Understanding the behaviour of wildfire on the scale of landscape: a 3-dimensional physical approach

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Introduction

Understanding the behaviour of wildfire can be attempted theoretically, experimentally or by modelling. The scientific literature teaches us that the propagation of wildfire and its impact result from mechanisms that even when taken singly are complex but, in fact, act together coupled in tandem: aerodynamics, heat transfer, thermal degradation of vegetation (pyrolysis), combustion. Though the theory of such mechanisms is well established and provides a qualitative understanding of each of them, their combination, allied to the highly variable nature of forest fuels and the need to quantify each phenomenon, necessitates experimentation and modelling. However, experimenting with forest fires in natural conditions is difficult: weather conditions and the level of moisture in the vegetation vary daily and are not easy to predict. Furthermore, carrying out measurements is complicated, while burning is subject to legal constraints and property rights. For such reasons, modelling has long been the preferred tool for studying the mechanisms of forest fires and forecasting their spread and impact.

The models for the propagation of wildfire belong to two broad categories, empirical and physical (SULLIVAN 2009a, b). Empirical models are designed using databases of experimental results, frequently obtained in the field, sometimes in the laboratory, and they establish a statistical connection between certain characteristics of fire, most often the speed of its advance, to environmental conditions (wind, slope) and the type of fuel. By the very nature of these models, the validity of the forecasts based on them is limited to the conditions which governed their design –a range of winds, slopes and vegetation- but which do not permit us to investigate the mechanisms of wildfire. Moreover, up until the 1990s, such models took no account of aerodynamics and simplified excessively the processes involved in combustion, generally confined to data about the characteristics of a flame. It is only since the end of the '90s that a more exhaustive physical approach has taken into account combustion and the aerodynamic effects which result from the interaction of atmospheric wind, winds induced by the fire, vegetation and topography. This approach requires projecting the equations for conservation in physics onto a spatial grid spread over time. The technological development in computational capacity has been largely responsible for this evolution. The models resulting from this approach are scarce (three or four in the world) and here we will focus on the HIGRAD-FIRETEC model developed jointly by the Los Alamos National Laboratory (USA) and INRA- Avignon (France) (LINN *et al.* 2005, PIMONT *et al.* 2010). This model makes it possible to carry out numerical simulations for the spread of wildfire including (i) three dimensions (ii) natural conditions and (iii) a small-scale landscape (< 2 km), such functional parameters are not as yet all present in other models. The spatial resolution of the model is around 2 m.

Using a few examples, we will show in what way the model helps to understand the propagation of forest fire and illustrate its potential for operational predictions.

Validating the model

The model used for investigating or forecasting the behaviour of wildfire must be validated if realistic conclusions are to be drawn from numerical simulations. Several validation procedures have been carried out for the HIGRAD-FIRETEC model. The three experimental fires visible in picture 1 were all ignited at the same time but with lines of fire of different widths. It is quite clear that the greater the width, the faster the fire spreads. The model was able to reproduce this observation (LINN *et al.* 2005). Predictions by the model about the speed of propagation were also compared to speeds observed in various conditions of plant cover and environment. Table 1 shows that predictions were very reasonable though it should be noted that the fires were in low-level vegetation (no trees). A farther-reaching comparison with experimental crown fires conducted in Canada is currently under way. Simulations of wind blowing within a forest have also been successfully validated on the basis of accurate data (PIMONT *et al.* 2009). This is an important validation because wind, an essential factor in the behaviour of wildfire, displays complex behaviour amid tree cover. The model has also been used in Galicia (Spain) to simulate experimental counter-fires and the qualitative conclusions drawn from the experiments and the model were similar.

It should be noted that validating a model is often a difficult procedure because the modeller must know in precise detail all the experimental conditions and be capable of representing them in the model. The procedure can lead to modifications in the model so as to enhance the forecasting but such modifications themselves entail yet further validation.

Picture 1: Experimental fires in Australian grassland. The three fires were started at the same time but with three different widths. *© P. Cheney and A. Sullivan* (Cheney *et al.* 1993).

