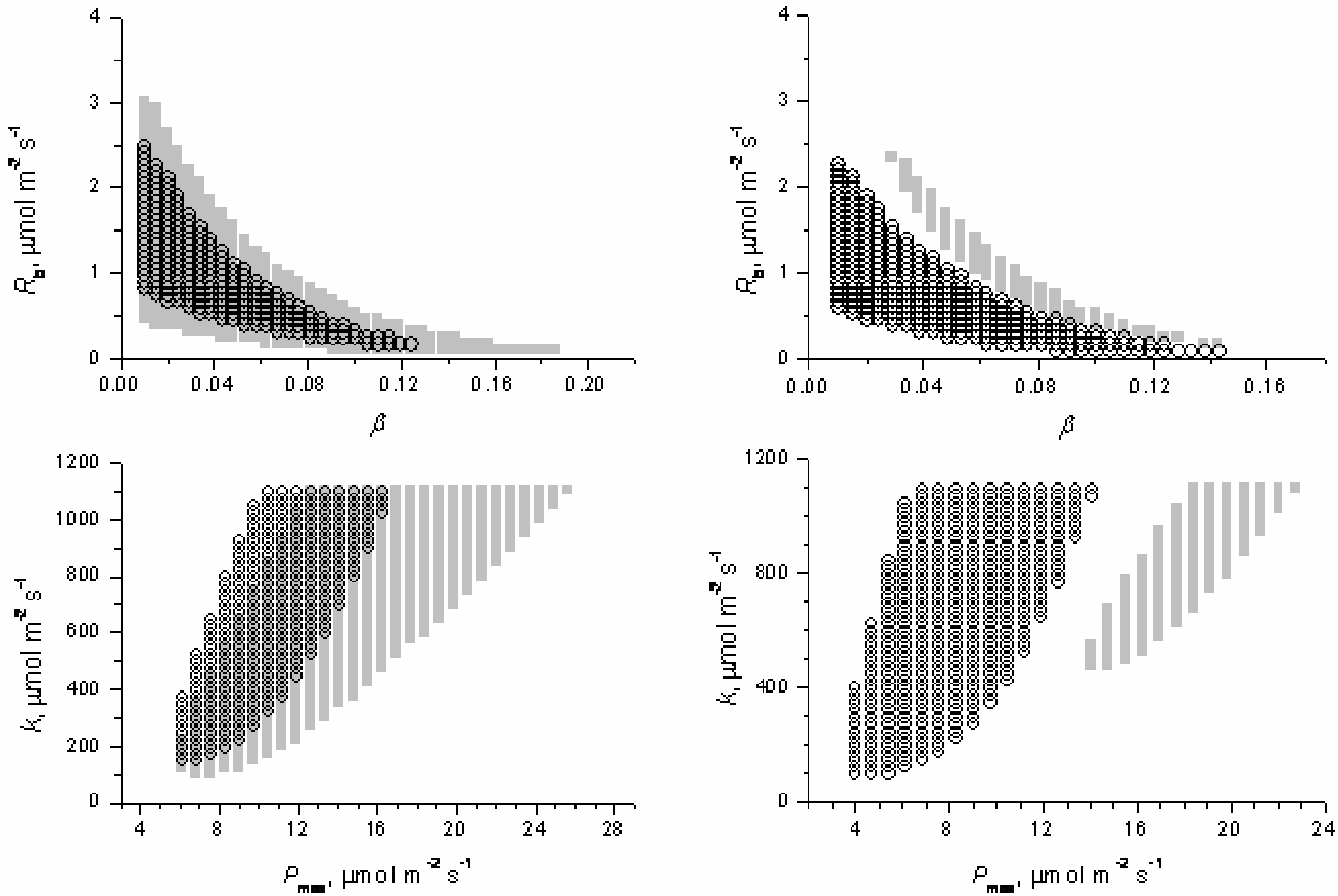


Figure 4. Williams et al. 2006; A comparison of acceptable parameters for the PIRT model applied to paired data sets. The left hand panels compare data collected for plot 1 (wet sedge), in periods 1 (open symbols) and 2 (grey symbols). There is clear parameter overlap for both the photosynthesis and respiration model parameters, indicating similar functional activity. The right hand panels compare data collected in period 1, for Tussock wet (plot 3, open symbols) and Hilltop heath (plot 7, grey symbols). The lack of overlap in the photosynthesis parameters suggests different functional attributes of these sites. 2.56 million parameter combinations were tested for acceptability at the 95 % confidence interval for each dataset.



The PIRT model

(Williams et al. 2006)

$$\mathrm{NEE} = R_{\mathrm{b}} \mathrm{e}^{\beta T} - \frac{P_{\max} I}{k + I}$$

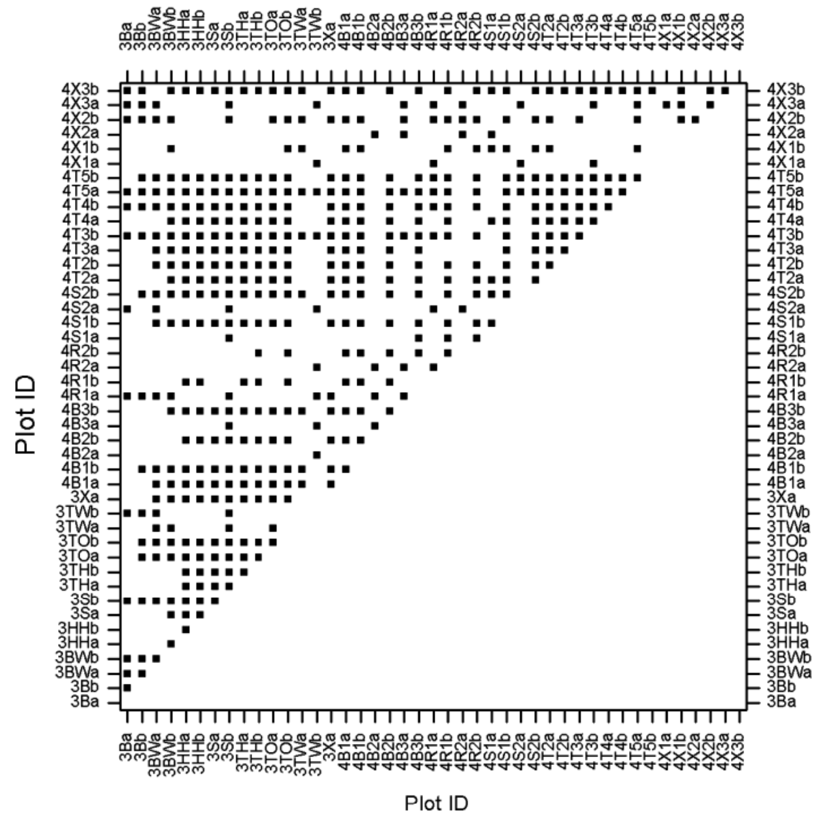


Figure 4. Common parameter analysis of the PIRT model for each site and each time period. *Symbols* indicate that a single parameter set in the PIRT model can acceptably predict C fluxes at both measurement sites and/or periods. The *lack of a symbol* indicates that no common parameters were found (significant at 95% level). Sites and periods are identified by plot ID code (see Table 1). The suffixes *a* and *b* indicate that measurements were from the first or second time period, respectively, for the site.

Table 6. Generic Parameter Sets for the PIRT Model

Generic Parameters	$P_{\max}$	k	R_{b}	β	Number of Acceptable Curves
1	14.1	1000	0.535	0.076	18
2	17.0	825	0.172	0.129	8
3	9.7	550	0.39	0.086	23
4	14.8	625	1.622	0.043	6
5	17.7	500	0.39	0.1	5
6	11.9	525	0.897	0.081	4
7	25.7	725	2.928	0.024	4

$P_{\max}$, k, R_b and β are fitted parameters. The total number of light curves for which each generic parameter set was acceptable is also shown.

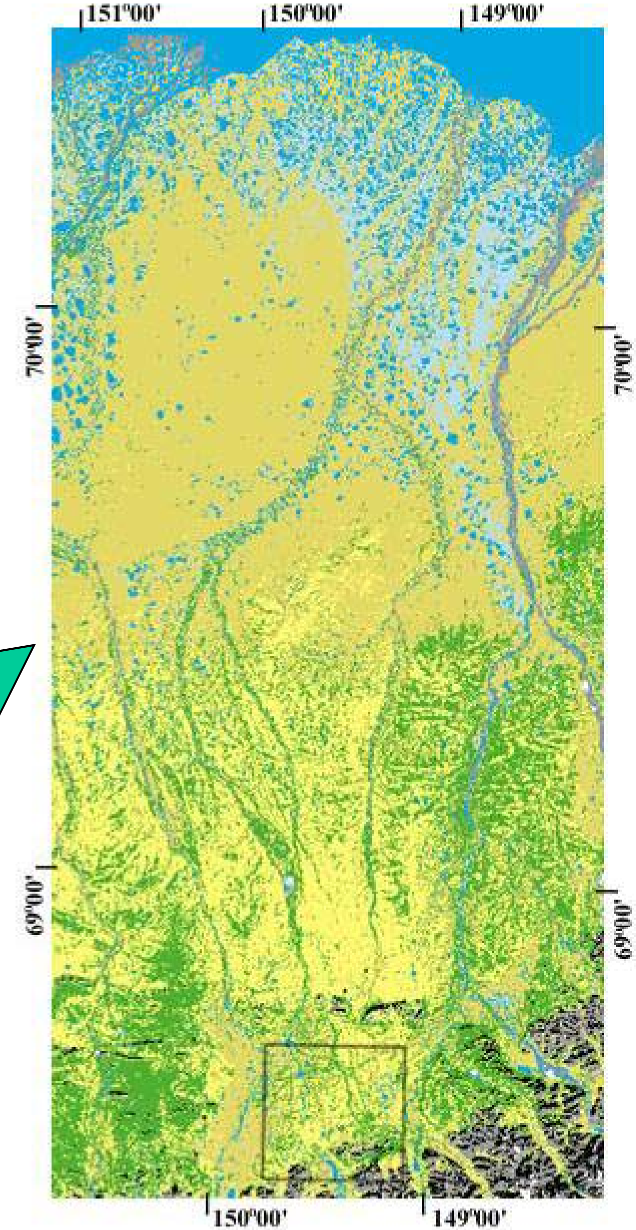
For Imnavait Creek data set:

Mean RMSE of prediction using generic parameters: 0.70 umol m-2 s-1

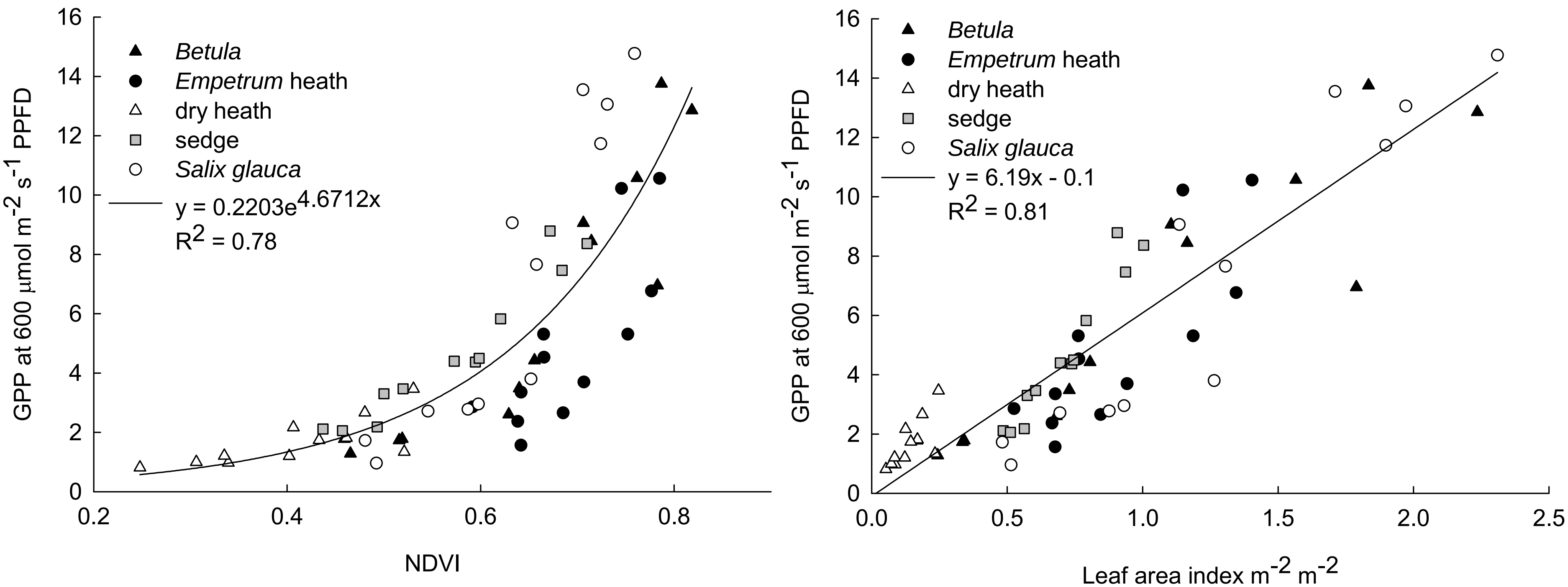
Methodological error: 0.53 umol m-2 s-1

Another problem: Scale of measurement is different from scale of prediction

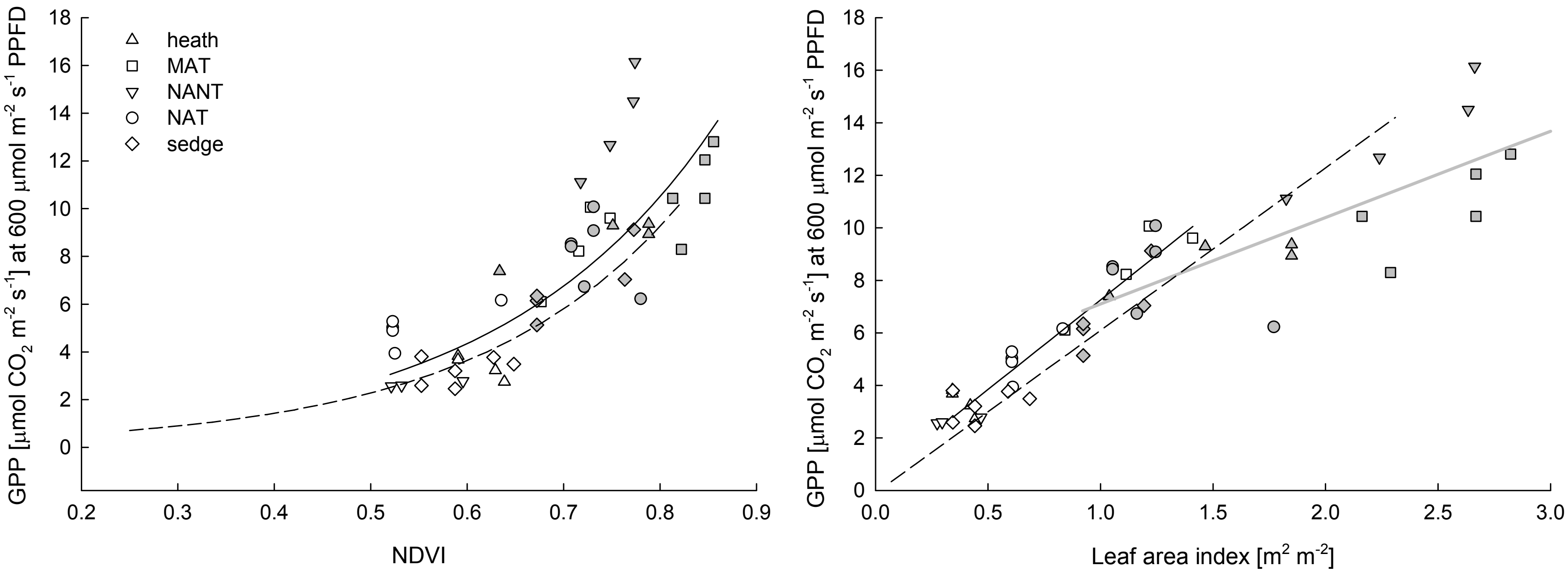
How can we relate plot-scale controls to stocks and fluxes predicted over much larger areas?



Same data, different analysis



Leaf area (and NDVI) alone explains 80% of the variation in canopy photosynthesis (GPP @ 600 μmol PAR) among diverse Low Arctic ecosystems at Abisko, Sweden



Experimental plots in Alaska show the same relationships among photosynthesis, NDVI, and leaf area as in Scandinavia (except at very high leaf area in fertilized plots)

Cross-site modeling:

$$NEE = \left(\left(R_0 * e^{\beta T} * LAI\right) + R_x\right) - \left(\frac{P_{maxL}}{k} * \ln\left(\frac{P_{maxL} + E_0 * I}{P_{maxL} + E_0 * I * e^{-k*LAI}}\right)\right)$$

Where:

NEE is the measured or predicted net CO2-C flux (µmol C per m^2 ground per second)

LAI is leaf area as calculated from the measured NDVI (m^2 leaf/m^2 ground)

I is the measured incident PAR(µmol photons per m^2 ground per second)

T is the air temperature during the measurement (°C)

R_o, R_x, b, P_{maxL}, k, and E_0 are parameters estimated by nonlinear regression

(Shaver et al. 2007)

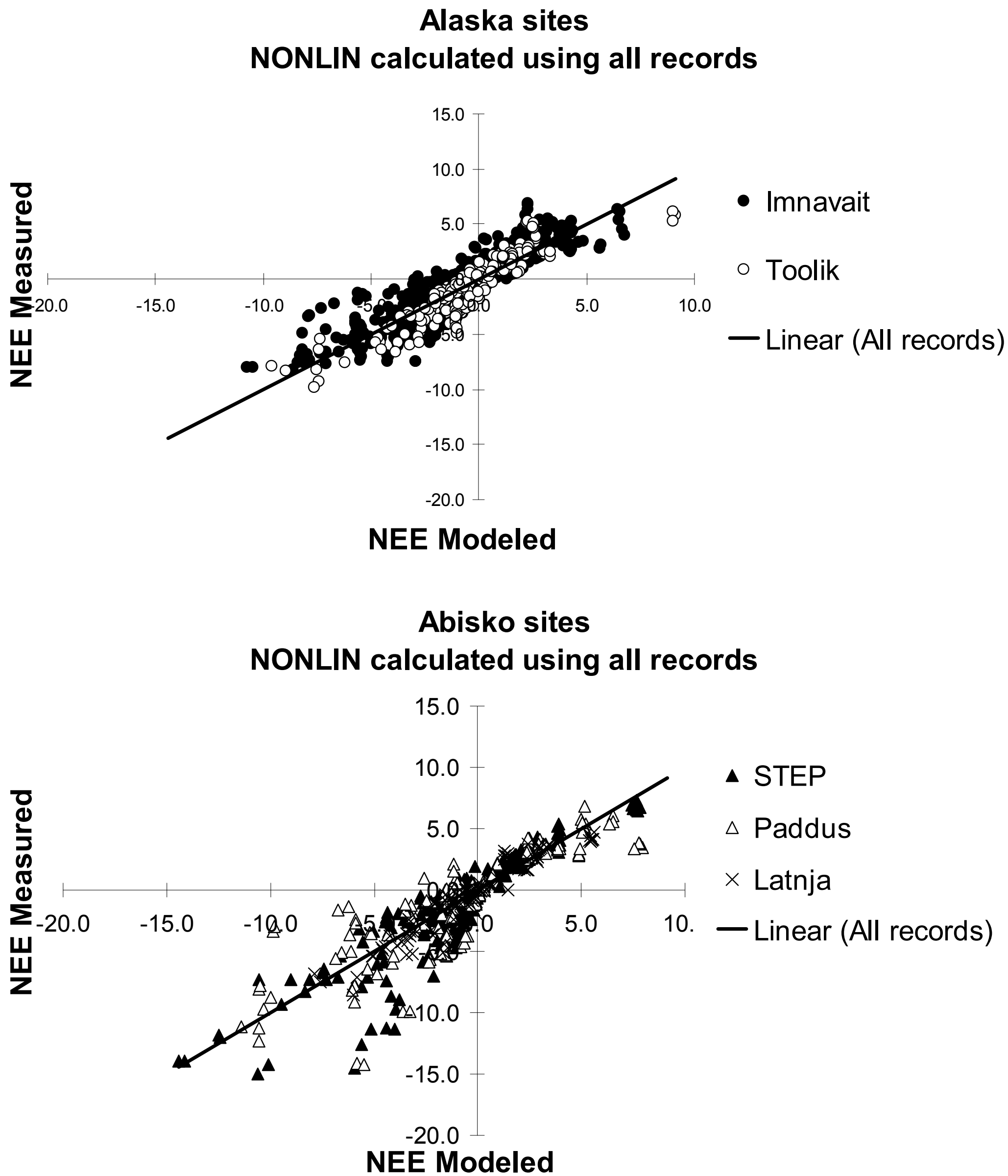
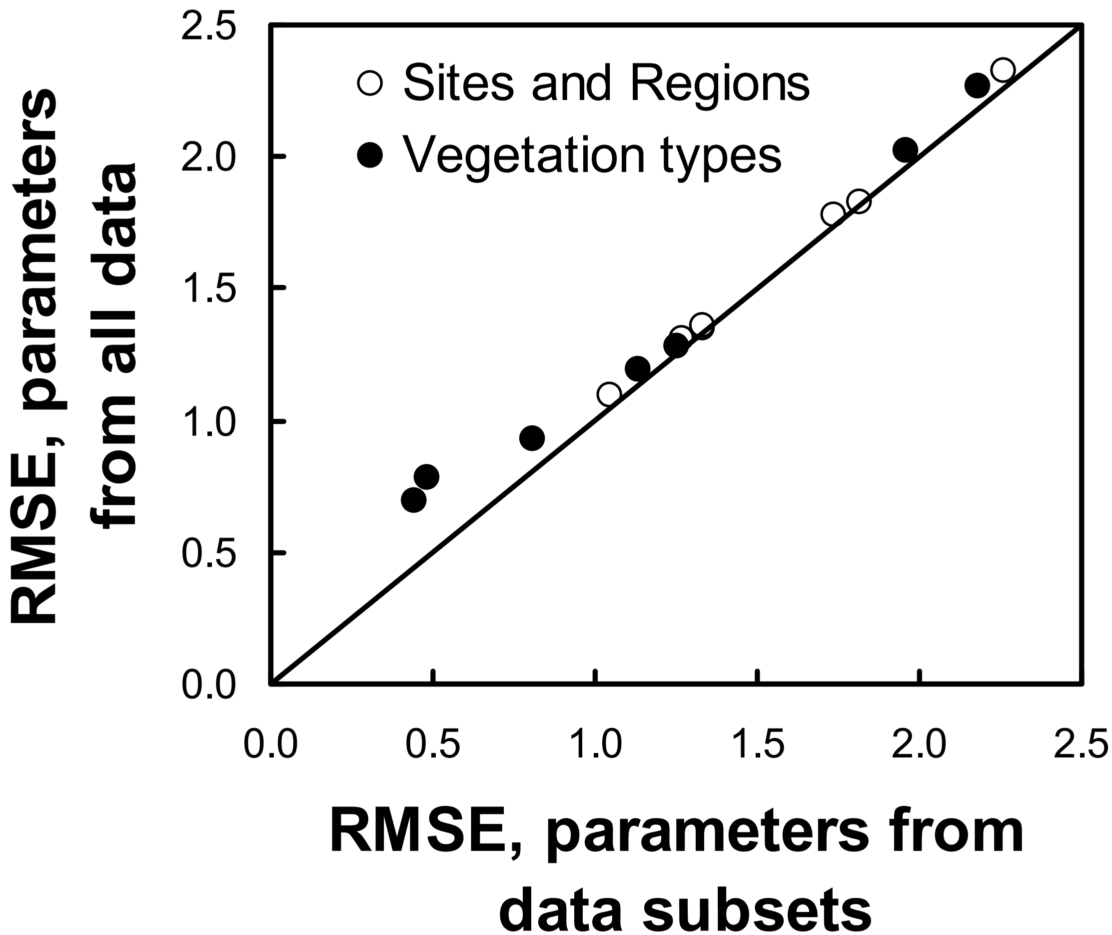


