Session 2 : Modeling Wildland-Urban Interface Fires with Physics-Based Approaches

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Modeling Wildland-Urban Interface Fires with Physics-Based Approaches

Anne GANTEAUME, INRAE

CONTEXT OF THE RESEARCH

- Global change => Increase in WUI surface areas (one of the main source of fire ignitions ~50% and high stake areas)
  => Increase in frequency of extreme fire events impacting WUI

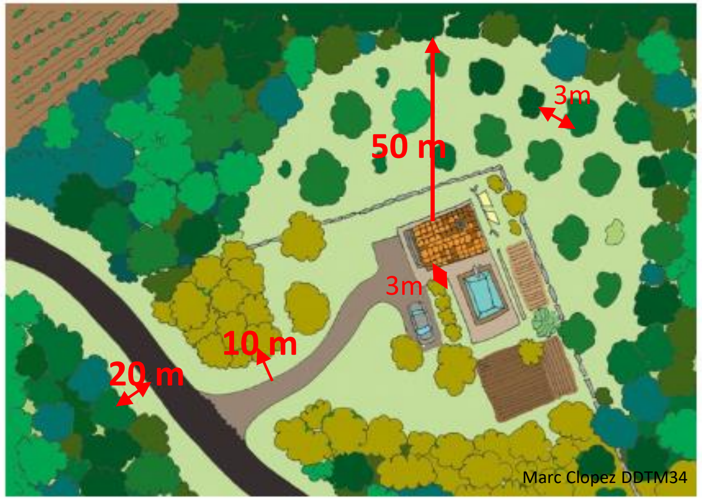
- WUI Vegetation differs from that of wildland => more heterogeneous structure and composition: exotic + native species
  => submitted to mandatory brush-clearing in SE France

- Most damage at WUI due to poor vegetation management despite the regulation (lack of implementation)

↳ *At fine scale (garden), need to **characterize the fire behavior in heterogeneous fuels** (intensity, propagation, etc.) and **impacts on structures** through fire experiments and modeling*

➡ ***Promote fire-resilient WUI** in a context of global change => Importance of **firewise landscape management***

Mandatory brush-clearing according to the Forest Code



Designing firewise landscaping for resilient WUI

Why? Regulation for fire prevention => fire risk mitigation in the Home ignition zone

Targets: Residents in WUI, Land managers

Goal: What and where Ornamental species have to be used for safe landscaping in high fire risk areas

Italian cypress

Pittosporum

Keep it away from buildings!

Avoid hedges close to buildings!

➢ Testing the efficiency of regulation for fire prevention at the WUI

Why? Regulation for fire prevention => fire risk mitigation at the WUI

Targets: Residents in WUI, Land managers

Goals: Possibly refine the regulation for fire prevention based on expert-opinion (Mandatory distances for brush-clearing)

Is the regulation efficient?

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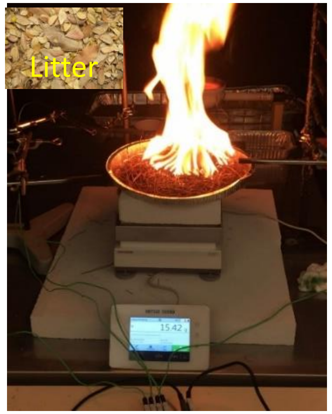
HOW TO REACH THE GOALS

RECOVER
risks - ecosystems
vulnerability - environment - resilience

➢ Experimental approaches (input data, validation for modeling)

✓ Laboratory burning experiments at different scales ➡ Species' flammability



➡ Database on > 50 WUI species (flammability & fuel characteristics)

✓ Outdoor burning experiments

➡
- No damage on aluminum shutters
- Higher impact at the roof level (flame angle affected by slope and wind)

=> Slope and wind will have to be accounted for in the regulation

HOW TO REACH THE GOALS

➢ Digital approaches

1. **FIREWUI model** derived from raster-based fire spread model SWIFFT (De Gennaro et al. 2017)

⇒ accounting for thermal degradations of structures, wildland and ornamental vegetation, leading to damage to building

=> featuring multi-fuel scenes, canopy fire parameterizations to account for the increase in fire intensity and residence time due to passive and potentially active crowning and coupled with a module of fire-induced thermal degradation of structures

=> tested in two different zones (damage vs no damage) of WUI impacted by past fires

➡ ***Evaluation of the vulnerability and resilience to fire of WUI at fine scale (with georeferenced vegetation items)***

Fernandez et al., Advances in Forest Fire Research, 2018

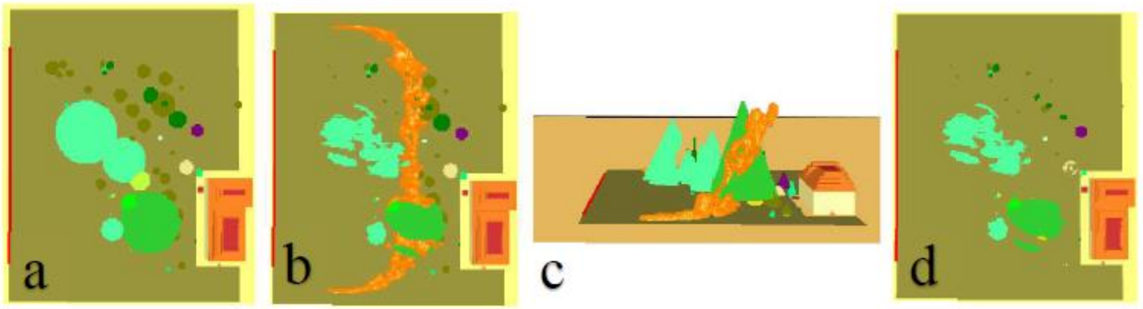
➡ Simulation matched quite well the post-fire survey but not accurate when fire spreads vertically (surface fire -> crown fire)

HOW TO REACH THE GOALS

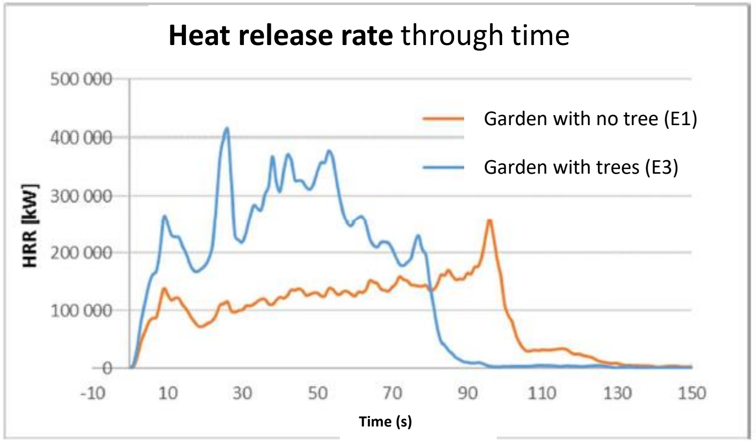
2. Physics-based modeling using CFD model : WFDS

- Modeling the fire behavior in a garden according to 3 scenarios (E1, E2, E3) of vegetation distribution around the house
  E1: no tree, only grass, E2 : trees, E3 trees + big tree in front of the house

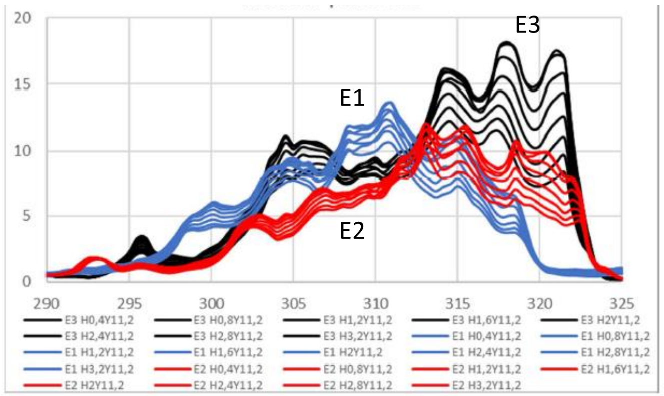
- Domain 450x468x80 xyz directions; Mesh: 0,5m résolution; Wind :1 to 8 m/s; Slope = 0 ; Georeferenced Vegetation items



a) vegetation before fire, b) Flame front propagation, c) Flame height, d) post-fire vegetation



