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Abstract

We examined how fire hazard was affected by prescribed burning and fuel recovery over the first six years following treatment. Eight common Mediterranean fuel complexes managed by means of prescribed burning in limestone Provence (South-Eastern France) were studied, illustrating forest and woodland, garrigue and grassland situations. The coupled atmosphere-wildfire behaviour model FIRETEC was used to simulate fire behaviour (ROS, intensity) in these complex vegetations. The temporal threshold related to the effectiveness of prescribed burning in reducing the fire hazard was assessed from derivated fuel dynamics after treatment. The study showed that prescribed burning treatment was effective for the first two years in most of the Mediterranean plant communities analysed. Thereafter, all forests and shrublands were highly combustible with a fire line intensity of more than 5000 kW/m except for pine stands with or without oak (medium intensity of 2000 kW.m-^{1} 3 years after treatment). Low fire line intensity (900 kW.m^{-1}) was obtained for grassland which was entirely treatment-independent since the resprouter hemicryptophyte, *Brachypodium retusum*, is highly resilient to fire. Fire behaviour was greatly affected by fuel load accumulation of *Quercus ilex* in woodland, and by standing necromass of *Rosmarinus officinalis* in treated garrigue. Pure pine stands with shrub strata similar to garrigue showed a lower fire intensity due to wind speed decrease at ground level under tree canopy, underlining the advantage of maintaining a proportion of canopy cover in strategic fuel-break zones.

Keywords

Mediterranean fuel complexes; prescribed burning; fuel dynamics; FIRETEC; fire behaviour.

1. Introduction

Prescribed burning corresponds to the controlled application of fire to vegetation in either its natural or a modified state, under specified environmental conditions that allow the fire to be confined to a predetermined area while at the same time limiting fire intensity and rate of spread to the requirements of planned resource management objectives (FAO and GFMC, 2003). **Prescribed burning** is used in most parts of the world, but for different purposes such as for regenerating forests, clearing virgin land for cultivation, managing pasture-land and preserving fire-dependent plants and animals (Wade and Lunsford, 1989). In some countries of the Mediterranean (France, Spain, Portugal, …), and in North America and Australia, prescribed burning is an integral part of fire prevention as it is primarily used to control fuel build-up at strategic places in wildland areas and thereby reduce the wildland fire hazard (Wright and Bailey, 1982; Sneeuwjagt, 1994; NIFC, 2001; Lazaro, 2008).

Fuel modification is the main option used to reduce the fire risk. **Fuel treatments** can be applied extensively onto the landscape to modify fire behaviour by fuel reduction (Finney, 2001; Pyne and Laven, 1996) or locally onto fuel breaks to contain a fire. Green (1977) defines a fuel-break as "a strategically located wide block, or strip, on which a cover of dense, heavy, or flammable vegetation has been permanently changed to one of lower volume or reduced flammability". Wildfire containment by fuel isolation in a network of fuel breaks is the main option adopted in South Eastern France (Rigolot and Alexandrian, 2006; Xanthopoulos et al., 2006), though such infrastructure may also be assigned to decreasing fire ignition events or decreasing the effects of fire on people and property (Rigolot, 2002). The effectiveness of fuel breaks has been discussed by several authors (Agee et al., 2000; Rigolot, 2002; Rigolot et al., 2004) and results have shown that isolation by fuel breaks can be efficiently improved by combining with area-wide fuel modification (Agee et al., 2000). European forest managers use a variety of fuel modification techniques including mechanical treatment, controlled grazing, herbicides and prescribed burning (Rigolot et al., 2009), either separately or in combination. Although mechanical treatment is the most common fuel reduction technique in South European countries, prescribed burning is increasingly being considered in Southern Europe, with contrasted levels of adoption between countries (Lazaro, 2008). Prescribed burning as a fuel reduction technique is more likely to be used extensively on the landscape (Fernandes and Botelho, 2003), but can also be employed to maintain fuel breaks (Xanthopoulos et al., 2006).

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Active prescribed burning plans for purposes of fuel reduction need to be assessed and monitored to optimize the fire return interval and the spatial pattern of fire application. Fernandes and Botelho (2003) analysed three approaches to assessing the effectiveness of burning in reducing the fire hazard: computer simulation of fire propagation models, an analysis of case studies, and changes in fire regimes.

Fire propagation models can be used to predict the effect of fuel reduction on a potential fire hazard. Three main types of models have been developed to assess fire behaviour. Empirical, quasi-physical and physically-based (Sullivan 2009 a and b). Empirical models are based on correlation between experimental fire spread rate and weather, fuel and terrain characteristics (see for example McArthur 1966) and their calibration required a significant number of experimental fires within a given fuel type. Using this type of models is not really appropriate to investigate fuel reduction effects in multiple fuel types, unless if a large data set of experimental fire is available, which is scarcely the case. Quasi-physical models are based on a simple analysis of fire physics to assess basic relationships, using parameters. These parameters are derived from laboratory experiments. The most famous model in this category is BEHAVE fire behaviour prediction and fuel modelling system (Burgan and Rothermel, 1984). Since it takes into account direct fuel characteristics, such as fuel load, moisture content and fuel particle thickness, it can provide a prediction of fire spread rate and intensity, within any given fuel type when main fuel characteristics are known. For this reason, this model has been widely used for this purpose (Loureiro et al., 2002; Stephens, 1998; Stephens and Moghaddas, 2005; van Wagtendonk, 1996; Finney et al., 2007). However, a very significant limitation of quasi-physical models is the fact that they do not explicitly take into account the 3D structure of the fuel. For example, BEHAVE averages in a unique layer all the fuel available and only consider fuel below approximately 6m. Fuel structure after treatment is very heterogeneous with clumps of fuel with very different properties: unburnt old fuel, burnt dead fuel, young resprouters have very different load and moisture. Averaging these clumps of fuel without taking into account distances between them is probably a very coarse assumption. More recently, physically-based fire models that explicitly take the spatial structure of the fuel has been developed (Linn 1997; Morvan & Dupuy 2001; Mell et al. 2007). These computational fluid dynamic models (cfd) have demonstrated their ability to take fuel structure into account when assessing the impact of fuel treatment on fire propagation (Dupuy and Morvan, 2005; Linn et al., 2005b; Parsons, 2007; Pimont et al., 2010). In complex fuel, wind flows are affected by the vegetation itself which creates a turbulent regime, with short periods of gusts due to Kelvin-Helmholtz instabilities (Finnigan, 2000). The more complex the fuel structure, the more complex this behaviour with a multitude of small scale heterogeneities resulting from prescribed burning. Physical models can be very valuable in this context because they are able to take account of the small-scale heterogeneities that are solved on their mesh. The FIRETEC modelling system is a three-dimensional, two-phase transport model that solves the conservation equations of mass, momentum, energy and chemical species (Linn, 1997; Linn and Cunningham, 2005; Pimont et al., 2009). FIRETEC includes representations of vegetation used for the simulation of turbulent flows and fire propagation (~m) within and above heterogeneous vegetation canopies. Simulations can be run on a two-metre scale near the ground. Fuel structure can be taken into account explicitly at this scale, and its impact on fire behaviour investigated (Linn et al., 2005a; Pimont et al., 2010). FIRETEC can be used to assess two major components of **wildland fire risk** by calculating fire rate of spread, and fire line intensity and duration. **Fire rate of spread** (ROS) quantifies the propagation danger part of a fire. **Fire line intensity and duration** express the effects of a fire on the ecosystem, i.e. ecosystem vulnerability. FIRETEC can be used to compute variables characterizing wildland fire behaviour including fire rate of spread, fire line intensity and fire line duration (residence time). Fire rate of spread and intensity are used to assess fire hazard, fire line intensity and duration influence the effects of fire on the ecosystem and are important to assess ecosystem vulnerability. Fire hazard combines with ecosystem vulnerability to constitute the wildland fire risk (Marzano et al., 2006).