Figure 5. Measured versus modeled NEE, using all available data from 32 site/vegetation type combinations.

$r^2 = 0.799$
slope = 1.000
intercept = 0.000
RMSE = 1.53 μmol m^{-2} s^{-1}

Parameter	All data, all sites	Abisko data only	Alaska data only
P_{maxL}	15.831	14.821	16.579
k	0.500	0.500	0.500
E_0	0.036	0.038	0.035
R_0	0.602	0.608	0.614
β	0.074	0.073	0.075
R_x	0.547	0.410	0.564
RMSE	1.529	1.816	1.337
r^2	0.799	0.803	0.798
Slope	1.000	1.000	1.000
intercept	0.000	0.000	0.000
n=	1410	490	920
Parameters applied to all data, all sites			
Slope & intercept	1.00, 0.00	1.01, 0.19	0.99, 0.11
RMSE	**1.529**	**1.543**	**1.536**
r^2, modeled vs. measured			
All data, all sites	**0.799**	0.798	0.798
Abisko sites combined	0.802	**0.803**	0.800
Alaska sites combined	0.798	0.795	**0.798**

Model parameterized with data from either Abisko or Alaska predicts CO2 flux equally well at either site or in whole data set



Model parameterized with data from any Low Arctic site or vegetation type predicts NEE accurately in other sites or vegetation

Figure 4. Root Mean Square Error (RMSE, μmol m^{-2} s^{-1}) for predictions of NEE in individual sites, regions, or vegetation types when the NEE_2 model parameters are developed by regression on the same data subsets (horizontal axis) or on the whole data set (vertical axis). Points above the 1:1 line indicate larger RMSE, and thus less accuracy, using the whole data set.

Patch models vs continuous variation

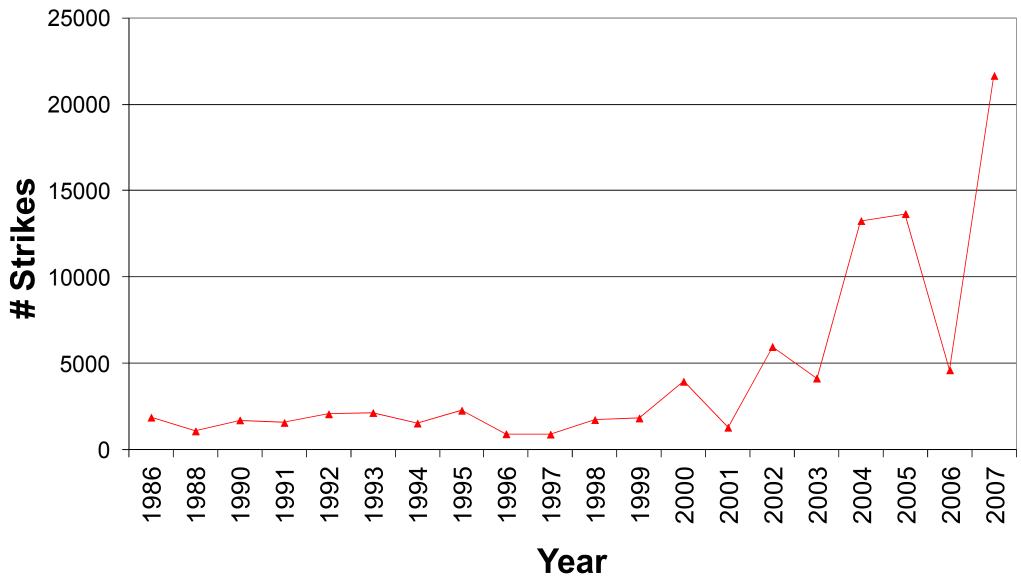
- Patch models can be very accurate (RMSE only slightly larger than measurement error) but require separate parameterization of each patch type
- Patch models are subject to additional errors of classification and within-patch variation
- Continuous variation model has about 2x larger RMSE than patch model but requires only a single parameterization
- Continuous variation model parameterized with data from one part of the Arctic can be used to predict CO_2 fluxes in other parts of the Arctic
- In continuous variation model, patch size is the same as the scale of measurements on which predictions are based

But, more importantly:

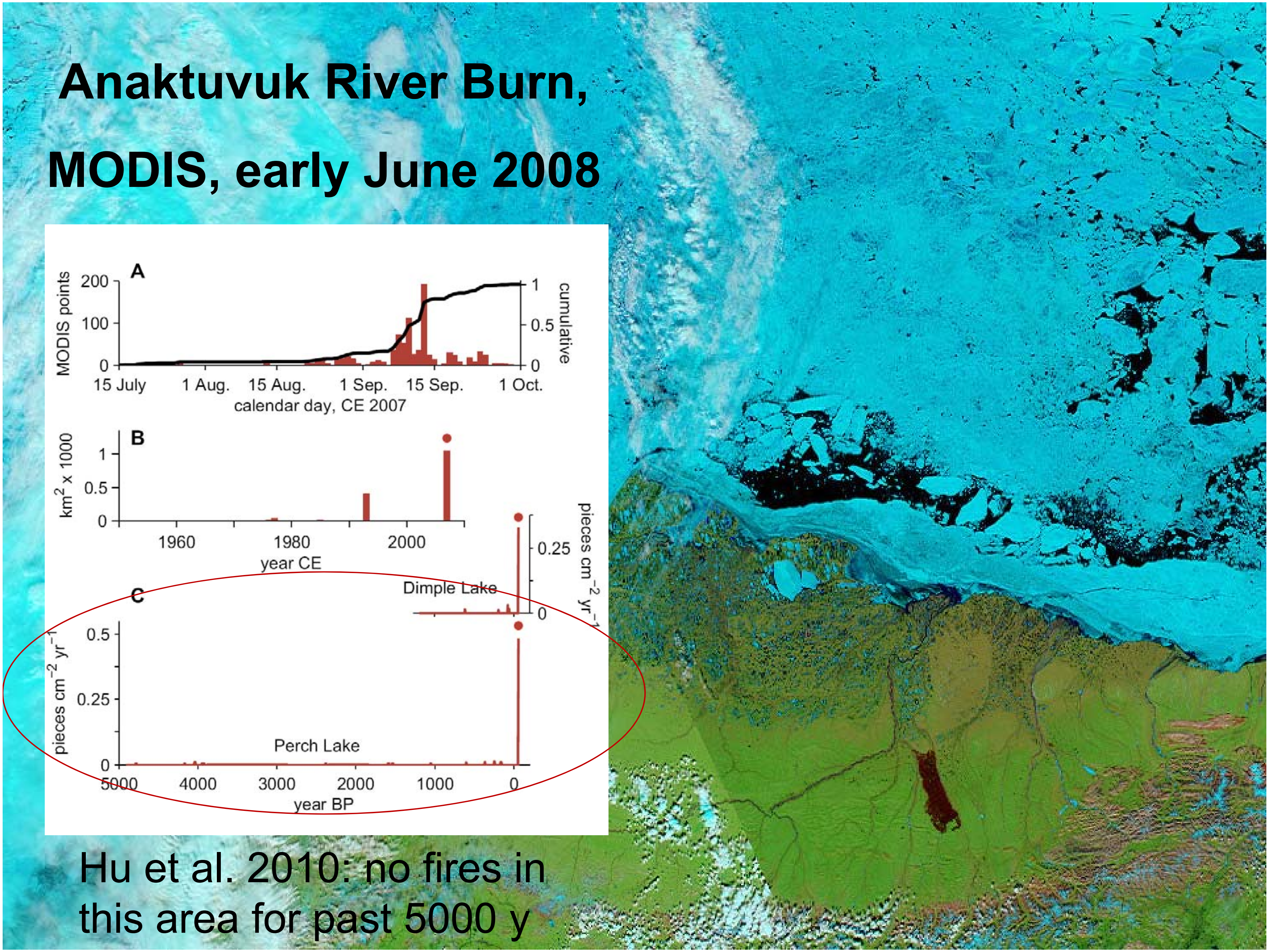
- 80% of the variation in net CO_2 flux (NEE) for a wide range of low arctic ecosystems can be explained knowing only leaf area, air temperature, and light (PAR)
- Species/functional type composition doesn't seem to matter—composition changes dramatically and often abruptly along climatic gradients but NEE changes smoothly with leaf area
- Success of continuous model indicates high level of convergence in canopy structure and function among diverse tundras

