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ORIGINAL PAPER

Impacts of tree canopy structure on wind flows and fire propagation simulated with FIRETEC

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Abstract

- ***Introduction*** Forest fuel management in the context of fire prevention generally induces heterogeneous spatial patterns of vegetation. However, the impact of the canopy structure on both wind flows and fire behavior is not well understood.
- ***Material and methods*** Here, a coupled atmosphere wildfire behavior model, HIGRAD/FIRETEC, was used to investigate the effects of canopy treatment on wind field and fire behavior in a typical Mediterranean pine ecosystem.
- ***Discussion*** First, the treatment-induced winds were simulated with the model. We observed that with decreasing cover fraction the wind velocity increased within the treated zone. The wind spatial variability increased when the vegetation was aggregated into larger clumps. Fire simulations indicated that a decrease of fire intensity occurred after several meters of propagation in the treated zone. This intensity decrease was significant with a cover fraction below 25%, but negligible with a cover fraction greater than 50%. The treatment also induced a more significant inclination of the plume away from vertical. The size of the tree clumps did not show significant effects on fire behavior.
- ***Conclusion*** This study was a preliminary investigation of wind/fire interaction over various canopy treatments, by using a physically based model. It gives some practical considerations for discerning the appropriate cover fraction and open perspectives for further investigations.

Keywords Canopy structure · Forest fire · Windflow · Modeling · FIRETEC

1 Introduction

Fuel management, including fuel reduction and segregation of pockets of fuel, is frequently used to reducing fire intensity and crowning (Xanthopoulos et al. 2006). Fuel management often results in heterogeneous spatial patterns of vegetation. A better understanding of the fuel spatial patterns effects on fire intensity and crowning is frequently sought by forest managers to help management planning. Several case studies of fuel-break impacts on fire behavior can be found in the literature (Lambert et al. 1999; Finney et al. 2007).

Among modeling studies, physics-based models have been used to assess fire propagation in various fuel treatments (Dupuy and Morvan 2005; Linn et al. 2005; Pimont et al. 2006). Parsons (2007) performed a statistical analysis of a set of numerical simulations of fire moving across fuel breaks. However, detailed numerical studies of physical processes occurring as winds or fire transition from forest to treated areas and back to forest have not been performed.

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Accurate wind simulations are generally considered to be critical for fire behavior prediction (Butler et al. 2006). In canopies, wind flows are dominated by turbulent mixing, with intermittent strong downward gusts developing as in a plane mixing layer flow (Finnigan 2000). The presence of clearings of several times the height of the canopy and of fuel treatments that result in increased distances between crowns and low cover fraction, affect significantly the wind flow (Raupach et al. 1987; Lee 2000).

The HIGRAD/FIRETEC modeling system is a three-dimensional two-phase transport model that solves the conservation equations for mass, momentum, energy, and chemical species. A detailed description of the physical and chemical formulation of the model (hereafter referred to as FIRETEC) is available in Linn and Cunningham (2005) and Pimont et al. (2009). FIRETEC represents three-dimensional structure of vegetation at ~2 m scales and resolves fluctuating winds within and above the canopy at the same scales by using a large eddy simulation approach. In previous studies, it has been shown that this model is useful for investigating the impact of fuel structure on fire behavior (Linn et al. 2005; Pimont et al. 2006), and that it simulates accurately flows and turbulence over complex fuel configurations such as fuel breaks (Pimont et al. 2009). Because of these attributes, a physically based coupled fire/atmosphere model such as FIRETEC can be a valuable tool for the investigation of the fuel treatment effects.

In the present study, FIRETEC is used to assess the impact of canopy treatments on both wind flows and fire behavior, in an exploratory study of a typical Mediterranean pine ecosystem. After a description of the numerical simulations, the sensitivity of the wind field and fire behavior to the parameters characterizing the fuel treatment is analyzed. Then, the relevance of the simulation results is discussed in terms of comparisons with previous observations, as well as consequences of fuel-break design on fire behavior, modeling, and prevention.

