Assessment of the plume theory predictions of crown scorch using transport models

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Resume :

Crown scorch was assessed using transport model, which gives the following conclusions. Canopy has an effect on the plume development, which tends to increase scorch height. Even weak winds strongly tilt the plume from vertical. Wind speed has small effect on scorch height (heat source is set to a constant value). Plume theory predicts strong effect of wind speed on scorch height through inclination of the plume.

Abstract :

The aim of our work is to study numerically crown scorch as the effects of a fire line spreading through surface fuel under a tree canopy. The objective was to assess the usual assumptions made when one uses the Van Wagner criteria, which are indeed simple predictive models for crown scorch height, to estimate crown scorch. For this purpose the FIRESTAR 2D and FIRETEC wildfire simulators are used. We simulated the fire line by a heat source at ground level and mainly investigated the temperature field. As a first step, we ran computations of thermal plumes with no-wind and with no canopy, for first comparison to plume theory. The influence of crown existence on the temperature field above the heat source, as well as on crown scorch, was then investigated. As a second step, the effect of a wind to the plume, as well as to crown scorch, was shown for the no-canopy and canopy cases.

Keywords : Crown scorch, plume theory, Van Wagner criteria, FIRESTAR 2D and FIRETEC wildfire simulators

1 Introduction

The Van Wagner criteria are simple predictive models for crown scorch height, based on plume theory. These criteria are widely used by forest engineers to assess the risk of crown scorch in the prescribed fire operations.

Following some preliminary work [1, 2], Van Wagner derived from the plume theory a formula relating the crown scorch height with the linear fire front intensity [3]:

$$h_s = k \frac{I^{2/3}}{60 - t_a} \sin A , \qquad (1)$$

where h_s (m) is the crown scorch height, I (kW/m) is the linear fire front intensity, t_a (°C) is the ambient temperature, A is the plume inclination angle. The numerical constant can be derived from the experimental data (Tab. 1).

k estimates	**k**	**Wind speed m / s**	**Intensity kW / m**	**Tree species**
Field exp. (scorch height) :				
Saveland and Neuenschwander (1990)	**2.7**	?	70-3600	Pinus banksiana,resinosa,strobus, Quercus rubra
Van Wagner (1973)	**4.5**	1	80-1250	Pinus ponderosa
Burrows et al. (1989)	**8.7**	0 to 2	20-220	Pinus radiata
Finney & Martin (1993)	**8.9**	0 to 2	60-2350	Sequoia sempervirens, Pseudotsuga menziesii
Lab. Exp. (thermocouple data)				
INRA lab. data (2007)	**11.5**	no wind	49-240	-

TAB. 1 – Experimental estimates for the Van Wagner coefficient.

Crown scorch was assumed to appear at the usual value of 60 °C. This temperature threshold is actually well adapted for the prediction of tree foliage necrosis, even if higher thresholds should be used for vegetative buds [4]. Vegetative buds have indeed a higher response time to a heat flux than needles, due to their lower surface-to-volume ratio. Here, we will consider that the fuel elements are in thermal equilibrium with the gaseous phase, which thus is well supported for foliage (except during water evaporation process), but not for buds. A basic assumption of plume theory is to consider points far enough from the heat source. It also means that the main mechanism of heat transfer is convection, since heat-conduction or radiation should only be significant close to the source. Van Wagner criterion also assumes that the plume structure is not significantly affected by the presence of a canopy. In [3], Van Wagner investigated the effect of a weak wind on crown scorch. By a weak wind, we mean that plume structure is not destroyed with wind, but just inclined [2]. The inclination angle is given with the expression:

$$\tan A = \left(\frac{0.026\, I}{U^{3}} \right)^{1/2}, \tag{2}$$

where U (m/s) is the wind velocity.

In the present study, we intended to assess the main assumptions made in the previous theory. To investigate numerically crown scorch as the effects of a fire line spreading through surface fuel under a tree canopy, we used two different physically-based fire models: FIRESTAR 2D [5] and FIRETEC [6]. In both models, a heat source was implemented, as a rectangle area located in the middle of the domain and put at ground level. The heat source represents a steady fire line of given intensity (power in kW/m). The influence of a canopy and an ambient wind were also included.