Lightning strikes have increased 10-fold since 2000

Lightning detections on the North Slope, 1986-2007 (BLM data)



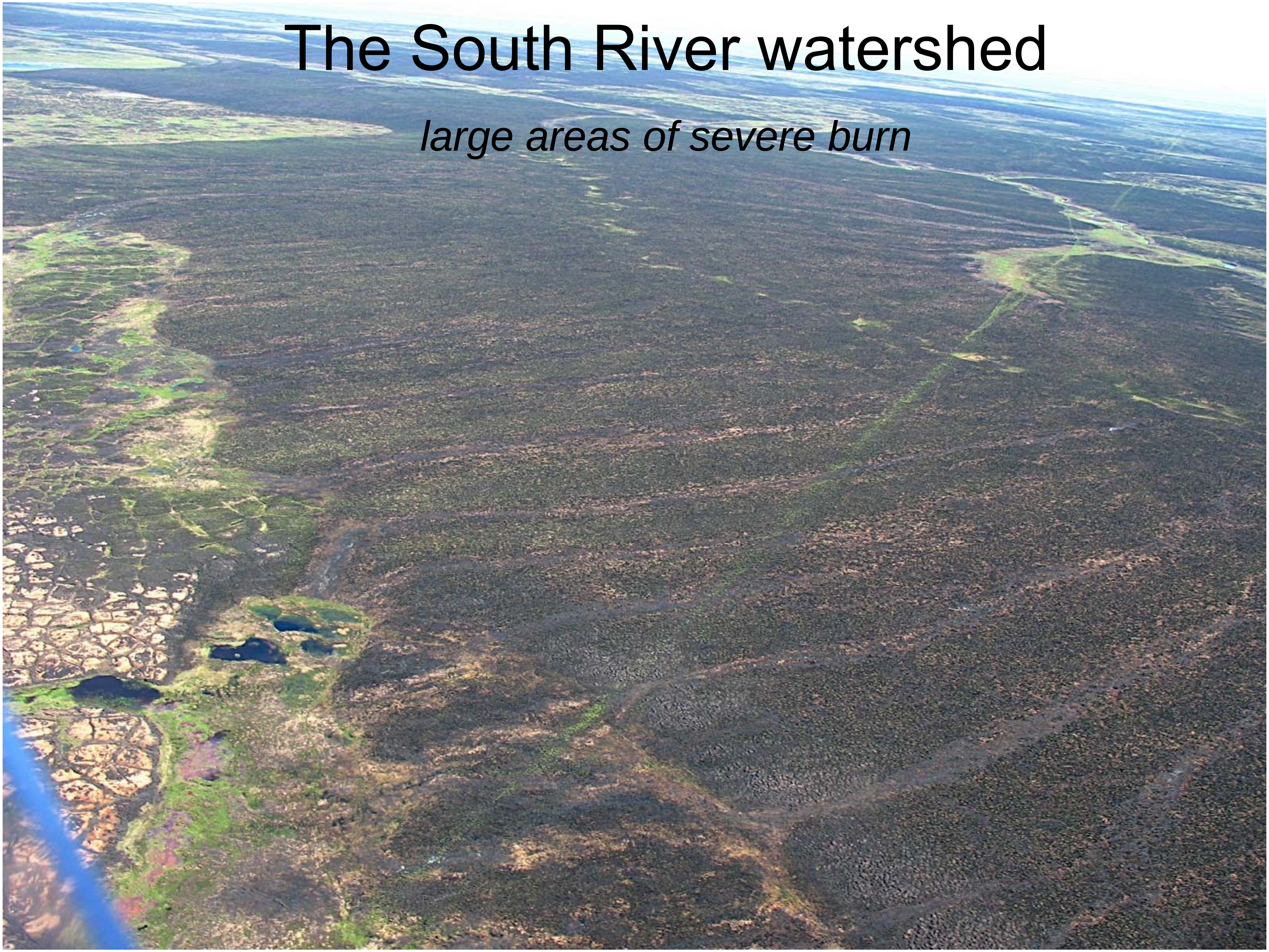
Anaktuvuk River Burn, MODIS, early June 2008



Hu et al. 2010: no fires in this area for past 5000 y

The South River watershed

large areas of severe burn



The Shrew River area

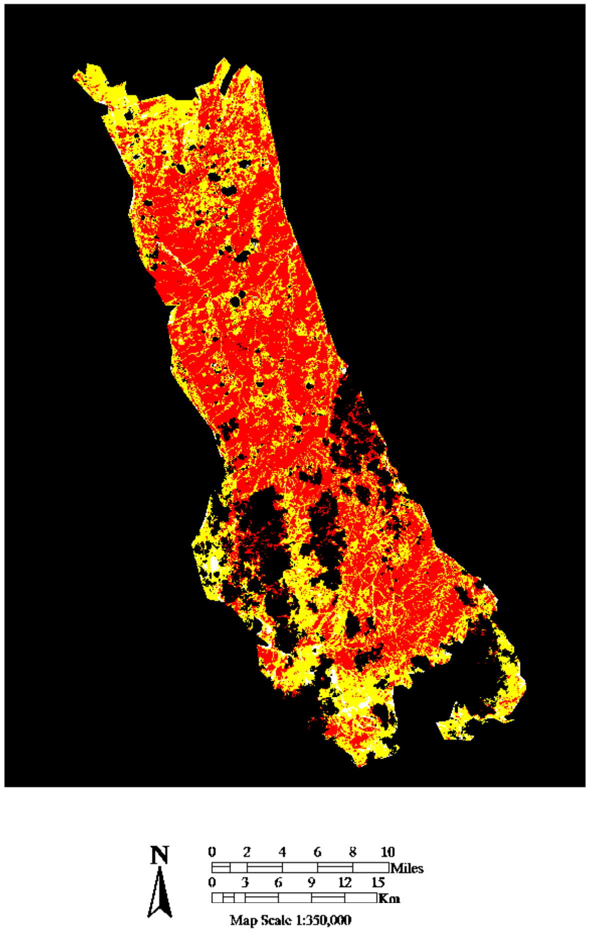
variable burn, less riparian damage

Ice-Wedge Polygons

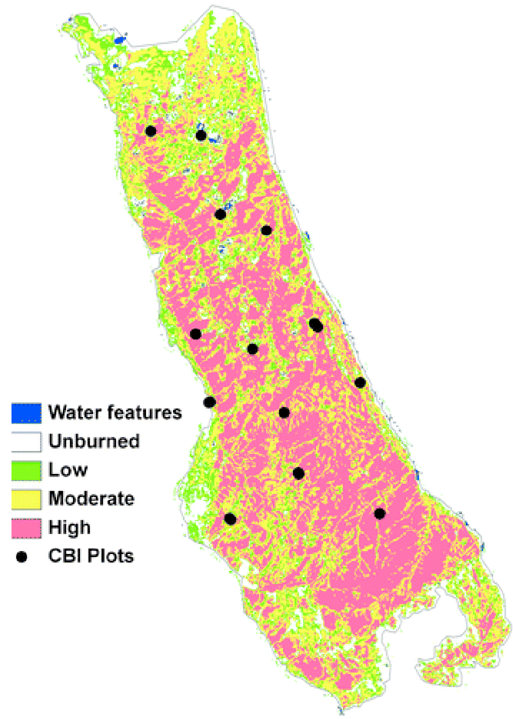
Complete loss of organic mat in some areas


7
8
10
11
12

Boelman et al. 2010

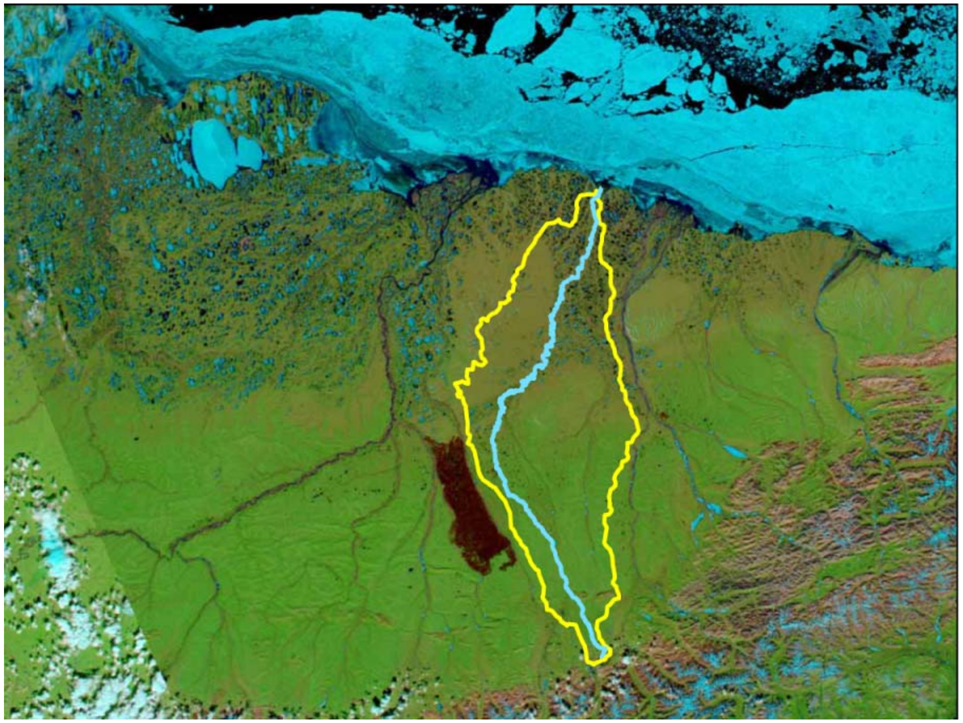


Jones et al. 2009



		Unburned	Moderate	Severe
Burn severity:	% of 1039 km2	3%	34%	63%
	Area (km2)	31	353	655

COMBUSTION LOSSES VS ANNUAL NEE OF KUPARUK BASIN:



Combustion loss was
~2.16 Tg over 1039 km2
(measured by Mack et al 2011)

Annual NEE of the Kuparuk R. catchment: 0.218 Tg net C LOSS (measured 1995-96 by Oechel et al. 2000) or 0.23 Tg net C GAIN (modeled 1980-2100 by McGuire et al. 2000) in 9200 km2.

