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Numerical characterization of structures heat exposure at WUI

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Abstract

In the forthcoming years, self-protection of communities will be a first priority over fire suppression in order to tend to more fire-resistant and resilient WUI communities. All around the world, countries facing WUI fires apply different recommendations or regulations often issued from post-fire surveys. Still, more efforts are necessary to understand how and why dwellings are damaged or completely destroyed under WUI fires attack. In particular, there is a need to quantitatively assess the effectiveness of the current legal prescriptions for homeowners concerning the defensible space around dwellings. Three-dimensional, time dependent, computational fluid dynamics fire behavior models can take into account the factors interacting and contributing to WUI fires (i.e., weather conditions, terrain configuration, fire, vegetation and structures). Moreover, they allow the spatially-explicit modelling of vegetation elements (i.e., trees, shrubs, etc.). Thus, they can be supporting tools to quantitatively assess the heat (radiative and convective) exposure of structures during the approach of a WUI fire, in order to investigate how the characteristics of the defensible space can protect a dwelling or not against such a fire. This study addresses the characterization of heat exposure conditions of a dwelling in common Mediterranean WUI scenarios by using the three-dimensional, time dependent, computational fluid dynamics forest fire behavior model WFDS. To this purpose, WUI fire simulations have been carried out at the landscape scale, taking into account the different zones that a fire burns before it might approach and reach a home structure. This is, a forested area and the defensible space or cleared area around a dwelling. Two different scenarios have been studied, where different spatial patterns for the raised vegetation at the defensible space have been considered. One vegetation pattern has a low level of aggregation corresponding to a sparse spatial distribution of plants, whereas the other vegetation pattern has a higher level of aggregation representative of a clumpy distribution of plants. Both scenarios, in agreement with the current regulations in Corsica, have the same amount of available fuel load, as well as, the same number and characteristics of raised vegetation elements. Fire simulations for these two scenarios have been carried out at different wind and ambient conditions representatives on one side of normal dry summer conditions and on the other side of severe dry summer conditions. Heat exposure conditions have been characterized in terms of radiative and convective heat fluxes received by the structure. Special attention has been given on the role of fire – vegetation – wind interactions for the results and discussion.

1. Introduction

Fire events occurring at the Wildland Urban Interface (henceforth WUI), are responsible not only for important structure losses but also for human fatalities. In order to plan successful mitigation actions, it is necessary to understand the complex interactions between weather conditions, terrain configuration, fire, vegetation and structures during a WUI fire.

The existing wildfires risk mitigation strategies and the associated regulations concern different scales, from community scale (i.e., land use and fire regulations) to individual dwelling scale (i.e., building codes) (Duerksen et al., 2011). However, the susceptibility of a dwelling to undergo wildfire damages is strongly determined by its characteristics in relation to the immediate surroundings (Calkin et al., 2014), as already demonstrated by several studies (Cohen 2000; Cohen & Stratton, 2003; 2008).

The most common strategies to reduce dwelling's loss at individual property scale involve building construction materials (i.e., combustible, non-combustible, fire resistant), building design features (i.e., details of its different

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parts and the weak points in the building envelope like openings), and a defensible space around the dwelling by clearing ornamental vegetation and other material or secondary structures (i.e., sheds, fences, etc.) which can burn and impact the dwelling. However, self-protection plans of WUI settlements mainly concern the defensible space around dwellings since generally, building policies at WUI are only mandatory for new structures.

In the forthcoming years, self-protection of communities will be a first priority over fire suppression in order to tend to more fire-resistant and resilient WUI communities (Pastor et al., 2020). All around the world, countries facing WUI fires apply different recommendations or regulations often issued from post-fire surveys (Laranjeira & Cruz, 2014; Intini et al., 2019). Still, more efforts are necessary to understand how and why dwellings are damaged or completely destroyed under WUI fires attack. In particular, there is a need to quantitatively assess the effectiveness of the current legal prescriptions for homeowners concerning the defensible space (Mell et al., 2010).

