Forest Fire Model Validation

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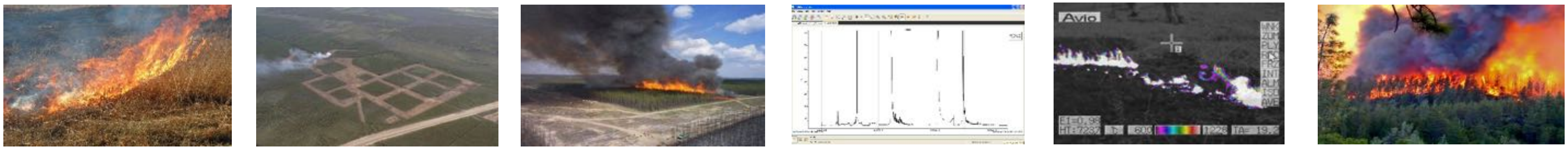
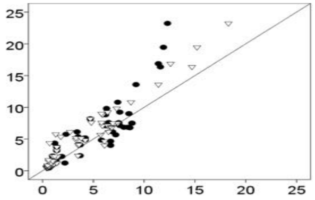


Objectives of fire field experiments

1. Collect fire behaviour data to calibrate and validate fire behavior models



2. Test equipments used during fire fighting (e.g., protection dispositives, fire shelter)

3. Assess building flammability at the Wildland Urban Interface

4. Correlate fire behavior to ecological fire effects (e.g. emissions, tree mortality)

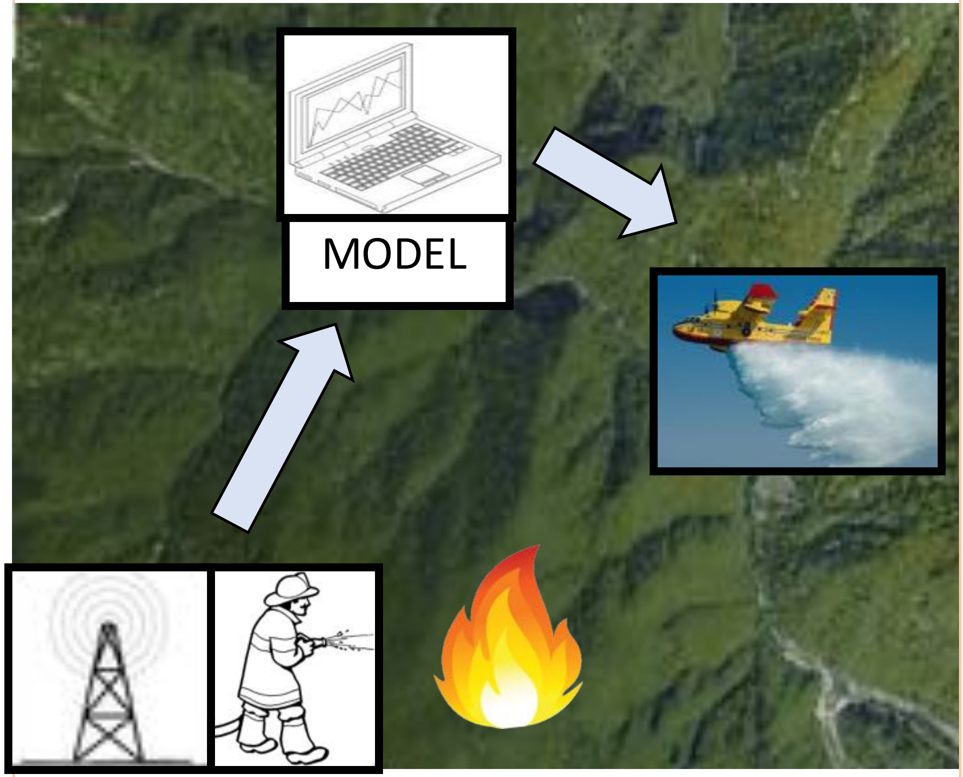
5. Others objectives (e.g. fire operators risks, train firefighters…)

Summary

1. Why fire evolution modelling
2. Experimental data
3. Empirical model validation through experimental data
4. Physical model validation through experimental data

Possible uses of models in operation

FAST SIMULATION MODEL DURING FIRE EVENTS



DETERMINISTIC APPROACH

MULTI-SCENARIO STOCASTIC MODEL

PROBABILISTIC APPROACH

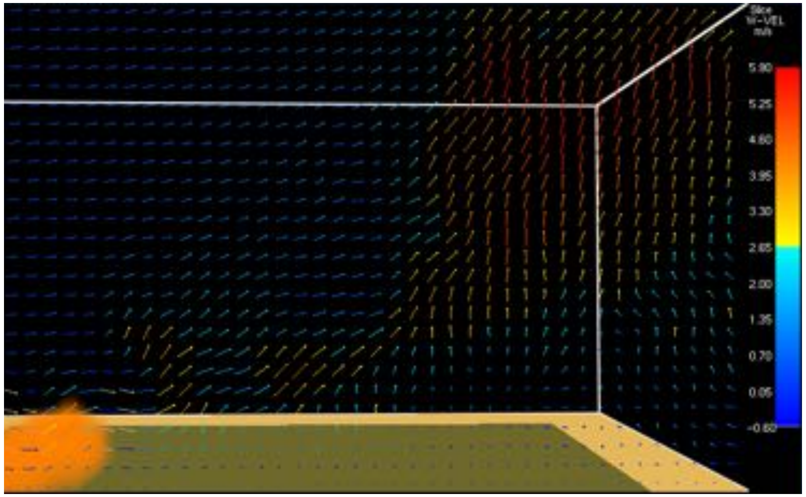
Information available from modeling

- Optimize the resources for fire extinction (fire fighters,canadair).
- Carry out evacuation plans and reduce fire fighters risk.
- Reduce risk and improve effectivness payload delivery.

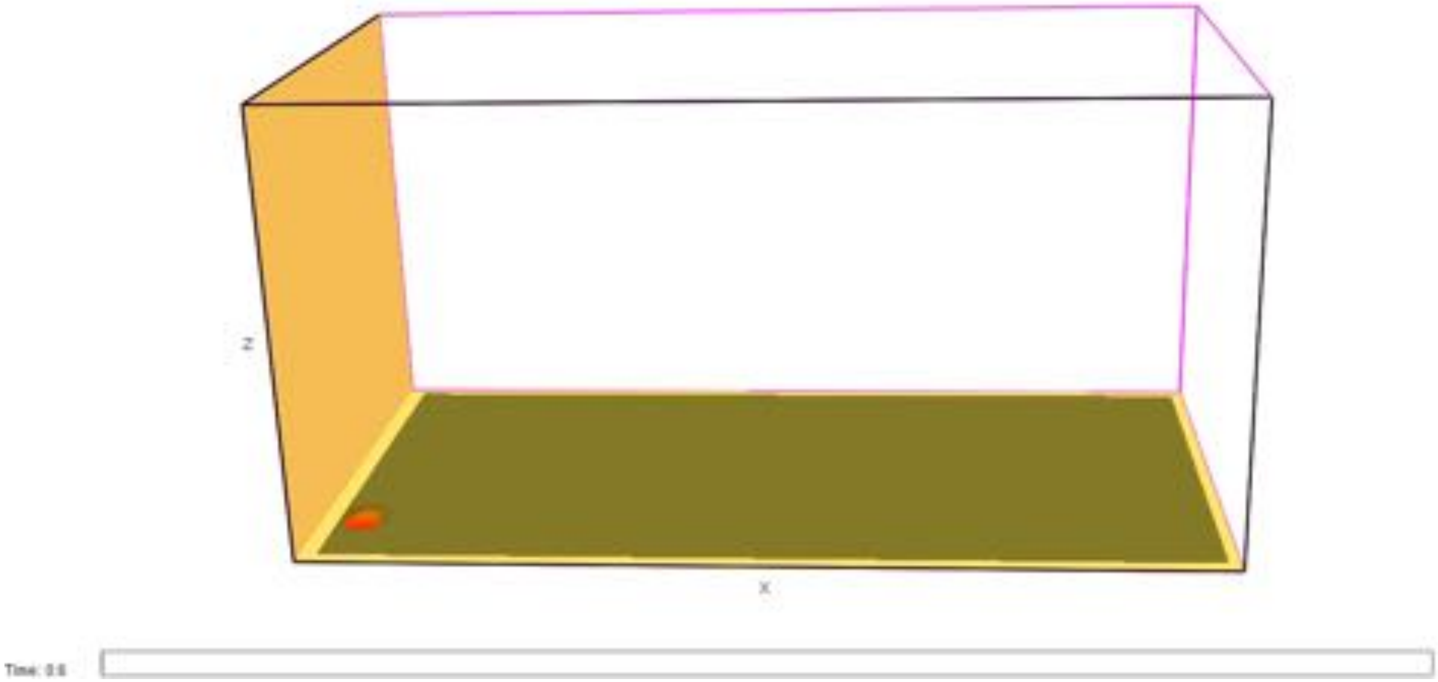
Models for prediction of:

FIRE FRONT EVOLUTION

EFFECTS OF FIRE ON THE SURRONDING ATHMOSPHERE



Physical Models



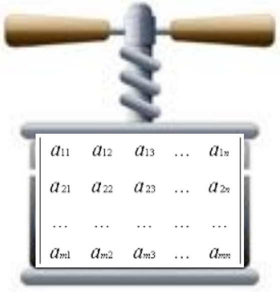
- PROVIDES LARGE AMOUNT OF INFORMATION
- QUITE ACCURATE IF INPUT IS ACCURATE
- TOO SLOW AS MANAGEMENT TOOLS

Physical Models

Are there reasonable ways to make wildfire physical models suitable for fast simulations?

An option is

model reduction



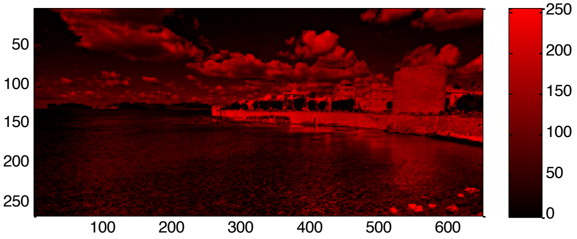
Physical Models

How much information do we need
in order to obtain the main features of a matrix?

