Carbon, Trace Gas, and Particulate Emissions from Wildfires in the Boreal Regions of North America

Presented by

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"Emission Inventories: Integration, Analysis, Communication"

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Outline

- Background
  - Atmospheric CO_2
  - Boreal ecology & Fire
- Estimating wildfire emissions
  - 3 approaches
- Atmospheric sampling of boreal wildfire emissions
  - Illustration from the mid-Atlantic
- Mercury Emissions from boreal wildfire
- Summary and future areas of research

Boreal Ecology

- Cold temperatures & low solar insolation
  - → ↓ potential ET, ↓ NPP
  - → Permafrost
  - → Forest structure, soil development

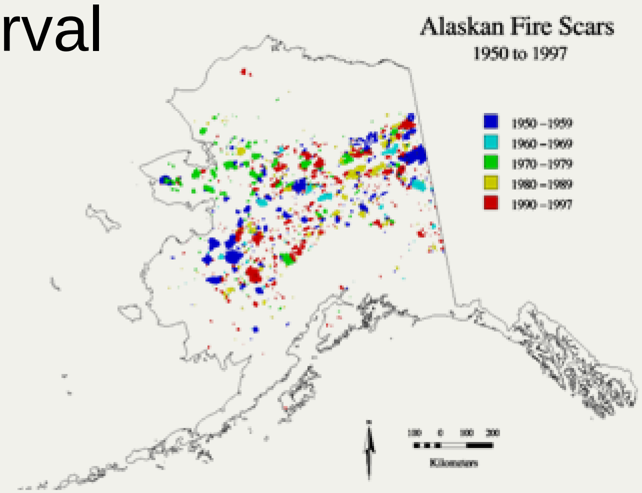
- Low soil nutrients
- High carbon reserves in soil
- Fire prone climate esp. in continental regions
- Disturbance adapted ecosystems (fire and insects)

Fire in Northern Forests

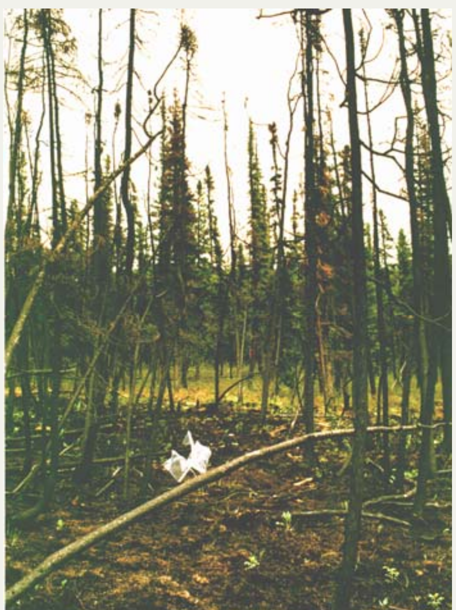
- Many northern forest ecosystems are fire-prone (esp. conifers)
- Fire is a natural process so trees are adapted to fire
- Forest succession is fire & site (drainage) driven
- Fire acts to renew ecosystems by releasing nutrients from the soil
- Permafrost is impacted by fire – increase in active layer

Fire in boreal Alaska:

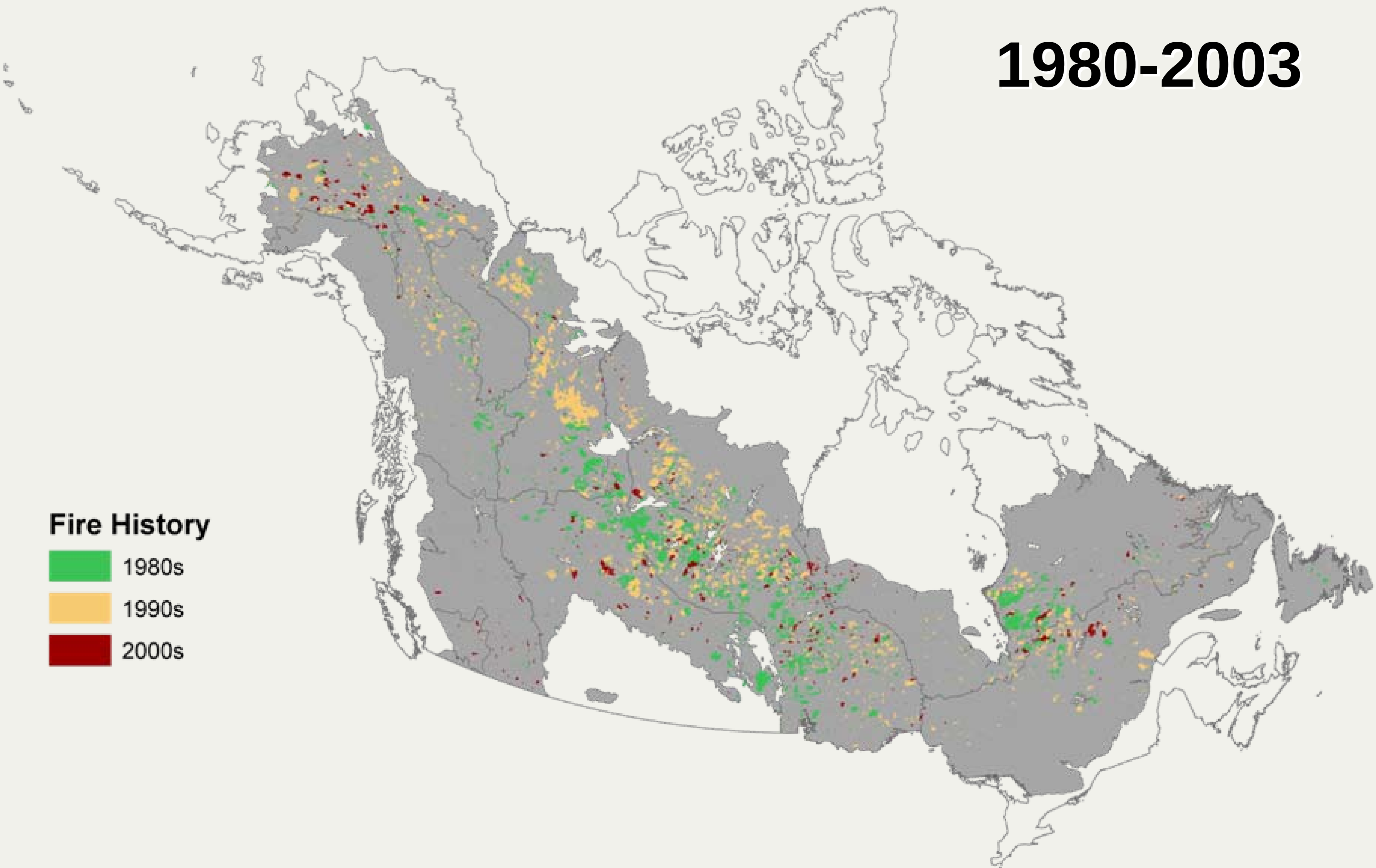
- 44% of region is black spruce
- Average area burned ~250,000 ha/yr highly variable (1.28 M ha in 1990)
- Large, stand-replacement burns
- 50-200 year fire return interval



