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Measuring Byram's Fire Intensity from Infrared Remote Sensing Imagery

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Heat Transfer

Convection

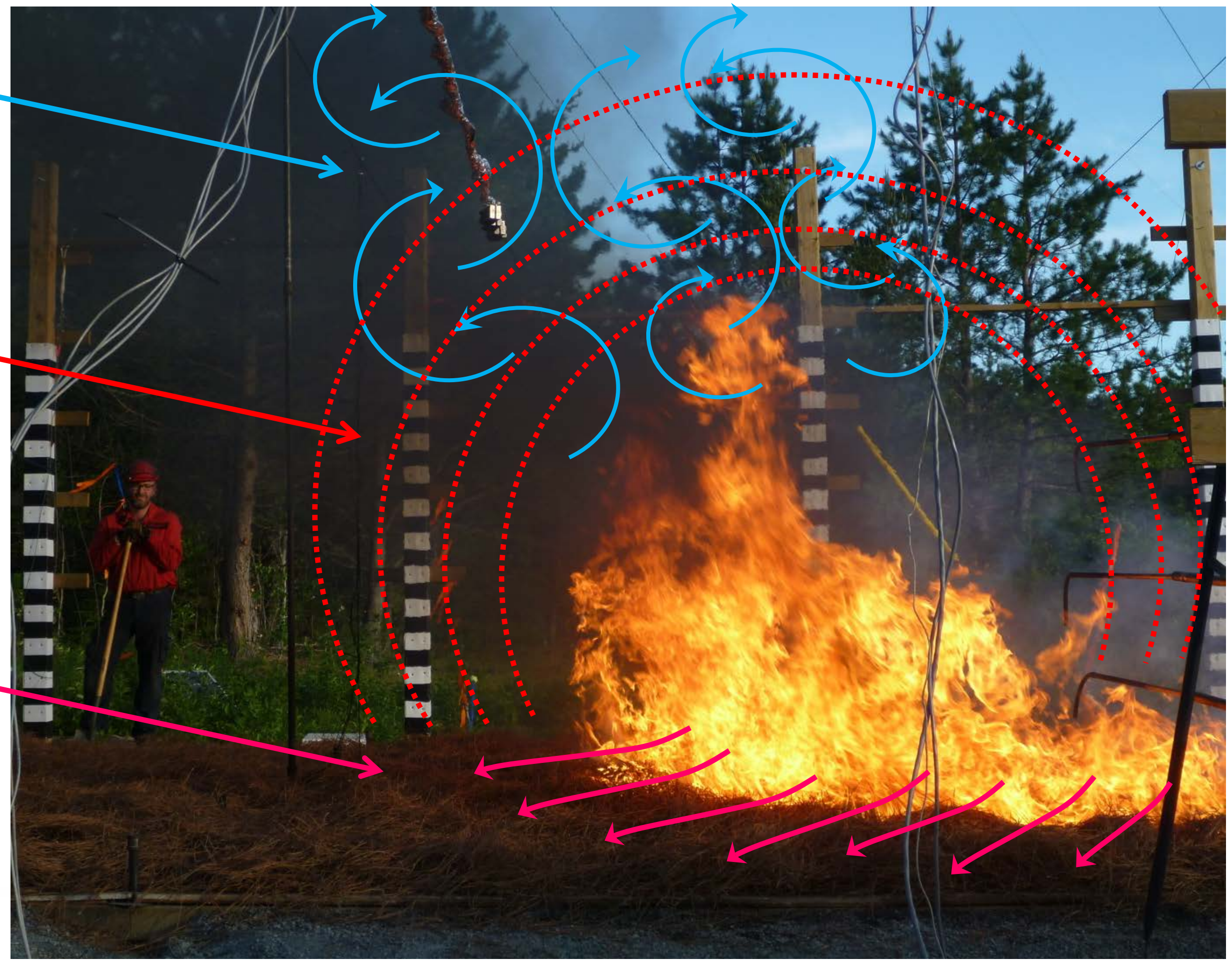
- Particle energy physically moves the body

Radiation

- Energy is emitted via electromagnetic energy

Conduction

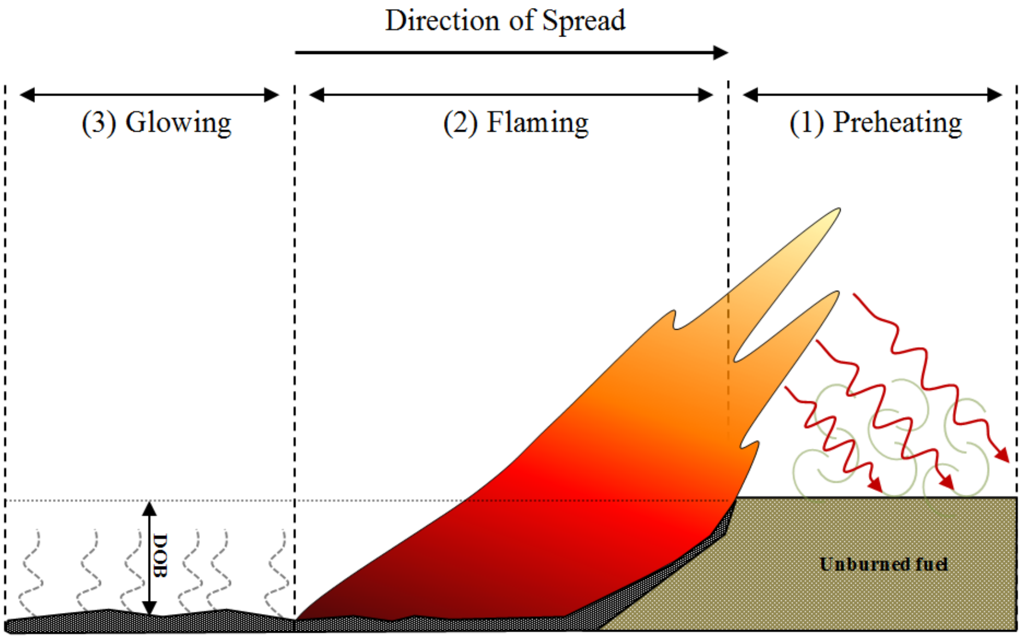
- Particles transfer kinetic energy via collisions



Byram's Fire Intensity

Byram's fire intensity (FI; kW m^{-1}):

- the rate of energy (or heat) release per unit time per unit length of the fire front (Byram 1959)
- Energy released by convection, conduction *and radiation* (now)
- Pertains to the active combustion along the perimeter (typically flaming) not smouldering which occurs within the burned area (Alexander 1982)



Calculating FI

Byram's Equation: FI = Hwr

Where:

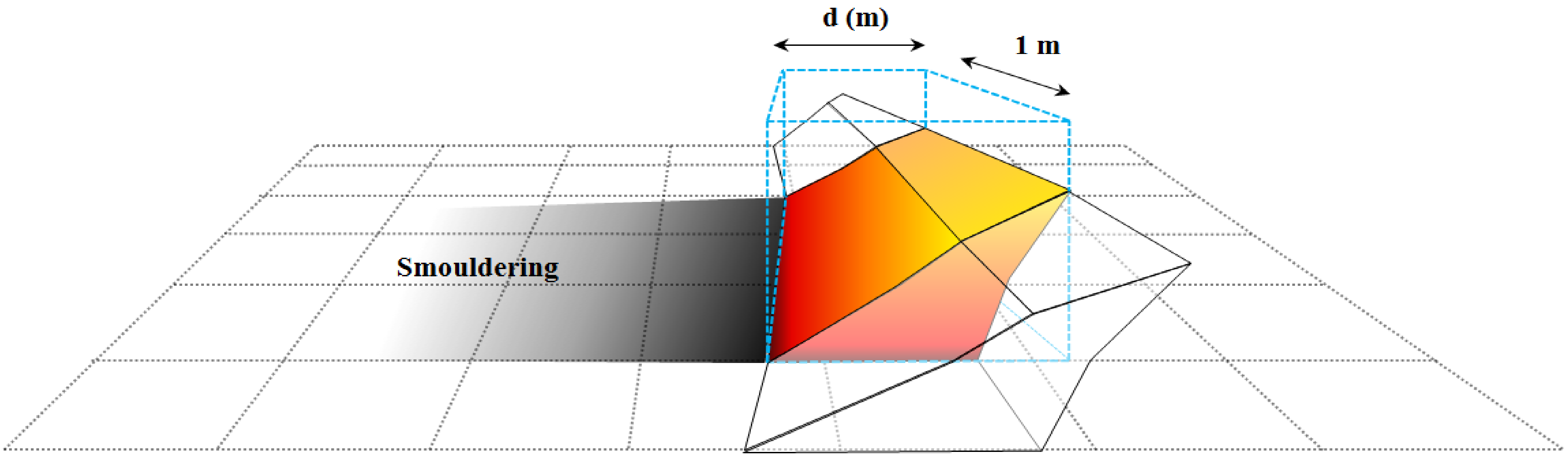
FI = fire intensity (kW m^{-1})

H = low heat of combustion (kJ kg^{-1})

w = fuel consumed (kg m^{-2})

r = ROS (m s^{-1})

