

Modeling the spreading of large-scale wildland fires

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Team: Fire dynamics

Simulation of forest fire Cargèse 13-17th

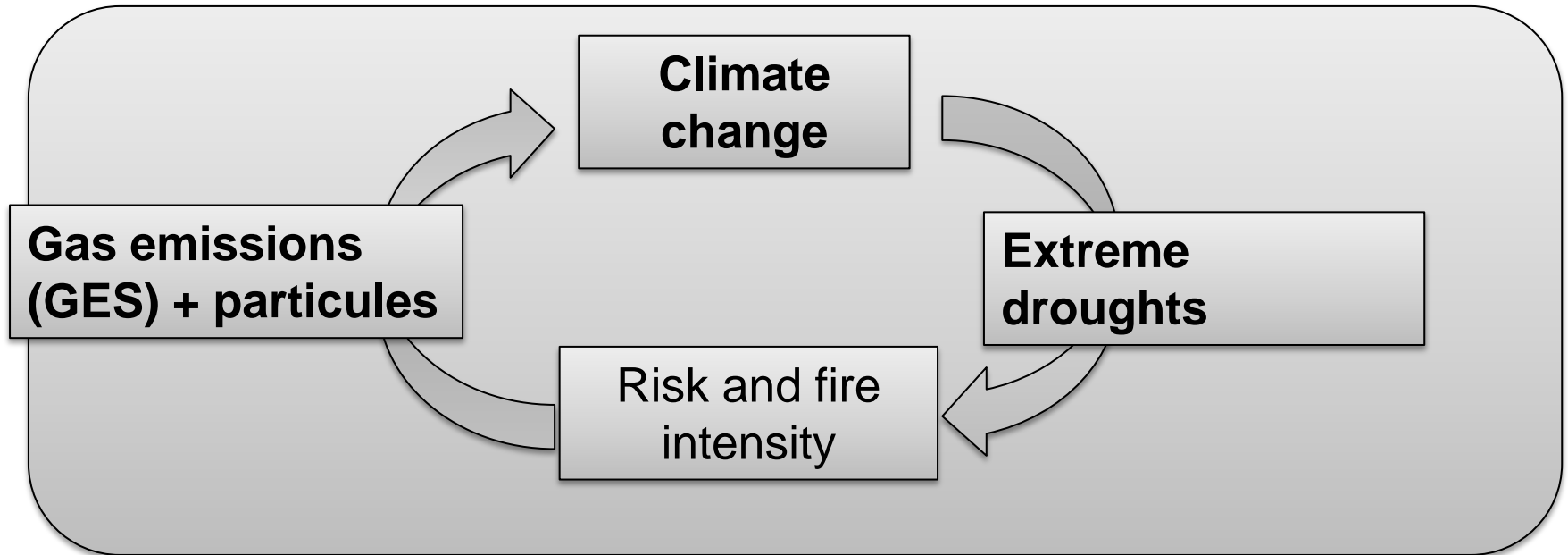
Summary

- ❖ **Background**
- ❖ **Presentation of the propagation model**
- ❖ **Some study cases**
- ❖ **Validation of the propagation model on prescribed burn and on a real fire**
- ❖ **Sensitivity study**
- ❖ **Conclusions and prospects**

- **Background**

Environmental and societal problem

Wildfires: an environmental problem



Environmental needs:

Evaluation of emissions → Estimation of masses and surfaces burned

Satellite measurements (ex: MODIS 1km×1km) → uncertainties of ±50%

- Development of propagation models
- Experiments (real fires, prescribed burns)

Environmental and societal problem

Forest fires: a societal problem with the multiplication of peri-urban interfaces

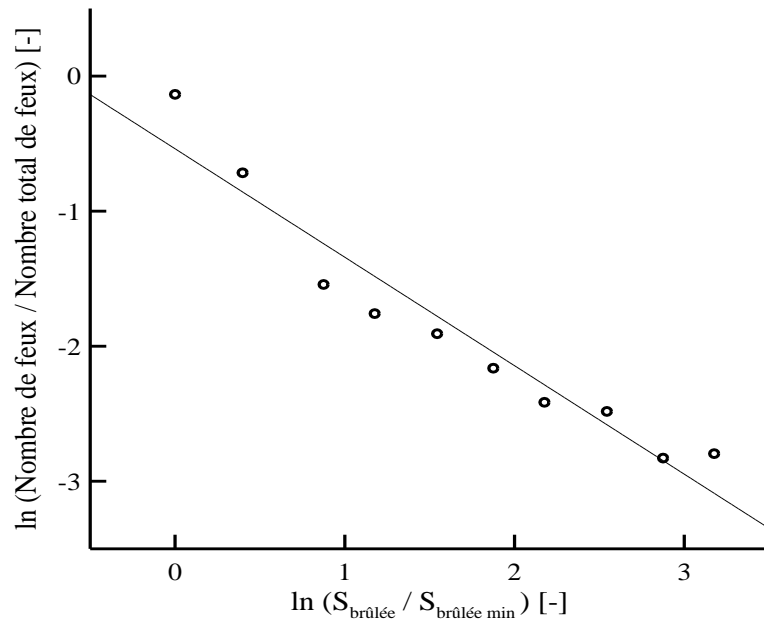


Needs:

- Improve prevention through better fire risk assessment
- Good decision support in crisis phase by efficient sizing and positioning of fighting tools.
 - Development of propagation models
 - Experiments (real fires, prescribed burns)

Two observations

First one: the distribution of the number of fires vs. burned area follows a power law called **Pareto law**:
« a fire of large amplitude is relatively rare, while conversely, a small-scale fire is likely to occur ».



$$Prob(X > x) = \left(\frac{x}{x_{min}} \right)^{-k}$$

Feux PACA:

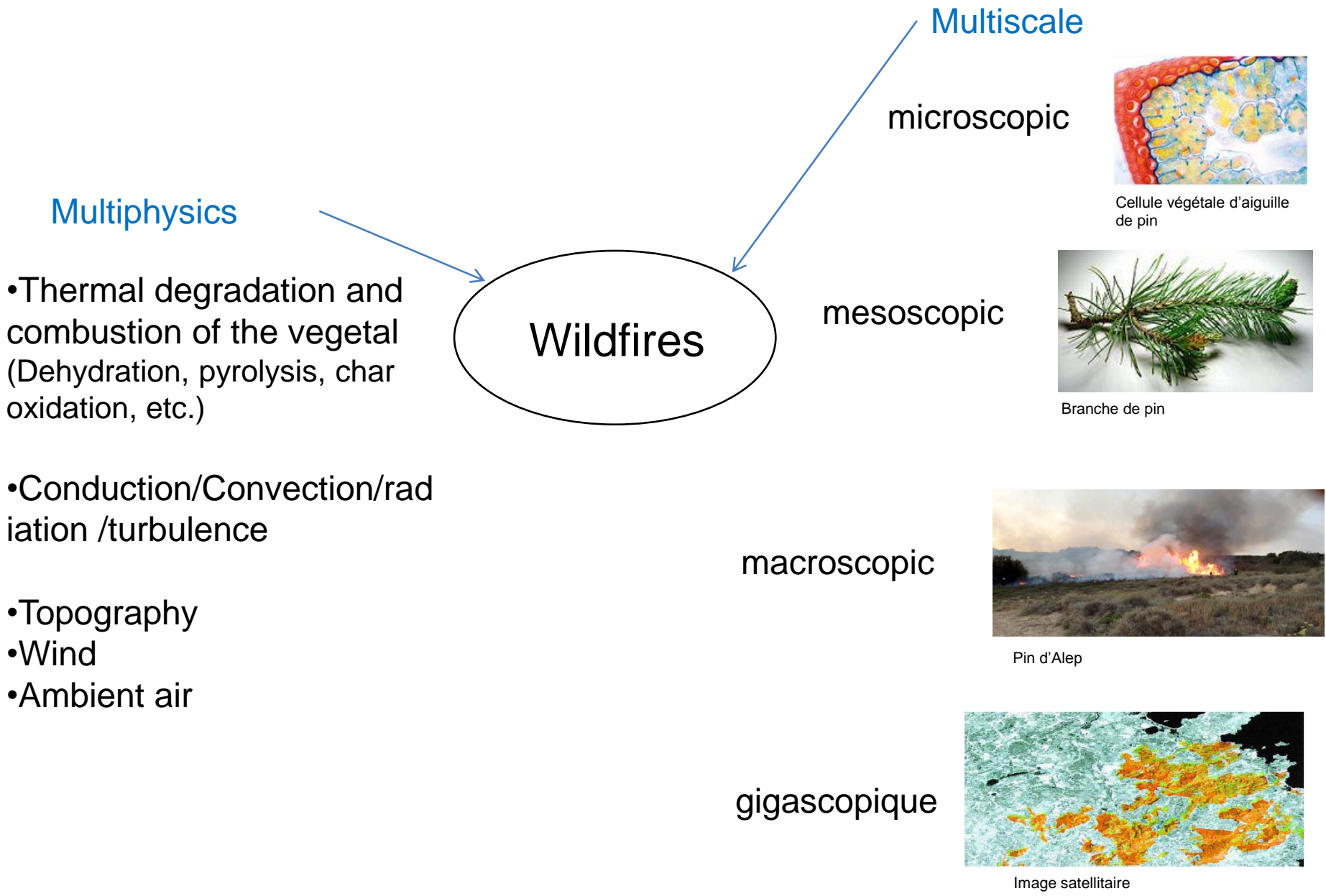
$$x_{min} \approx 1 \text{ ha} ; k \approx 0.833$$