=

COLORED IMAGE =MATRIX
obtained as a sum of
three matrices

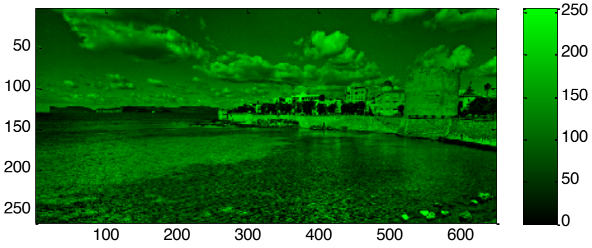
$$A = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & \cdots & a_{1n} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & \cdots & a_{2n} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & \cdots & a_{3n} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & \cdots & a_{4n} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & \cdots & a_{5n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \cdots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & a_{n4} & a_{n5} & \cdots & a_{nn} \end{pmatrix}$$



Matrix R

$$A = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & \cdots & a_{1n} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & \cdots & a_{2n} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & \cdots & a_{3n} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & \cdots & a_{4n} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & \cdots & a_{5n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \cdots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & a_{n4} & a_{n5} & \cdots & a_{nn} \end{pmatrix}$$

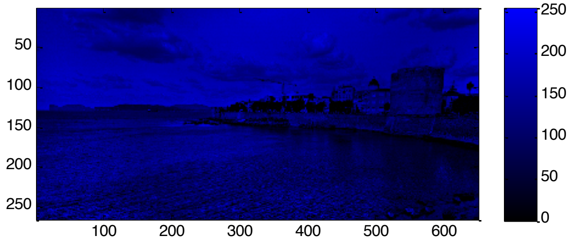
+



Matrix G

$$A = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & \cdots & a_{1n} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & \cdots & a_{2n} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & \cdots & a_{3n} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & \cdots & a_{4n} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & \cdots & a_{5n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \cdots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & a_{n4} & a_{n5} & \cdots & a_{nn} \end{pmatrix}$$

+

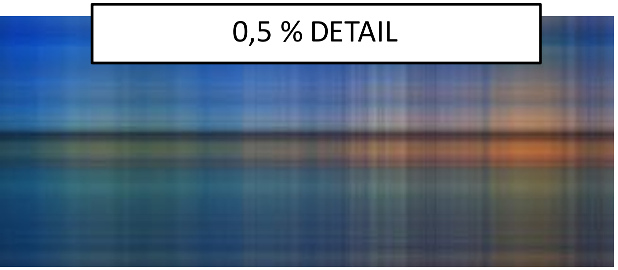


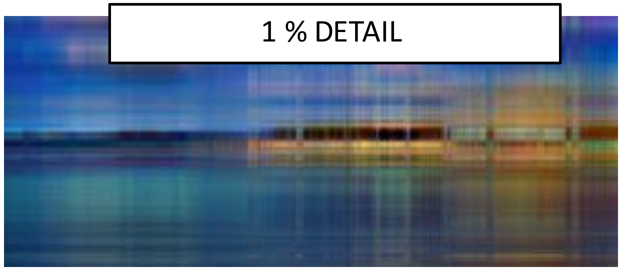
Matrix B

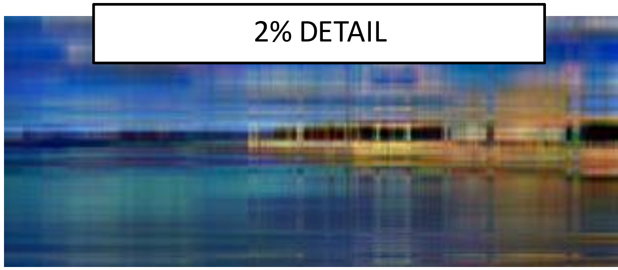
$$A = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & \cdots & a_{1n} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & \cdots & a_{2n} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & \cdots & a_{3n} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & \cdots & a_{4n} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & \cdots & a_{5n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \cdots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & a_{n4} & a_{n5} & \cdots & a_{nn} \end{pmatrix}$$

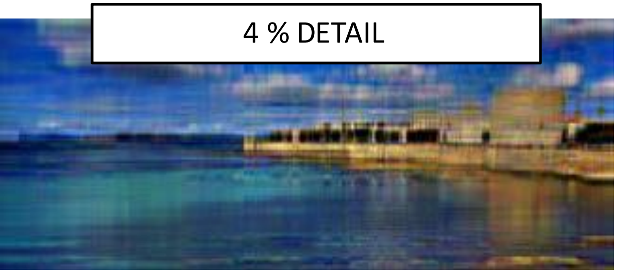
Reduced Physical Models

How much information do we need
in order to obtain the main features of a matrix?


0,5 % DETAIL


1 % DETAIL


2% DETAIL


4 % DETAIL


7,5 % DETAIL

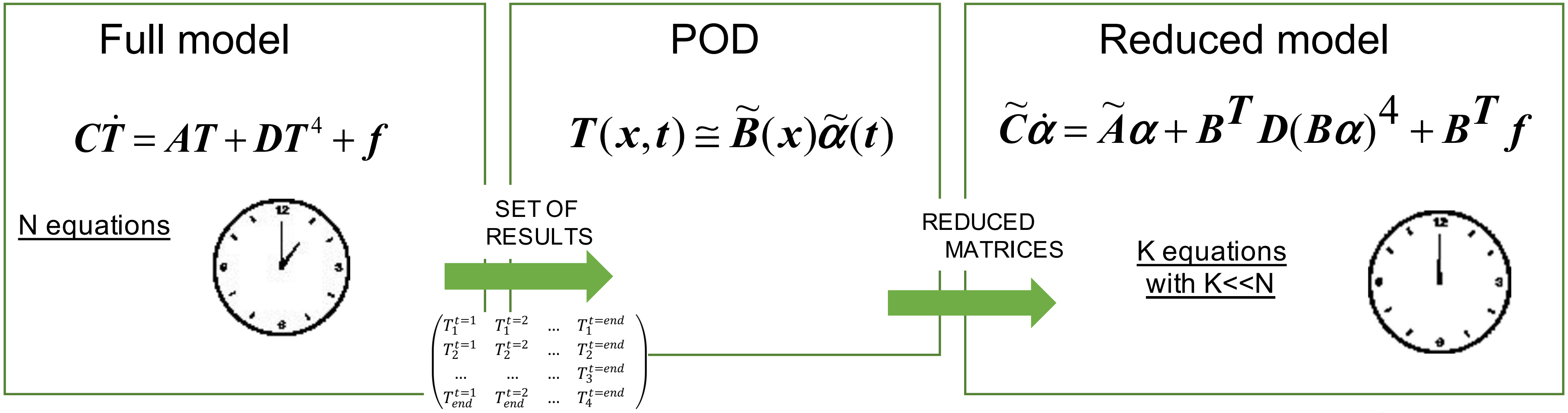

10% DETAIL


20% DETAIL


40% DETAIL


100% DETAIL

Reduced Physical Models



Full model

$$C\dot{T} = AT + DT^4 + f$$

N equations

SET OF RESULTS

$$\begin{pmatrix} T_1^{t=1} & T_1^{t=2} & \dots & T_1^{t=end} \\ T_2^{t=1} & T_2^{t=2} & \dots & T_2^{t=end} \\ \dots & \dots & \dots & T_3^{t=end} \\ T_{end}^{t=1} & T_{end}^{t=2} & \dots & T_4^{t=end} \end{pmatrix}$$