Heat fluxes (kW/m^2) received by the sensors (located at 11.2m from flame front)



Successful modeling of fire behavior in WUI vegetation

But:

Improvements needed for modeling :
- under intermittent wind conditions (not possible with WFDS)
- with FMC>25%
- on a larger domain
- using DTM (slope > 0)

HOW TO REACH THE GOALS

3. Physics-based modeling using CFD model : FDS (v. 6.7.5)

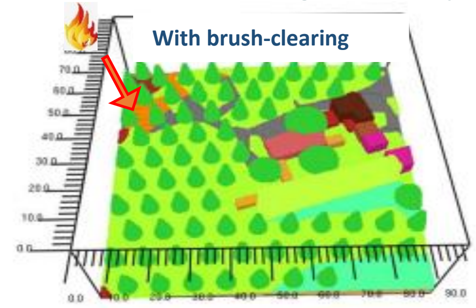
Ganteaume et al., IJWF, 2023

- **Comparing FDS simulation results to post-fire damage** recorded during a past fire => assess the functional capacity of the model using the complexity of the overall environment
- Running the modeling on **different scenarios of vegetation management** (brush-clearing *vs* no brush-clearing) to assess the role of the regulation (fuel reduction) on the fire mitigation at WUI

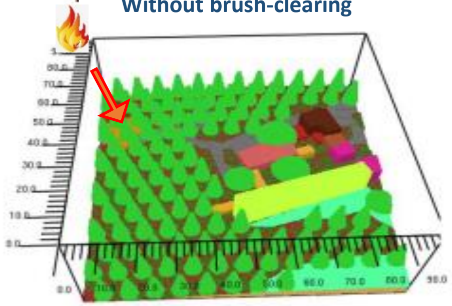
Before the fire

After the fire

DEM + Georeferenced vegetation map + urban soil sealing



Property impacted by past-fire



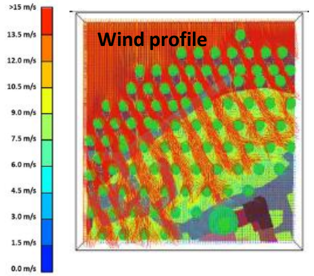
MODELING INPUT DATA:

- **topographical data** (resolution of 25m; Copernicus programme)

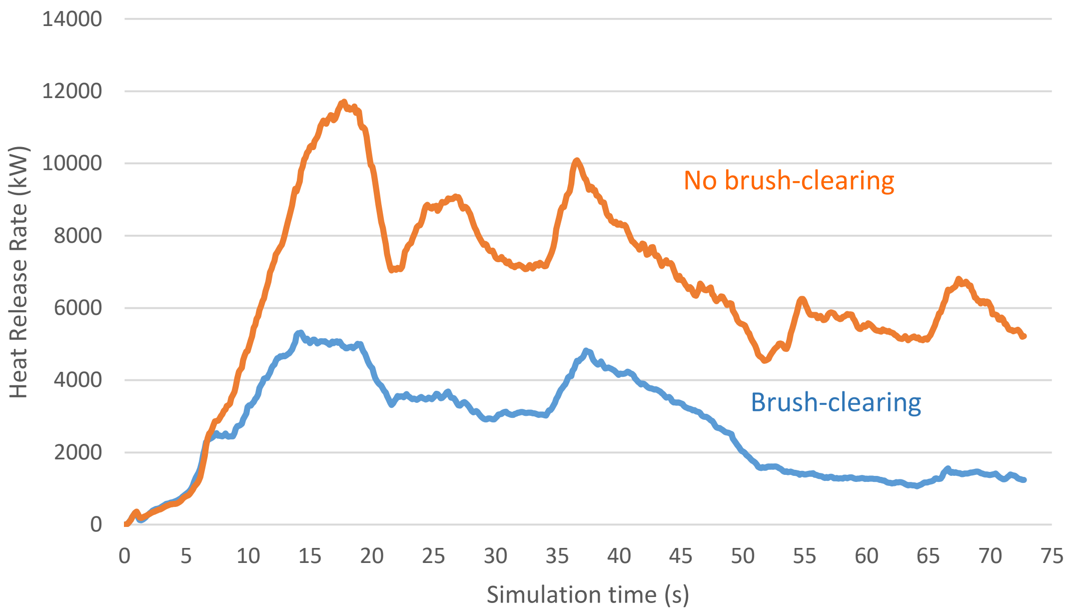
- **vegetation data:** * plants recorded with as much precision as possible (georeferenced in the field during the post-fire survey and using aerial or satellite images available before the fire)

  * species parameters (Surface-to-Volume Ratio, Bulk Density, etc.) from Inrae's database

- **wind data** : The wind speed considered is 11 m s^{-1} on average over 5 min. The **intermittent wind** is modeled by a simple alternation every 15 s of 2 m s^{-1} and 20 m s^{-1} (typical of the dominant wind, Mistral, in the study area).



OUTPUTS:



Evolution of the heat release rate

POST-FIRE DAMAGE:

Modeling:

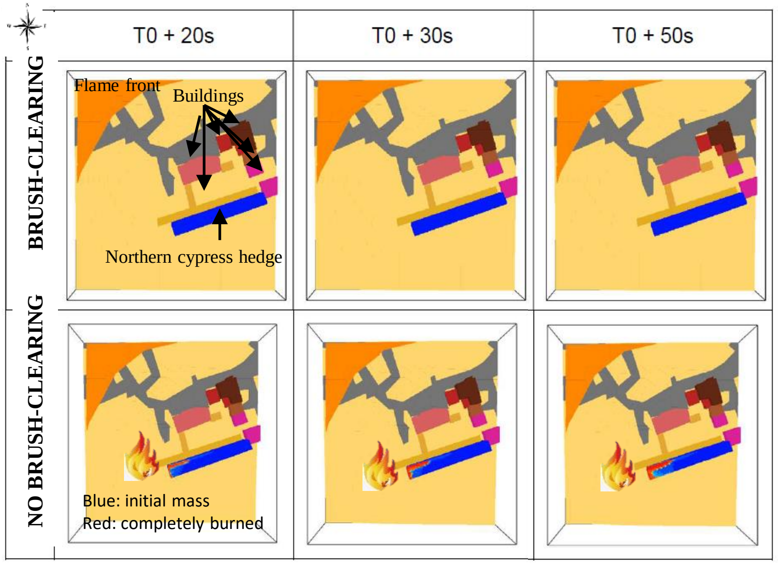
Brush-clearing significantly decrease HRR
Brush cleard < 6000kW
No-brush-clearing => more impact on vegetation and buildings (up to 12000kW)

Post-fire damage assessment :
Fire coming from untreated pine stand reached **the buildings that completely burned**

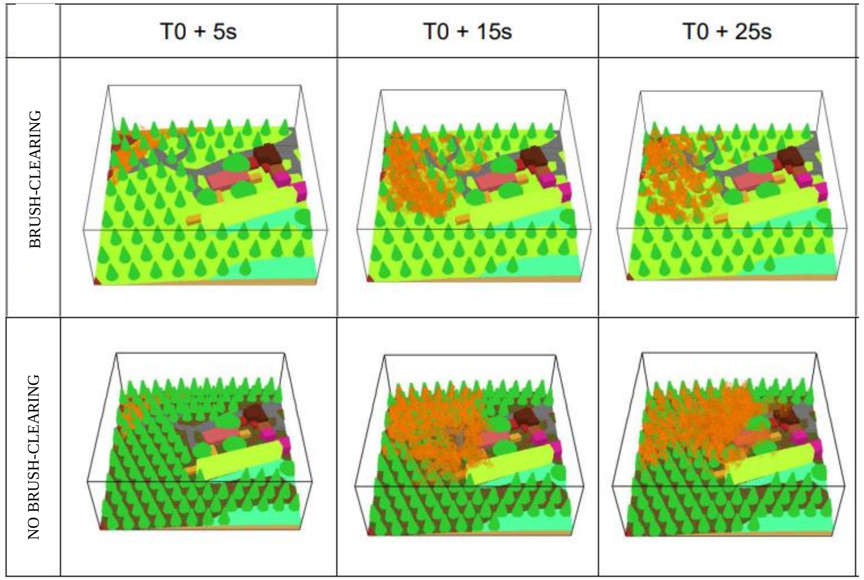
Simulation matched quite well the post-fire survey

