Fire Behavior and Effects Monitoring

Matthew Dickinson - *US Forest Service, Northern Research Station*

Outline

- Fire behavior monitoring
  - General problem
  - Direct monitoring of fire behavior
  - Indirect monitoring techniques
- Fire effects monitoring (brief)

Focus on monitoring methods, not results.

Fire behavior monitoring

Can't just go out an put something in a fire and expect to get good results that you can interpret: making useful measurements is the end point in (typically) a long R&D process.

The R&D goal is a device that is easy to use and that gives you estimates of fire behavior.

Getting to that point, slowly.

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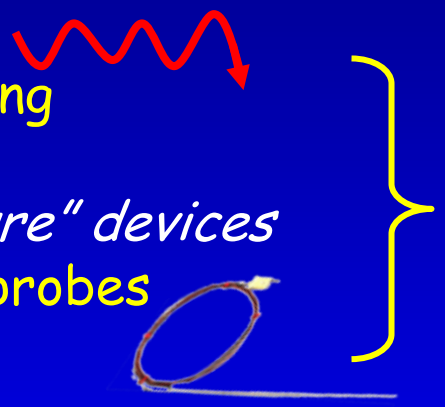
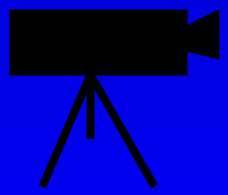
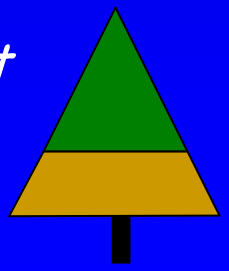
      - Airborne mapping
      - Ground sensors
    - *In-fire "temperature" devices*
      - Thermocouple probes
      - Paint tags
    - *Miscellaneous*
      - Videography
      - Flame height sensors
      - Gas sensing
  - Indirect techniques
    - *Scorch and branch kill height*
    - *Char height*







Sports car ($ & fickle)

Volkswagen beetle

Fire behavior monitoring – aerial surveillance

Estimate fire radiative power (FRP, W/m^2) using single band IR sensor in an airplane and 2-5 calibrated ground sensors (lab calibrated by heat flux from a black body).

Camera and ground-sensors synchronized by GPS clock & look at same pixel for calibration.

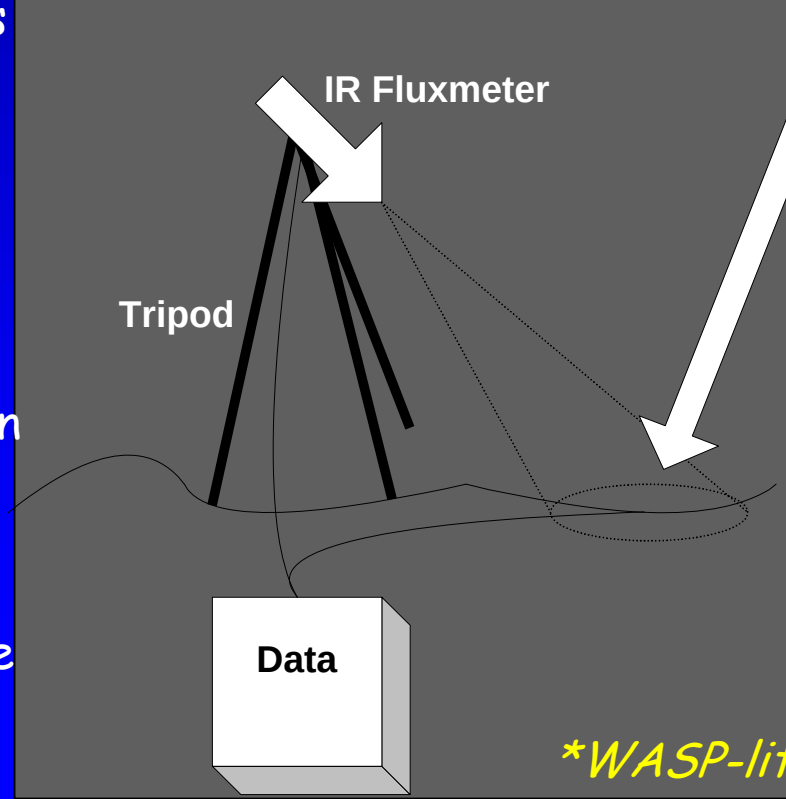
Having ground sensors allows you to correct for atmospheric interference in FRP estimate and variable lens temp.

FRP – fuel consumption rate
FRE – fuel consumption

WASP – Wildfire Airborne Sensor Program, Rochester Institute of Technology (RIT)

Airborne infrared camera

WASP (3-band) & *WASP-lite* (2-band)*

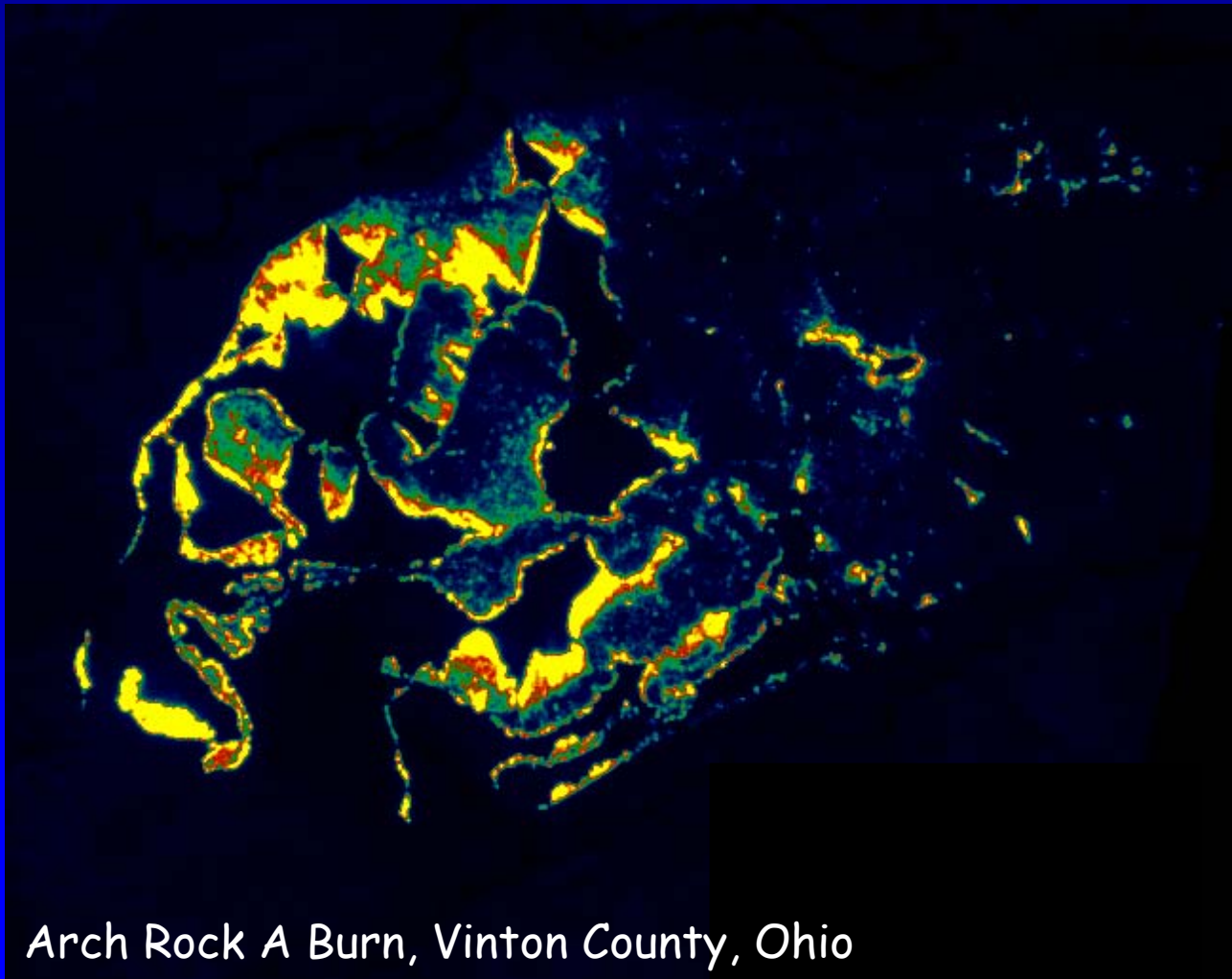


Ground-based calibration

**WASP-lite flys in a Cessna 172*

Fire behavior monitoring – aerial surveillance

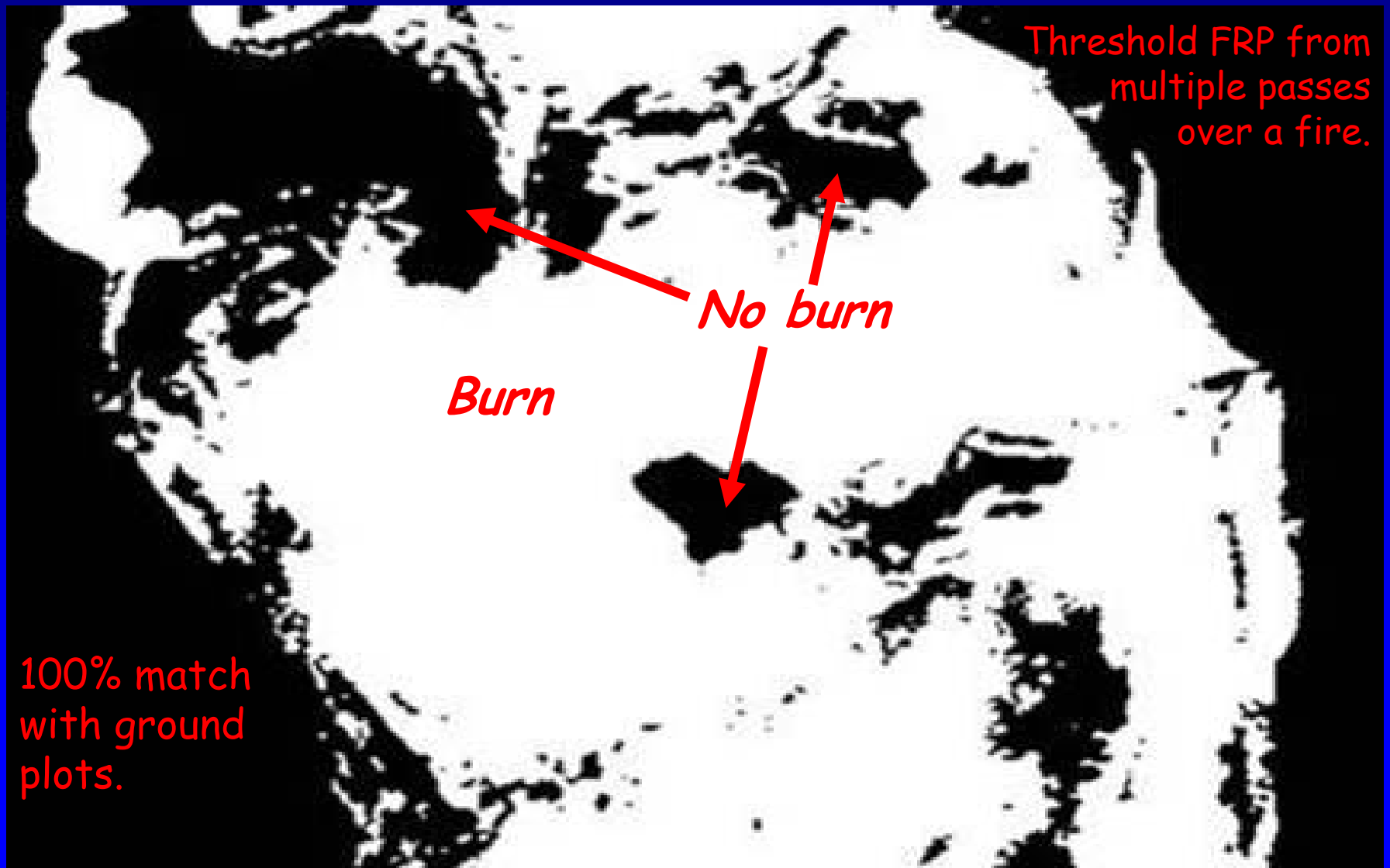
Initially just relative heat, uncalibrated snapshot



Arch Rock A Burn, Vinton County, Ohio

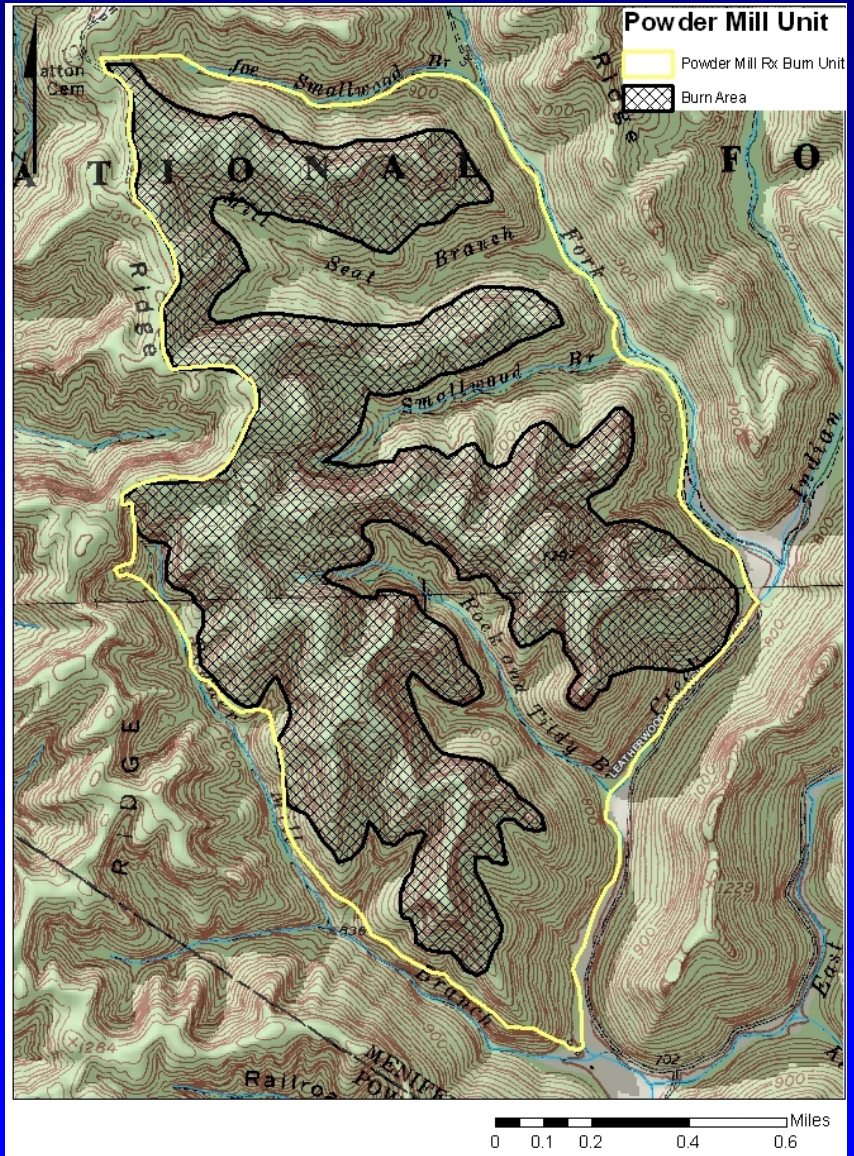
Fire behavior monitoring – aerial surveillance

Landscape pattern of burning important for a variety of reasons, including herb/shrub/tree population dynamics and litter dwelling fauna recovery.