A prescribed burning programme has been ongoing in the Petit Luberon State forest (South-Eastern France) since 1992. After an eight-year long initial trial and adjustment period, the programme has been fully operational since 2000, although the annual area burnt has been kept relatively low (20-30 ha) due to the short supply of trained personnel, and administrative and climatic constraints. Managers of the Luberon State forest promote prescribed burning combined with controlled grazing because these techniques are more cost effective and more efficient in reducing fine and dead fuel material than the mechanical clearing used in the past. In the present study, the FIRETEC fire propagation model was used to assess fire behaviour in structurally different successional stages of some common Mediterranean ecosystems in the Luberon State forest following prescribed burning treatments. The specific aims of this study were (i) to determine the reduction in fire hazard induced by prescribed burning, and (ii) to determine for how long the treatment was efficient. We also wanted (iii) to investigate whether the use of prescribed burning for reducing fire hazard is more appropriate in certain fuel complexes than in others (in terms of efficiency of the intensity reduction), and thereby contribute new knowledge to help improve prescribed burning practices.

2. Material and methods

2.1. Study area

The Luberon forest area (43°48'00''N, 5°20'00''E) corresponds to a limestone formation emerging between the Durance River and the Calavon plains in South-Eastern France near Avignon. We focused for this work on the State forest (3,312 ha) of the Petit Luberon forest area (14,000 ha), which included two (Trou-du-Rat and Mayorques) of the five fuel breaks in this area located in the western part of the Luberon forest area (21,365 ha) (Fig. 1). The fuel breaks date back to the last major wildfires in 1989 and 1991 that led to the conception of a fire prevention management plan for the Petit Luberon forest area based on a network of 5 strategic fuel breaks. The fuel breaks are managed by the State Forest Service which uses a combination of clearing treatments, grazing and prescribed burning to reduce the build up of fuel loads. The landscape consists of a rough topography of great heritage value between 110 m and 720 m a.s.l. The climate is typically Mediterranean with hot dry summers, a mean annual temperature of 13.6° C and mean annual precipitation of 677.5 mm.

[Fig. 1]

2.2. Vegetation types

The dominant vegetation in the State forest area consists of Holm oak (*Quercus ilex*) coppice forests accounting for 44.7 % and pure or mixed (with Holm oak) Aleppo pine (*Pinus halepensis*) forests accounting for 15.3 % (ONF, 2008). Shrublands are also widespread over a total area of 923 ha (28 %) consisting mainly of xerophilous garrigue made up of Kermes oak (*Quercus coccifera*) with aromatic plants. The last dominant vegetation type is grassland covering 7 % of the surface area (Fig. 1). The remaining 5 % consists of pine and cedar plantations, and deciduous tree stands that we did not take into account in this work.
Yearly monitoring of shrub stratum phytovolume has been used by forest managers as a fuel

encroachment indicator to assess the forest fire risk (Etienne and Rigolot, 2001). The method consist in visualy estimating the heights and the cover fractions of the 3 main shrub species for each mapping unit. When total shrub cover is higher than the sum of three specific covers, it is also taken into account with the list of the most represented complementary species. Fuel reduction treatments are scheduled when the phytovolume exceeds the threshold value of 2500 $m^3.ha^{-1}$ (Etienne et al. 1991; Beylier et al., 2006). We used the phytovolume field survey carried out by the State Forest Service from 2003 to 2006 to select and describe the most common plant communities in the two fuel breaks (Trou-du-Rat and Mayorques) to be used for fire simulations. Phytovolume data can provide a precise classification of vegetation types and establish composition in terms of the main species represented. Eight plant communities were selected on the basis of this database and their current distribution in the two fuel break areas was checked. Fuel complexes at the control stage were also characterized by field descriptions in the State forest where the vegetation is not treated. For each plant community, the cover fraction and the height of the dominant shrub species were determined on an area of about 1000 m^2 as well as tree characteristics (cover, height, dbh) when the strata was present. These observations were used to build the virtual fuel complexes used in the simulations and presented in Table 1.

[Table 1]

2.3. Fuel build-up dynamics after prescribed burning

Prescribed burning consists of low intensity fires that generally do not impact on trees but reduces fine fuels in lower strata. We therefore considered vegetation dynamics only for the shrub and herbaceous layers in the various post-treatment stages. Moreover, forest managers of the Luberon State forest take into account the fire risk but also the conservation of the natural biodiversity. In that way, prescribed burning teams didn't burn all the area treated but maintained patches of unburnt vegetation that created a vegetation mosaic favourable to wildlife (Pons et al., 2003). We took into account this management practiceby considering the presence of unburnt individuals in some fuel complexes.

Numerous studies by Trabaud (Trabaud, 1970, 1980, 1983, 1989,1991; Trabaud and Lepart, 1981) on post-fire fuel dynamics show that six years are required for *Quercus coccifera* garrigue to recover entirely. In the present study, Kermes oak was a dominant species of the various garrigues and was also present in the understorey of most of the forest types (Table

1). For this reason, fuel build-up dynamics in all the selected plant communities (except grassland, one stage) were analysed based on six annual stages:

- Stage C: corresponding to the control and where the plant community was stable at its maximum phytovolume.
- Stage 1: representing the fuel one year after prescribed burning.
- Stages 2 to 5: representing the fuel 2 to 5 years after prescribed burning, respectively.

Grassland was considered only at the control stage because the vigorous post-fire dynamics of *Brachypodium retusum* meant that the entire herbaceous phytovolume was recovered in the year following the treatment (Dureau, 2003).

Fuel complexes were generated for the various stages of the plant communities based on coupled approaches (Table 2):

- Phytovolume evolution after treatment from phytovolume data collected in fuel break areas (2003-2006) where prescribed burning was applied;
- documented post-fire recovery data for the understorey of *Pinus halepensis* forest and kermes oak garrigue, from the scientific literature (e.g. Trabaud, 1985, 1991; Trabaud and Lepart, 1981; Koukoura 1987 ; Sala and Sabate 1987 ; Cañellas and San Miguel 2000; Dureau et al. 2003)
- expert appraisal, particularly to take account of the proportion of unburnt fuel during the treatment.

These approaches involved an assessment of the typical properties required to describe the dynamics of each fuel complex, e.g. species presence and its physiological status (unburnt: live material; burnt: dead material; resprout: new live shoots after burning), together with the height and cover fraction of each species (Table 1 and 2).

[Table 2]

2.4. Description of the different fuel complexes in FIRETEC

In FIRETEC, fuel is described by means of three main input data: bulk density ρ (kg.m^{-3}), area per volume ratio σ (m^{-1}), and fuel moisture content *MC* (%). These variables are represented on a three dimensional mesh with resolution of about 2 m that results in fuel distribution near the ground generally being under-resolved. To reduce the inaccuracies induced, a fourth variable corresponding to actual fuel height in the shrub layer, is introduced.

This is used to improve the computation of both flow movement and radiative transfer in shrubland, based on a more realistic geometry (Pimont, 2008). A simple fuel editor is used to build these four, three-dimensional arrays required for the fuel description in FIRETEC (Pimont, 2008), and is based on certain stand parameters and physical properties. Horizontal heterogeneous patterns are randomly assessed for each species based on cover fraction (*C* in %) and mean clump size (*L* in m). Vertical fuel distribution takes account of species height (h in m) and crown base height (cbh in m). In our study, heights and cover fractions for trees, shrubs and herbaceous species at the various post-fire stages were assessed by the three approaches described previously (see paragraph 2.3 and Tables 1 and 2), together with crown base height. The mean bulk density of each species (given its height and status: unburnt, resprout or burnt) was assessed from fuel databases (DBClump and DBparticles, http://www.eurifirestar.org/index.php). Only the physical characteristics of fine fuels (leaves and twigs <2mm) were considered to compute bulk density because thicker materials are generally not involved in the combustion process at the fire front (Table 3) (Rothermel, 1983). With regard to burnt individuals, only remaining fine twigs were taken into account. The area to volume ratio for each species was computed from the database (DBClump). The last variable required was the moisture content of each species, given its status. *P. halepensis* and *B. retusum* moisture content was determined from the literature (Caraglio et al., 2005; Cohen and Deeming, 1985; Dimitrakopoulos et al, 2007). A multi-annual regional field survey (http://reseau-hydrique.org/) was used for the other species. Values were expressed as moisture content for live fuels and ranged from 66% to 100% during the summer. Moisture content for dead material was considered to be 20% in the case of burnt *R. officinalis* skeleton.

[Table 3]

From this description of the various fuel complexes, the total fuel load was calculated and then distributed spatially for each vegetation scenes analyzed in FIRETEC.

2.5. Fire simulations

The aim of the study was to compare the combustibility of 43 cases (7 fuel complexes at 6 different stages, and grassland). As this represents a significant computational cost, we used two procedures to save computational time: (i) we defined initial wind flow conditions before fire ignition, together with boundary conditions based on empirical laws, and (ii) we used cyclic lateral boundary conditions during fire propagation simulations.