MODELING OUTPUT DATA:

POST-FIRE DAMAGE:



Evolution of the tree mass loss



Evolution of the flame front propagation

Modeling:

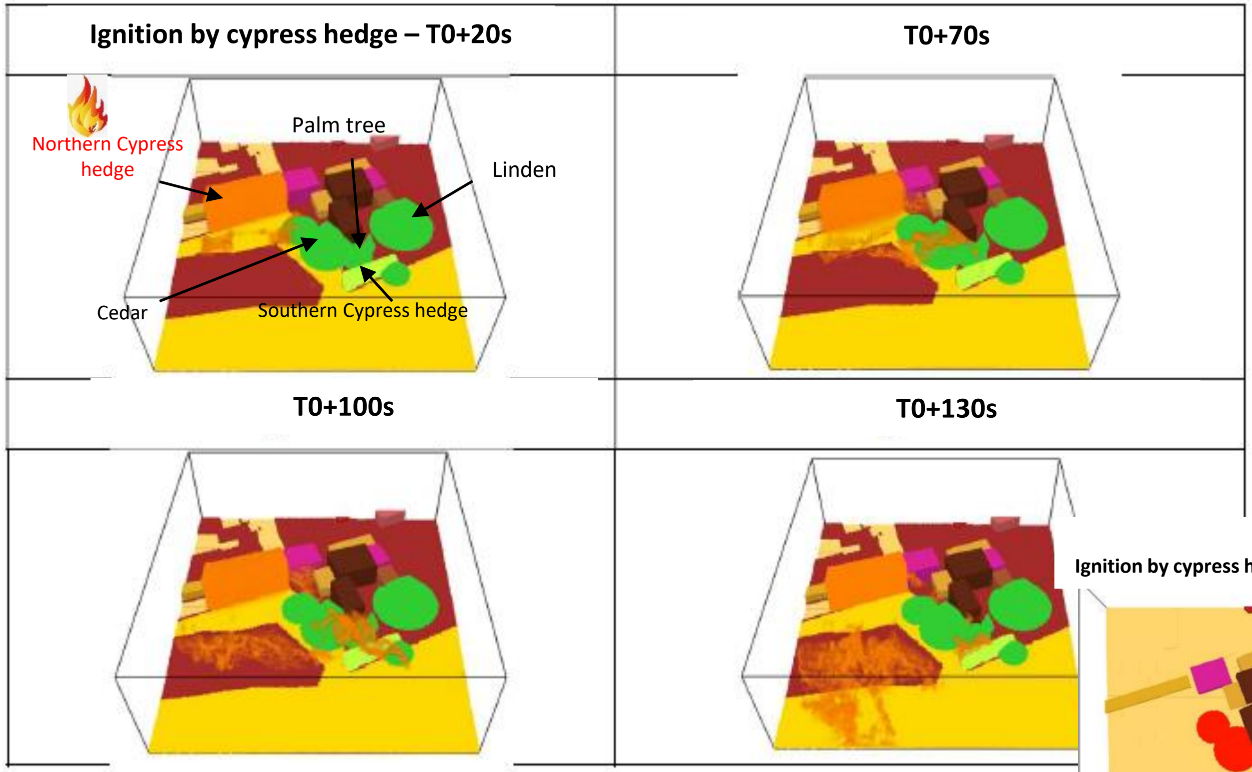
Cypress hedge partially impacted by the fire
in the modality with no brush-clearing

Post-fire damage assessment :
Fire coming from untreated pine stand reached **the tall cypress hedge that completely burned**

Underestimation of fire propagation in the hedge by the model

MODELING OUTPUT DATA:

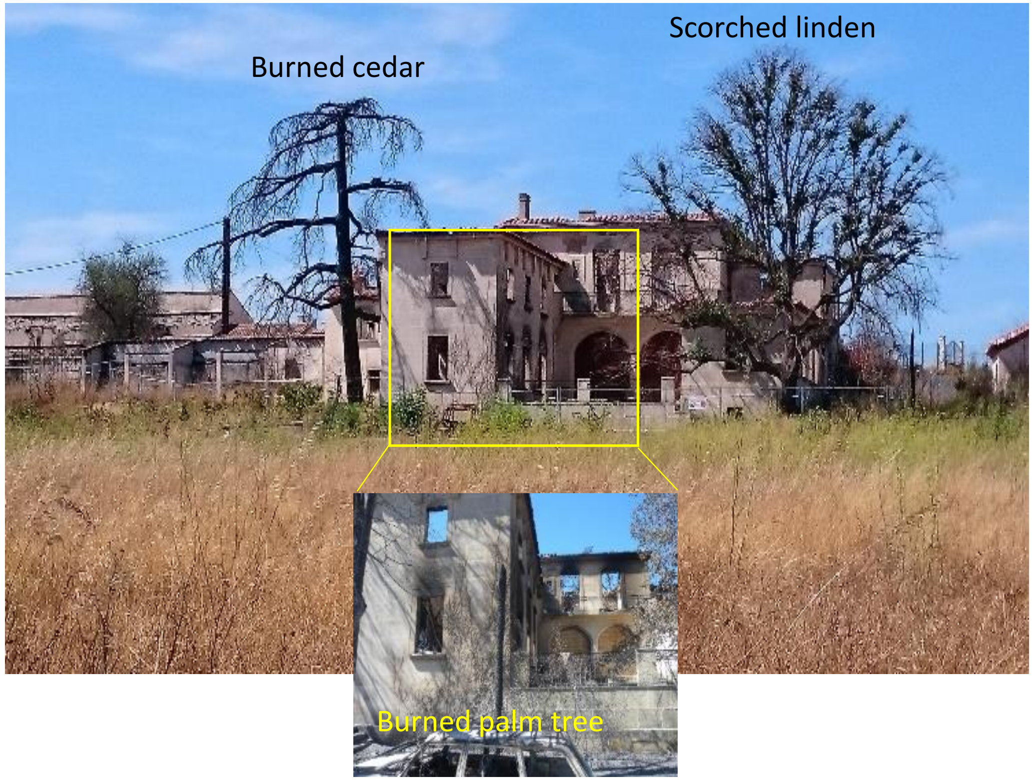
POST-FIRE DAMAGE:



Evolution of the flame front starting in the northern cypress hedge

Ignition by cypress hedge – T0+180s

Trees mass loss



Modeling:

Tall cedar burned first, then southern cypress hedge and palm tree were reached by the fire but **linden tree little affected**.