2 Material and methods

2.1 Fuel complexes

The computational domain represented a 640×320 m forest with a horizontal resolution of 2 m. A portion of the canopy, stretching across the domain in the crosswind direction between 240 and 440 m from the domain inlet, was considered the "treated zone" (Fig. 1). Seven types

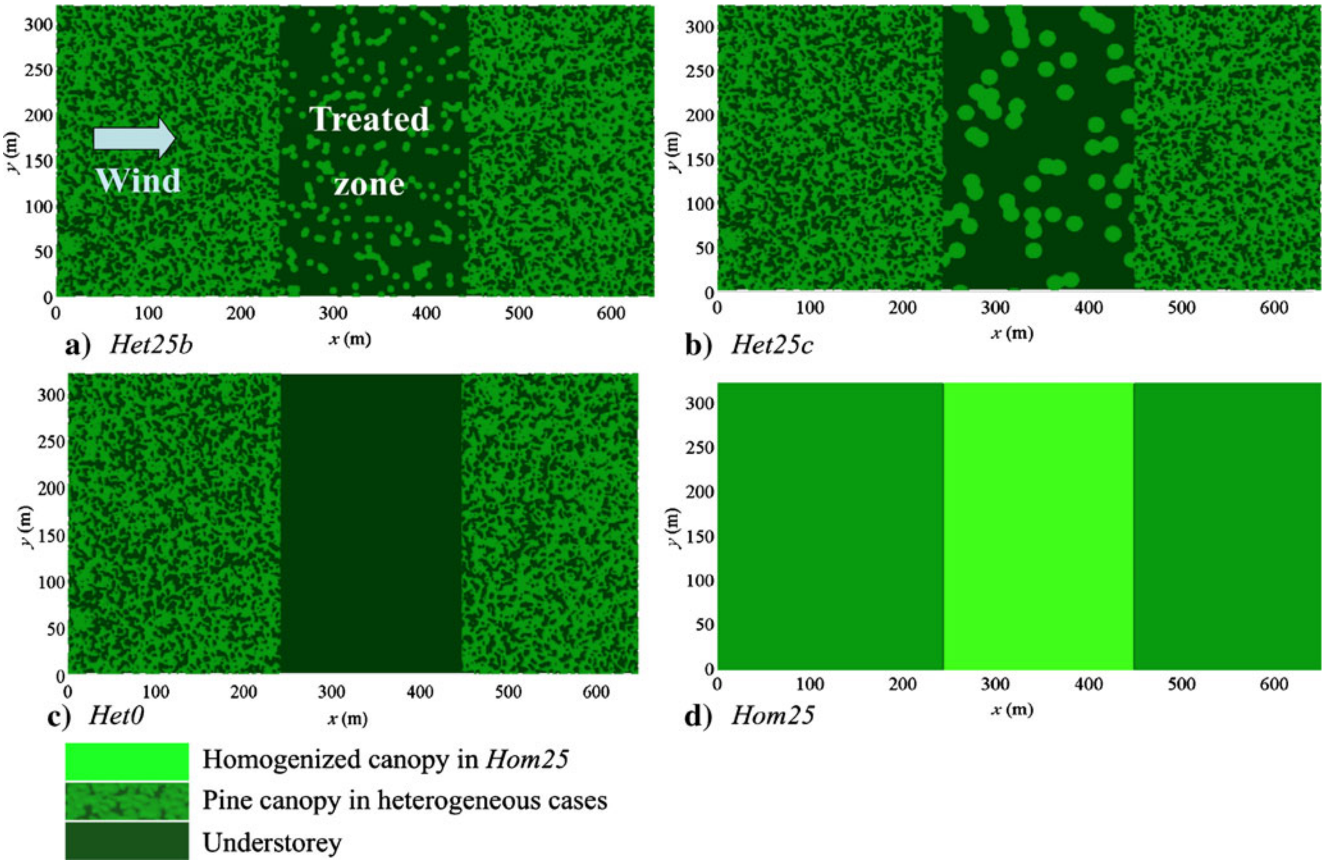


Fig. 1 Downward-looking view of selected plots from an elevated upwind location

of treated zone have been considered in this study, by varying (1) tree cover fractions C, from 0% to 75% (referred hereafter as *Het0*, *Het25*, *Het50*, *Het75*) with various aggregations, and (2) clump size L, by considering three values: 4, 10, and 20 m (labeled: a, b, c; Table 1). Clump size effects were investigated at low cover fraction only (25%), because a canopy with a high cover fraction has small gaps at all clump sizes. A homogenized fuel (*Hom25*) was also designed with the same load as *Het25 cases* within the forest and treated zone. It can be envisioned as infinitely small clump size cases.