2 No wind simulations (FIRESTAR 2D)

2.1 No canopy simulations

We first considered the case without any crown and compare the results of FIRESTAR simulations (‘virtual crown’) with predictions of Van Wagner formula for crown scorch. In both models crown scorch was assumed to occur when gas temperature reached 60 °C. Fig. 1 shows the minimum intensity necessary to get crown scorch at a given height above the ground.

The predictions of FIRESTAR were fitted to a power law of the fire intensity as shown at Fig. 1 leading to the following formula

$$h_s = 11.6\, \frac{I^{2/3}}{60 - t_a}. \tag{3}$$

The obtained Van Wagner coefficient value is 11.6, that is close to INRA lab. data (Tab. 1). The agreement in crown scorch predictions is excellent.

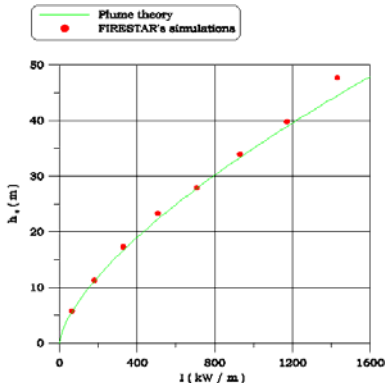


FIG. 1 – Crown scorch height as predicted by FIRESTAR 2D in absence of tree canopy (‘virtual crown’).

2.2 Tree canopy influence

We defined a tree canopy model based on field measurements of a variety of Aleppo pine (Pinus halepensis) forests in Greece [7]. The maximum density was 0.16 kg/m^3 and the average value was about 0.08 kg/m^3. We added a second family of fuel representing the smallest twigs (0-6 mm diameter) with a maximum density half the one of the needles and the same vertical profile. This tree canopy model is called ‘light crown’ in the following.

We also defined a very dense tree canopy by setting the maximum value of needles density to 0.8 kg/m^3 (five times denser than the light crown). This second canopy modeled is called ‘dense crown’ in the following (we ignored twigs in this case). The dense crown can be viewed as a limiting case, not as a realistic canopy.

We used a area-to-volume ratio of 10000 m^{-1} and a material density of 800 kg/m^3 for needles (data measured on Pinus halepensis, INRA).

Fig. 2 shows scorch heights computed for different pine densities. We also plotted the plume theory prediction and the prediction of FIRESTAR with no crown (‘virtual crown’) for comparison. Obviously the presence of the canopy increased the crown scorch height with respect to the ‘virtual crown’ or plume theory predictions. Furthermore, the presence of the canopy had more effect for a dense canopy.

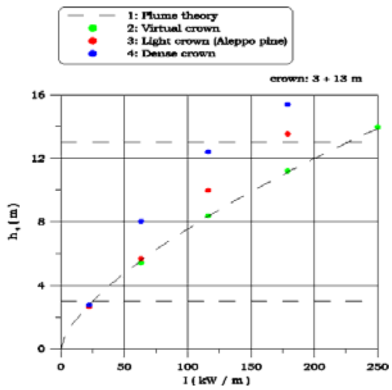


FIG. 2 – Crown scorch heights as function of heat source intensity for crowns ranging between 3 and 13 m.

3 Wind case results (FIRETEC)

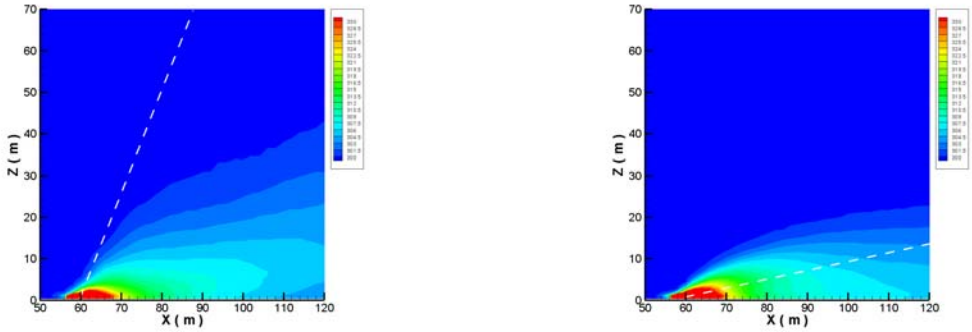
Here, we considered the effect of a wind on the plume above the heater for the no-canopy and canopy cases, using the FIRETEC code.

