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Potential crown fire behaviour in *Pinus pinea* stands following different fuel treatments

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Abstract

Forest fires are permanent seasonal threats that have been accentuated in recent years by climate change. Taking this problem into consideration, forest policies must propose courses of action to mitigate the effects of fires on ecosystems and their surrounding populations. The aim of this study is to assess the effectiveness of fuel treatments on the potential fire behavior of *Pinus pinea* polewood stands.

Evaluating fire behavior requires a characterization of the fuel at its two levels: surface and crown layers. As crown fuel characterization is highly time consuming, field inventory has yielded an equation from which canopy fuel load can be obtained without cutting trees. A complete characterization of the fuel allows for a prediction of fire behavior for each silvicultural treatment and whether or not it will be virulent enough for the start and spread of crown fire.

Polewood stands of *P.pinea* are susceptible to crown fires because canopy base height is usually overrun by dense and flammable understory. Thinning and pruning treatments on the stand do not contribute in themselves to eliminating crown fire susceptibility. This study raises the need for fuel treatments combination (both surface and crown treatments) to ensure the effectiveness of extinction efforts. Given current budgetary constraints, fuel treatments are limited to 23.40% of the study area for mitigating possible crown fire impacts on forested area that have a future leading role in the socioeconomic development of surrounding populations.

Key words: forest fires; fuel management; conifer stands; fuelbreaks.

Resumen

Comportamiento potencial del fuego de copas en masas de *Pinus pinea* bajo diferentes tratamientos selvícolas

Los incendios forestales constituyen una amenaza estacional de carácter permanente, acentuada en los últimos años por el cambio climático. Las políticas forestales deben considerar este problema y plantear líneas de actuación para la mitigación de los efectos del paso de las llamas sobre los ecosistemas y la población circundante. El objetivo de este estudio radica en la evaluación de la eficacia de diferentes tratamientos selvícolas en masas de *Pinus pinea* en estado latizal en relación con sus efectos en el comportamiento potencial del fuego.

La evaluación del comportamiento del fuego requiere de una caracterización del combustible en sus dos niveles: superficial y aéreo. Dados los costes de esta última caracterización, el inventario de campo ha permitido obtener una ecuación a partir de la cual se puede obtener la carga de combustible aéreo sin necesidad de apeo de árboles. La caracterización completa del combustible permite la predicción del comportamiento del fuego de cada tratamiento selvícola, y si éste es suficientemente virulento como para producir una transición a fuego de copas.

Las masas en estado latizal de *P.pinea* adquieren mucha susceptibilidad a la ocurrencia de incendios de copa debido a que generalmente la parte inferior de las copas se encuentra invadida por un sotobosque denso e inflamable. Los tratamientos aéreos, como claras y podas, no contribuyen por si solos a eliminar esta susceptibilidad a fuego de copas. Este estudio plantea la necesidad de tratamientos del combustible superficial y aéreo de forma conjunta para asegurar la eficacia de las labores de extinción. Dada la limitación presupuestaria actual se limitan los tratamientos del combustible al 23.40% del área estudiada con objeto de mitigar en la medida de lo posible los impactos de los incendios de copa en unas masas arboladas de indudable protagonismo futuro para el desarrollo socioeconómico de su población circundante.

Palabras clave: incendios forestales; ordenación del combustible; masas de coníferas; áreas cortafuegos.

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Introduction

Mediterranean forest management devotes much of its efforts in seeking a diversified production of their resources. This has led forest managers to guide silviculture towards the resource or resources that, because of higher demand, have higher market prices. In Mediterranean pine forests, the *Pinus pinea* is one of the most important because of social demands for non-timber products, such as pine nut and hunting, that are of high socio-economic importance to the surrounding population (Montero *et al.*, 2004). In Spain, the *Pinus pinea* occupies an area of 475,000 ha (Montero *et al.*, 2004), demonstrating a high ecological and socio-economic vulnerability to the greatest disturbance in the Mediterranean area: forest fires. This susceptibility has been accentuated by the impact of climate change which has changed the frequency and severity of forest fires (Flannigan and Corns, 2000; Flannigan *et al.*, 2001, 2006; Millán *et al.*, 2005), increasing the fire impacts either directly (tangible assets) or indirectly (environmental services and landscape goods) (Molina, 2008). Forest fires are a complex process that varies over time and space because of weather, topography and vegetation (Heikkilä *et al.*, 2007). Surface vegetation characteristics such as the flammability of the species, density or shrub height; the sustained ignition and surface fire behavior. Crown fires, however, are the most dangerous events since they cause tree mortality and have the largest economic impacts (Molina *et al.*, 2009). Crown fires are a serious problem for forest management because fire suppression efforts are much more complex than surface fires due to fire-line intensity, spread rate, smoke production, spotting and entropy energy (Rodríguez y Silva, 2009).