POD

$$T(x,t) \cong \tilde{B}(x)\tilde{\alpha}(t)$$

REDUCED MATRICES

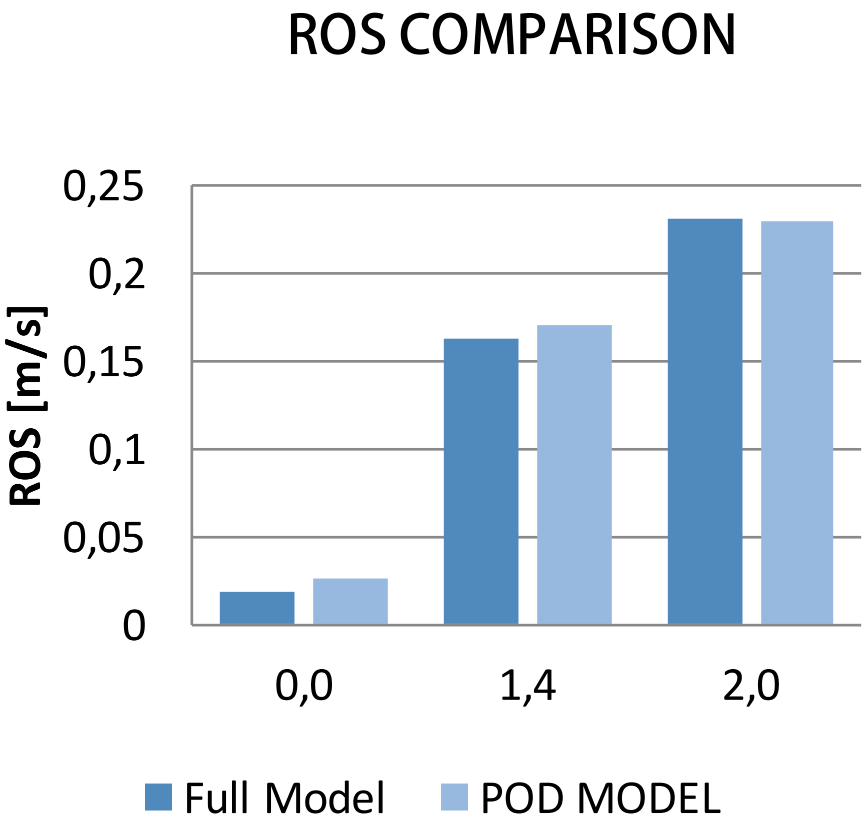
Reduced model

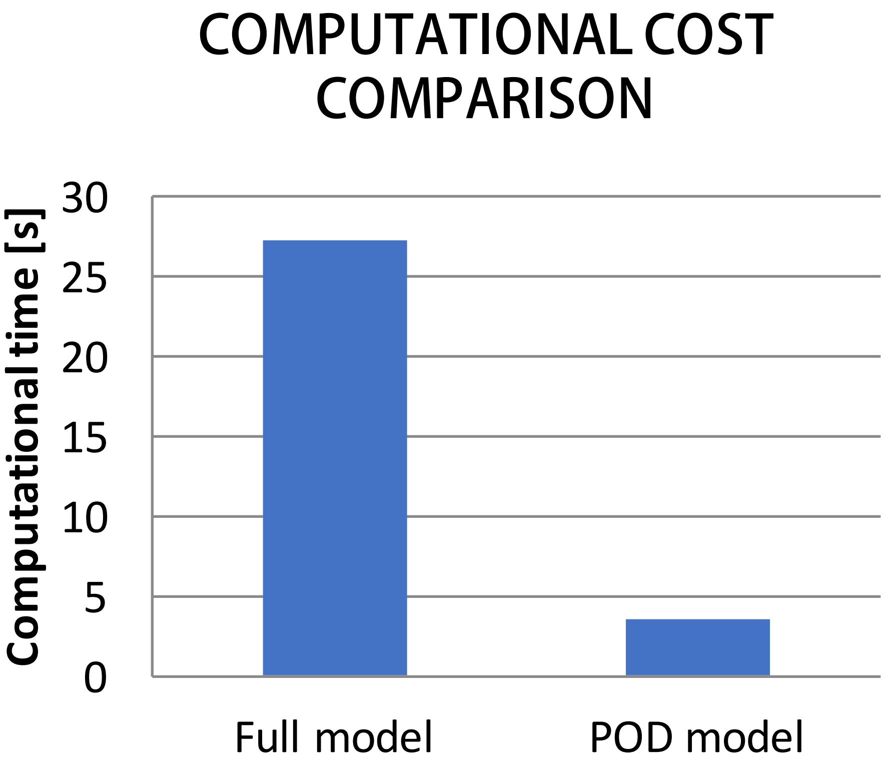
$$\tilde{C}\dot{\alpha} = \tilde{A}\alpha + B^T D(B\alpha)^4 + B^T f$$

K equations with K<<N

- 85% of the computational cost

Reduced Physical Models





Summary

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2. Experimental data
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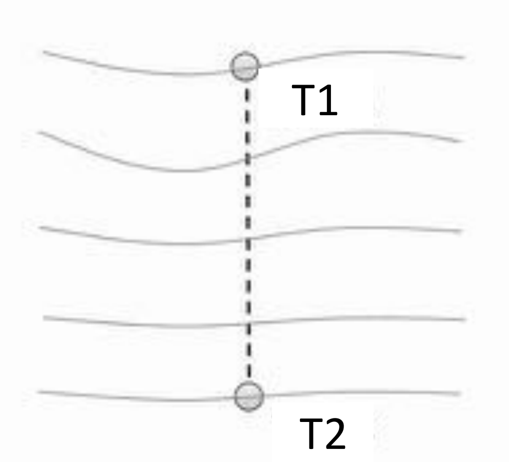
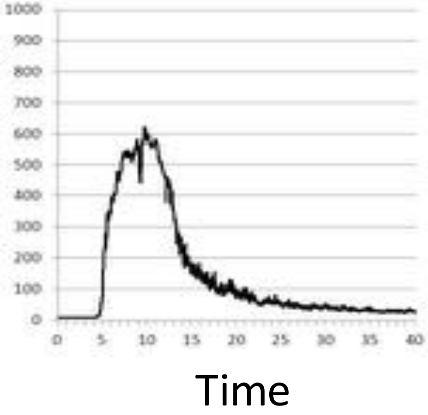
What to measure?

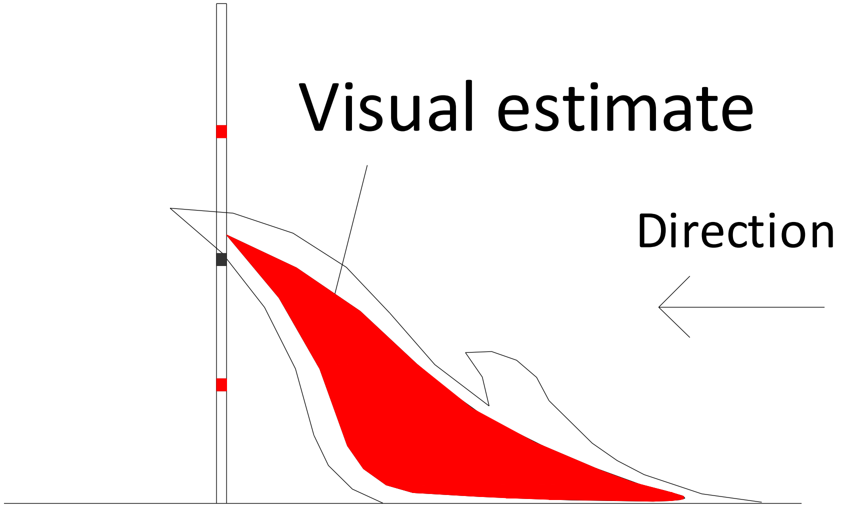
Fire descriptors

- Flame length (m)
- Rate of spread head, back, flank of the fire front (m/min)
- Fireline intensity (kW/m)
- Fire temperature (°C)
- Radiant energy fluxes (kW/m²)