* FI is calculated based on measurements of H, w, and r



Fire Radiative Power

Fire Radiative Power (FRP):

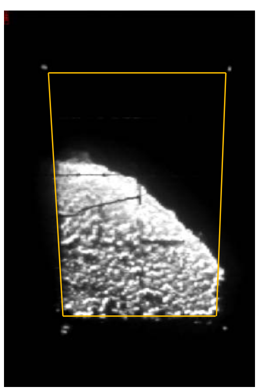
- A measure of the rate of radiant heat output from a fire

Fire Radiative Energy (FRE)

- The time integral of FRP over the life of a fire

- FRP and FRE can be calculated using a wide range of different IR detectors, most commonly it is recorded from a nadir viewing position

HANDHELD



AIRBORNE

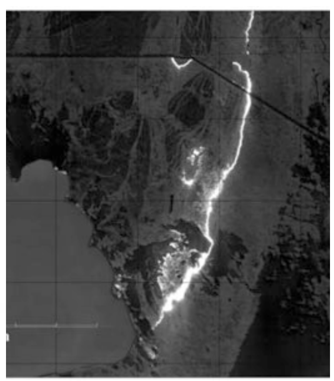


Fig. 18.9 Wooster, *et al*. (2013)

POLAR-ORBITER   GEOSTATIONARY

BIRD MIR   MODIS MIR   GOES MIR

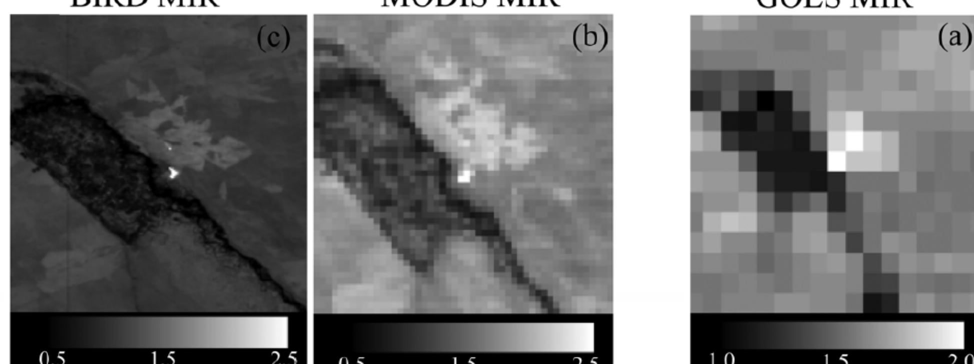
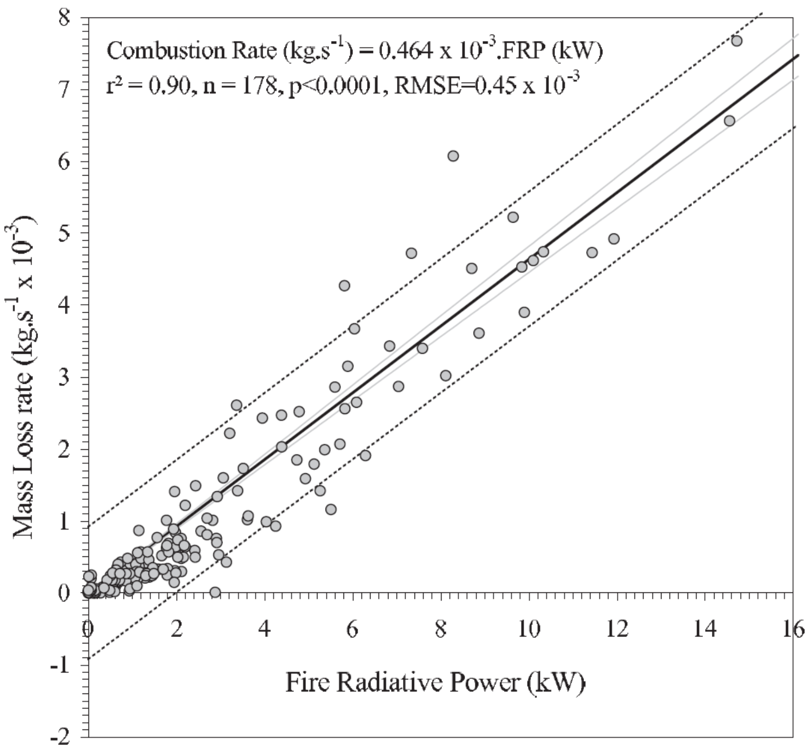
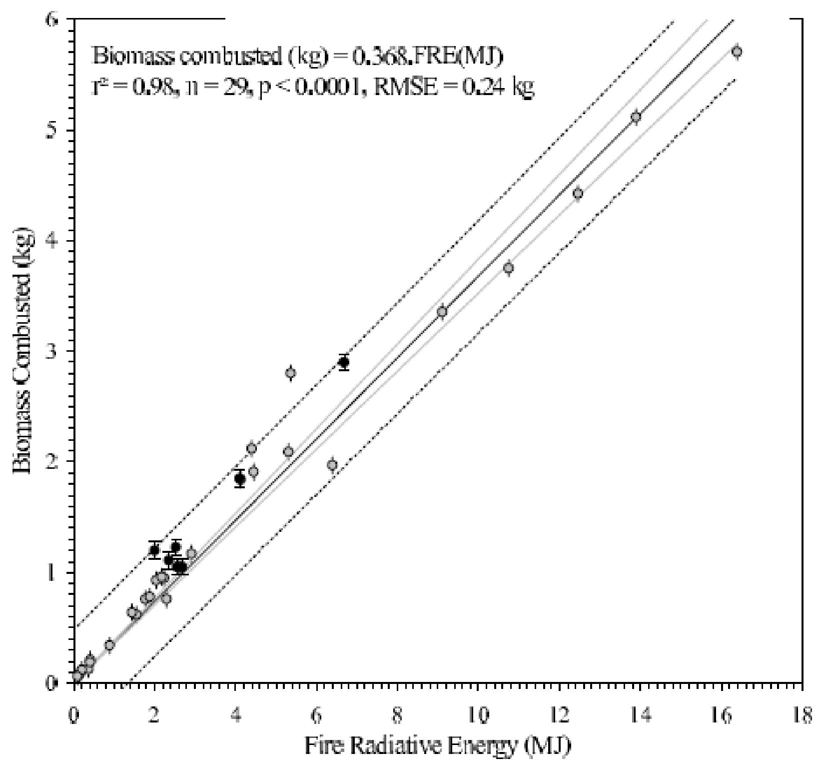


Fig. 1:   Wooster, *et al*. (2005)

Fire Radiative Power

FRP can be used to quantitatively measure the amount of biomass burning, *regardless of fuel type*





Wooster, *et al*. (2005)

Fire Radiative Power
IS NOT
Fire Intensity

(as understood by fire researchers and managers)

- FRP is frequently referred to as “fire intensity” by the remote sensing community
- Often FRP and Byram’s fire intensity can be seen being discussed interchangeably in the literature
- A very clear distinction can be drawn between FRP and FI
- FRP is a stepping stone to a unique understanding of actual FI

FRP IS ONLY RADIATIVE ENERGY

Convection

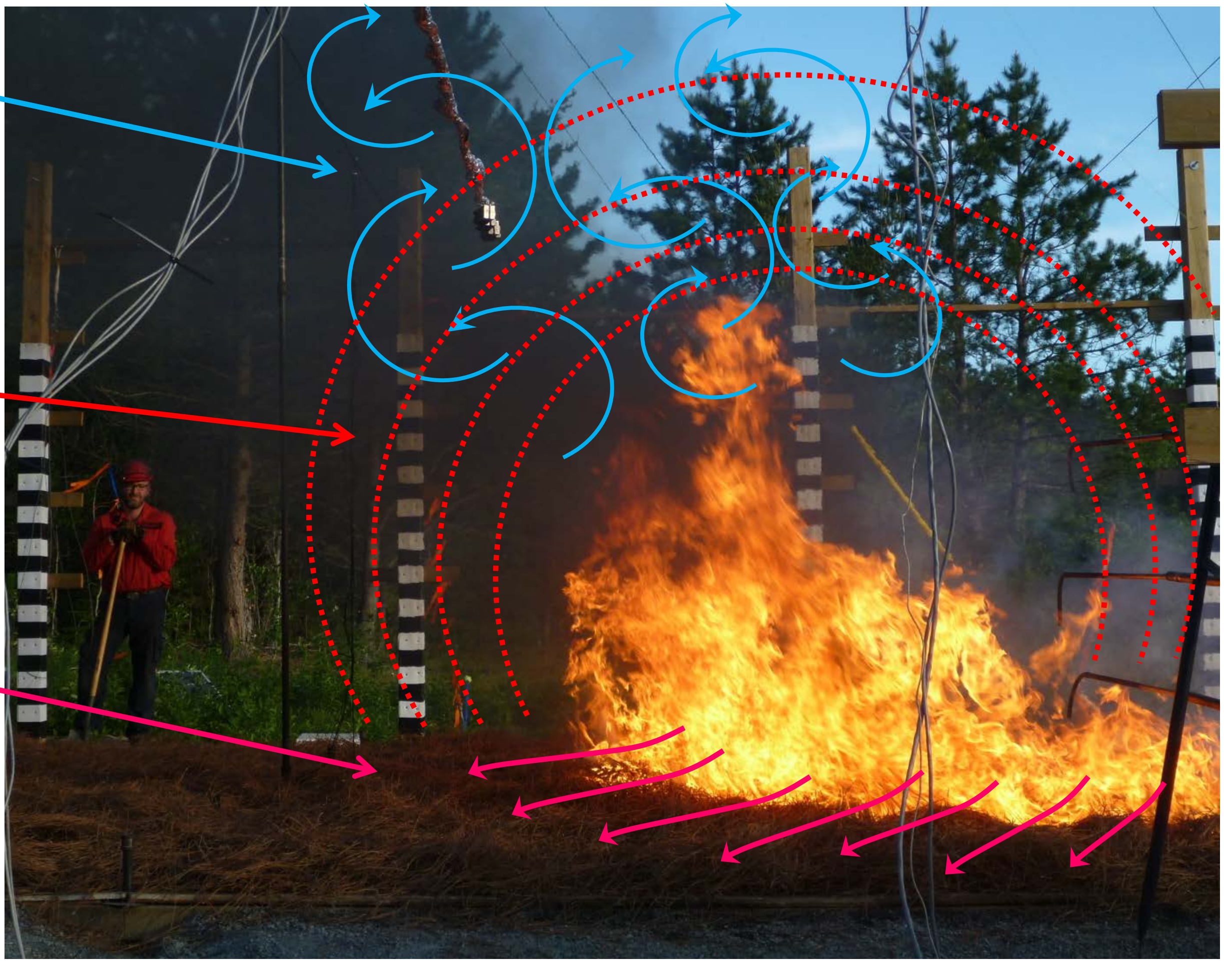
- Particle energy physically moves the body