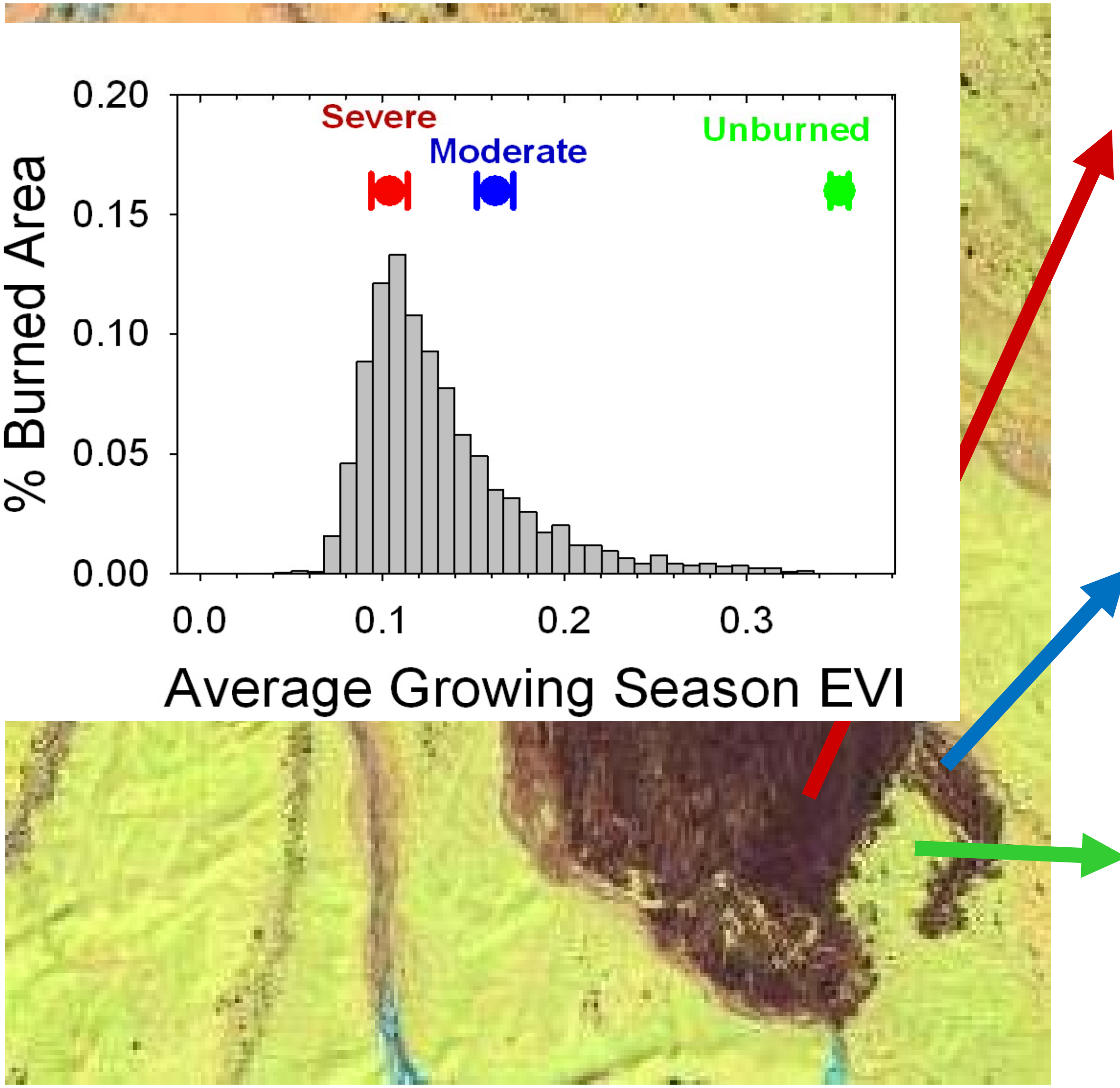
OR: Fire released as much CO2 to the atmosphere as annual NEE of 9-10 Kuparuk River watersheds in ~10-15% of the area of one watershed

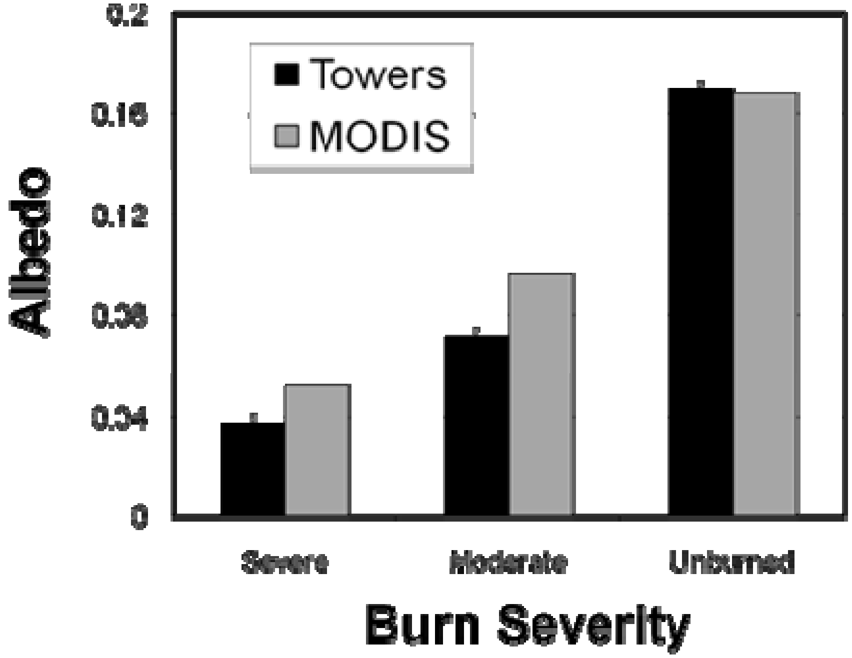
Panarctic tundra biome C sink averaged 3 - 4 Tg C/y over the last 10 years of the 20th century (McGuire et al. 2009).

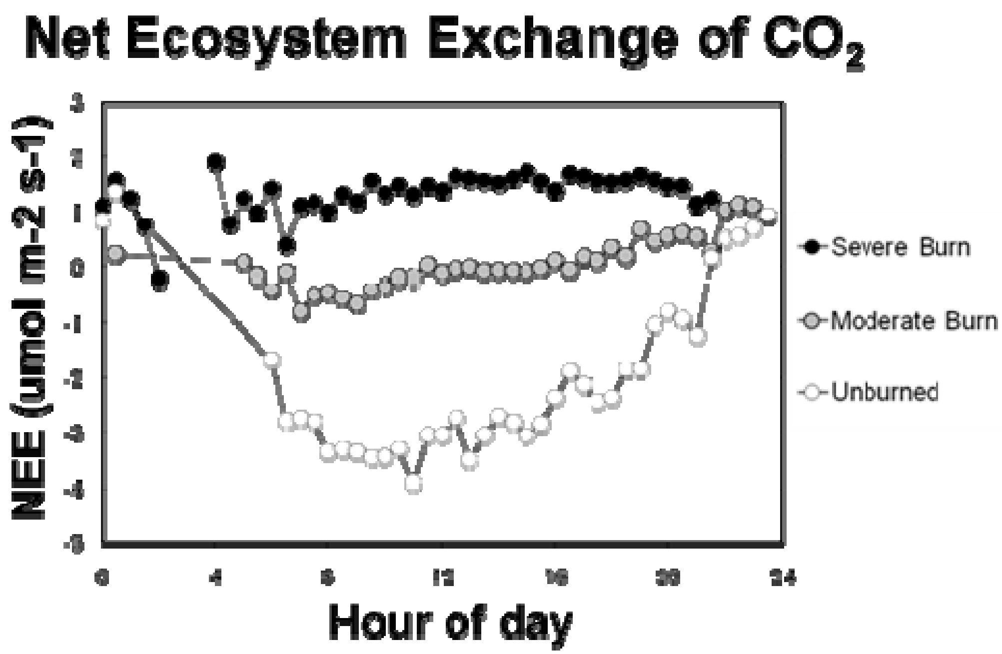
Anaktuvuk River Fire

Area burned : 1039 km2

C released : ~2.16 Tg




Albedo
0.2
0.16
0.12
0.08
0.04
0
Towers
MODIS
Severe
Moderate
Unburned
Burn Severity


Net Ecosystem Exchange of CO_2
NEE (umol m-2 s-1)
3
2
1
0
-1
-2
-3
-4
-5
0
4
8
12
16
20
24
Hour of day
Severe Burn
Moderate Burn
Unburned


Unburned Tundra, 4 July
Severe Burn, 31 May
Severe Burn, 4 July

What controls NEE across burn severity gradient?