The transition between surface fire and crown fire depends on meteorological and fuel conditions (Van Wagner, 1977). In this sense, spread models that simulate the potential behavior of crown fires are directly dependent on the canopy fuel characteristics (Scott and Reinhardt, 2001). Van Wagner (1977) pointed out crown base height (vertical distance between ground surface and the base of the live crown fuels) and foliar moisture content as the parameters that condition crown fire initiation. Once the transition produces, the crown fire rate depends on wind speed, canopy bulk density and the estimated fine fuel moisture content (Cruz *et al.*, 2002, 2005, 2006). Behavioral assessment of potential crown fire through these models can be useful in defining and distributing fuel treatments for forest fire protection (Graham *et al.*, 1999; Mitsopoulos and Dimitrakopoulos, 2007).

The spatial arrangement of fuels to landscape scale can reduce forest susceptibility to crown fires (Gustafson *et al.*, 2004; Duguy *et al.*, 2007). Efficiency in locating fuelbreaks plays a key role because of current budgetary constraints. A fuelbreak is a strategically localized wide block on which a cover of dense and flammable vegetation has been permanently changed to one of lower fuel volume or reduced flammability; and therefore, having less potential fire-line intensity (Agee *et al.*, 2000). This transformation requires an implementation of silvicultural treatments that increase the chances of fire suppression success, although generally they are insufficient in themselves in stopping the fire (Agee *et al.*, 2000). Fuel treatments aimed at decreasing stand susceptibility can include composition alteration, spatial continuity or surface fuel height modification as well as increasing the canopy base height or cutting trees to create gaps in canopy cover (Brose and Wade, 2002; Agee and Skinner, 2005). Treatments aimed at altering surface fuel are usually accomplished through mechanical fuel treatment (Mason *et al.*, 2007) or prescribed burning to reduce fuel loads (Knapp *et al.*, 2005; Ritchie *et al.*, 2007). As for canopy fuel treatments, pruning increases the distance between the ground surface and the base of the crown fuel (Cruz *et al.*, 2006) and crown thinning reduces the basal area and canopy bulk density (Graham *et al.*, 1999). All of these fuel treatments used alone or in combination are options available for the spatial arrangement of fuels in order to mitigate the consequences of crown fires.

The aim of this paper is to assess the effectiveness of six fuel treatments on the potential crown fire behavior of *Pinus pinea* polewood stands. The development of a field inventory permitted the gathering of the surface and crown fuel characteristics needed to apply to fire behavior models. Due to time difficulties and the cost of destructive crown fuel inventories, an equation was constructed to estimate a 1-h time-lag fuel for every tree, providing a highly effective tool for developing future inventories. Applying potential fire behavior models allowed us to estimate the effects of different treatments on potential surface fire behavior, its threshold before transferring to crown fire and the active crown fire rate. Lastly, one should not forget that in forest fire suppression, a correct definition for silvicultural treatment based on its effect on potential fire behavior becomes as important as its strategic location. In this sense, an optimization of fuel treatments is proposed on the basis of minimum travel time, consistent with current budget constraints.

Material and methods

Study area

Pinus pinea forests have great importance in the province of Cordoba, located in southern Spain, occupying an area of 63,000 ha (Molina, 2008). The province of Cordoba is characterized by a Mediterranean climate with a pronounced dry period and daytime summer temperatures above 40°C. The occurrence and severity of fires, therefore, is a serious problem, with official statistics indicating an average of 119 fires per year and an affected forest area of 835 hectares (period 1999-2009).This study was conducted in the «Belmez, Villanueva del Duque and Espiel» forests, all of public domain, located in the northwestern province of Cordoba (Fig. 1). The study area is located approximately 60 km north of Cordoba (latitude 38° 4' 31", longitude 5° 4' 31"), located between 530 and 920 m above sea level, with an area of 3,200 ha of *P. pinea*. The average slope is between 15-30%, showing preference to exposures in the south and west.