Empirical laws were used to set initial flow conditions before fire ignition and establish upwind and downwind boundary conditions. These laws are based on wind profiles that depend on the Leaf Area Index (LAI) of the stand (Raupach, 1994; Su et al., 1998), and are described in Appendix A. This avoided any precomputation of ambient wind based on Large Eddy Simulation (LES), which can accurately compute the flows within and above heterogeneous canopies, but which also has a very significant computational cost (Pimont et al., 2009). Ambient wind flow was considered to be in equilibrium with the canopy, which means that transitions between fuel types were neglected. The wind was blowing along the x-axis and with a reference value at 40 m height above ground U_{40}^{amb} of 10 m.s^{-1}.

It is noteworthy that the same geostrophic ambient wind was used for all the simulations but the wind at 2 or 6 m height could be very different depending on the vegetation, being far lower in dense canopies than in light shrublands. This part of the methodology was crucial as it guaranteed an objective comparison of the different stages and complexes under the same ambient conditions which is never the case in field experiments or in modelling when fuel effects are not explicitly taken into account in the flow computation.

The use of cyclic lateral boundary conditions in the y-direction was the other approach adopted to save computational time. It means that the physical system behaved in exactly the same manner on both lateral sides of the domain. Such a configuration was used to simulate an infinite fire line. Computations were still three-dimensional in this solution, but allowed us to reduce the number of cells along the y-axis, saving computational time and reproducing accurately behaviour of large wildfires (Linn et al., 2010). In terms of fire behaviour, the consequence of these assumptions is that the simulations of the present study deal with large fires (more than 100 m wide) that should be seen as “worse case” scenarios. However, head fires arriving on fuel-breaks might be much narrower (due to local topography, wind and fire history). In this case, fire intensity and spread rates will be much lower that in our study, because fire width affects a lot the spread, especially below 50 m (Cheney et al., 1998; Linn et al., 2005a; Linn et al. 2010).

The computational domain was represented on a three-dimensional 320 m × 40 m × 615 m grid (Fig. 2), with a horizontal resolution of 2 meters. The use of only 20 cells along the y axis was rendered possible through the use of cyclic lateral boundary conditions. The mesh was stretched in the vertical direction, starting from 1.5 m resolution near the ground up to 40 m at the top of the domain (615 m). This resolution was sufficient to represent clumps larger than 2 m wide. The fire line was ignited at x=80 m.

[Fig. 2]

Additionally, the vertical profile of potential temperatures was constant at 300 K (neutral atmosphere), and the atmosphere was dry. A 0.01 s time step was used.

Fire behaviour was analysed on the basis of ROS, computed from the position of isosurface 600 K, and intensity, computed from predicted fuel consumption, using Byram's law. Mean ROS and intensity data were computed over the period during which the fire was located in the 100 m long area located between x=140 and 240 m (Fig. 2). This of course was possible only when the fire spread over the entire domain; when it stopped after a few meters of propagation, initial ROS and intensities where estimated (derived from the first half distance gone over by the fire, before the slow down preceding extinction).

3. Results

3.1. Standing fuel load and fuel build-up after prescribed burning

The total fuel load (Fig. 3) of untreated woody plant communities ranged between 8.2 and 14.5 t.ha^{-1}. The highest values were found in Pure pine and Dense oak coppice stands, both having the highest canopy closure (50 %), with 14.5 t.ha^{-1}and 13.0 t.ha^{-1} respectively. A mean value of 11.4 ± 0.33 t.ha^{-1} characterized partly closed Mixed oak-pine, as well as Sparse oak coppice and high garrigue (Holm oak garrigue and Kermes oak garrigue). The low Mixed garrigue had the lowest load of all woody communities with 8.2 t.ha^{-1}.

Prescribed burning reduced total fuel load by at most 50 % in closed to partly closed forest stands where the mean annual increase in phytomass was calculated to be 1.2 t.ha^{-1} in the first years after burning (Fig. 3). Phytomass stabilized after 4 years in pine stands (Pure pine stand and Mixed oak-pine) and after only 3 years in Dense oak coppice. In all open ecosystems (including Sparse oak coppice), prescribed burning reduced total fuel load by more than 50% (between 54 and 78%) one year after treatment, but these plant communities showed a considerable mean annual increase in phytomass of about 2.3 $t.ha^{-1}$ over the first three post-treatment years. Total phytomass thus began to stabilize at stage 3. Phytomass growth dynamics in Mixed garrigue was lower with a mean annual phytomass increase of 1 $t.ha^{-1}$ over the first three years.

Brachypodium retusum grassland was insensitive to prescribed burning and its total phytomass was estimated to be 1.1 $t.ha^{-1}$.

[Fig. 3]

Shrub fuel loads (Tables 1 and 2) were calculated as the sum of the phytomass less than 2 m in height. Results showed similar trends to those noted for total fuel load. Shrub fuel load was reduced by 46, 53 and 62% in the three forest stands in the first year after prescribed burning. The phytomass recovered by more than 80% in 4 years for pine stands and 3 years for Dense oak coppice. The fuel load decrease in all garrigues and Sparse oak coppice ranged between 56% and 84% the year after the prescribed burning. They required three years to recover 70% of their initial phytomass.

3.2. Wind profiles computed by FIRETEC

FIRETEC solves Navier-Stokes equations and includes a drag and turbulence model to compute wind around and within a given type of vegetation (Fig. 4). Graphs represent the typical wind profiles obtained in the different fuel complexes with no treatment. It is noteworthy that for the same ambient wind (10 $m.s^{-1}$ at 40 m high), the wind profiles in and above the fuel were completely different, with a far higher wind velocity above the grassland or the garrigues, than within pine stands or Dense oak coppice.

[Fig. 4]

3.3. Global analysis of fire behaviour

As a general rule, fire intensity in the different plant communities was significantly lower in the first two years after prescribed burning (stage 1 and 2) than in the control (Table 4). The fire also stopped in the early stages after burning, except in Mixed garrigue. High forest stands (Pure pine stand and Mixed oak-pine) were generally characterized by lower rate of spread (for the same ambient wind) than in lower plant communities, due to a marked reduction in wind velocity at ground level (Table 5). Prescribed burning in these plant communities greatly reduced fire intensity for 3 years after treatment. In lower oak coppices forest stands and Kermes oak and Mixed garrigues, the effects of prescribed burning were highly significant only for the first two years after treatment.

[Table 4]

[Table 5]

Table 6 outlines the distances covered by the fire in fuel complexes where the fire was not sufficiently intense to cross the entire domain. The fuel reduction in the shrub strata by prescribed burning led to fire extinction up to 3 years after treatment in Aleppo pine forest stands (Pure pine stands and Mixed oak-pine) whereas this effect lasted only one year in oak forest types (Dense and Sparse oak coppices) and oak shrublands (Holm oak garrigue and Kermes oak garrigue). Fire propagation did not exceed 32 m (highest value found in Dense oak coppice) in the first year after prescribed burning. In Mixed oak-pine stands, the presence of Holm oak trees added fuel in the shrub layer compared to Aleppo pine stands, and this impacted on fire propagation.

[Table 6]

3.3. Complexes by simulation results

3.3.1. Pine stands: Pure pine stand and Mixed oak-pine

The Pure pine and Mixed oak-pine stands showed similar fire behaviour. Fire intensity was low for the first two years after treatment, with values ranging between 1300 and 1500 $kW.m^{-1}$ for Pure pine stand and values between 600 and 730 $kW.m^{-1}$ for Mixed oak-pine. At stage 3, fire intensity increased to 2000 kW.m^{-1} and 2300 kW.m^{-1}, respectively, while it reached between 5500 and 6000 kW.m^{-1} in stages 4 and 5, as well as in the control. It should be noticed in this case that intensity can be a little lower in the control (5500kW.m-1), than in stage 4 and 5. This was explained by lower rate of spread in the control. ROS values in the Pure pine stand were lower than in Mixed oak-pine, even four years after prescribed burning with a mean ROS of 0.37 m.s^{-1} compared to 0.45 m.s^{-1} in the mixed stand. In both plant communities, extinction in the earlier stages can be explained by the wind reduction at ground level due to drag. This also explains their ROS values that were generally lower than in the garrigues for the same ambient wind (Fig. 5a).

