Severity Mapping for Estimating Fire Emissions: Remote Sensing Advantages and Issues in the Boreal Region

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With contributions from
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Talk Outline

1. Participants & Scientific Objectives
2. Methods of estimating fire emissions
3. Alaskan black spruce studies
4. Evaluation of dNBR as a predictor of CBI
5. Limitations on using dNBR in Alaska
6. Evaluation of CBI as a predictor of fire severity
7. Conclusions

Participants

- N.H.F. French (Michigan Tech Research Institute) NASA New Investigator Program Grant #NNG04GR24G
- E.S. Kasischke, E. Hoy (Univ. of MD) and M.R. Turetsky (Mich State) NASA Carbon Cycle Science Grant NNG04GD25G – Burning of Organic Soils in Boreal Forests and Peatlands
- E.S. Kasischke (Univ. of MD) and J. Johnstone (Univ. of AK) NASA North American Carbon Science Program Grant NNX06AF85G – Remote Monitoring of Boreal Forest Cover Change as a Function of Fire Severity
- D. Verbyla and J. Johnstone (Univ. of AK) Joint Fire Science Project 05-1-2-06 - Managing Fire With Fire in Alaskan Black Spruce Forests: Impacts of Fire Severity on Successional Trajectory and Future Forest Flammability.

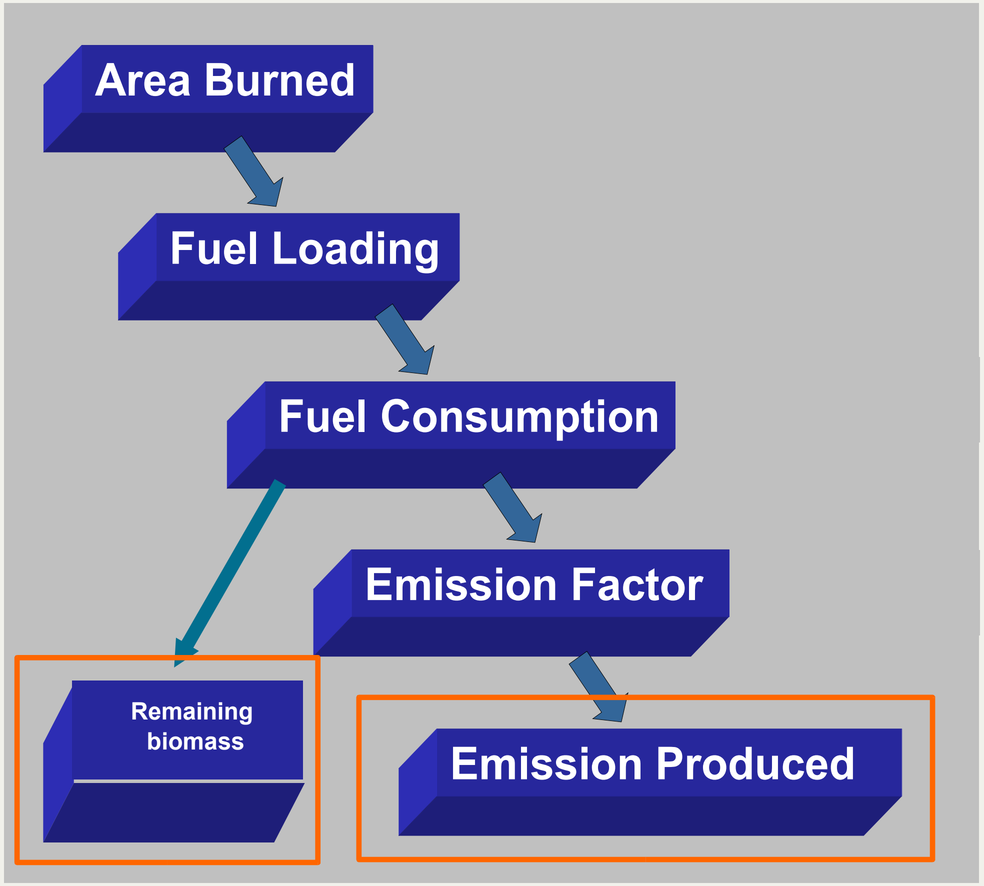
Scientific Objectives

To develop a way to use satellite data to map variations in fire severity in order to:

2. Improve estimates of carbon consumption and trace gas emissions during boreal fires
3. Identify black spruce sites that are vulnerable to change (permafrost degradation and changes in post-fire succession)

Estimating Emissions

4 factors to know

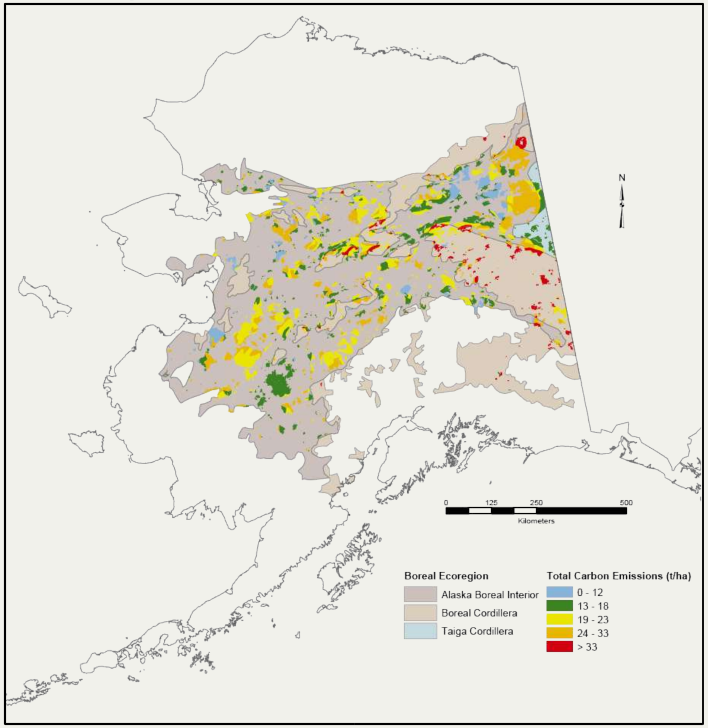


- Highest uncertainty:
  - Fuel loading (biomass density)
  - Fuel consumption (what proportion burns)
- Provides estimated:
  - Emissions
  - Remaining biomass

Regional-scale Emissions Estimates

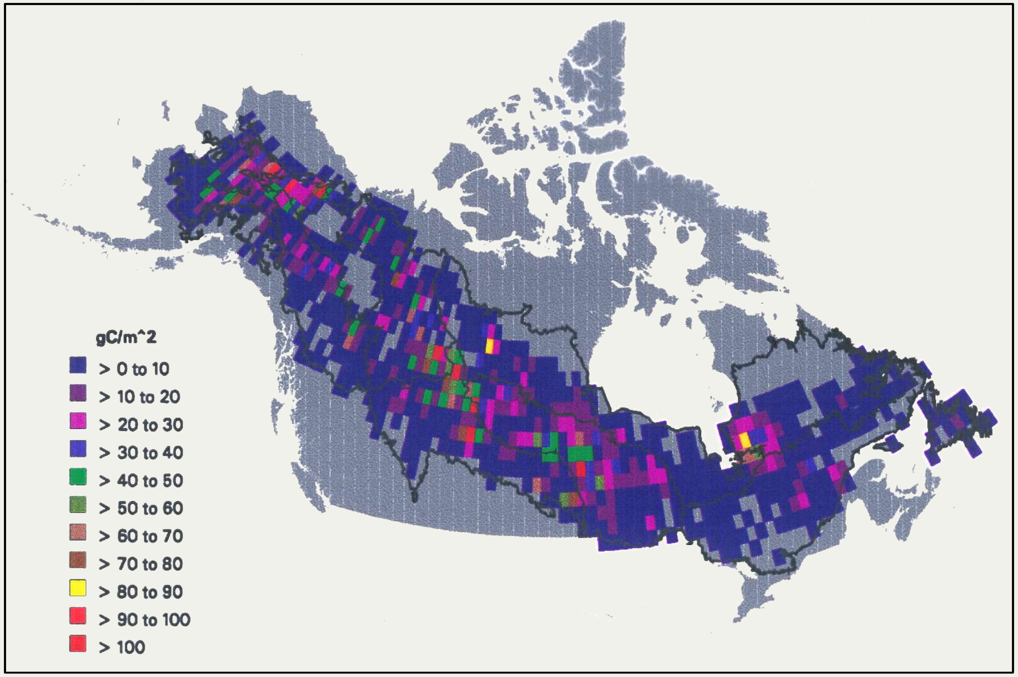
- Early work provided geospatial fire emissions
  - Annual Alaska 1950-1998 (French et al. 2002)
  - North America 1980-1994 (French et al. 2000)

Average Annual Emissions for Alaska



French NHF, et al. (2002) Variability in the emission of carbon-based trace gases from wildfire in the Alaska boreal forest. *J. of Geophy. Res.* **107**, 8151.

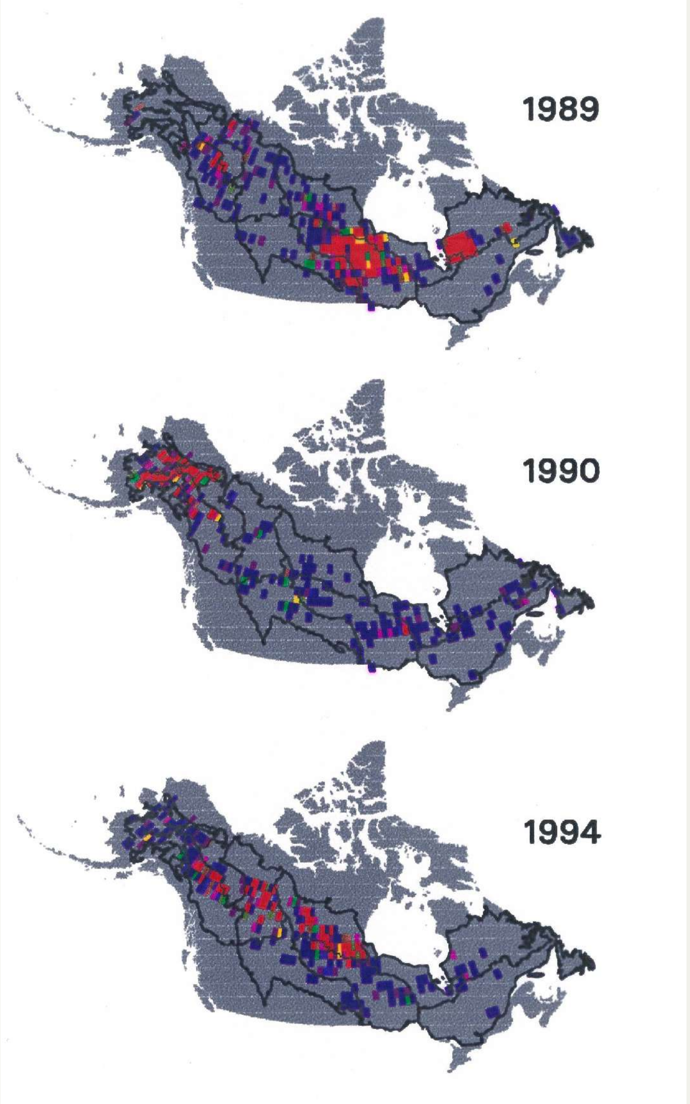
Average Annual Emissions for Boreal North America