The study area has been managed from the viewpoint of non-timber resources, mainly hunting, yet with prospects of future pine nut harvests. Forestry planning of the study area includes six stands with the following main objectives: the search for an optimal density for pine nut production, the mosaic distribution of grassland-shrub-trees to provide food and shelter for game wildlife and the forest fires prevention. To achieve these objectives, the following silvicultural treatments are used alone or in combination: moderate crown thinning, heavy crown thinning, pruning and mechanical fuel reduction. The distribution of treatments is as follows: «Stand 1» (moderate crown thinning), «Stand 2» (heavy crown thinning-pruning-mechanical fuel reduction),

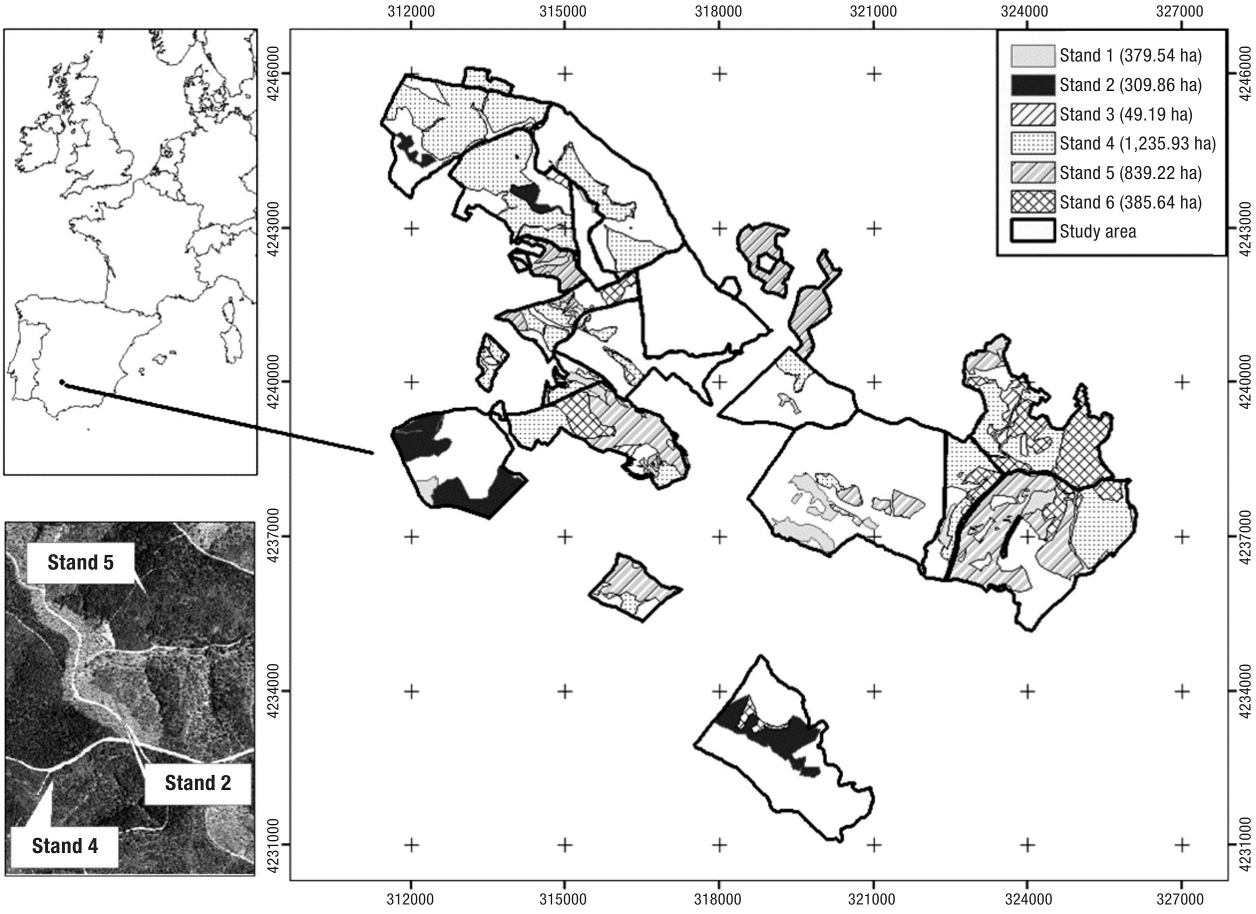

Figure 1. Study area location.

«Stand 3» (moderate crown thinning), «Stand 4» (moderate crown thinning-pruning), «Stand 5» (heavy crown thinning-pruning) and «Stand 6» (pruning). Silvicultural treatments of «Stands 1, 2, 3 and 4» have been implemented in the last five years and «Stand 2» even receives regular maintenance.

Field inventory

The field inventory, in accordance with existing structural diversity, was carried out in circular plots with a 10 m radius using the stratified random sampling method. According to the «Manual of Forestry Management in Andalusia» (Junta de Andalucía, 2004), for a random stratified inventory, a maximum sampling error of 30% is allowed with a fiducial probability of 95%. Based on this condition and using statistical variable stand density, we calculated the theoretical number of plots for each stratum according to an optimal and proportional allocation (Table 1). The theoretical size of the sample amounted to 19 plots located across the different stands, far exceeding the inventory developed with statistical requirements.

The data sampling collected information about surface and canopy fuel in order to predict potential surface fire behavior, transition to crown fire and the spread rate of both. The characterization of surface fuel was conducted through destructive transects using the line-intercept method (Stephens and Moghaddas, 2005). The canopy fuel inventory was conducted in depth by incorporating variables such as diameter