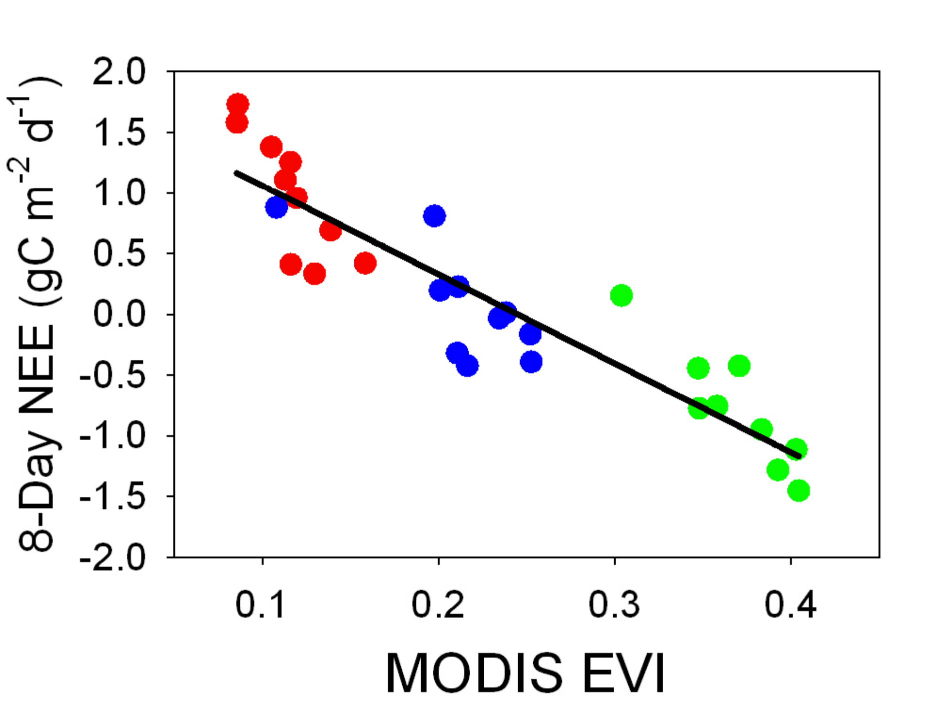
MODIS EVI and NEE correlated

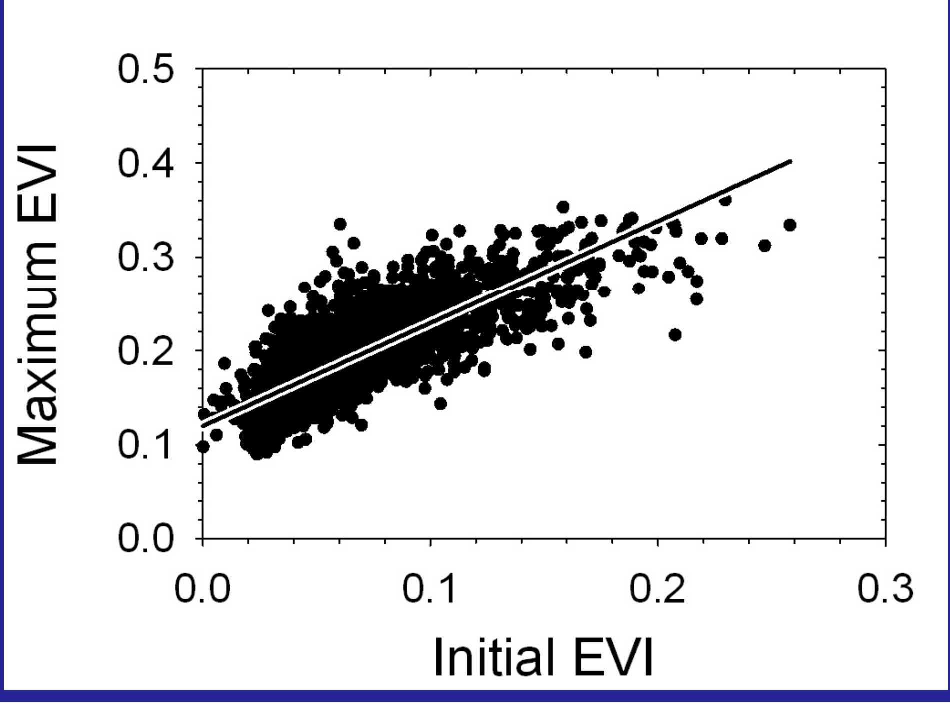
NEE controlled by LAI

Does burn severity control recovery of LAI in burn?

Burn severity = Initial EVI

LAI recovery = Max EVI





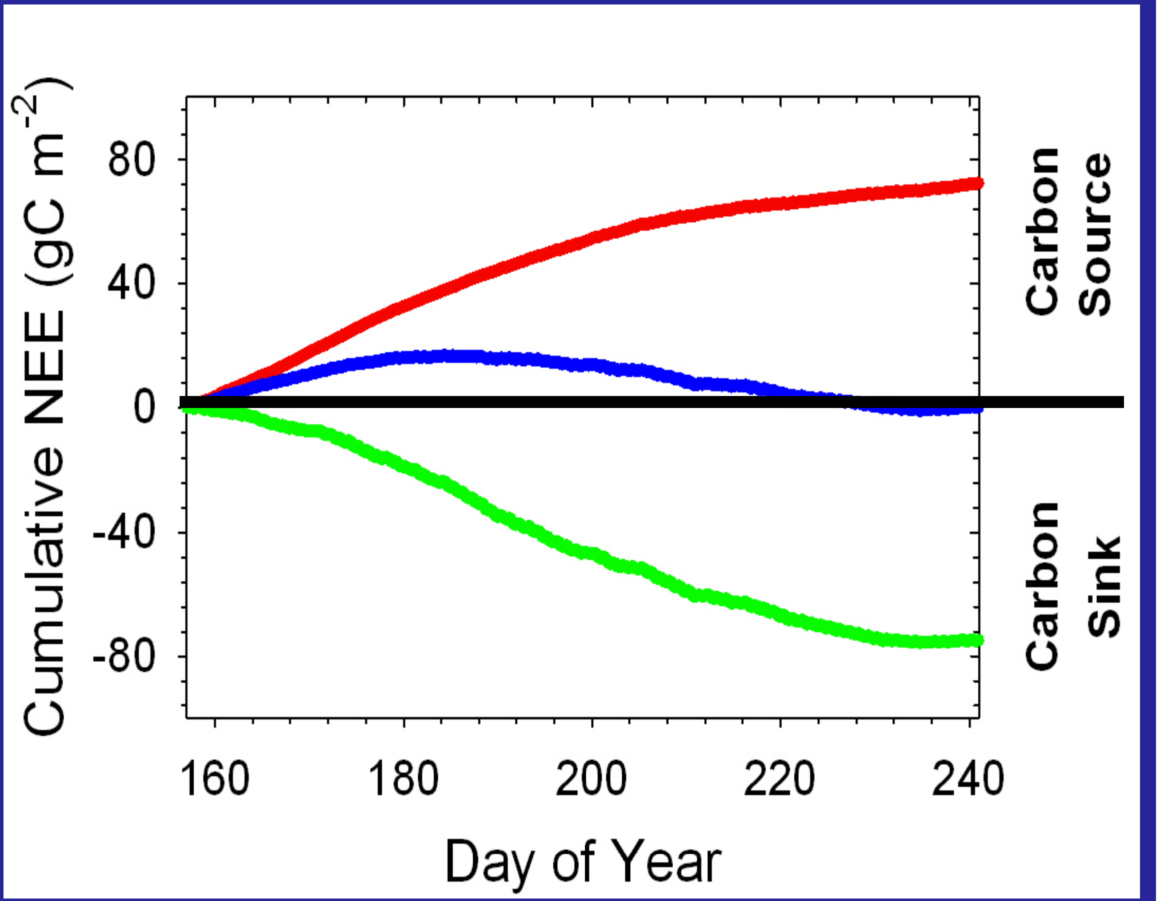
How did burn severity influence the growing season carbon balance?

Sink strength decreased with burn severity

Severe site CO_2 loss

Moderate site small CO_2 source or sink

Unburned site CO_2 gain

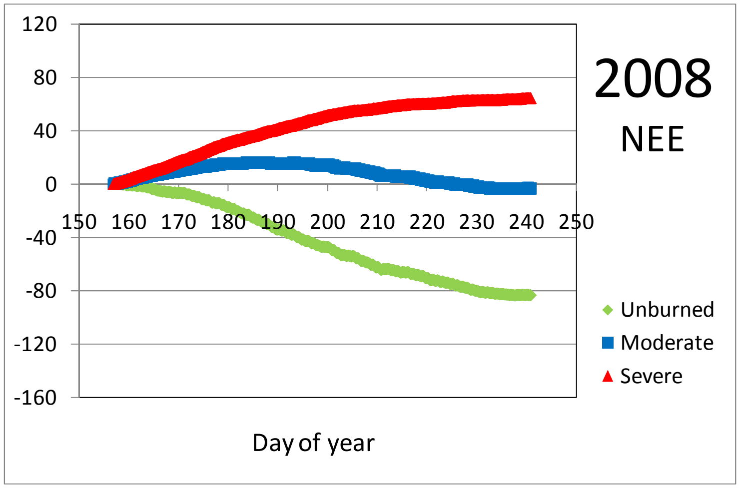


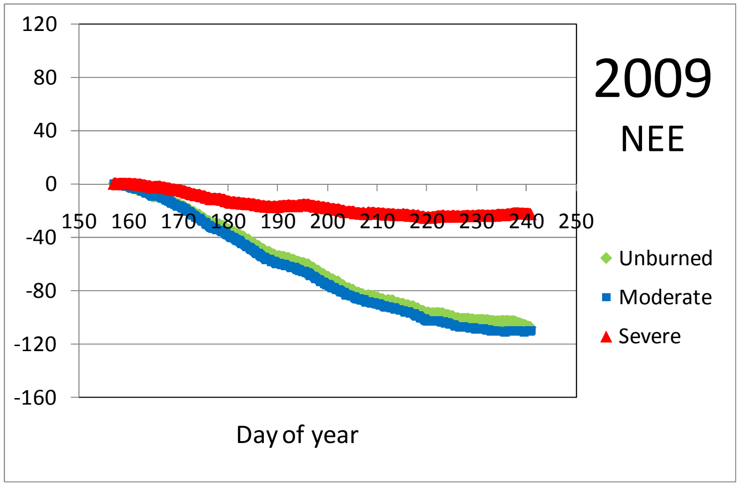
Summary of initial changes in C balance due to climate change and fire

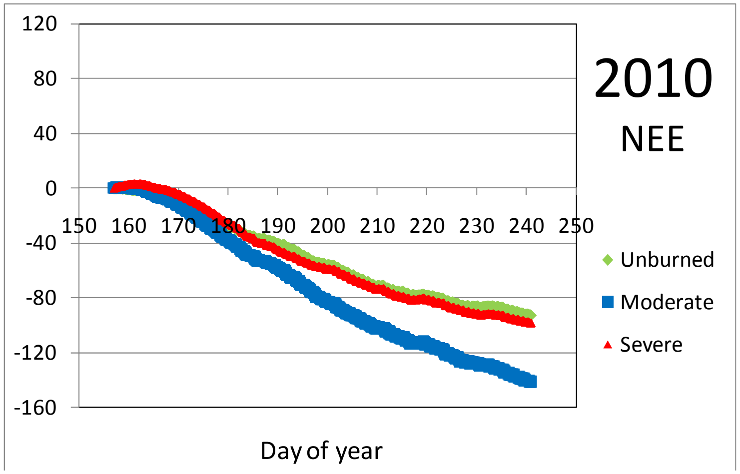
	Yearly NEE	Change in NEE in 1 year due to:			
	(mean predicted)	Warming	Combustion	Recovery	Aquatic loss
Area:			2007	2008	2008
one m2	-15 gC	< -1 g C	2.02E+3 gC	80-140 g C	1-2 g C
AR Burn	-15.6E+09 gC	<-1.04E+09 g C	2.09E+12 gC	1.25E+11 g C	1-2E+09 gC
N Slope	-2.8E+12 gC	<-1.88E+11 g C			

- Combustion losses/m2 were opposite in sign and ~100x annual NEE; combustion losses were >2000x expected gains due to warming alone; losses on AR Burn were >2/3 the yearly C gain of the entire N Slope (200x larger area) and >10x predicted gains due to warming only
- In summer 2008, increased NEE (C loss) in recovering vegetation was 5-9 x predicted gains as annual NEE and >100x changes in NEE due to warming in equal area, and similar (but opposite in sign) to warming gains on entire N Slope
- In summer 2008, aquatic losses in burned catchments were10% of unburned NEE and ~1-10x NEE gains due to warming

Continued change in NEE in burned tundra in 2009-2010 (and 2011)