The non-treated forest, referred hereafter as "forest", is similar in all simulations (except *Hom25* which is homogenized). It is modeled as a canopy with a height h=12 m and a crown base height of 4.5 m. The tree canopy was made of cylindrical trees with individual crown diameters of 4 m, a bulk density of 0.1 kg m^{-3} and a moisture content of 100%. They were randomly distributed with a cover fraction C=75%, which is representative of dense natural pine forests. The fuel load was 0.54 kg m^{-2} and the leaf area index (LAI) was 2.9, which is typical of Aleppo pine stands (Mitsopoulos and Dimitrakopoulos 2007). The understory was a homogeneous shrubland of 0.5 m height, 1 kg m^{-3} bulk density, and 70% moisture content.

2.2 Wind simulations

The wind flows were simulated under the same conditions as those used by Pimont et al. (2009). The reference wind intensity in the open area was about 8 ms^{-1} at 12 m high, which could be considered as a moderate to strong ambient wind. This ambient wind was used to set the initial conditions in the model, which includes a drag force and a turbulence model in order to compute realistic flows inside and above the canopy according to its leaf area density. Initial wind conditions used a logarithmic velocity profile and its direction was parallel to the x-axis. Neutral atmospheric stability was assumed with a potential temperature of 300 K. For these wind calculations, the time step was 0.04 s. Lateral boundary conditions were cyclic. A Rayleigh damping layer was used at the top of the domain. The 440 m of forest sections were greater than a 35h length, which was long enough to obtain wind flows that recover from the influences of one fuel break before winds reached the next fuel break (Chen et al. 1995, Lee 2000).

Mean flow fields presented hereafter were deduced from the simulated instantaneous fields by averaging them on one simulated hour.

2.3 Fire simulations

A fire line was ignited in the upwind forest area. The ambient conditions including evolving series of turbulent fluctuations were fed at domain boundaries from the computed wind fields described above, to reproduce realistic ambient conditions, including well-developed resolved turbulent structures. Cyclic boundary conditions in the y-direction were used in order to simulate an infinite fire line approaching infinitely long fuel break. This assumption simplifies the analysis of fire behavior, by eliminating impacts of fire-line length and corresponding shapes.

The fire behavior was not only mainly characterized by fire intensity, but also plume inclinations and temperatures. In three-dimensional simulations, the temporal and spatial

Table 1 Spatial characteristics of canopy fuel on the treated zones

Case	ρ^a (kg m^{-3})	L^b (m)	C^c (%)	LAI[d]	Load[e] (kg m^{-2})
Het75a (no treatment)	0.1	4	75	2.9	0.54
Het50a	0.1	4	50	1.9	0.36
Het25a	0.1	4	25	0.97	0.18
Het25b	0.1	10	25	0.97	0.18
Het25c	0.1	20	25	0.97	0.18
Hom25	0.025	0	100	0.97	0.18
Het0	0.0	–	0	0.0	0.0

Het0, *Het25a*, *Het50a* and *Het75a* have treated zones with 2 m clumps and cover fraction of respectively 0%, 25%, 50%, and 75%. *Het25b* and *Het25c* have treated zones with cover fraction of 25% with clumps of 5 and 10 m. *Hom25* has homogeneous fuel with same load as *Het25a*, *b*, and *c*

[a] Crown bulk density

[b] Tree clump size

[c] Cover fraction

[d] Leaf area density at fuel break scale (including needles and small twigs)

[e] Fuel load at fuel break scale

variability of the different instantaneous variables is significant compared to their mean values as also seen in experiments (Morandini et al. 2006). With its long fireline assumption, this modeling study is able to compute spatial and temporal averages from three-dimensional fields, to understand general features of the plume.

3 Results

3.1 Wind simulations

A two-dimensional view of instantaneous wind field at $z=6.5$ m along the forest-treated zone-forest pattern is presented in Fig. 2. It illustrates the channeling of the wind, which results in some wind accelerations in corridors between fuel clumps in the treated zone, with the development of elongated eddy structures at the canopy top.

Figure 3 represents the mean vertical streamwise velocity profile in the middle of the treated zone for different values of cover fraction and clump size. In case *Het75a* (no treatment), the profile was characterized by an inflection near $z=2/3\,h$. In thinned cases, the fuel reduction was associated with a lower average drag force over the treated zone that induced an increase of mean streamwise velocity compared to the forest values. The effect of the canopy structure happened between heights of 0 and 2 h. The profile inflection was less severe with decreasing cover fraction and completely disappeared in *Het0* (Fig. 3a). A 25% (*Het25a*) cover fraction resulted in wind speeds that were 0.25–0.5 of those in no canopy case.