at breast height, tree height, canopy base height, crown diameter, crown projection area, canopy fuel load, canopy bulk density, branch whorl number and foliar and twig moisture content. The fuel load expressed as the 1-h time-lag fuel, both needles and twigs, was estimated through destructive inventory. Since the collected material could include differences in moisture content, a 48 h drying process was required at a temperature of 70°C (Elvira and Hernando, 1989), after which the fuel weight remained constant. This process was done separately for both needles and twigs. Although differences can be found in the case of the needles based on their age, this study does not consider these differences and adopted a mean value for foliar moisture content.

Surface fire behavior

Predicting potential surface fire behavior can be accomplished through various decision support systems, such as Farsite (Finney, 1998), Behave (Rothermel, 1972; Burgan and Rothermel, 1984), Behave Plus (Andrews, 2003), Visual Behave and Visual Cardin (Rodríguez y Silva *et al.*, 2010), based on the identification of fuel models (field inventory), topographic attributes and weather conditions. In this study, fire behavior simulation was carried out using Visual Behave and Visual Cardin, software that allows the use of the fuel models proposed by Scott and Burgan (2005) to be adapted to Mediterranean conditions (Vélez, 2009). Surface fire behavior was determined from modal conditions during the summer months (temperature, relative humidity, wind speed and direction) and was represented using three parameters: rate of spread, flame length and fire intensity. These parameters were estimated for each stand, indicating its mean and standard deviation, with special attention paid to surface intensity, for its role in the transition to crown fire.

Table 1. Results of stratified random inventory

Stand	P_j	S_j^2	S_j	n_j	n_{js}
1	0.191	3	1.7	2	5
2	0.047	2.2	1.5	1	3
3	0.032	13.2	3.6	1	4
4	0.361	19.3	4.4	9	10
5	0.043	1.2	1.1	1	3
6	0.326	10.1	3.4	5	5
		Standard error		0.775	
		Sampling error		1.55	
		Standard error of the mean		7.88	

P_j: representativity. S_j^2: variance. S_j: standard deviation. n_j: theoretical number of plots for each stand. n_{js}: real number of plots (field sampling).