Fire behavior monitoring – aerial surveillance

Pattern also important for bats



Fire behavior monitoring – ground calibration

Ground-based infrared (IR) sensors for calibrating aerial imagery.

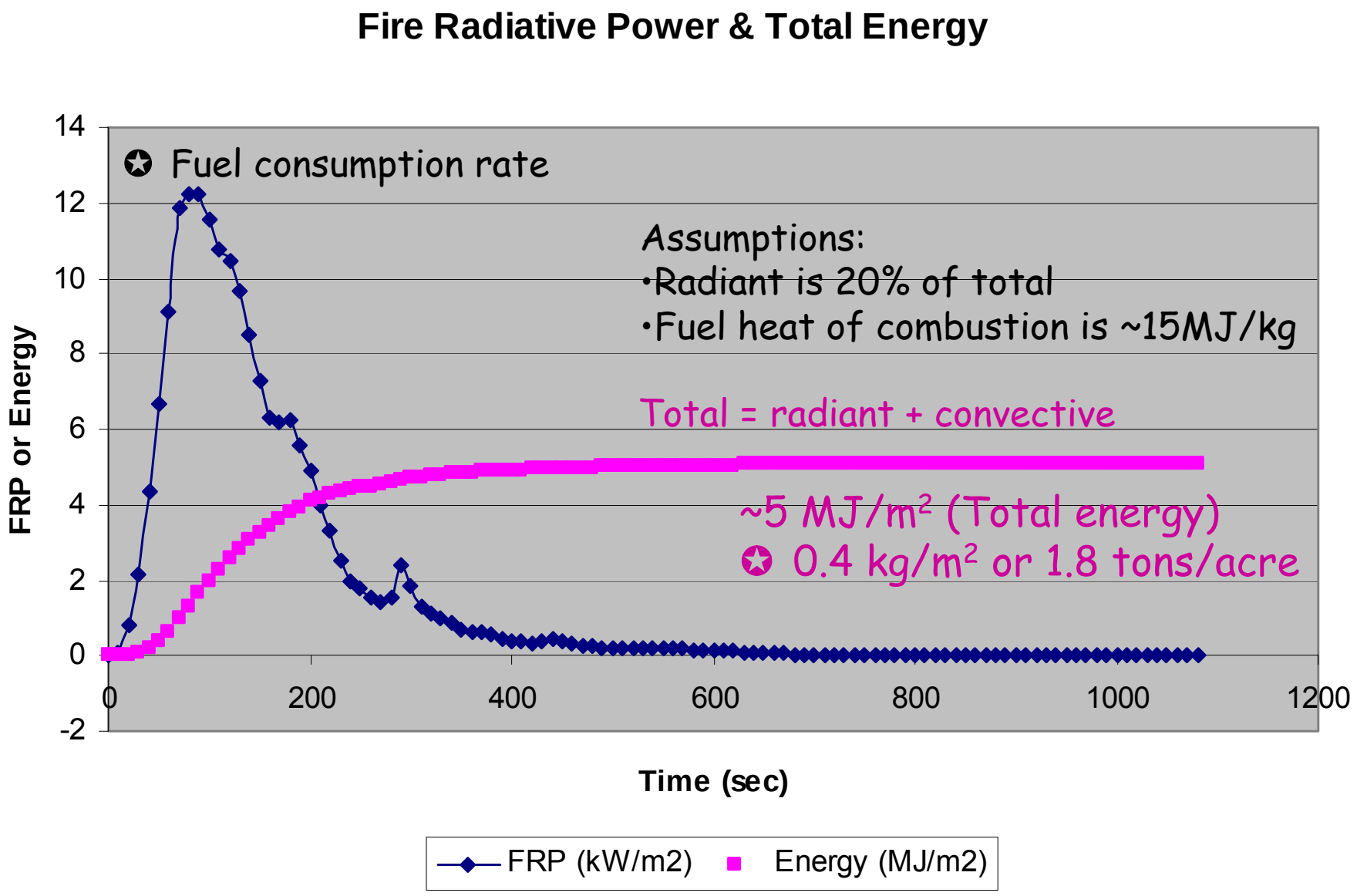
Calibrated for FRP against a black body in the lab.

"Cutting edge, like an IPod, but cheap" (like a Walkman?)

Fire behavior monitoring – ground calibration

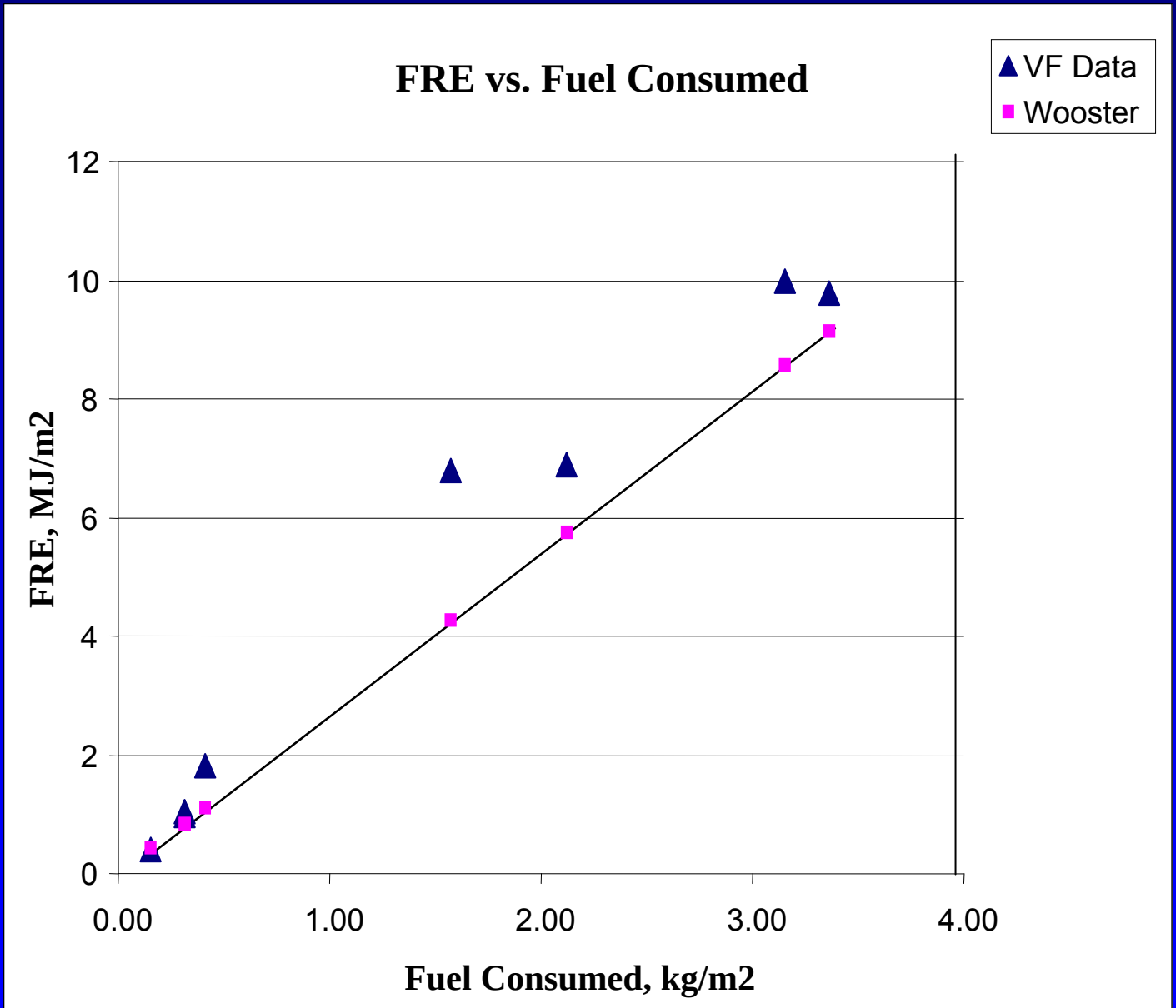
We further calibrate the ground sensors for fuel consumption.

Fire behavior monitoring – ground calibration



Fire behavior monitoring – ground calibration

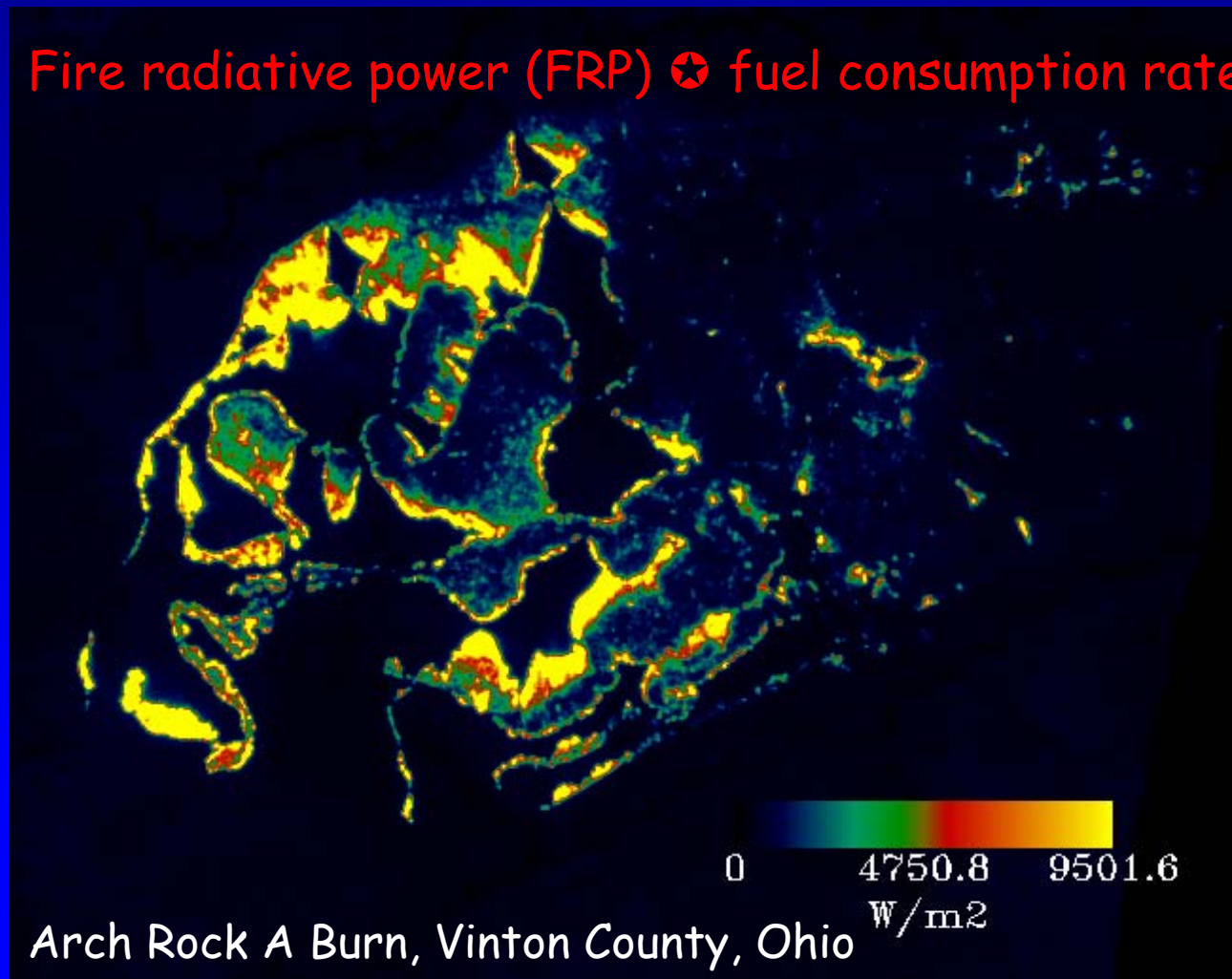
Just to show that correlation between energy and fuel consumption is good



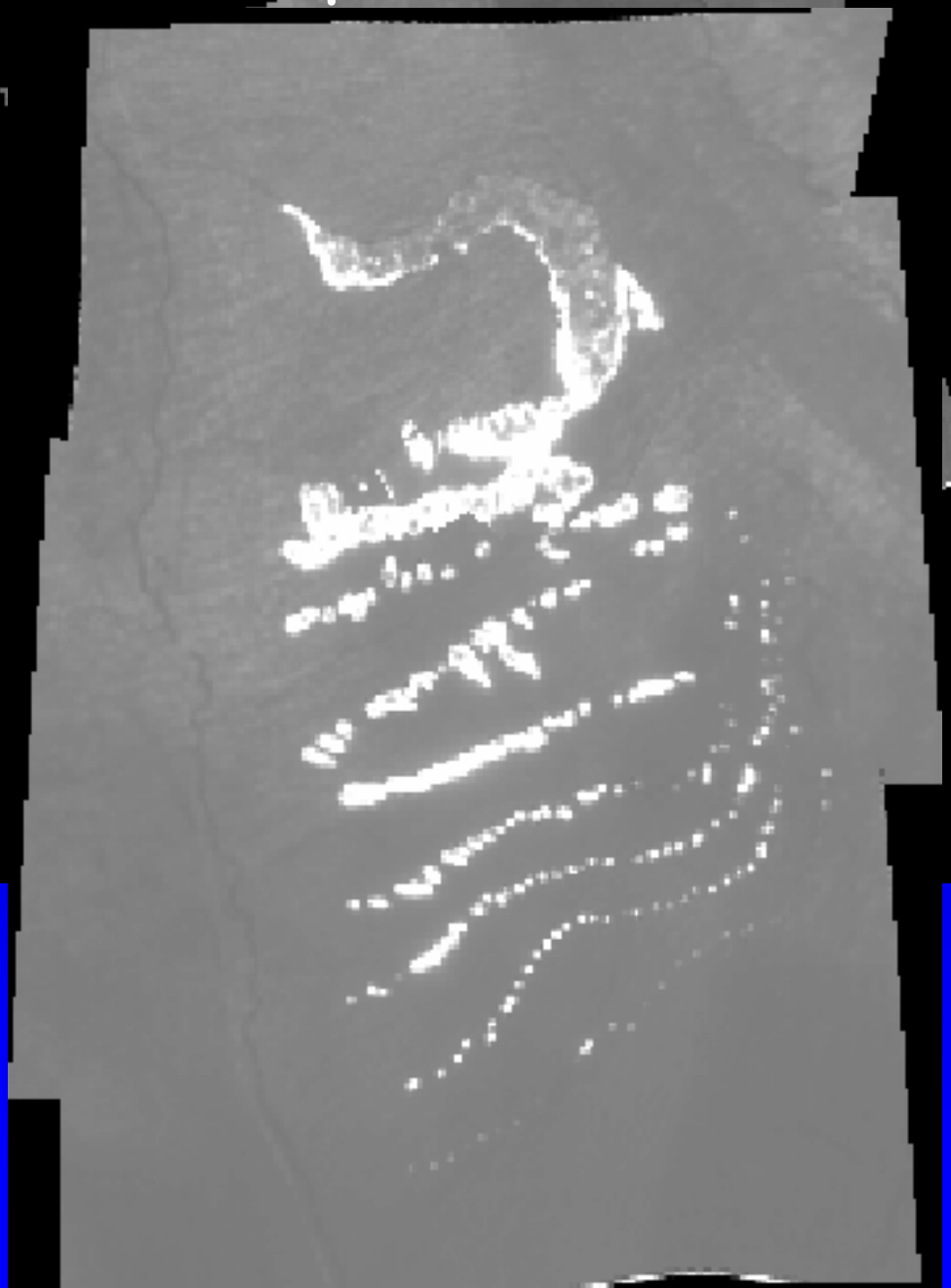
Fire behavior monitoring – aerial surveillance