3.3.2. Dense oak coppice

In Dense oak coppice, the fire spread in all stages except one year after burning, where the fire covered 32 m before it stopped. Fire intensity increased from a low level (less than 2000 kW.m^{-1}) for stages 1 and 2, to a very high level (more than 13,000 kW.m^{-1}) for stages 3 to 5 and for the control. Stages 1 and 2 were also characterized by partial combustion of the domain (Fig. 5b) and ROS values were considerably lower than those for the other stages (Table 5). It is noteworthy that prescribed burning did not result in a major reduction in fuel cover fraction or load because the large Holm oak did not burn well in the winter season. This resulted in a high fuel load and very high combustibility in the latest stages. The reason for the significant threshold between stage 2 and 3 could not be fully elucidated based on fuel characteristics.

[Fig. 5]

3.3.3. Sparse oak coppice and Holm oak garrigue

The fire in Sparse oak coppice and Holm oak garrigue spread in all stages except one year after burning and in this case covered 24 m and 12 m, respectively (Fig. 5c). Fire intensity increased from a low level (less than 1000 kW.m^{-1} and 1600 kW.m^{-1}) in stages 1 and 2, to high levels (more than 8000 kW.m^{-1} and 6400 kW.m^{-1}) in stages 3 to 5 and for the control. This behaviour was consistent with the biomass pattern that was very low for stages 1 and 2 (between 2.5 and 4.4 t.ha^{-1}) but far higher for stages 3 to 5 and the control (between 7.2 and 11.5 t.ha^{-1}). This resulted in a fire behaviour threshold between stages 2 and 3. ROS values in stages 1 and 2 were also considerably lower than those in the other stages (Table 5). It should be noted that ROS values decreased between stage 3 and stage 5 and were lower in the control. The fastest fire was obtained for stage 3 and here was about 40% faster than that in the untreated case.

3.3.4. Kermes oak garrigue

The fire in Kermes oak garrigue spread in all stages except one year after burning and in this case covered 30 m before stopping (Fig. 5d). Fire intensity increased from a low level (less than 900 $kW.m^{-1}$) in stage 1 and a moderate level in stage 2 (3600 $kW.m^{-1}$), to a high level (more than 5400 $kW.m^{-1}$) in stages 3 to 5 and in the control (no treatment). ROS values ranged between 0.32 and 0.43 $m.s^{-1}$. The fastest fire was obtained for stage 2 (Table 5). ROS values decreased between stage 2 and stage 5 and were lower in the control.

3.3.5. Mixed garrigue

The fire in Mixed garrigue spread in all stages, even one year after burning. But, it is noteworthy that the fire propagated erratically and did not burn the entire domain in this case, or in stage 2. Fire intensity increased from a low level (less than 1500 $kW.m^{-1}$) in stage 1 and a moderate level in stage 2 (3300 $kW.m^{-1}$), to a high level (more than 5700 $kW.m^{-1}$) in stages 3 to 5 and in the control (no treatment). ROS values ranged between 0.35 and 0.6 $m.s^{-1}$ (Table 5). The fastest fires were obtained for stages 2 to 4, and were relatively fast for shrubland fires. It should be noted in this case that a significant amount of dead rosemary remained after prescribed burning, with a low moisture content.

3.3.6. Grassland

Fire intensity in the grassland fuel complex was as low as the lowest fire intensity recorded for the Sparse oak coppice fuel complex 2 years after prescribed burning (900 $kW.m^{-1}$), while fire rate of spread was the highest (0.82 $m.s^{-1}$) of all the fuel types tested.

4. Discussion

In our study, fuel load was reduced in the various plant communities by about 50-60% in dense stands and 60-80% in sparse ecosystems in the first year after treatment. Our study therefore showed that prescribed burning did not reduce fuel loads by the 75-80% threshold proposed by Wade and Lunsford (1989) for efficient prescribed burning plans. However, this less marked fuel reduction is a good compromise between a total fire risk mitigation objective and vegetation management for nature conservation, which is the secondary objective pursued by managers of the Luberon State forest. A vegetation mosaic created by juxtapositioning burnt (by prescribed burning) and unburnt patches is favorable to wildlife (Pons et al., 2003).

Prescribed burning therefore results in a very heterogeneous fuel structure, with patches of unburnt fuel, low resprouters and clumps of trees. It is very difficult to evaluate fire behaviour in this context and only a model that accurately represents the three-dimensional fuel structure has any hope of doing so. This is the case with FIRETEC and the reason why the model is appropriate for such a study. However, due to certain assumptions made in the combustion model (particularly the fact that there is no transport of pyrolysis product, which is burnt locally), the model should not be run with a grid cell size of less than two meters. With this resolution, some of the clumps of unburnt and resprouting fuel are merged, as are some small areas with no vegetation. For this reason, FIRETEC tends to represent fuel with small-scale heterogeneities in a more continuous manner than in reality. Some investigations into radiative transfer (Pimont et al. 2010) have already shown that small-scale heterogeneities may affect fire behaviour and tend to reduce its rate of spread. It is likely that the spatial resolution in FIRETEC causes fire intensity to be overestimated, particularly in cases where heterogeneity is small compared to grid cell size. In our study we questioned on which heterogeneity would be responsible of the threshold between stage 2 and stage 3 in the Dense oak coppice compared to the grid cell size. The increase in fuel phytomass with a high cover fraction in stage 3 (cover of 60%) can explain the increase in fire intensity. However, we can also hypothesize that in addition areas with no vegetation, reduced by half between the two stages, were merged according to the low resolution of the model and therefore could not be taken into account adequately. Another limitation stemming from model resolution is seen when the fire stops, mostly in stage one. This FIRETEC prediction means that a fire will not propagate through convection and radiation under these conditions. But, the model does not take account of the small-scale conduction processes that might make a fire propagate in the field. Thus, caution should be exercised when the model predicts fire extinction.

Our results showed that the corresponding immediate reduction in fire line intensity ranged from 75% to 95%. This is similar to the post-treatment reduction in fire line intensity found after different prescribed burning programmes, where values ranged from 80% to 98% (Fernandes et al., 1999; Rego et al., 1987). And although the Wade and Lunsdord (1989) thresholds were not reached, burning efficiency was satisfactory in the first year after treatment.

The prescribed burning return interval for each plant community can be calculated by comparing our results with a classification of fire line intensity (Hough and Albini, 1978; Hirsch and Martell, 1996; Lampin-Cabaret et al., 2002). The 3500 kW.m^{-1} threshold has been used to differentiate between i) low (<1700 kW.m^{-1}) and moderate (1700-3500 kW.m^{-1}) fire intensities - which are still controllable by fire fighters - and ii) high (3500-7000 kW.m^{-1}) and very high (>7000 kW.m^{-1}) fire intensities that are beyond the control of fire fighters. The present study therefore showed that prescribed burning was efficient for 2 years in most of the Mediterranean plant communities analysed (fire intensities below the 3500 kW.m^{-1} threshold value). After this stage, all forests and shrublands were highly combustible with a fire line intensity that exceeded 5000 kW.m^{-1} except for pine stands with or without Holm oak (medium intensity of 2000 kW.m^{-1} at stage 3).

Mediterranean communities are recognized as highly fire resilient thanks to autosucession processes involving resprouter and obligate seeder species (Pausas, 2006; Pausas and Verdu, 2005). In the present study, the shrub strata of the plant communities were dominated by two resprouter species, *Q. coccifera* and *Q. ilex*, which explained the short post-fire vegetation recovery time. The ability of these species to rapidly mobilize underground reserves (water, nutrients, carbohydrates) for new sprouts (Pausas, 2001) allows the plant cover to recuperate in the first few years after a fire (Trabaud, 1974; Trabaud, 1985). In eastern Spain, only 3.5 years were required after a wildfire for a *Q. coccifera* garrigue to return to its pre-fire condition (Delitti et al., 2005). In France, several studies (Bertrand et al., 1991; Rigolot, 1997; Trabaud, 1974; Trabaud, 1991) have shown that between 2 and 7 years are necessary for *Q. coccifera* phytomass or phytovolume to recover after prescribed burning. In the present study we considered that plant communities recovered more than 60% of their phytomass 3 years after treatment, even though a series of burning treatments in several plots of the same plant community may lead to different fuel reduction levels (Fernandes et al., 2000). Low fire line intensity (900 kW.m^{-1}) was obtained for grassland which is entirely independent of the treatment since the resprouter hemicryptophyte, *Brachypodium retusum*, is highly resilient to fire (Baeza and Vallejo, 2008; Caturla et al., 2000).