Canada 1959-1997: 3% of fires account for 90% of burnt areas

Corsica 2003-2009: 1% -----84%-----

→ Need to focus on the major forest fires (large scale)

Wildfire: a multiphysics and multiscale phenomenon



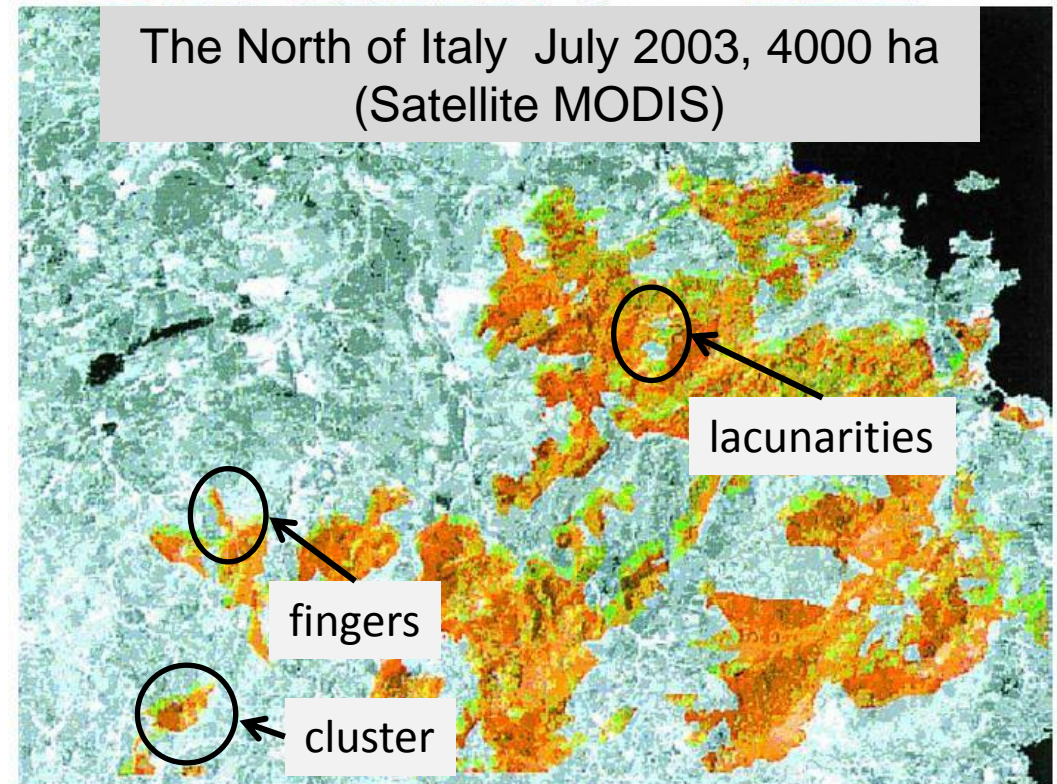
Second observation: Fractal behavior of large fires.

At this scale, the fire shows a **fractal behavior**

due to local heterogeneities
(Wind, topography,
vegetation)



Stochastic modeling of the erratic behavior of large fires



Burned surface: $D_f \approx 1.8$

- **Presentation of the propagation model**

Network construction



Homogeneous and uniform
vegetation

Monodisperse network based
structure : square or hexagonal.



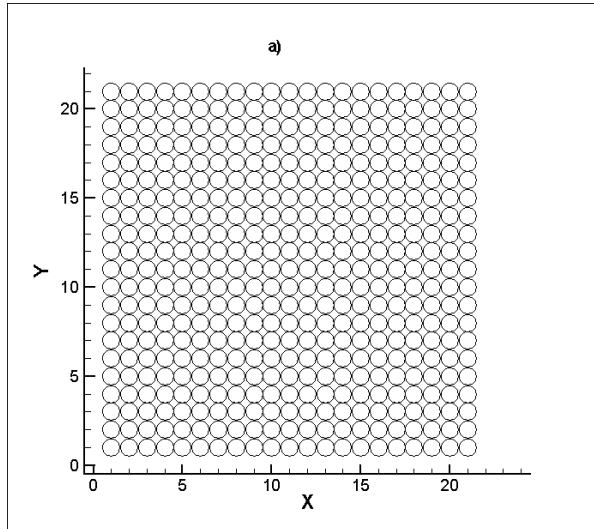
Sparse vegetation + random distribution

Polydisperse amorphous network with a
predefined filling ratio.



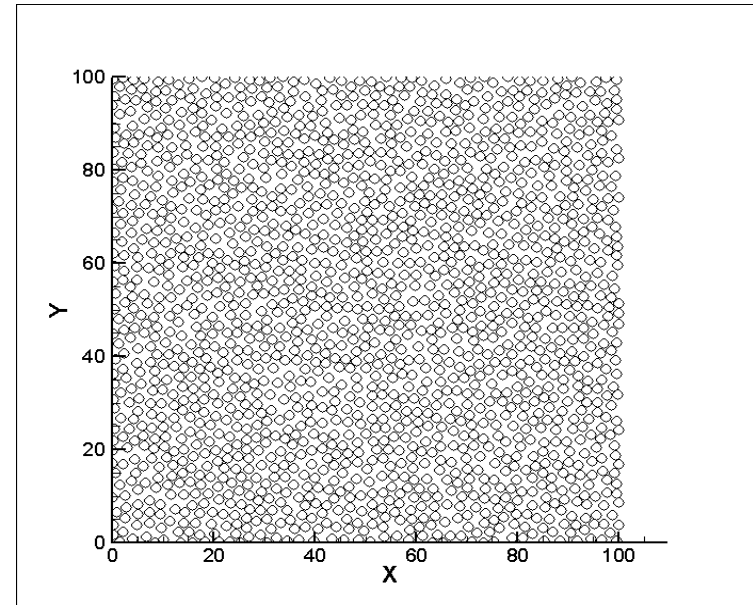
Methods for generating non-overlapping sites

✓ Underlying structure: square or hexagonal



- ➔ limited to monodisperse networks or polydisperse networks weakly doped
- ➔ unrepresentative of the real vegetation

✓ The « fly » generation

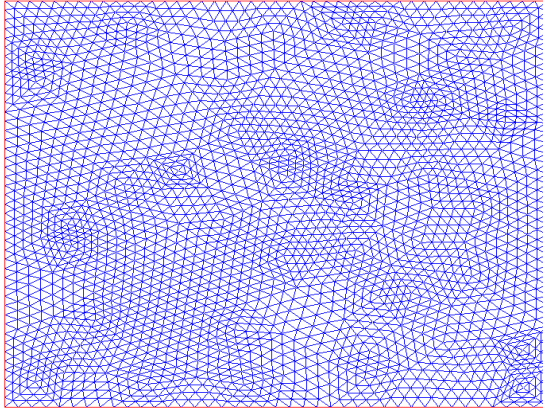


Monodisperse doped amorphous network to 56%.

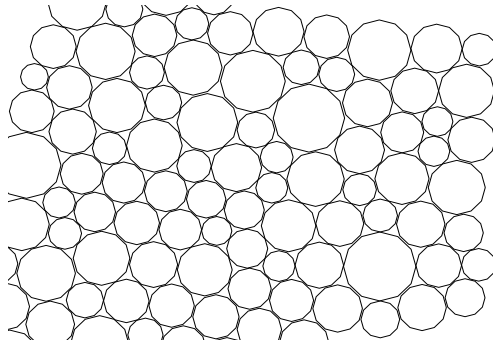
- ➔ difficult to achieve high filling rate (max. 0.56 in monodisperse case)

Network construction

- ✓ Minimisation of functional

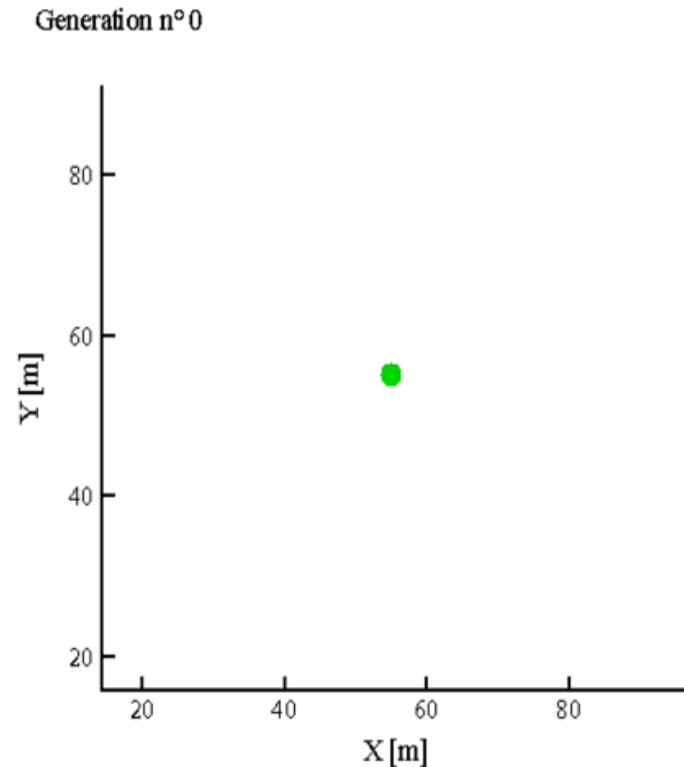


Unstructured triangular Delaunay mesh .