Importance of 3-dimensional modelling

Some physical models represent fire only in two spatial dimensions, for example on a vertical plane (vertical cross-section of a line of fire); this offers the advantage of a reduction in the time needed for calculating a simulation. But the need to take into account three dimensions appears in a study applied to counter-fires. The efficacy of a counter-fire is assumed to be enhanced by a draught created some tens of metres or more in front of the fire being fought (ARÉVALO 1968, BENOIT DE COIGNAC 1986). Three-dimensional simulations with the HIGRAD-FIRETEC model revealed that in numerous situations the

Fuel type	Fuel height (m)	Fuel load (kg/m²)	FMC (1) (%)	Fire width (m)	Wind speed (m/s)	Rate of spread (m/s) FIRETEC	Experiment
Shrubland France (2)	0.3	0.5	80	10	2.7 at 2 m	0.08	0.07
	0.4	0.8	140	10	5.6 at 6 m	0.10	0.07
	0.4	0.8	70	10	5.7 at 6 m	0.12	0.09
Shrubland Spain (3)	0.5	2.2	65	25	2.1 at 2 m	0.039	0.043
Grassland Australia (4)	0.7	0.7	5	50	3.0 at 2 m	0.7	0.7-0.8
	0.7	0.7	5	50	6.0 at 2 m	2.8	1.8-2.7

Tab. I:
FIRETEC predicted versus experimental rates of spread in shrubland and grassland fires.

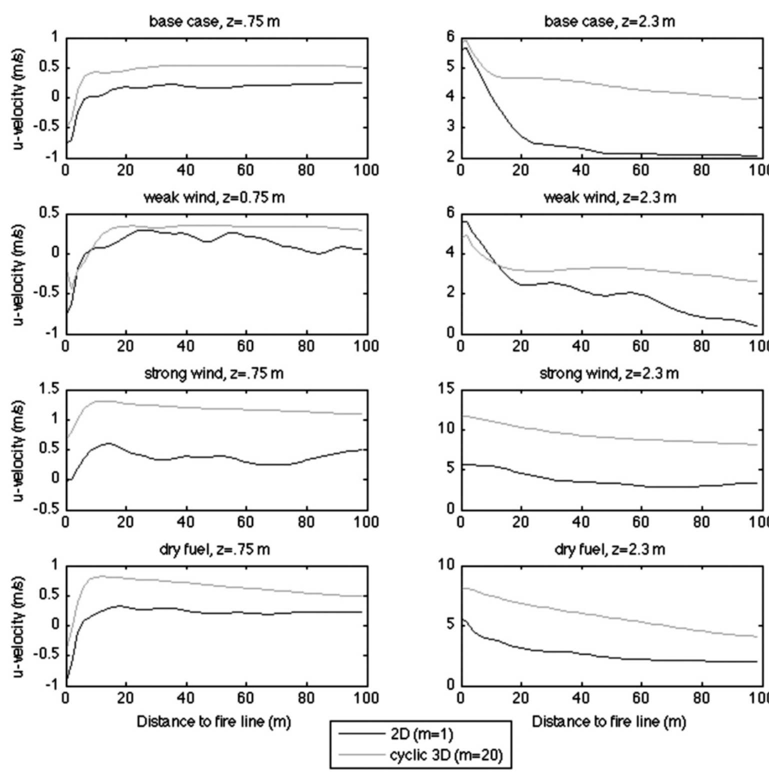
(1) FMC Fuel moisture content
(2) INRA's data, Beauchamp and Trou du rat experiments
(3) CIFL's data, Edres and Carballas sites, Galicia
(4) Cheney *et al.* 1993

reality of such draughts is limited to only a few metres. In fact, only special topographical conditions (fire travelling down a slope) may give rise to such a draught before the fire at distances having a material effect on operations. These results corroborate observations recorded during the course of experimental counter-fires.

To highlight the role of a three-dimensional matrix in aerodynamic phenomena associated with wildfire, the propagation of surface fires in various conditions of wind and vegetation were simulated in both two and three dimensions using the HIGRAD-FIRETEC model. The horizontal profiles of the local wind, in front of the fire as well as at the height of vegetation, were extracted from the simulations and compared for the two positions (cf. Fig. 1). It appears that the "lee- or up-fire" wind is systematically underestimated by two-dimensional calculations and that a draught at a significant distance from the fire can appear in such simulations. In a three-dimensional calculation, the prevailing wind can "blow through" the line of fire at certain points and be deflected upwards by the strength of the plume at points nearby whereas in two-dimensional calculations the prevailing wind can only "pass" above the flames or "flatten" the flames and the plume. It can be seen from such wind profiles that a two-dimensional calculation will predict conditions more favourable for igniting a counter-fire than will a three-dimensional one. Finally, while draughts can eventually occur locally and momentarily in front of the fire-line, they are unstable from one minute to the next or from one spot to another. This makes the efficacy of draughts from counter-fires that much more haphazard. Figure 2 shows why: the wind "downwind" of the fire acquires a structure made up of lines of wind in parallel, with speeds alternately fast and slow; and close to the line of fire there appear localised updraughts coexisting along with countervailing air flows in the direction of the prevailing wind. The result shown in Fig.2 was obtained with the prevailing wind speed assumed to be constant, which explains the air flow pattern of parallel lines. A wind with a varying direction would generate more complex structures.