Fuel load accumulation therefore greatly influences the behaviour and intensity of a fire, and some specific residual fuel has a particularly marked impact.

Fuel load recovery in the shrub strata and FIRETEC intensity predictions were fairly sensitive to the presence of *Q. ilex*. This can be explained by the distribution of a part of the phytomass below 2 m in height (even reaching the ground for some individuals) and that was not consumed during prescribed burning. This residual fuel load rapidly induced vertical fuel continuity between Holm oak trees and shrub layers, resulting in crown fire. Regarding *Q. ilex* plant communities, the dense cover provided by oak trees (50 %) in the Dense oak coppice explained its very rapid fuel load recovery (more than 65 % only 2 years after treatment). But, fire intensity was significantly reduced (<2000 $kW.m^{-1}$) in the early post-fire years due to sufficient horizontal and vertical heterogeneity.
The two garrigues also showed different fire behaviours. Despite a lower fuel load in the Mixed garrigue, the presence of burnt *R. officinalis* in the fuel complexes contributed to higher fire propagation at all stages. The production or retention of dead material is the most critical factor in explaining a greater or lesser susceptibility to fire (Baeza et al., 2006). Burnt *R. officinalis*, which does not resprout as an obligate seeder species, holds up in prescribed burning areas in the form of dead skeletons devoid of leaves but not the fine fuel fraction composed of twigs (own observations). A substantial quantity of standing necromass is thus maintained in post-fire Mixed garrigue, resulting in high flammability.

According to our results, tree canopy also plays a significant role in fire behaviour. Fire propagation was twice to three times faster in Kermes oak garrigue than in Pure pine stands in the first three years after treatment, whereas fuel shrub composition was very similar. Pure pine stands were associated with a lower shrub load than the garrigue, but the main reason for the lower ROS in fuel complexes involving trees is that wind speed decreases at ground level under tree canopy (Shaw et al., 1988; Lee, 2000). Less fuel and low wind under pine trees even led to fire extinction in the earlier stages, showing that prescribed burns are more effective under tree canopy than in garrigue. These results also confirm the advantages of maintaining a proportion of canopy cover in fuel-break management. Pimont et al. (2010) have shown that 25% canopy cover in a *Pinus halepensis* stand significantly reduced fire intensity in comparison with a closed stand. These authors also noted a less inclined plume and a lower firefront temperature than in open fuel breaks, and this is a crucial point in fire fighting.

5. Conclusion

This work has generated useful data that help in the current need to characterize and classify Mediterranean fuels in relation to their potential fire behaviour. All 8 common fuels described (Control stages) in limestone Provence were highly combustible and their derivated fuel complexes provided valuable information on the effects of prescribed burning on immediate reduction in potential fire hazard and the effect of time since burning.

In this study, the spatial distribution of fuels before treatment was heterogeneous, but fuel modifications following the burn of a plot were applied in a homogeneous way and in the same way within plots of the same plant community. We must, in the future, take account of the fact that in reality, fuel consumption by prescribed burning within a plot is generally very variable (Robichaud and Miller, 1999) and a series of burning treatments in several plots of the same plant community may lead to different fuel reduction rates (Fernandes et al., 2000).

In conclusion this study identified useful information for prescribed burners, i.e. the fire behaviour and the temporal thresholds related to prescribed burning effectiveness in the reduction of fuel hazard in the different fuel complexes. However, to make recommendations to plan fuel treatment at the landscape scale the spatial distribution of the fuel complexes and their implication in the fire risk will be necessary.

Acknowledgements

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Appendix A. Empirical mean profile used to establish initial and boundary conditions in FIRETEC for the present study.

Fuel characteristics in each plot were used to compute a mean *LAI* for the stand:

Eq. (A.1) $$LAI = \frac{1}{2l_x l_y} \int_0^{h\max} \int_0^{ly} \int_0^{lx} \frac{\rho}{\rho_{wood}} \sigma \, dxdydz$$

l_x and l_y the horizontal dimensions of the domain along the x and y axes, and $hmax$ the

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maximum height of the fuel bed. ρ, ρ_{wood} and σ are the bulk density, wood density and area to volume ratio of the fuel, respectively.

A typical wind velocity profile $\hat{u}(z)$ was computed, according to Raupach *et al.* (1994) and Su *et al.* (1998):

Eq. (A.2) $$\text{if } z \leq hmax,\ \hat{u}(z) = \exp\left(-c4\left(1 - \frac{z}{hmax}\right)\right)$$

Eq. (A.3) $$\text{if } z \geq 2hmax,\ \hat{u}(z) = \frac{c1}{\kappa}\ln\left(\frac{1}{c3}\left(\frac{z}{hmax} + c2 - 1\right)\right)$$

if z is between *hmax* and *2hmax*, a regression was made between $\hat{u}(hmax)$ and $\hat{u}(2hmax)$

Eq. (A.4) $$c1 = \frac{u*}{U_h} = \min(\sqrt{0.003 + 0.15LAI}, 0.3)$$

Eq. (A.5) $$c2 = 1 - \frac{d}{h} = \frac{1 - \exp\left(-\sqrt{7.5LAI}\right)}{\sqrt{7.5LAI}}$$

Eq. (A6) $$c3 = \frac{z0}{h} = c2\exp\left(-\frac{\kappa}{c1} - \ln(2) + 0.5\right)$$

Eq. (A.7) $$c4 = \max\left(\min\left(\frac{3.2 - 1.7}{4 - 1}(LAI - 1) + 1.7; 3.2\right); 1.7\right)$$

Ambient wind flow was then considered in equilibrium with the canopy. Its direction was parallel to the x axis and it was defined as follows:

Eq. (A.8) $$u^{amb}(x, y, z) = u_{40}^{amb}\frac{\hat{u}(z)}{\hat{u}(40)},\quad v^{amb}(z) = w^{amb}(z) = 0$$

where the upper script amb indicates the ambient value. The ambient wind velocity U_{40}^{amb} at 40 m above ground level was 10 m.s^{-1}. This ambient wind flow was used to initiate the flow and to assess the upwind and downwind boundary conditions of the domain through a relaxation process.

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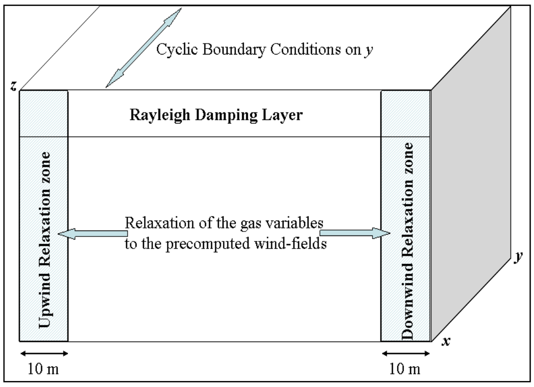

Schematic representation of boundary conditions on the computational domain

Table Abreviation and symbols

hmax	maximum fuel bed height
LAI	leaf area index
l_x, l_y	horizontal dimensions of the domain
ρ	fuel bulk density (kg/m3)
ρ_{wood}	fuel bulk density (kg/m3)
σ	volume ratio of the fuel (1/m)
$\hat{u}(z)$	normalized wind profile ($\hat{u}(h\max) = 1$)

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Figure captions

Figure 1. Location of the Petit Luberon State forest area and the five fuel-breaks network. Areas of the two fuel breaks studied, Trou-du-Rat and Mayorques, are represented by black lines on State forest vegetation map.