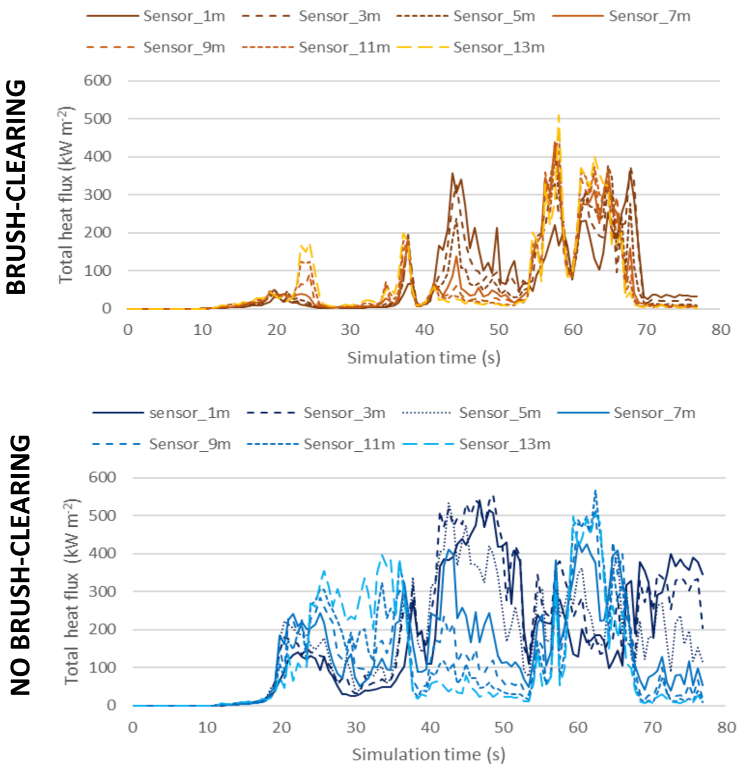
Post-fire damage assessment :

Tall trees and southern cypress hedge impacted by the fire coming from the northern cypress hedge (variable burned severity according to the tree), participating to the damage to building.

➡ Simulation matched quite well the post-fire survey

MODELING OUTPUT DATA:

Heat sensors at different heights



Evolution of the total heat flux received at different heights according to the fuel management modality

Modelling :

- **Flux sensors quickly reached by the flames** (intensities higher than 80 kW m^{-2}) in both modalities.
- **Highest heat sensor** (13 m) strongly affected by the wind gusts in both modalities.

POST-FIRE DAMAGE:

Post-fire damage assessment :

Fire propagation uphill in the brush-cleared garrigue:

-Damage mostly due to a windward window left open => indoor fire due to incoming firebrands.

-A large part of the windward ornamental vegetation also impacted in contrast of the leeward side of the house.

First floor more impacted than ground floor

Conclusions on the use of CFD modeling (FDS)

- Simulations results matched quite well the post-fire survey
- Relevance of the fuel reduction measures in terms of fire mitigation
- Need to strengthen the regulation when synergy wind-slope (3m between tree and building is not enough)
- Functional capacity of the model used to predict the fire behaviour at the WUI scale despite some biases inherent to the model (e.g. low simulated FMC).

Improvements to be made to the FDS model for a better use in the context of WUI fire propagation

- ✓ Improving the code FDS for modeling fire propagation in a vegetation with high moisture content (>100%) (see Guillaume et al. Fire & Material, 2024)
- ✓ Modeling fire behavior at different vegetation spatial resolutions for planning firewise WUI

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De Gennaro M, Billaud Y, Pizzo Y, Garivait S, Loraud J-C, El Hajj M, Porterie B (2017) Real-time wildland fire spread modeling using tabulated flame properties. Fire Safety Journal 91, 872–881. doi:10.1016/j.firesaf.2017.03.006

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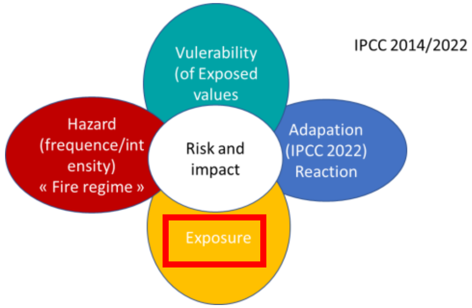
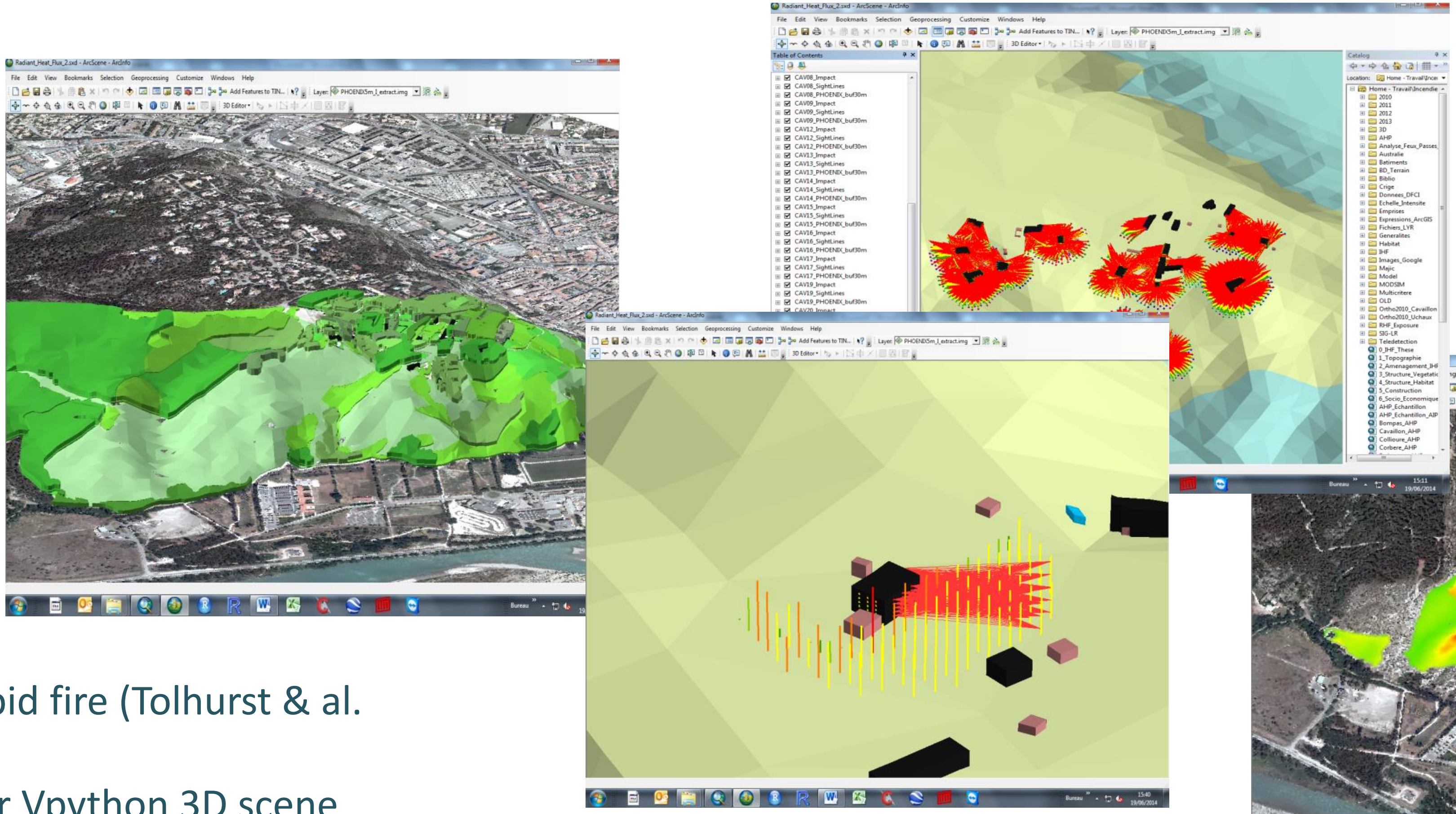
Ganteaume A, Guillaume B, Girardin B, Guerra F. (2023) CFD modelling of WUI fire behaviour in historical fire cases according to different fuel management scenarios. Int. J. Wildland Fire 32(3), 363–379. https://doi.org/10.1071/WF22162