Fire Site Characteristics

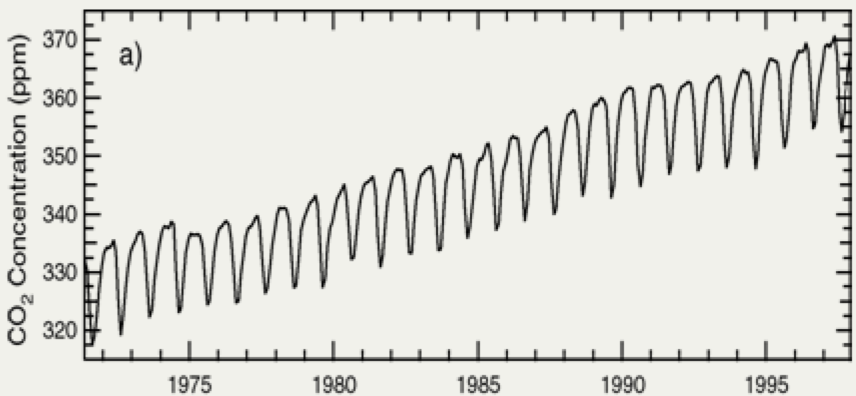


Fire in Boreal North America

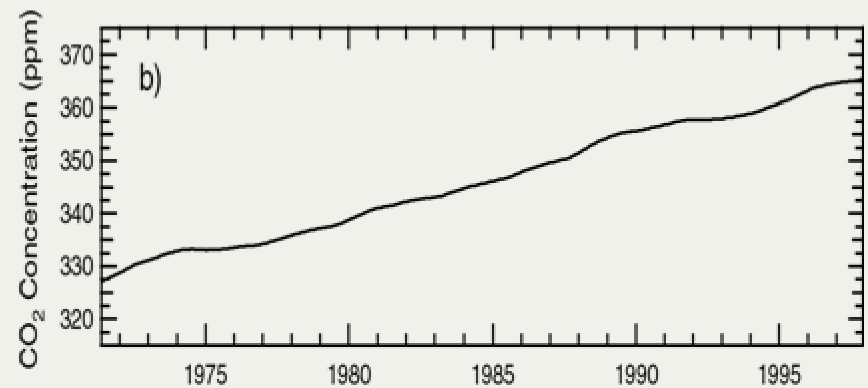


Trends in CO_2 Concentration

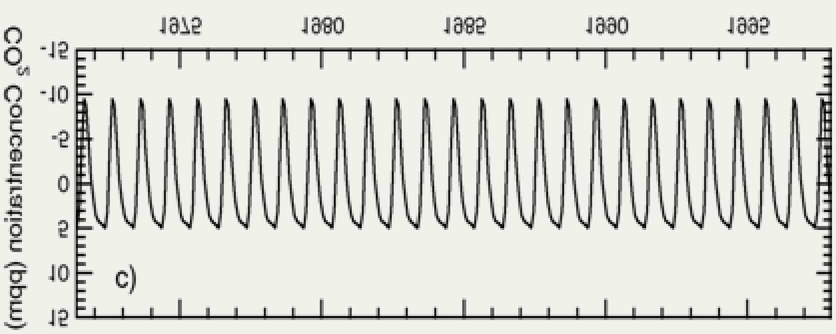
Atmospheric CO_2 at Point Barrow, Alaska



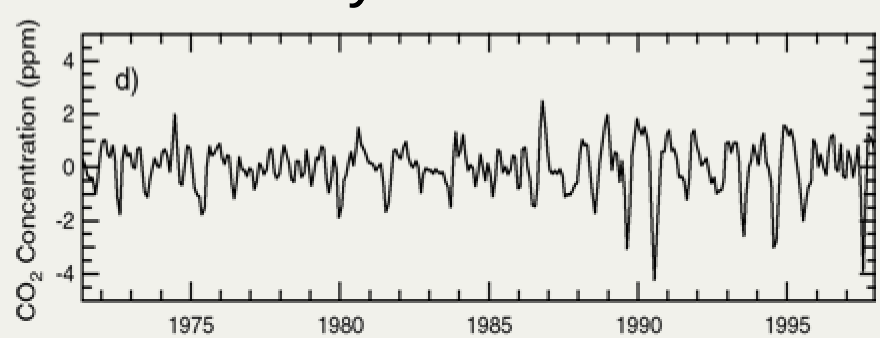
Long-term trend



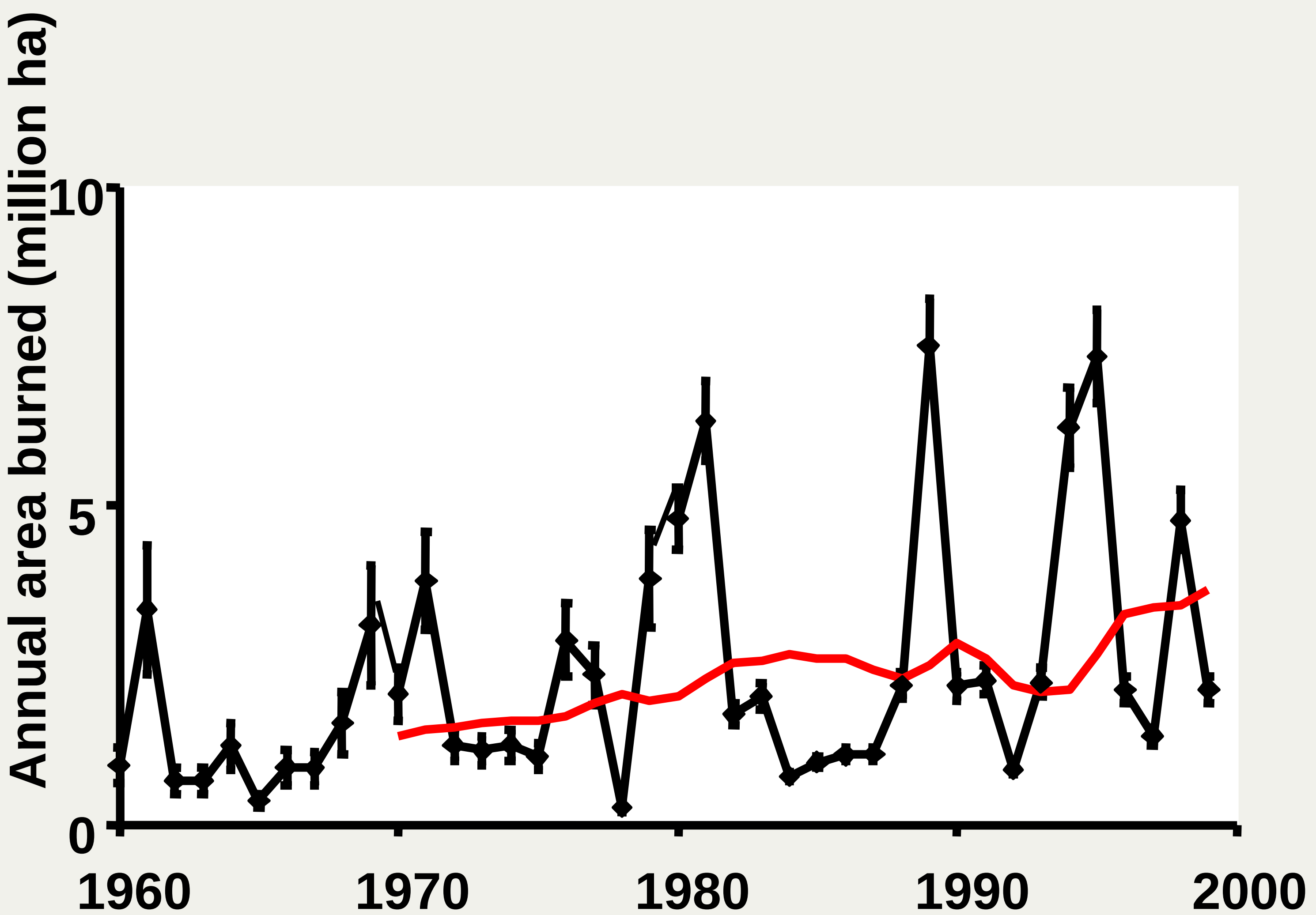
Seasonal Trend



Monthly Anomalies

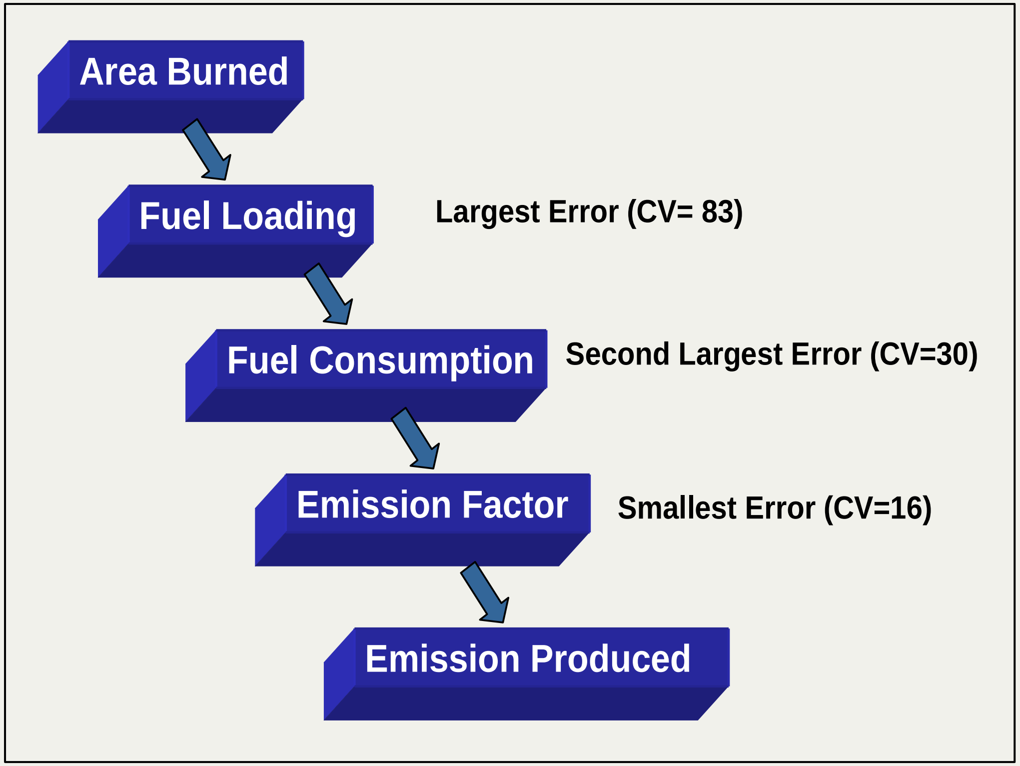


Area burned in Alaska & Canada



Estimating Emission Source

- 4 factors to know
  - Area
  - Fuel loading (biomass)
  - Consumption
  - Emission factor
- Fuel loading and the proportion of fuel consumed (converted to atmospheric constituents) have highest uncertainty



Errors stated here are from Peterson, J. L., *Analysis and reduction of the errors of predicting prescribed burn emissions*, Thesis, University of Washington, Seattle, 1987.