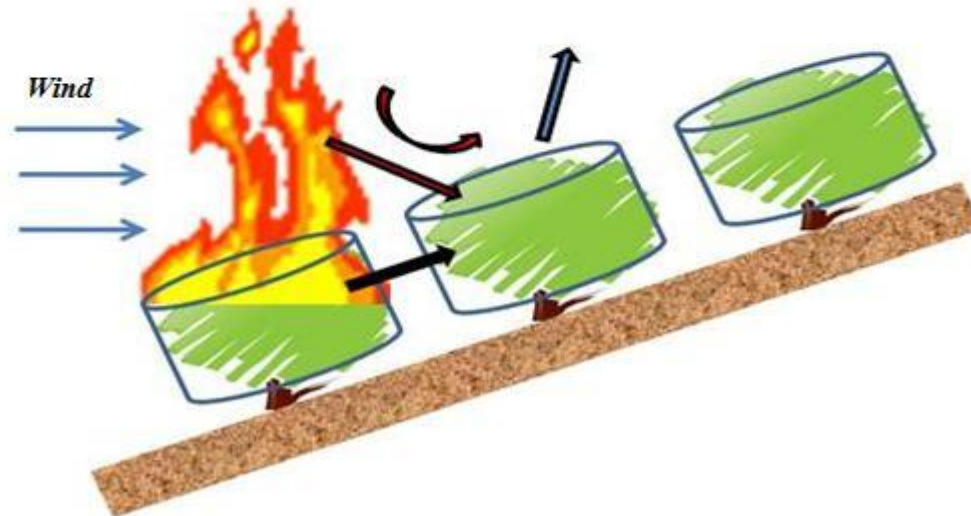
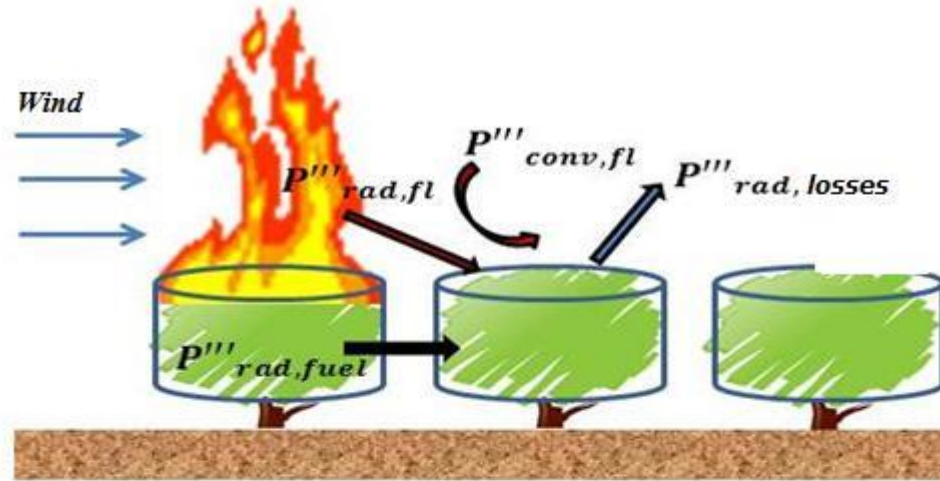
→ difficulty to control the randomness and the polydispersity

- ✓ Genetic algorithm
Selection criterion based on the distance to six nearest neighbors



→ good control of randomness and polydispersity
→ High CPU

Macroscopic model of combustion



- The fine particles (typically <0.6 cm) spread flames fire.
- Thick elements are involved in the combustion (usually flameless) behind the front.

Flame radiation model

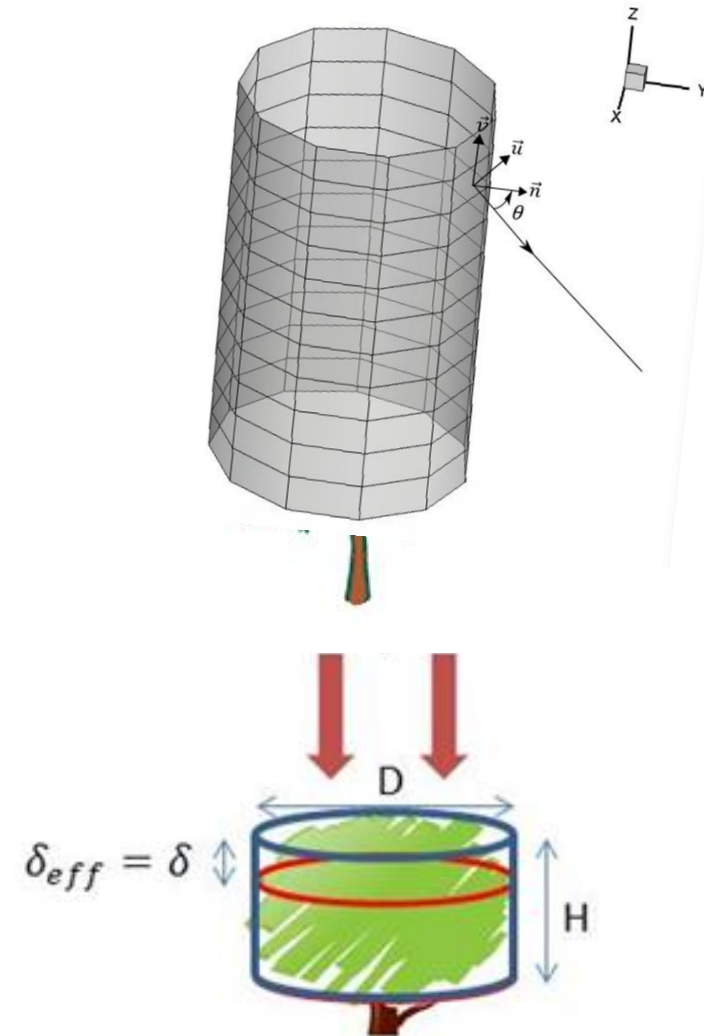
Flame radiation model = Solid flame model + Monte Carlo method

Solid flame model:

- flame = solid body of simple geometry
- Radiation emitted by the surface

Stochastic Monte Carlo method

- Emitting N quanta from each surface element of the flame (m^2),
- Each quantum has a power q
- The emission direction is randomly generated but according to a probability law that respects macroscopic radiation emission law by a surface
- Power received by the target : $n \times q$



$$\delta_{eff} = \min(H, \delta) \text{ with } \delta = 4/\sigma_k \alpha_k$$

Determination of geometrical and thermo-physical properties of a flame of vegetation



Power released by the flaming combustion of pyrolysis products

$$\dot{Q} = \frac{m_{pyr} \Delta h_c}{t_c}$$

Fraction lost by convection in the plume

Radiated fraction $\chi_r \dot{Q}$

Emissive power of the flame :

$$P''_{fl} = \frac{\chi_r \dot{Q}}{S_{fl}}$$

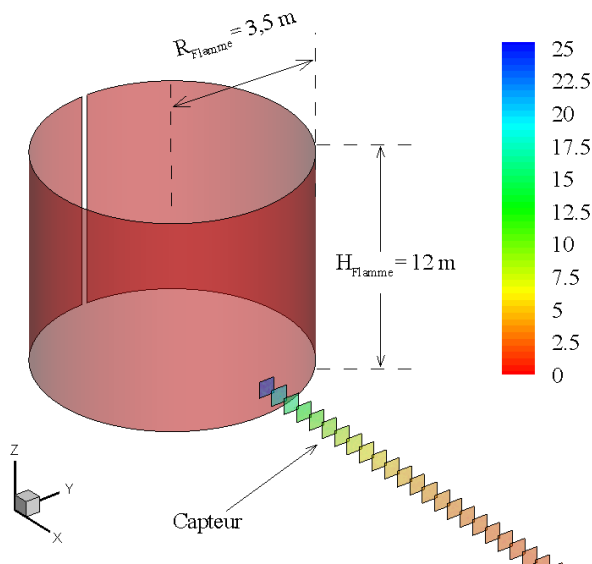
Geometric properties of the flame

- Flame height without wind $H_{fl0} = 0.0148 \dot{Q}^{2/5} - 1.02D$ (Heskestad)
- Flame height with wind $H_{fl} = H_{fl0} (1 + 4Fr_{H_{fl0}}^2)^{-0.5}$ (Putnam)
- Tilt angle due to wind $\tan \alpha = 1.22 Fr_{H_{fl}}$ (Albini)
- Flame length $L_{fl} \propto Fr_D^{-0,11}$ (Thomas et al. , Nmira)