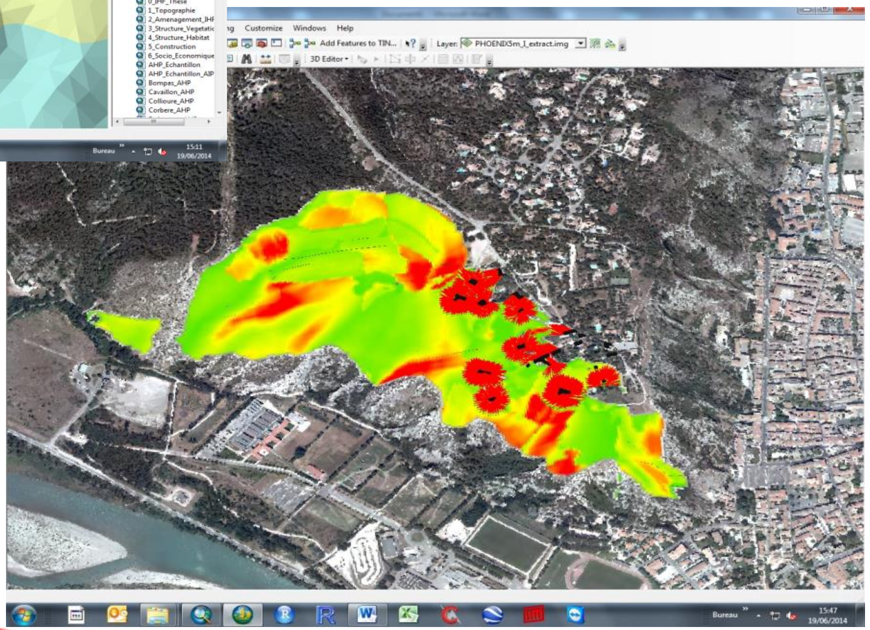
Guillaume B, Ganteaume A, Majeri M, Fayad J, El Houssami M, Pizzo Y, Porterie B (2025) New Laboratory Results on Ignition and Propagation in Live Vegetation Paving the Road to a Semi-Empirical Model. Fire and Materials, 2025; 0:1–12. https://doi.org/10.1002/fam.3273

Model-based 3D exposure assessment at the scale of WUI zone

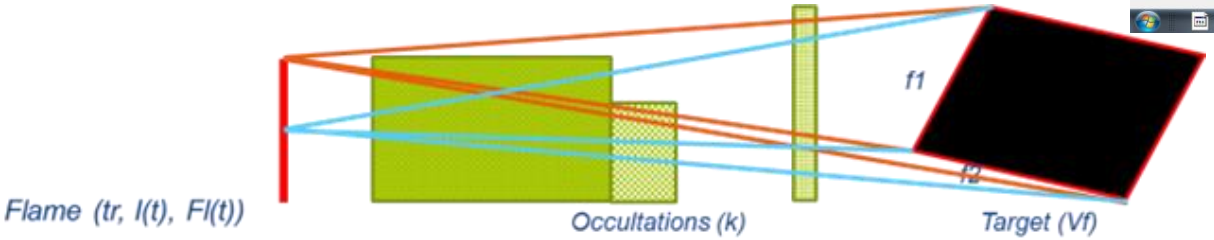
RECOVER
risks - ecosystems
vulnerability - environment - resilience





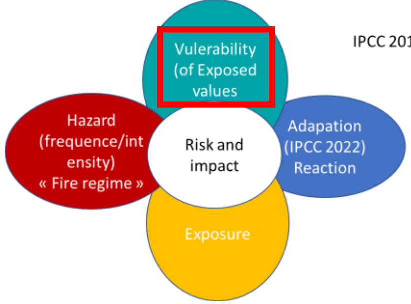


- ✓ Phoenix rapid fire (Tolhurst & al. 2011)
- ✓ SketchUp or Vpython 3D scene (Pugnet, Leonard & Blanchi 2010)



WUI and risk mapping at local scale

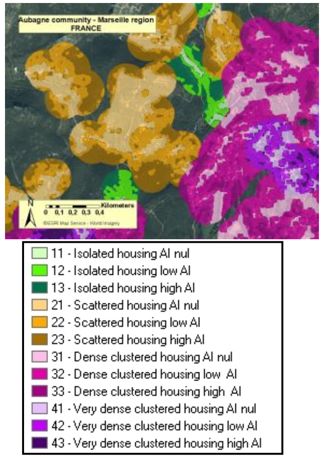
(related to session 5)



IPCC 2014/2022

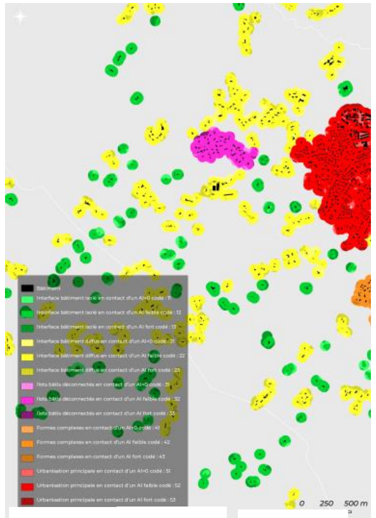
Global risk (hazard & vulnerability) assessment with spatial analysis: Wildland Urban Interface (WUI) Analysis and Mapping

Assessing the spatial relationship between vegetation fuel & vulnerable geographical objects (buildings) to assess the « global risk » at local scale



WUIMap standard (Lampin & al. 2010)

- ❑ Building density
- ❑ Building aggregates population
- ❑ Fuel horizontal aggregation



WUIMap II (Le Fur & al. 2024)

- ❑ Contiguity
- ❑ Shape complexity
- ❑ Land use semantics (concepts of urbanized/not urbanized area)

Better correlation with fire risk indicators (ignition points, fire frequency) and impact indicators (burnt area ratio, houses damaged…)

Global risk assessment

Experts' opinion rule-based models (using the multicriteria formalism…)

Risks components :

Contextual hazard (CH)
Unit vulnerability (UV)
Buildings at stake population (BP)
Cumulated vulnerability (CV)
Global risk (GR)