Because the turbulence model of FIRETEC is based on a LES-approach, the most significant part of the turbulence is explicitly solved by the model. In order to obtain mean results, the outputs of FIRETEC were averaged over a significant period of time. To get mean scorch height, we used also series of the average procedures during each one minute, that is a characteristic crown scorch resistance time.

A vertical wind profile was introduced at the inlet boundary as

$$U_x = U_0 \left(\frac{z}{H} \right)^{1/7}, \quad (4)$$

where the reference height H is equal to 30 m. The wind speed is defined here with the reference velocity U_0 . We tested four wind velocity levels: 1 m/s, 2 m/s, 5 m/s and 10 m/s; and three power levels: 250 kW/m, 500 kW/m, and 1000 kW/m.

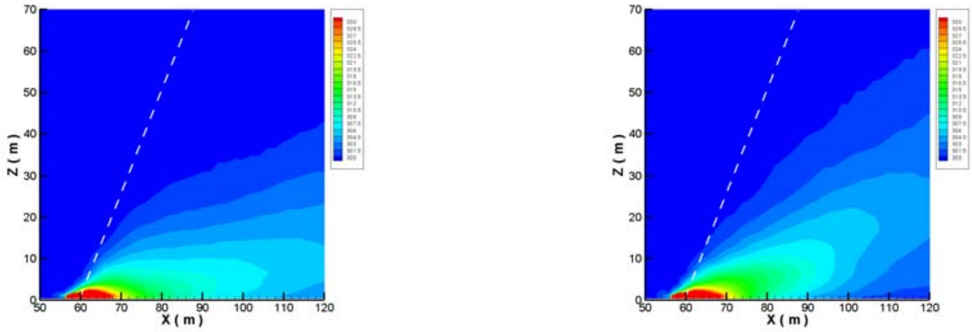


a) Power 250 kW/m and wind 1 m/s b) Power 250 kW/m and wind 5 m/s

FIG. 3 – Images of the plume temperature field for two wind velocity levels and one power level.

One can see significant inclining of the plume with rather weak wind (1 m/s) (Fig. 3). We observed a similar effect with FIRESTAR 2D simulator. As expected, the plume is colder when wind speed is higher. The dash lines at fig. 3 present the plume inclination calculated with the plume theory and show significant difference between the plume theory and the FIRETEC data.

We then tested the effect of the tree canopy presence on the plume. The density was 0.085 kg/m^3. The canopy extended between 3 and 13 m in both cases. A pre-computation of the wind field using cyclic-conditions at inlet and outlet boundaries of the domain was performed to properly establish the turbulence due to the canopy layer. Canopy strongly reduced wind under the canopy, but wind is the same at the top of the domain in no-canopy and canopy cases.



a) No canopy b) Canopy density 0.085 kg/m^3

FIG. 4 – Images of the plume temperature field for power 250 kW/m and wind 1 m/s for the no-canopy (a) and canopy (b) cases.

Fig. 4 illustrates that the canopy existence makes the plume much less inclined. Hence we expect a significant effect of the presence of the canopy layer on the plume and on the temperature distribution, as compared to the predictions of plume theory, which does not consider the canopy effect. One can see it at fig. 5 where vertical temperature profiles are presented. Profiles are rather similar for the different wind cases, but The difference with no-wind case is huge.

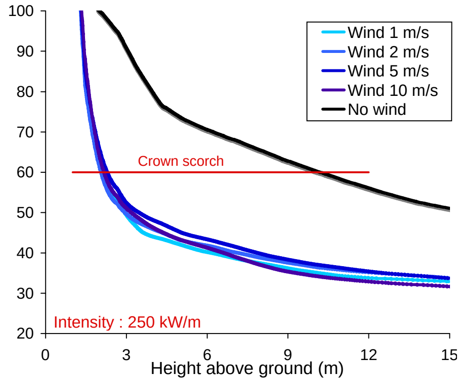


FIG. 5 – Vertical profile of maximum temperature within the canopy layer.

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