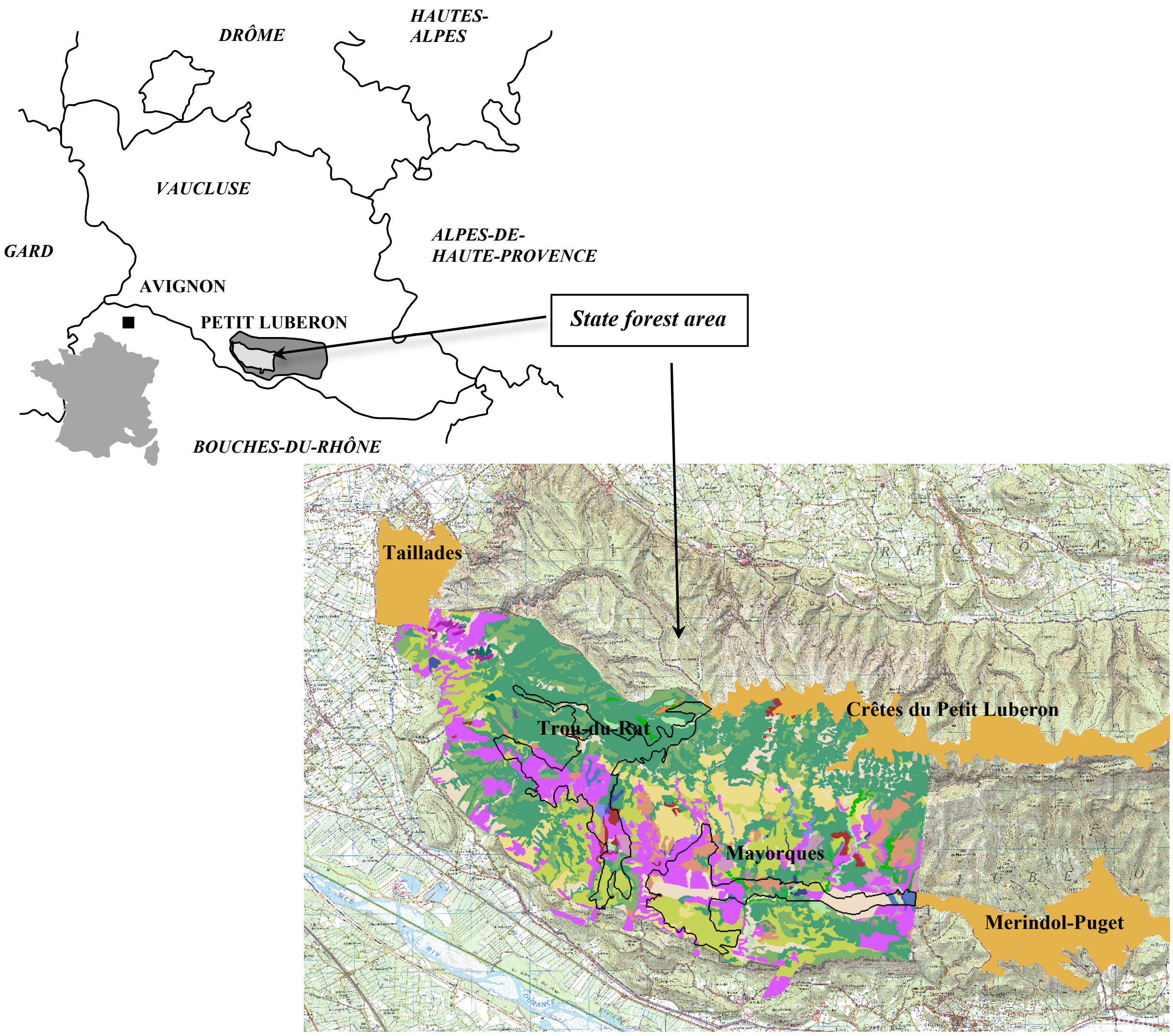
Figure 2. Top view of the fuel scene.

Figure 3. Total fine fuel load ($t.ha^{-1}$) for the different fuel complexes at the different stages. The dashed line represents the biomass of the untreated plot for a given community.

Figure 4. Wind profile computed with FIRETEC in the lower part of the domain for the control stage of the fuel complexes.
These data were extracted after 30s of real-time computation (just before ignition), at x=160 m

Figure 5. Views of fire propagation in the Control stage for a) Pure pine stand, b) Dense oak coppice, c) Sparse oak coppice and d) Kermes oak garrigue.

Figures 1, 2 and 5 are intended for color reproduction on the web and in print



(from SIG_EAM ONF Avignon, 2008)

Legend :

- Cedrus plantation: *Cedrus atlantica*
- Mixed stand : *Quercus ilex* and *Cedrus atlantica*
- Mixed stand : *Pinus halepensis* and *Cedrus atlantica*
- Pine stand : *Pinus halepensis*
- Mixed stand : *Pinus halepensis* and *Quercus ilex*
- Pine stand : *Pinus Brutia*
- Pine stand : *Pinus nigra* subsp *laricio*
- Pine stand : *Pinus nigra*
- Pine stand : other Conifers
- Oak stand: *Quercus pubescens*
- Dense oak stand : *Quercus ilex*
- Sparse oak stand: *Quercus ilex*
- Mixed stand: *Quercus pubescens* and *Quercus ilex*
- Broad-leaved garrigue
- Garrigue with trees
- Garrigue without trees
- Heathland
- Grassland

Figure 1

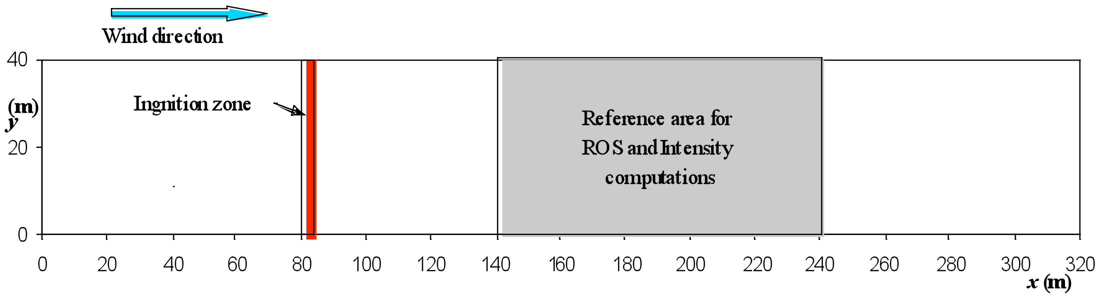

Wind direction
Ingnition zone
Reference area for
ROS and Intensity
computations
40
20
0
y (m)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
x (m)

Figure 2

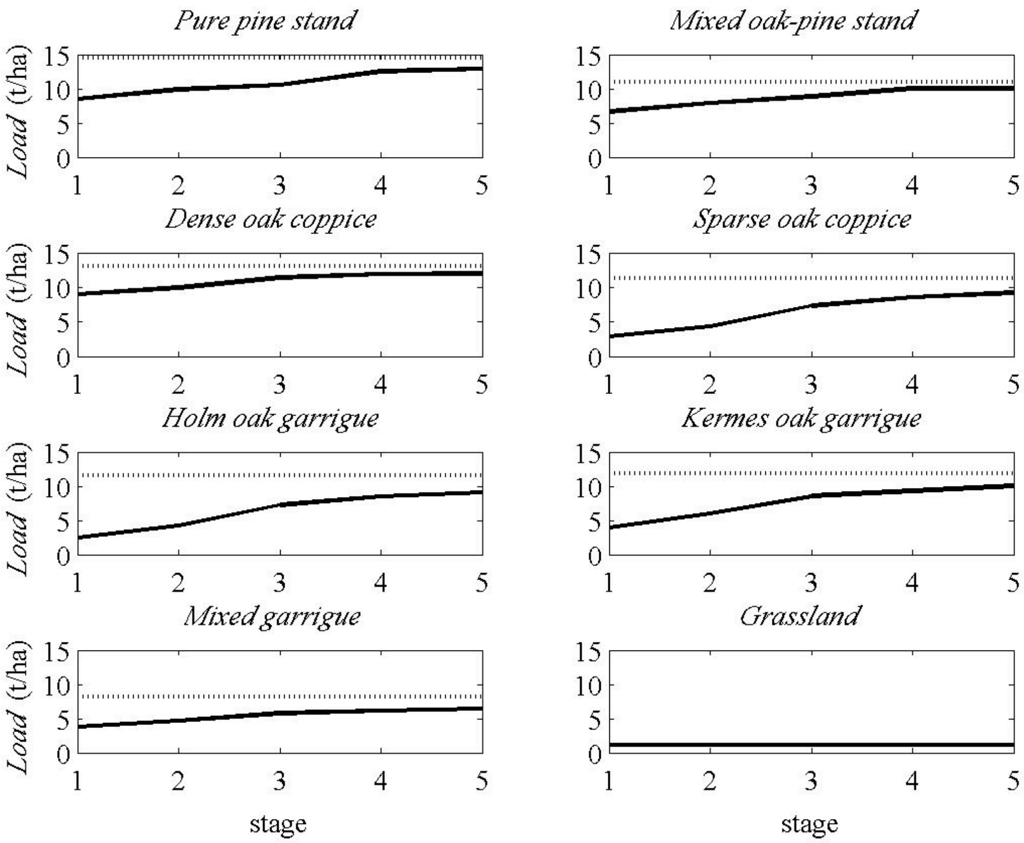

Pure pine stand
Mixed oak-pine stand
Dense oak coppice
Sparse oak coppice
Holm oak garrigue
Kermes oak garrigue
Mixed garrigue
Grassland
Load (t/ha)
stage
0
5
10
15
1
2
3
4
5