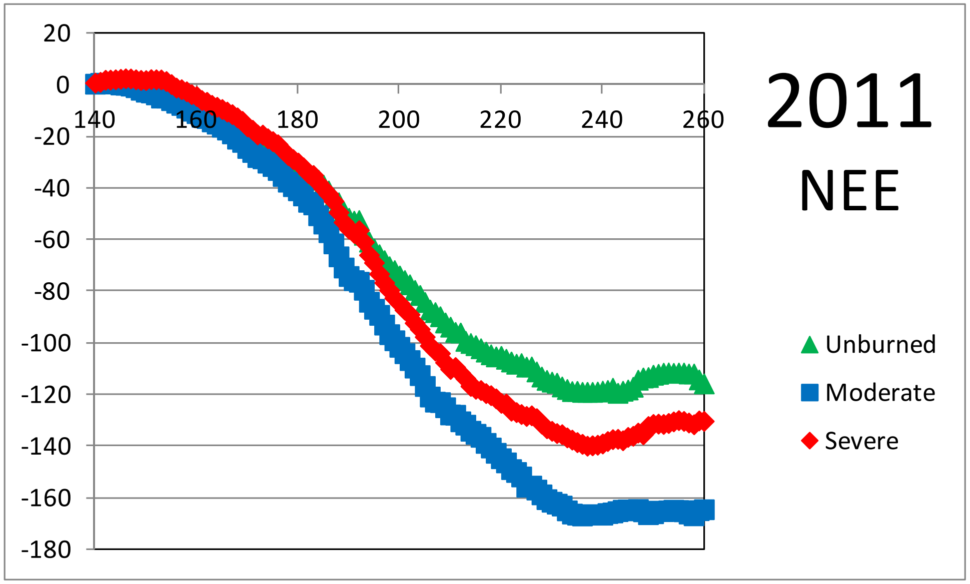


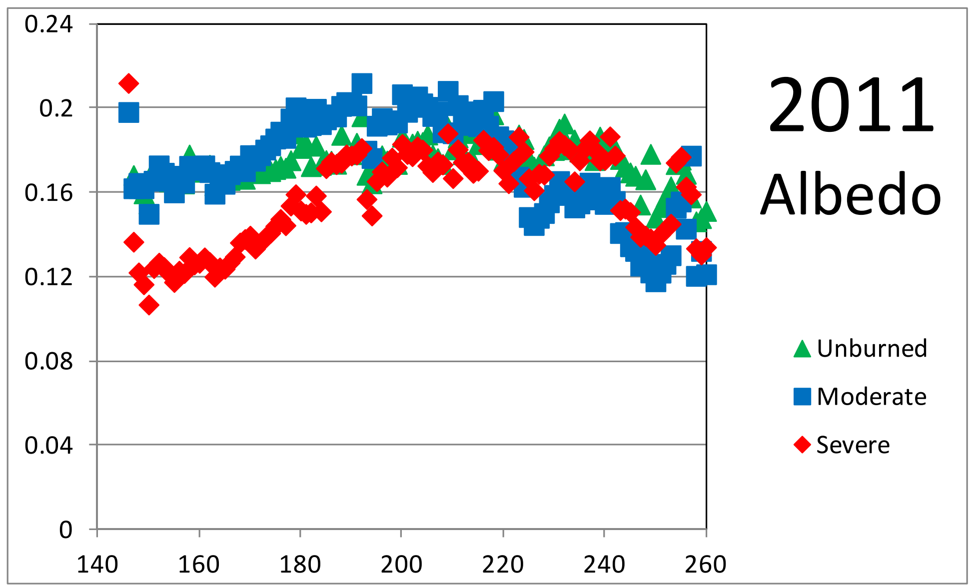


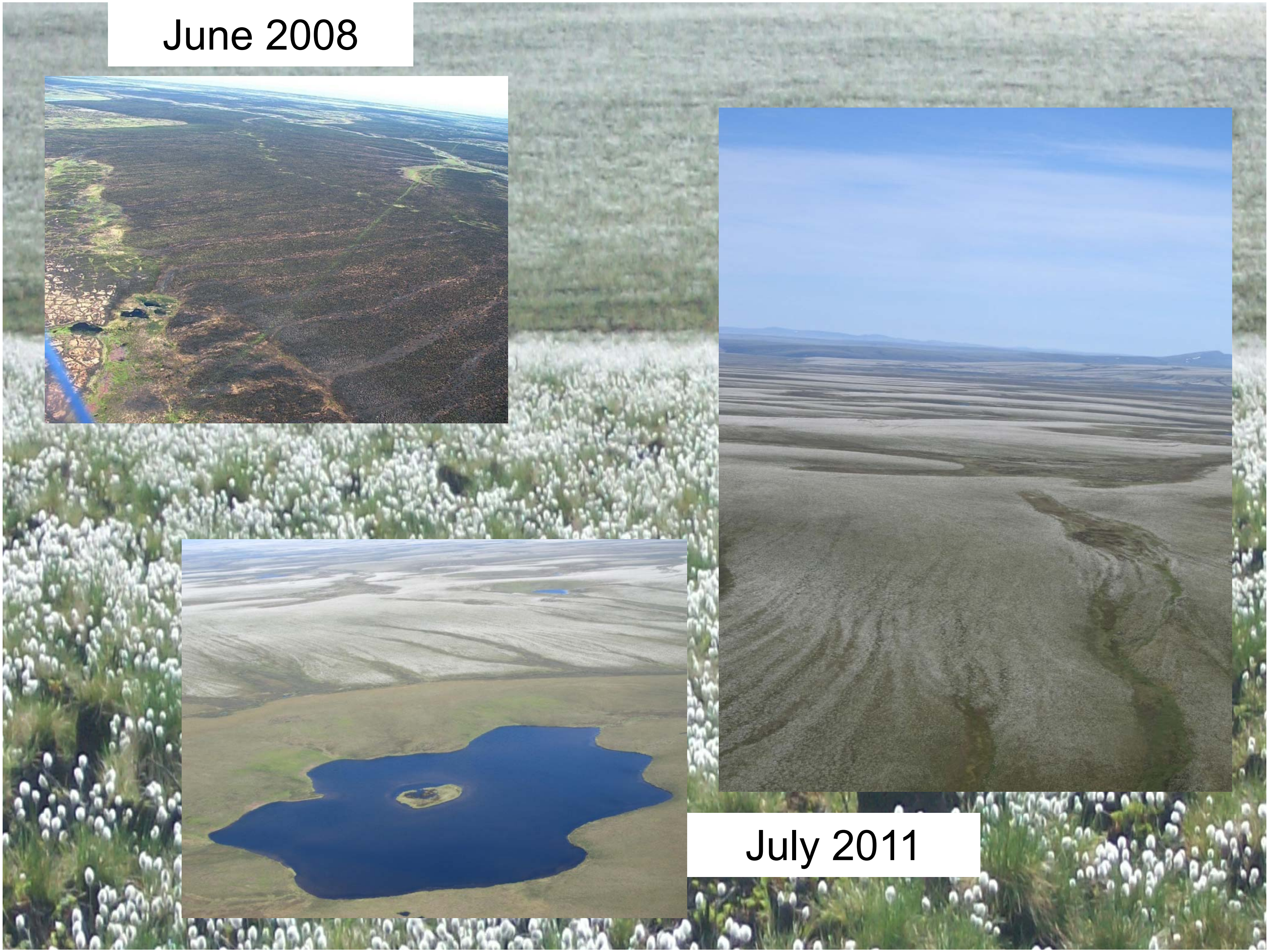
Severe Burn
July 2009

Severe Burn
June 2010

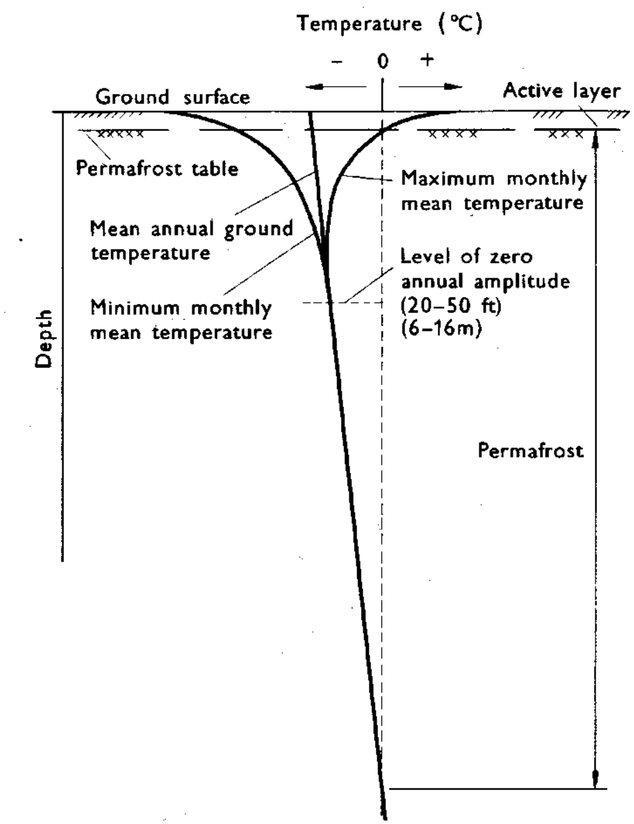
Data: A Rocha


20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
140
160
180
200
220
240
260
2011
NEE
Unburned
Moderate
Severe


0.24
0.2
0.16
0.12
0.08
0.04
0
140
160
180
200
220
240
260
2011
Albedo
Unburned
Moderate
Severe


June 2008
July 2011

Interactions with permafrost may override these direct impacts of fire on C cycling



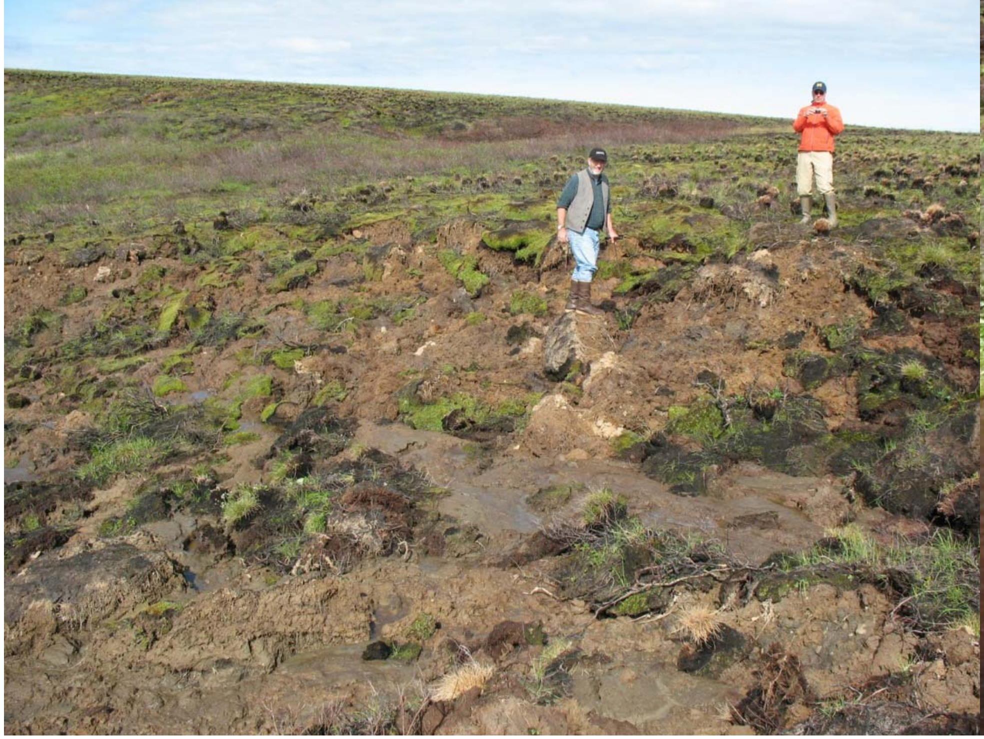
3.27 Typical temperature regime in permafrost (*after R. J. E. Brown, 1970, 11, Figure 6*)