Fire Radiative Power (FRP) – kW/m^2
FRP is ~30% of total combustion energy

Snapshot of a fire



Fuel consumption and smoke mgmt

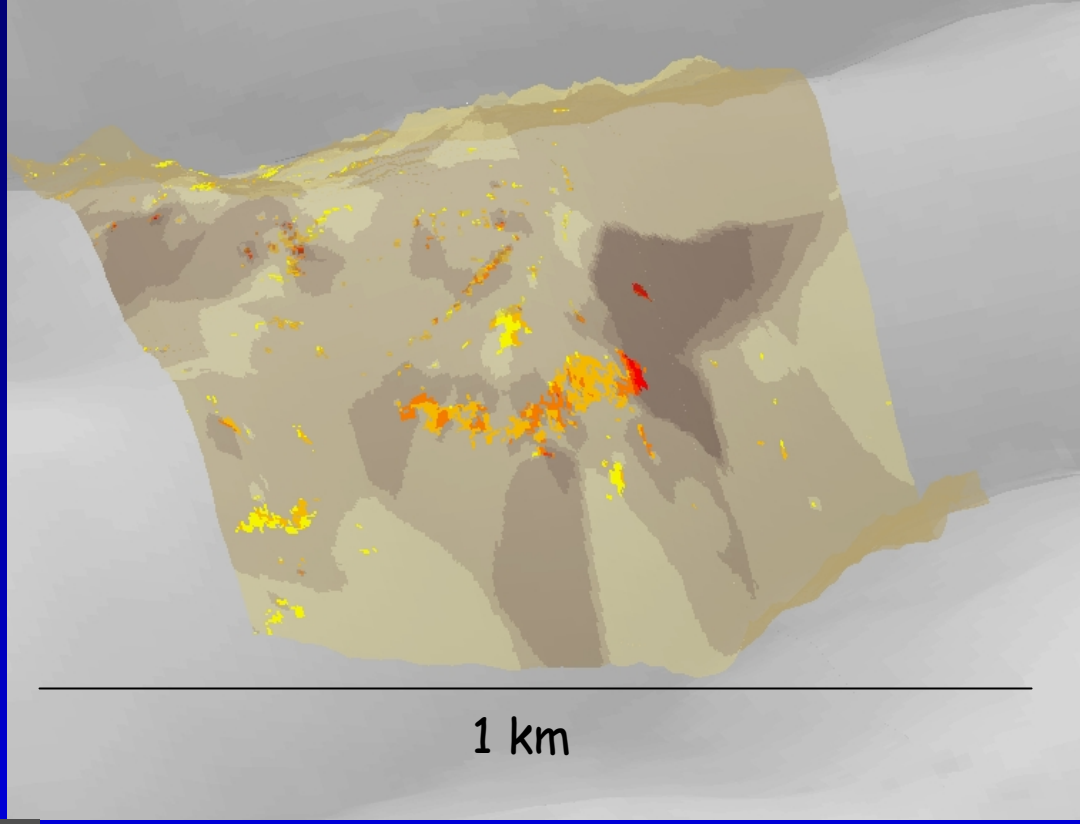


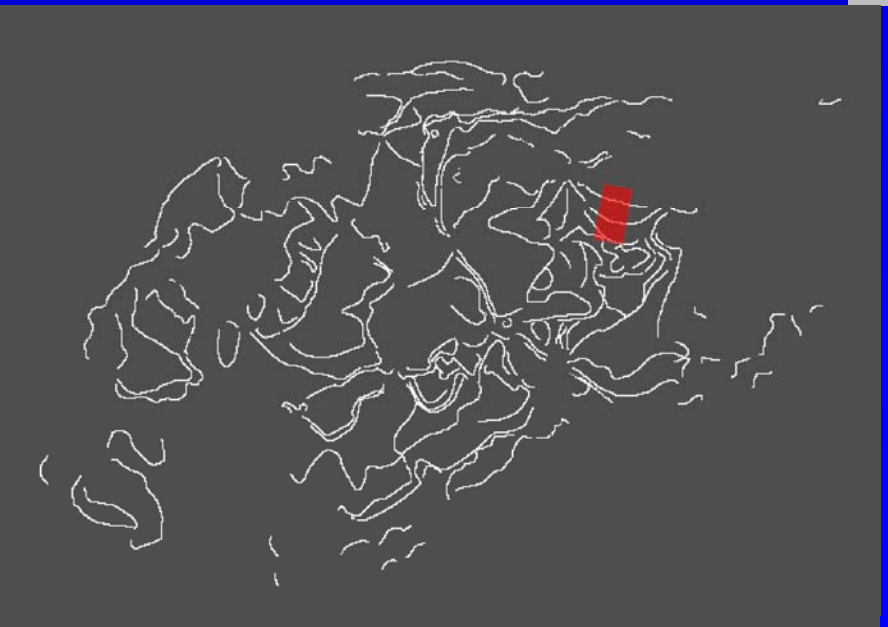
Open Tar Hollow animation with Internet Explorer/Google Earth.

http://lias2.cis.rit.edu/wasp2/kml/tarhollow/tarhollow.kml

Fire behavior monitoring – mapping process

1. Identifying fire lines
2. Finding pixels with peak Fire Radiative Power
3. Integrating through time for Fire Radiative Energy
4. Mapping by extrapolation
5. Conversion to fuel consumption





Peak FRE (MJ/m^2)	Interpolated FRE (MJ/m^2)
0.63 - 0.96	0.63 - 0.78
0.97 - 2.49	0.79 - 2.18
2.50 - 4.01	2.19 - 3.58
4.02 - 5.54	3.59 - 4.99
5.55 - 7.06	5.00 - 6.39
7.07 - 13.47	6.40 - 13.47

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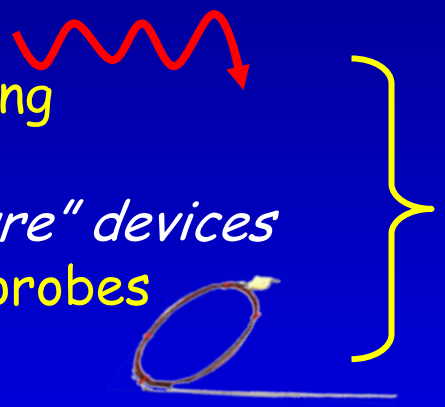
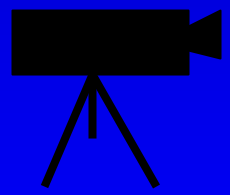
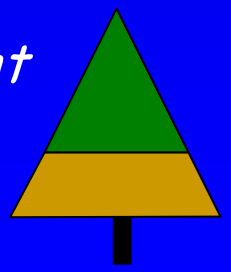






Cadillac

Volkswagen beetle

Fire monitoring – "fire temperature"

"Maximum temperatures in most forest flames are about 800 to 1000 °C and occur in a single burning pine needle as readily as a crown fire."

-C.E. Van Wagner and I.R. Methven, *Can. J. For. Res.* Vol. 8, 1978

Max excess flame temperatures

ΔT = 1040 °C (Dupuy 2003)

ΔT = 898 °C (Yuan and Cox 1996)

ΔT = 980 °C (McCaffrey 1979)

Flame temperature ≠ Device temperature

Devices used in fires:

- thermocouple probes (TCPs)
- temperature-sensitive paint tags

"The temperature reached by a device in a fire is a function of both fire behavior (i.e., flame temperature, gas velocity, etc.) **AND** the properties of the device and how it is deployed."

-Paraphrasing Robert Essenhigh, OSU Mechanical Engineering

ARE TCPs AND PAINT TAGS USELESS?

No, but results of different devices, deployed in different ways can't be compared.

Solution? Calibration.

Will show process for TCPs.

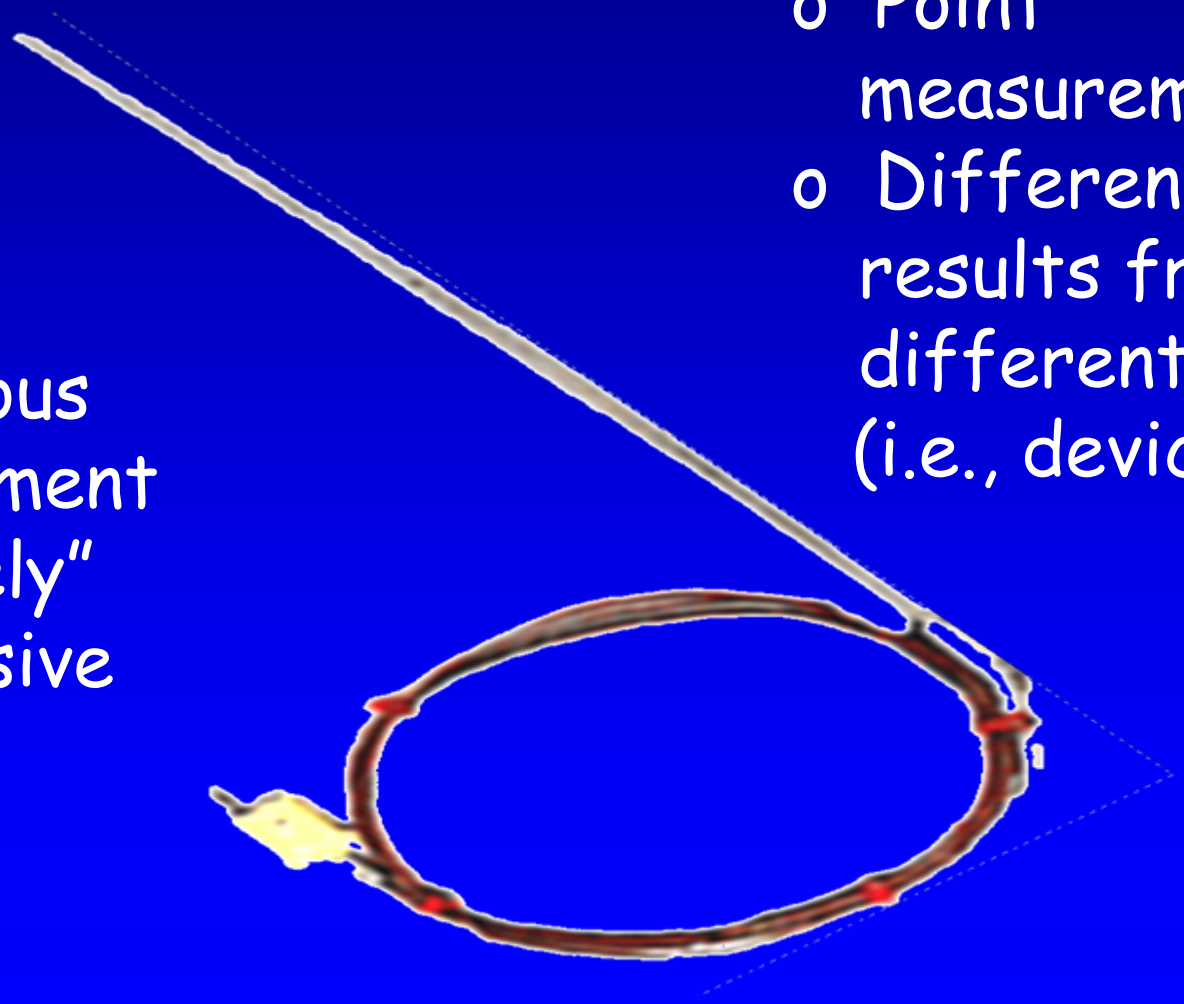
Thermocouple probes

Caveats:

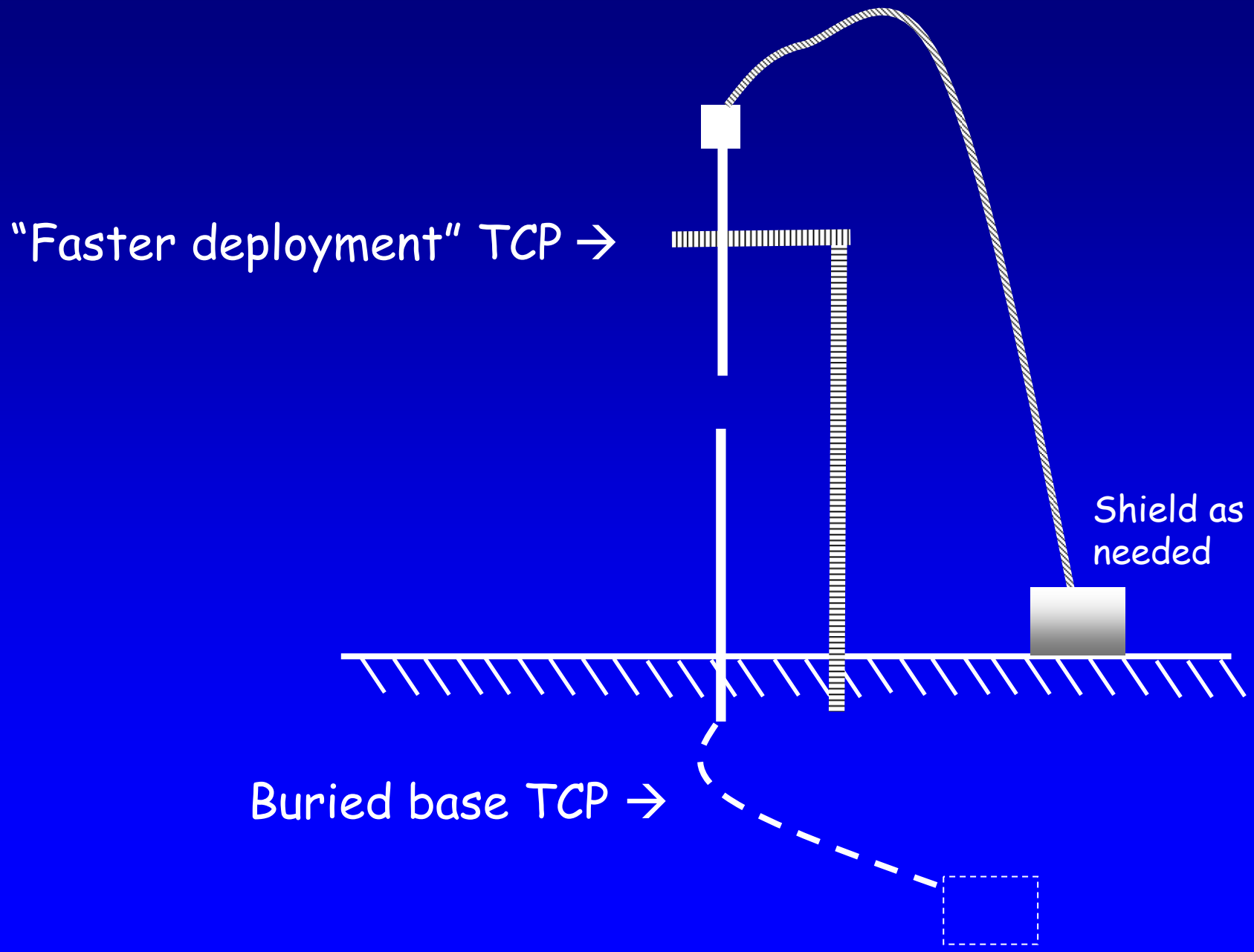
- o Point measurement
- o Different results from different TCPs (i.e., devices)