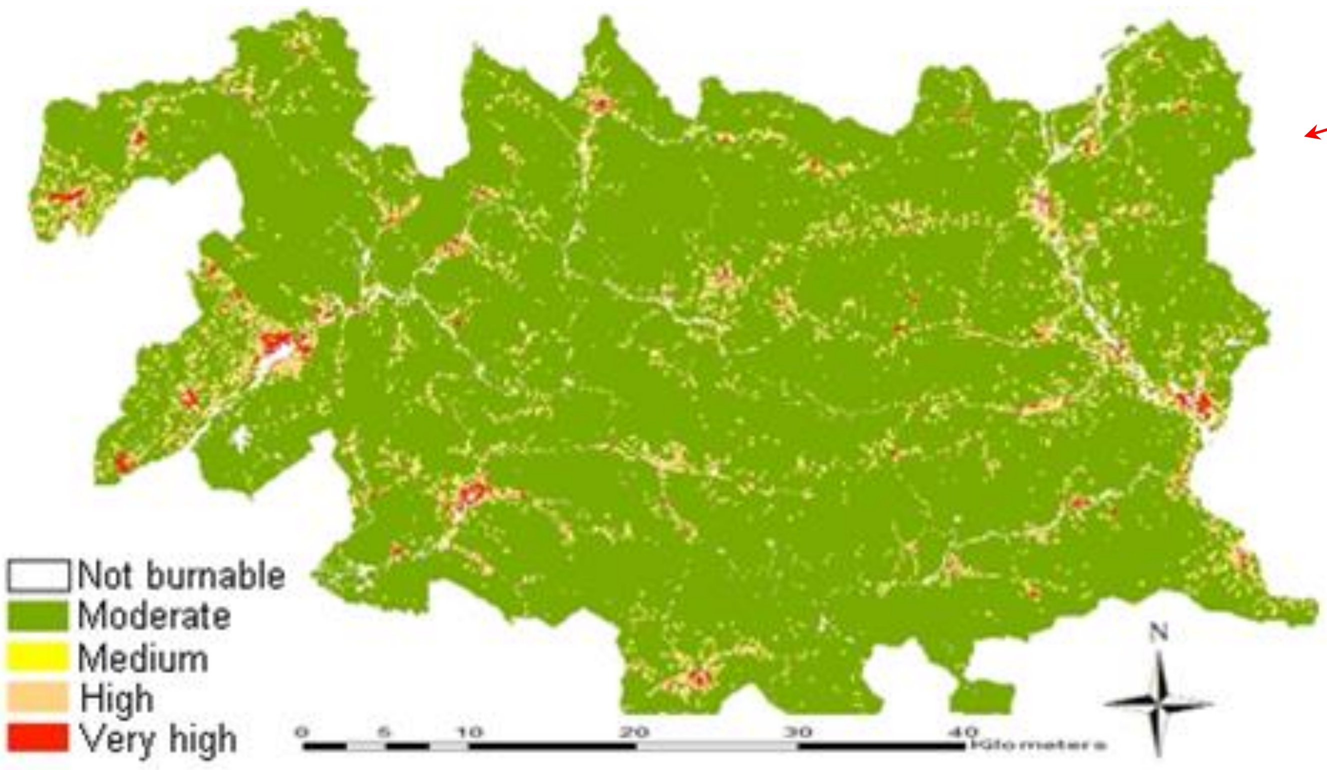
WUI classes		*CH*	*UV*	*BP*	*CV*	*GR*
500	Isolated buildings, no aggregated fuel	+	++++	+	+++	+
501	Isolated buildings, semi-aggregated fuel	++	++++	+	+++	++++
502	Isolated buildings, aggregated fuel	++++	++++	+	+++	+++++
400	Scattered buildings, no aggregated fuel	+	+++	++	++++	++
401	Scattered buildings, semi-aggregated fuel	++	+++	++	++++	+++
402	Scattered buildings, aggregated fuel	++++	+++	++	++++	++++
300	Clustered internal buildings, no aggregated fuel	+	++	+++	++	+
301	Clustered internal buildings, semi-aggregated fuel	++	++	+++	++	++
302	Clustered internal buildings, aggregated fuel	++++	++	+++	++	+++
310	Clustered peripheral buildings, no aggregated fuel	+	+++	+++	+++	0+
311	Clustered peripheral buildings, semi-aggregated fuel	++	+++	+++	+++	+
312	Clustered peripheral buildings, aggregated fuel	++++	+++	+++	+++	++

Spatial decision support tool (SDS)

Addressed to:

- **Foresters**: WUI vegetation management, fuel breaks & equipments setting up…
- **LULC managers** : land « shaping », risk mitigation…
- **Citizens**: risk culture & awarness, fuel clearing practices…

Example of results



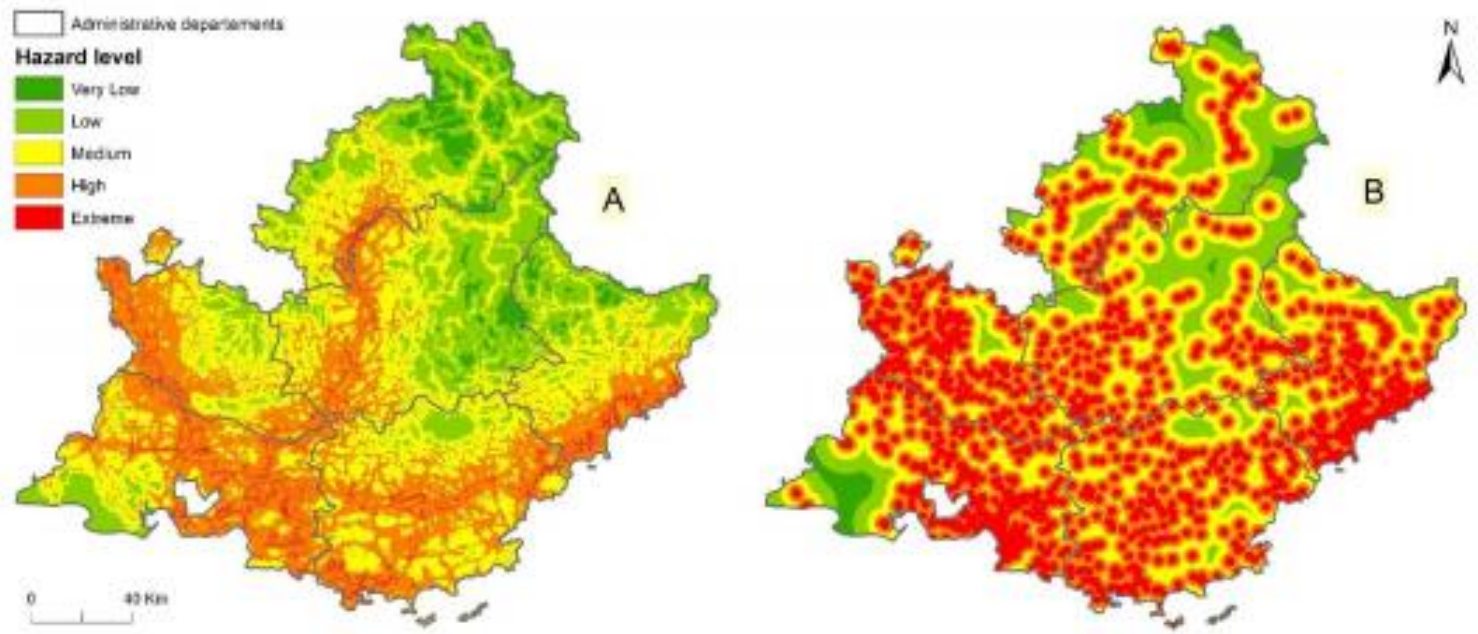
Relative potential of ignition in the Baronnies area
(Baronnies Provençales Regional Natural Parc)

The map is structurated by the Interfaces map, including both network infrastructures and buildings aggregates interfaces

Example of results at regional scale

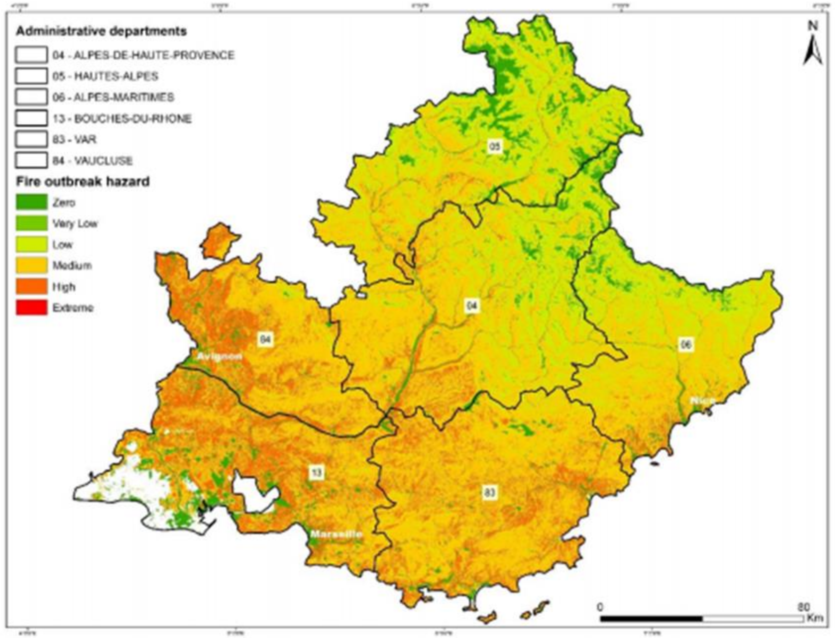
RECOVER
risks - ecosystems
vulnerability - environment - resilie

(outputs of the MEDSTAR project)



Ignition Risk maps for each causative element. (A) Transport infrastructures. (B) Population centres and scattered rural buildings.