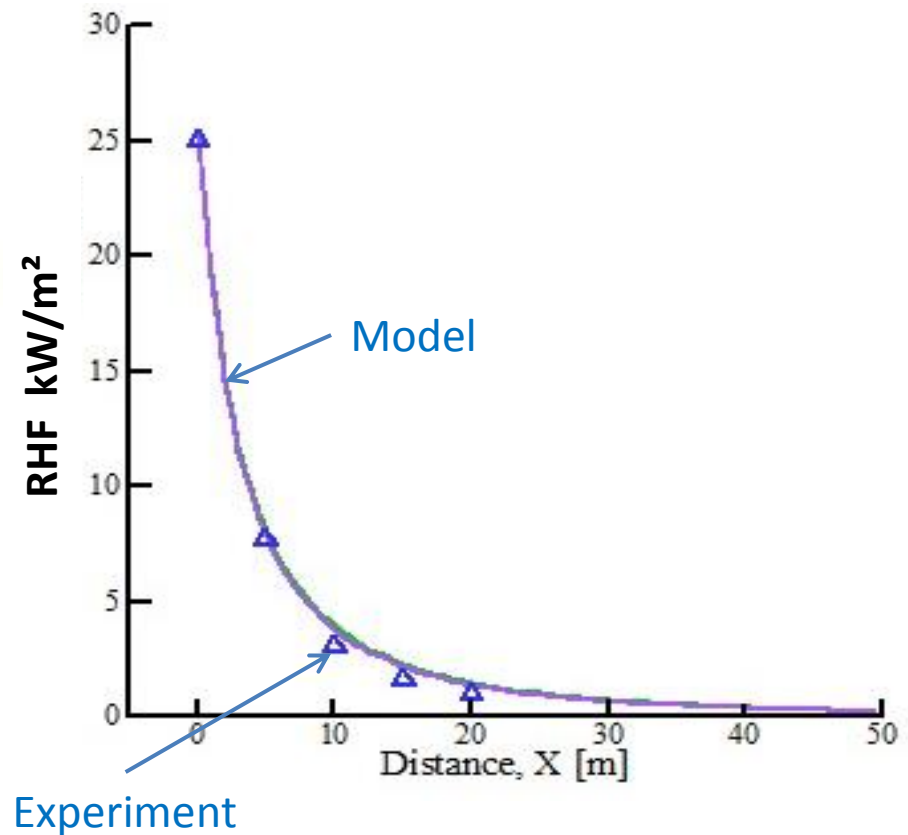
$$\rightarrow L_{fl} \sim H_{fl0}$$

Flame radiation (Y. Billaud, 2011)

Model validation SFM + MCM on a large ethanol flame (12m high, 7m diameter)



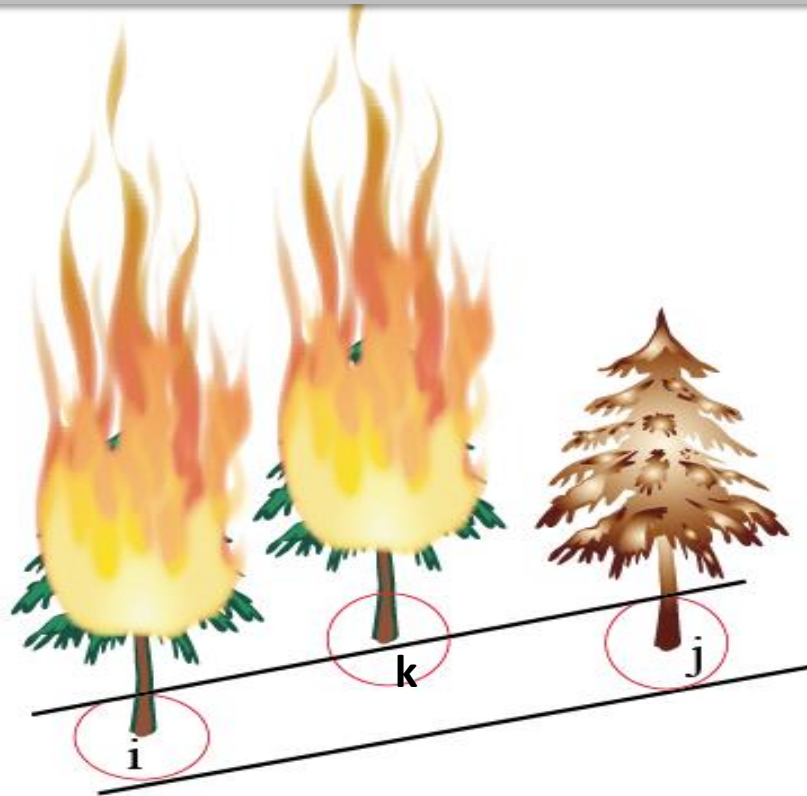
Radiative flux received by a sensor as a function of the distance from the flame



Radiation model

Screen effect

In the presence of a site k in fire between the fire site i and a virgin site j → j receives only a part of the radiation emitted by i



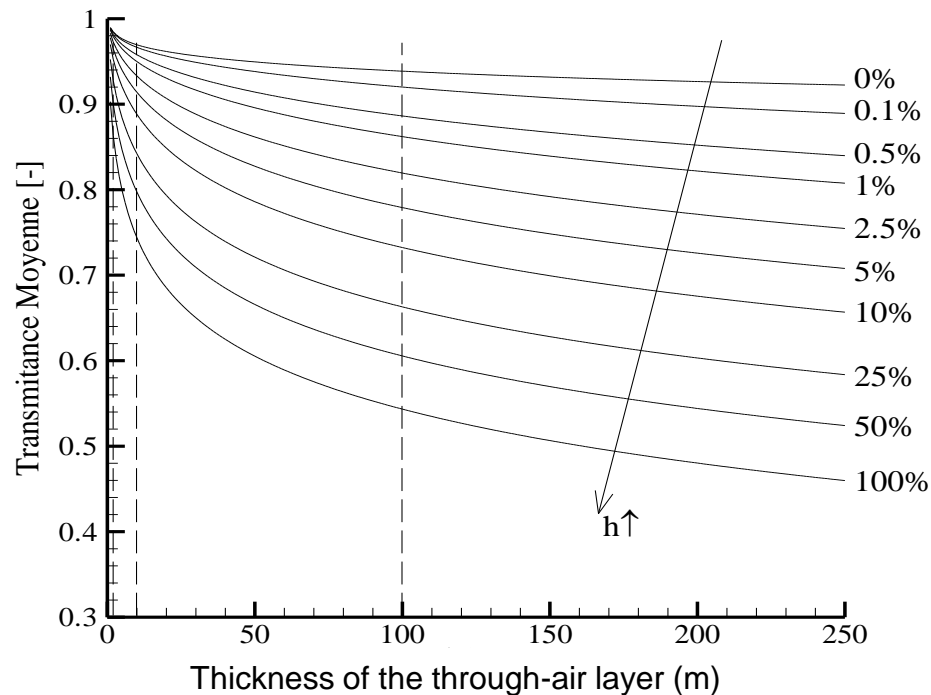
MCM : A quantum emitted by the site i and which arrives in the area of the solid flame of the site k is lost and does not contribute to preheat the site j

Radiation model

Attenuation of the radiation by the layer of atmospheric air between a site in fire and a receptor site (coll. Y. Billaud et A. Collin)

SNB model (isothermal homogeneous medium, decorrelation of emission absorption spectra gaz)

→ The average Transmittance as a function of gaz transmittances (CO_2, O_2, CO, N_2, H_2O) of the air , and this for different RH.



Approximate law

$$\bar{\tau}_{approx} = a + bl^c$$

RH%	a	b	c
10	1,096	-0,120	0,241
25	1,213	-0,253	0,170
50	1,407	-0,467	0,118
100	1,792	-0,881	0,076

Convection and radiative losses (inspired from the model of Koo et al. (2005))

• Convective power received by the site exposed to fire

- Exponential decay with distance (characteristic distance $\sim 3L_{fl}$)

$$P'''_{conv} = \frac{h}{\delta_{eff}} (T_{fl} - T) \exp(-0.3 y/L_{fl})$$

h : mean coeff. of convection (flat plate)

T_{fl} : flame temperature

δ_{eff} : effective penetration depth of radiation

• Radiative power of embers

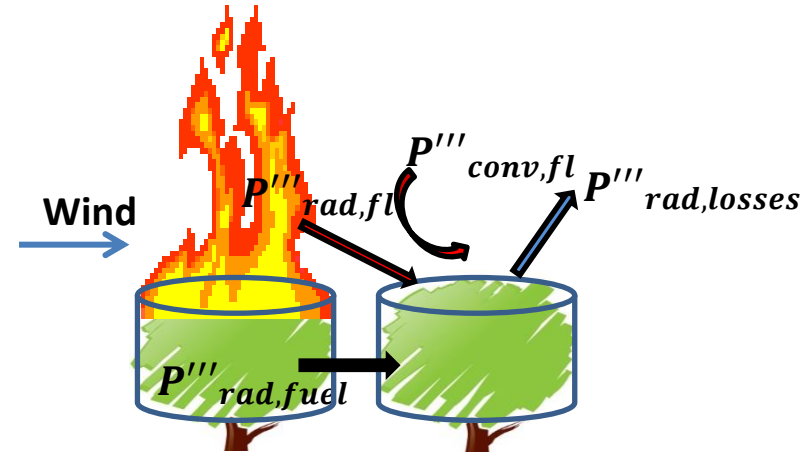
- Exponential decay with distance
- (characteristic distance $\sim \delta$)

$$P'''_{rad, fuel} = a_{fb} \sigma T_b^4 \exp\left(-\frac{y}{\delta}\right)$$

a_{fb} : absorptivity of the stratum

T_b : temperature of embers

δ : effective penetration depth



• Radiative losses of a site exposed to fire

$$P'''_{rad, losses} = \frac{\epsilon_{fb} \sigma (T^4 - T_{\infty}^4)}{\delta_{eff}}$$

