Remote Measurements of
Active Fire Behavior and Post-Fire Effects

Alistair Smith (and many many others ...)

Remote Sensing: A very Brief Overview

~ 5 million years B.C.: Humans Begin to Understand their Environment

Wildlife Management
Hazard Assessment

The Remote Sensing Process

We aim to: Physically relate surface process to remotely derived measures
What’s Happening?

Fire-Remote Sensing Essentials: Reflectance

More than just red
Energy emitted \( q_\lambda \) at a given wavelength and temperature is given by the Stefan-Boltzmann law:

\[
q_\lambda = \varepsilon \sigma T^4
\]

\( \varepsilon = \text{emissivity, } 0 \leq \varepsilon \leq 1, \) and is the efficiency that surface emits energy when compared to a black body.

Fires follow the curve

Terminology
Fire Intensity, Fire Severity, and Burn Severity...

<table>
<thead>
<tr>
<th>Environmental Characteristics before the Fire</th>
</tr>
</thead>
<tbody>
<tr>
<td>After the Fire</td>
</tr>
<tr>
<td>Pre-Fire Environment</td>
</tr>
<tr>
<td>Fire Environment</td>
</tr>
<tr>
<td>Post-Fire Environment</td>
</tr>
<tr>
<td>Post-Fire Environment</td>
</tr>
<tr>
<td>Post-Environmental</td>
</tr>
</tbody>
</table>

Source of Confusion: The Terms Fire Severity and Burn Severity are used inconsistently in the Remote Sensing literature

### The Severity Concern

**Value Laden Term**
- Negative Connotations: severity = bad
- Public & Policy Miscommunication
- Multiple Definitions in the Literature
  - Fire duration and heat transfer
  - Vegetation consumption
  - White ash production
  - Change in surface reflectance
  - Alteration in soil properties
  - Changes in the litter and duff layers
  - Long-term vegetation mortality and recovery
The Need for Clarification

Simplifying the Fire Disturbance Continuum:
• Limit use of the Terms Fire Severity & Burn Severity
• Describe and Quantify the Actual Processes Being Assessed
• Make sure that satellites CAN also measure these processes

What Can Remote Sensing do for Fire Science?
Vegetation Mortality & Ecosystem Recovery
How about the Post-Fire Measures?

Need immediate Active or Post-fire measures that:
• Relate to active fire characteristics (i.e. intensity) &
• Predict post-fire effects (i.e. severity)

From Unburned to Burned Surfaces

DECREASE in Visible-NIR
(in General)

INCREASE in SWIR reflectance

Trigg and Flasse (2000)
From Unburned to Burned Surfaces

**INCREASE in surface temp**

![Image](image_url)

Trigg and Flasse (2000); Smith and Wooster (2005)

Several Remote Methods Use These Changes

- **NDVI** = \( \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}} \)
- **NBR** = \( \frac{\text{NIR} - \text{SWIR}}{\text{NIR} + \text{SWIR}} \)
- **dNBR** = \( \text{NBR}_{\text{prefire}} - \text{NBR}_{\text{postfire}} \)

Produce Maps of Area Burned and Maps of Vegetation Mortality and Recovery

The Severity Concern

**Subjective & Value Laden Term**

\( \Delta \text{NBR} \): non-linear asymptotic relationship with CBI that varies with sensor spatial resolution and environment

![Image](image_url)


Highlights need to evaluate alternative methods
Multiple Agencies use the dNBR method.

dNBR is a good Measure of Current Canopy Condition.

Remember our Aim:

To physically relate surface process to remotely derived measures.

The rapid-response measurement of active fire behavior and immediate post-fire effects is very difficult.

Need easy measure that can be related to the fire behavior. From fire behavior we can predict or model the longer-term ecosystem condition.

Use Cover Fractions Within a Pixel:

- Direct Measure via Remote Sensing
- Comparable Measure via Field Methods
- Similar to traditional %Green, %Brown, % Black

Source: Hudak, Morgan, Hardy et al
Use Cover Fractions Within a Pixel

- Inherently Scalable
- Use Existing 30m Immediate Post-fire Landsat Data
- Physically Related to Carbon and Water Processes

<table>
<thead>
<tr>
<th>Ecological Model</th>
<th>Fire Effects Reference</th>
<th>Linkages to C and H2O Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire severity</td>
<td>Litter et al. (2013), Trabucco (2005)</td>
<td>Fire severity and soil erosion</td>
</tr>
<tr>
<td>High severity</td>
<td>Giglio et al. (2011)</td>
<td>Fire severity and soil erosion</td>
</tr>
<tr>
<td>Moderate severity</td>
<td>Levine et al. (2015)</td>
<td>Plant productivity and water availability</td>
</tr>
<tr>
<td>Low severity</td>
<td>Smith et al. (2010)</td>
<td>Soil nutrient cycle</td>
</tr>
<tr>
<td>None</td>
<td>Smith et al. (2005)</td>
<td>Soil nutrient cycle</td>
</tr>
</tbody>
</table>

Source: Smith et al. in prep.