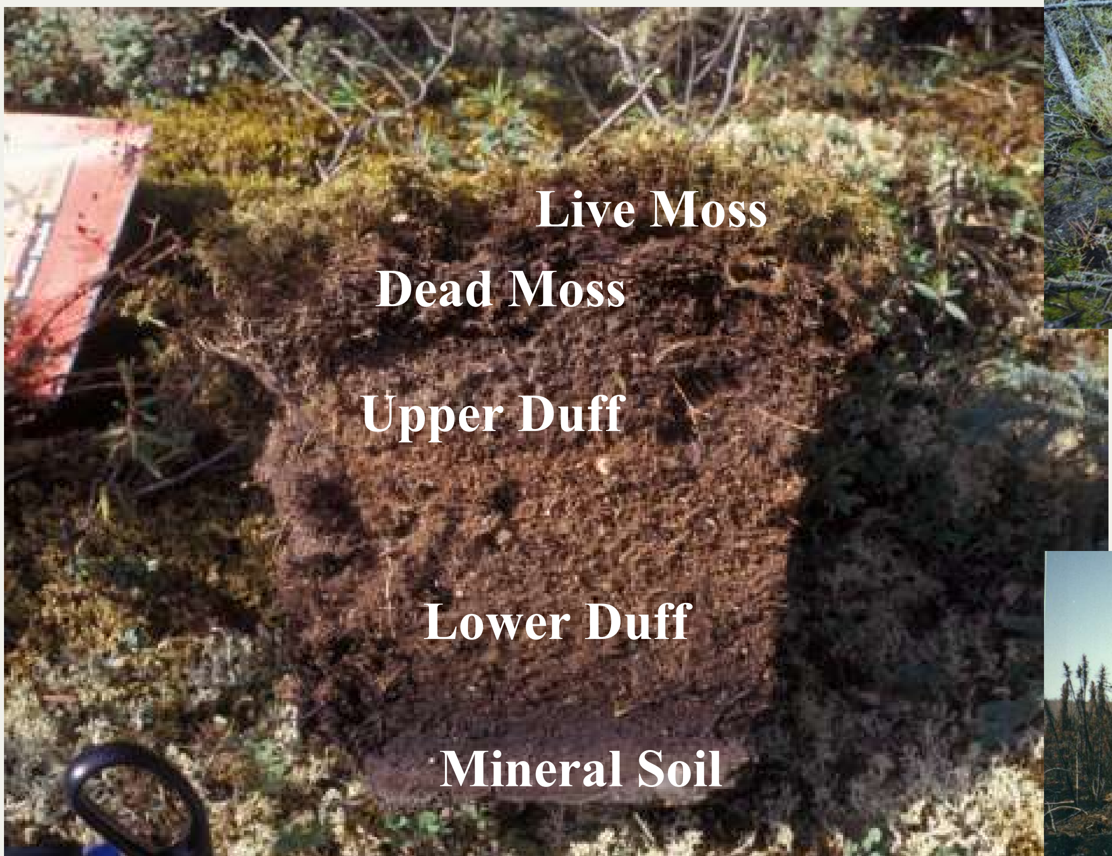
French NHF, et al. (2000) Carbon release from fires in the North American boreal forest. In 'Fire, Climate Change, and Carbon Cycling in the Boreal Forest'. (Eds ES Kasischke and BJ Stocks) pp. 377-388. (Springer-Verlag: New York)

Regional-scale Emissions Estimates

- Provided a map of carbon emissions based on ecoregion-specific data inputs & actual fire locations
- Assumed single value for each ecoregion for
  - Biomass (fuel) density
    - but partitioned between aboveground and surface fuels
  - Proportion of biomass consumed
  - One set of flaming/smoldering combustion ratios
- No good way to assess uncertainty since variability of inputs was poorly known