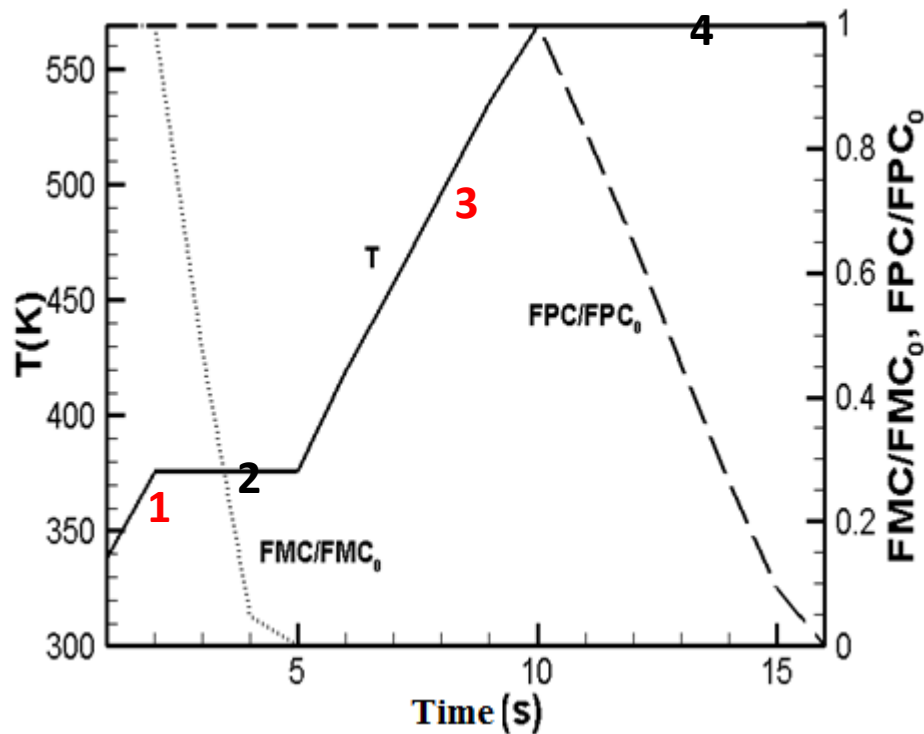
ϵ_{fb} : emissivity of the bed fuel

T : site temperature

Thermal degradation of a receptor site

Balance equation : a receptor site exposed to N sites in fire

$$\sum_{i=1}^N [P'''_{rad,fl}(i) + P'''_{rad,fuel}(i) + P'''_{conv}(i)] - P'''_{rad,losses} = \begin{cases} \rho_{WFF} c_{p,WFF} \alpha \frac{dT}{dt} & \text{if } T < T_{vap} \\ -\rho_{DFE} L_{vap} \alpha \frac{dFMC}{dt} & \text{if } T = T_{vap} \\ \rho_{DFE} c_{p,DFE} \alpha \frac{dT}{dt} & \text{if } T_{vap} < T < T_{pyr} \\ -\rho_{DFE} L_{pyr} \alpha \frac{dFPC}{dt} & \text{if } T = T_{pyr} \end{cases}$$



Phase 1: preheating of the wet fuel

Phase 2: dehydration of the fuel

Phase 3: preheating of the dry fuel

Phase 4: pyrolysis

Ignition criterion:

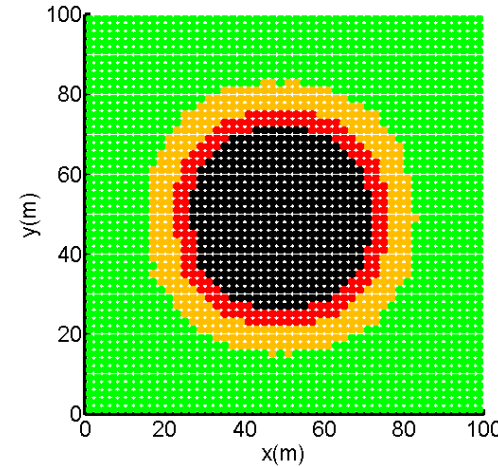
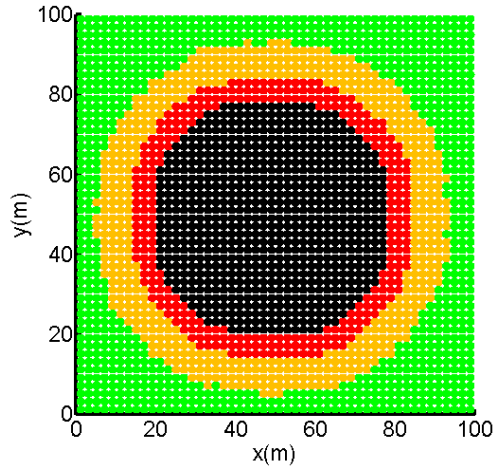
$T = T_{pyr}$ and $\dot{m}''_{pyr} > \dot{m}''_{cr,pyr}$
 (in thiswork: $\dot{m}''_{cr,pyr} = 0$)

Some case studies

Spread on a flat terrain without wind

Effect of RH ($p=100\%$)

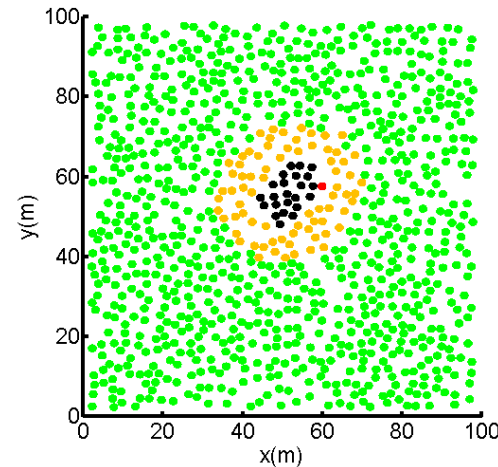
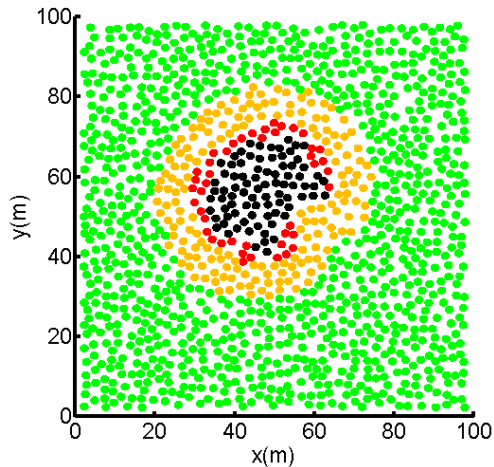
HR=25%



RH=100%

Effect of doping (RH=25%)

$p=40\%$

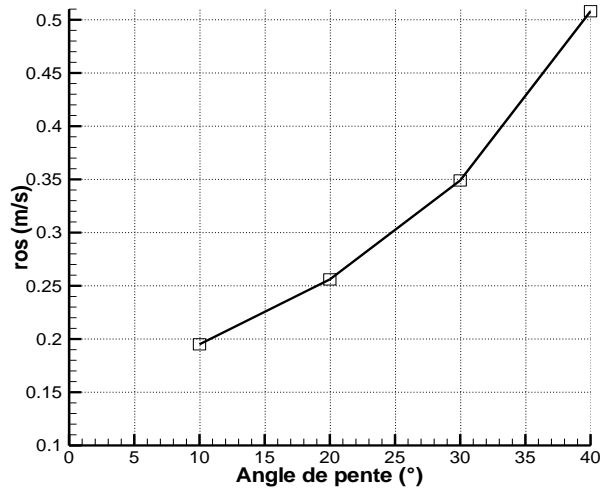


$p=30\%$



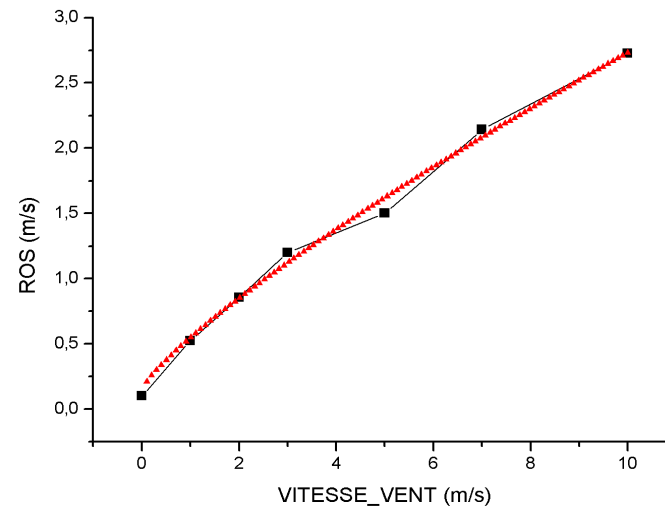
The fire stops
($p < p_c$)