Three-dimensional, time dependent, computational fluid dynamics fire behavior models can take into account the factors interacting and contributing to WUI fires (i.e., weather conditions, terrain configuration, fire, vegetation and structures). Moreover, they allow the spatially-explicit modelling of vegetation elements (i.e., trees, shrubs, etc.). Thus, they can be supporting tools to quantitatively assess the heat (radiative and convective) exposure conditions of structures during the approach of a WUI fire, in order to investigate how the characteristics of the defensible space around a dwelling can protect it or not against such fire.

This study addresses the characterization of heat exposure conditions of a dwelling in common Mediterranean WUI scenarios by using the three-dimensional, time dependent, computational fluid dynamics fire behavior model WFDS (Mell et al., 2007; 2009; Pérez-Ramirez et al., 2017). Heat exposure conditions have been characterized in terms of radiative and convective heat fluxes received by the structure, paying special attention to the openings in the building envelope (e.g., windows, shutters, etc.). It is worth noting that even though different exposure conditions are responsible for dwellings damage at WUI, this is, flame radiation, direct flame contact and firebrands (Caton et al, 2017), only the two first mechanisms have been considered in this study.

2. Numerical Modelling

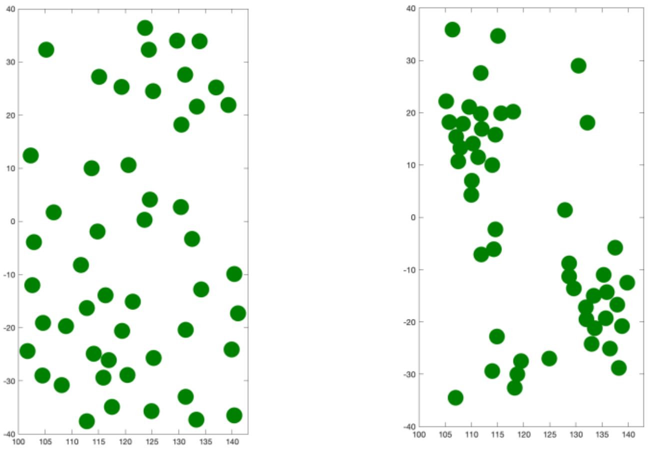
WUI fire simulations with WFDS have been carried out at the landscape scale to take into account the different zones that a fire has to burn before the fire front might approach and reach the home structure. This is, a forested area and the defensible space around the dwelling. The defensible space includes ornamental vegetation in the immediate surroundings of the dwelling and a cleared area.

2.1. Vegetation modelling

The forested area implemented corresponds to a high-density cork oak forest, composed by a canopy stratum of cork oaks (*Quercus suber*), a shrub layer of plants of rockrose (*Cistus monspelliensis*), tree heath (*Erica arborea*) and strawberry tree (*Arbutus unedo*) and a litter layer. To model the cork oak forest, data from field sampling, as well as, from the literature were used. Several hypotheses were considered to model trees and shrubs; this is, plants per species have the same dimensions and they have a uniform distribution of fine particles in the crown. Spatial patterns of raised vegetation plants were modelled by using spatial statistics and in particular a point process based on a hard core pairwise interaction model.

The defensible space was modelled by taking into account the current regulation in Corsica which concerns its dimensions (i.e., distance between the house and the forest), the specifications on tree thinning and the required tree spacing (i.e., trees/shrubs and/or hedges spacing in this area). The immediate surroundings to the dwelling are composed by grass and a hedge, which is a common ornamental vegetation structure used in Mediterranean WUI communities to delimit properties. The area in between the forested area and the immediate surroundings of the dwelling is the result of the clearing of the cork oak forest stand, and is thus constituted by a canopy layer of cork oaks and the resprouting of the shrub layer (i.e., 20 cm height).