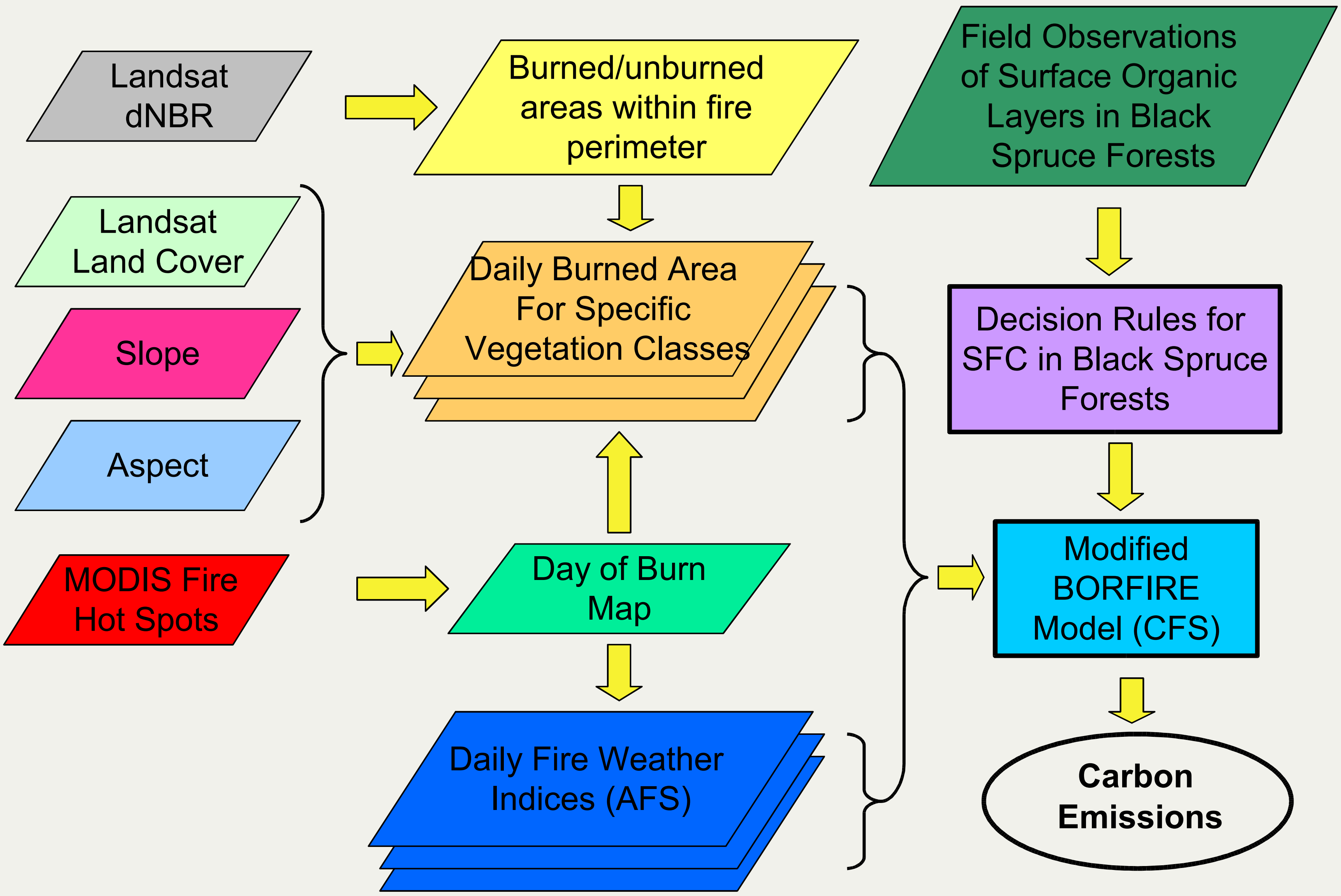
Variability of Fuels & Consumption

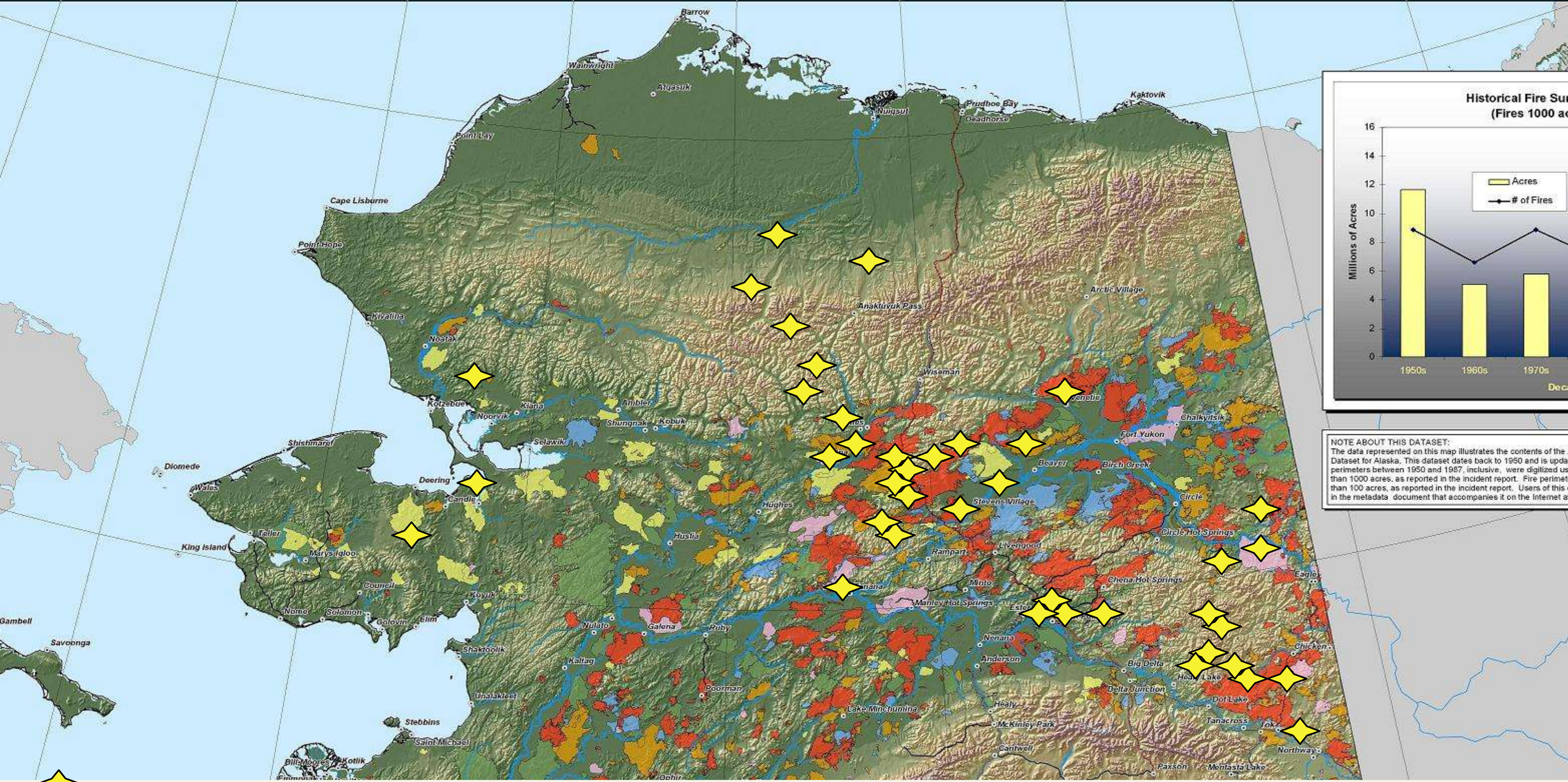


BACKGROUND: Estimating Emissions

- Approaches for quantifying emissions:
  - BWEM (Kasischke, French and others)
    - GIS-based regional emissions model
    - Initially concerned with quantifying burned area
    - Recently concentrated on characterizing duff consumption & relating consumption to biophysical variables
  - BORFIRE (Canadian Forest Service)
    - Uses fire weather data to estimate fuel consumption
    - Emphasis has been on aboveground (crown) fire
    - Now working on improved duff consumption
  - CONSUME 3.0 (USDA Forest Service FERA lab)
    - Developed for use at the plot or fire level
    - Empirically-based model for each FCCS fuelbed in NA
    - Potential for regional application

Fire Emissions Estimation in Alaskan Boreal Forest





Our research is based on data collected in plots in 36 fire events and unburned stands

- Used to measure fire severity and surface fuel consumption in black spruce forests

Studies by researchers at ERIM, UMD, MSU, UAF, USFS, USGS, USFWS

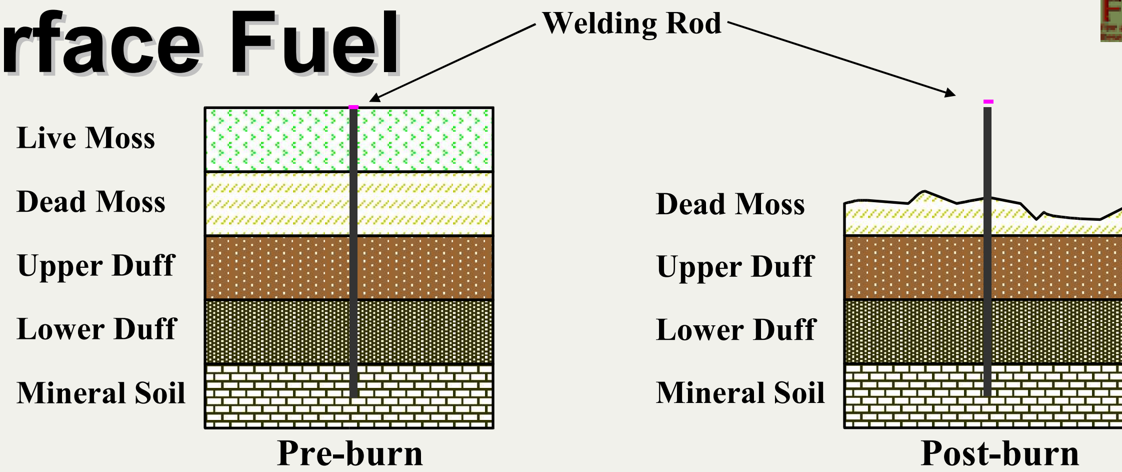
284 plots in unburned stands, 465 plots in burned stands

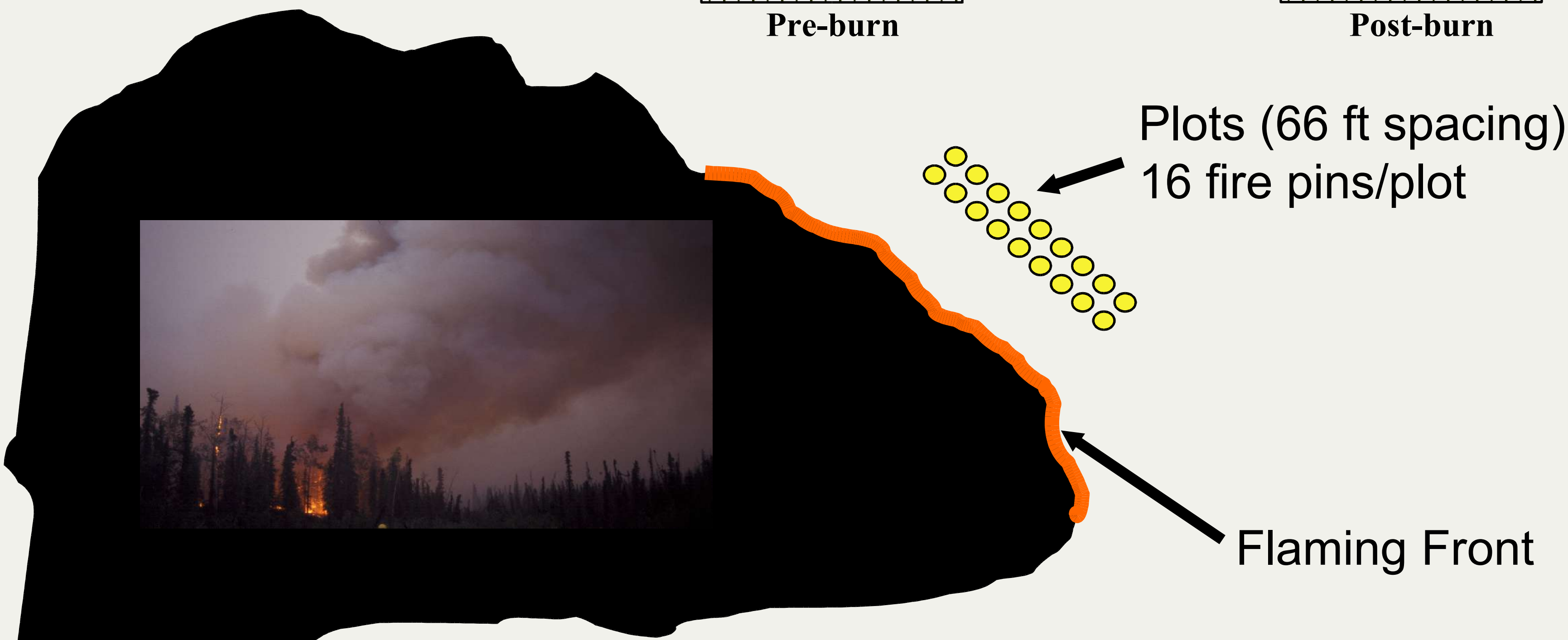
8,447 organic layer depth measurements in unburned stands, 10,140 in burned stands

>2,000 organic layer samples collected for lab analysis to determine bulk density and % C


Jennifer Harden
Kathy O'Neill
Tok 1994
USGS: 1999-2007
Kasischke/Turetsky
NASA/NSF/USFS
2005-2007
Nancy French
Bettles 1991
Ottmar USFS
2003-2004
NASA/EPA/NSF
1991-2004

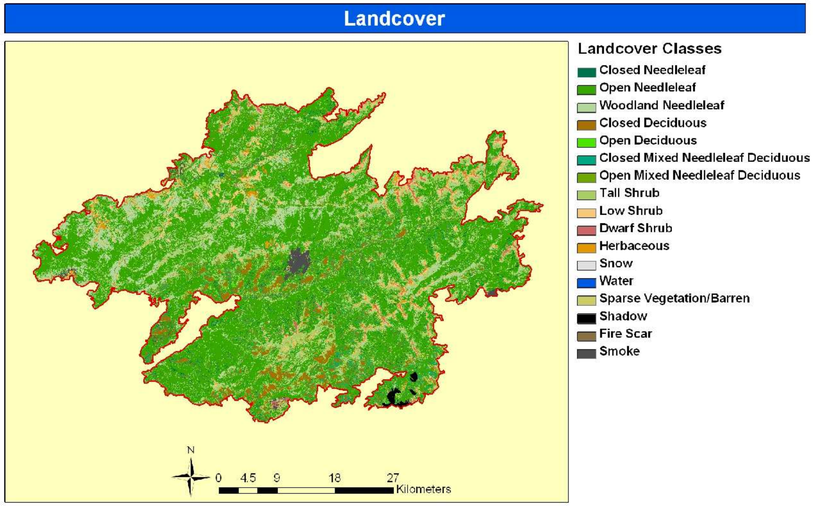
CONSUME 3.0
Measuring Surface Fuel Consumption



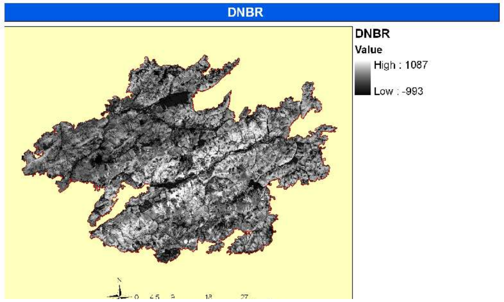


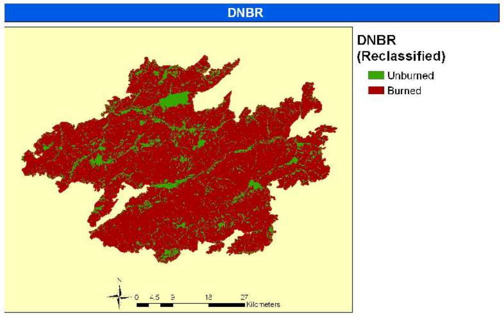
Proportion Forest Floor Reduced = EXP (y) / (1+EXP (y))

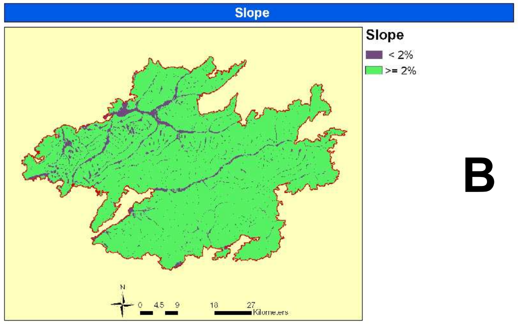
where y = 1.2383 – (0.0114 x Duff FM)