Regular network+ without wind



→ Quadratic behavior
(Mendes-Lopes et al., 2003;
Tihay et al., 2012)

Regular network + a flat terrain



$$ros = 0.207 (1 + 0.082 U^{1.55})$$

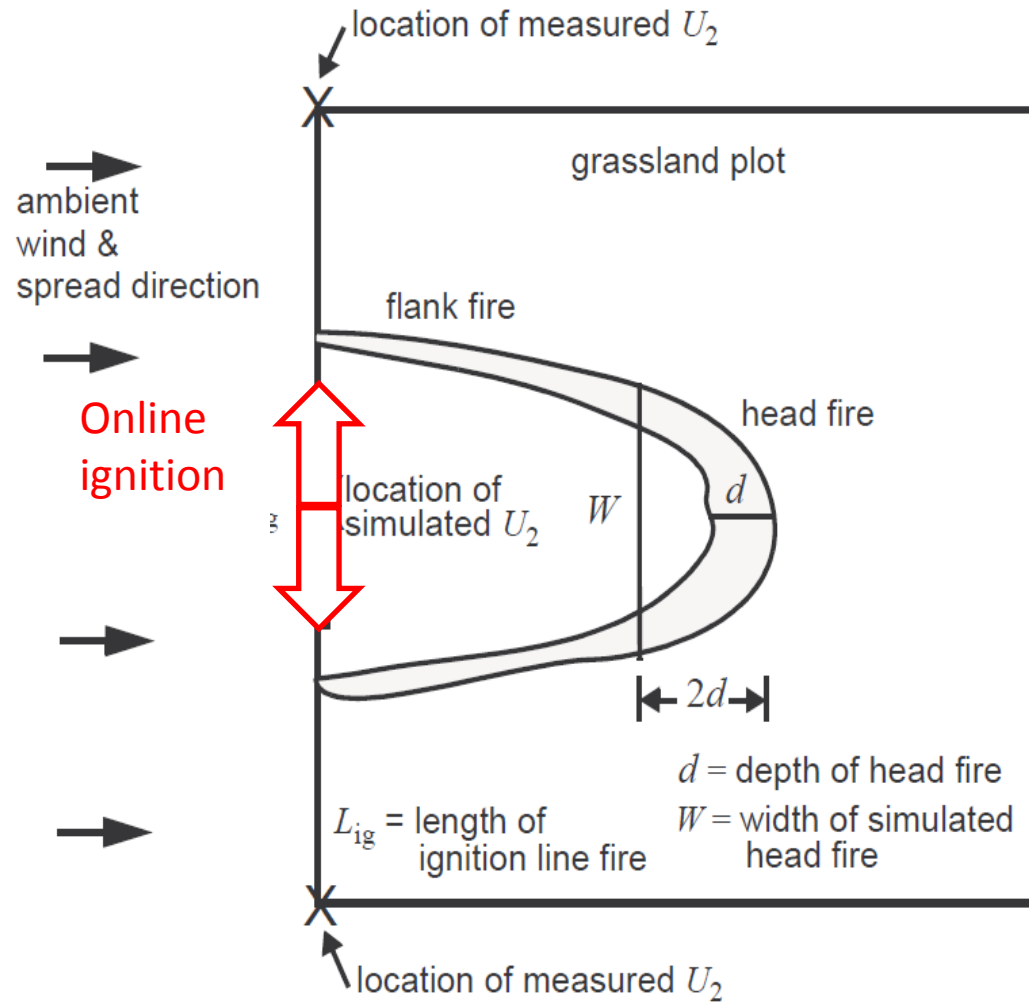
(Rothermel, 1972)

Model validation

Validation of the propagation model

Validation on a prescribed burn (Cheney et al. , 1986)

- A plot 200mX200m
- Homogeneous and continuous herbaceous vegetation
 - Moisture content : 6%
- The ambient temperature: 34°C
- A constant wind: 4.8m/s
 - RH of the air: 20%

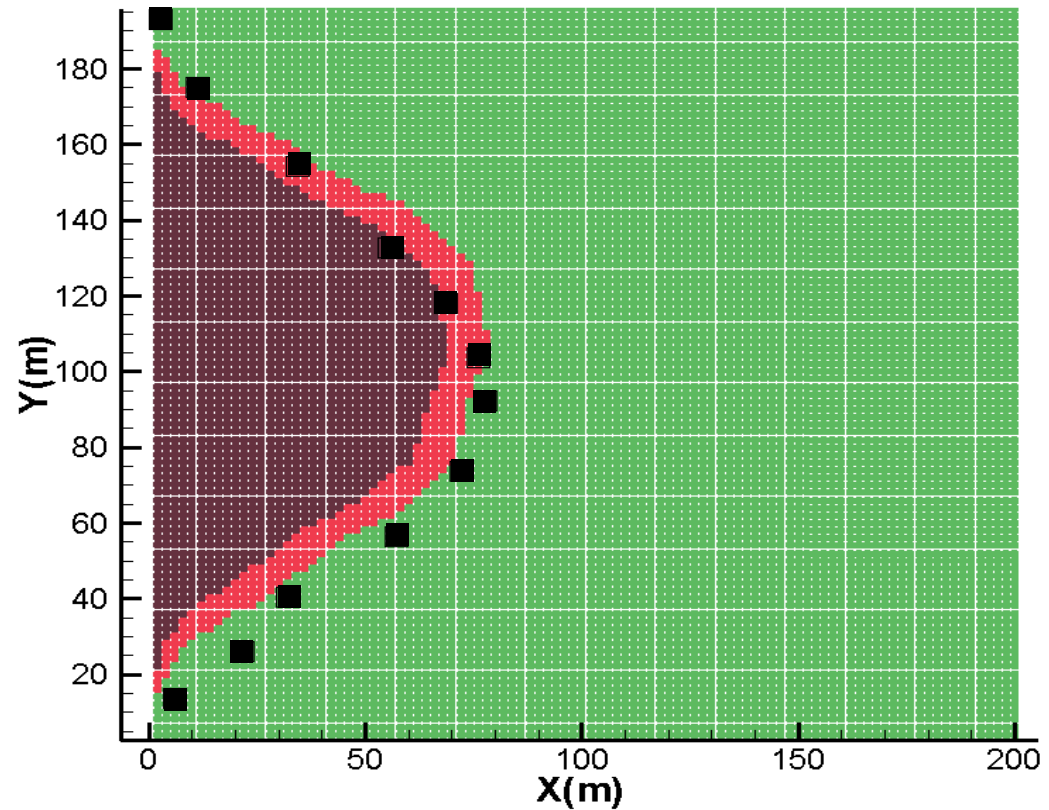


Validation of the propagation model

(Cheney et al. , 1986)



Front fire at $t = 56s$

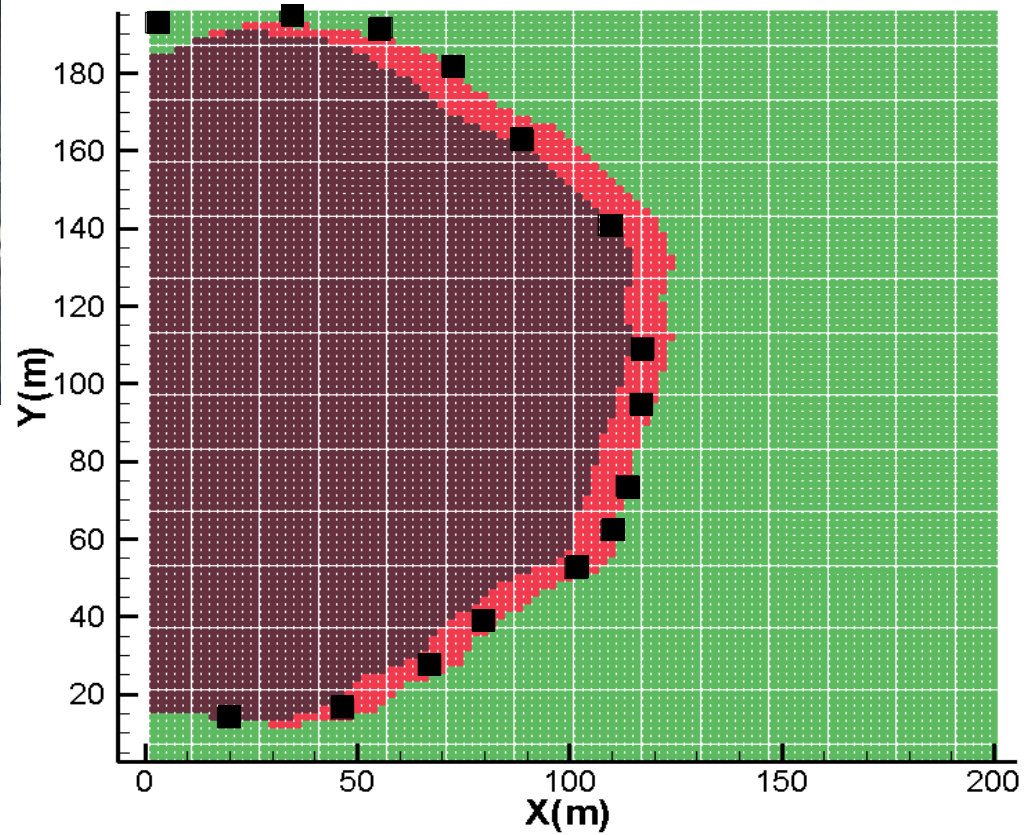


Thickness of the front fire: 10m (model) vs. 11m (exp.)