Estimating Emission Source

- Three approaches:
  - BWEM (Kasischke, French and others)
    - Initially concerned with quantifying burned area
    - Recently concentrated on duff consumption with less attention to aboveground consumption
  - CONSUME 3.0 (USDA Forest Service FERA lab)
    - Empirically-based model for each fuelbed
    - Alaska field measurements in 2003 & 2004
  - BORFIRE (Canadian Forest Service)
    - Use fire weather data to estimate fuel consumption
    - Emphasis has been on aboveground (crown) fire
    - Now need to better quantify duff consumption

Estimating Carbon Emissions

Total Carbon Emissions:

$$C_t = A\, B\, f_c\, \beta$$

C_t is the total carbon emissions

A is the total area burned (ha)

B is the biomass density (t ha^{-1})

f_c is the fraction of the biomass that is carbon

Carbon density

β is the fraction of biomass consumed during biomass burning

Carbon Gas Emissions:

CO_2, CO, CH_4, NMHC

$$E_g = C_t\, E_{fg}$$

Emission Factor for each gas species (g gas/kg fuel)

Estimating Carbon Emissions (cont)

C and β are divided into aboveground and surface-layer components

$$C_t = A(\underline{C_a\beta_a} + \underline{C_g\beta_g})$$

Area burned

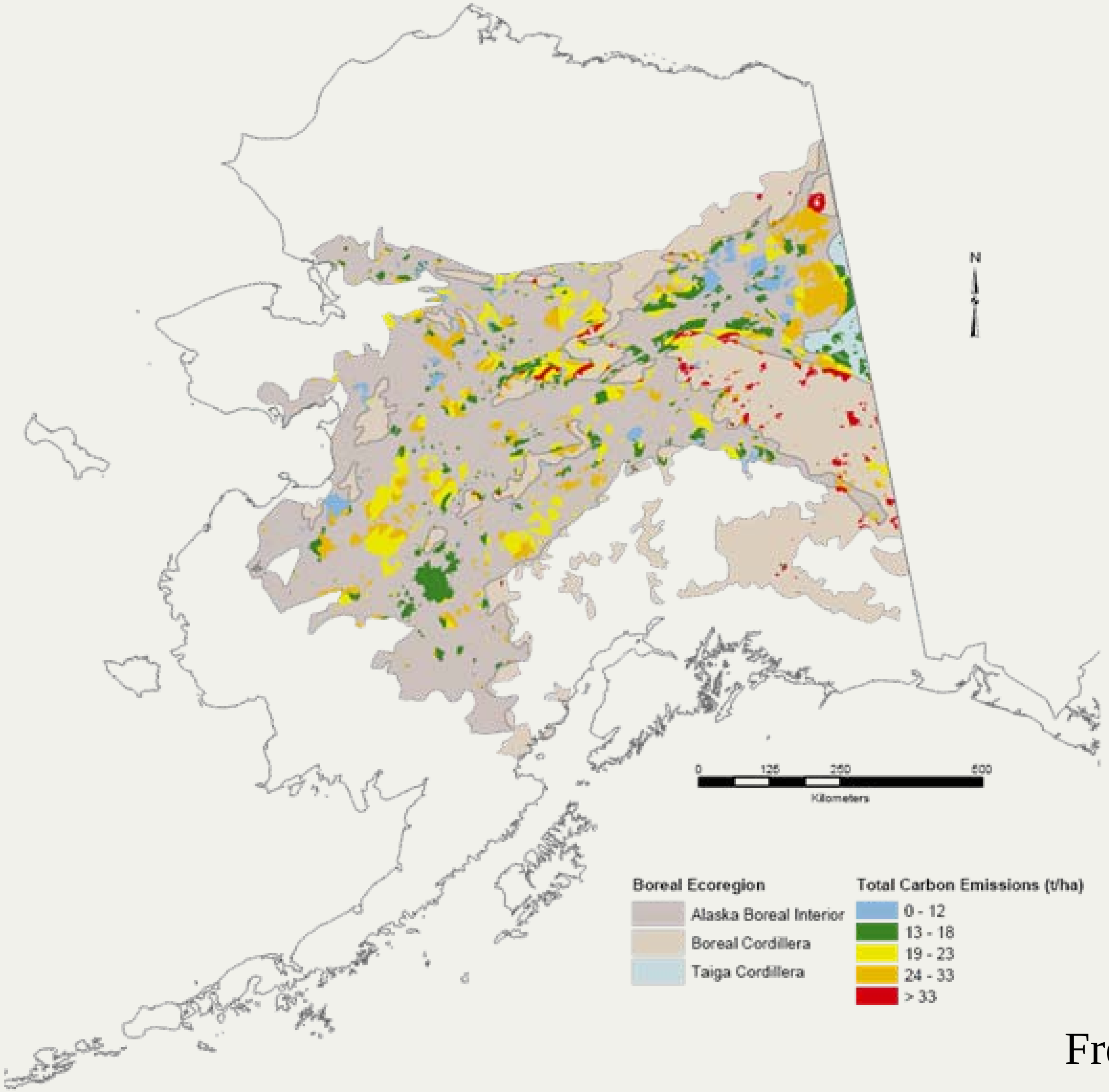
Aboveground (plant)

Surface organic matter (ground layer; duff)

Flaming and smoldering burning is partitioned when applying emission factors for each gas

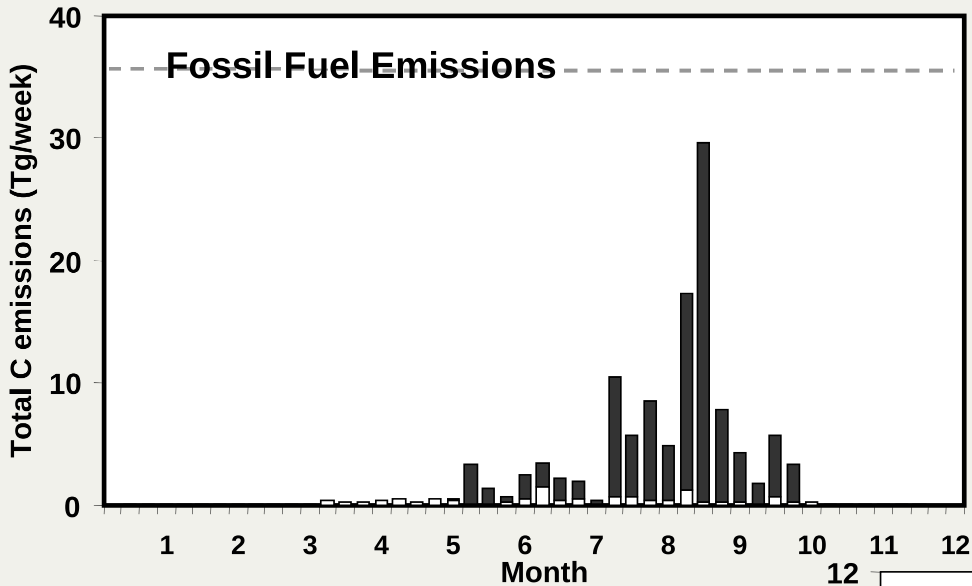
$$E_g = A\,[C_a\beta_a\,(0.8\,E_{fg\text{-}f} + 0.2\,E_{fg\text{-}s}) + C_g\beta_g\,(0.2\,E_{fg\text{-}f} + 0.8\,E_{fg\text{-}s})]$$