Radiation

- Energy is emitted via electromagnetic energy

Conduction

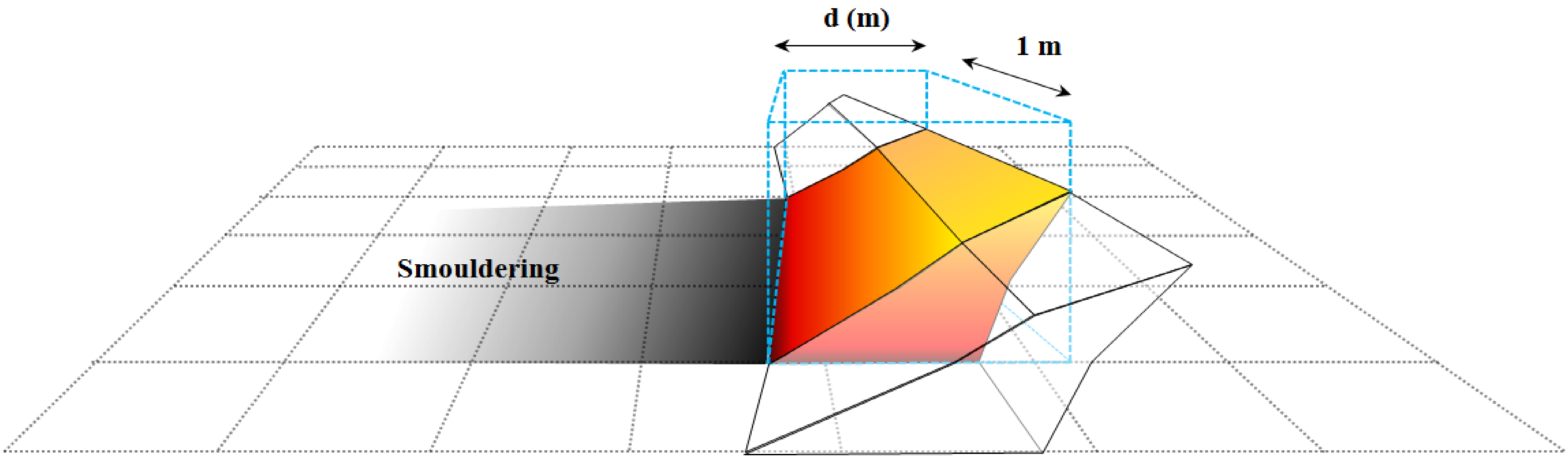
- Particles transfer kinetic energy via collisions



FRP and FI have Different Physical Extents

FI = $kW\ m^{-1}$

FRP = kW (or $kW\ m^{-2}$)

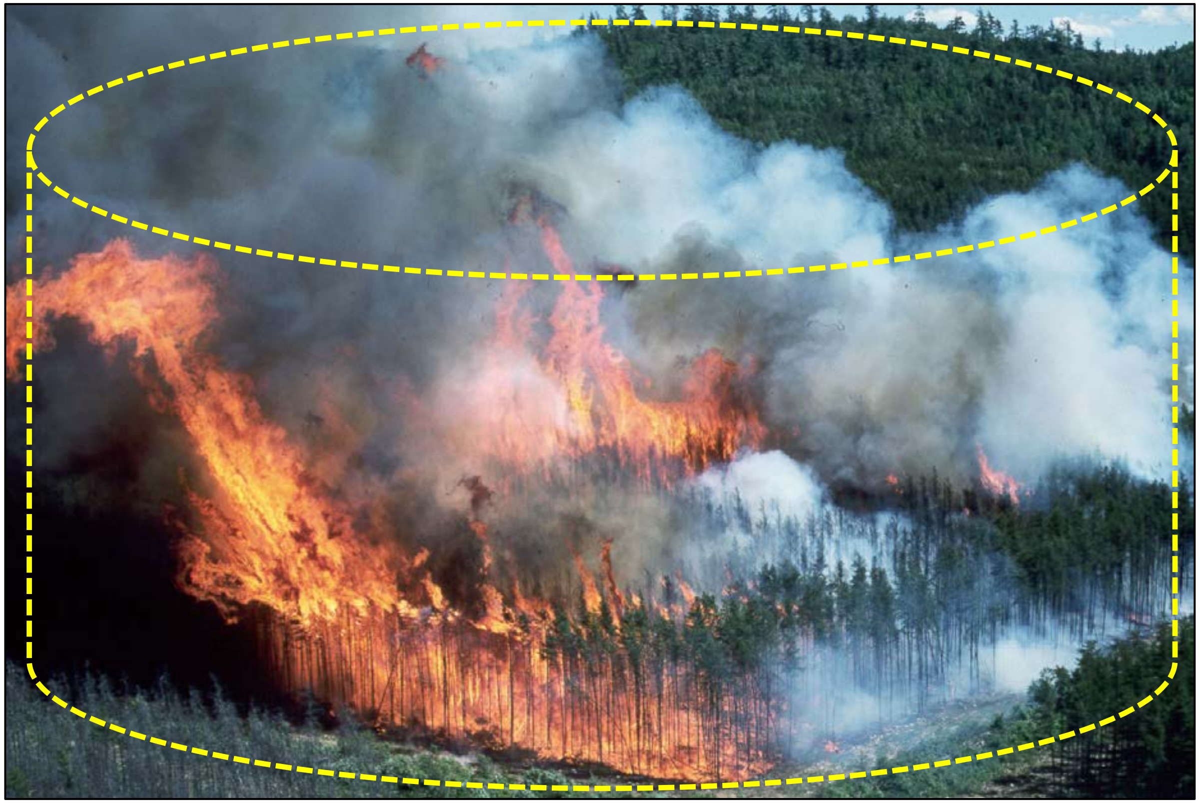


How would Byram define FRP?

Byram (1959)

Total Fire Intensity:

- the rate of heat release from the fire as a whole (kW)
- Avoids interest in the flame front or its advancement
- FRP is the radiative total fire intensity



Calculating FI: Part 2

Byram's *other* equations

$FI = Er$

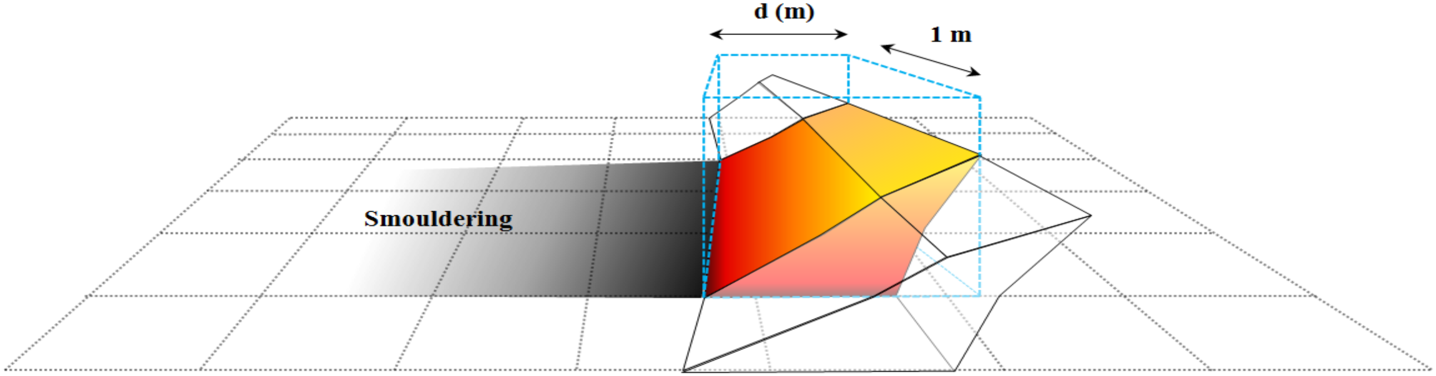
Where:

FI = fire intensity (kW m^{-1})
E = available fuel energy (kJ m^{-2})
r = ROS (m s^{-1})

$FI = Rd$

Where:

FI = fire intensity (kW m^{-1})
R = combustion rate (kW m^{-2})
d = depth of the combustion zone (m)



Calculating FI: Part 3

Byram meets FRP

FI = Er ≈ $FI_{rad} = FRE \times ROS$

Where:

FI = fire intensity (kW m^{-1})

E = available fuel energy (kJ m^{-2})

r = ROS (m s^{-1})

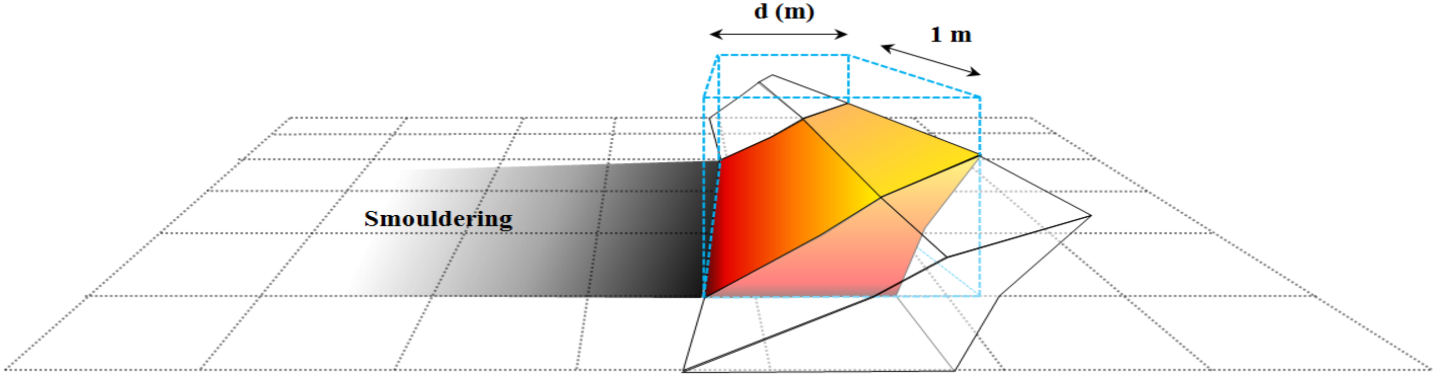
FI = Rd ≈ $FI_{rad} = FRP \times d$

Where:

FI = fire intensity (kW m^{-1})

R = combustion rate (kW m^{-2})

d = depth of the combustion zone (m)



Calculating FI: Part 3

Byram meets FRP

FI = Er ≈ $FI_{rad} = FRE \times ROS$

Where:

FI = fire intensity (kW m^{-1})
E = available fuel energy (kJ m^{-2})
r = ROS (m s^{-1})

FI = Rd ≈ $FI_{rad} = FRP \times d$

Where:

FI = fire intensity (kW m^{-1})
R = combustion rate (kW m^{-2})
d = depth of the combustion zone (m)

$$FI = \frac{1}{Q_{rad}}\left(\int_{\tau} FRP\, dt\right) \times \frac{D}{\tau}$$

Where:

FI = fire intensity (kW m^{-1})
Q_{rad} = the radiative fraction
FRP = kW m^{-2}
D = distance traveled in τ (m)
τ = time domain (sec)

Rose Experimental Burn Station

- 60 Ha of forest in Rose twp. North of Thessalon Ontario
- Originally used for spray trails by CFS in 1980’s
- Jack and Red pine forest, with large clearing in the NE corner of the plot due to scleroderris canker
- 30 m scaffold tower, burning pit, lab and accommodation trailers

FUELS

Date	*Burn*	*Fuel load (kg/m²)*	*Fuel depth (m)*	*Moisture (H_2O / fuel)*
June 7, 2013	1	0.988 (± 0.028)	0.122 (± 0.001)	0.073 (± 0.012)
	2	0.972 (± 0.041)	0.120 (± 0.010)	0.094 (± 0.016)
June 9, 2013	1	0.977 (± 0.018)	0.098 (± 0.008)	0.080 (± 0.025)
June 12, 2013	1	0.918 (± 0.048)	0.102 (± 0.001)	0.079 (± 0.011)
	2	0.911 (± 0.078)	0.074 (± 0.002)	0.063 (± 0.006)
	3	1.296 (± 0.060)	0.133 (± 0.002)	0.096 (± 0.010)
June 14, 2013	1	0.838 (± 0.040)	0.106 (± 0.003)	0.059 (± 0.011)
June 16, 2013	1	0.878 (± 0.098)	0.114 (± 0.003)	0.111 (± 0.013)
	2	0.894 (± 0.056)	0.083 (± 0.001)	0.084 (± 0.014)
	3	0.878 (± 0.032)	0.094 (± 0.005)	0.087 (± 0.011)
June 17, 2013	1	0.574 (± 0.044)	0.056 (± 0.007)	0.091 (± 0.006)
	2	1.255 (± 0.031)	0.123 (± 0.017)	0.106 (± 0.019)
	3	1.289 (± 0.080)	0.130 (± 0.006)	0.110 (± 0.031)
June 18, 2013	1	0.851 (± 0.022)	0.102 (± 0.006)	0.096 (± 0.022)
	2	1.282 (± 0.080)	0.136 (± 0.007)	0.090 (± 0.008)
	3	1.376 (± 0.023)	0.081 (± 0.007)	0.095 (± 0.013)
	4	0.915 (± 0.032)	0.080 (± 0.006)	0.104 (± 0.014)
	5	0.906 (± 0.059)	0.061 (± 0.008)	0.093 (± 0.033)
	6	1.347 (± 0.042)	0.126 (± 0.006)	0.097 (± 0.004)
	7	0.634 (± 0.026)	0.063 (± 0.003)	0.107 (± 0.008)
	8	1.401 (± 0.003)	0.153 (± 0.007)	0.089 (± 0.014)

Pinus palustris	*Mean (stdev)*	*units*	*n*
SA to V ratio	59.95 (± 13.98)	cm^{-1}	92
Density	756.44 (± 454.74)	kg/m^3	38
Mineral Content	0.001 (± 0.001)	(g mineral)/(g fuel)	3
Heat of combustion	20.696 (± 378.98)	MJ/kg	3