A







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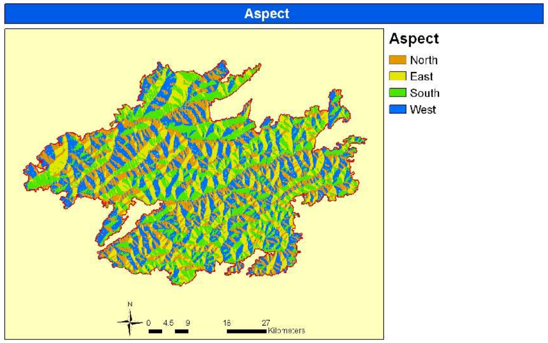
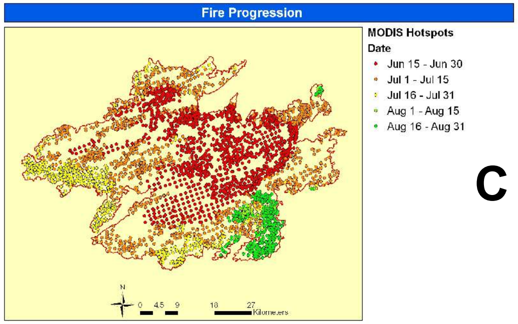
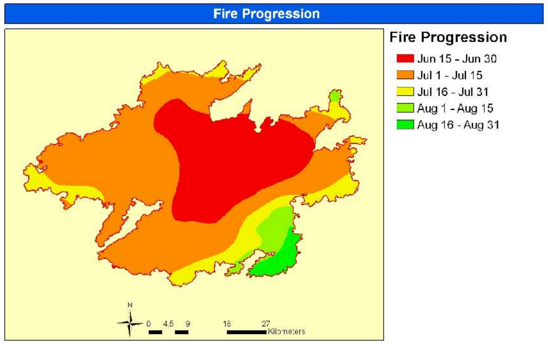




C



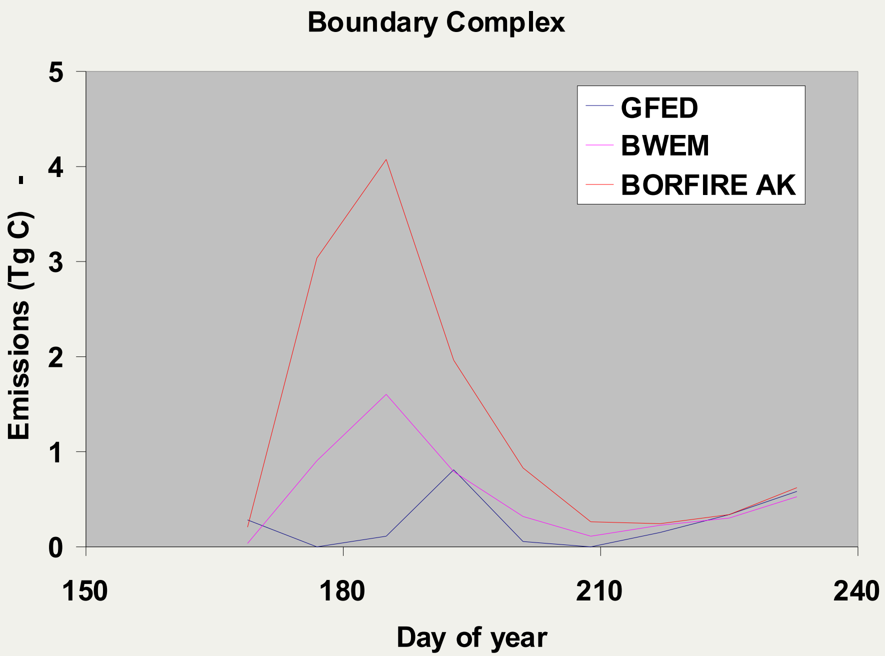
Carbon consumption during fires in Alaska is a function of

A. vegetation cover of burned areas

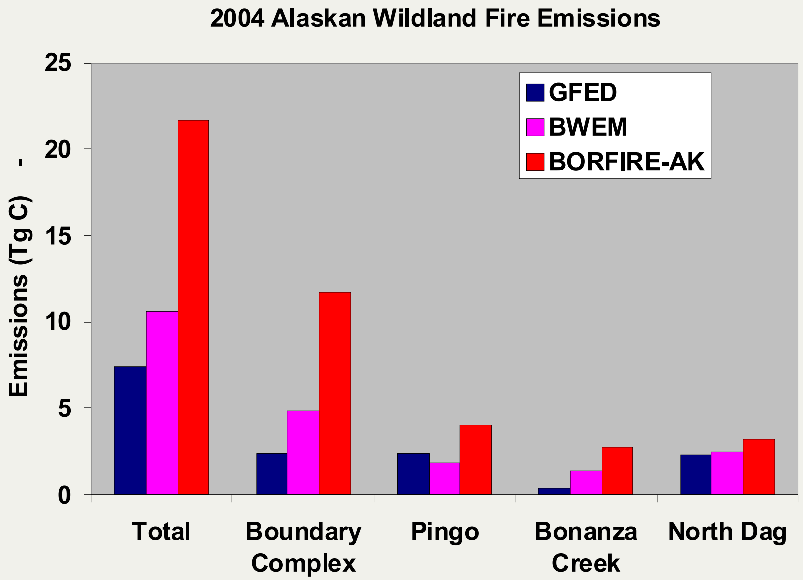
B. topographic position

C. fuel moisture at the time of the fire = f (day of burning)

Results

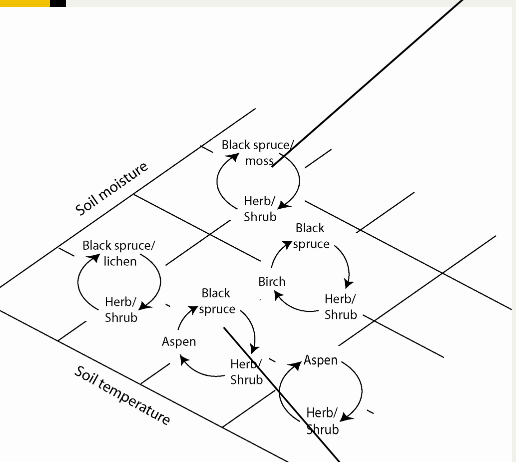


Boundary Complex
Emissions (Tg C)
Day of year
GFED
BWEM
BORFIRE AK
0
1
2
3
4
5
150
180
210
240



2004 Alaskan Wildland Fire Emissions
Emissions (Tg C)
GFED
BWEM
BORFIRE-AK
0
5
10
15
20
25
Total
Boundary Complex
Pingo
Bonanza Creek
North Dag

Post fire succession in black spruce forests



Shallow burning of the organic layer

Herbs/seedlings	Shrubs (resprouting) Spruce seedlings	Young spruce
		
Herbs/seedlings	Saplings (seedlings) Spruce seedlings	Young aspen/spruce
		
Year 2	**Year 10**	**Year 45**

Deep burning of the organic layer

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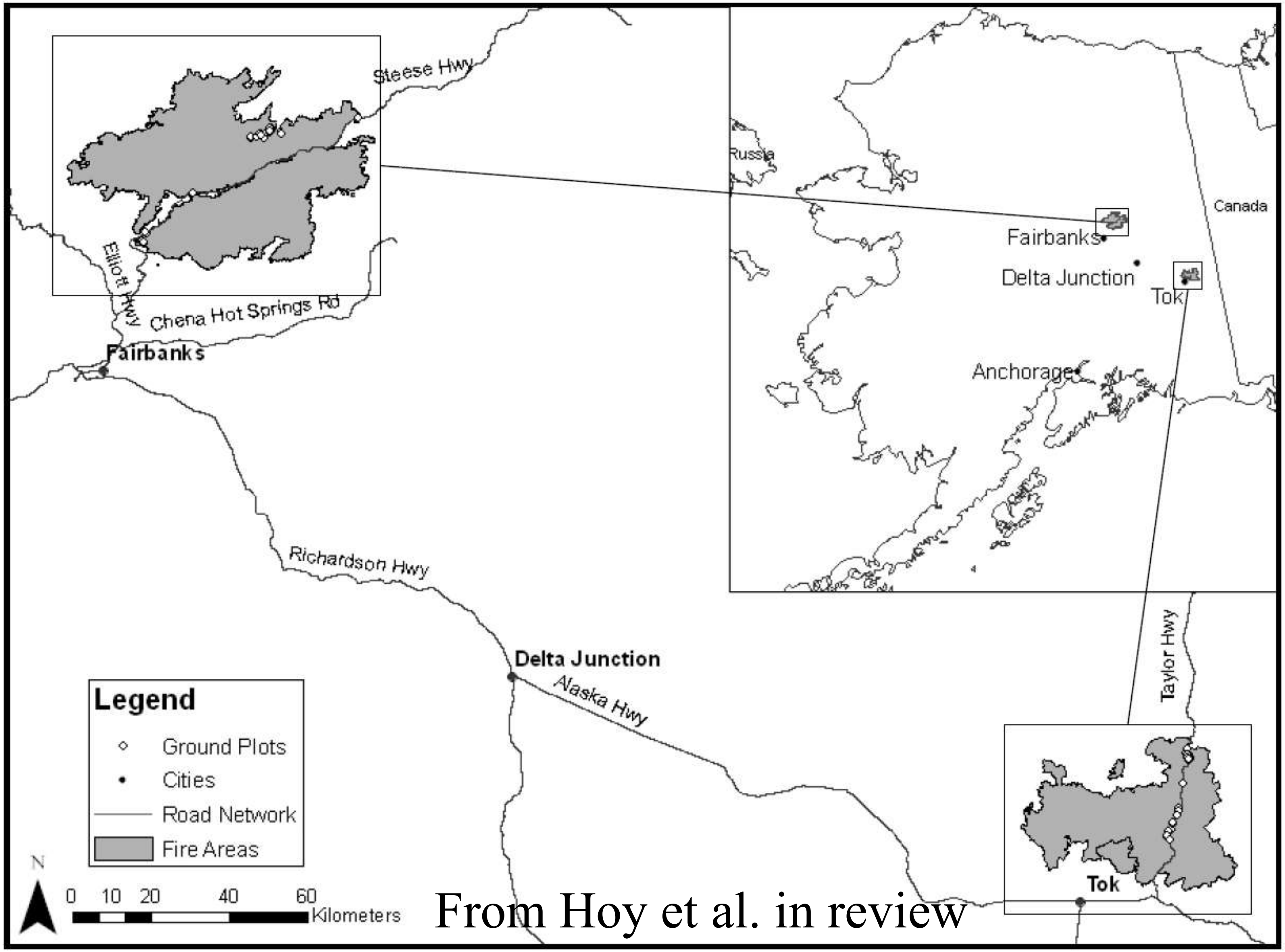
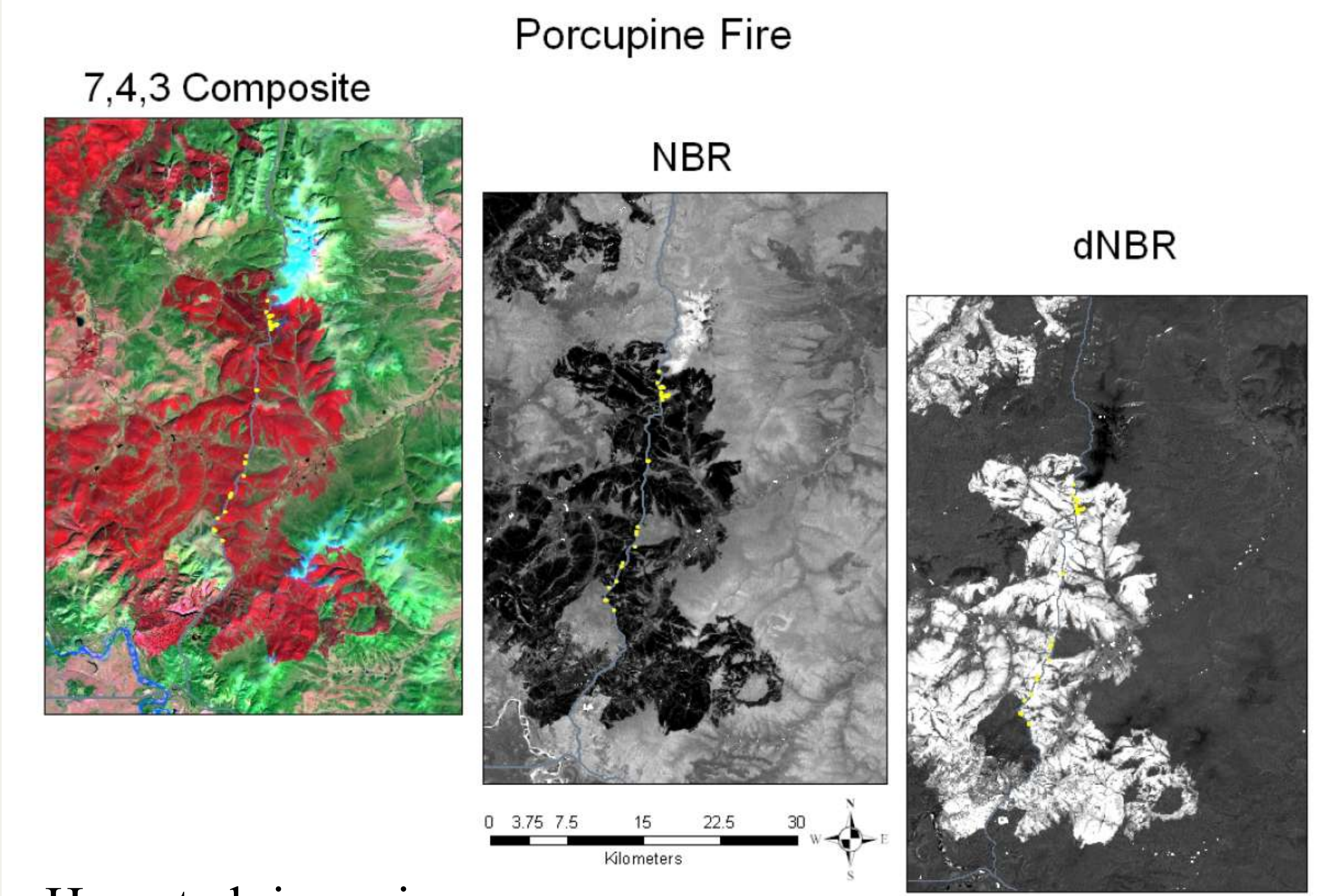
2004 Fires