These conclusions do not call into question the principle of counter-fires used to deprive a wildfire of fuel. They indicate that a line of counter-fires ignited close to the front of the

Fig. 1: "Down-fire" wind speed as a function of the distance from the fire line at 0.75 m from the ground (left) and at 2.3 mm from the ground (right). In *black*: two-dimensional simulations, in *grey*: three-dimensional simulations. In the basic context, the vegetation is a homogeneous *garrigue* bush cover with kermès oak and a moderate prevailing wind (20km/hr at 10 m above ground level). The weak wind corresponds to a 10 km/hr wind, strong wind to 40 km/hr, with the same vegetation. Dry fuel (bottom) was also tested (scrubland in summer).



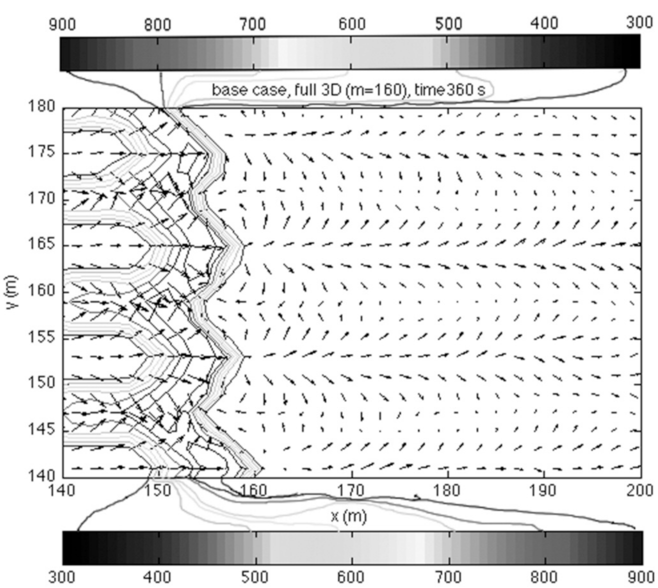
wildfire does not guarantee a positive effect related to a draught being created whereas such a line certainly increases the degree of risk in comparison to fires set off farther away from the wildfire.

Behaviour and impact of wildfire in tree stands

The simulation of fires in plant cover representing a stand of Aleppo pine thinned out in its centre made it possible to quantify the effect of thinning as a function of its severity and structure (PIMONT *et al.* 2010). The degree of severity was defined by stands left after thinning with 50%, 25% or 0% cover (an untouched stand having a cover of 75%). The structure of the thinned area (clumps of trees) was tested for a stand showing 25% tree cover, using clumps of 4, 10 and 20m diametre, as well as for a theoretical case in which the tree cover was uniform throughout the thinned area. The low bush cover remained unchanged in the thinned-out area, thus likely to represent a fuel break lacking in upkeep.

Figure 3a shows a clear reduction in the intensity of the wildfire (strength in kW/m) with 25% thinning. 50% tree cover led to no significant reduction from an operational point of view. With no trees (0%), the strength was equivalent to the 25% level: without trees, the total biomass is less (which reduces the intensity of the fire) but the wind at the level of the bushes is stronger (increasing the speed of propagation of the fire and hence its intensity). The model takes into account these effects. Figure 3b shows that the clump structure has no impact on the intensity of the fire. In fact, additional simulations have shown clumps impact on the intensity of the fire when the trees have a thick, densely-leaved canopy to an extent not found in Mediterranean pines.

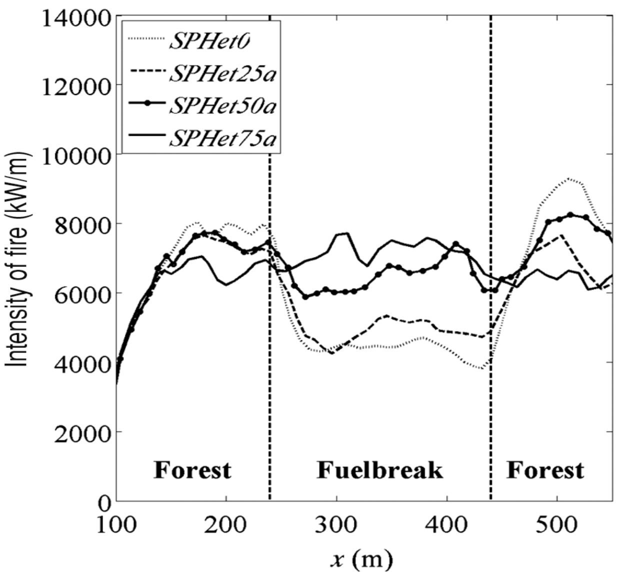
Fig. 2: Local "down-fire" winds, seen from above. The prevailing wind is blowing from left to right in direction x. The coloured contour lines represent gas isotherms (temperature in Kelvin). The vectors represent the horizontal dimension of local wind speed.