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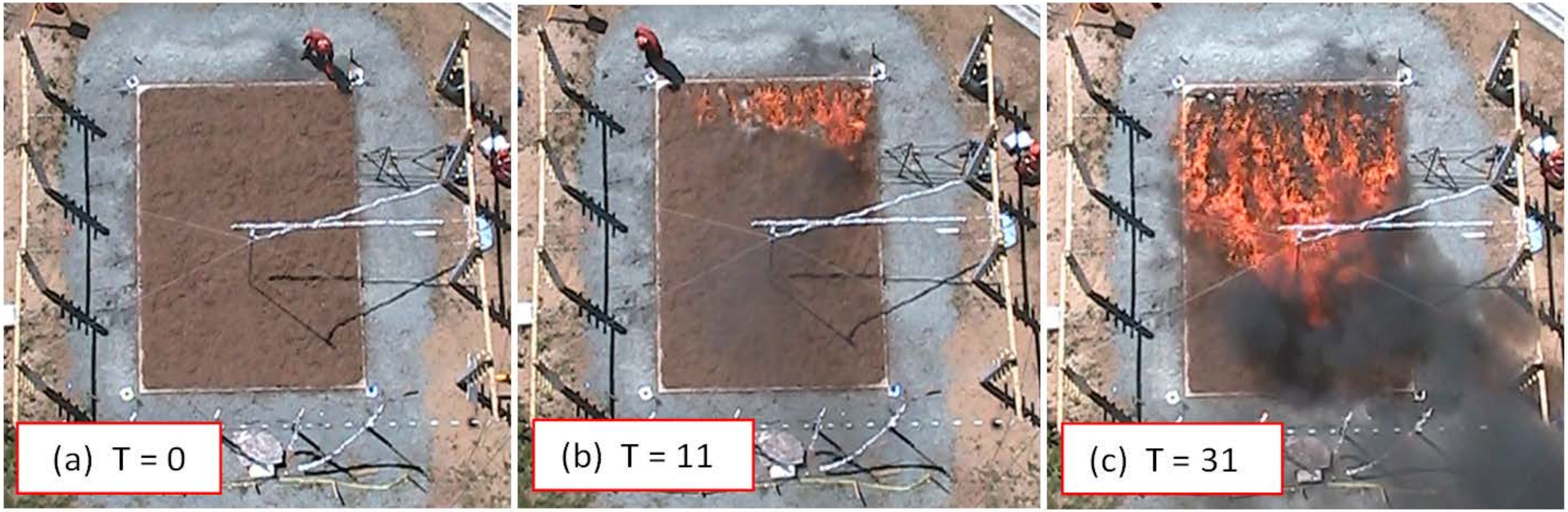
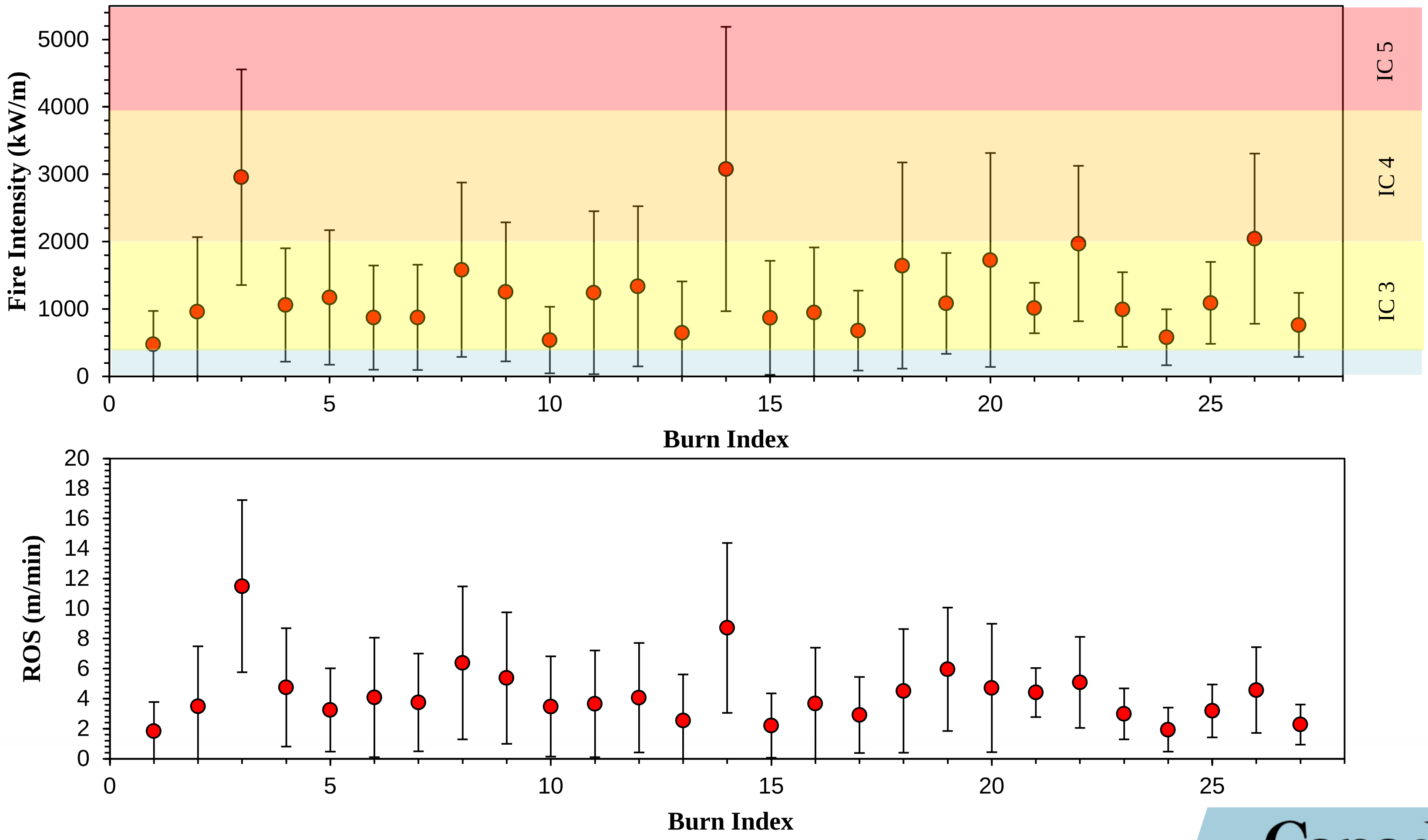
Burn protocol

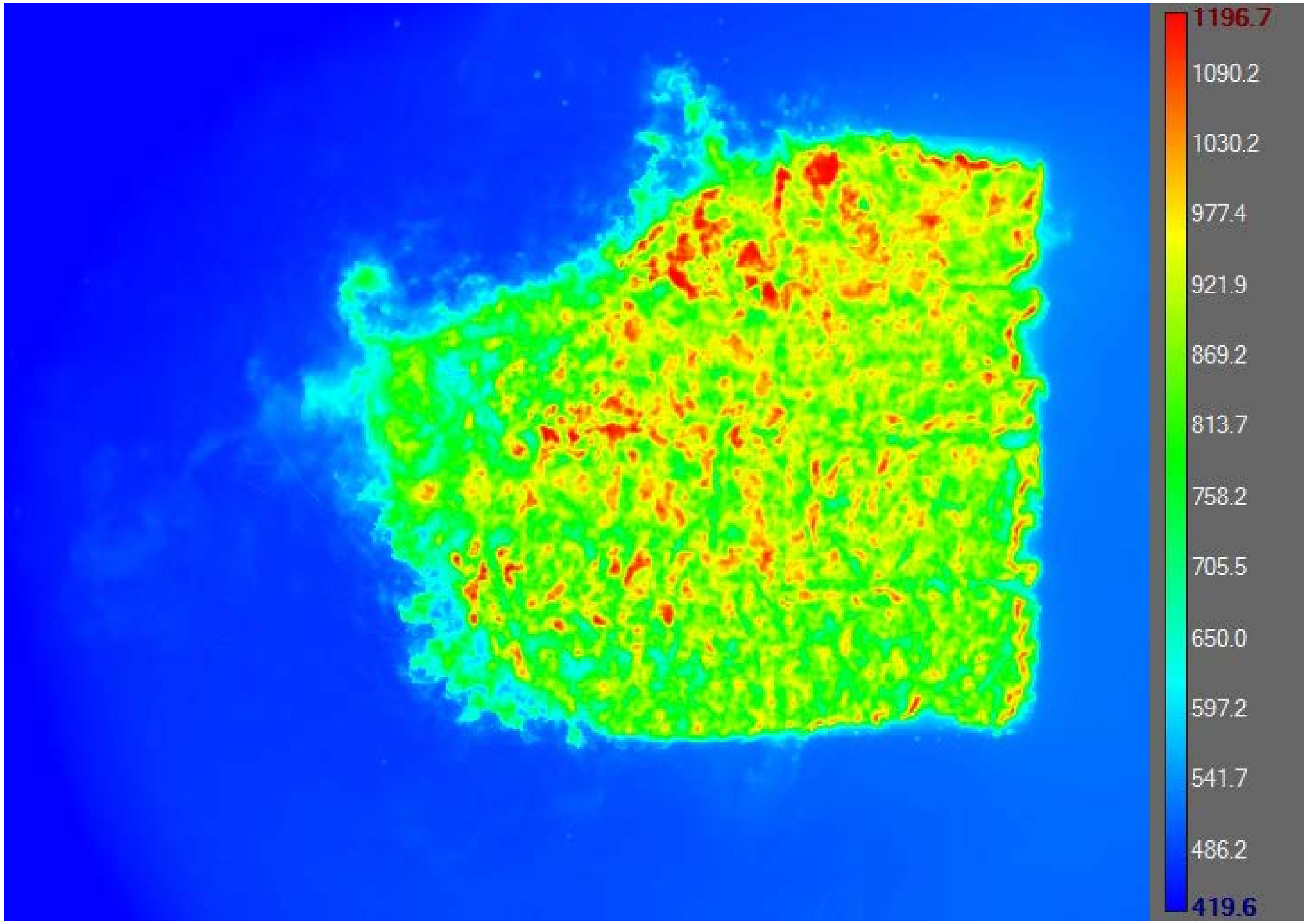
- Ignition by applying a drip torch line across the rear of the pad 0.5 m into the fuel bed
- This method was used to help accelerate fires to a peak intensity state rapidly
- Burns were allowed to smoulder until virtually all visible smoke was gone
  - ➢ UNLESS winds were too strong