The same hypothesis and methods were used for the modelling of the canopy layer in the cleared area. Two different vegetation patterns in terms of the spatial distribution of cork oaks were tested in this area, resulting in two different scenarios. These two vegetation patterns are in agreement with the regulation in Corsica but present a different level of aggregation for the canopy layer. One vegetation pattern has a low level of aggregation (cleared area type 1) corresponding to a sparse spatial distribution of trees, whereas the other vegetation pattern has a higher level of aggregation (cleared area type 2) representative of a clumpy distribution of trees (Figure 1). Both scenarios have the same amount of available fuel load, as well as, the same number and characteristics of trees. Consequently, only the spatial distribution of trees changes between these two configurations.



a) *b)*

Figure 1 – Vegetation spatial patterns in the cleared area. a) Sparse distribution. b) Clumpy distribution.

2.2. Numerical cases setup

Fire simulations for the two scenarios (i.e., forest – cleared area type 1 – ornamental vegetation – dwelling and forest – cleared area type 2 – ornamental vegetation – dwelling) were carried out for different wind and ambient conditions. Two wind velocities were tested corresponding to a mild to moderate wind and a strong wind, representative for more extreme conditions. In the same way, two sets of ambient conditions and fuel moisture content were studied, one set being characteristic of normal dry summer conditions and the other set being representative of severe dry summer conditions. Fuel moisture content values for the different species considered were obtained from historical records of the French operational network called "Reseau Hydrique" (Martin-StPaul et al, 2018). Table 1 summarizes the different scenarios and conditions tested in this study.

Table 1- Specifications of the different scenarios and conditions tested (RH: Relative Humidity, FMC: fuel moisture content on dry basis)

Forested area	**Cleared area**	**Wind conditions**	**Ambient conditions – Fuel moisture content**
High-density cork oak forest stand	**Vegetation distribution type 1**	**Low-moderate wind**	**Dry conditions**
	Low aggregation pattern	25 km/h	32°C, 20 % RH 52 % - 81 % FMC
	Vegetation distribution type 2	**Strong wind**	**Severe dry conditions**
	High aggregation pattern	45 km/h	40°C, 10 % RH 23 % - 60 % FMC

The computational domain size was 275 m x 80 m x 70 m (Figure 2). The domain was subdivided into two area, the first one covering all the surface of the domain up to 32 m height, and the second one covering the upper part of the domain. In the first area, where combustion takes place, the grid cell size was $\Delta x=\Delta y=\Delta z=25$ cm, whereas in the second area the grid cell size was $\Delta x=\Delta y=\Delta z=50$ cm. A 1/7th power law profile was used at the inlet of the domain to implement the wind condition. Ignition was delayed to allow the wind field to fully develop in the whole domain. Periodic conditions were applied at both left and right sides of the domain. A free slip conditions was used for the top boundary, while an open boundary condition was prescribed at the outlet of the domain.