Estimated Emissions



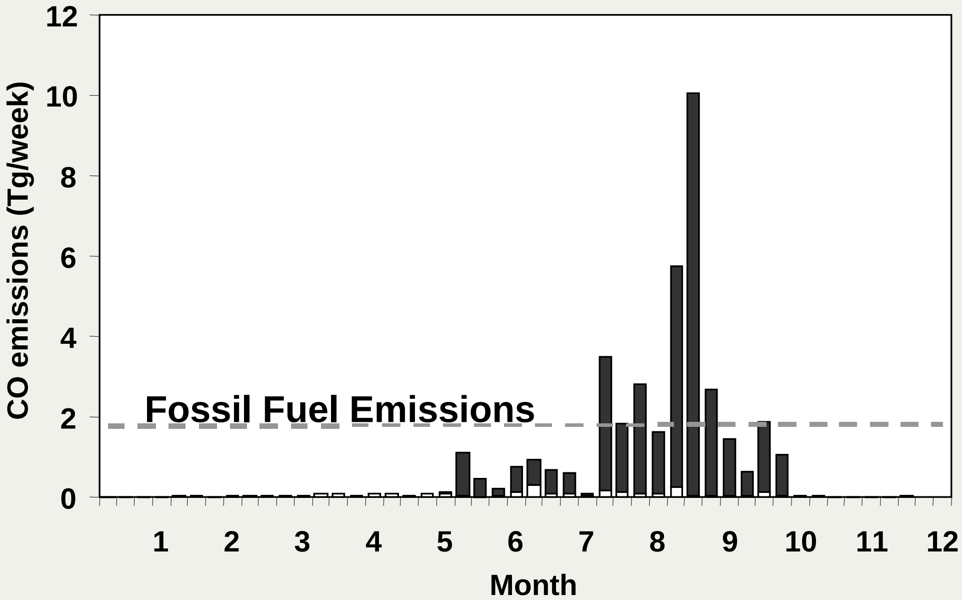
French et al. 2002

Wildfire Emissions Estimates



Total North American Carbon Emissions from fire for 1998

Carbon Monoxide Emissions

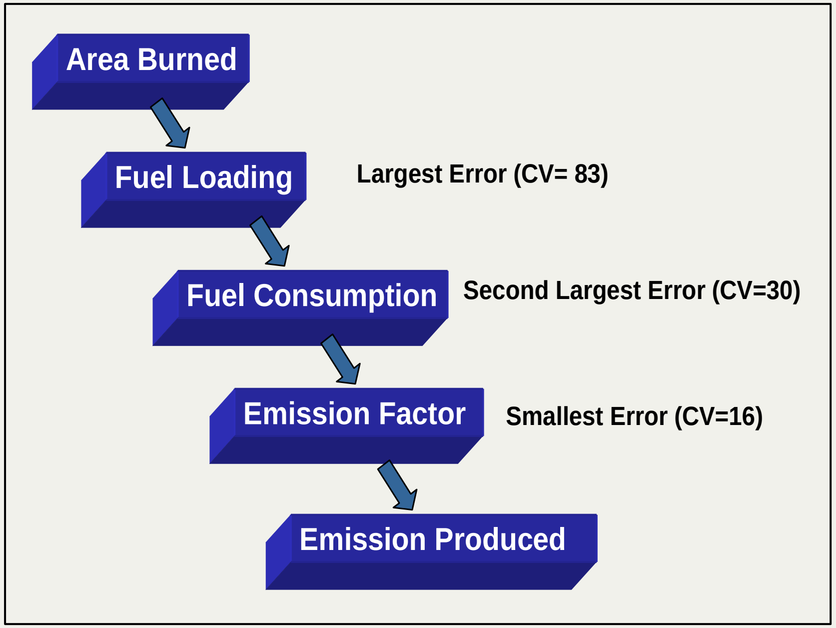


From analysis presented in:
Kasischke et al. 2005

Estimating Carbon Emissions (cont)

- Area Burned (A): ± 10%
  – Derived from fire records and/or remote sensing

- **Fuel Loading (C) and Fuel Consumption:**
  – Based on field data
  – Difficult to quantify
  – Error unknown
  – Surface organic material (duff) very important in boreal, and very under-sampled



- Emission Factors: ± 15%
  – Based on field data (ground, airborne) and lab measurements
  – Easy to quantify some species

CONSUME 3.0

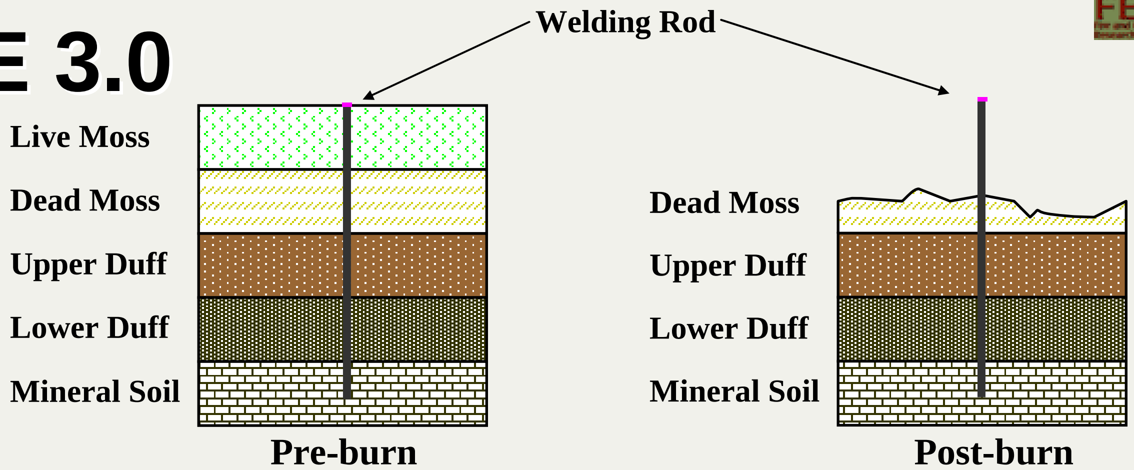
- Decision-making tool to assist resource managers in planning for prescribed fire and wildfire
- Predicts fuel consumption, pollutant emissions, and heat release based on
  - fuel loadings
  - fuel moisture
  - and other environmental factors
- Uses information collected on fuel consumption and emissions through field collections

Pre-fire

Site Inventory

Post-fire

Alaska Field Collections For CONSUME 3.0



CONSUME 3.0 (cont)

Alaska Field Collections For CONSUME 3.0

- Forest floor reduction was measured using fire pins placed before the active fire front.
- Additional data collected
  - Surface fuels amount & moisture
  - weather variables (relative humidity, temperature, days since rain, and wind speed)
- Linear regression models developed to predict fuel consumption for all fuelbed types
- Forest floor consumption predicted by pre-burn forest floor depth and upper duff moisture content

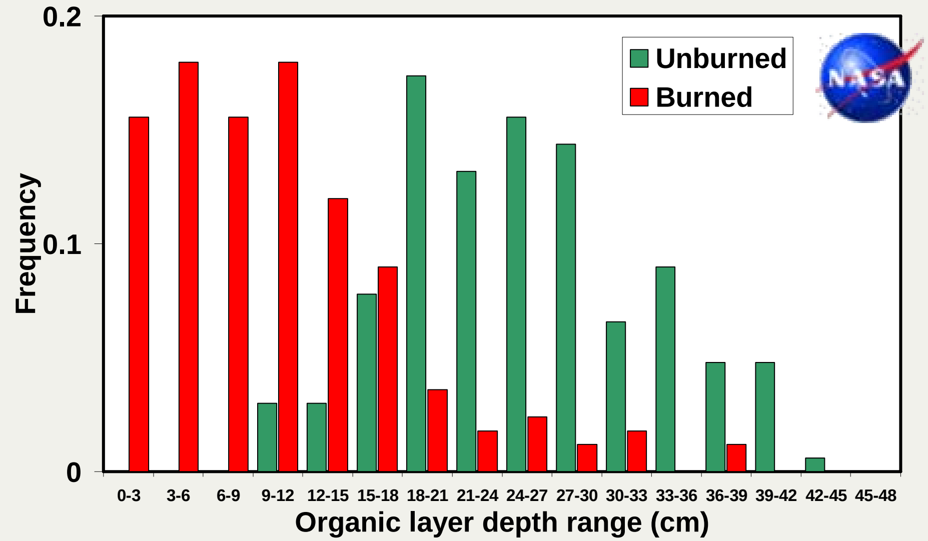
CONSUME 3.0 (cont)