Pros:

- o Durable
- o Continuous measurement
- o "Relatively" inexpensive



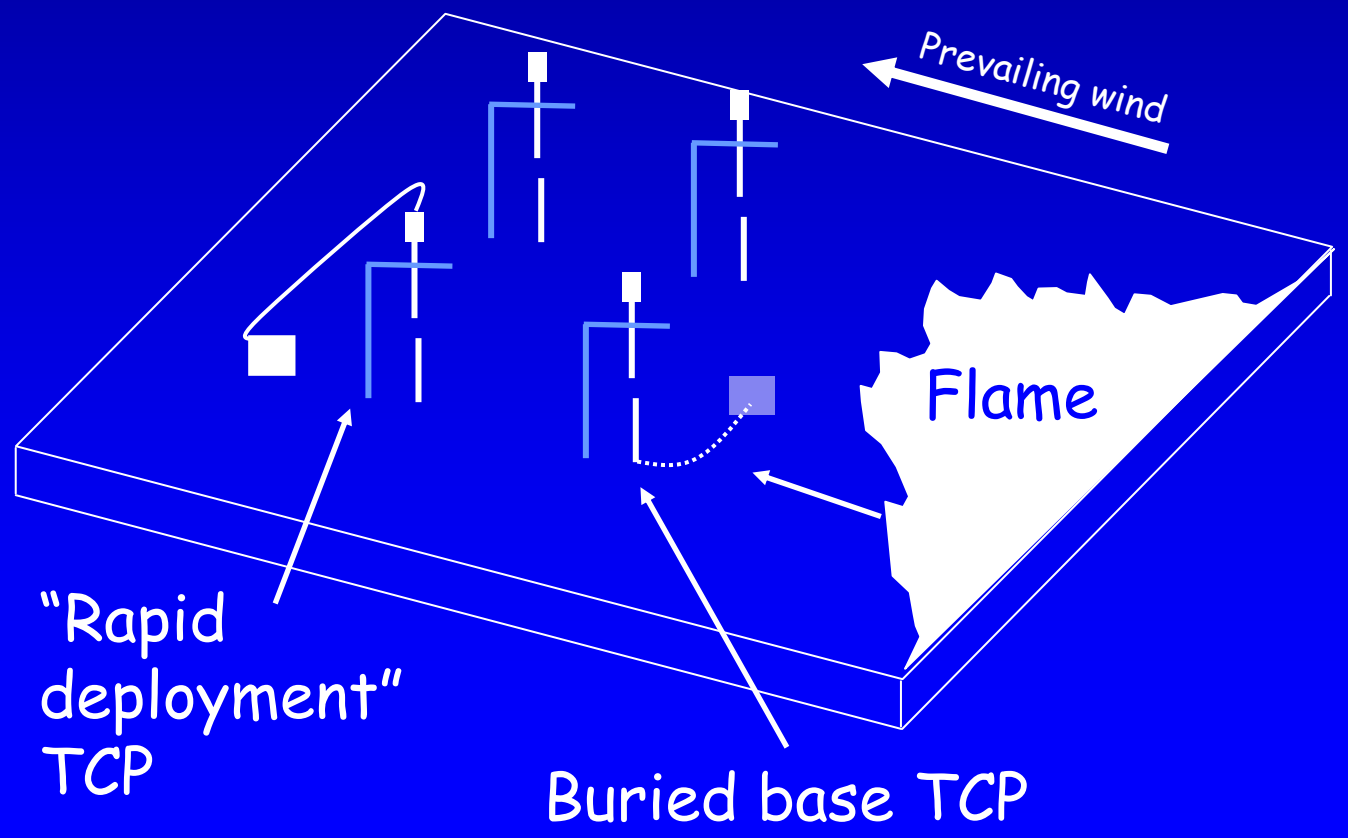
Thermocouple probes - deployment



Thermocouple probes – calibration experiment

Plot: 8 m x 8 m

Fuels: dry leaf litter, milled pine sticks

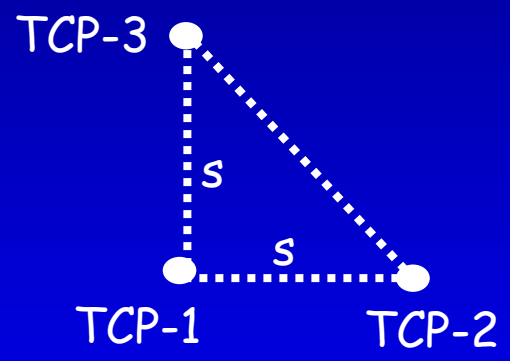


Rate of Spread

Can also do this with rate of spread clocks

TCP array generates accurate estimates of rate of spread

Simard A. J., Eenigenburg J. E., Adams K. B., Nissen R. L., & Deacon A. G. 1984. A general procedure for sampling and analyzing wildland fire spread. Forest Science 30[1], 51-64.

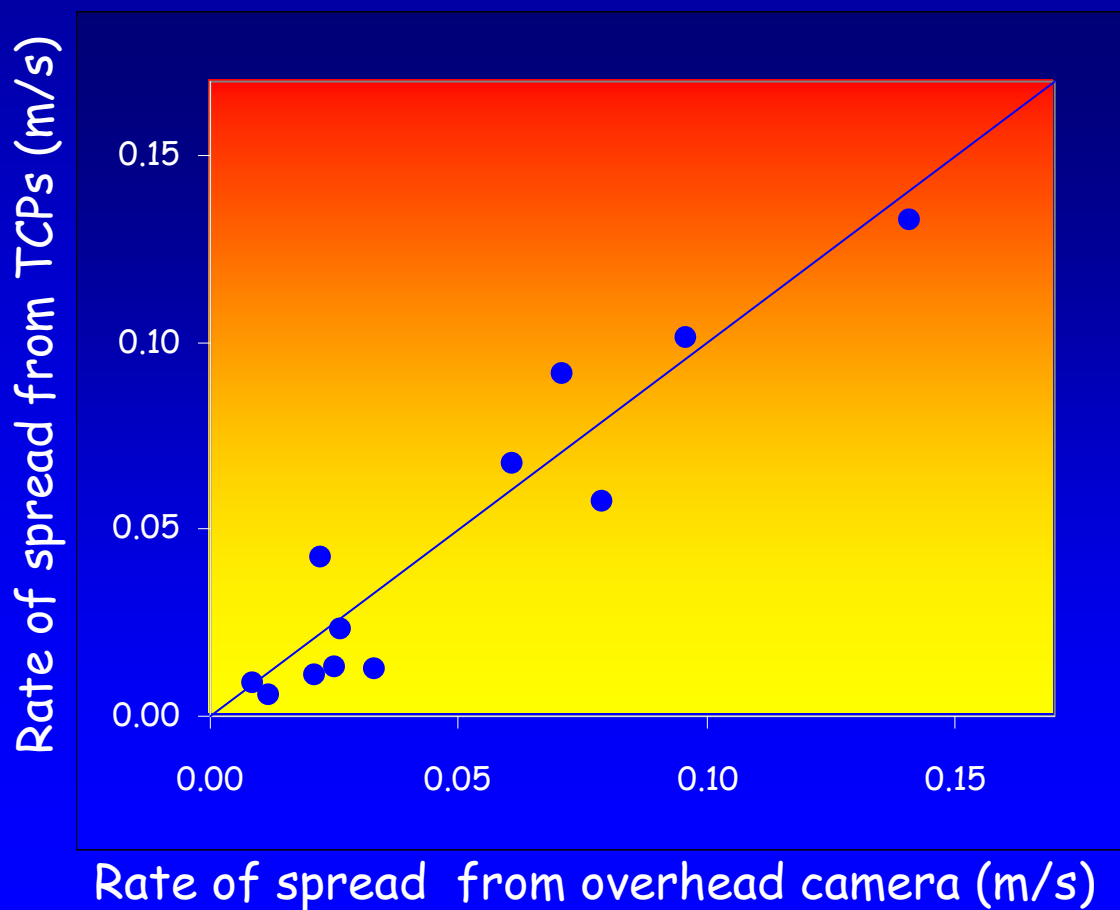


$\theta = \tan^{-1}[(t_3-t_1)/(t_2-t_1)]$

$ROS = s \cdot \cos\theta / (t_2-t_1)$

where t = arrival time

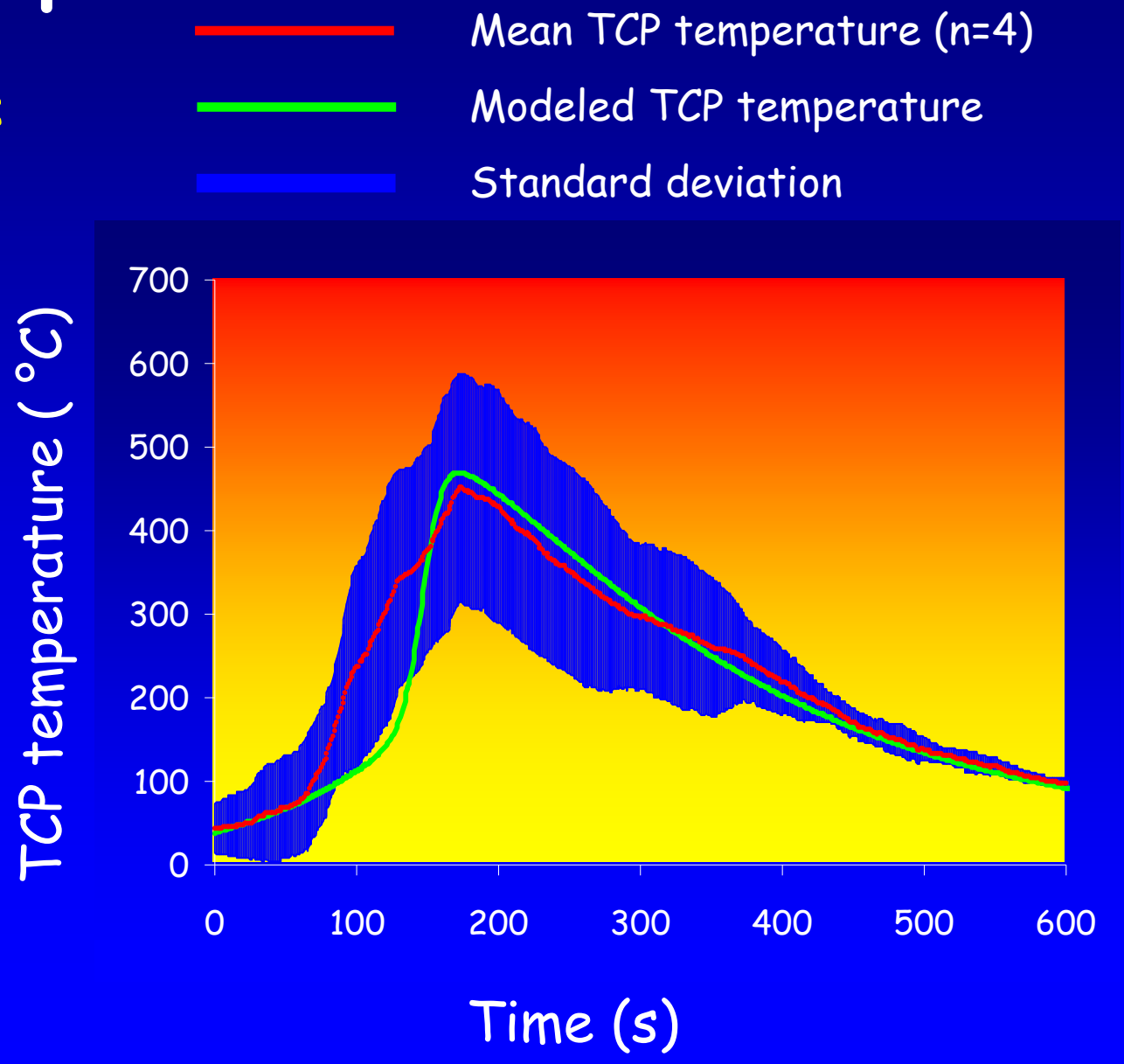
Simard et al. 1984



Thermocouple probes – continuous output

Outputs of interest:

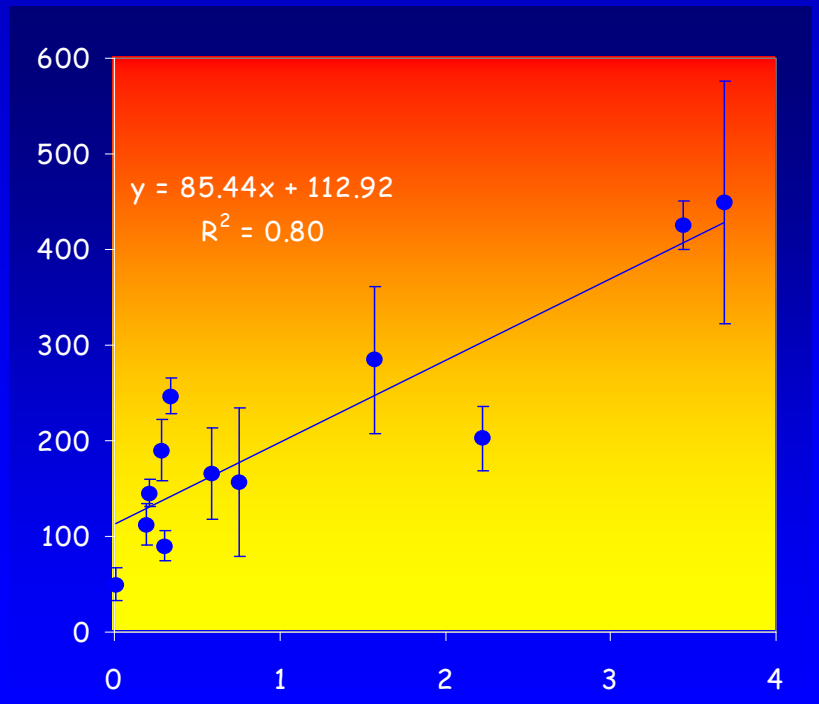
- Peak temperature
- Time-integrated temperature



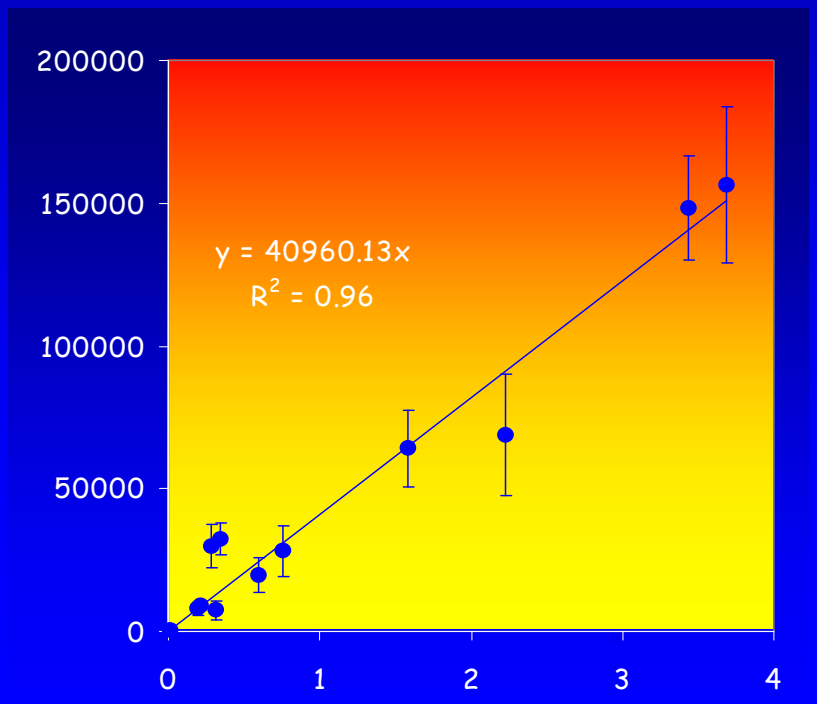
Thermocouple probes – calibration equations

Consumed loading (or H_c) correlated well to max & time-integrated temperature.