From Hoy et al. in review

Landsat-derived dNBR



From Hoy et al. in review

Additional Field Data

As part of the UMD/MTU/MSU study, in addition to the observations required to estimate CBI, we collected other surface measures of fire severity in black spruce studies

3. Rating of tree canopy foliage consumption
4. Percent of downed canopy trees
5. Depth of the remaining surface organic layer
6. Depth of burning of the surface organic layer
7. Soil layer exposed during the fire

Linear correlation (R^2) between satellite indices (single date) and field measures of fire severity in black spruce stands A: $p < 0.0001$, B: $p < 0.001$, C: $p < 0.05$)

Spectral Index	Overall CBI	Understory CBI	Depth Remaining	Absolute Depth Reduced	Relative Depth Reduced
		Boundary Fire			
NBR	**0.59**^{A}	**0.55**^{A}	0.37^B	0.08	0
Ratio7/5	**0.66**^{A}	**0.61**^{A}	**0.51**^{A}	0.12^C	0.22^C
Ratio7/4	**0.49**^{A}	**0.47**^{A}	0.31^C	0.12^C	0.30^C
Ratio4/5	**0.50**^{A}	**0.48**^{A}	0.26^C	0.06	0.24^C
NDVI	**0.53**^{A}	**0.52**^{A}	0.36^B	0.10	0.11^C
SAVI	**0.53**^{A}	**0.53**^{A}	0.36^B	0.10	0.23^C
MSAVI	**0.54**^{A}	0.53^A	0.36^B	0.11^C	0.16^C
		Porcupine Fire			
NBR	0.30^C	0.25^C	0.28^C	0.00	0.21^C
Ratio7/5	0.42^B	0.40^C	0.33^B	0.00	0.24^C
Ratio7/4	0.23^C	0.23^C	0.24^C	0.00	0.17^C
Ratio4/5	0.20^C	0.16^C	0.26^C	0.00	0.20^C
NDVI	0.14	0.11	0.24^C	0.00	0.15^C
SAVI	0.15^C	0.12	0.24^C	0.00	0.15^C
MSAVI	0.15^C	0.13	0.22^C	0.00	0.14^C

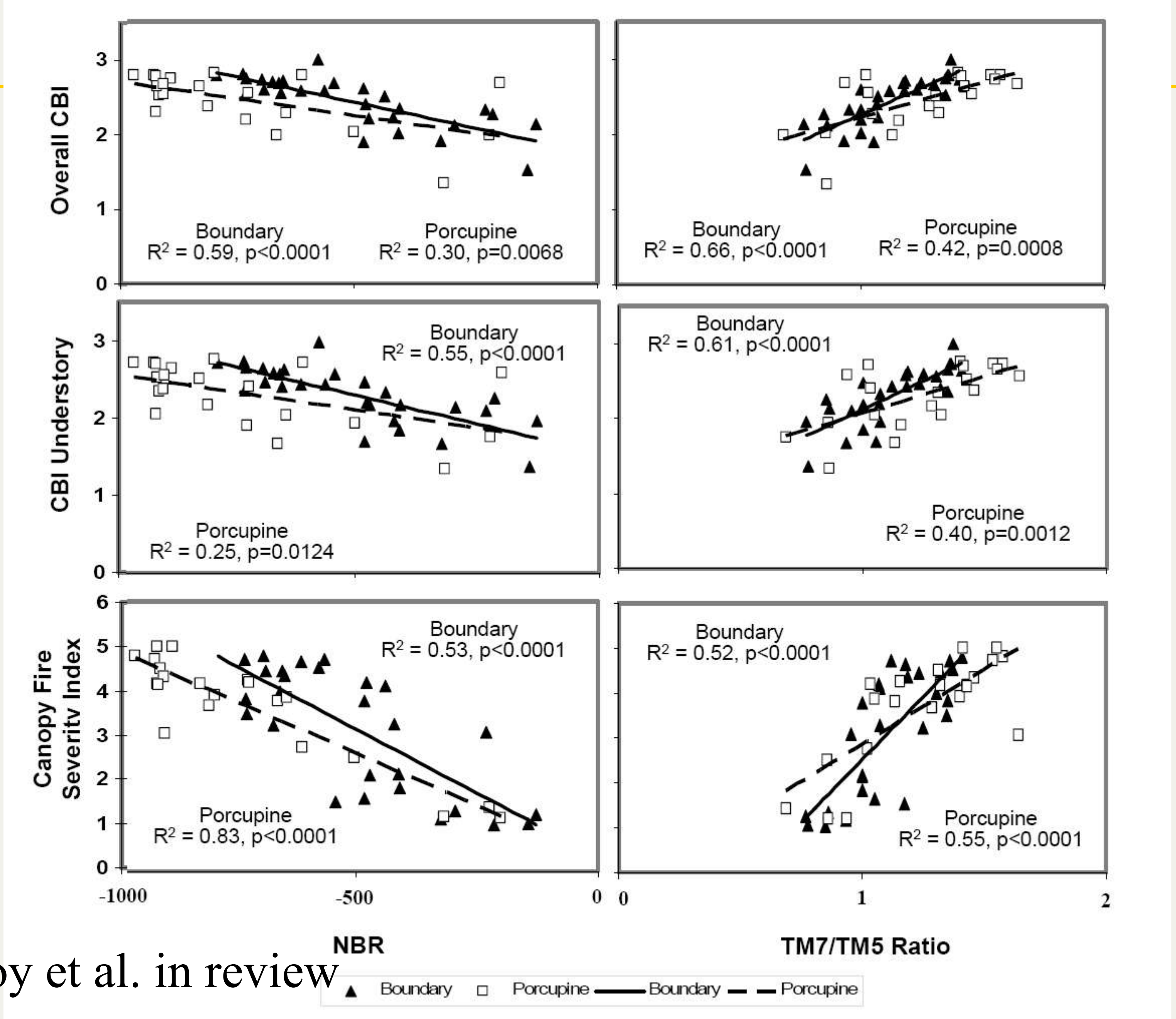
From Hoy et al. in review

Linear correlation (R^2) between satellite indices (two-date difference) and field measures of fire severity in black spruce stands