The increase of the clump size L (from 4 to 20 m) induces a slight increase of mean streamwise velocity (Fig. 3b). Indeed, larger clumps induced larger gaps for a same cover fraction. The wind had more tendency to channel in the gap when the clumps are larger. The homogeneous case (*hom25*) was associated with the lowest mean streamwise velocities, which was consistent with the notion that the homogenized fuel bed can be thought of as having very small clump. The magnitude of clump size effect on mean flow was far less significant than the cover fraction effect. However, the clump size affected the spatial variability of the mean streamwise velocity as indicated by normalized standard deviation profiles of the mean wind velocity along the spanwise direction (Fig. 4). The velocity variability was lower than 5% of the mean velocity in cases where vegetation was homogeneous (*Het0*, *Hom25*), but increased with the clump size in heterogeneous canopy to reach 30% at $2/3h$ in *Het25c*, and was associated with more channeling between trees.

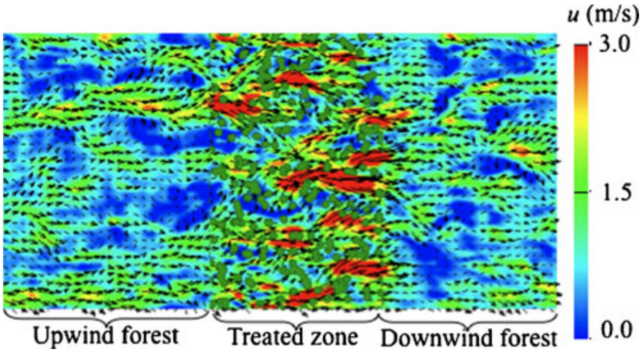
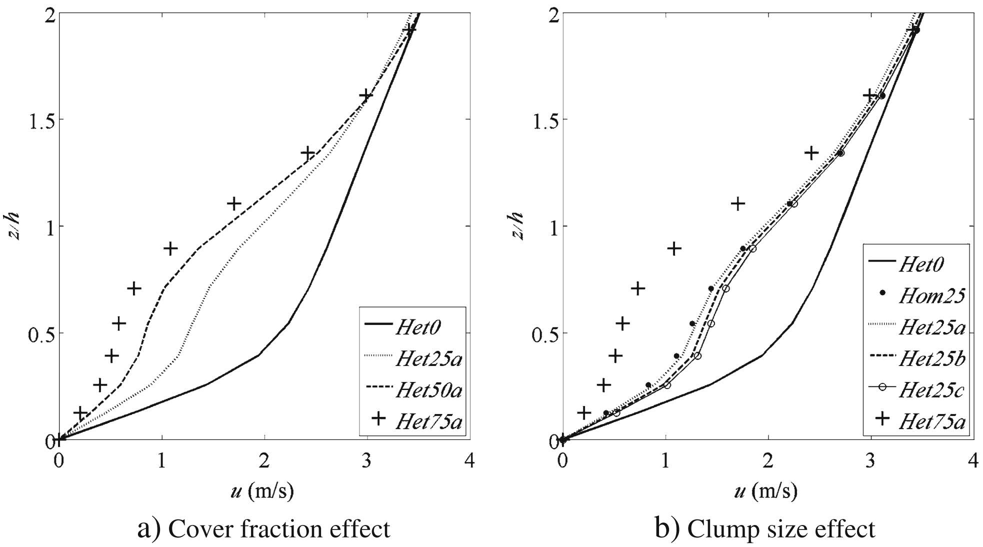


Fig. 2 Top view of the flows within the canopy ($z=6.5$ m) for *Het25b*, at $t=4000$ s (640×320 m) The color map was used to represent the instantaneous streamwise component of the wind velocity, u. The vectors represent the horizontal flow components. Green circles represent the tree clumps on the treated zone. For visualization reasons, trees were represented only on this zone and not in upwind and downwind forested areas, where their cover fraction (75%) would have obscured the wind field

3.2 Fire simulations

Figure 5b–d illustrates for the *Het25a* case the fire propagation from the upwind forest area, through the treated zone, and into the downwind forest area. Figure 5a illustrates the y-averaged fire intensity as a function of position x relative to the domain inlet. The fire intensity increased after ignition until the quasi-steady fire propagation was established. The movement into the treated zone was associated with a decrease in fire intensity. Its minimum value was obtained when the fire had traveled 60 m into the treated zone. As the fire traveled downwind beyond the leading edge of the downwind forest, the fire intensity increased up to the same values as in the upwind forest area, before decreasing again when the fire reached the end of the domain. The rate of spread was close to 0.8 ms^{-1}, with no significant modification over the treated zone. Some strips of fuel remained minimally affected by the fire (Fig. 5d). A close-up image on an area where these strips were present reveals that they were tied to coupled fire/atmosphere-induced vortices (Fig. 6), characterized by a downward flow above the strips of fuel that are left and an upward flow above the torching regions. The width of these vortices was about 30–50 m.