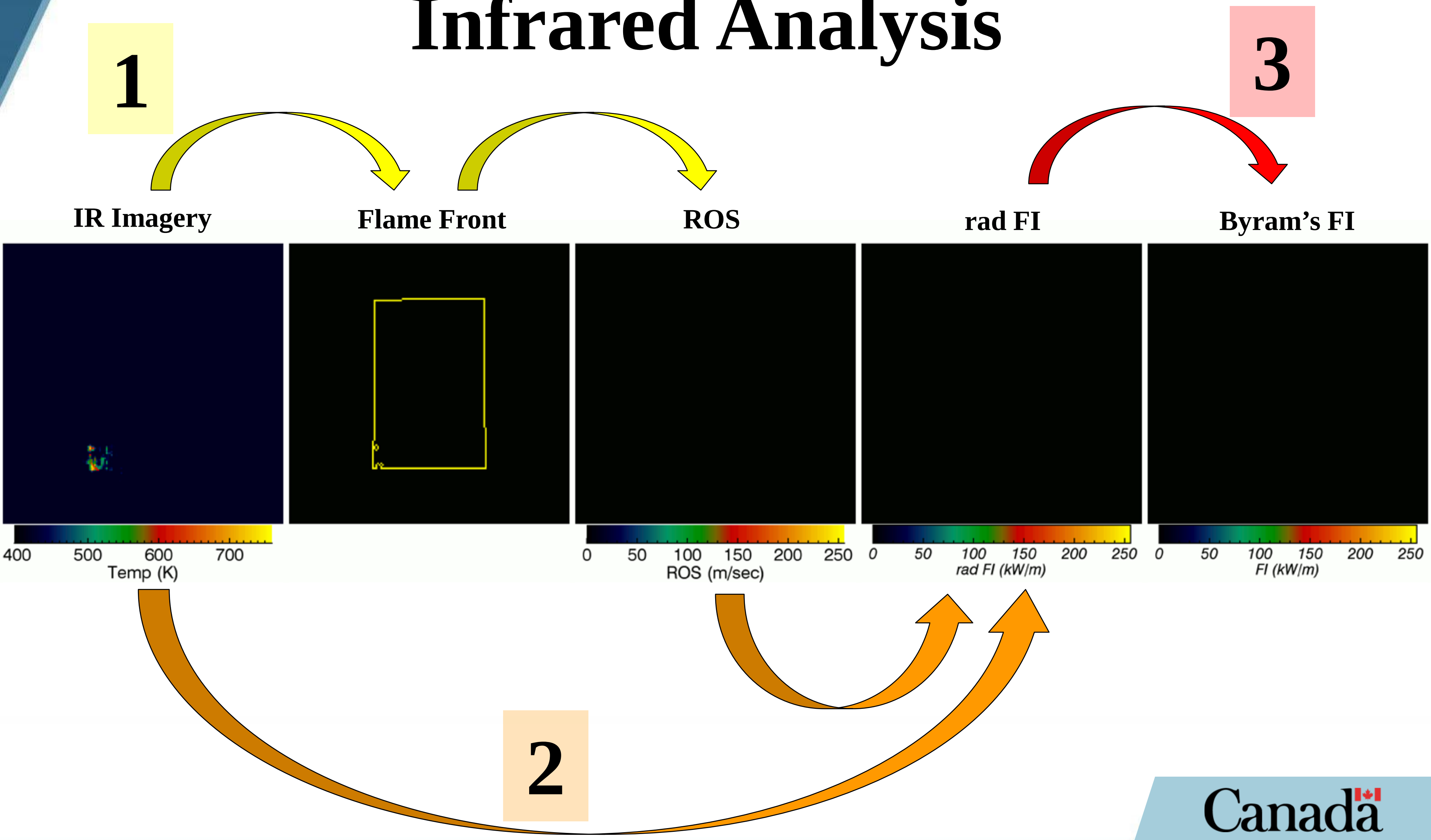
Fire Behavior



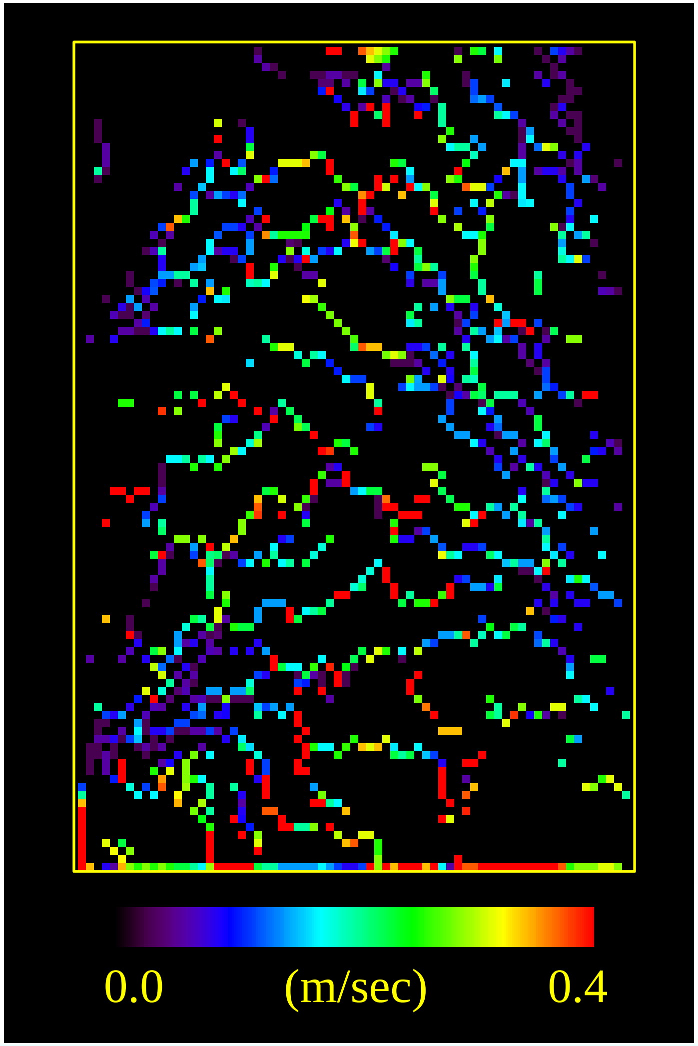
Raw Data


1196.7
1090.2
1030.2
977.4
921.9
869.2
813.7
758.2
705.5
650.0
597.2
541.7
486.2
419.6