Crown fire behavior

Forested areas with dense understory are susceptible to the transition of surface fire to the crown fuel layer. The crown fire model used in this study allowed us to determine the threshold for transition to crown fire and whether or not the fire fulfilled the conditions for the start and spread of crown fire (Van Wagner, 1977, 1993). The initiation of crown fire depends largely on the distance between the surface and crown fuel layers:

$$I_0 = [0.01\ \mathrm{CBH}\ (460 + 25.9\ \mathrm{M})]^{3/2} \qquad [1]$$

where: «I_0» is the threshold for transition to crown fire (kW m^{-1}). «CBH» is the vertical distance between the ground surface and the base of live crown fuel (m) and «M» is the crown foliar moisture content (%).

The crown fire typology (passive or torching and active) is determined by the threshold for active crown fire spread rate:

$$\mathrm{Rc} = 3.0 / \mathrm{CBD} \qquad [2]$$

where: «Rc» is the minimum critical rate needed for active crown spread (m/min). «CBD» is the canopy bulk density (kg m^{-3}) and «3» is the product of a conversion factor and an empirical constant defined by the critical mass flow rate through the crown layer for continuous flame (Van Wagner, 1977). It should be noted that although this research is committed to using this product, it has been modified by some authors (Dickinson *et al.*, 2007).

Therefore, the existence of active crown fire depends directly on surface fire behavior. The development of an active crown fire requires a surface intensity greater than the threshold needed for the transition to crown fire. For defining active crown fire, Van Wagner (1993) proposes the use of an objective criterion (crown fraction burned, defined as the proportion of trees involved in the crowning phase of the fire):

$$\mathrm{CFB} = 1 - e^{-0.23\ \mathrm{x}\ (\mathrm{R-Rc})} \qquad [3]$$

where: «CFB» is the crown fraction burned (ranging from 0 to 1), «R» is the rate of surface fire spread (m min^{-1}) and «Rc» is the critical surface spread rate to begin a transition to crown fire spread (m min^{-1}).

Once the existence of crown fire is determined, there are two main approaches in predicting the crown fire spread rate (Finney, 1998; Alexander *et al.*, 2006). The first approach is the Rothermel model (Rothermel, 1991), which is based on the relationship between the predicted surface spread rate and the velocities observed in crown fires. While the spread rate of a passive crown fire (torching or candling) is assumed equal to that of the surface fire, the active crown fire spread rate is expressed by the following equation.

$$R_{\mathrm{active}} = 3.34\ (R_{10})_{40\%}\ E_i \qquad [4]$$

where: «R_{active}» is the maximum active crown fire spread rate (m min^{-1}), «3.34» is an empirical constant, «$(R_{10})_{40\%}$» is the active crown fire spread rate determined from a correlation with the forward surface fire spread rate for U.S. fuel model 10 (Anderson, 1982) using a 0.4 wind reduction factor (m min^{-1}) and «E_i» is the fraction of the forward crown fire spread rate (%).

The second approach is for an active crown fire model based on wind speed, canopy bulk density and fuel moisture content, corrected for the mean slope of the terrain (Cruz *et al.*, 2002, 2005, 2006):

$$\mathrm{CROS} = 11.76 \times U_{10}{}^{0.86} \times \mathrm{CBD}^{0.18} \times\ e^{(-0.17 \times \mathrm{EFFM})} \qquad [5]$$

$$\mathrm{CROS}_{\Phi} = \mathrm{CROS} \times e^{3.533\ (\Phi/100)\wedge 1.2} \quad 0 \leq \Phi \leq 60 \qquad [6]$$

where: «CROS» is the active crown fire spread rate (m min^{-1}), «U_{10}» is the wind speed measured at a 10 m height in the open (km h^{-1}), «CBD» is the canopy bulk density (kg m^{-3}), «EFFM» is the estimated fine fuel moisture content (%), «$\mathrm{CROS}_{\circ}$» is the active crown fire spread rate corrected for the mean slope of the terrain (m/min) and «Φ» is the average slope of the terrain (degrees).

Statistical analysis

Analysis of variance (ANOVA) was used to determine if significant differences ($p < 0.05$) existed in vegetation (stand density, stand height, canopy base height, dry canopy fuel load, canopy bulk density), surface fuel (fuel load, fuelbed depth), surface fire behavior (spread rate, flame length, fire intensity) and crown fire behavior (threshold for transition to crown fire, threshold for active crown fire spread rate, crown fraction burned, crown fire spread rate) for each fuel treatment. SPSS 10© software was used in all analyses. If significant differences were detected, a Tukey HSD test was performed to determine which specific fuel treatment was different from another.