Validation du modèle de propagation



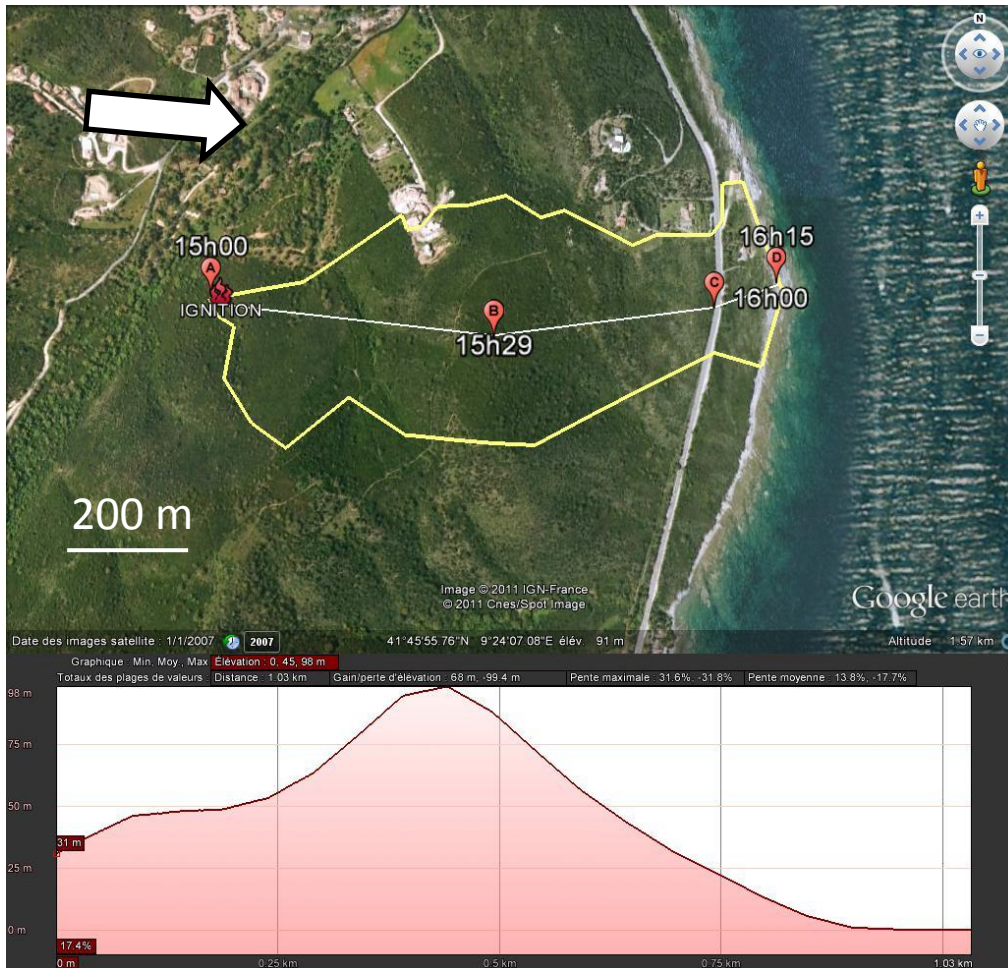
(Cheney et al. , 1986)



Contour fire at $t = 86s$

Validation of the propagation model

Validation on the Favone Fire (Corse, 2009)



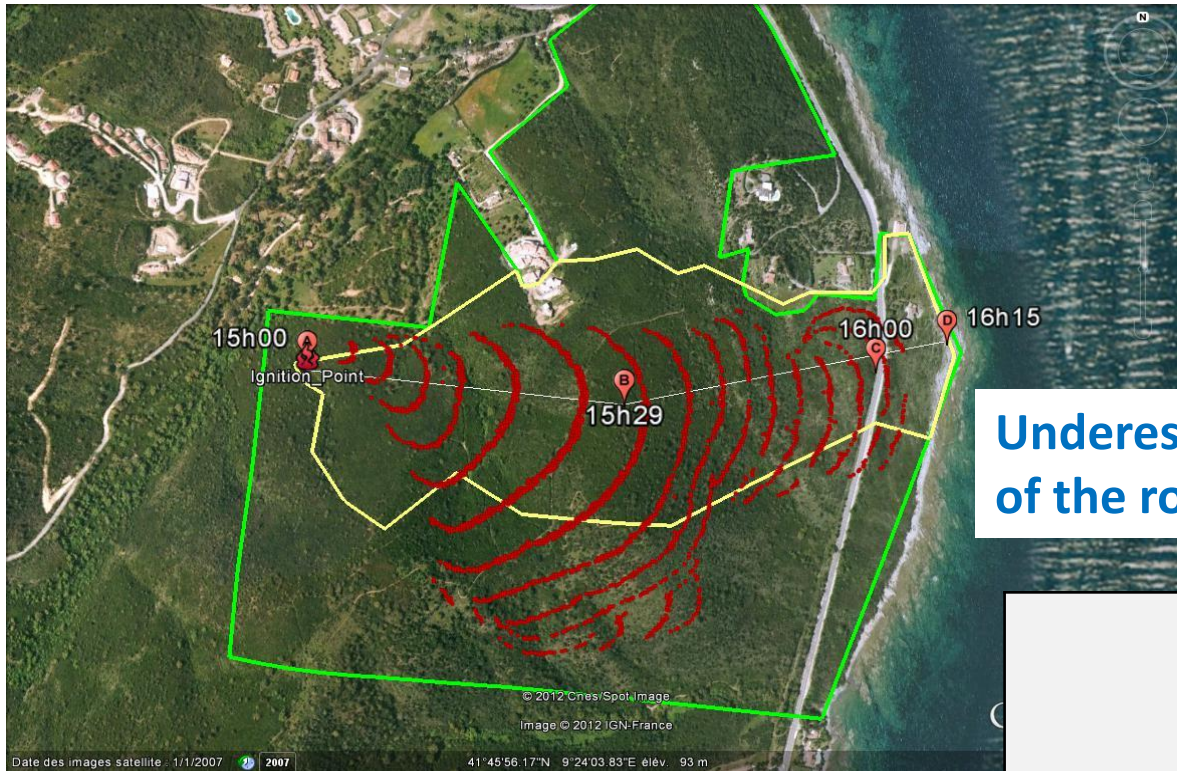
- Area burned: 29 ha
- Spread time: 1h15min
- point and time of passage of fire (Santoni *et al.*, 2011)

- Digital terrain model
25m×25m
- Dominant specy: *Erica arborea*
- Moisture content: 69%
 - The Fill rate: 50%
- Calculation of the local wind from the mean wind (7m/s) (Flowstar)
 - RH of the air : 42%

(Santoni *et al.*, 2011)

Validation of the propagation model

Validation on the Favone Fire



Underestimation of the ros

Overestimation of the burned surface

	Ros (m/min)		Aire Brûlée (ha)
	[A-B]	[B-C]	
Real (SPE)	16.8	13.3	29
Predicted	14.0	10.8	34
Relative error	17%	19%	17,2%

Differences due:

- Shift of the mean wind
- Not taking into account the means of fighting .
- Poor estimation of some parameters

➔ sensitivity study

Sensitivity study

Is to study the effect of changes in some factors (input) on some responses (output) → identify and prioritize the important parameters of the model

- Regular network , a plot 100m ×100m
- Homogeneous fuel : Kermès Oak
- Strata of 2 m diameter and 2.5 m height

Full factorial design
6 factors
2 levels

Factor	Baseline	Low level (-1)	High Level (+1)
Dry load of the fuel (kg/m ²)	3.0	2.5	3.5
Residence time of flame (s)	30	27	33
Initial moisture content	0.2	0.16	0.24
<i>Ignition temperature(K)</i>	550	540	560
Fraction radiated	0.5	0.45	0.55
Wind speed (m/s)	5	4	6



2⁶=64 simulations

Sensitivity study

Matrix

Response

Simulation	M''_{DFP}	t_c	χ_r	FMC_0	T_{ign}	$\ \vec{wind}\ $	$ROS(m.s^{-1})$
	X_1	X_2	X_3	X_4	X_5	X_6	
1	-1	1	-1	1	-1	-1	0.697
2	1	1	1	-1	-1	1	2.222
3	1	1	1	-1	1	-1	1.276
4	-1	1	1	1	1	-1	0.714
5	-1	-1	1	1	-1	-1	1.017
.
.

$$\begin{aligned}
 ros = & \beta_0 + \underbrace{\sum_{i=1}^6 \beta_i X_i}_{\text{main effects of order 1}} + \underbrace{\sum_{i=1}^6 \sum_{j>i}^6 \beta_{ij} X_i X_j}_{\text{interactions of order 2}} + \underbrace{O(3)}_{\text{interactions of order 3}} + \dots + \underbrace{O(6)}_{\text{interactions of order 6}}
 \end{aligned}$$

Rate of spread obtained by the simulation using the reference values for all factors.