Figure 7 illustrates the variation of the fire intensity over the path for different cover fractions (a) and clump sizes (b). The leveling of the lines relative to their initial climbs indicates the attainment of a quasi-steady state. Some differences can be seen in the intensity level reached before the treated zone, due to small differences in flow fields. As expected, the intensity within the treated zone decreased with cover fraction (Fig. 7a). An analysis of variance of intensity values on the treated zone as a function of covers was highly significant (F value=98.3; Pr(F)<2.2 e-16) and Tukey's test showed that mean intensities on treated zone



a) Cover fraction effect

b) Clump size effect

Fig. 3 Vertical profiles of mean streamwise velocity in the middle of the treated zone (x=340 m), for different cover fractions and clump sizes. *Het0*, *Het25a*, *Het50a* and *Het75a* have treated zones with 2 m clumps and cover fraction of respectively 0%, 25%, 50%, and 75%. *Het25b* and *Het25c* have treated zones with cover fraction of 25% with clumps of 5 and 10 m. *Hom25* has homogeneous fuel with same load as *Het25a*, *b*, and *c*

differ for the different cover fraction (95% confidence intervals). However, it is worth noting that a fuel reduction to the level of 50% cover fraction (from the initial 75%) had minimal effect on fire intensity, whereas a reduction to 25% had a significant effect. The effects of clump size on averaged fire intensity were almost negligible at 25% cover fraction (Fig. 7b). An analysis of variance of intensities as a function of covers was not significant (F value=2.16; Pr(F)<0.145). *Hom25* tends to decrease fire intensity, as well as flame heights, but differences were small and not significant.

The details of the local fire behavior can be very complex, as shown in Fig. 6. To describe the mean fire behavior, y-average velocity vectors were derived from instantaneous velocity components in the middle of the treated zone. Figure 8 depicts velocity vectors in the shrub layer (z=0.75 m) and close to mid-canopy height (z=6.5 m). In this figure, the position x=0 m corresponds to the firefront position in the shrub layer. At the two considered heights, the position of the plume is related to the location of positive vertical velocity components. The plume was more horizontal with lower cover fraction. 15 m downwind to the fire at heights below 1.5 m, the gas temperatures in the treated zone were 10–20°C higher for lower cover fractions. This result might seem surprising since fire intensity was higher with a higher cover fraction, but this facet of the results is a consequence of the more horizontal trajectory of the hot gases with low canopy cover, which induced higher temperatures downwind.