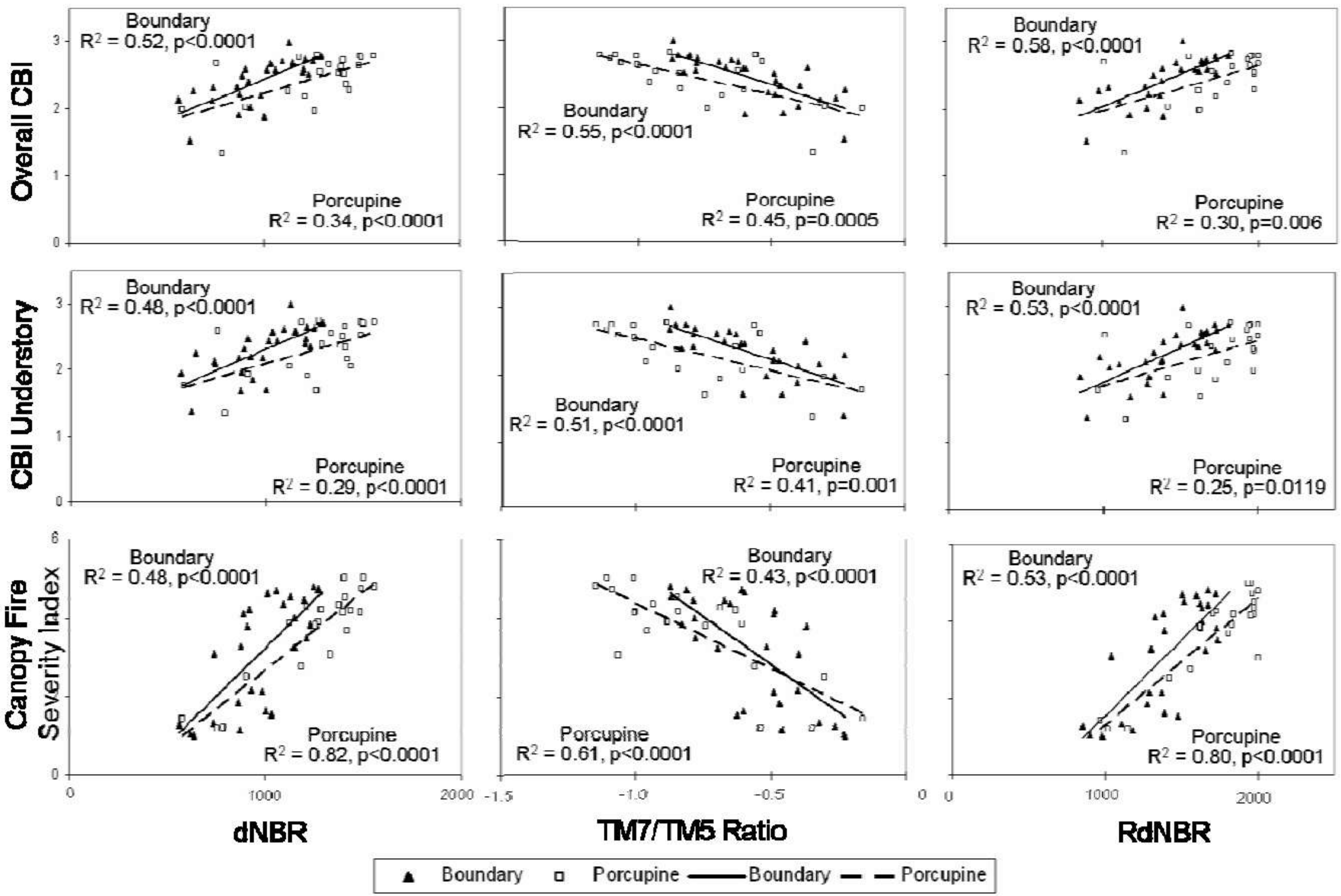
A: $p < 0.0001$, B: $p < 0.001$, C: $p < 0.05$

Spectral index	Overall CBI	Understory CBI	Depth Remaining	Absolute Depth Reduced	Relative Depth Reduced
Boundary Fire					
dNBR	**0.52**^{A}	**0.48**^{A}	**0.46**^{A}	0.13^C	0.29^C
RdNBR	**0.58**^{A}	**0.54**^{A}	0.37^B	0.08	0.21^C
Ratio7/5	**0.55**^{A}	**0.51**^{A}	**0.58**^{A}	0.13^C	0.35^B
Ratio7/4	**0.49**^{A}	**0.47**^{A}	0.32^B	0.12^C	0.23^B
Ratio4/5	0.00	0.00	0.02	0.00	0.00
NDVI	**0.45**^{A}	**0.43**^{A}	**0.42**^{A}	0.10	0.25^C
SAVI	**0.46**^{A}	**0.44**^{A}	**0.43**^{A}	0.10	0.25^C
MSAVI	**0.51**^{A}	**0.49**^{A}	0.40^B	0.11^C	0.26^C
Porcupine Fire					
dNBR	0.34^C	0.29^C	0.29^c	0.00	0.21^c
RdNBR	0.30^C	0.25^C	0.26^C	0.00	0.20^C
Ratio7/5	0.15^C	0.12	0.29^C	0.00	0.19^C
Ratio7/4	0.16^C	0.12	0.25^C	0.00	0.17^C
Ratio4/5	0.16^C	0.13	0.00	0.00	0.00
NDVI	0.45^B	0.41^B	0.22^C	0.00	0.14^C
SAVI	0.23^C	0.23^C	0.22^C	0.00	0.14^C
MSAVI	0.00	0.00	0.21^C	0.00	0.13^C

From Hoy et al. in review

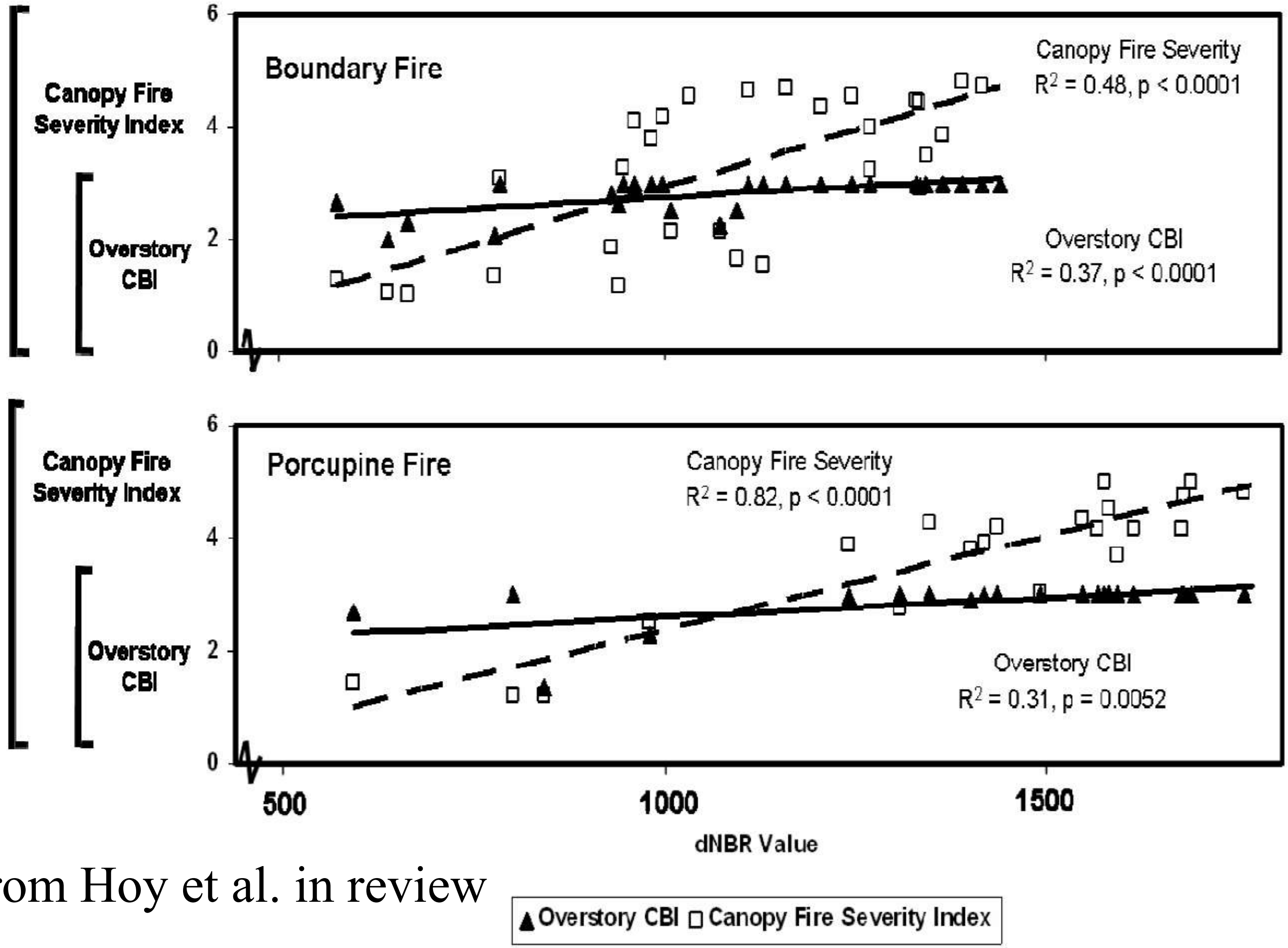


From Hoy et al. in review



From Hoy et al. in review

Canopy Fire Severity vs. Overstory CBI in Black Spruce



From Hoy et al. in review

Talk Outline

1. Participants and Scientific Objectives
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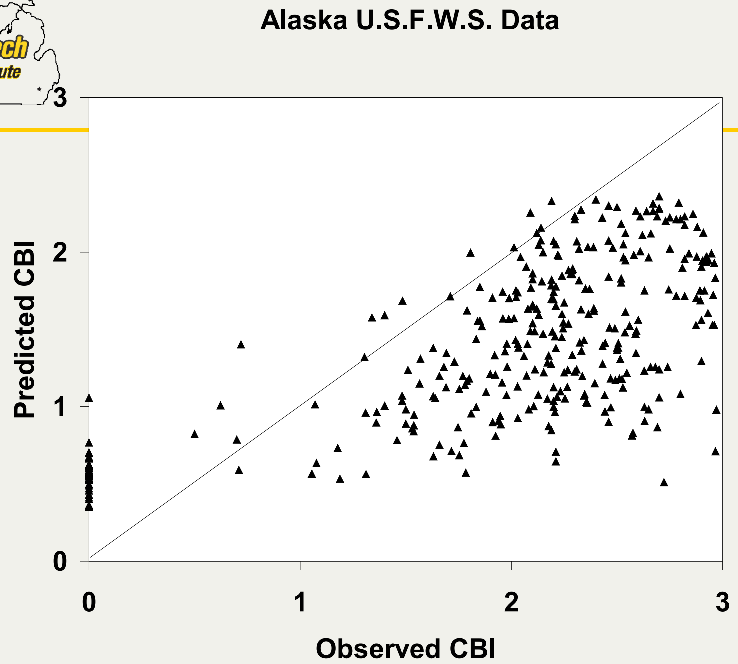
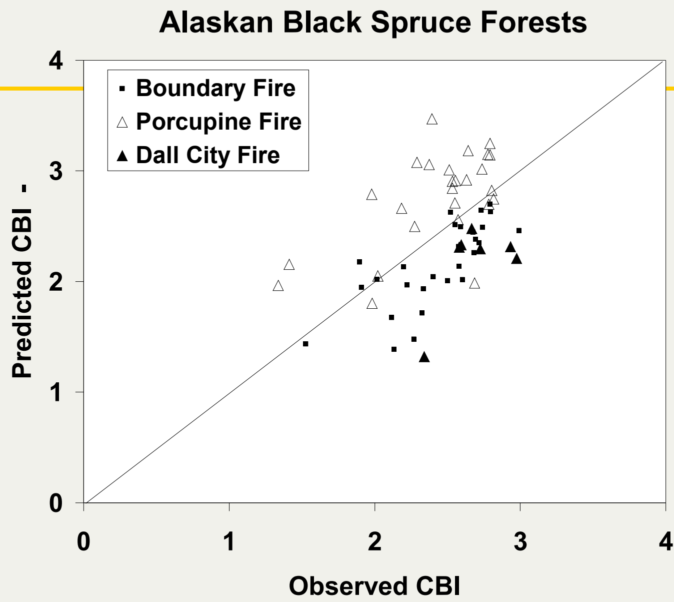
dNBR vs. CBI