Figure 3

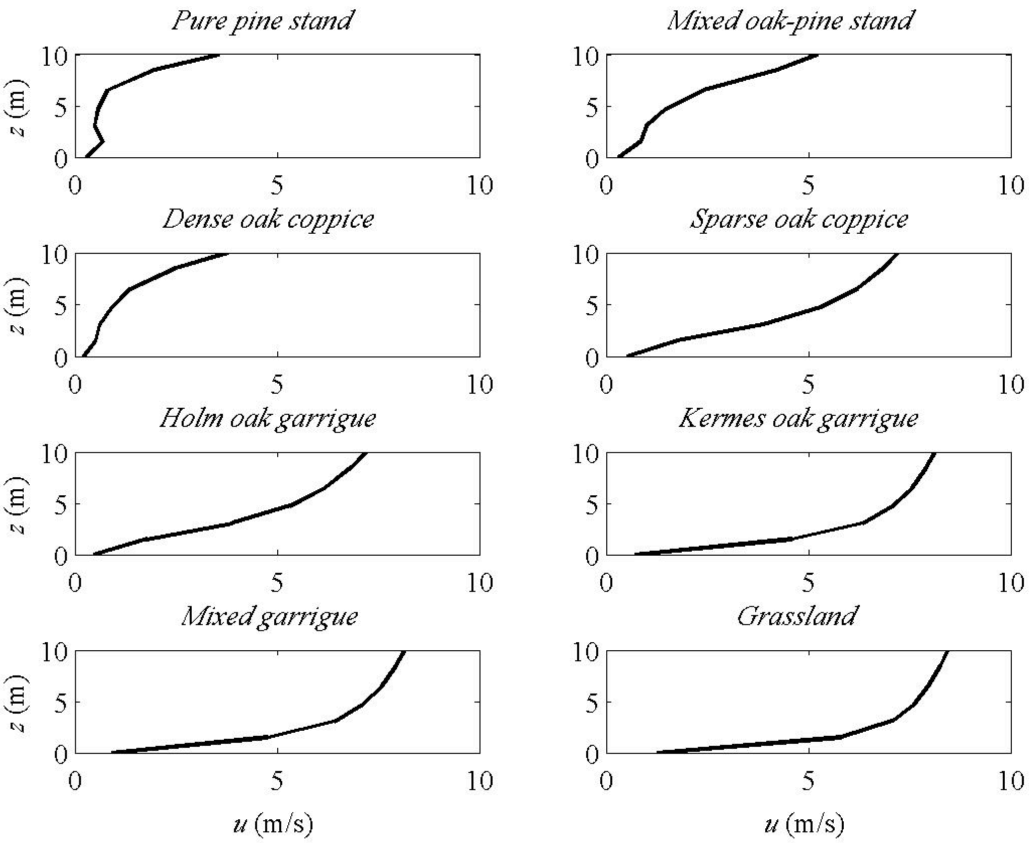
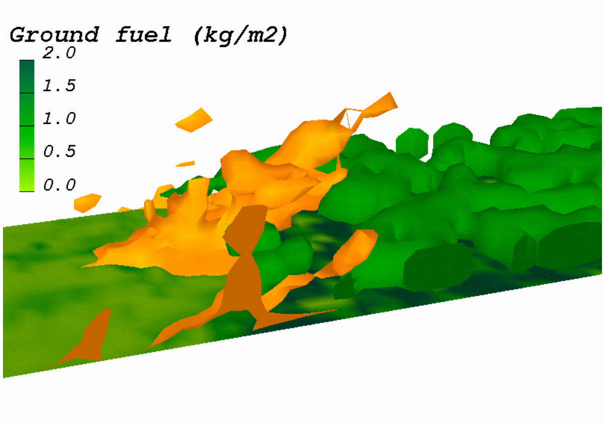
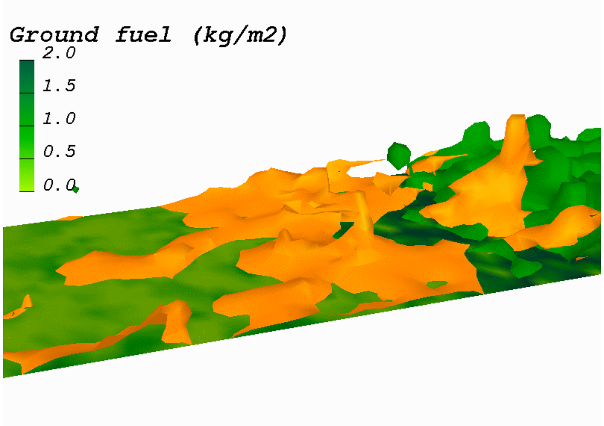

Pure pine stand
Mixed oak-pine stand
Dense oak coppice
Sparse oak coppice
Holm oak garrigue
Kermes oak garrigue
Mixed garrigue
Grassland
z (m)
u (m/s)
0
5
10

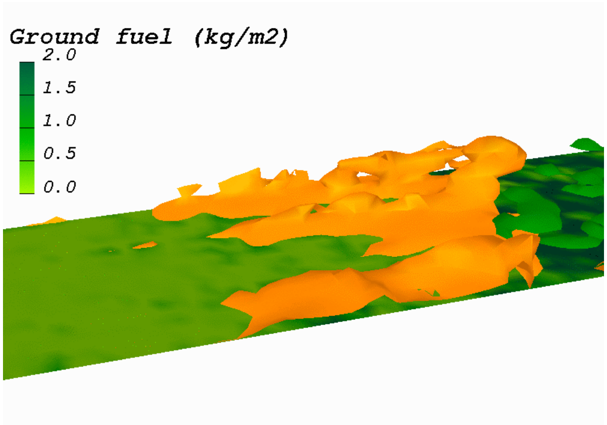
Figure 4



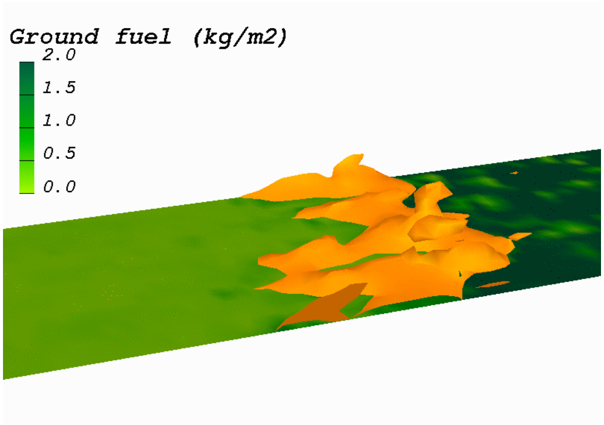
5.a) Pine stand (C), 4min after ignition



5.b) Dense coppice (C), 3min after ignition



5.c) Sparse coppice (C), 4min after ignition



5.d) Kermes garrigue (C), 5min30sec after ignition

Figure 5

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Table 1. Characteristics of the eight untreated plant communities selected at their maximum phytovolume (Control stage) and their shrub fuel load.
(h: height; cbh: crown base height; C: cover fraction)