Measuring Cover Fractions in a Pixel

Standard and Simple Method: Linear Spectral Unmixing

Pixel: Green (Leaf) + Brown (dry grass) + Black (char)

We can break a pixel down into component fractions

Mapping Burned Areas: Woodland Savannah
Setting a Char Fraction Threshold

>50% Charcoal

Mapping Burned Area: Comparison

Using Char Fractions to Predict Post-Fire Effects?

Jasper Fire, South Dakota started
24th Aug 2000
~33,800 ha Burned in 9 days
Ponderosa Pine Forest
1-Yr post-fire Measures in 80 sites
Landsat Image: 14th Sept 2000
Also Measure Immediate Post-Fire ΔNBR

Compare both ΔNBR and Char Fraction Cover to 1-yr Post-Fire Field Canopy and Sub-Canopy Measures

Landsat 7:5:4

ΔNBR
Char Fraction

Canopy Variables: 1-Yr Post Fire

Smith, Lentile et al. IJRS (in review)

Char Fraction

R²=0.56

Percentage Live Tree

Canopy Variables: 1-Yr Post Fire

Lentile, Smith et al. (in review)

Char Fraction

R²=0.52

Total Crown Effects (Crown Scorch + Crown Consumption)
Retrospective Measurement of the Fire Intensity

Bole Scorch (surrogate of flame length $\rightarrow$ Intensity)

What's Potentially Happening with Bole Scorch?

Char Fraction = 100%

Prediction of Sub-Canopy Ecosystem Condition

Litter Organic Weight (g/m$^2$)
Sub-Canopy Variables

What Can Remote Sensing do for Fire Science?

Fire Behavior and Active Fire Effects

How Much Fuel (Carbon) is Combusted?

Fire Line Intensity: $I = HWR$

$H$ is known

Need Measurement of:

$W$ – Fuel Combusted

$R$ – Rate of Spread

In Crown Fires $W$ can be ‘very Difficult’
Also Many Large Fires Occur in Remote Areas

Andrews and Rothermel 1982 – Heat Per Unit Area:

\[ W_f = \frac{HPA}{H} \]

\[ \text{Energy} = \varepsilon \sigma T^4 \]

HPA = Energy from Combusting Fuel
- Energy Absorbed by Background

\[ HPA = \varepsilon \sigma (T^4_{\text{fire}} - T^4_{\text{background}}) \]

This Equation can be Applied to Satellite Data

Accurate Measures


MODIS and BIRD FRP data in Boreal Forest


Regional W Estimates

A Week of W: Southern Africa


**Biomass**: 3.2 million tonnes (1.5 Mtonnes C)

**Combusted**: (4.3-5.1 million tonnes adj. for cloud)

Cloud eff
From Energy to Fire Behavior

Head and Backing Grassland Fires


---

From Energy to Fire Behavior

<table>
<thead>
<tr>
<th>Field</th>
<th>FLI (kW m⁻²)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Headfire</td>
<td>400-1000</td>
<td>Stocks et al. (1996)</td>
</tr>
<tr>
<td></td>
<td>50-150</td>
<td>Trollope et al. (1996)</td>
</tr>
<tr>
<td></td>
<td>8-15</td>
<td>Smith (2004)</td>
</tr>
<tr>
<td>Backfire</td>
<td>20-100</td>
<td>Trollope et al. (1996)</td>
</tr>
<tr>
<td></td>
<td>11-20</td>
<td>Trollope (1996)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Image</th>
<th>ΣPRP (GJ/ha)</th>
<th>Radiative FLI (W/m²)</th>
<th>Fire front length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Head</td>
<td>3405</td>
<td>16.9</td>
<td>10</td>
</tr>
<tr>
<td>Range Head</td>
<td>82</td>
<td>36</td>
<td>3</td>
</tr>
<tr>
<td>Mean Back</td>
<td>385</td>
<td>6.0</td>
<td>12</td>
</tr>
<tr>
<td>Range Back</td>
<td>4</td>
<td>3.4</td>
<td>2.8</td>
</tr>
<tr>
<td>Head:Back mean ratio</td>
<td>18.5</td>
<td>2.4</td>
<td>2.8</td>
</tr>
</tbody>
</table>

From Energy to Fire Behavior

Crown and Surface Boreal Forest Fires

Fire Behavior $\rightarrow$ Model Emissions (CONSUME/EPM)

Directly Relate Energy to PM Emissions

Future: Linking Active Fire Measures to Post-fire Effects
"As a young man, my fondest dream was to become a geographer. However, while working in the Patent's Office, I thought deeply about the matter and concluded that it was far too difficult a subject. With some reluctance, I then turned to physics as an alternative."

- Albert Einstein