Spatial optimization of fuel treatments

The fuel treatments optimization was based on the minimum travel time theory, which calculates fire growth and behavior by searching for the set of pathways with minimum spread times from a point, line or polygon ignition source (Finney, 2002). For this treatment optimization to become real and effective, an important factor lies in the economic considerations of the proposed actions, either by treatment fraction or treatment dimension. The treatment fraction is the maximum proportion of the study area that can be treated with the available budget. Treatment dimension is the minimum fuelbreak width recommended for satisfactory fire suppression. In this study, fuelbreak dimension was estimated using the «Rodríguez y Silva model» (Rodríguez y Silva, 1998; Rodríguez y Silva *et al.*, 2010), based on the potential fire-line intensity, slope, fuel model and the flame angle (angle between flame and horizontal).

Fuelbreaks were usually located in the southern and western slopes of the mountains (Weatherspoon and Skinner, 1996) or along existing linear infrastructures such as roads, paths and fire-break with the objective of facilitating fire suppression efforts and their construction and as a direct result, their costs. In this study, roads located along the broad valley bottom and areas bordering woodlands have also been considered adequate for treatment implementation, roads near sinuous slopes and canyons, however, were avoided due to the risk of eruptive phenomena.

Results

Field inventory

Surface fuel characterization was performed individually for each stand, based on the results from the line-intercept method. Although a large amount of additional variables was collected during the inventory, such as live fuel load, dead fuel load by particle size class (1-h, 10-h and 100-h time-lag), surface area to volume ratio or surface fuel moisture content, only a summary of the three most important are presented here: fuel type, total fuel load and fuelbed depth (Table 2). The surface fuel was dominated by shrubs highly flammable in summer (*Cistus* spp.), except in the case of «Stand 2» which was dominated by short grass. The fuel load was very high, exceeding 30 t ha^{-1} in all stands except those dominated by grassland. Average fuel load was significantly increased in the «stand 3» when compared with the «stands 5 and 6». Although fuelbed depth was significantly reduced in «stand 2», average shrub height was the most variable parameter ranging from 81.54 to 173 cm. In relation to surface fuel characteristics, «stand 3» (maximum shrub height with a full fuel load) can be pointed out as the most virulent, although closely followed by «stands 1 and 4».

Although the crown fuel inventory collected many variables, Table 3 presents only some of them in order to provide a quick characterization of each stand. The first parameter, stand density, identified three significant groups: low density («stand 2»), medium density («stands 1, 3 and 4») and high density («stand 6»). Stand height was less than 10 m in all stands, although «stands 5 and 6» surpassed the rest. The low canopy base height of all stands stood out above all other variables, in particular the 0.75 m of «stand 3». Canopy base height was significant reduced in the «stands 1, 2 and 4» when compared with the «stands 5 and 6». The dry fuel loads varied significantly based on the treatments carried out, highlighting an increase for stands subjected to intense thinning («stands 2 and 5»). A notable parameter of interest not included in Table 3 is the low crown fuel moisture content registered in June, with a mean value of 98.28% (± 20.49) in

Table 2. Average surface fuel characteristics (standard error) for each stand

	Stand 1	Stand 2	Stand 3	Stand 4	Stand 5	Stand 6
Fuel type	Shrub (*Cistus ladanifer*)	Grass	Shrub (*Cistus* spp.)	Shrub (*Cistus ladanifer*)	Shrub (*Cistus* spp.)	Shrub (*Cistus* spp.) mixed with litter or dead fuel from forest canopy
Fuel load (t ha^{-1})	43.97^{ab} (8.87)	1.44^{c} (0.42)	57.39^{b} (7.40)	40.65^{ab} (17.23)	31.65^{a} (25.44)	32.43^{a} (24.16)
Fuelbed depth (cm)	163^{a} (7.65)	18.2^{b} (11.51)	173^{a} (4.5)	144^{ac} (48.63)	120^{ac} (78.17)	81.54^{bc} (71.84)

Mean values in a row followed by the same letter are not significantly different ($p < 0.05$).