Chai-Allah, Maillé, Bouillon 2021

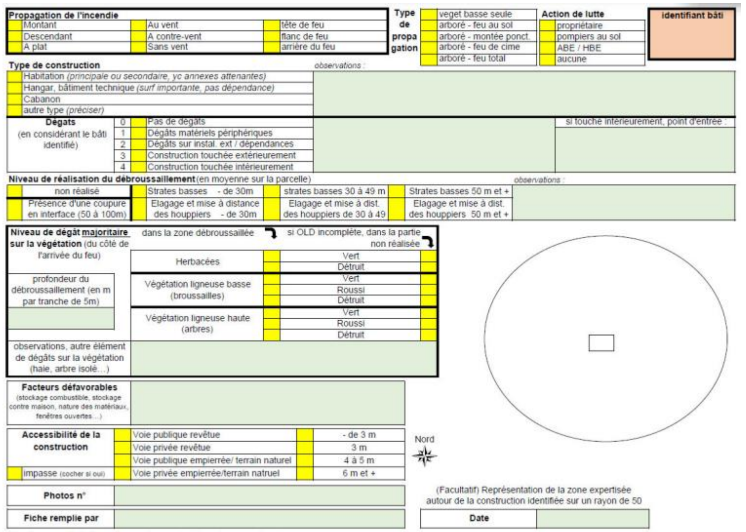


Fire Outbreak map

Focus on built up plots vulnerability

Collection, storage and analysis of damage data

Protocols



Propagation de l'incendie
Montant | Au vent | tête de feu
Descendant | A contre-vent | flanc de feu
A plat | Sans vent | arrière du feu

Type de propagation
veget basse seule
arboré - feu au sol
arboré - montée ponct.
arboré - feu de cime
arboré - feu total

Action de lutte
propriétaire
pompiers au sol
ABE / HBE
aucune

identifiant bâti

Type de construction
Habitation *(principale ou secondaire, yc annexes attenantes)*
Hangar, bâtiment technique *(surf importante, pas dépendance)*
Cabanon
autre type *(préciser)*
observations :

Dégats (en considérant le bâti identifié)
0 Pas de dégats
1 Dégâts matériels périphériques
2 Dégâts sur instal. ext / dépendances
3 Construction touchée extérieurement
4 Construction touchée intérieurement
si touche intérieurement, point d'entrée :

Niveau de réalisation du débroussaillement (en moyenne sur la parcelle)
non réalisé | Strates basses - de 30m | strates basses 30 à 49 m | Strates basses 50 m et +
Présence d'une coupure en interface (50 à 100m) | Elagage et mise à distance des houppiers - de 30m | Elagage et mise à dist. des houppiers de 30 à 49 | Elagage et mise à dist. des houppiers 50 m et +
observations :

Niveau de dégât majoritaire sur la végétation (du côté de l'arrivée du feu)
dans la zone débroussaillée | si OLD incomplète, dans la partie non réalisée
Herbacées: Vert, Détruit
Végétation ligneuse basse (broussailles): Vert, Roussi, Détruit
Végétation ligneuse haute (arbres): Vert, Roussi, Détruit
profondeur du débroussaillement (en m par tranche de 5m)
observations, autre élément de dégâts sur la végétation (haie, arbre isolé…)

Facteurs défavorables (stockage combustible, stockage contre maison, nature des matériaux, fenêtres ouvertes…)

Accessibilité de la construction
Voie publique revêtue | - de 3 m
Voie privée revêtue | 3 m
Voie publique empierrée/ terrain naturel | 4 à 5 m
Voie privée empierrée/terrain natruel | 6 m et +
impasse (cocher si oui)

Nord

(Facultatif) Représentation de la zone expertisée autour de la construction identifiée sur un rayon de 50

Photos n°

Fiche remplie par

Date

Maison	Flux moyen simulé (kW/m²)	Exposition (min)	Équipement	Dommage observé
CAV_2	5,6	19	Gouttière PVC	Légèrement fondue
CAV_6	13,26	20	Volet BOIS	Noirci + Trace de charbon
CAV_8	18,4	34	Gouttière PVC	Fondue + Décrochée
	7,3	10	Gouttière PVC	Légèrement fondue
CAV_13	20,1	23	Fenêtre	Vitre brisée + Encadrement BOIS noirci
CAV_15	34	28	Gouttière ZINC	Partiellement fondue
	18,7	40	Volets BOIS	Partiellement consumé
	36	27	Établi BOIS	Entièrement détruit
CAV_16	16	56	Volet BOIS	Noirci + Trace de charbon
CAV_20	28,9	36	Volets BOIS	Partiellement consumé

Three levels of damages

- Site (« built up unit ») (s0: not damaged) -> s5: « totally destroyed »
- Main building b0: not damaded -> b5: « totally destroyed » (remain concrete walls)
- Objects (o0: not damaged) -> o5 « disappeared or totally destroyed…