Plant communities	Tree species	h	cbh	C	Shrub species	h	C	Herb species	h	C	Fuel load (t/ha)
Pure pine stand	*Pinus halepensis*	9m	3m	50%	*Quercus coccifera*	0.6m	49%	*Brachypodium retusum*	0.25m	30%	**9.7**
					Quercus ilex	1.2m	11%				
					Rosmarinus officinalis	0.7m	11%				
Mixed oak-pine stand	*Pinus halepensis*	7.5m	2.5m	20%	*Quercus coccifera*	0.6m	36%	*Brachypodium retusum*	0.25m	30%	**8.22**
	Quercus ilex	4.5m	0m	15%	*Quercus ilex*	0.6m	15%				
					Rosmarinus officinalis	0.7m	9%				
Dense oak coppice	*Quercus ilex*	4m	0.5-1m	50%	*Quercus coccifera*	0.6m	30%	*Brachypodium retusum*	0.25m	30%	**8.84**
	Pinus halepensis	9m	3m	15%	*Quercus ilex*	0.75m	15%				
					Rosmarinus officinalis	0.5m	15%				
Sparse oak coppice	*Quercus ilex*	3m	0.5-1m	25%	*Quercus ilex*	1.5m	40%	*Brachypodium retusum*	0.25m	30%	**10.36**
					Cistus alba	0.5m	10%				
Holm oak garrigue	*Quercus ilex*	3m	0m	10%	*Quercus ilex*	1.5m	40%	*Brachypodium retusum*	0.25m	30%	**10.82**
					Cistus alba	0.6m	20%				
Kermes oak garrigue					*Quercus coccifera*	0.7m	64%	*Brachypodium retusum*	0.25m	30%	**11.44**
					Quercus ilex	1.2m	16%				
Mixed garrigue					*Quercus coccifera*	0.75m	48%	*Brachypodium retusum*	0.25m	30%	**7.88**
					Rosmarinus officinalis	1m	20%				
Grassland								*Brachypodium retusum*	0.25m	100%	**1.1**

Table 2. Characteristic of shrub fuel complexes at the different stages after treatment expressed in height and cover fraction and their shrub fuel load (Qc: Quercus coccifera; Qi: Quercus ilex; Ro: Rosmarinus officinalis; Ca: Cistus alba)

		stages				
		1y	2y	3y	4y	5y
Plant communities	**shrub**					
Pure pine stand	*Qc unburnt*	0.6m (14%)	0.6m (14%)	0.6m (14%)	0.6m (14%)	0.6m (14%)
	Qc resprout	0.15m (11%)	0.25m (18%)	0.3m (21%)	0.4m (28%)	0.45m (35%)
	Qi resprout	0.25m (4%)	0.35m (7%)	0.45m (7%)	0.6m (11%)	0.75m (11%)
	Ro unburnt	0.7m (11%)	0.7m (11%)	0.7m (11%)	0.7m (11%)	0.7m (11%)
	Fuel load (t/ha)	**3.67**	**5.04**	**5.75**	**7.69**	**8.07**
Mixed oak-pine stand	*Qc unburnt*	0.6m (12%)	0.6m (12%)	0.6m (12%)	0.6m (12%)	0.6m (12%)
	Qc resprout	0.15m (9%)	0.25m (15%)	0.3m (18%)	0.4m (24%)	0.45m (24%)
	Qi resprout	0.15m (6%)	0.2m (12%)	0.25m (15%)	0.3m (15%)	0.4m (15%)
	Ro unburnt	0.7m (9%)	0.7m (9%)	0.7m (9%)	0.7m (9%)	0.7m (9%)
	Fuel load (t/ha)	**3.85**	**5.13**	**6.12**	**7.31**	**7.28**
Dense oak coppice	*Qc unburnt*	0.6m (12%)	0.6m (12%)	0.6m (12%)	0.6m (12%)	0.6m (12%)
	Qc resprout	0.15m (6%)	0.25m (12%)	0.3m (18%)	0.4m (18%)	0.45m (18%)
	Qi resprout	0.15m (6%)	0.2m (9%)	0.25m (15%)	0.3m (15%)	0.4m (15%)
	Ro unburnt	0.5m (15%)	0.5m (15%)	0.5m (15%)	0.5m (15%)	0.5m (15%)
	Fuel load (t/ha)	**4.79**	**5.78**	**7.21**	**7.72**	**7.79**
Sparse oak coppice	*Qi resprout*	0.25m (10%)	0.35m (20%)	0.45m (40%)	0.6m (40%)	0.75m (40%)
	Ca resprout	0.1m (5%)	0.2m (10%)	0.3m (10%)	0.4m (10%)	0.5m (10%)
	Fuel load (t/ha)	**1.82**	**3.34**	**6.27**	**7.47**	**8.17**
Holm oak garrigue	*Qi resprout*	0.25m (10%)	0.35m (20%)	0.45m (40%)	0.6m (40%)	0.75m (40%)
	Ca resprout	0.1m (10%)	0.2m (20%)	0.3m (20%)	0.4m (20%)	0.4m (20%)
	Fuel load (t/ha)	**1.74**	**3.46**	**6.49**	**7.74**	**8.34**
Kermes oak garrigue	*Qc unburnt*	0.7m (16%)	0.7m (16%)	0.7m (16%)	0.7m (16%)	0.7m (16%)
	Qc resprout	0.15m (28%)	0.25m (36%)	0.35m (44%)	0.45m (48%)	0.5m (48%)
	Qi resprout	0.25m (4%)	0.35m (8%)	0.45m (16%)	0.6m (16%)	0.75m (16%)
	Fuel load (t/ha)	**3.56**	**5.68**	**8.24**	**8.98**	**9.74**
Mixed garrigue	*Qc unburnt*	0.7m (12%)	0.7m (12%)	0.7m (12%)	0.7m (12%)	0.7m (12%)
	Qc resprout	0.15m (16%)	0.25m (20%)	0.35m (28%)	0.45m (32%)	0.5m (32%)
	Ro unburnt	1m (5%)	1m (5%)	1m (5%)	1m (5%)	1m (5%)
	Ro burnt	0.9m (15%)	0.9m (15%)	0.9m (15%)	0.9m (15%)	0.9m (15%)
	Fuel load (t/ha)	**3.44**	**4.3**	**5.45**	**5.77**	**6.12**

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Table 3. Fine fuel physical properties for each species.

	Pinus halepensis	*Quercus ilex*		*Quercus coccifera*		*Rosmarinus officinalis*		*Cistus alba*		*Brachypodium retusum*
Parameters		trees	shrubs				(dead)			
ρ (kg.m^{-3})	0.15	0.25-0.4	2.11-3.26	1.65-3.31		1.17-1.64	0.5	0.85-1.3		0.44
	leaves	leaves	twigs 0-2mm	leaves	twigs 0-2mm	leaves	twigs 0-2mm	leaves	twigs 0-2mm	leaves
σ (m^{-1})	9000	4054	2452	5818	2870	4383	2641	3640	2590	20000
MC (%)	100	74		76		66 (20)		72		15

Table 4. Fire intensity computed in the different fuel complexes (in kW.m^{-1})

Stage / **Plant Community**	1	2	3	4	5	Control
Pure pine stand	(1300)	(1500)	(2000)	6000	5800	5500
Mixed oak-pine	(600)	(730)	2300	5500	5500	5800
Dense oak coppice	(1500)	2000	13100	13800	13900	14800
Sparse oak coppice	(650)	900	8100	9300	9400	10500
Holm oak garrigue	(350)	1600	6400	6400	6600	7700
Kermes oak garrigue	(900)	3600	5300	5400	5600	6300
Mixed garrigue	1500	3300	5800	5900	5700	6000
Grassland	900	900	900	900	900	900

NB: the numbers in brackets correspond to initial intensity (for runs where the fire stopped)

Table 5. Firefront Rate Of Spread (ROS) for the different fuel complexes (in m.s^{-1})

Stage / Plant community	1	2	3	4	5	Control
Pure pine stand	(0.12)	(0.14)	(0.2)	0.37	0.35	0.28
Mixed oak-pine	(0.3)	(0.16)	0.16	0.45	0.41	0.37
Dense oak coppice	(0.2)	0.29	0.7	0.7	0.73	0.75
Sparse oak coppice	(0.23)	0.29	0.7	0.65	0.6	0.53
Holm oak garrigue	(0.3)	0.37	0.54	0.47	0.44	0.39
Kermes oak garrigue	(0.32)	0.43	0.38	0.38	0.34	0.34
Mixed garrigue	0.35	0.57	0.59	0.6	0.54	0.43
Grassland	0.82	0.82	0.82	0.82	0.82	0.82

NB: the numbers in brackets correspond to initial ROS (for runs where the fire stopped)

Table 6. Distances covered by the fire before extinction

Fuel complexes	Distances (m)
Pure pine stand (1y)	15
Pure pine stand (2y)	26
Pure pine stand (3y)	64
Mixed oak-pine (1y)	22
Mixed oak-pine (2y)	84
Dense oak coppice (1y)	32
Sparse oak coppice (1y)	24
Holm oak garrigue (1y)	12
Kermes oak garrigue (1y)	30