Mean maximum temperature (°C) vs consumed fuel loading (kg/m²).



Time-integrated temperature (°C·s) vs. consumed fuel loading (kg/m²).

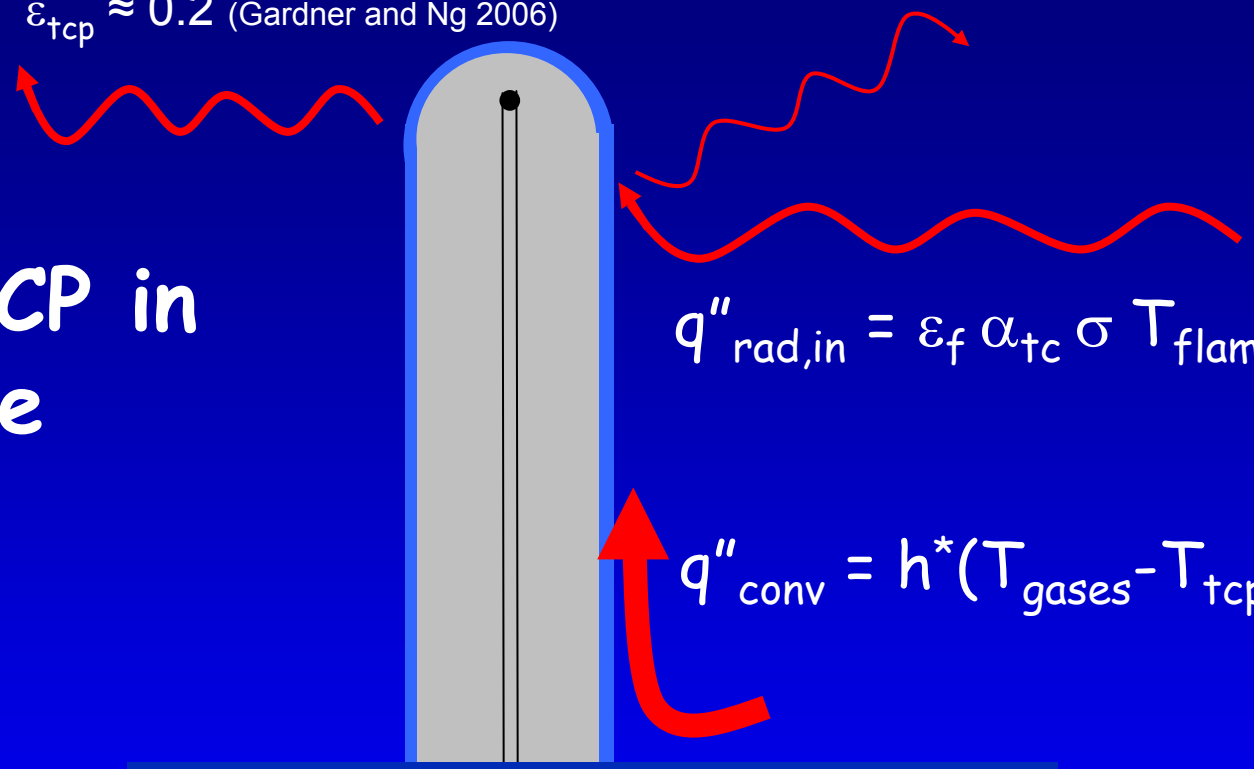


Modeling a TCP in a surface fire

TCP response to heat

$$q''_{rad,out} = \varepsilon_{tcp}\, \sigma\, T_{tcp}^{4}$$

$\varepsilon_{tcp} \approx 0.2$ (Gardner and Ng 2006)



$$q''_{rad,in} = \varepsilon_f\, \alpha_{tc}\, \sigma\, T_{flame}^{4}$$

$$q''_{conv} = h^{*}(T_{gases} - T_{tcp})$$

$$q''_{net} = q''_{conv} + q''_{rad,in} - q''_{rad,out}$$

$$dT/dt = 2\, q''_{net} / \rho_{tc}\, r_{tc}\, C_p$$

$$^{*}\ h = 2.8\, (v^{0.466} / D^{0.534}) \quad (W\ m^{-2}\ K^{-1})$$

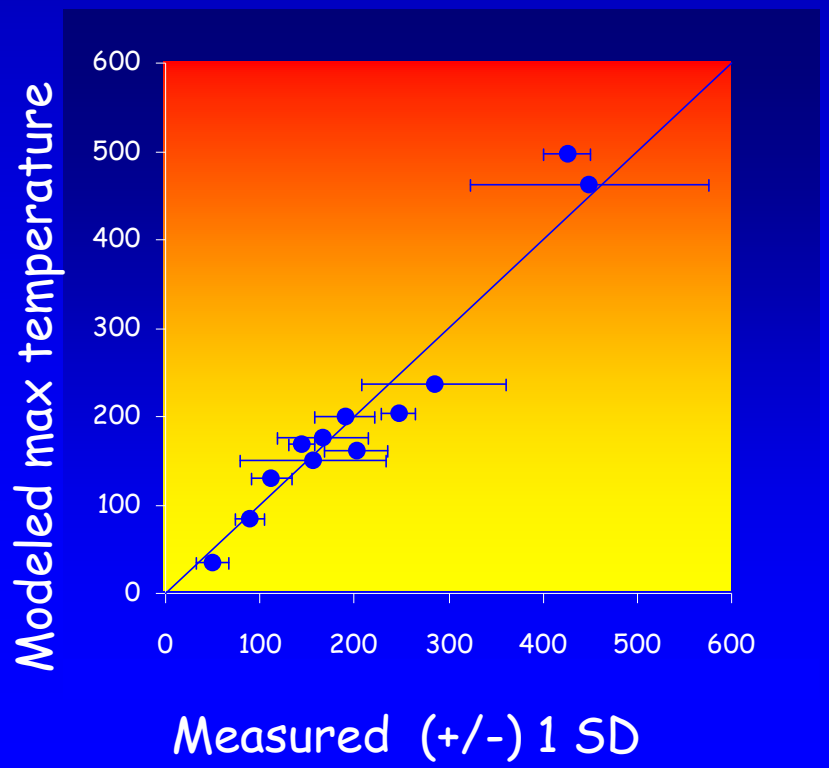
Adapted from Incropera and DeWitt 2002

Model vs.Experiment

Maximum temp (°C)

R^2=0.95

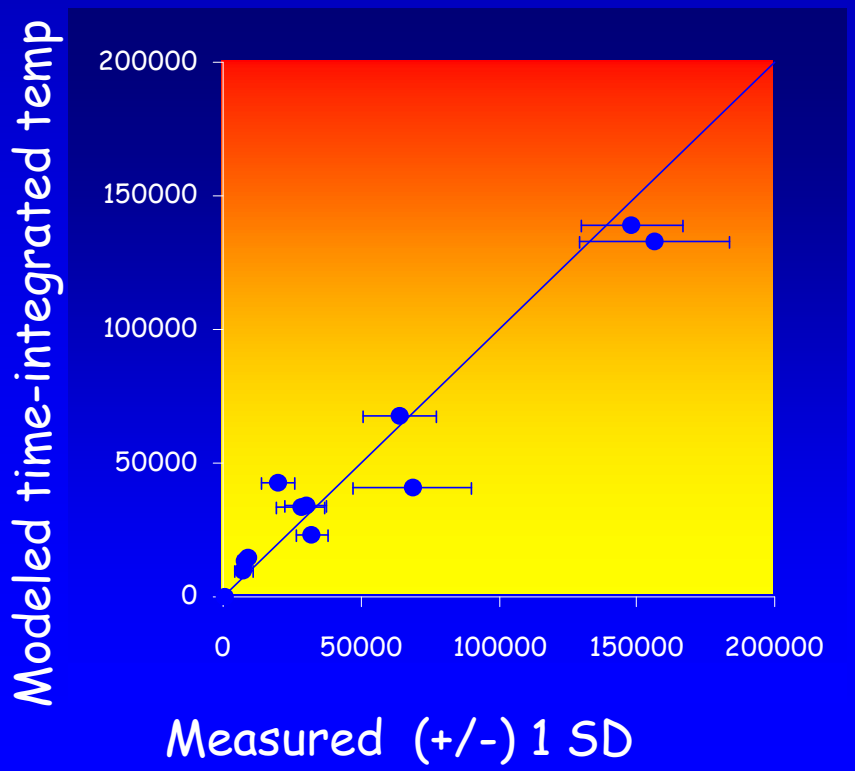
Mean error: 23.5 °C



Time-integrated temp (°C·s)

R^2=0.94

Mean error: 10,000 °C s



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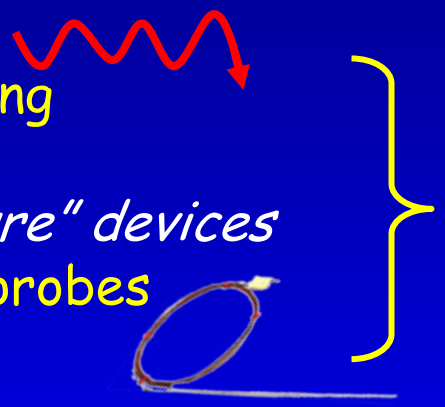
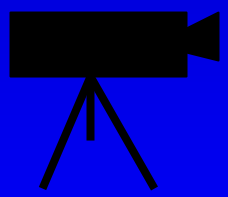
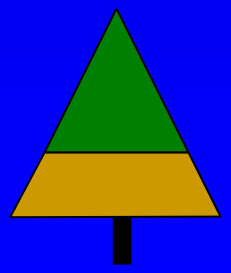






Cadillac

Volkswagen beetle

Paint tags

Cheap!