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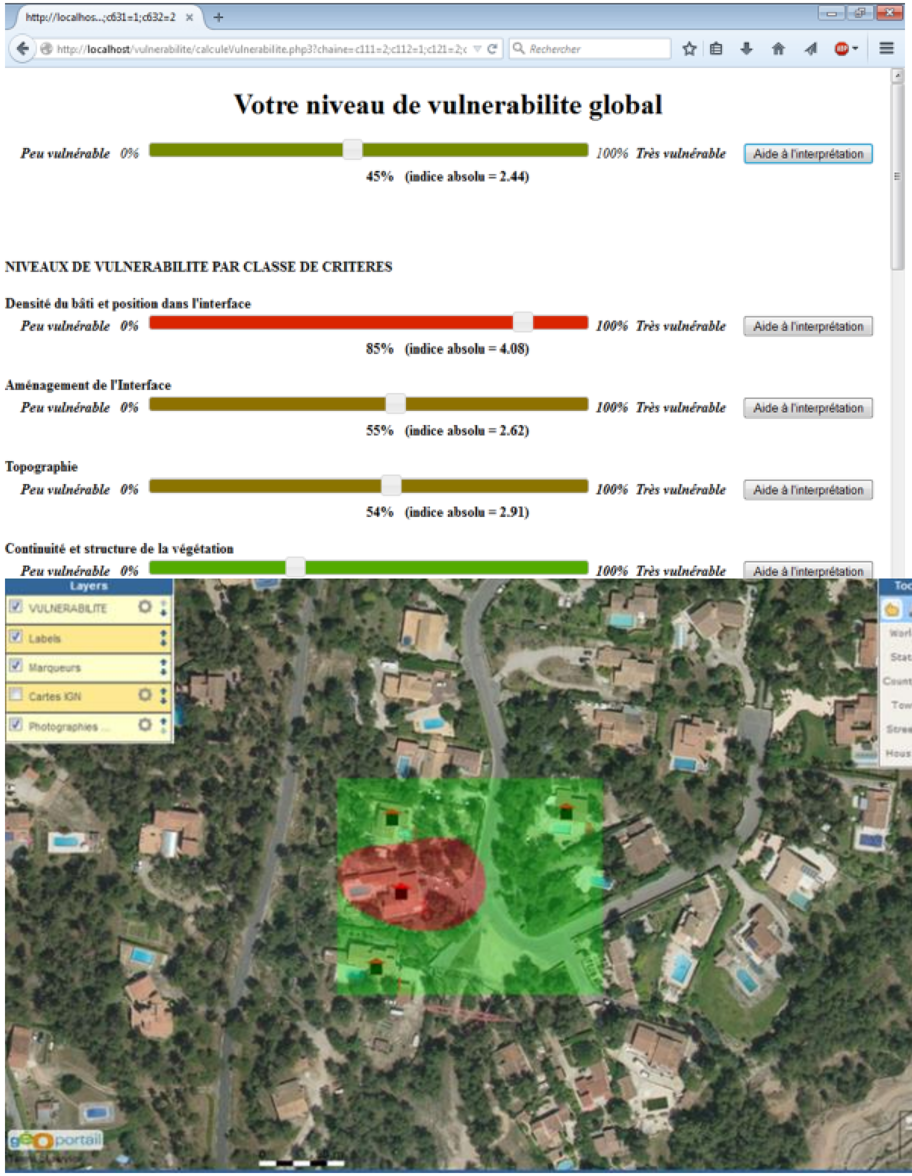
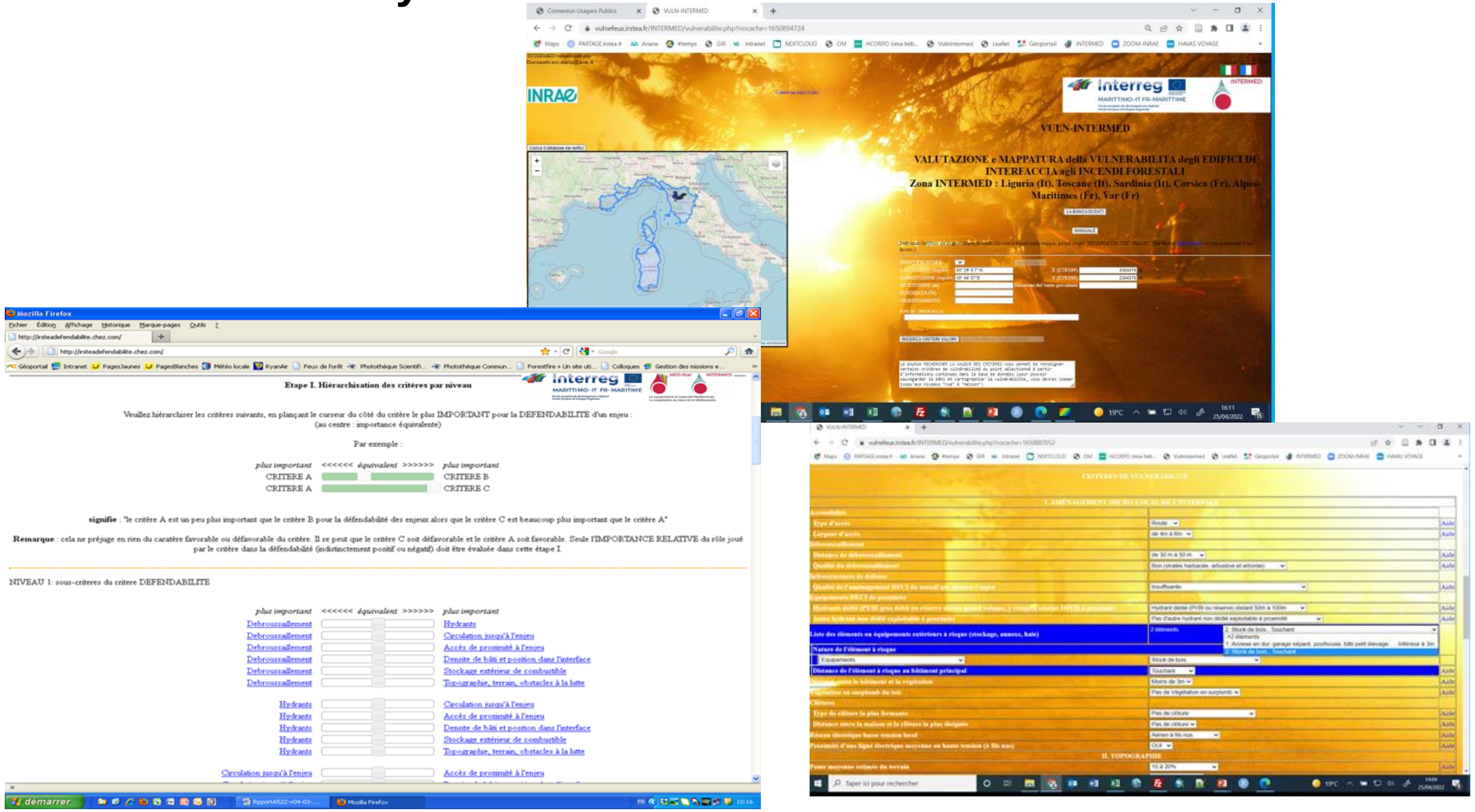
Experts' opinion based multicriteria modelling of vulnerability

RECOVER
risks - ecosystems
vulnerability - environment - resilience

- **Limitations of real size experimentation**

- **Experts opinion based modelling => multi-criteria analysis**





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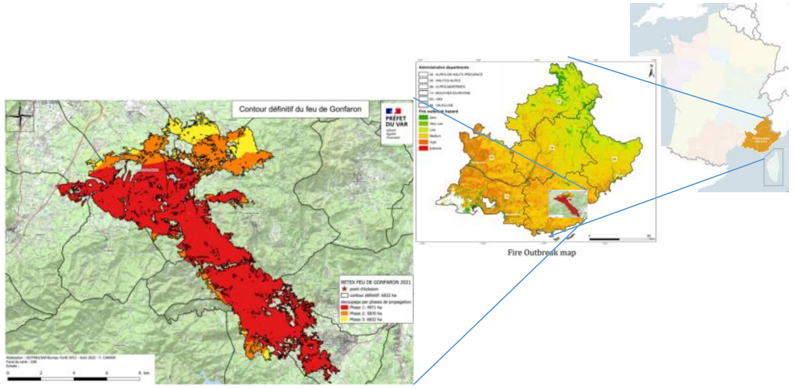
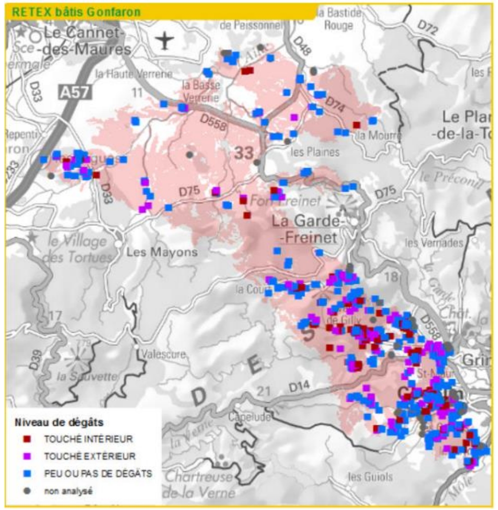
Damages explanation

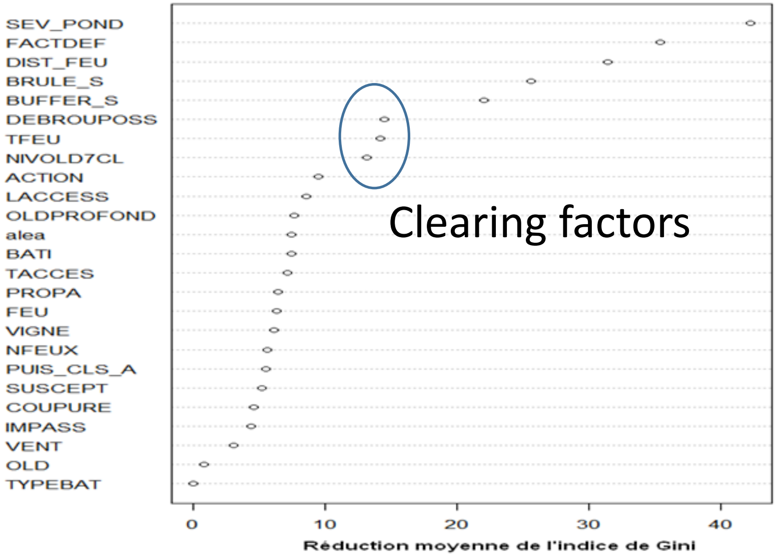
RECOVER
risks - ecosystems
vulnerability - environment - resilience



Gonfaron Fire,16-24/08/2021, 6832ha, 2 civilians dead
632 dwelling houses exposed, 346 damaged



Random forest (contribution to the Gini index reduction)



Clearing factors (logistic regression damaged/not damaged…)