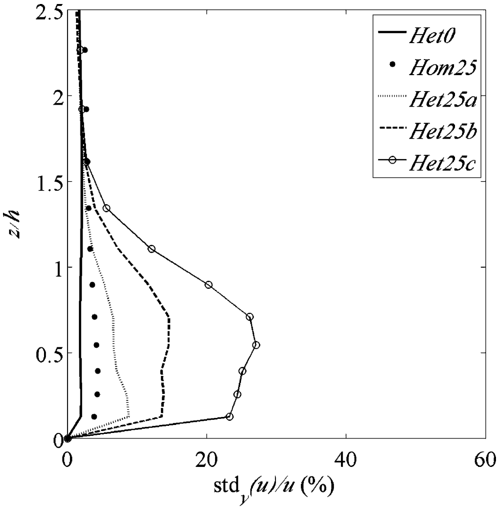


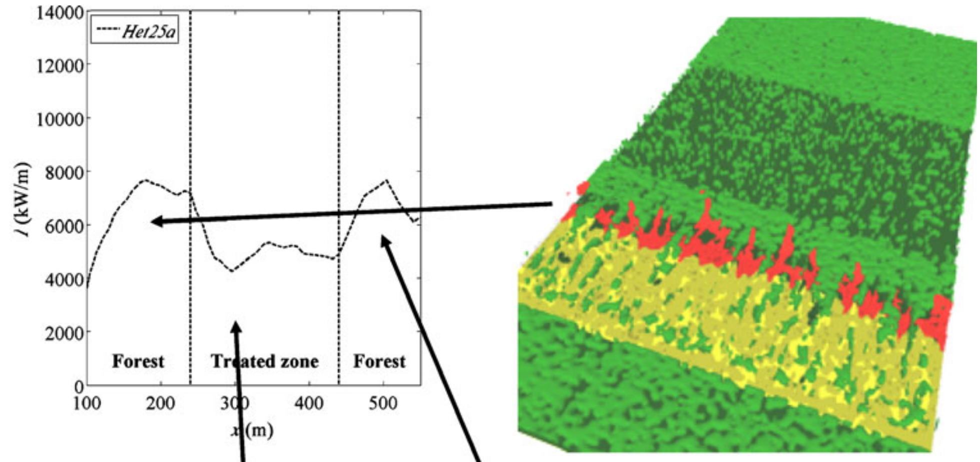
Fig. 4 Effects of clump size L on the standard deviation of the mean wind velocity (in percentage of u) along the cross wind direction, in the middle of the treated area

4 Discussion

4.1 Simulations versus experimental data

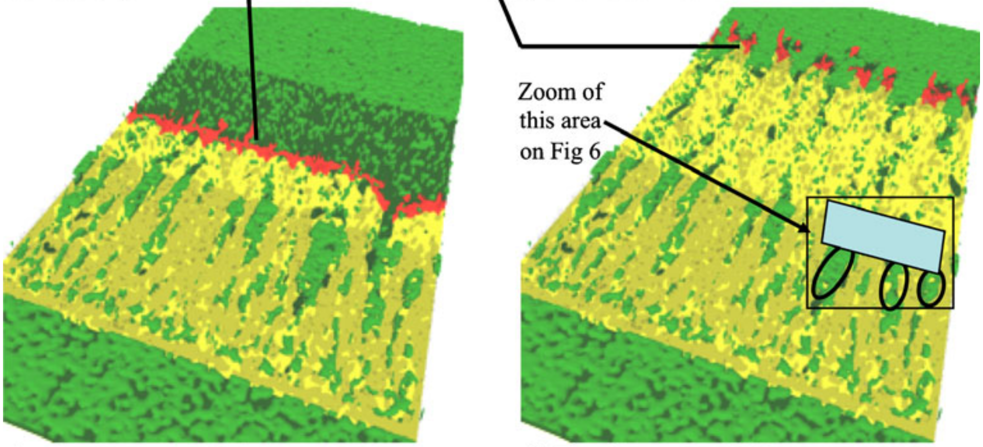
The model used here for wind computation above and within the canopy has already been validated against experimental data in the context of homogeneous canopy and fuel break (Pimont et al. 2009). The results obtained here were consistent with this previous study, as well as others. For example, the wind acceleration mainly took place in the first 100 m of the treated zone, i.e., between 8 and 10 h, which is in agreement with Chen et al. (1995) or Lee (2000).

Observed crown fire intensities usually range between 8,000 and 40,000 kWm^{-1} (Trabaud 1989). In our simulations, intensities were close to 8,000 kWm^{-1}. This relatively low value can be explained by the moderate wind, but also low fuel loads in Aleppo pine canopies, that induced mostly torching. Indeed, simulations done in the same configuration with heavier load provided intensity of more than 35,000 kWm^{-1} (result not shown). The average rate of spread was not significantly affected by canopy fuel



a) Intensity

b) Fire front at x=200 m



c) Fire front at x=300 m

d) Fire front at x=500 m

Fig. 5 **a** Fire intensity variation along the forest-treated zone–forest pattern (case *het25*: C=25%, L=4 m). Fire behavior at three locations: within the upwind forest (**b**), within the treated zone (**c**), and within the downwind forest (**d**)

structure and generally ranged around 0.8 ms^{-1}, for a wind speed equivalent to 8 ms^{-1} in open area. In similar wind conditions, Taylor et al. (2004) reported mean rates of fire spread of 0.4–0.9 m/s in Canadian pine forests. Rate of spread tends to increase with fire front length (Cheney et al. 1998; Linn and Cunningham 2005), because a large front prevents lateral indrafts that can cool the fuel in front of the fire. In the present simulations, the fire line was considered infinite, which may explain why our predicted spread rates were in the upper part of Taylor et al.'s range.