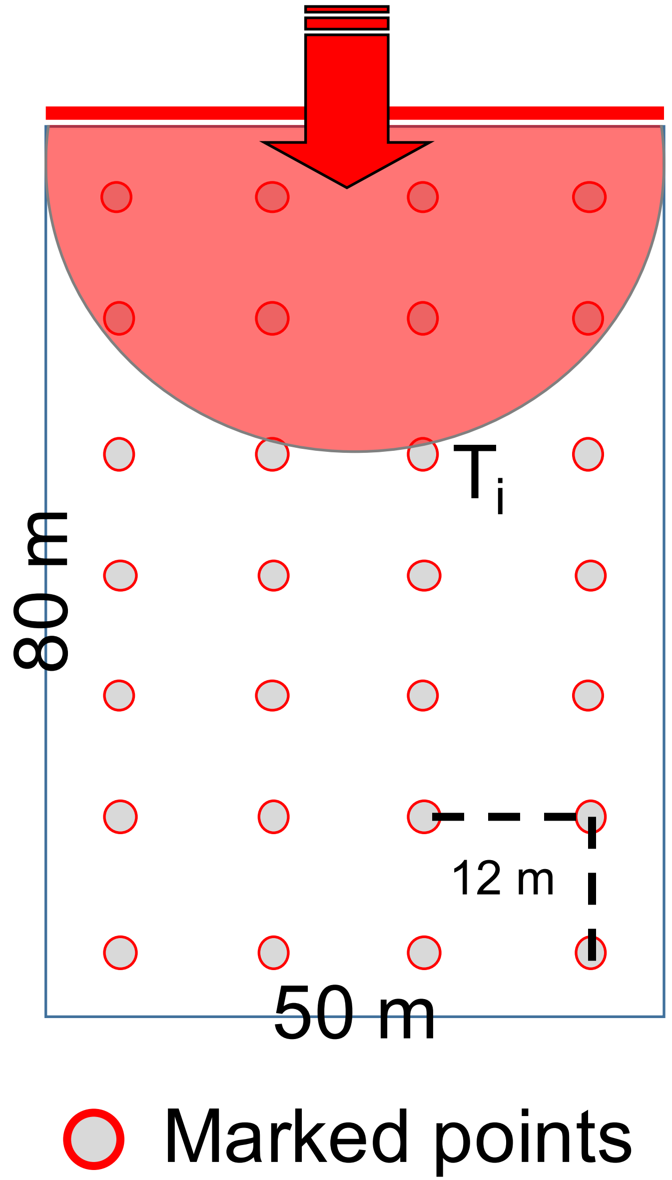


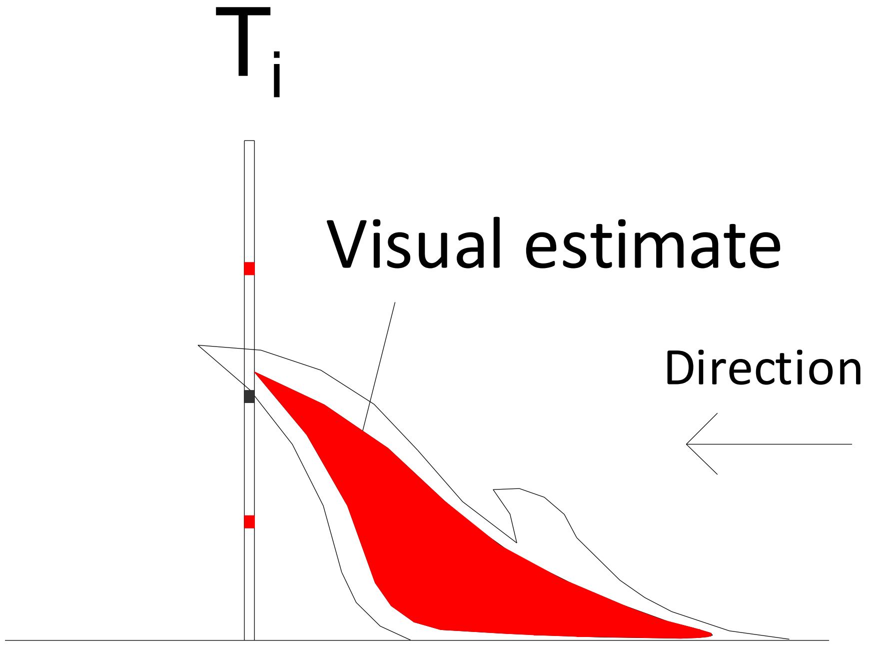
Flame length



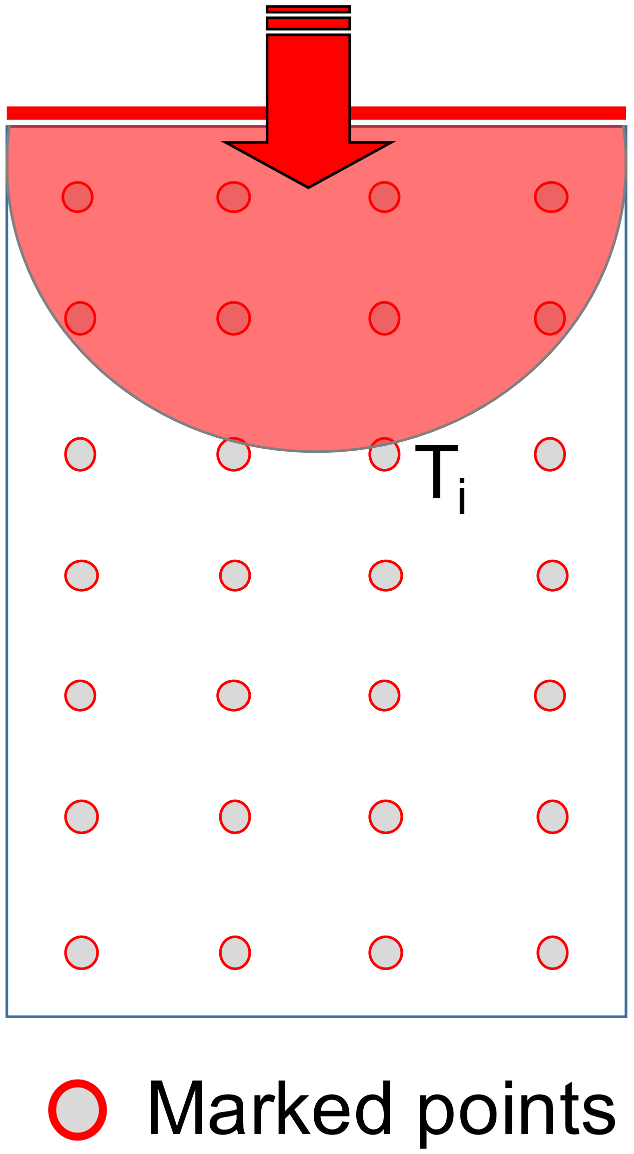
Flame length is the distance from the **average flame tip** to the **middle of the flaming zone** at the base of the fire.

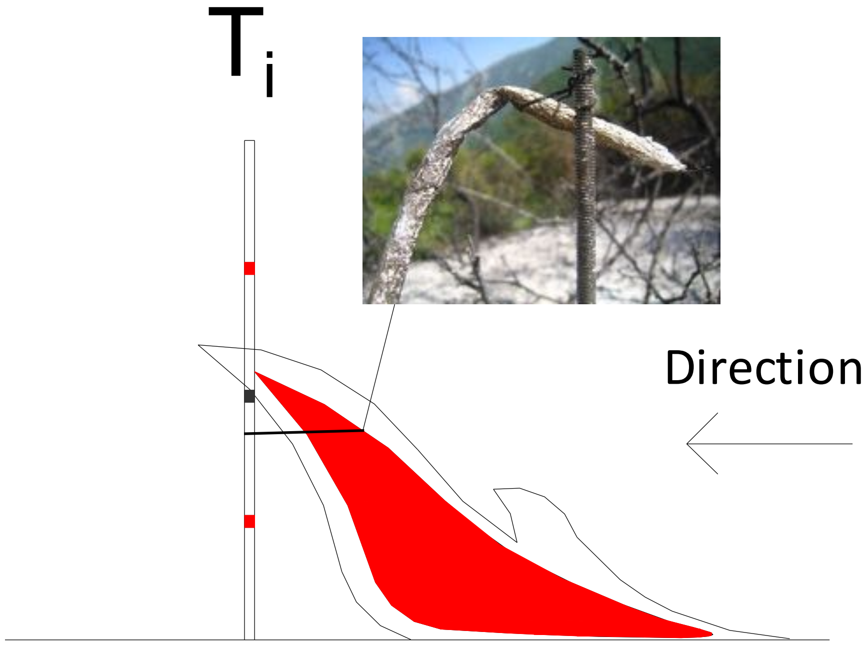
Rate of spread: visual estimate

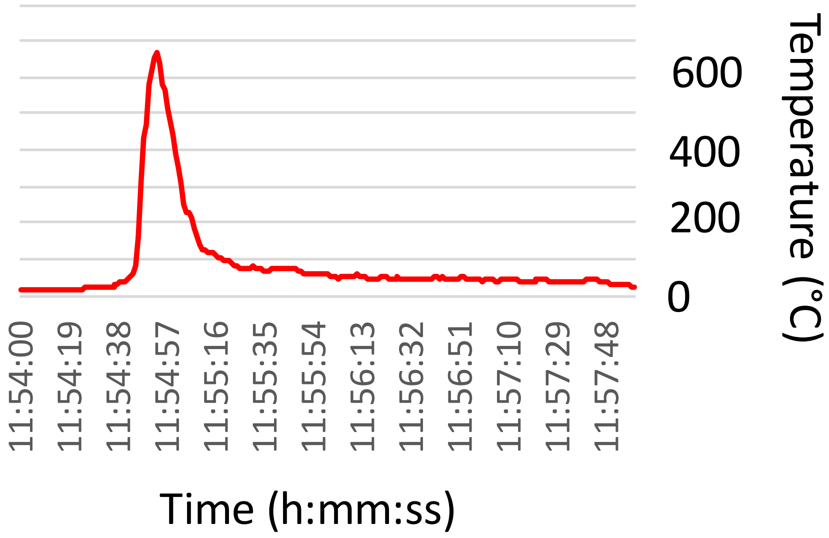




Rate of spread: thermocouples







Temperature and heat flux

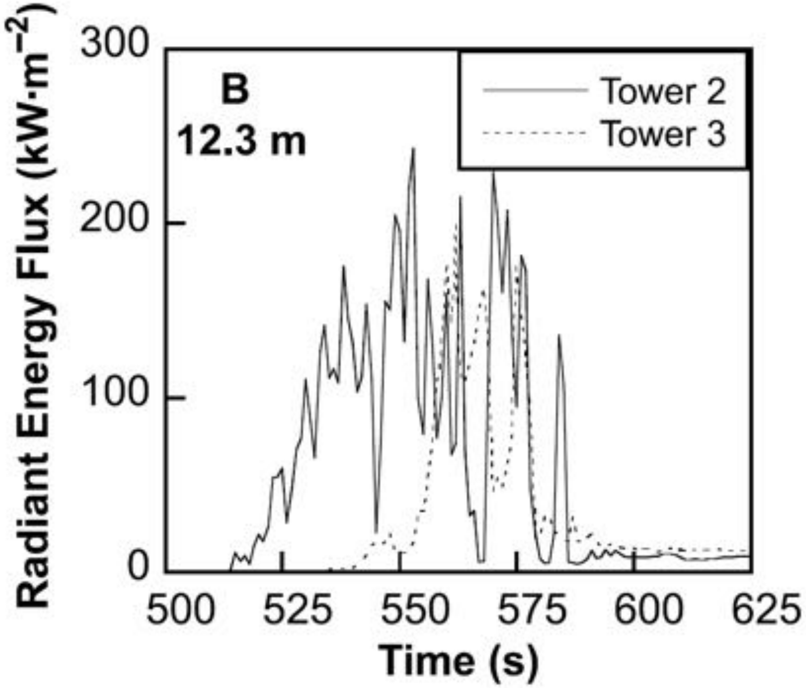
Heat flux-meter

Thermocouple

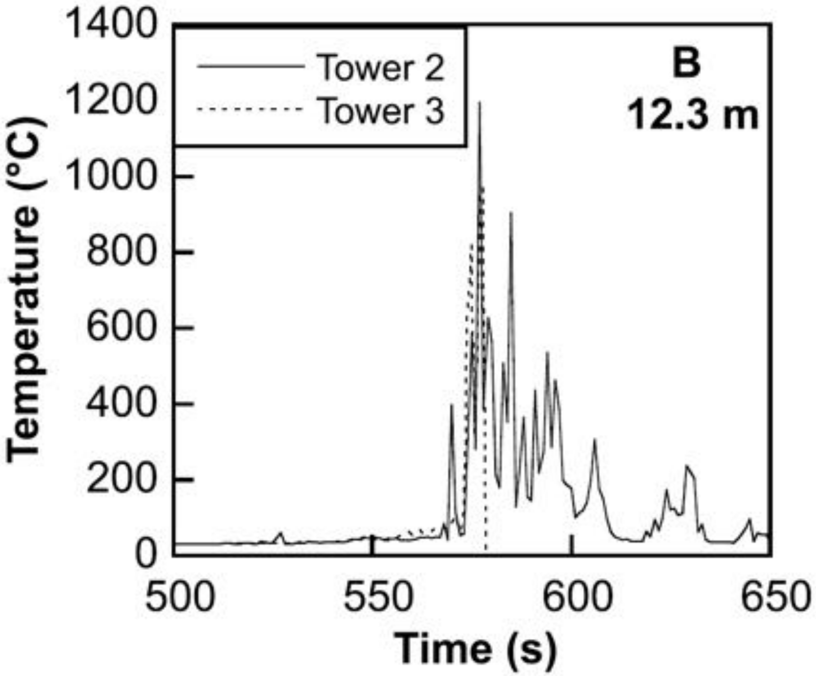
Data-logger

Source: Frédéric Morandini et Xavier Silvani

Temperature and heat flux



Butler B.W. et al. 2004
Measurements of radiant emissive
power and temperatures in crown fires
Canadian Journal of Forest Research
34(8): 1577-1587