Table 3. Average vegetation structure (standard error) for each stand

	Stand 1	**Stand 2**	**Stand 3**	**Stand 4**	**Stand 5**	**Stand 6**
Stand density (trees ha^{-1})	477^{a} (55.4)	143^{b} (47.25)	540^{a} (115.68)	427^{ac} (139.72)	250^{bc} (34.64)	1,063^{d} (110.87)
Stand height (m)	4.3^{a} (0.57)	5.67^{ab} (0.29)	7.37^{cd} (0.48)	6.87^{bc} (0.93)	9de (0.5)	9.5^{e} (1.29)
Canopy base height (m)	1.62^{a} (0.18)	2.4^{a} (0.17)	0.75^{b} (0.29)	2.39^{a} (0.35)	3.37^{c} (0.32)	3.8^{c} (0.77)
Dry canopy fuel load (kg tree^{-1})	9.57^{a} (2.85)	19.17^{ab} (1.55)	12.15^{a} (0.61)	12.32^{ab} (3.86)	31.04^{b} (2.01)	16.54^{ab} (4.74)
Canopy bulk density (kg m^{-3})	0.14^{ab} (0.05)	0.08^{c} (0.02)	0.11^{ac} (0.01)	0.17^{ac} (0.11)	0.15^{ac} (0.01)	0.30^{b} (0.02)

Mean values in a row followed by the same letter are not significantly different ($p < 0.05$).

needles and 77.04% (± 7.96) in twigs (1-h time-lag). Finally, the canopy bulk density was modified based on crown treatments, showing a significant reduction in «stand 2».

The canopy fuel load was the most difficult variable to measure due to the need for tree cutting and the time required to collect needles and twigs (De los Santos, 2008). These difficulties led to the search of an easier method for estimating canopy load without cutting trees. In this sense, the field inventory yielded a multiple regression model to estimate the dry fuel load (1-h time-lag) from two variables traditionally collected by forest inventories: diameter at breast height and crown projection area. Since the P-value in the Anova table was less than 0.01, there was a statistically significant relationship among variables at the 99% confidence level (Table 4). Moreover, the Durbin-Watson statistic showed that there was probably not any serious autocorrelation in the residuals.

Surface fire behavior

Spread rate, flame length and fire-line intensity were calculated analytically for each stand using the programs Visual Behave and Visual Cardin (Table 5). «Stands 1, 3, 4 and 5» stood out for their flame length virulence and fire-line intensity over 7.5 m and 20,500 kW m^{-1}, respectively. Although «Stand 2» presented the highest spread rate (75.99 m min^{-1}), flame length was significantly lower than those in the «stand 1, 3, 4 and 5». Average flame length (2.24 m) and fire-line intensity (1,481.21 kW m^{-1}) greatly increased the chances of fire suppression.

Crown fire behavior

The transition from surface fire to crown fire and their potential spread was assessed using the models

Table 4. Multiple regression model for 1-h time-lag canopy fuel (kg tree^{-1})

Parameter	**Estimate**	**Standard error**	**T-statistic**	**P-value**
Constant	–4.829	1.016	–4.753	0.001
Diameter at breast height (cm)	0.747	0.094	7.988	0.000
Crown projection area (m^{2})	0.778	0.095	8.205	0.001

R-squared = 98.431%
R-squared (adjusted for d.f.) = 98.117%
Standard error of estimation = 1.032
Std. error = 1.015
Durbin-Watson statistic = 1.441

Table 5. Potential surface fire behavior for each stand

	Stand 1	**Stand 2**	**Stand 3**	**Stand 4**	**Stand 5**	**Stand 6**
Spread rate (m/min^{-1})	24.36^{ab} (3.08)	75.99^{c} (6.43)	27.50^{ab} (4.14)	28.18^{a} (3.2)	24.05^{ab} (2.82)	17.53^{b} (1.95)
Flame length (m)	7.54^{a} (0.41)	2.24^{b} (0.9)	8.47^{a} (0.45)	8.57^{a} (0.44)	7.50^{a} (0.38)	4.80^{c} (0.24)
Fire intensity (kW m^{-1})	21,040.46^{a} (2,663.32)	1,481.21^{b} (125.32)	27,120.99^{a} (3,296.79)	27,791.32^{a} (3,139.42)	20,776.39^{a} (2,437.03)	7,998.21^{b} (884.01)

Mean values in a row followed by the same letter are not significantly different ($p < 0.05$).