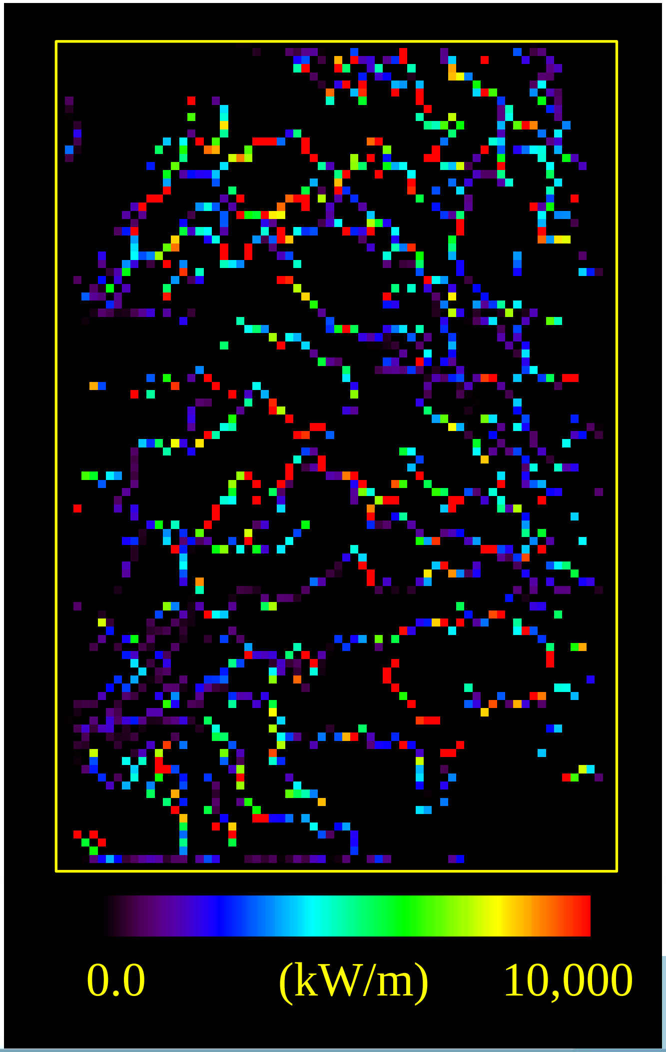
Infrared Analysis



ROS

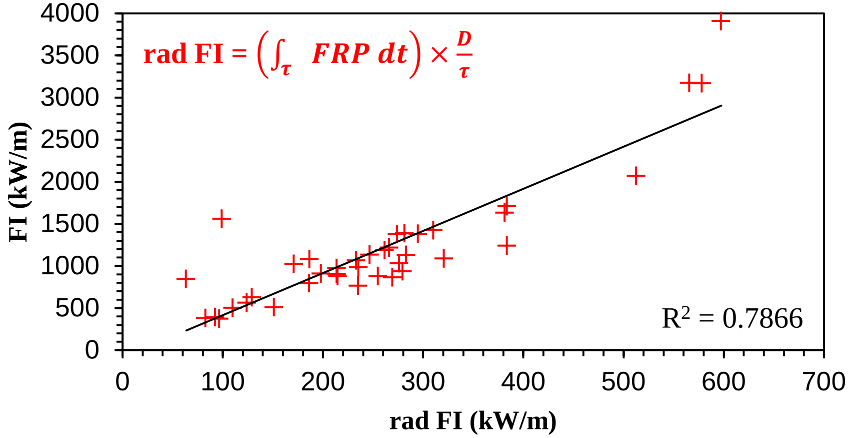


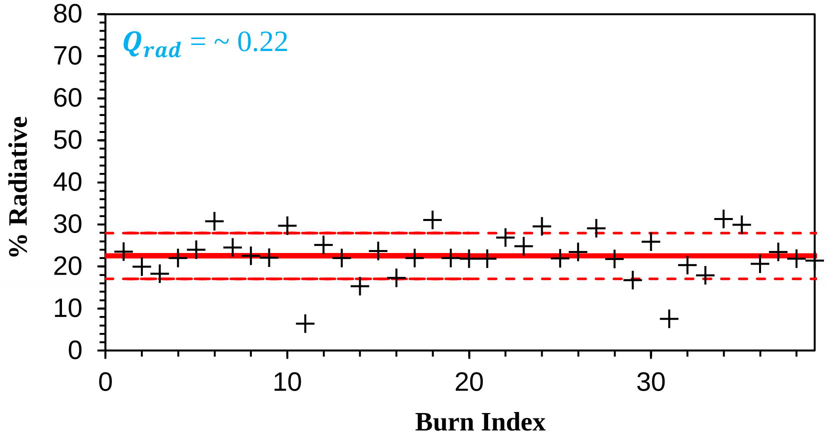
FI

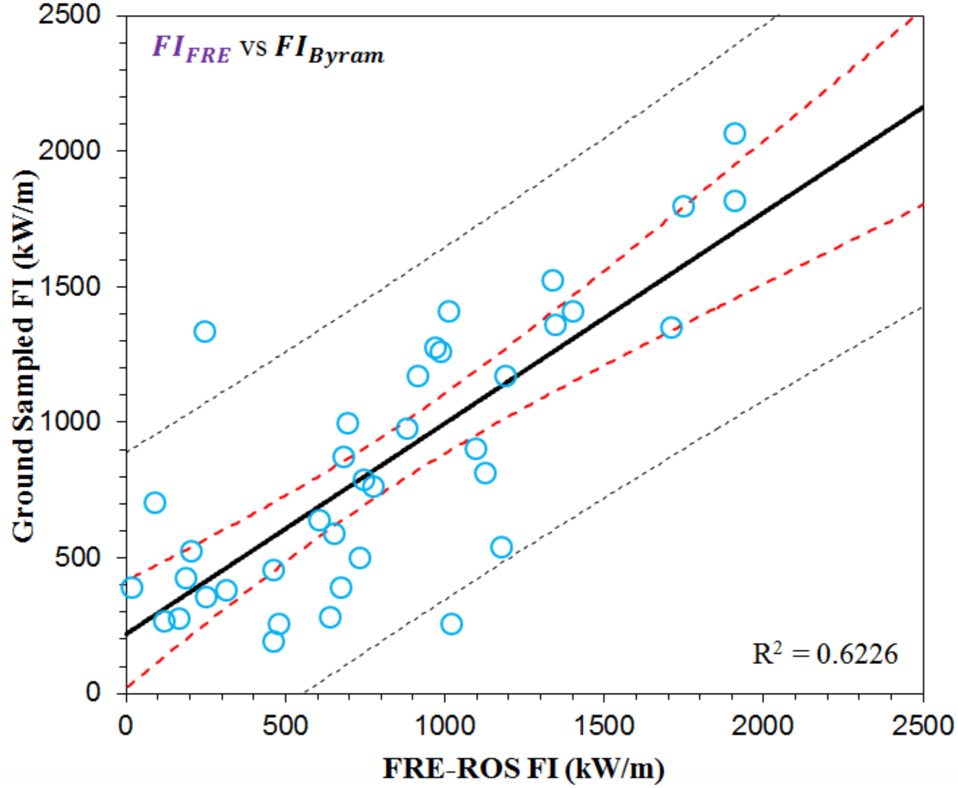


Infrared Analysis

$$FI_{Byram} = Hwr \quad \leftrightarrow \quad FI_{FRE} = \frac{1}{Q_{rad}} \left(\int_{\tau} FRP\, dt \right) \times \frac{D}{\tau}$$







Implications

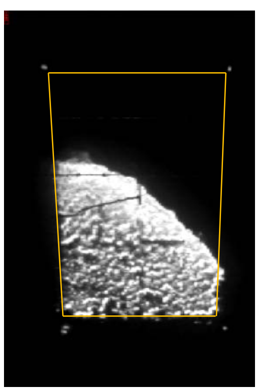
For Research:

- The ability to measure fire intensity
- Complete fire behavior data set without the need for ground sampling
- The ability to study wildfires

For Response:

- Decision support tool
- Near-real time spatial maps of :
  - Fire perimeters
  - ROS
  - FI
  - Flame length (modelled)
  - DOB (modelled)
  - etc…

HANDHELD



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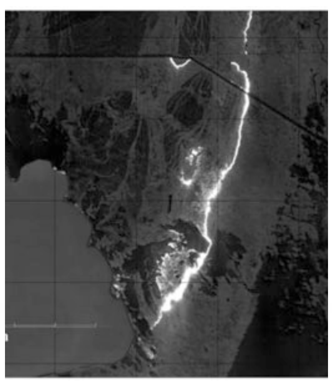

Fig. 18.9 Wooster, *et al*. (2013)

POLAR-ORBITER

GEOSTATIONARY

BIRD MIR

MODIS MIR

GOES MIR

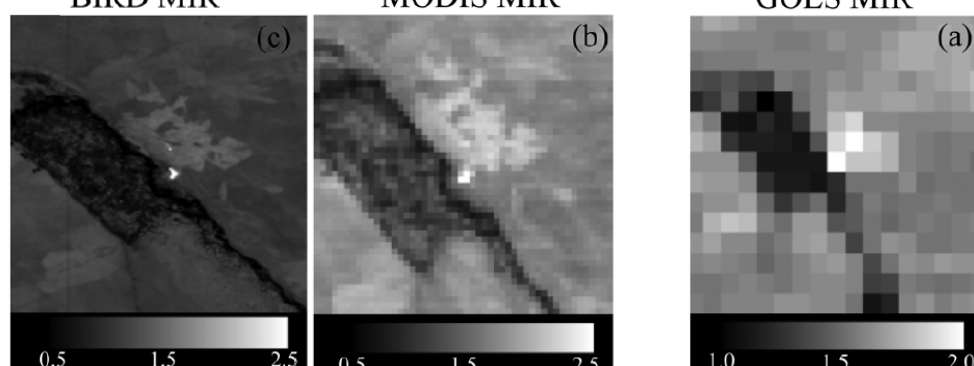

Fig. 1: Wooster, *et al*. (2005)

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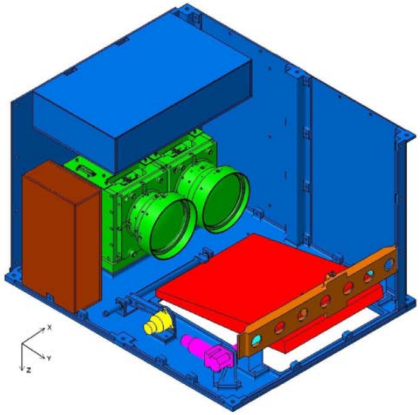
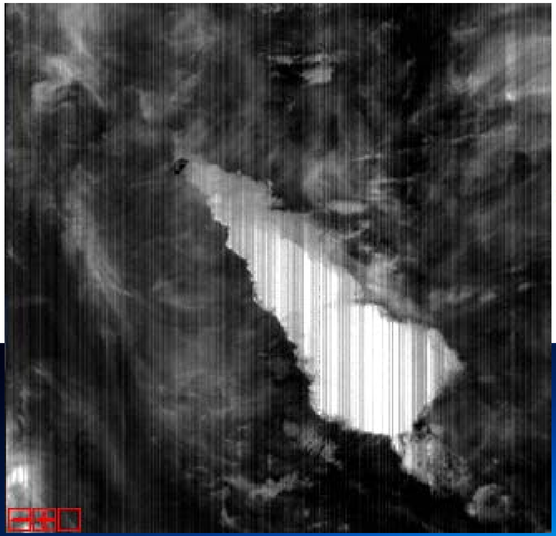
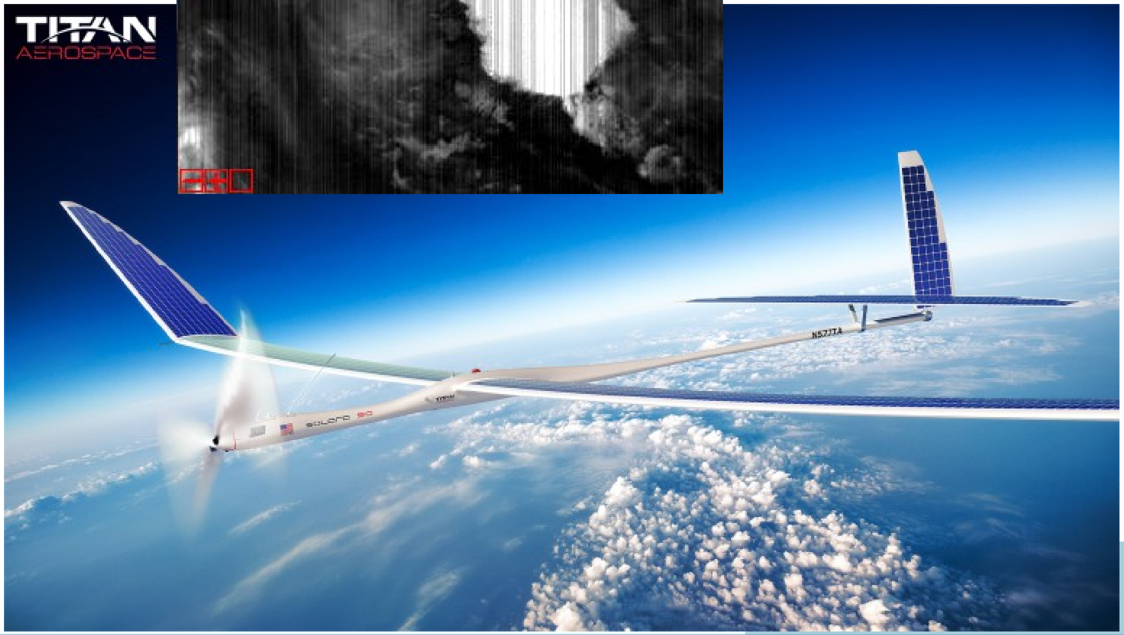
Future Work