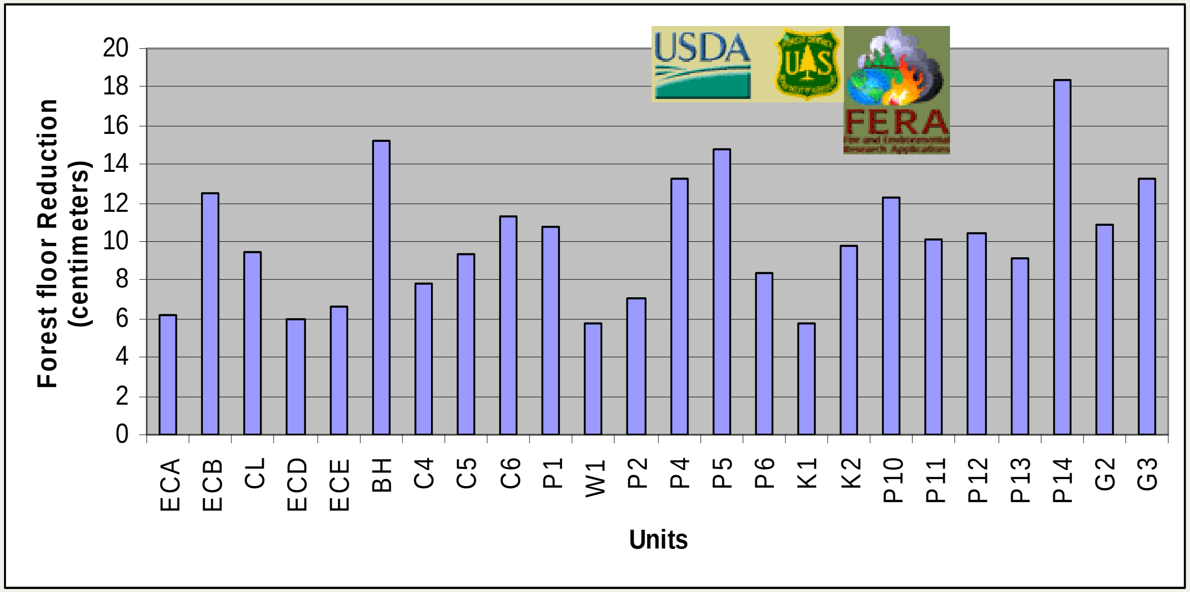
Alaska Field Collections For CONSUME 3.0

- Woody fuel consumption predicted by timelag category (i.e., 1- to 10,000-hr), and litter & duff consumption
- FAAS tower and instruments deployed to sample flaming & smoldering emissions to derive emission factors

Measuring Surface Fuel Consumption

Surface organic layer depths in Alaska burned and unburned black spruce
(E.S. Kasischke and others)

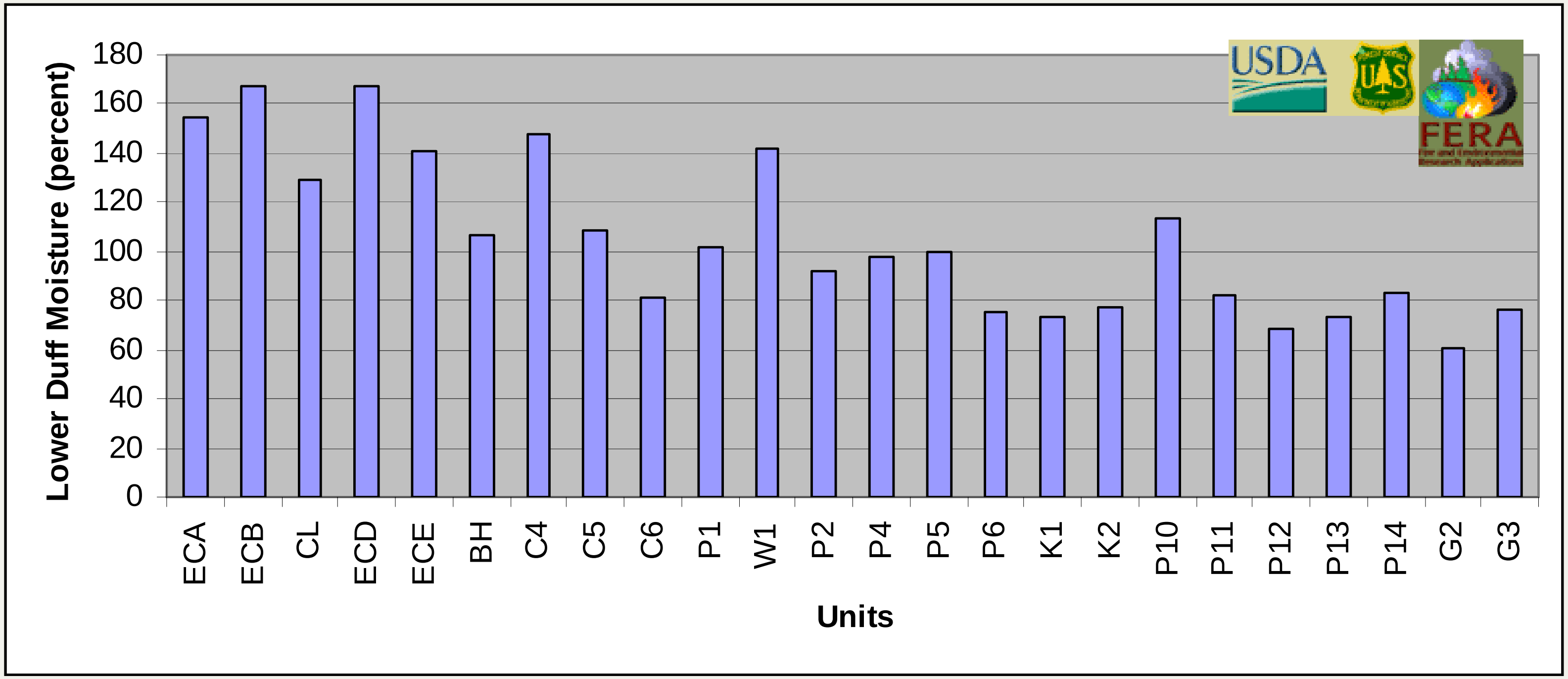




Forest floor reduction measured in Alaska during 2003 and 2004 wildfire season *(USFS)*

Modeling Surface Fuel Consumption

- Lower duff fuel moisture content for each area measured for forest floor reduction during 2003 and 2004 *(USFS)*



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

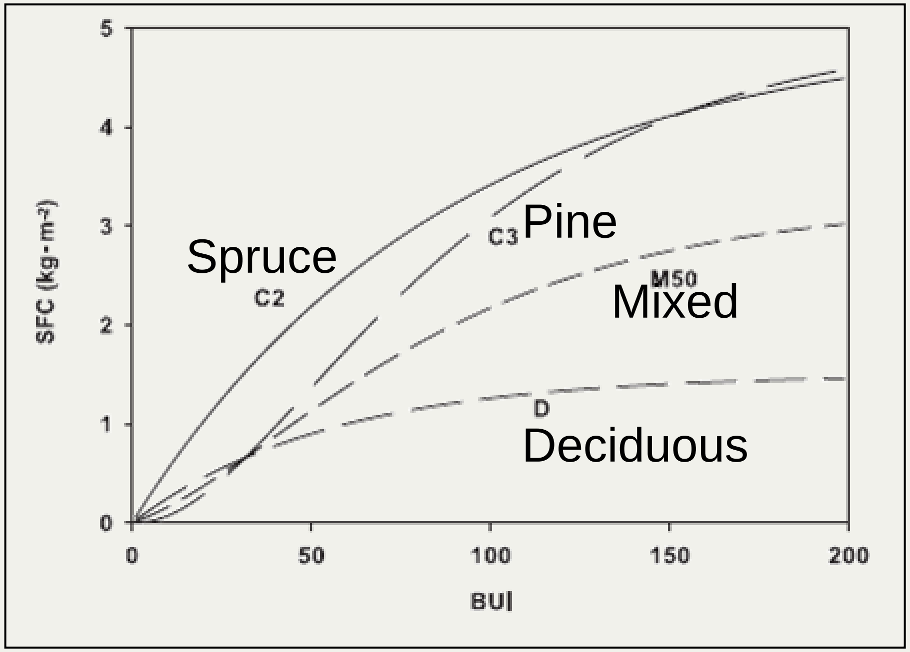
where y = 1.2383 – (0.0114 x Duff FM)