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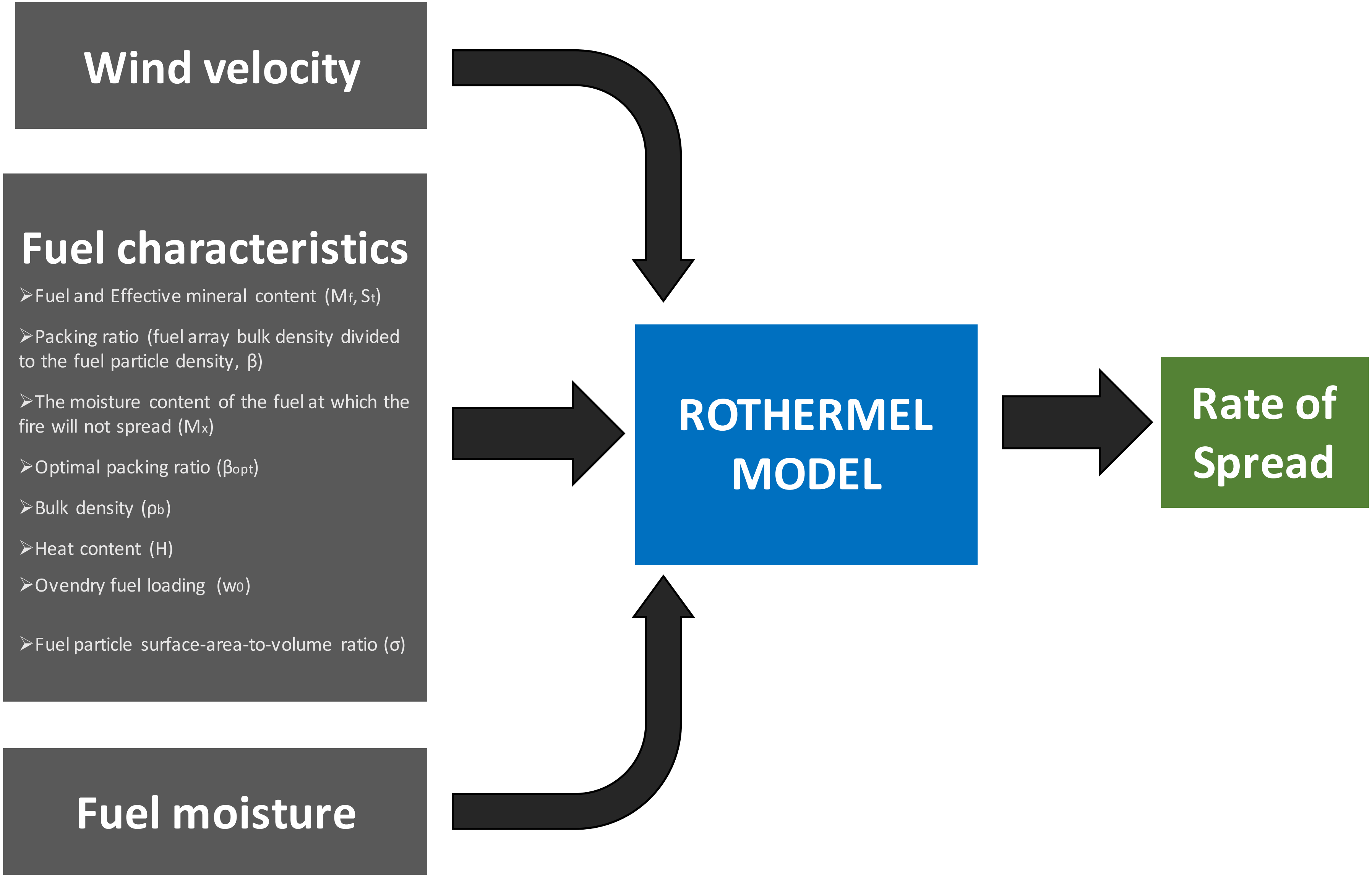
Rothermel model



Wind velocity

Fuel characteristics

- Fuel and Effective mineral content (M_f, S_t)
- Packing ratio (fuel array bulk density divided to the fuel particle density, β)
- The moisture content of the fuel at which the fire will not spread (M_x)
- Optimal packing ratio (β_{opt})
- Bulk density (ρ_b)
- Heat content (H)
- Ovendry fuel loading (w_0)
- Fuel particle surface-area-to-volume ratio (σ)

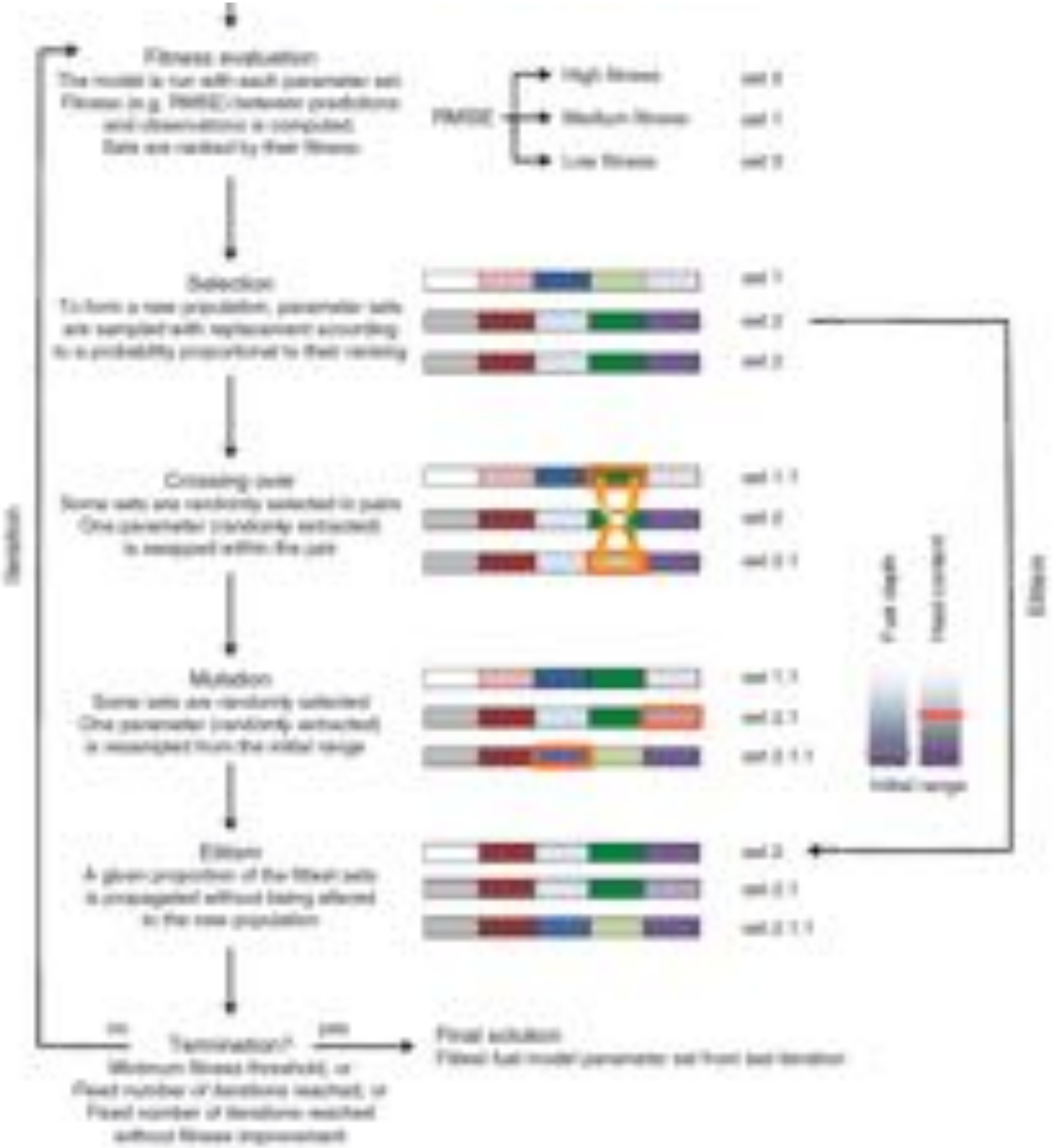
Fuel moisture

ROTHERMEL MODEL

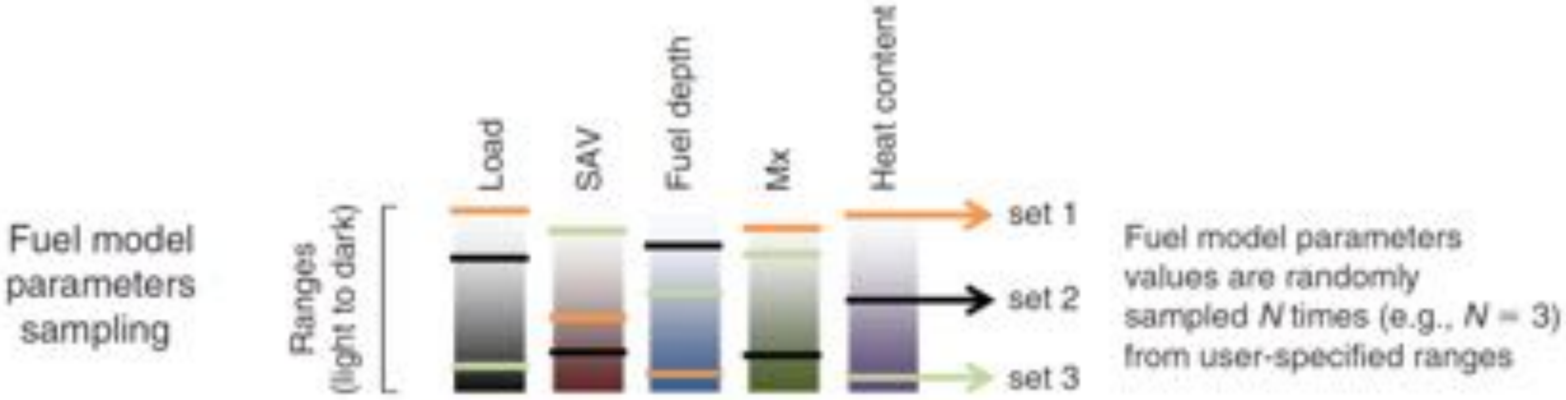
Rate of Spread

Genetic algorithm

Initial population



GA for fuel model



Fuel model parameters values are randomly sampled *N* times (e.g., *N* = 3) from user-specified ranges