Canopy Interception:

- Verify canopy interception FRP model
- Develop a method of implementing this model in analysis





Landscape scale validation:

- Fixed wing scans of PBs and Wildfires
- Optimising sampling patterns
- Explore the potential use of satellite and/or UAV imagery


Thank you
Questions?

REFERENCES

Alexander, M. E. (1982). Calculating and interpreting forest fire intensities. Canadian Journal of Botany, 60(4), 349-357. doi: 10.1139/b82-048

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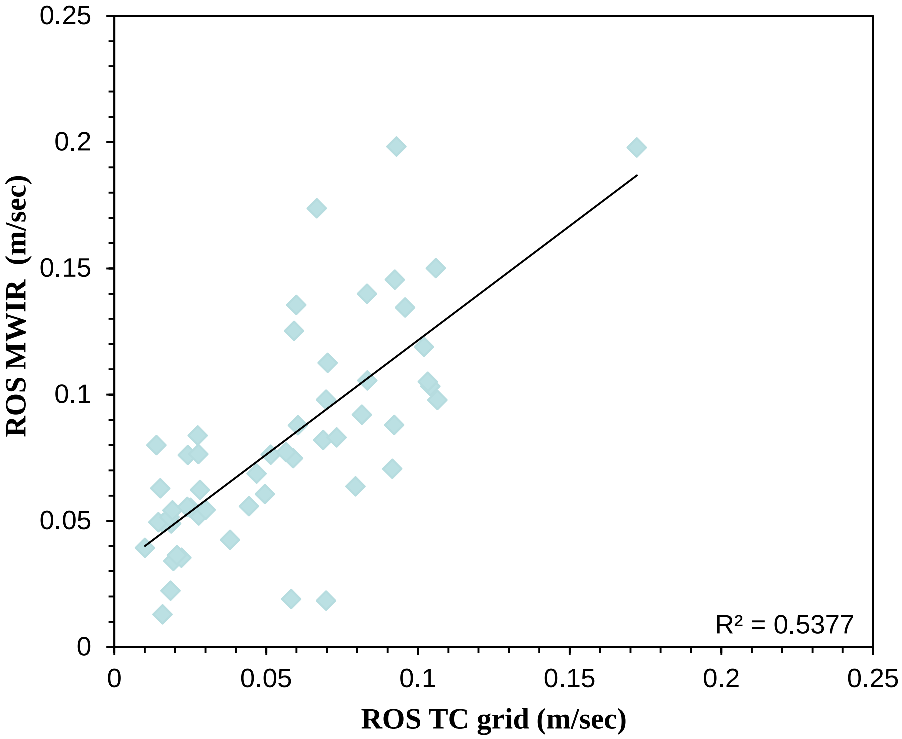
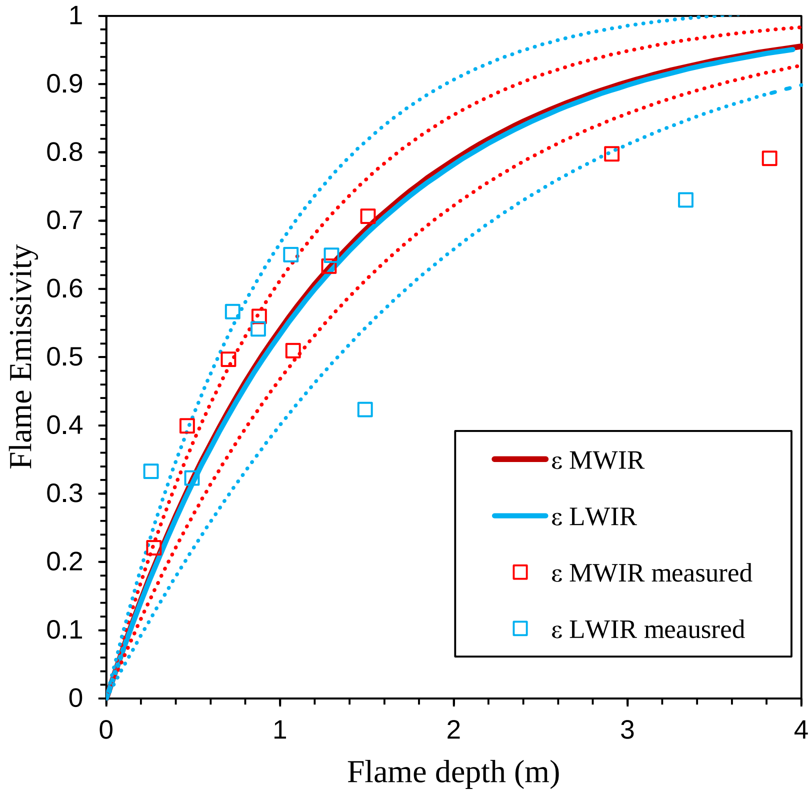
Wooster, M. J., G. Roberts, A. M. S. Smith, J. Johnston, P. Freeborn, S. Amici and A. T. Hudak (2013). Thermal Remote Sensing of Active Vegetation Fires and Biomass Burning Events. Thermal Infrared Remote Sensing. C. Kuenzer and S. Dech, Springer Netherlands. **17:** 347-390.

Additional Slides



Flame Emissivity

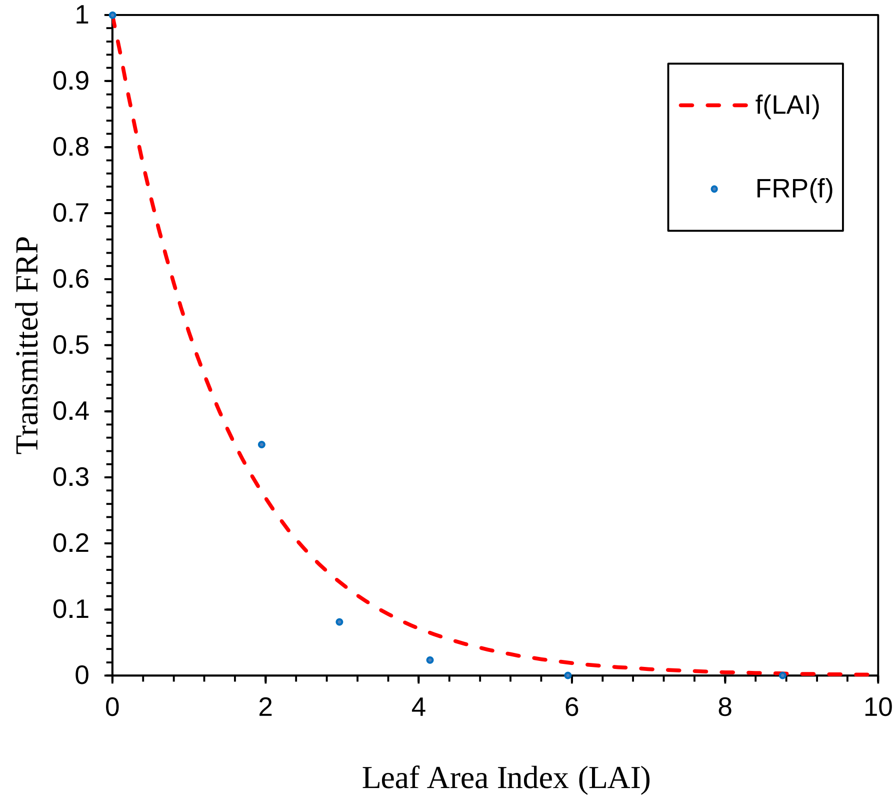


$$\varepsilon = 1 - e^{-k\,Fd}$$

MWIR: $k = 0.78$; $R^2 = 0.90$

LWIR: $k = 0.76$; $R^2 = 0.61$

Canopy Interception



$$FRP_{TRANS} = e^{-0.66\,LAI}$$

$R^2 = 0.98$