An unexpected outcome of the study is the identification of "streets" of tree crowns less affected by the fire (Fig. 4). Such streets are linked to a swirling effect of vortices around a longitudinal axis parallel to the prevailing wind. The swirling has a strong impact as it rises (upward movement of hot gases) and less as it plunges (descent of cooler air).

In a simulation of a surface fire spreading beneath a tree canopy, the HIGRAD-FIRETEC model predicted the air temperature within the canopy and notably made it possible to estimate the height of leaf scorching on the trees on the basis of a lethal temperature. The threshold is generally set equal to the exposure of pine needles to a temperature of 60° for one minute. Leaf scorching is often a reliable indicator of the likely mortality for pines after wildfire (FERNANDES *et al.* 2007). Simulations of a source of heat with a fixed intensity beneath an Aleppo pine stand showed that a limited mortality was only ensured at very low intensities (<500kW/m). This is particularly the case with Aleppo pine because the lowest branch with needles is close to the ground. The result indicates that there are only fairly limited slots for controlled burning. These simulations have revealed an insignificant impact by the prevailing wind (straight wind or wind high above the canopy) on leaf scorching when fire intensity is fixed. But leaf scorching increases with wind because the intensity of surface fires is increased by wind. Finally, a greater leaf scorching density leads to leaf higher up (when the leafy area is uniformly spread out horizontally i.e. no gaps between the trees). The more dense the vegetation, the more it hinders the movement of air, thus limiting the mixture of fresh air with the combustion gases. The temperature then rises at the same level above the ground when the leaf cover is denser (effect observed for an index of leaf surface area from 2 to 6).

3a



3b

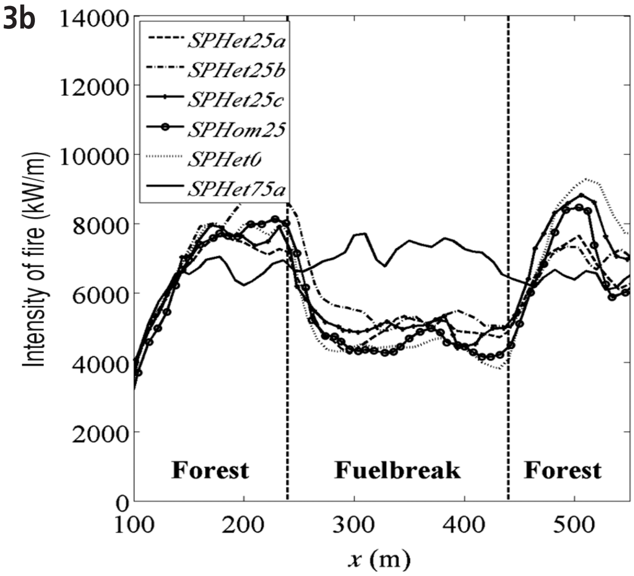


Fig. 3: Intensity of fire (strength in kW/m of width of fire front) as a function of the distance covered. The fire, starting up in an unthinned Forest, is spreading from left to right towards a thinned but uncleared stand (Firebreak).
(a) percentage of tree cover in the thinned areas (75%=unthinned, 0%=no trees).
(b) size of clumps (a: 4 m, b: 10 m, c: 20 m; Hom: homogeneous); unthinned=75%, mentioned again.