Pareto chart

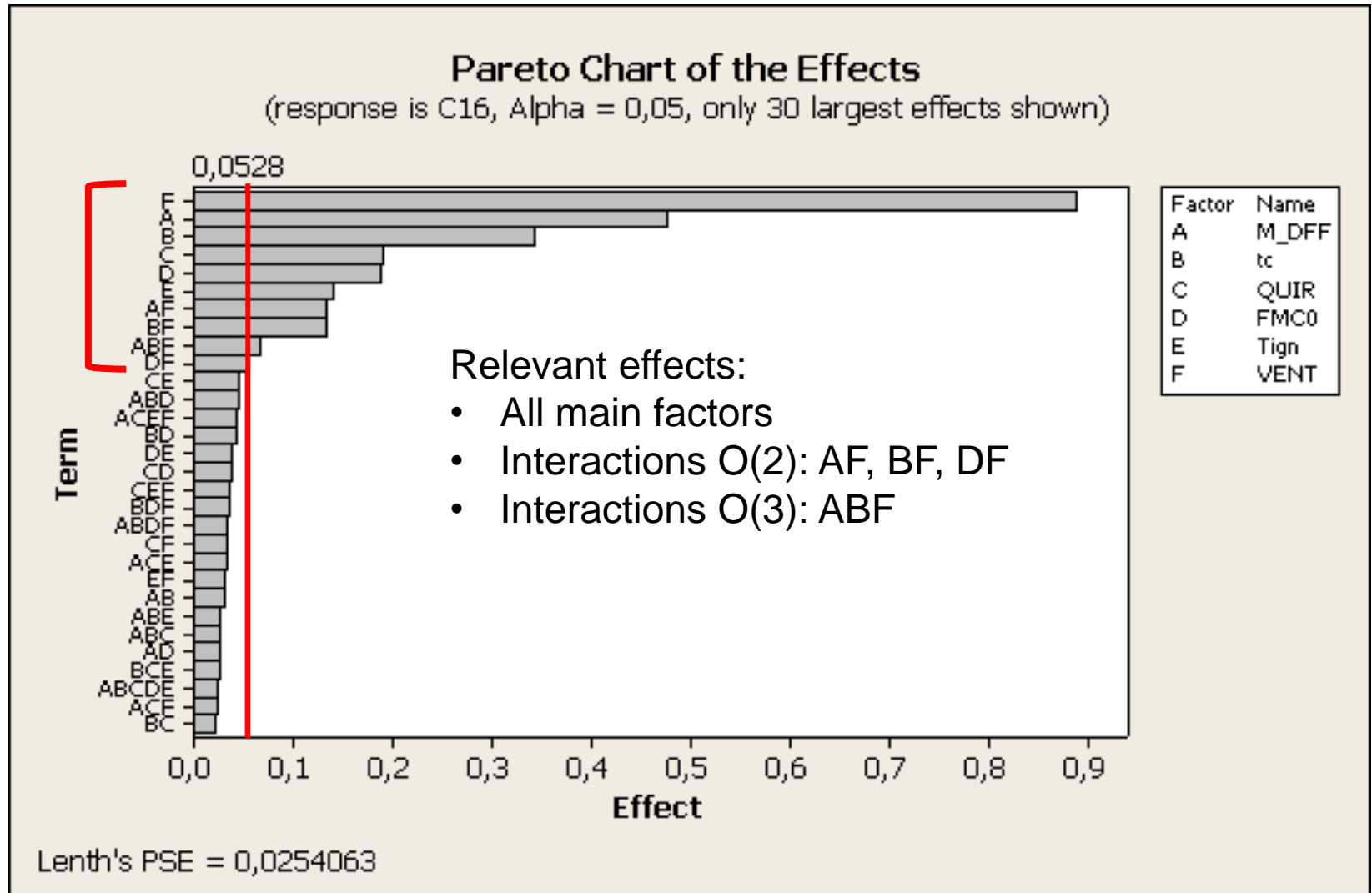
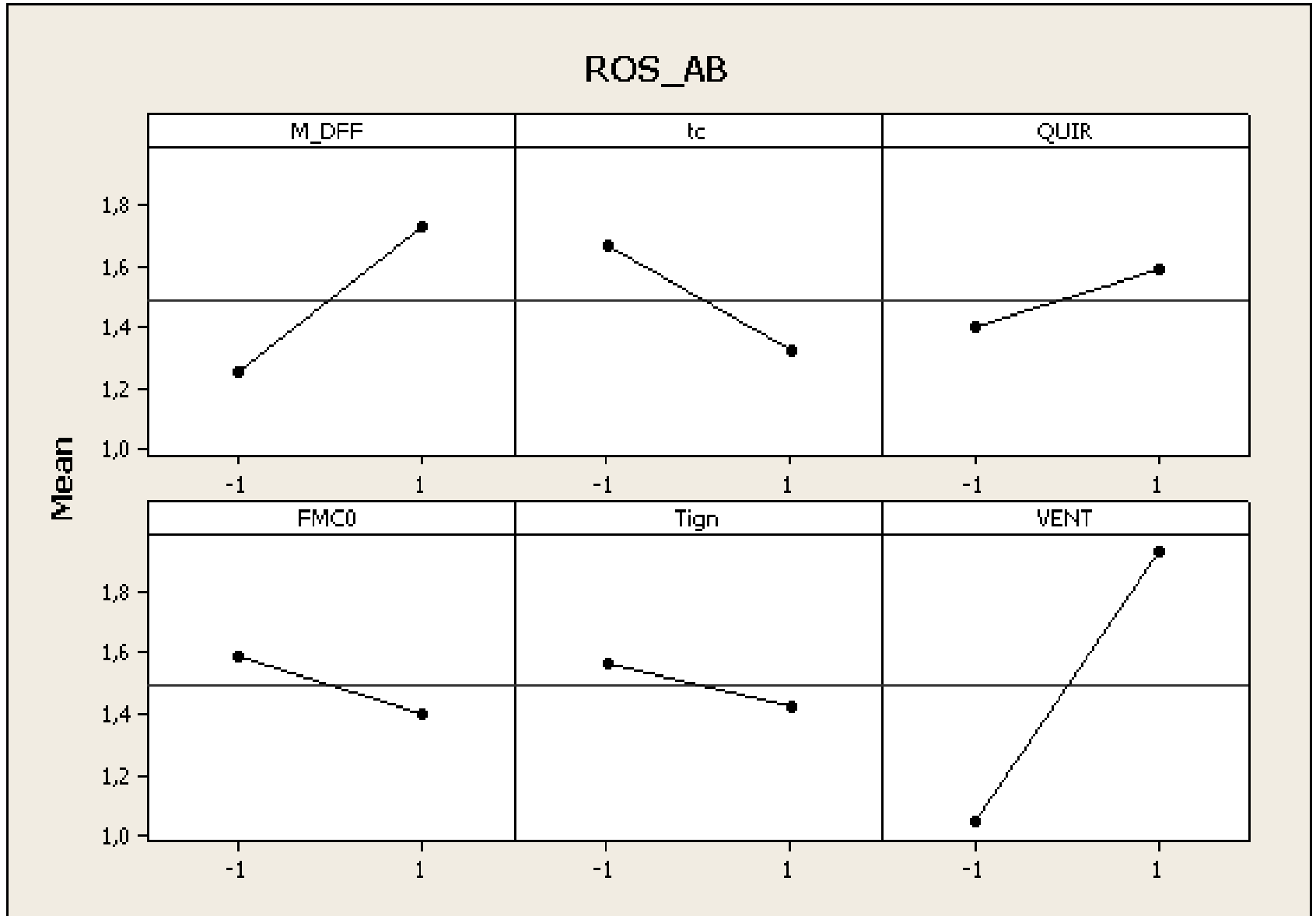


Diagram of the main effects



Conclusions

- ✓ The developed hybrid model can now :
 - ✓ take into account the convection and radiative losses in the preheating of a site exposed to fire
 - ✓ a better reflection of the reality of the landscape (randomness, polydispersity)
- ✓ The model was validated on a prescribed burn and on a real fire
- ✓ The sensitivity analysis has allowed to:
 - ✓ identify and prioritize the most influential model parameters
 - ✓ Establish simple correlations between the ROS and the most influential parameters

Prospects

- ✍ Study atypical configurations (thalweg , slope break, Canyon effect)
- ✍ Establish a risk mapping for a given region
- ✍ Improvement of the criterion of ignition → to characterize by experiment, the critical pyrolysis mass loss rate.
- ✍ Improvement of the solid flame model (emitting volume, coll. LEMTA)
- ✍ Study the behavior of fire in the case of a polydisperse vegetation with a significant vertical distribution (transition surface to crown fire).
- ✍ Study of the role of spotting on the spread.

Thank you for your attention