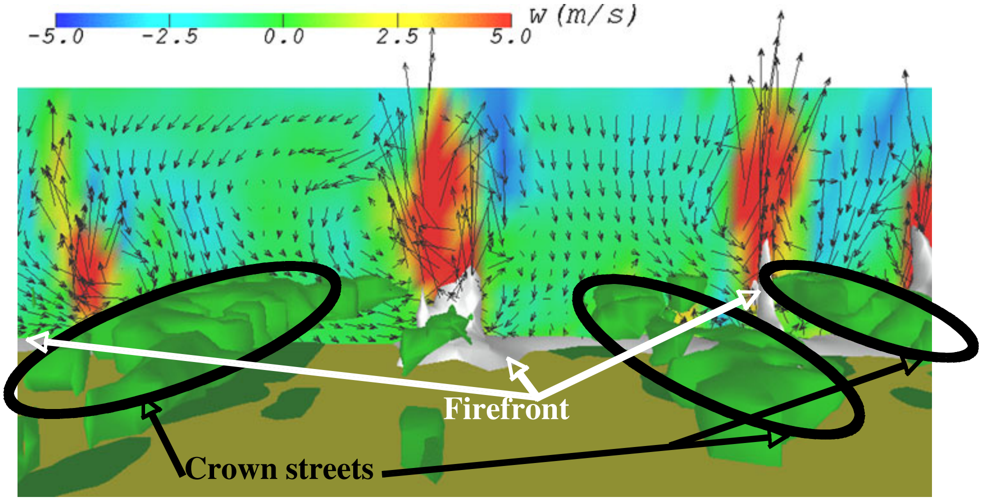
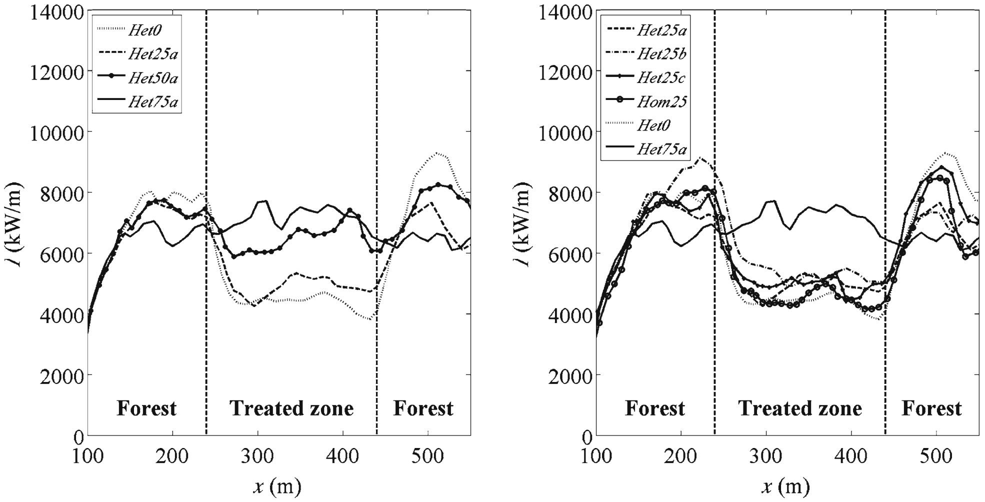


Fig. 6 Upwind view of (looking at the back of the fire) flow fields above the firefront (*white*) for case Het25a (t=190 s after ignition). This view is a zoom of the window represented in Fig 5d. The flow field is represented in the vertical (y–z) plane x=216 m; v and w components are represented by the vectors and w is also represented by the color map



a) Cover fraction effect b) Clump size effect

Fig. 7 Fire intensities along the forest-treated zone–forest pattern for different cover fractions (**a**) and clump size (**b**). *Het0*, *Het25a*, *Het50a*, and *Het75a* have treated zones with 2 m clumps and cover fraction of respectively 0%, 25%, 50%, and 75%. *Het25b* and *Het25c* have treated zones with cover fraction of 25% with clumps of 5 and 10 m. *Hom25* has homogeneous fuel with same load as *Het25a*, *b*, and *c*