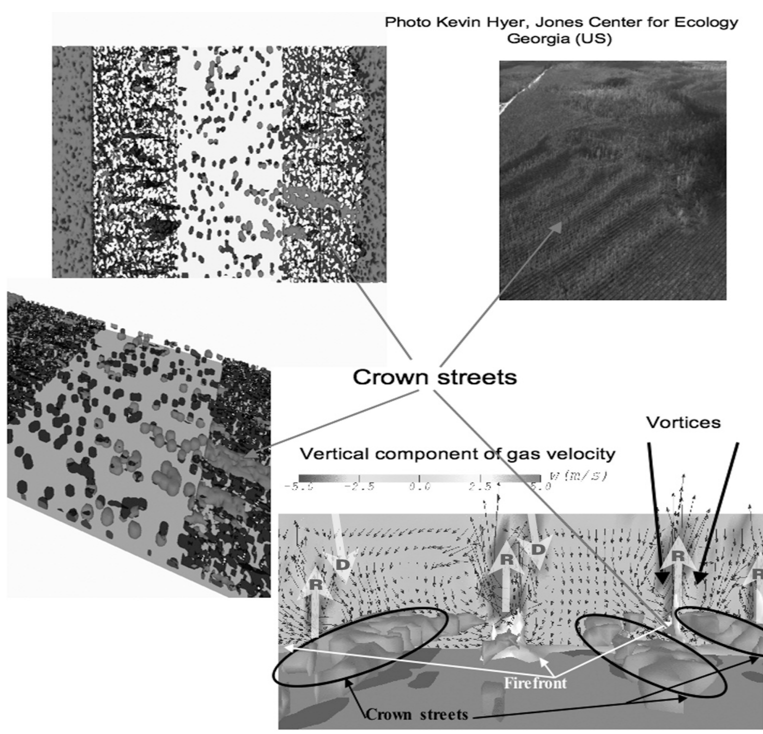
Wildfire and topography

In order to simulate the propagation of a wildfire on a map, existing operational simulators must combine the effects of the local wind and the slopes in the possible directions of propagation. Such combinations are achieved using relatively simple empirical models that consider the effect to be the addition or the multiplication of the two factors. The simulations performed with the HIGRAD-FIRETEC model do not accept this approach. Figure 5 shows fire speed simulated as a function of the slope of the terrain for a strong and for a light wind and for a narrow and a wide fire (front of 20 or 50 m). Clearly, in general the effects are neither cumulative by addition nor multiplication. Furthermore, such effects are highly dependent on the size of the fire, a factor not taken into account by existing models.

In furtherance of this study, the simulation of a fire starting out in a canyon highlighted a rapid conflagration up the steeper sides after fairly slow burning in the canyon bottom. The line of fire at the foot of the slopes can reach a great length which in turn favours a very rapid conflagration up the canyon walls. Such behaviour should be borne in mind in relation to serious accidents during operations when a weakly-burning fire at the bottom of a canyon might lead people to think there is no particular danger involved.

Overall, these results can be attributed to the complex interaction between wind, topography and fire which together modify the air flow depending on the situation.

Fig. 4: Damage to trees and crown streets spared by the fire. The images on the left represent the degree of leaf density remaining in the canopy after fire (black: low; grey: high), as calculated by HIGRAD-FIRETEC.
The photo above left, taken in the USA, shows that a street can form a simple pattern. The image below right represents the algebraic value of the vertical component of the local wind: rising currents (R), descending (D). The arrows represent the component of the wind in a vertical plane, enabling the swirling effect – to be seen.
Such local winds are also calculated by the model



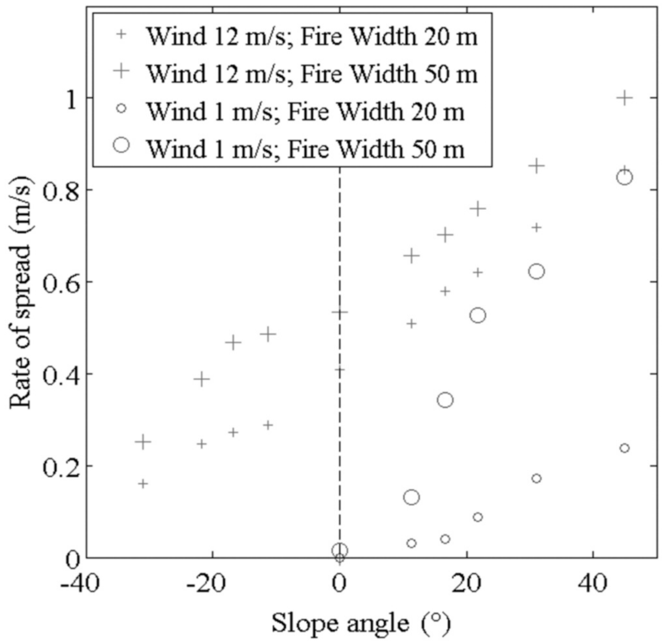


Fig. 5:
Rate of spread as a function of the slope angle for two wind speeds and two fire widths

Conclusion

A model based on coupling fire and atmosphere, such as the HIGRAD-FIRETEC model, provides the scientist with a very powerful tool for investigating the complex interactions that occur during a forest fire. Both the means for calculating and the level of expertise involved are at a very high level such that it is hard to envisage their use by managers and policy makers. Even so, the operational scope for numerical simulations is indeed real and researchers should undertake to transfer to those involved in operations new knowledge acquired through such simulations. Eventually the use of this type of model by specialist consultancies should facilitate and accelerate such transfer.

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