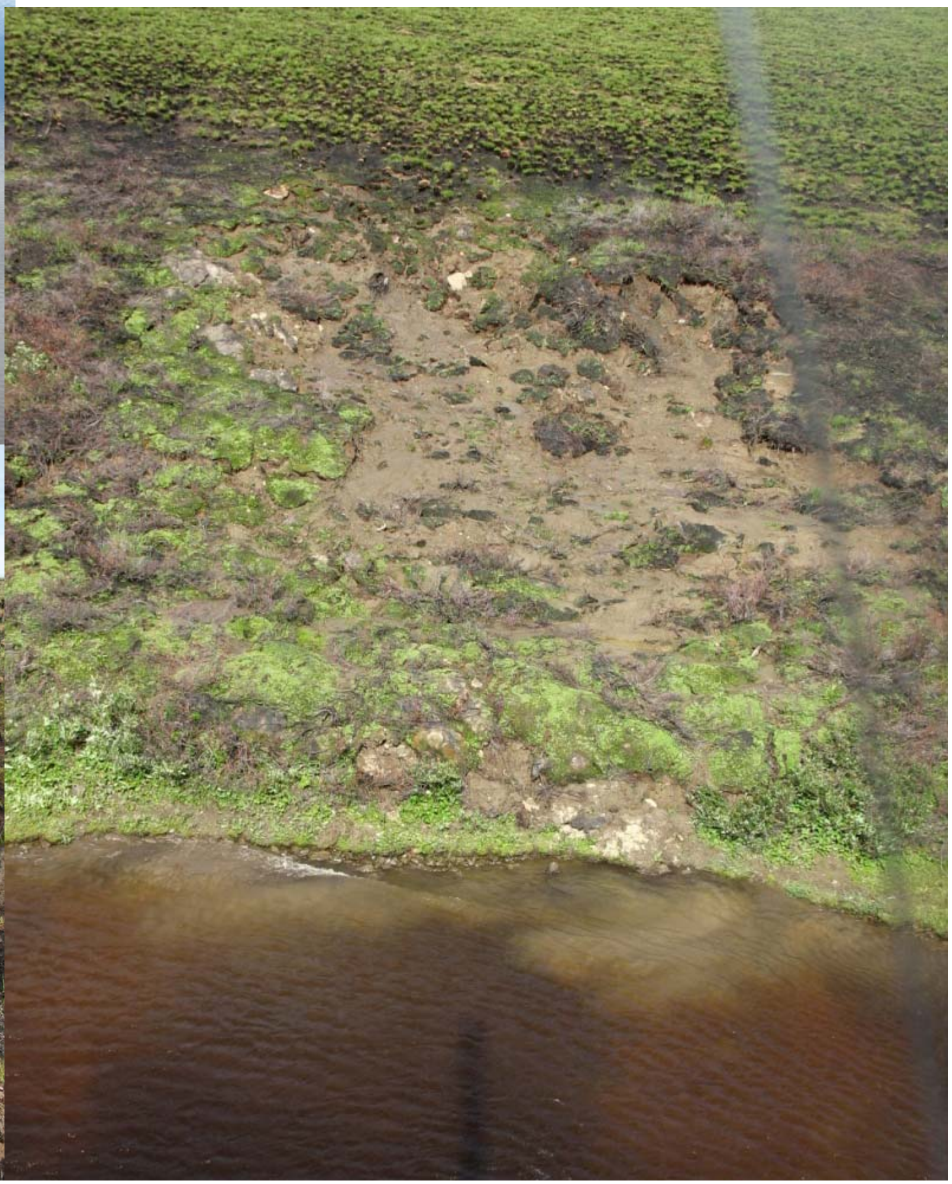
“The Valley of Thermokarsts”

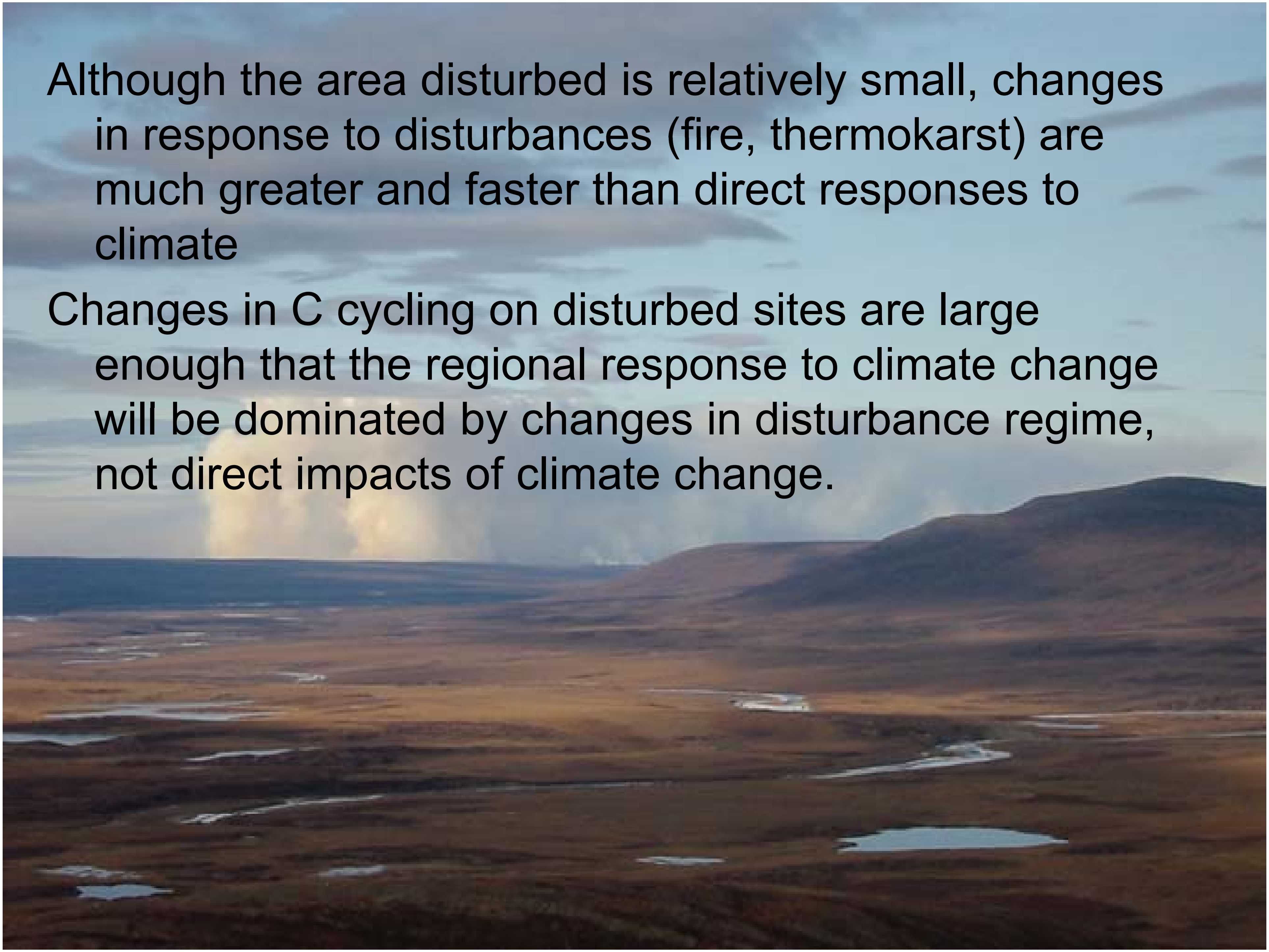
active layer displacement

Horn Lake

Retrogressive Thaw Slump

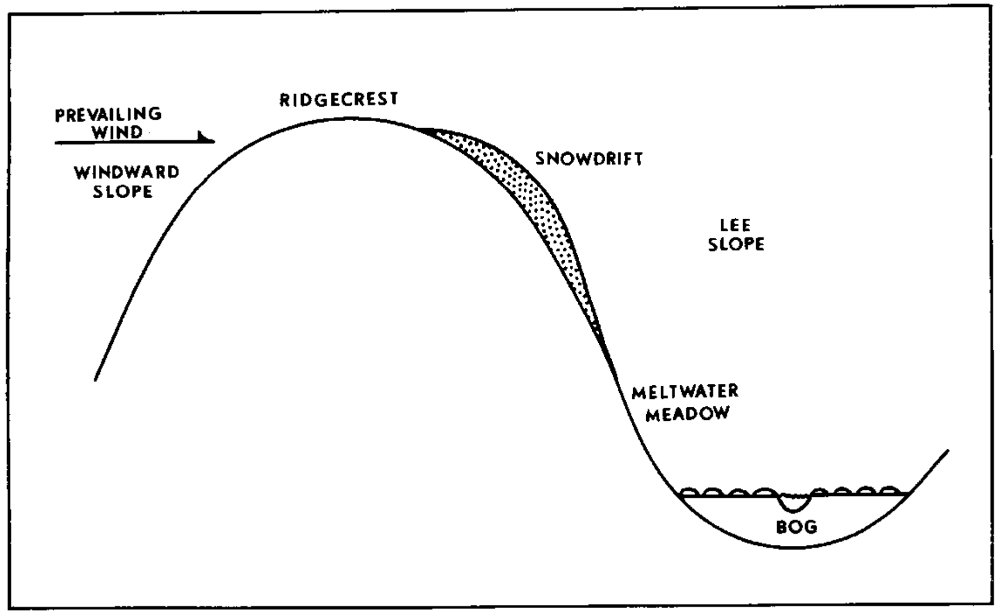






Although the area disturbed is relatively small, changes in response to disturbances (fire, thermokarst) are much greater and faster than direct responses to climate

Changes in C cycling on disturbed sites are large enough that the regional response to climate change will be dominated by changes in disturbance regime, not direct impacts of climate change.



W.D. Billings 1973: the "mesotopographic gradient"