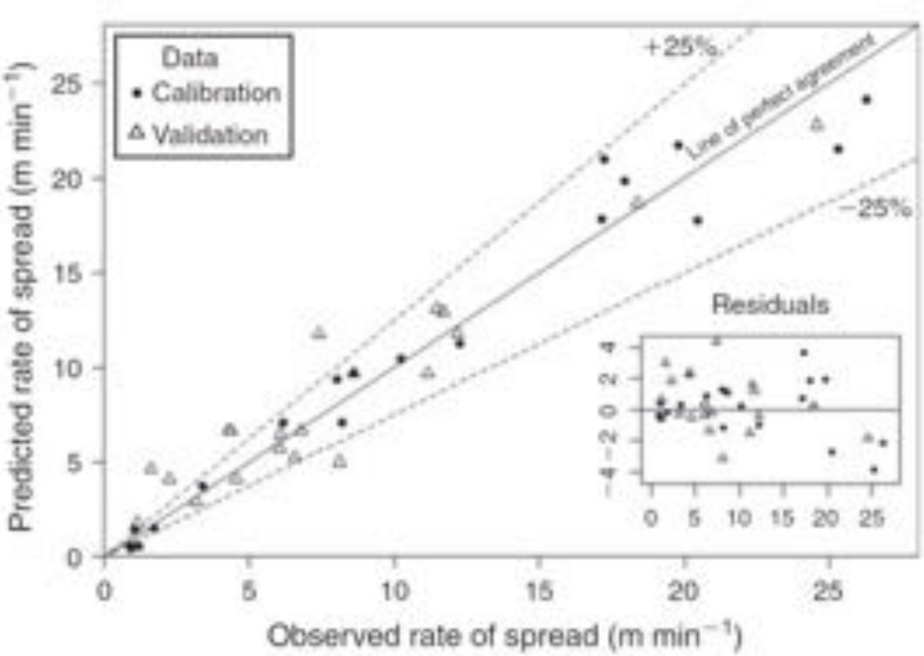
Rate of spread

Input ranges

GA MODEL

Fuel input

Results


Data
● Calibration
△ Validation
+25%
Line of perfect agreement
−25%
Residuals
Predicted rate of spread (m min^{-1})
Observed rate of spread (m min^{-1})
0
5
10
15
20
25
−4
−2
0
2
4

Results

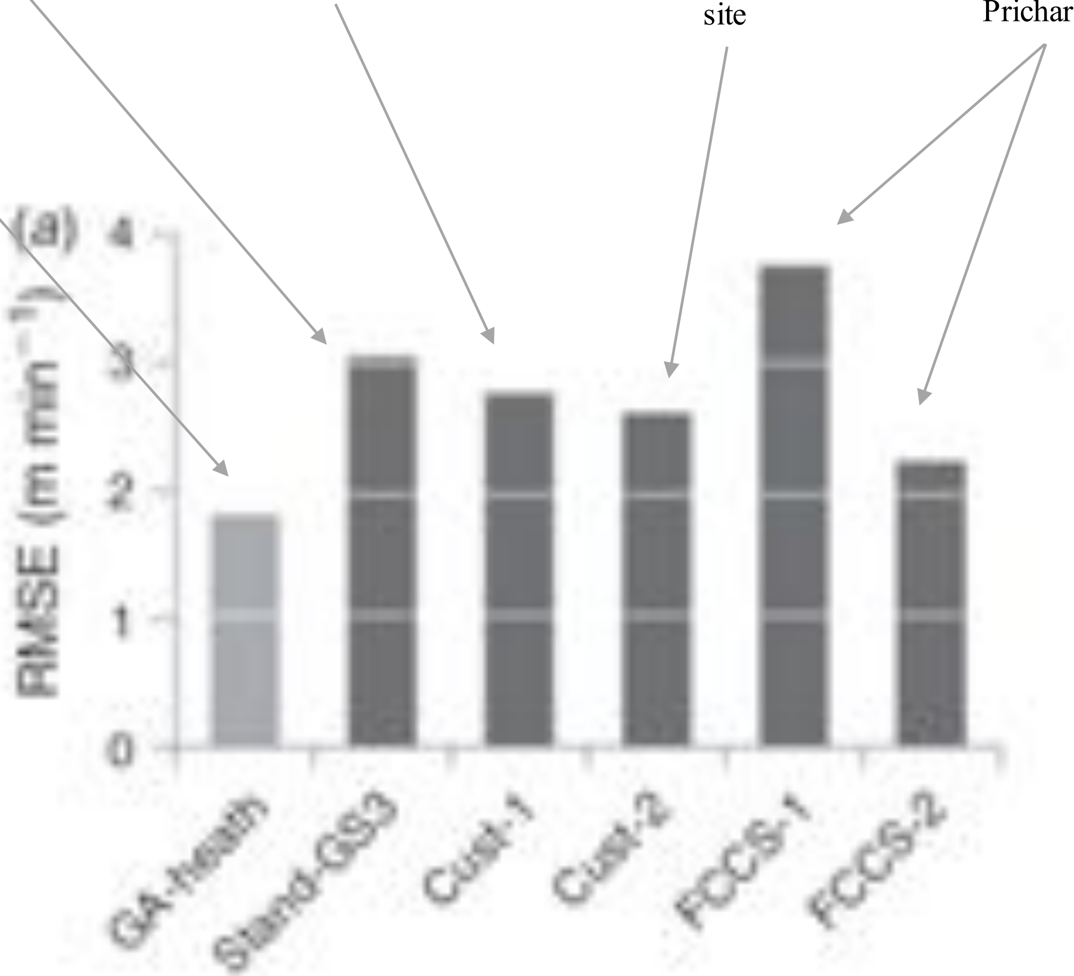
Rothermel calibrated using GA optimisation

Standard Rothermel fuel model

custom fuel model parameterised by averaging fuel characteristics

Site-specific custom fuel model parameterised by averaging fuel loadings and structure measured at each fire site

Rothermel model reformulation that is implemented in the Fuel Characteristics Classification System (Sandberg *et al.* 2007; Prichard *et al.* 2013).



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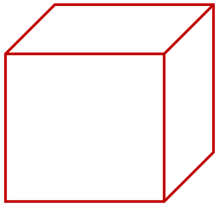
1D physical model



ENERGY AND MASS CONSERVATION EQUATION APPLIED TO A CONTROL VOLUME

$$\rho c\frac{\partial T}{\partial t}+k_v v\frac{\partial T}{\partial x}=k\frac{\partial^2 T}{\partial x^2}-h(T-T_e)-\frac{H}{s}\frac{dM}{dt}+\Phi_{RAD}$$

$$\frac{dM}{dt}=-aM$$

$$\Phi_{RAD}=\sum_j rF_{ij}\varepsilon\sigma\left(T_j^4-T^4\right)$$

Symbol	Explanation	Evaluation
P	Mixture air fuel density	Laboratory Analysis
C	Specific heat	(Campbell, Norman 2012)
k_v	Advective coefficient	GA using Thermocouple Measurements
K	Diffusive coefficient	GA using Thermocouple Measurements
h	Losses coefficient	GA using Thermocouple Measurements
H	Energy content	Laboratory Analysis
S	Fuel height	Field Analysis
A	Mass rate variation coefficient	GA using Thermocouple Measurements
R	Radiative coefficient	GA using Thermocouple Measurements

Experimental data

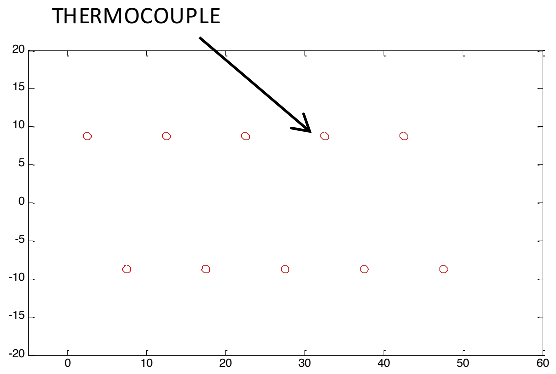
- 4 Field experiment are carried out in different wind conditions

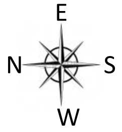
- Dead fully cured grasses (diameter< 6 mm). From laboratory and field analysis:

- Load 0,43 kg/m2
- Height 10 cm
- Packing Ratio 0,002
- Burned biomass 0,39 kg/m2
- Bulk density 5 kg/m3
- Heat power of fuel 18,5 MJ/kg
- Humidity 11% of dry fraction

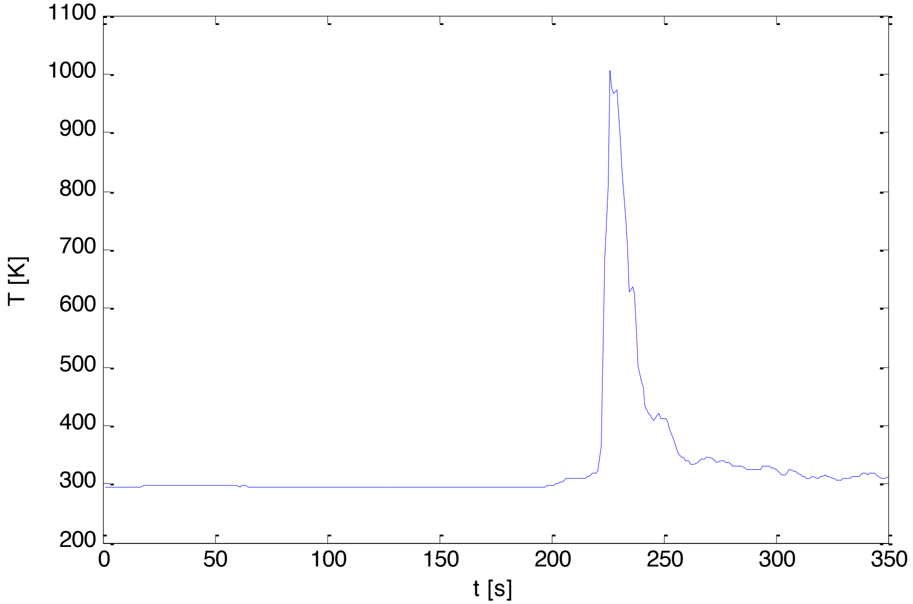
- Wind velocity and direction data are collected every 10 s