Duff FM = fuel moisture of upper duff layer

Modeling Surface Fuel Consumption

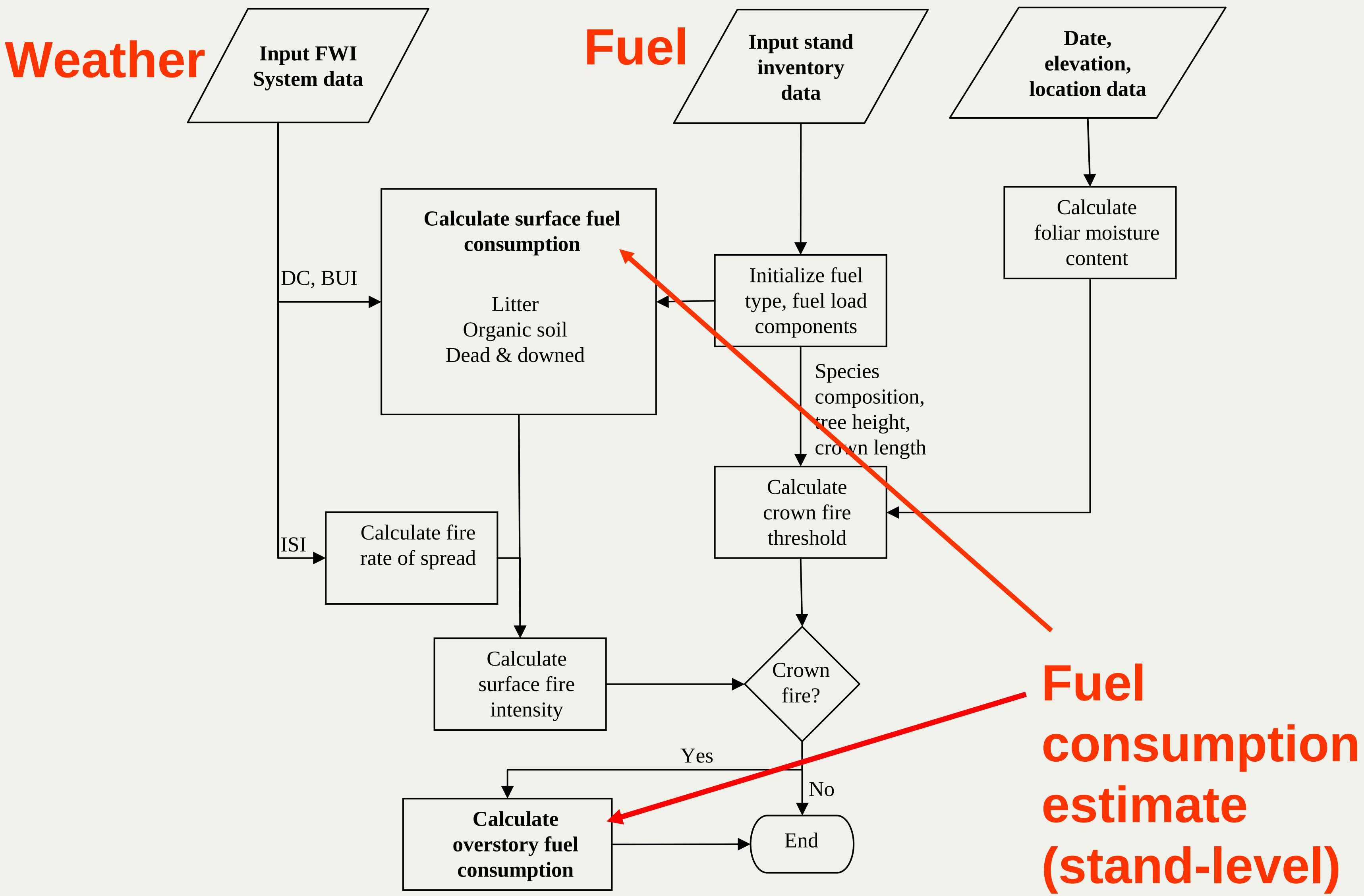
Surface fuel consumption modeled using duff moisture

- Buildup index (BUI)
- Drought code (DC)



from Amiro et al. *Can J. For. Res.*, *31*, 512-525, 2001.

BORFIRE

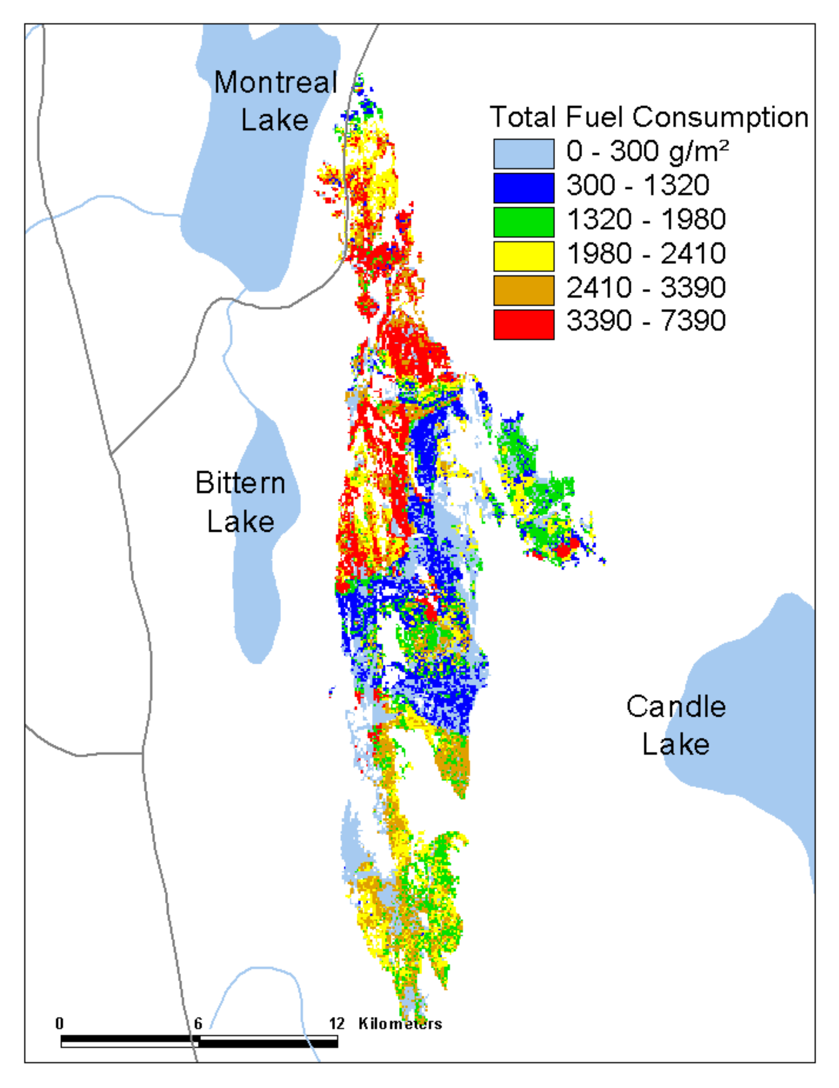

Weather
Fuel
Input FWI System data
Input stand inventory data
Date, elevation, location data
DC, BUI
Calculate surface fuel consumption
Litter
Organic soil
Dead & downed
Initialize fuel type, fuel load components
Calculate foliar moisture content
Species composition, tree height, crown length
ISI
Calculate fire rate of spread
Calculate crown fire threshold
Calculate surface fire intensity
Crown fire?
Yes
No
Calculate overstory fuel consumption
End
Fuel consumption estimate (stand-level)

BORFIRE
Estimated Emissions

Mapping carbon emissions

Inputs:

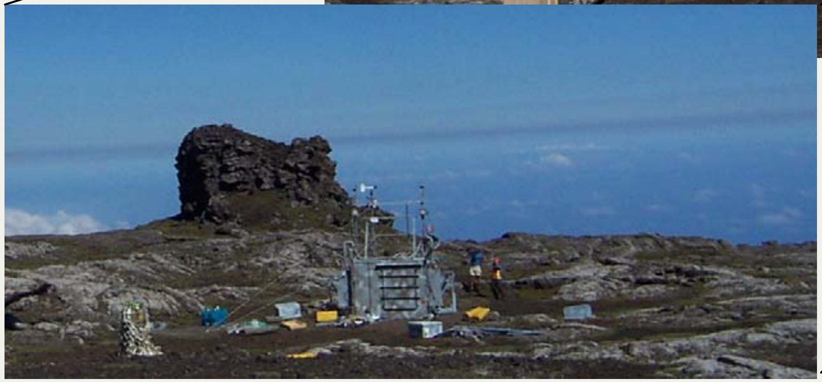
- Fuel type
  - Unpublished maps based on Landsat TM and forest inventory data from air photos
- Fuel consumption
  - Modeled with BORFIRE based on map of BUI from daily weather data
  - Burn date based on map of fire spread from AVHRR/MODIS hot spots