Medium

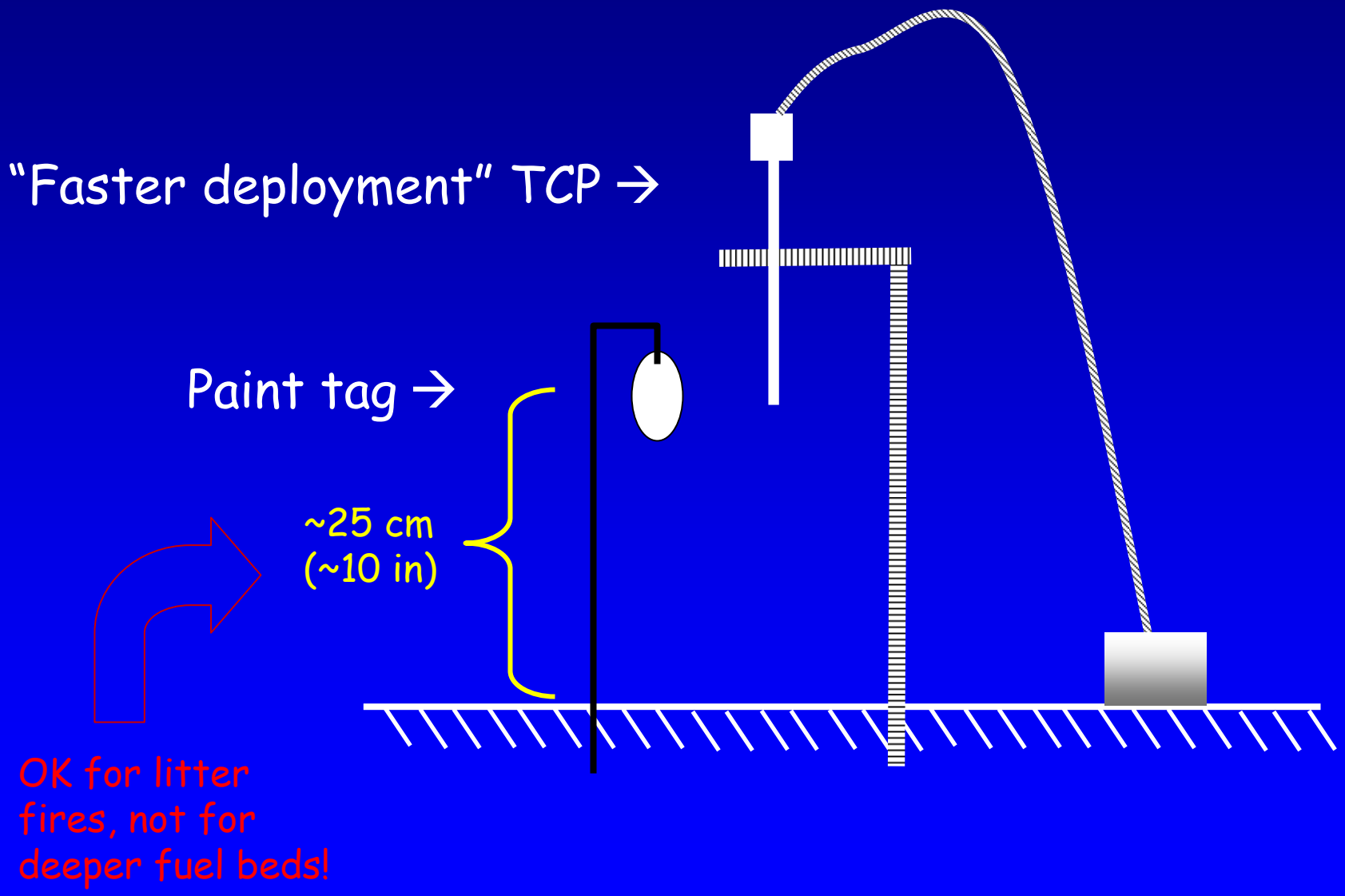
Low

High

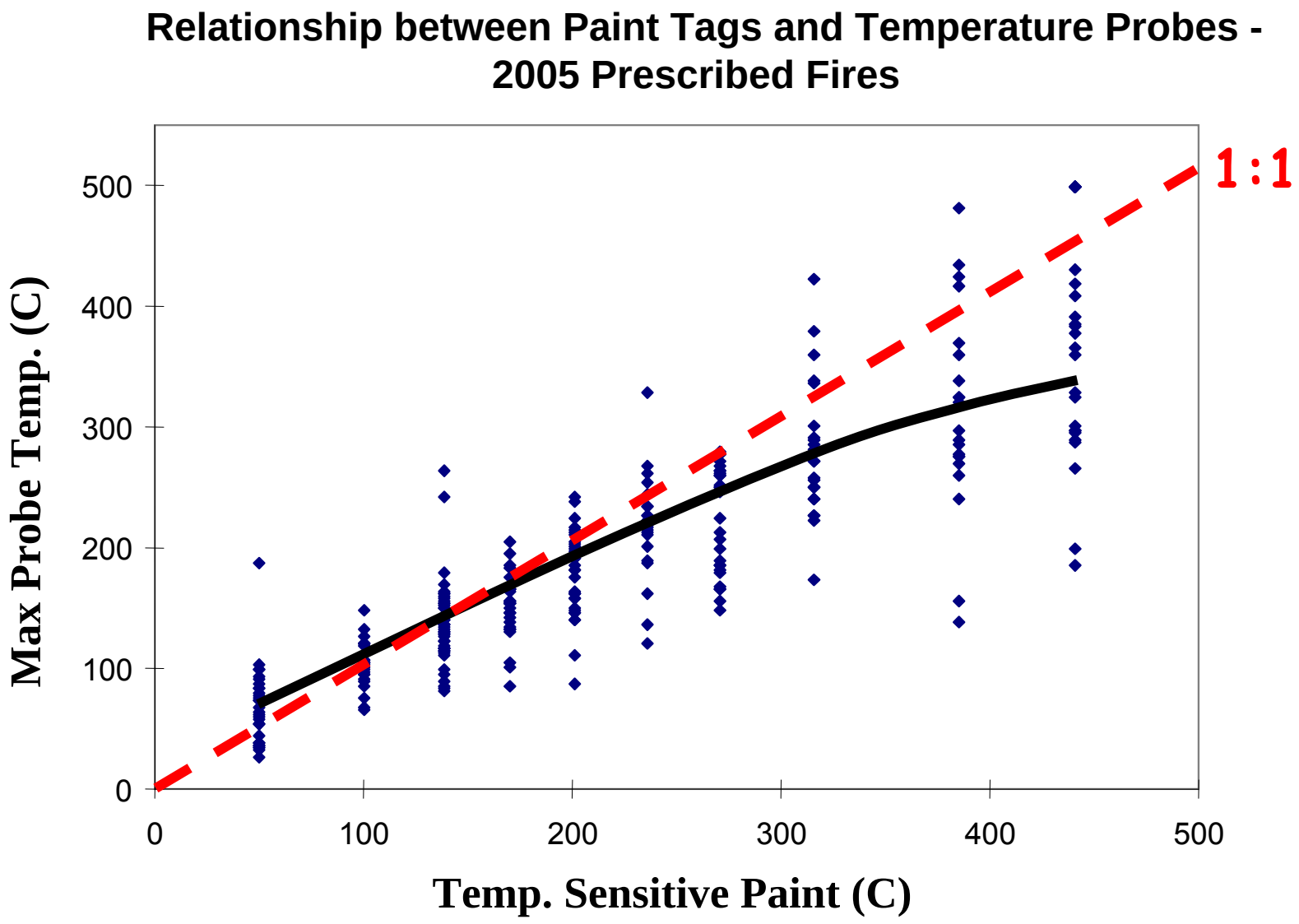
Problems – lowest intensity fires don't melt paint
- stairsteps

From J. Rebbeck

Paint tags - deployment

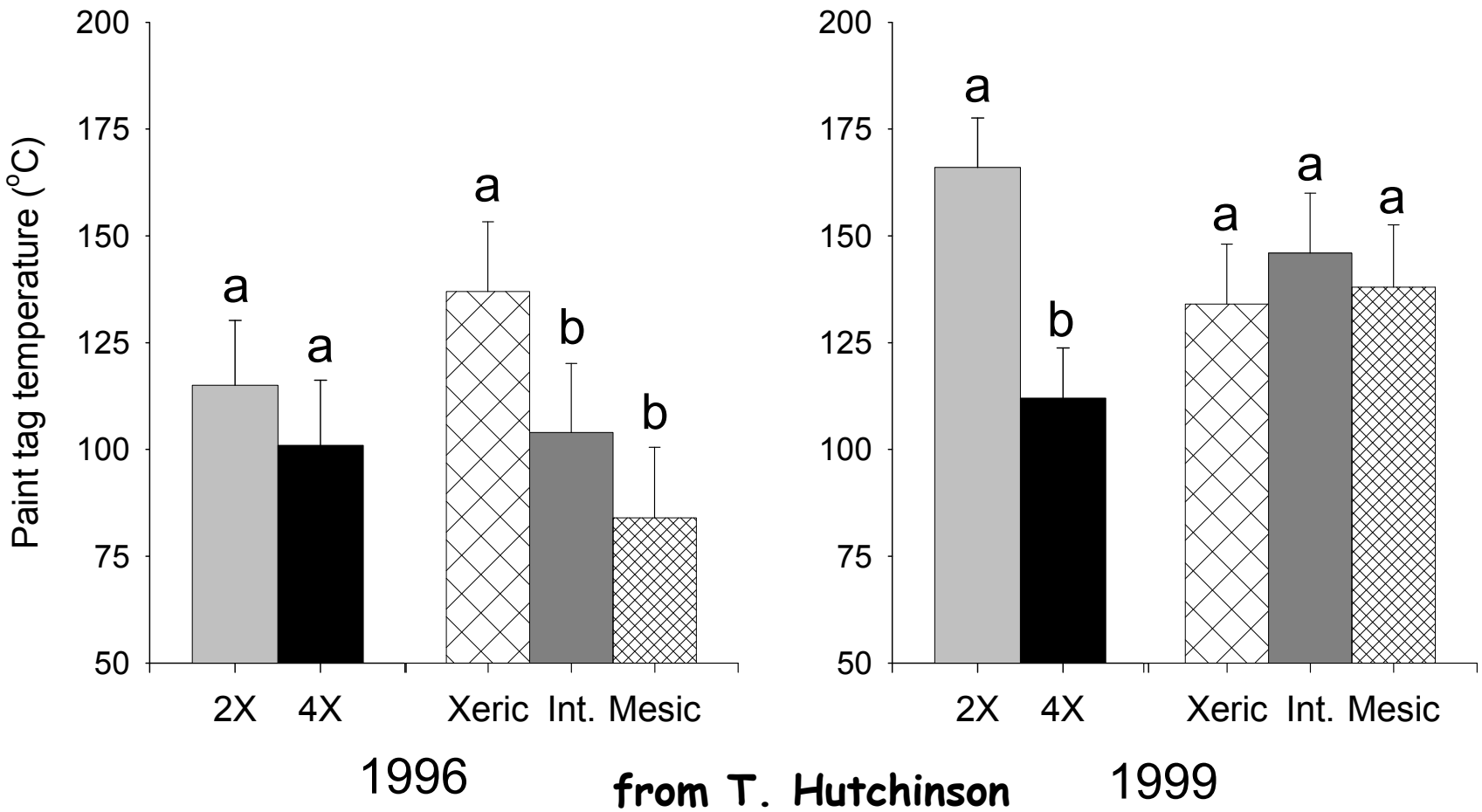


TCP temperature ≠ Paint tag temperature



Paint tag temperature
~index of fuel consumption

- After four annual fires, lower paint tag temperatures
- Effect of topography only during marginal conditions



from T. Hutchinson

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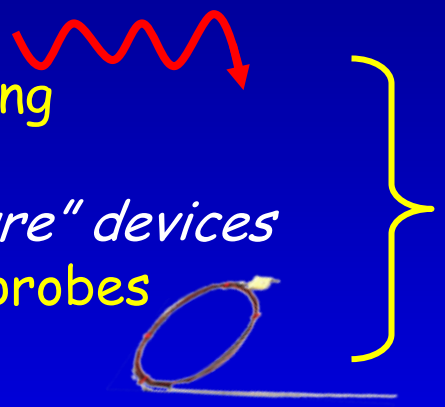
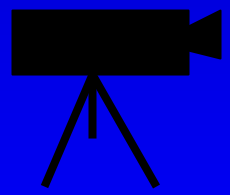
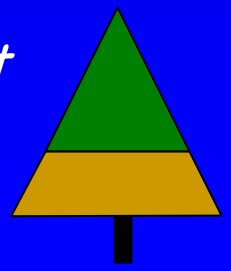






Cadillac

Volkswagen beetle

Miscellaneous monitoring methods - video

Difficult to get anything quantitative, except:

- Flame dimensions from comparison standards
- Oblique angle video and image analysis to get rate of spread

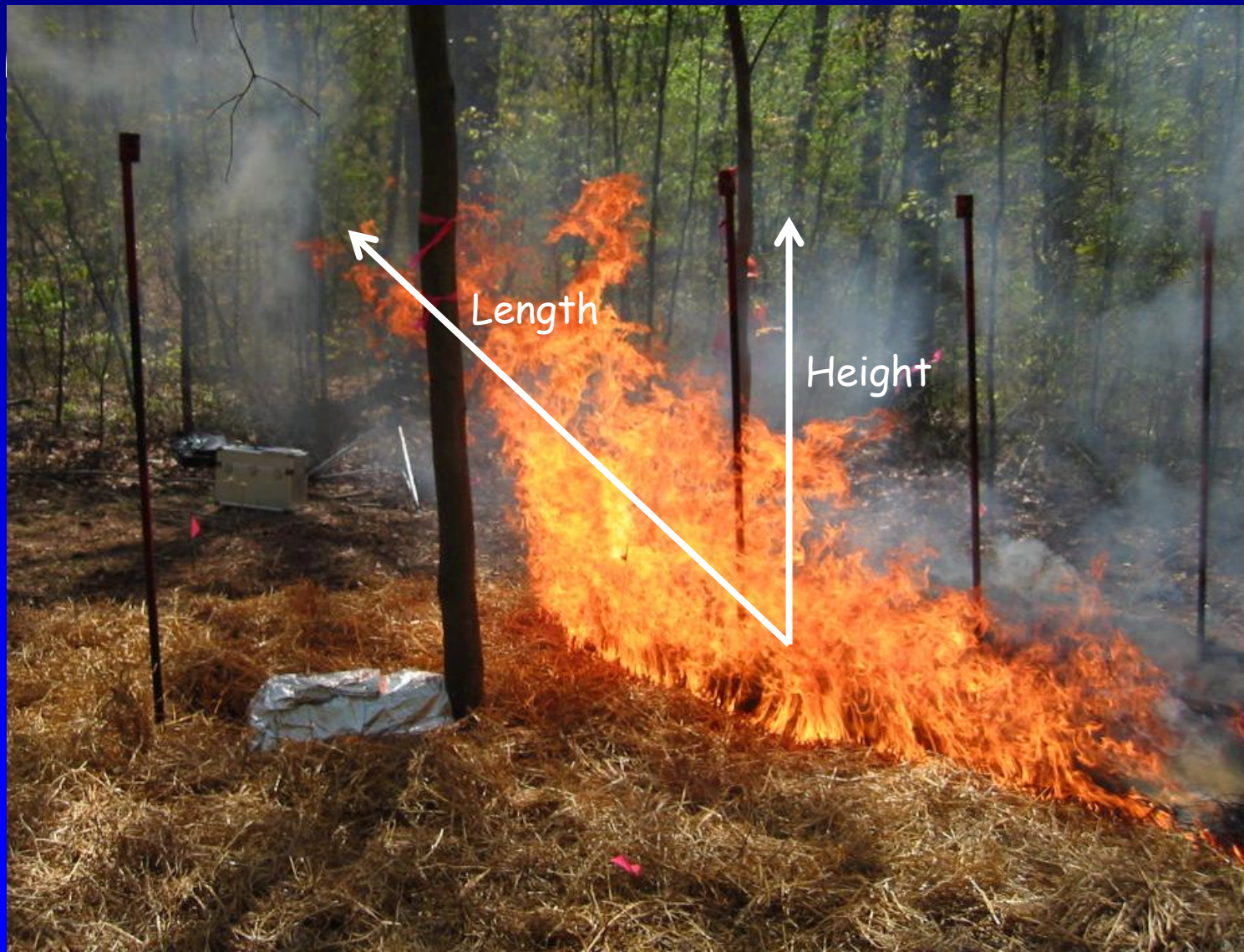
Good for qualitative sense of fire

Miscellaneous monitoring methods - video

Specific interest on the characteristics of standing leeward flames as model corroboration

Miscellaneous monitoring methods – flame height sensors

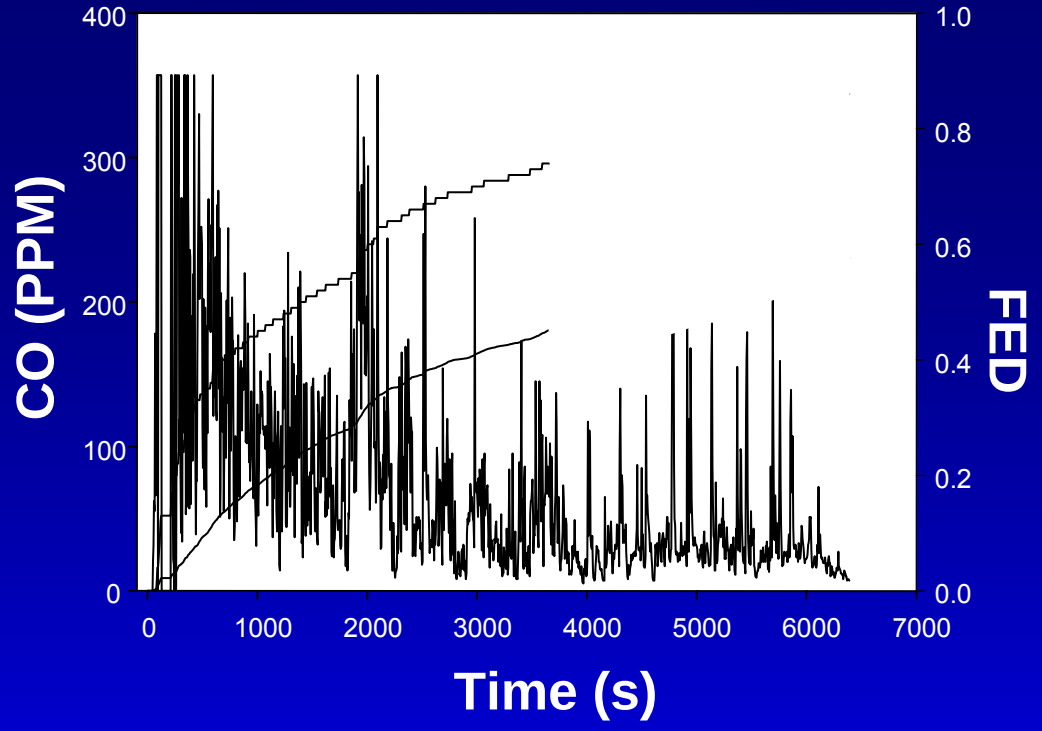
Flame length is more reflective of fire's power