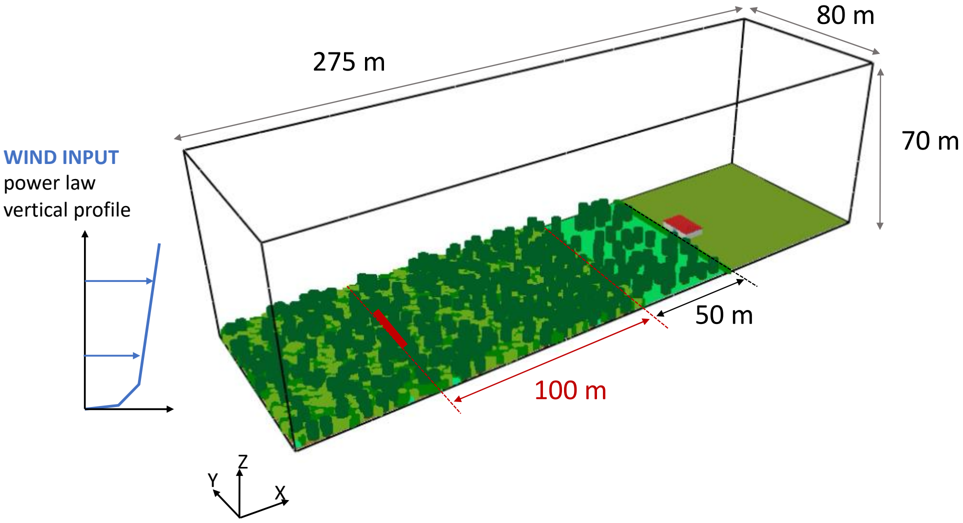


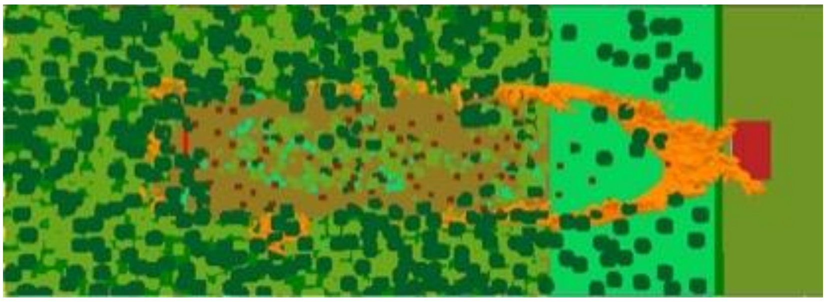
Figure 2 – Numerical domain implemented

Surface fuels (i.e., litter, grass and the shrubs regrowth in the cleared area) were implemented by using the fuel boundary model coupled with a linear pyrolysis sub-model for the thermal degradation of the solid-phase. The other vegetation elements were implemented by using the fuel element model combined to an Arrhenius type model for solid-phase degradation including char oxidation.

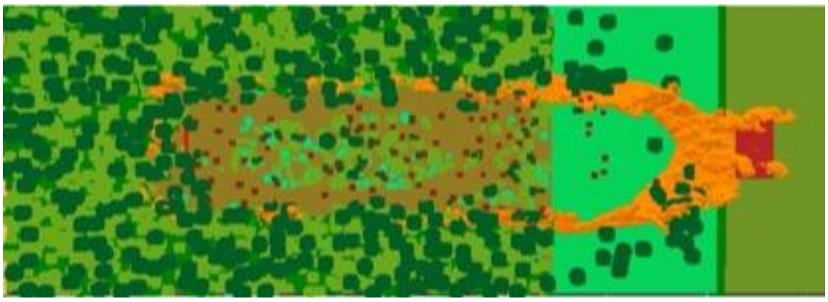
Different openings were implemented in the dwelling façade the most exposed to the fire, this is, a central French window and two windows on both sides of the French window.

3. Results and Conclusions

The distribution pattern of trees in the cleared area affects the wind patterns nearby the dwelling, which in turn affect the burning dynamics. As it can be seen in Figure 3 for the worst-conditions cases, this is cases spreading under a strong wind and very dry conditions, the position of the fire front and its shape at the same instant of time differ from one case to another. For the vegetation pattern corresponding to a low level of aggregation (Figure 3a)) the fire front shape is not symmetric to the centerline and thus the heat exposure conditions vary from one window to another (Figure 4a)). For the other vegetation scenario (Figure 3b)), the fire front profile is almost symmetric to the centerline so that the heat exposure conditions in terms of the duration and maximum heat exposure of windows are similar even though some differences are observed that can be explained by the presence of a group of trees in front of one of the windows (Figure 4b)).