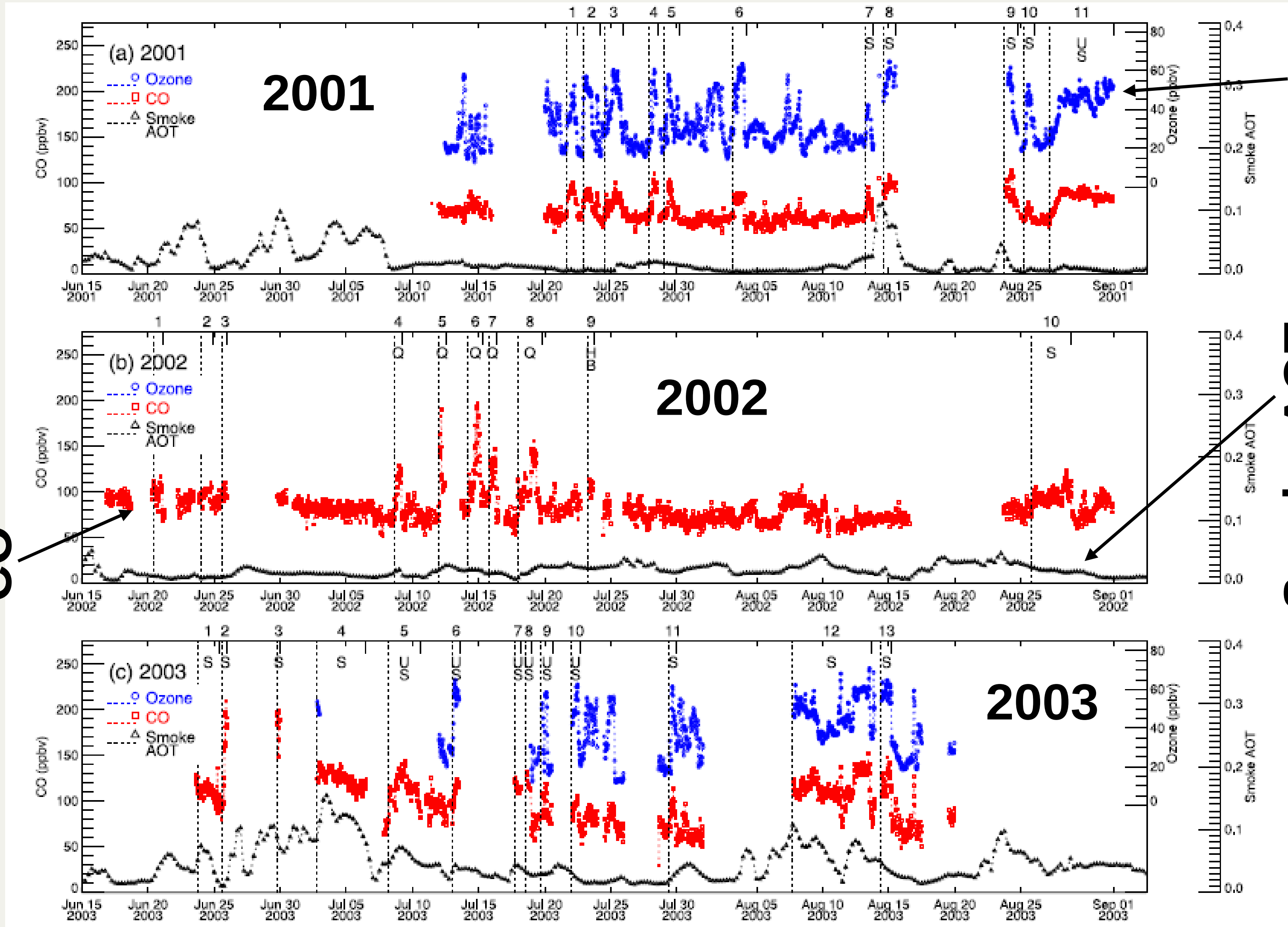
from de Groot 2007

Atmospheric measurements

- Measurements taken at Pico Mountain station, Azores (38.48 N, 28.40 W)
- CO, O_3, NO_x
- Air mass from boreal NA can be sampled without NE-US anthropogenic emissions



CO, O_3 & AOT at Pico Mt Station



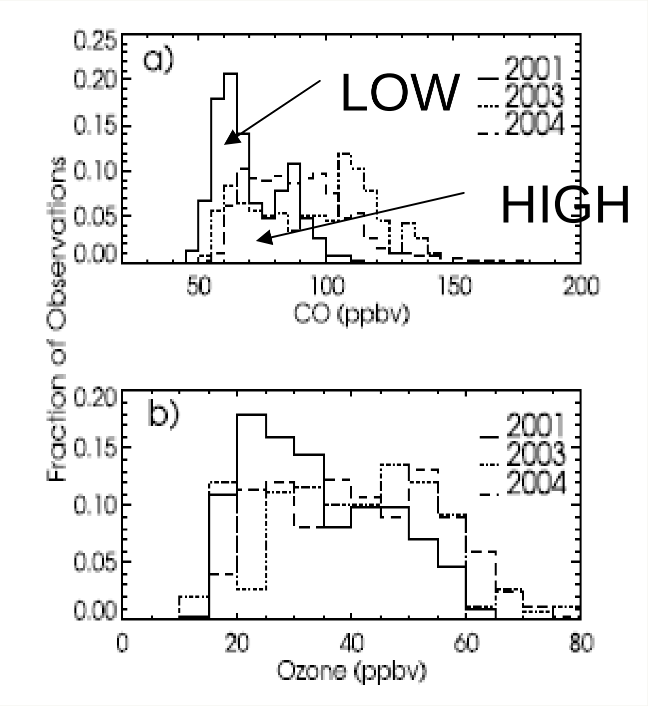
CO

Smoke AOT

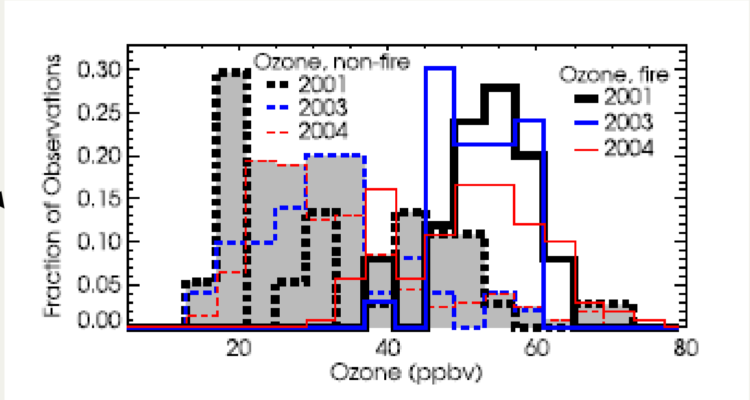
O3

Distribution of CO & O_3 for Low & High Fire Years

- Distributions of (a) CO and (b) O_3 for 3 years 2001- LOW fire year 2003 & 04 – HIGH fire year



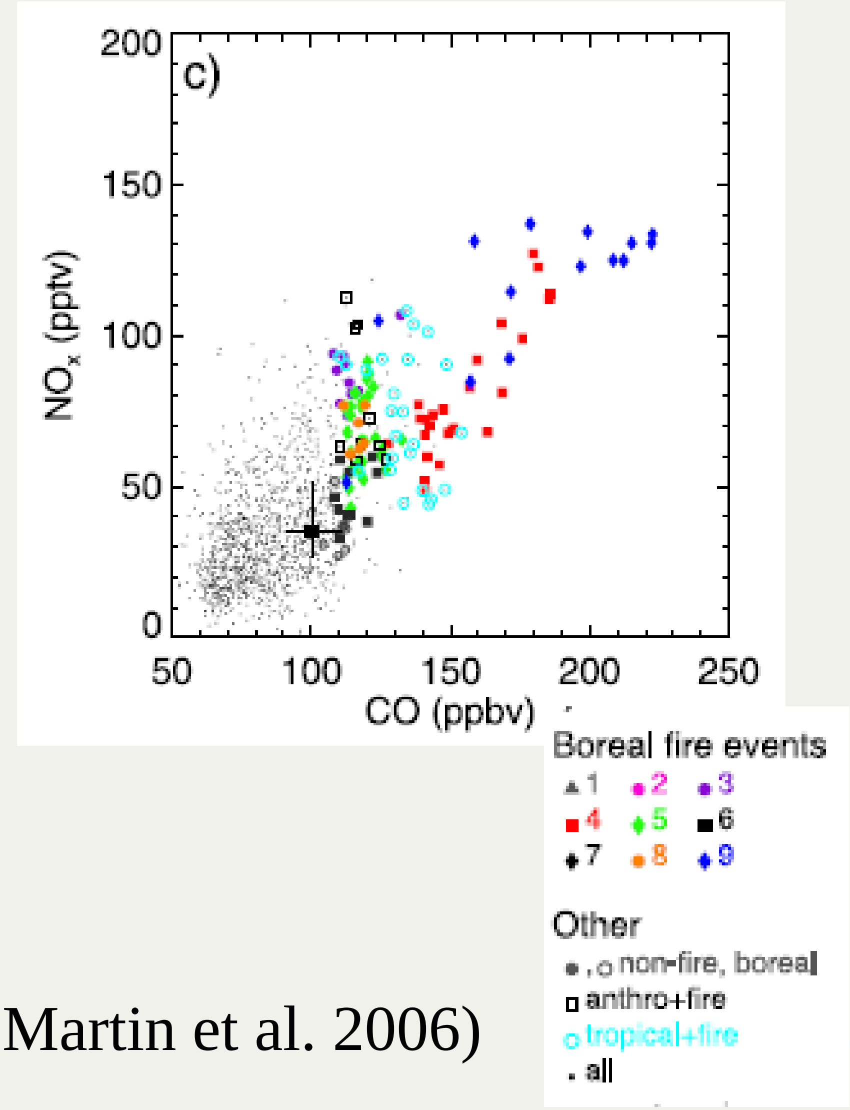
- O_3 frequency distribution in Northern N. American flow, fire and non-fire subsets.
  The area under the non-fire O_3 distributions is shaded



(from Lapina et al. 2006).