4.2 Treatment effects on wind

For a given fuel load, the average flow velocity increased with clump size. It should be noted that other computation done at higher LAI (8) reveals more significant effects on mean flow. In the present Aleppo pine ecosystem, the spatial variability of velocity increases with increasing clump size, due to channeling between clumps. When gaps were large, the fast winds from above the canopy had more opportunity to be easily entrained into the canopy space. In our simulation, the mean gap size could reach 5*h* (*Het25c*) and induced 30% of spatial variability. Comparing homogenized forest ("forest zone" of *Hom25*) with *Het75* reveals no significant effects on wind characteristics of heterogeneity for a 75% canopy cover. This is in agreement with results of Patton (1997), who reports negligible heterogeneity effects with canopy cover of 90%. In these cases, gap size was significantly smaller than *h*. To our knowledge, the effect of gaps between *h* and 5*h* on the wind flow at low cover fraction in terms of mean flow and spatial variability has not been investigated before.

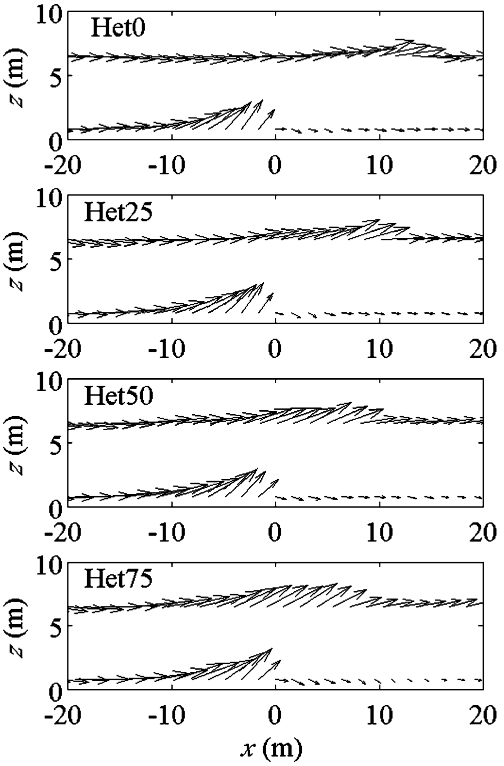


Fig. 8 Averaged flow vectors for different cover fractions on the treated zone. The position $x=0$ m corresponds to the fire head position

4.3 Treatment effects on fire

At the landscape scale, the treated zone induced a strong heterogeneity. Transition between forest to treated zone and back induced an adjustment of the fire behavior occurring over 50 m distance in downwind direction.

The rate of spread of the long fire line considered in this study was not significantly affected by heterogeneity. The decrease of fire intensity caused by the fuel load reduction could have resulted in a reduction of heat transfer to vegetation, because of the reduction of heat source strength. However, the wind pattern induced a more horizontal plume, which in turn advects more hot gasses over the vegetation and increases the heat transfer. This probably explains why the rate of spread was not strongly modified. In the case of a clean fuel break (with surface fuel cleared), this increase of wind speed in channels is likely to increase the fire spread.

Treatments tend to decrease fire intensity, with threshold values for cover fraction ranging between 25% and 50%. However, the presence of relatively heavy fuel load in the understory enhanced a high fire intensity. In Mediterranean region, the shrubland is very dynamic so that such loads can be reached between 3 and 6 years after treatment (Trabaud et al. 1985). Canopy treatments by themselves are clearly insufficient for efficient fire prevention and a frequent clearing of the understory is required. Our study also illustrates how the presence of a few remaining trees (25% cover) on the treated zone helped to keep the plume vertical and to reduce downwind temperature, without increasing fire intensity significantly. This behavior can probably be extrapolated to fuel breaks with cleared understory and be a way to improve the fire fighter safety. However, it should be kept in mind that these pines can be a source of spotting.

Finally, forest homogenization (*hom25*) was not significantly different from the heterogeneous cases *het25*. This suggests that in this ecosystem, detailing the crown structure is not very significant for propagation assessment. However, other simulations ran at heavier load (between 1 and 2 kg m^{-2}, results not shown) reveals significant differences, so details of canopy structure could have more significance in ecosystems with larger fuel loads.

5 Conclusion

This study was a first investigation of wind/fire interaction over various canopy treatments, by using a physically based model that explicitly takes into account fuel description at tree clump scale. This work illustrates how fuel heterogeneity affects fire as well as wind. It gives some practical considerations for discerning the appropriate cover fraction, taking into account the fire intensity, but also the plume angle. Further works and investigations on fuel breaks (including shrub clearing) with such models should define rules for fuel management in the future.

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