- Thermocouples detect temperature evolution during each experiment





Model calibration through experimental data



$$Err = w_1 * Err_{maxT} + w_2 * Err_{integral} + w_3 * Err_{arrive} + w_4 * Err_{burning}$$

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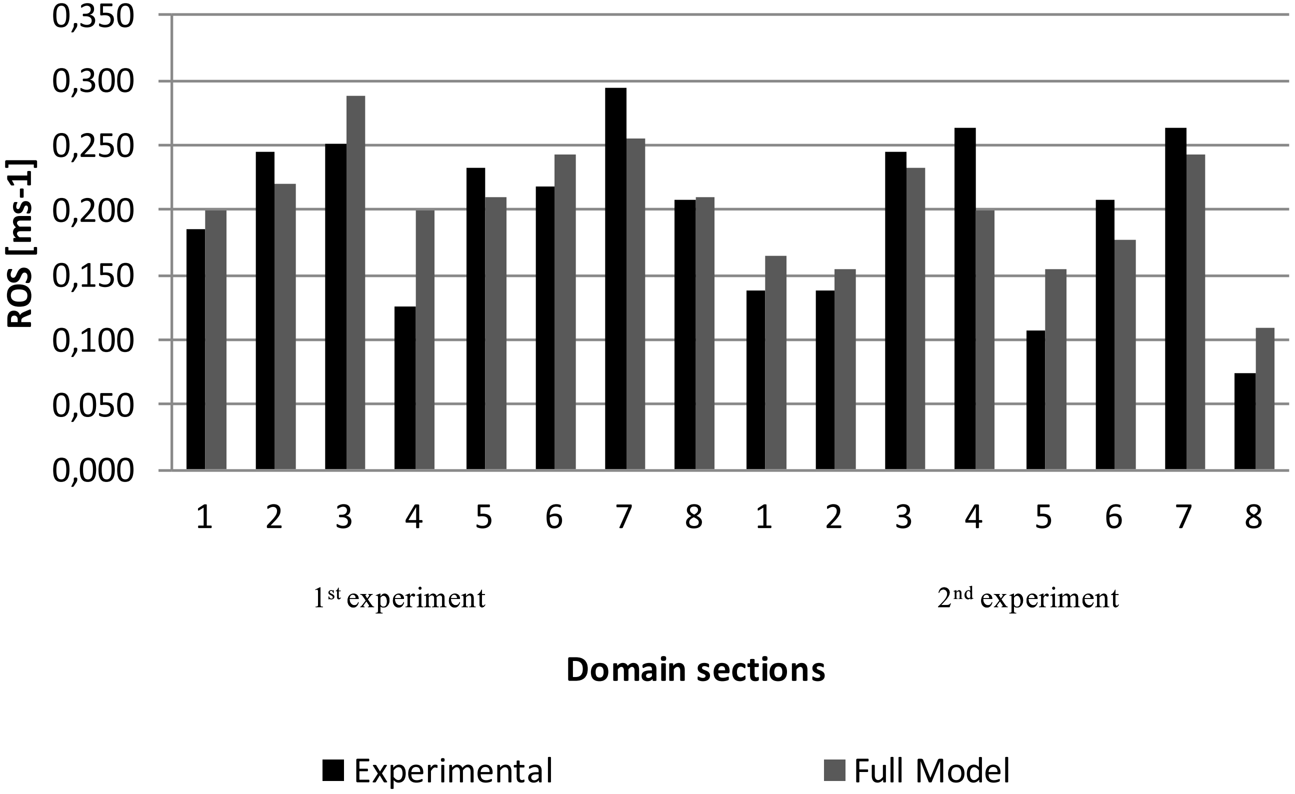

Thank you for the attention

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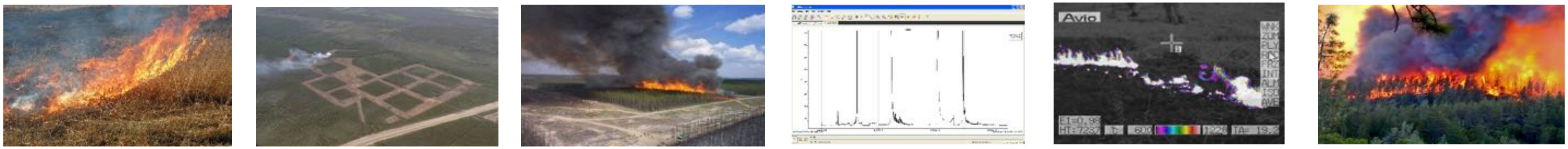
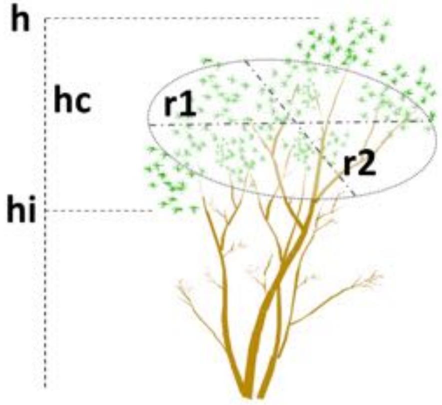
Vittorio Verda (Politecnico di Torino – Dip. Energia)



What to measure?

Fire environment

- Fuel structural characteristics: direct-indirect
- Fuel moisture: direct-indirect (eg fire danger index)
- Wind field (direction, speed)
- Air temperature – relative humidity
- Orography (slope, aspect, elevation)