Nitrogen Oxide from Boreal Fire

- NO_x and CO well correlated
- Total NO_x emissions during a typical fire season with ~61 Tg CO would be 0.24 TgN
- More than 2/3 of the eastern North American anthropogenic NO_x emissions for similar duration



(from Val Martin et al. 2006)

Issues & Uncertainty

- Model-based estimates of impacts of fire on tropospheric ozone remain highly uncertain
  - Limited direct measurements the magnitude and variability of boreal fire NO_x emissions
- Larger emissions of NO_x from flaming combustion than from smoldering combustion
  - Little data on flaming/smoldering combustion
  - Pico Mountain measurements can be used to provide important constraints on flaming/smoldering partitioning

Mercury Emissions

- Long-term accumulation from coal burning and other industrial activities in peat and duff in boreal regions allows of mercury accumulation
- Fire can release this mercury to the atmosphere due to burning of surface fuels

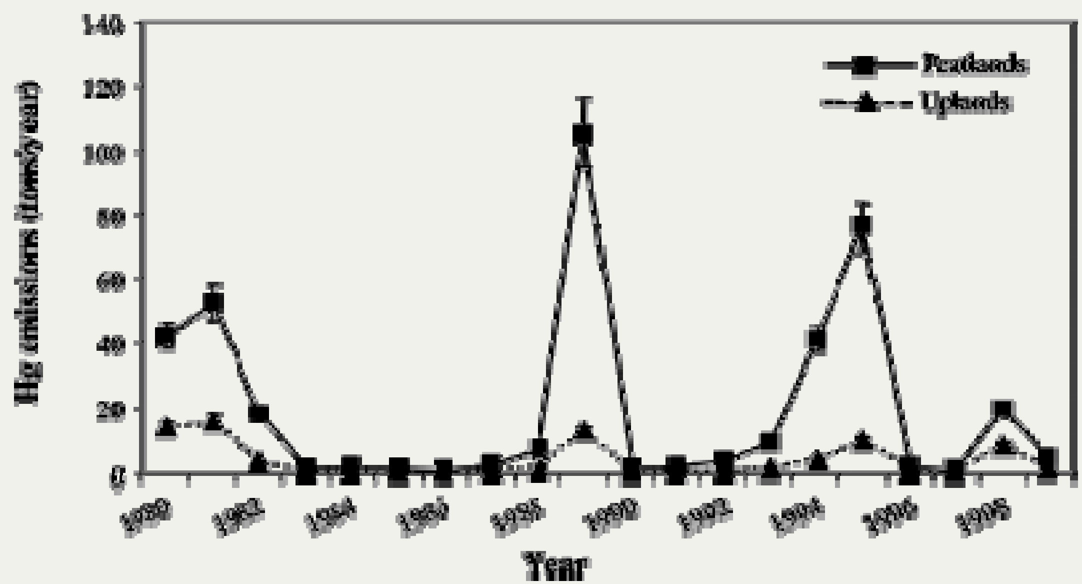
Turetsky, M. R., Harden, J. W., Friedli, H., Flannigan, M., Payne, N., Crock, J., and Radke, L., "Wildfires threaten mercury stocks in northern soils," Geophysical Research Letters 2006, 33doi:10.1029/2005GL025595.

Mercury Stocks and Emissions

Table 2. Organic Matter and Mercury Stocks in Ground Layer Fuels in Boreal Upland Forests and Peatlands Estimated From Organic Matter-Hg Stoichiometry and Regional Soils Databases[a]

	Organic Soil Depth, cm	Organic Matter Stocks, kg/m^2	Hg Stocks, mg/m^2
Upland Forest Stands (n = 390 Sites)			
Deciduous[b]	5.8 ± 0.3	4.28 ± 0.24	2.60 ± 0.20
Evergreen[b]	6.2 ± 0.4	4.36 ± 0.26	2.64 ± 0.22
All sites	6.0 ± 0.2	4.32 ± 0.18	2.62 ± 0.15
Peatlands (n = 336 Sites)			
Wet scenario	Surface 15 cm	26.74 ± 0.87	15.73 ± 0.56
Surface organic matter[c]	Surface 25 cm[c]	35.66 ± 1.17	20.04 ± 0.72
Drought scenario	Surface 35 cm	46.21 ± 1.34	25.14 ± 0.81

Combining mercury stocks with annual area burned, fuel loading, and fuel consumption provides annual estimate of mercury emissions.



Future Research Areas

- Improved fuel maps incl. surface fuel depths
- Fuel consumption measurements and model relationships – variability unknown
- Fire in N. American boreal peatlands
- Partitioning of flaming and smoldering combustion

Summary

- Ground-based (bottom-up) assessments of boreal wildfire emissions are being used to quantify fire emissions
  - Working towards a North America-wide approach
- Boreal wildfire is important to atmospheric (troposphere) concentrations of CO_2, CO, NO_x, O_3, and black carbon
- Improvements in fuels, fuel maps, and fuel consumption are needed
  - Flaming vs. smoldering combustion
  - Burning of deep peatland ecosystems

Key References

de Groot, W. J., Landry, R., Kurz, W. A., Anderson, K. R., Englefield, P., Fraser, R. H., Hall, R. J., Banfield, E., Raymond, D. A., Decker, V., Lynham, T. J., and Pritchard, J. M., "Estimating direct carbon emissions from Canadian wildland fires.," International Journal of Wildland Fire 2007, (in press)

French, N. H. F., Kasischke, E. S., and Williams, D. G., "Variability in the emission of carbon-based trace gases from wildfire in the Alaska boreal forest," Journal of Geophysical Research 2002, 107, 8151. doi:10.1029/2001JD000480.

French, N. H. F., Goovaerts, P., and Kasischke, E. S., "Uncertainty in estimating carbon emissions from boreal forest fires," Journal of Geophysical Research 2004, 109, D14S08. doi:10.1029/2003JD003635.

Honrath, R. E., Owen, R. C., Martin, M. V., Reid, J. S., Lapina, K., Fialho, P., Dziobak, M. P., J. Kleissl, a., and Westphal, D. L., "Regional and hemispheric impacts of anthropogenic and biomass burning emissions on summertime CO and O_3 in the North Atlantic lower free troposphere," Journal of Geophysical Research 2004, 109, D24310, doi:10.1029/2004JD005147.

Kasischke, E. S., Hyer, E. J., Novelli, P. C., Bruhwiler, L. P., French, N. H. F., Sukhinin, A. I., Hewson, J. H., and Stocks, B. J., "Influences of boreal fire emissions on Northern Hemisphere atmospheric carbon and carbon monoxide," Global Biogeochemical Cycles 2005, 19, GB1012. doi:10.1029/2004GB002300

Lapina, K., Honrath, R. E., Owen, R. C., Val Martin, M., and Pfister, G., "Evidence of significant large-scale impacts of boreal fires on ozone levels in the midlatitude Northern Hemisphere free troposphere," Geophys. Res. Lett. 2006, 33, L10815. doi:10.1029/2006GL025878.

Ottmar, R. D. and Baker, S. P., "Forest Floor Consumption and Smoke Characterization in Boreal Forested Fuelbed Types of Alaska. Final Report JFSP Project #03-1-3-08," 2007, 35 pp.

Ottmar, R. D., Sandberg, D. V., Riccardi, C. L., and Prichard, S. J., "An overview of the Fuel Characteristic Classification System (FCCS) - quantifying, classifying, and creating fuelbeds for resource planning," Canadian Journal of Forest Research 2007, (in press)

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