The groups working on evaluating the dNBR/CBI approach carried out studies in > 20 different fire events and collected field data from > 970 plots for comparison to satellite indices

Study	# Fire Events	# Plots	Range in R^2	Vegetation
USNPS/UAF	10	286	0.45 to 0.88, avg = 0.83	All
			0.58 to 0.78	Specific types
UAF	1	85	0.45	All
CFS	4	161	0.82 to 0.85, avg = 0.82	All
USFWS	6	347	0.11 to 0.66	All
UMD/MTU	2	49	0.34 to 0.52, avg. = 0.34	Black spruce





We evaluated the ability of dNBR to predict fire severity (as measured by CBI)

3. We extracted dNBR values from the plots where USFWS and UMD/MTU/MSU scientists had collected field data required to calculate the Composite Burn Index
4. We used the relationships developed from USNPS data to estimate CBI from dNBR, and compared these with the observed values
5. For the USFWS plots, the USNPS algorithm under-estimated CBI
6. For the UMD/MTU/MSU plots, the USNPS algorithm either over or under-estimated CBI for each fire event

From French et al. in review

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Possible Reasons for Poor Performance of the dNBR Approach in Alaska

- Lack of archive imagery & difficulty with anniversary images due to clouds/shadows
- Variable interannual phenology, therefore anniversary images poorly match phenologically
- Solar Elevation Angle Effects
  - Very low solar elevation esp. in Aug/Sept
- Topographic Influences on Bi-Directional Reflectance
- Signal saturation in high severity fires

Solar Elevation Angle & NBR

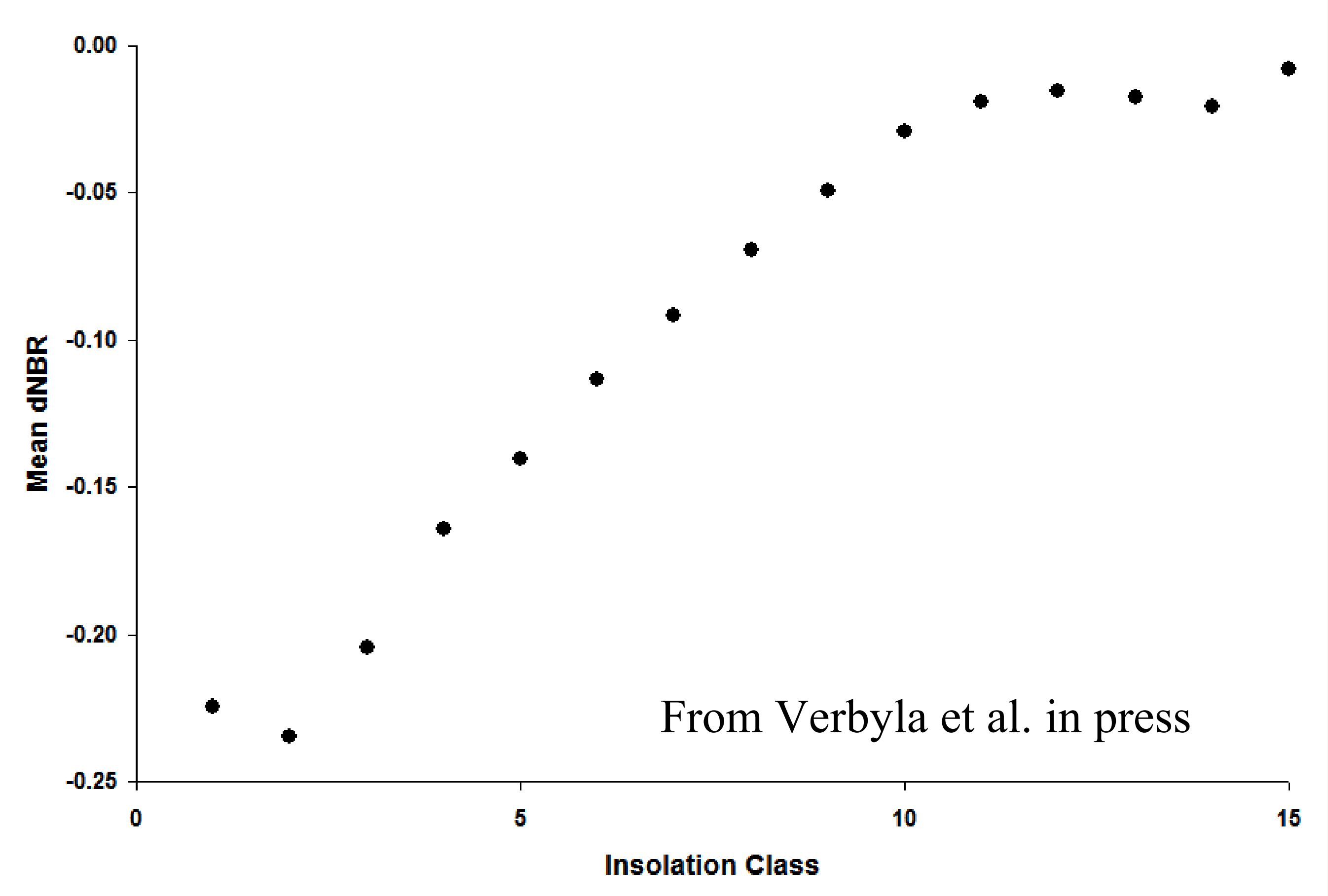
Boundary Burn Unburned Pixels					
Image Date	Sensor	Mean NBR	Std. Dev. NBR	Solar Elevation (degrees)	Solar Azimuth (degrees)
18-June-2001 (pre-fire)	ETM+	0.503	0.102	47.33	164.34
18-July-2003 (pre-fire)	ETM+	0.476	0.188	44.36	159.06
4-August-2004 (post-fire)	ETM+	0.466	0.221	40.8	163.7
6-September-2004 (post-fire)	TM	0.398	0.213	30.0	166.1

Porcupine Burn Unburned Pixels					
Image Date	Sensor	Mean NBR	Std. Dev. NBR	Solar Elevation (degrees)	Solar Azimuth (degrees)
3-August-2002 (pre-fire)	ETM+	0.536	0.110	42.30	161.56
10-Sept-2001 (pre-fire)	ETM+	0.472	0.150	31.20	165.01
9-Sept-2004 (post-fire)	ETM+	0.420	0.111	30.25	166.37

- Used unburned pixels to look at NBR as a function of solar elevation
- As solar elevation angle decreases, so does NBR in unburned forests
- Thus, for the same forest type, dNBR will be lower for the same fire severity for fires that occur late in the growing season compared to those occurring early in the growing season

From Verbyla et al. in press

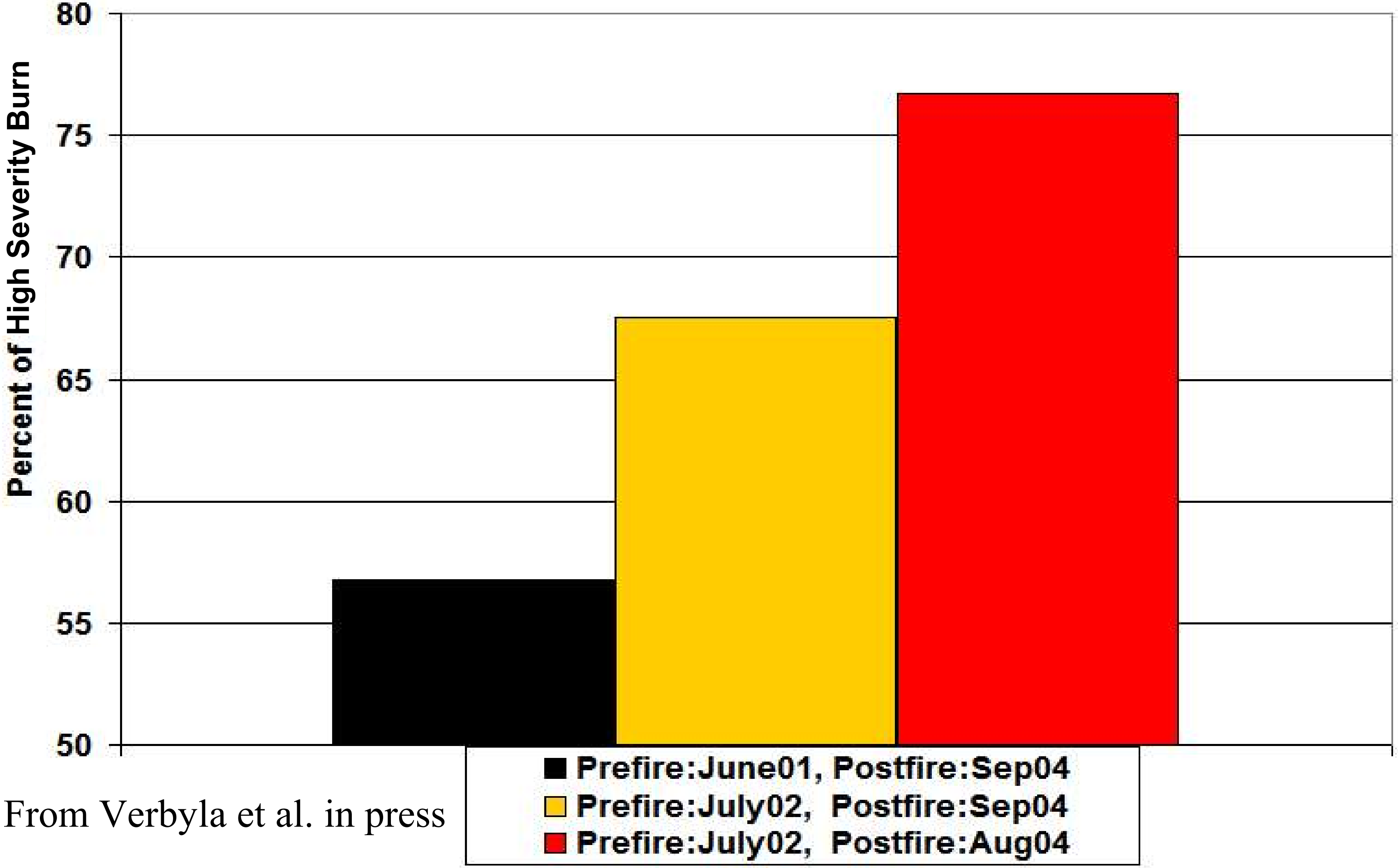
NBR varies with slope/aspect



- Post-burn dNBR” computed from August and September images of the Boundary Fire
- Result: Fire severity is underestimated for stands in valley bottoms and north-facing slopes