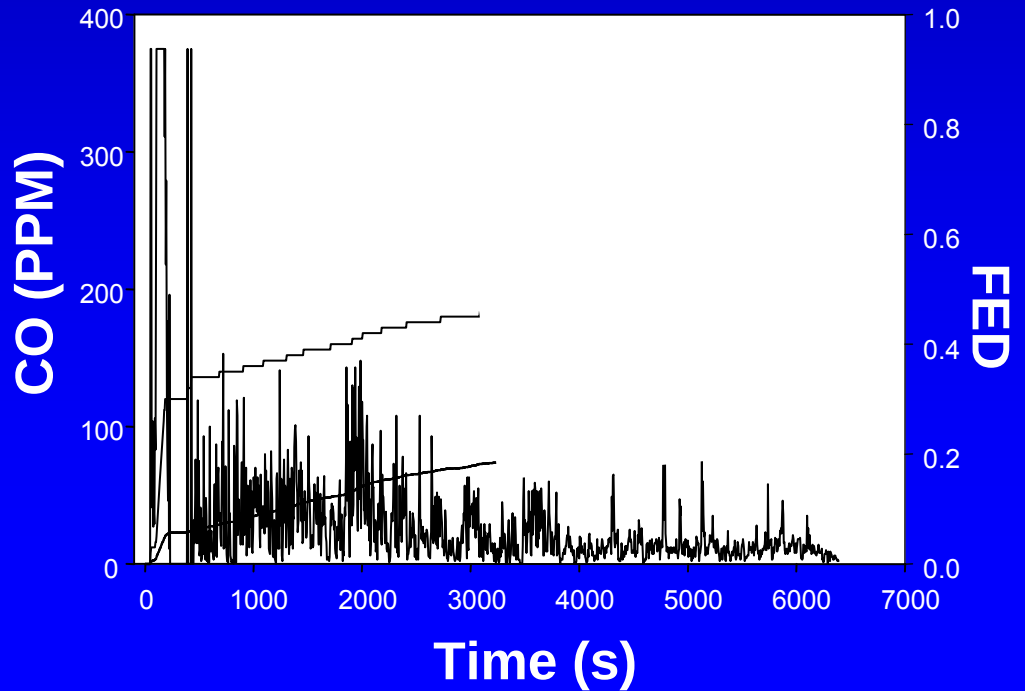


Miscellaneous monitoring methods – gas sensing (CO)

Smoke is irritating, but gases from typical fires won't kill bats because exposure times and concentrations are too low.

(Heat is a different story)



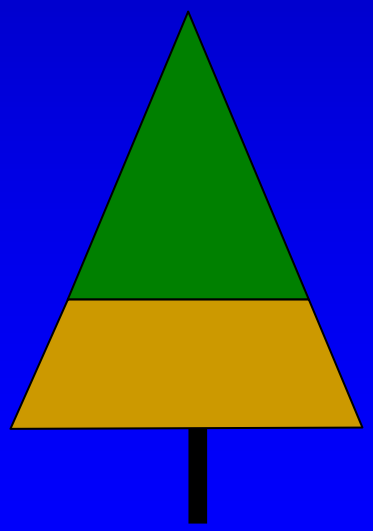


Indirect techniques – scorch height

Scorch height – good technique because it relates to plume power

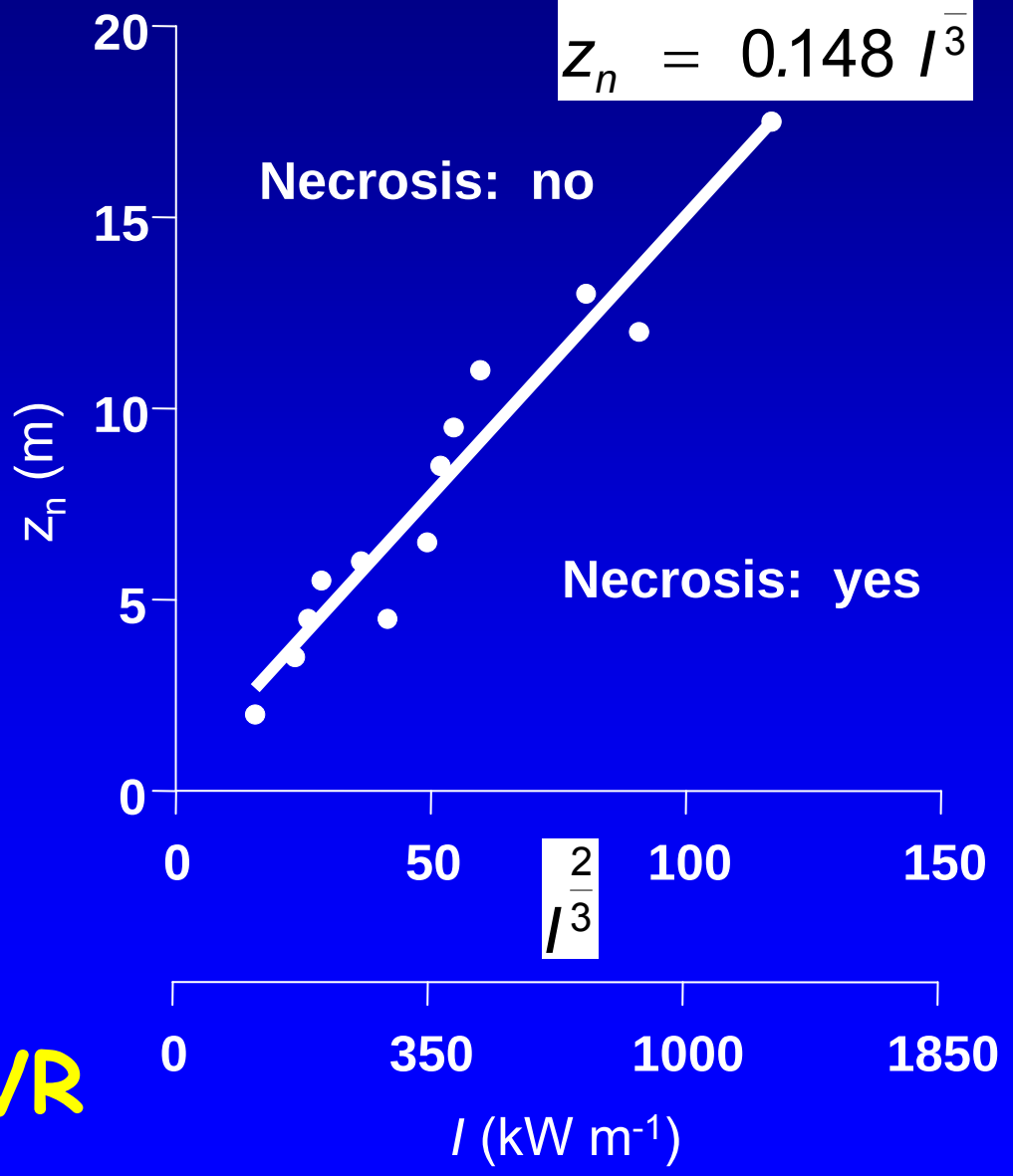
Suited for conifers or leafed-out deciduous trees.

Back out fire intensity from Van Wagner's relationships



Van Wagner 1973

$$z_n = 0.148\, I^{\frac{2}{3}}$$



I = HWR

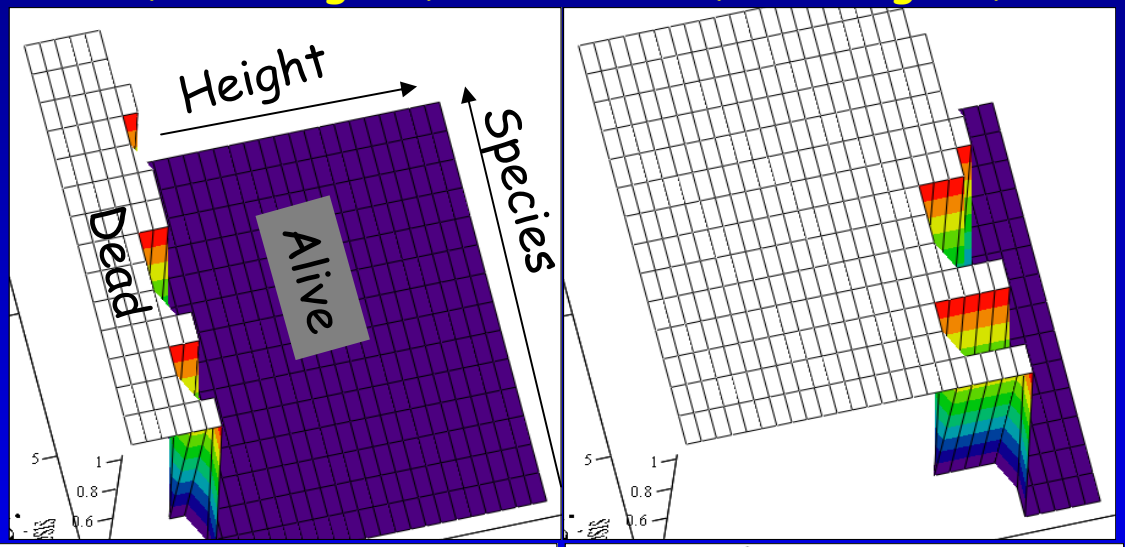
Indirect techniques – branch kill height

Model of branch kill height – good for deciduous trees.

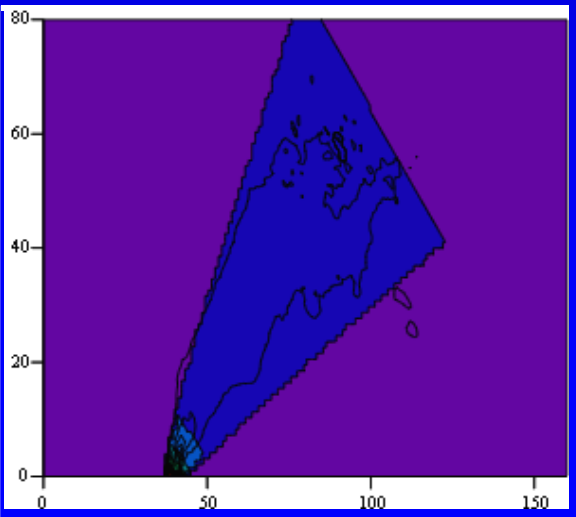
Inputs are rate of spread and fuel consumption

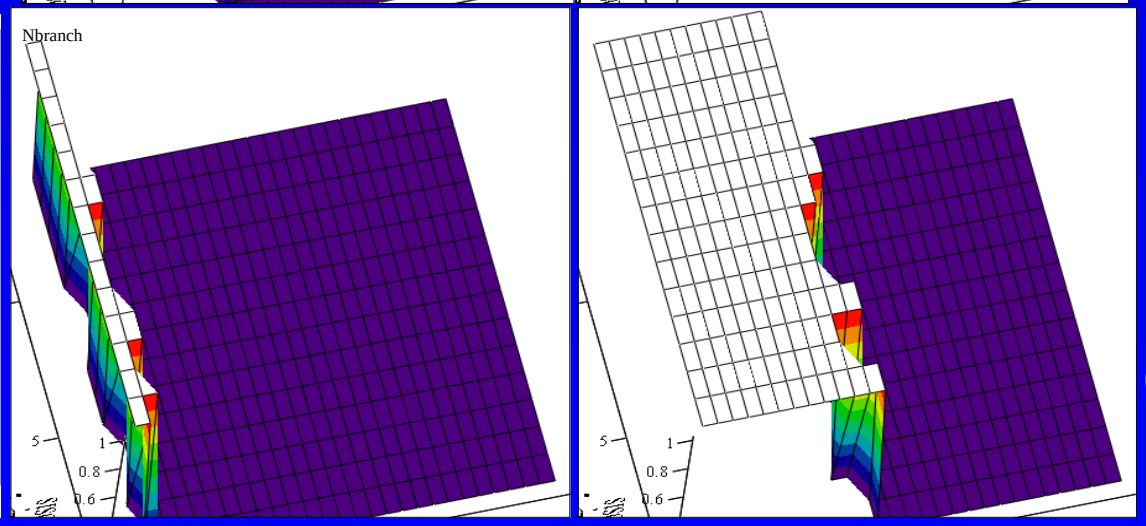
Intensity 400 kW/m
(4 ft lengths)

Intensity 1600 kW/m
(8 ft lengths)



No wind





Wind
3 m/s
(10 ft/s)

Indirect techniques – char height

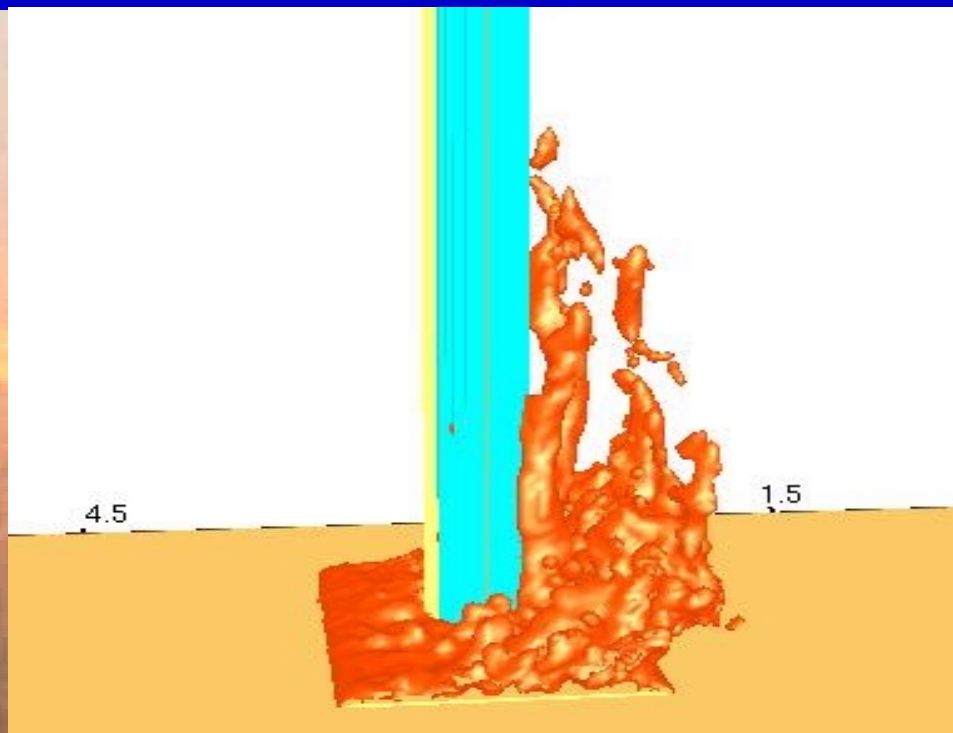
Char height – confounded by wind speed and diameter of tree bole.