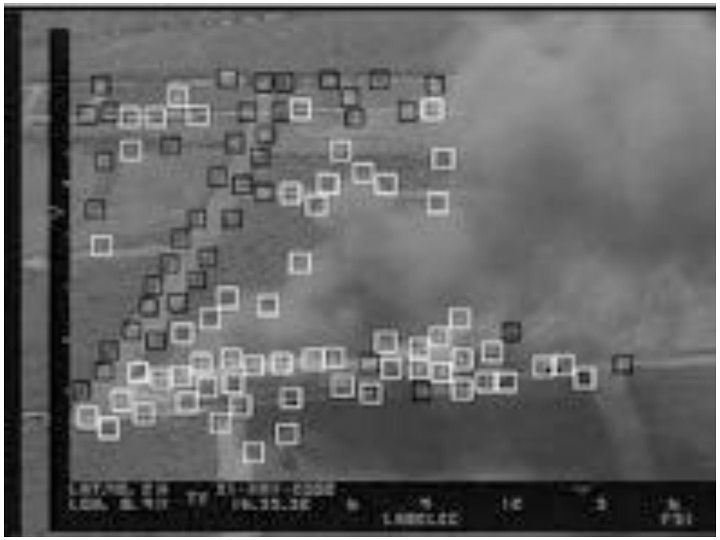


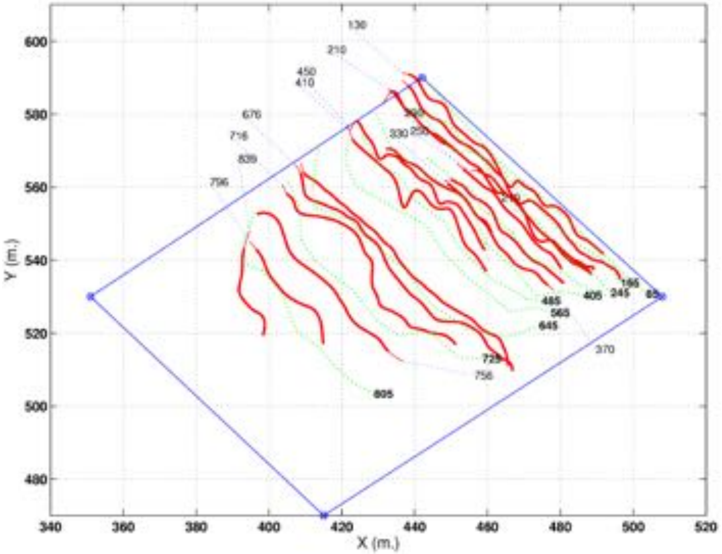
Rate of spread: photos

Exp. 7 – M1.3

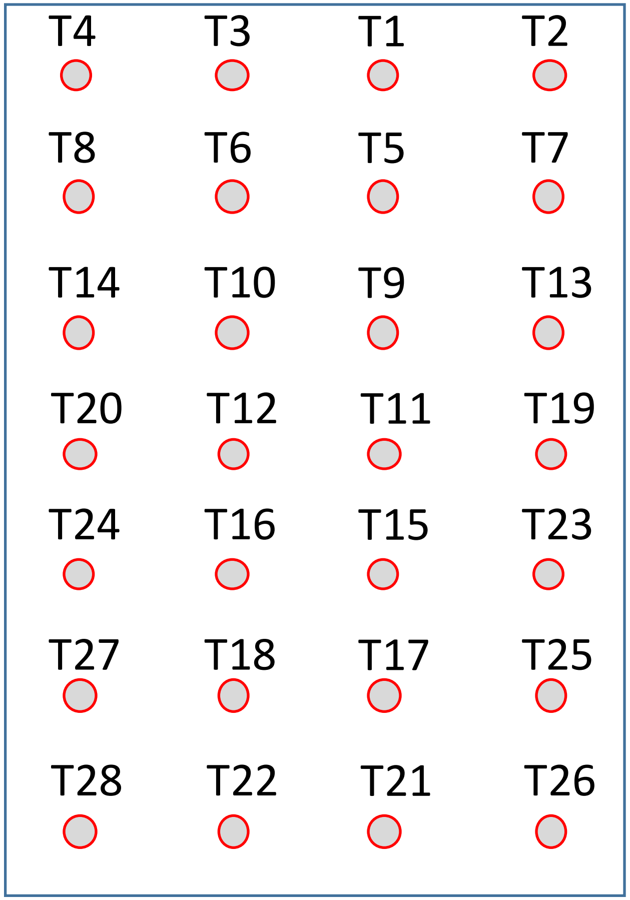
Rate of spread: IR techniques

Martinez-de-Dios et al. 2011



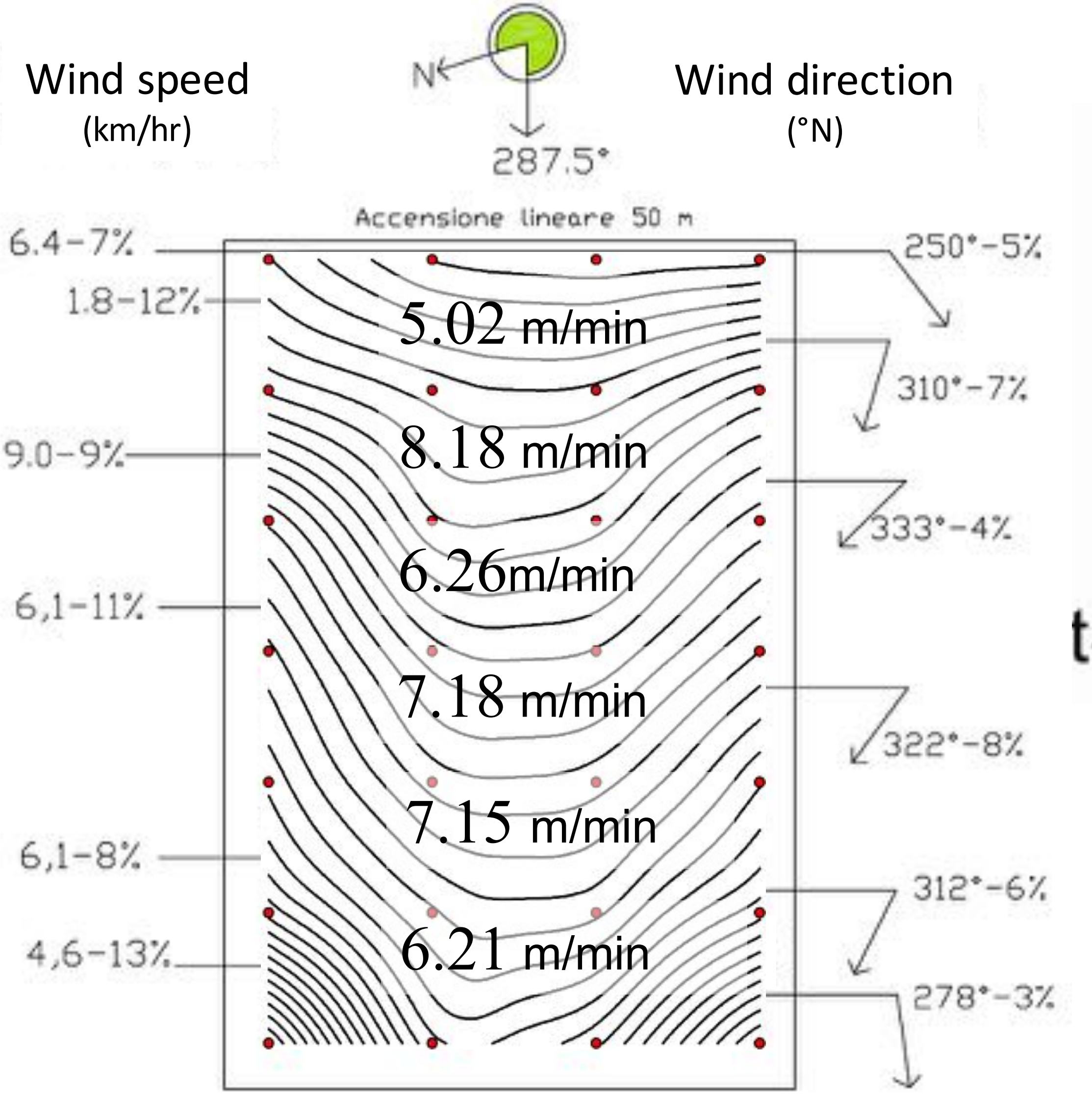


Rate of spread



T4	T3	T1	T2
T8	T6	T5	T7
T14	T10	T9	T13
T20	T12	T11	T19
T24	T16	T15	T23
T27	T18	T17	T25
T28	T22	T21	T26

Rate of spread


Wind speed (km/hr)

Wind direction (°N)

5.02 m/min

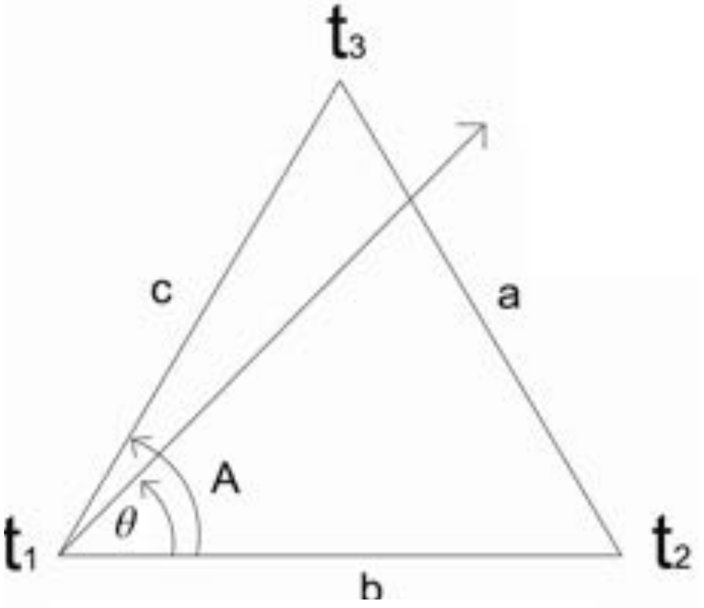
8.18 m/min

6.26m/min

7.18 m/min

7.15 m/min

6.21 m/min



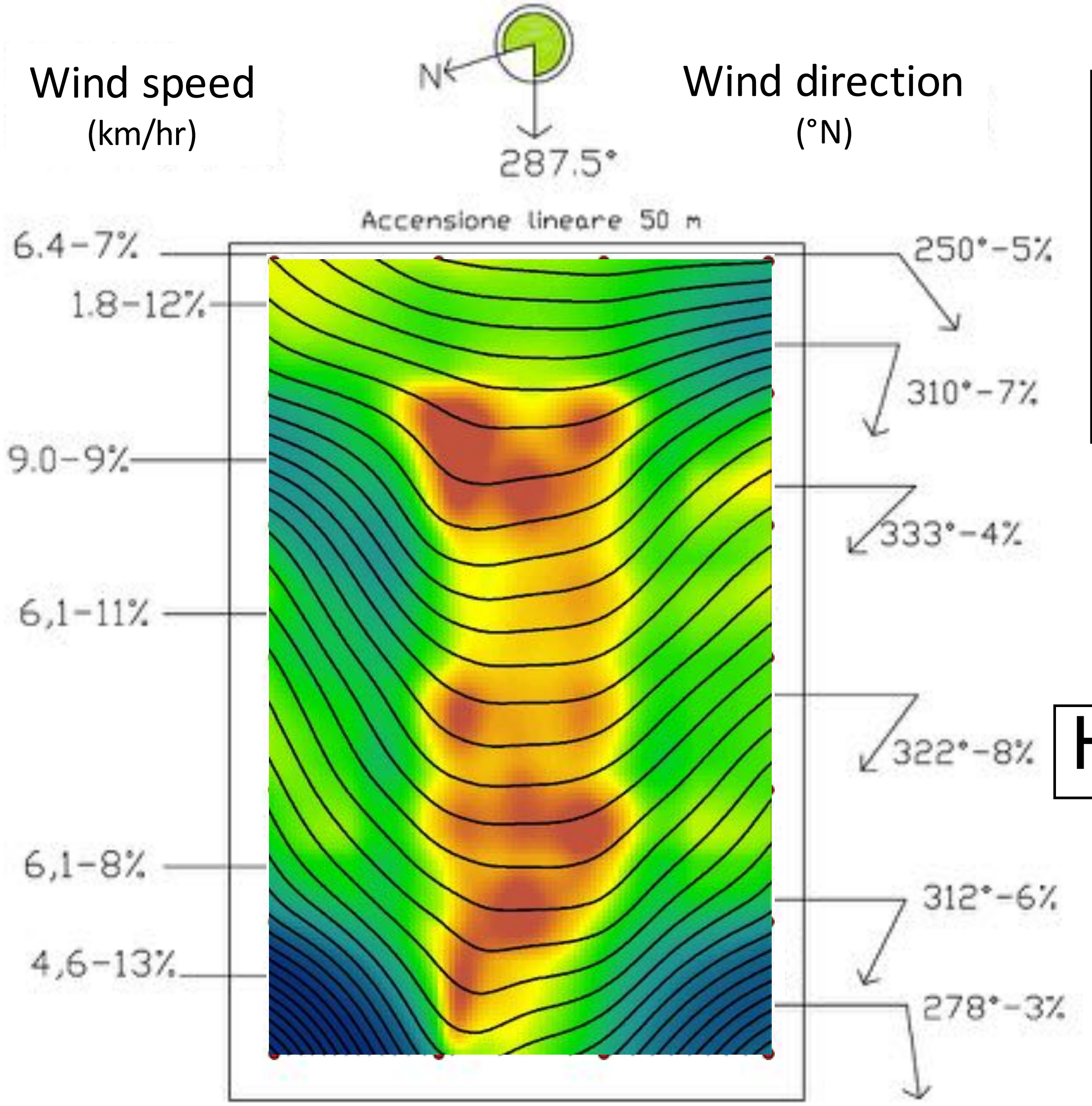
Fire Front Direction

$$\Theta = \tan^{-1}\left[\left(\frac{t_3-t_1}{t_2-t_1}\right)\left(\frac{b}{c\sin A}\right)-\frac{1}{\tan A}\right]$$

Fire Rate of Spread

$$V=\frac{b\cos\theta}{t_2-t_1}$$

Fireline intensity



Fuel samples

PRE - POST = W (kg m $^{-2}$)

W = fuel comsumed

X

ROS (m s^{-1})

X

H = 18*10^3 kj kg^{-1} heat content

$I_{(kW\,m^{-1})}$ = ROS x W x H

Byram (1959)