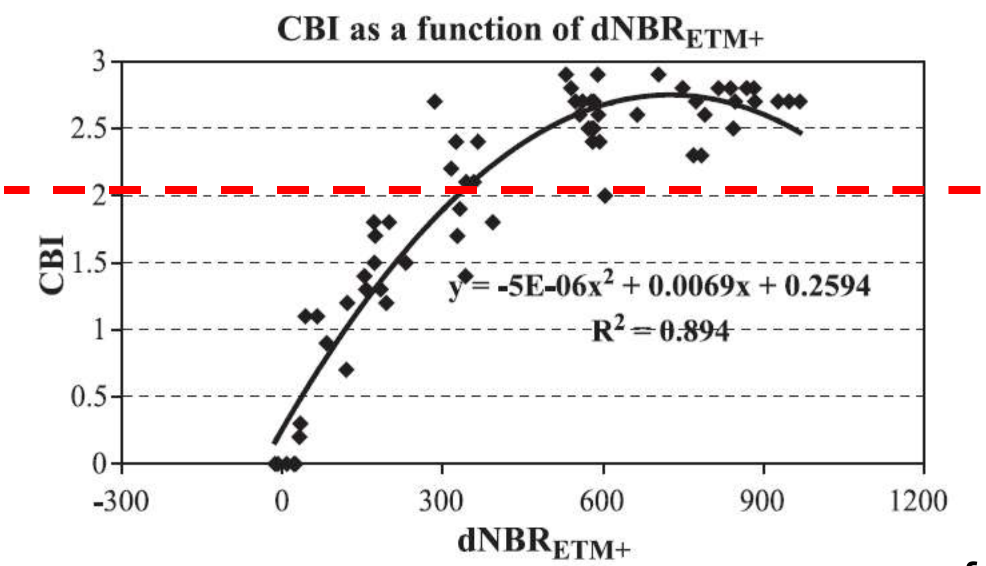
False Trends in dNBR

10% more high-severity area using July vs. June pre-burn image



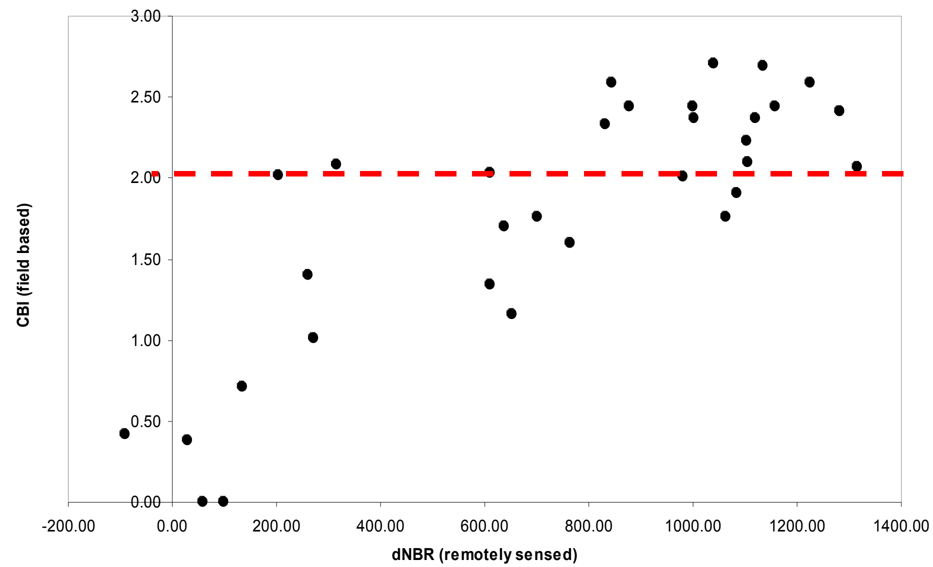
From Verbyla et al. in press

Examples of Signal Saturation



from van Wagtendonk et al. 2004

from Epting et al. 2005 (r=0.82)



The linear relationship between CBI and dNBR breaks down when CBI > 2

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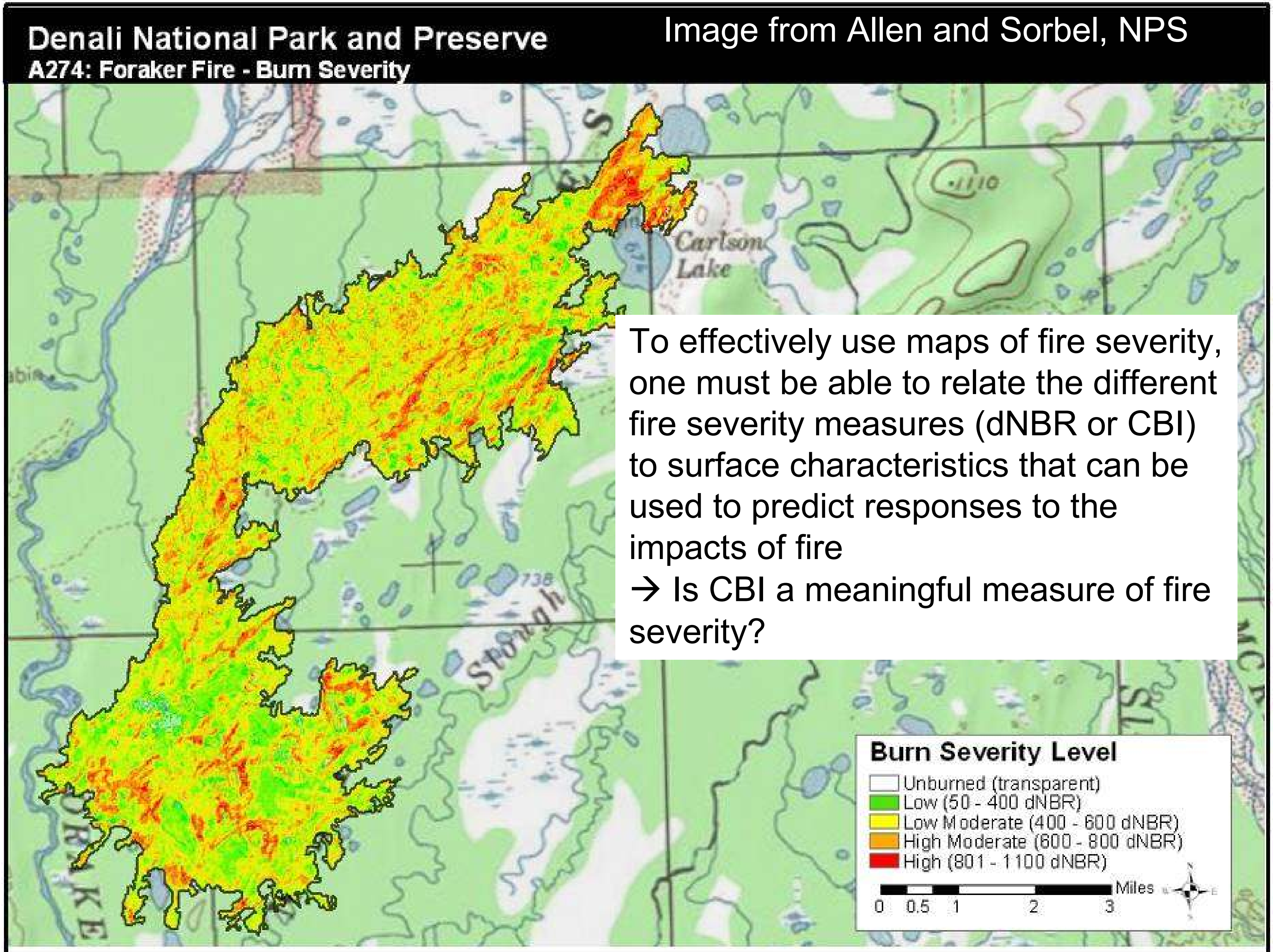
Image from Allen and Sorbel, NPS



To effectively use maps of fire severity, one must be able to relate the different fire severity measures (dNBR or CBI) to surface characteristics that can be used to predict responses to the impacts of fire

→ Is CBI a meaningful measure of fire severity?

As part of the UMD/MTU/MSU study, in addition to the observations required to estimate CBI, we collected other surface measures of fire severity in black spruce studies

3. Rating of tree canopy foliage consumption
4. Percent of downed canopy trees
5. Depth of the remaining surface organic layer
6. Depth of burning of the surface organic layer
7. Soil layer exposed during the fire

We found low correlation between CBI and other surface measures of fire severity in Alaskan black spruce forests, indicating that CBI is not a good surface measure of fire severity in this ecosystem

Dependent variables	**Independent Variables**					
	CBI total		**CBI canopy**		**CBI substrate**	
	R^2	**p**	**R^2**	**p**	**R^2**	**p**
Canopy damage rating	0.37	<0.0001	0.36	<0.0001		
% standing trees	0.10	0.0023	0.00	0.48	0.35	<0.0001
Organic layer depth	0.26	<0.0001			0.35	<0.0001
Absolute depth reduction	0.00	0.45			0.06	0.014
Relative depth reduction	0.22	<0.0001			0.39	<0.0001
Substrate exposure index	0.22	<0.0001			0.47	<0.0001

From Kasischke et al. in press

Conclusions on Satellite Fire Severity Mapping in Alaska Using the dNBR-CBI

- Landsat (and other remote sensing) provides unique information on fire effects unavailable through other means
- In some cases, maps of fire severity can be generated from processing of Landsat data using the dNBR index
- Other indices derived from Landsat data did not perform better than the dNBR index in black spruce sites
- In fires occurring during the large fire year of 2004, the relationships between CBI and dNBR were poor – maps of fire severity derived from dNBR are not reliable
- Issues of phenology, topography, cloud shadowing, and solar elevation are “enhanced” in the boreal region
- Landsat-derived severity (dNBR) relationship with field data (CBI) are not consistent from site-to-site
- Evidence that CBI is not effective for assessing fire severity in black spruce forests
  - Additional field-based measures might provide better connection to Landsat-derived fire-effects assessments

Photo of 2006 fire along the Parks Highway near Nenana, Alaska
Photo from helicopter by Adam Kohley, AK Fire Service