Need calibration with fire behavior (which doesn't exist)

A lot of interesting work to be done to develop this method.

Phenomena that a model must explain include:

1. Vortex production and shedding
2. Windward bow wave
3. Key (?) role of bark combustion
4. Fire induced cross-flow on slopes



Outline

- Fire behavior monitoring
- Fire effects monitoring
  - FFI – FEATS/FIREMON Integrated
  - What to monitor? Fuel load, discontinuity

FFI Fire Monitoring System

- FFI – "FEATS/FIREMON Integrated"
- FEATS – Fire Ecology Assessment Tool (DOI)
- FIREMON – Fire Effects Monitoring and Inventory Protocol (USFS)

Used widely by USFS, NPS, etc., for monitoring fuel loading, vegetation, and user-chosen elements

Flexible and as time-efficient as possible

http://frames.nbii.gov/portal/server.pt?open=512&objID=483&&PageID=2216&mode=2&in_hi_userid=2&cached=true

Software
Documentation
Training

*Need good monitoring plan and design

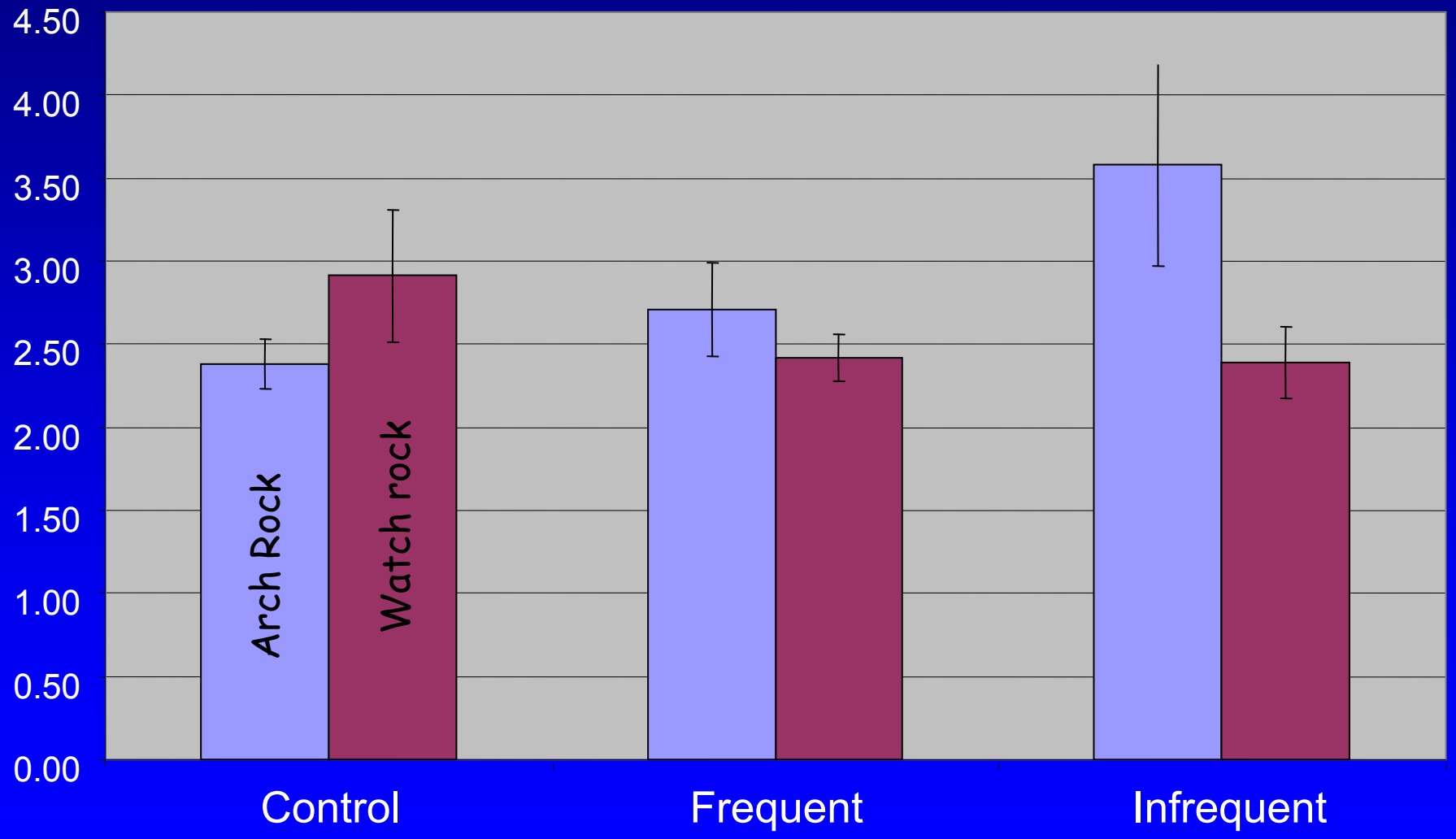
*Need sufficient replication of monitoring plots

FFI - fuel load sampling (mixed-oak)

Brown's transect for woody fuels

FFI fuel load sampling (mixed oak)

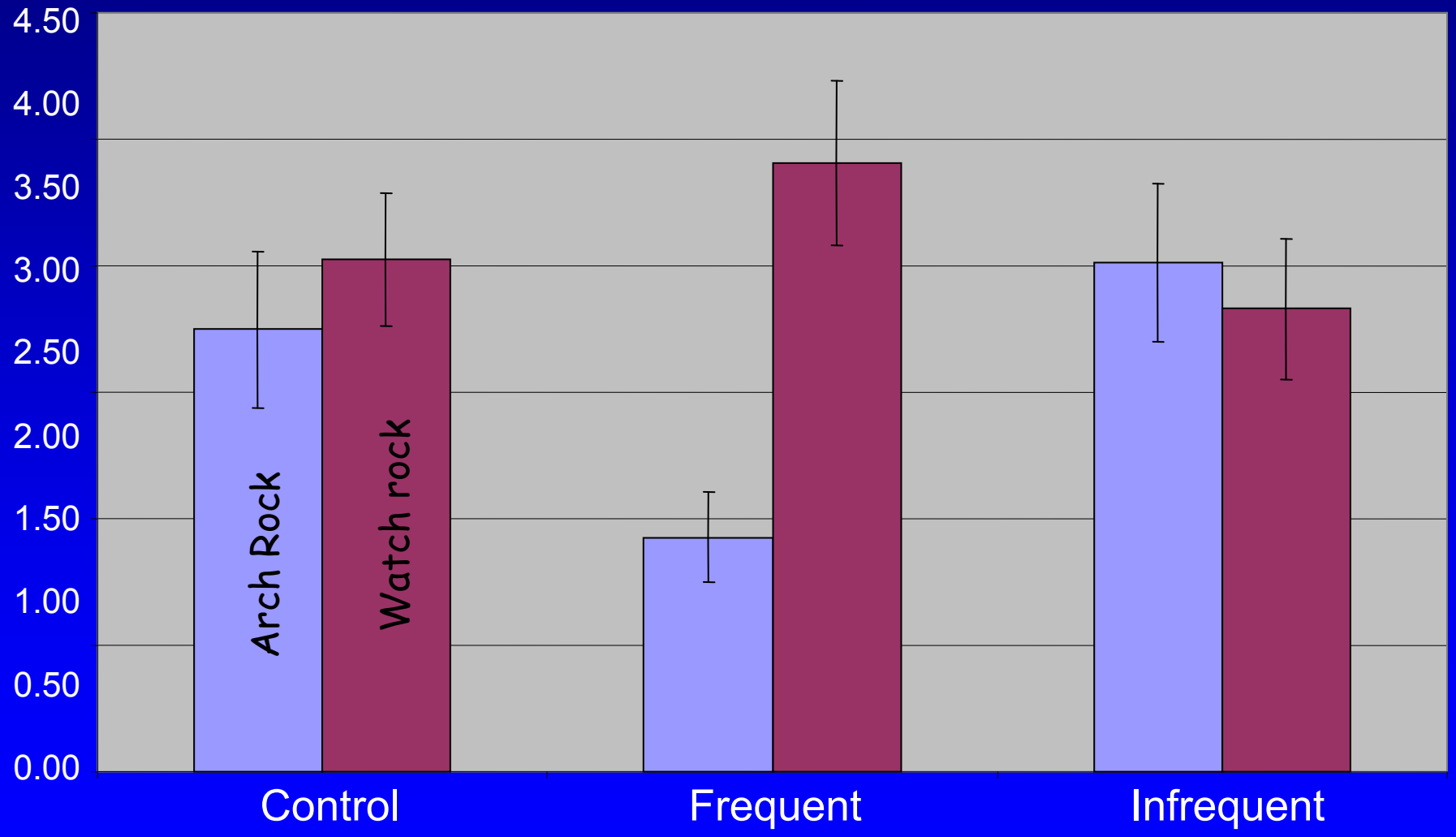
1-100 hr woody (tons/acre) – no reduction from burning



C. Kirschbaum (USFS, WNF)

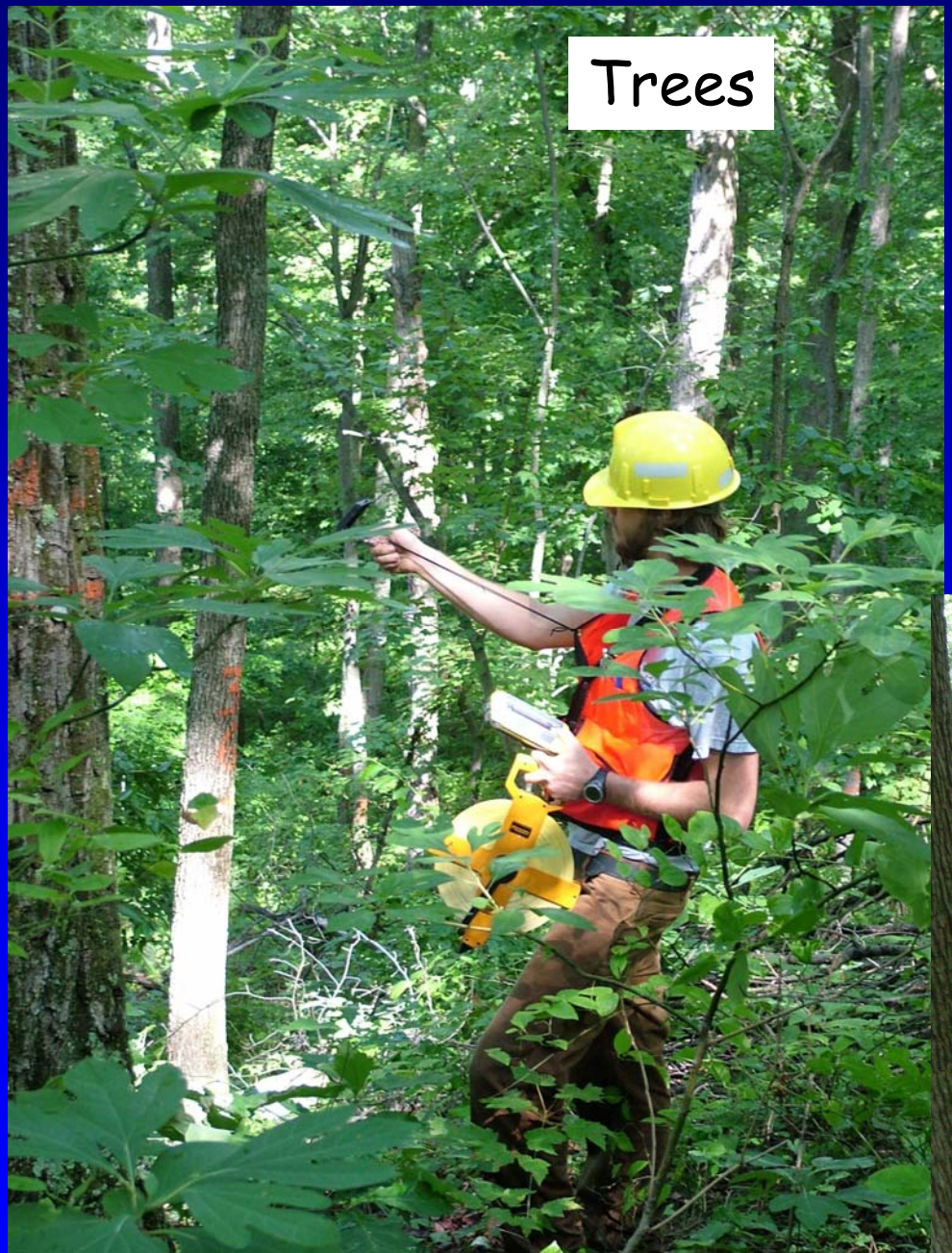
FFI fuel load sampling (mixed oak)

Duff (tons/acre) – mystery (differences in fire behavior?)



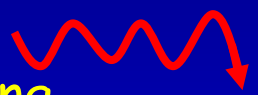
C. Kirschbaum (USFS, WNF)

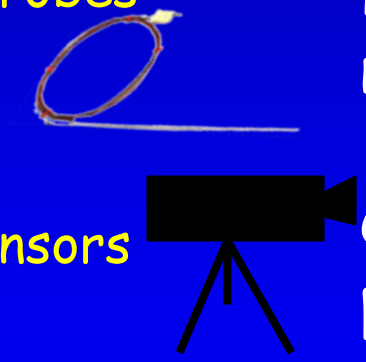
FFI sampling (mixed oak)

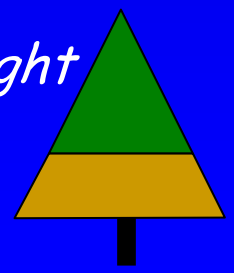


Outline

- Fire behavior monitoring
  - General problem
  - Direct techniques
    - *Infrared methods*
      - Airborne mapping
      - Ground sensors
    - *In-fire "temperature" devices*
      - Thermocouple probes
      - Paint tags
    - *Miscellaneous*
      - Videography
      - Flame height sensors
      - Gas sensing
  - Indirect techniques
    - *Scorch & branch kill height*
    - *Char height*
- Fire effects monitoring







Summary

Lots of options, room for innovation, & need for R&D

Call us if you want IR-based maps of your fires!

Device temperatures are not fire temperatures

Calibrate your devices to provide fire behavior

Consider FFI for fuels and effects monitoring

Cooperating Scientists

- Anthony Bova - *US Forest Service, Northern Research Station*
- Bob Kremens – *Rochester Institute of Technology*
- Mike Lacki – *University of Kentucky*
- Valerie Young - *Ohio University*
- Loredana Suciu – *Ohio University*

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