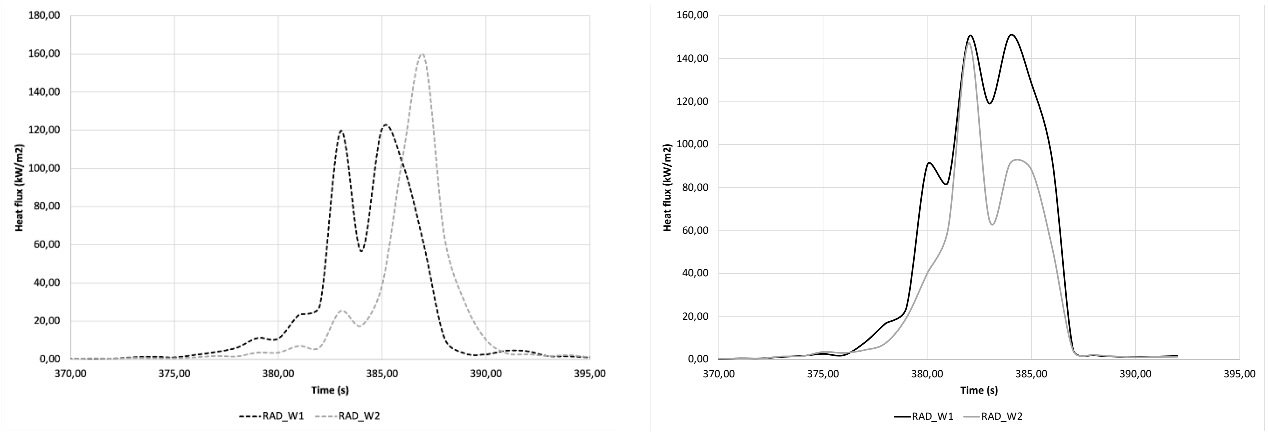


a)



b)

Figure 3 – Snapshots as rendered by Smokeview for the worst-conditions cases at the same instant of time. a) Vegetation distribution type 1. b) Vegetation distribution type 2.



a) *b)*

Figure 4 – Total heat fluxes received by side windows for the worst-conditions cases. a) Vegetation distribution type 1. b) Vegetation distribution type 2.

As illustrated in Figure 5, heat release rate tendencies for both cases are similar during the combustion phase in the forested area and differences are observed once the fire front reaches the cleared area (at about 340 seconds) due to the differences in combustion dynamics in this area. Results for the cases run in the other conditions (Table 1) are in agreement with these results.

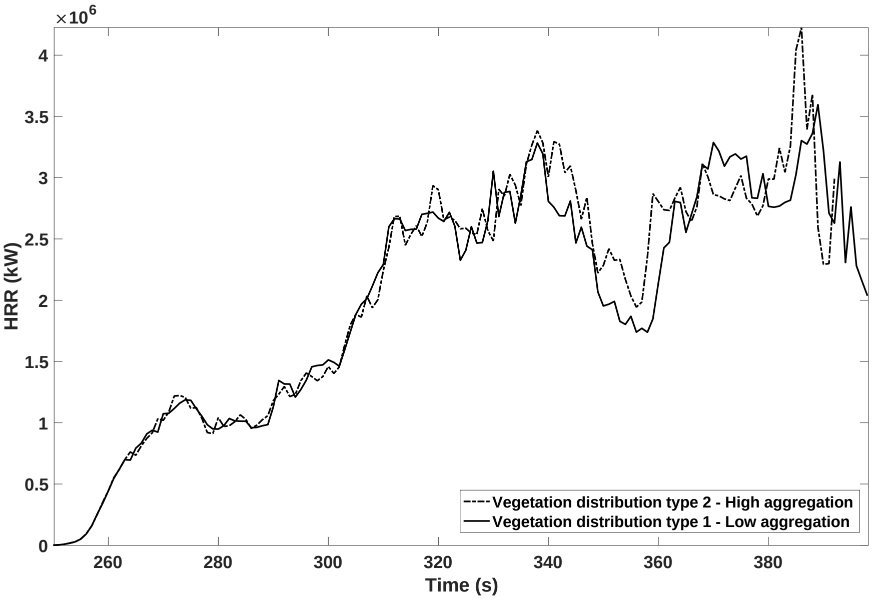


Figure 5 – Heat Release Rate for the worst-conditions cases

This study highlights the role of heterogenous patterns of vegetation on the burning dynamics for a WUI fire scenario and thus on the thermal exposure conditions of a dwelling, due to the interactions between vegetation, wind and fire itself. However, a deeper analysis including simulations of other vegetation patterns, is need to obtain statistically significant conclusions.

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