Table 6. Potential crown fire behavior for each stand

	Stand 1	**Stand 2**	**Stand 3**	**Stand 4**	**Stand 5**	**Stand 6**
Threshold for transition to crown fire (kW m^{-1})	350.1^{ab} (58.15)	630.17^{bc} (66.85)	169.3^{a} (15.01)	628.77^{b} (137.28)	1,049.53^{cd} (149.11)	1,266.8^{d} (380.61)
Threshold for active crown fire spread rate (m min^{-1})	0.4^{a} (0.1)	15^{b} (1.6)	0.1^{a} (0.05)	0.5^{a} (0.1)	1.2^{a} (0.15)	2.23^{c}) (0.65)
Crown Fraction Burned (CFB) (%)	99.5^{a} (0.22)	36.3^{b} (20)	99.8^{a} (0.09)	99.8^{a} (0.11)	99.4^{a} (0.29)	96.81^{a} (1.08)
Potential type of crown fire	Active	Passive	Active	Active	Active	Active
Crown fire spread rate (R$_{active}$) (m min^{-1})	13.98^{a} (1.26)	— —	13.53^{a} (1.04)	13.75^{a} (0.99)	13.83^{a} (1.15)	13.72^{a} (0.95)
Crown fire spread rate (CROS$_{\Phi}$) (m min^{-1})	65.10^{a} (12.67)	— —	57.54^{a} (10.77)	65.26^{a} (10.98)	64.79^{a} (11.75)	72.10^{a} (11.05)

Mean values in a row followed by the same letter are not significantly different ($p < 0.05$).

specified in subsection 2.4. As in the case of surface fire behavior, integrating weather conditions, topography and fuel characteristics determined the threshold for transition to crown fire, the threshold for active crown fire, the crown fraction burned, the type of crown fire and the active crown fire spread rate (Table 6). The effectiveness of silvicultural treatments was evaluated primarily on their ability to reduce potential for severe wildland fire. Only one of the silvicultural options managed to avoid the occurrence of active crown fire («stand 2»). While pruning significantly increased the threshold for transition to crown fire («stand 4» in relation to «stand 3»), this treatment was not enough to prevent active crown fire. In this sense, the largest crown fraction burned or tree mortality was estimated for «stands 3 and 4», but not significantly different from «stands 1, 5 and 6». Threshold for active crown fire spread rate was significantly higher in the «stand 2» when compared with the other stands. According to Table 6, there are not significant differences in crown fire spread rate, taking into account both Rothermel and Cruz *et al.*, approaches. But these two approaches predict crown fire spread rates noticeably different.

Discussion

In Mediterranean areas, forest fires gain such importance in themselves that they change forestry management patterns (González *et al.*, 2005). The study of potential fire behavior is essential for forestry management at the landscape level in order to develop strategies that mitigate fire impacts (Agee *et al.*, 2000; Brose and Wade, 2002; Agee and Skinner, 2005; Duguy *et al.*, 2007). Predicting crown fire behavior requires fuel characterization using a two-leveled field inventory: surface and crown fuel. The field inventory allowed us to generalize that our study area is dangerously susceptible to wildfire due to the presence of *P. pinea* polewood stands with large accumulations of highly flammable shrub biomass (Table 2). «Stands 1, 3, 4 and 5» present serious problems for fire suppression due to the presence of fire-line intensity similar to the fuel model 4 (Anderson, 1982) as *P. pinea* understory (Table 5).

For pine nut harvesting, *P. pinea* stand management requires their opening through silvicultural treatments. This being a critical point of debate since opening stands to commercial use directly affects their susceptibility to fire, increasing the concentration of woody biomass and wind speed (Stephens, 1998). In addition, silvicultural treatments for each stand (see Section 2.1) affect fuel characteristics like the vertical distance between ground surface and the crown fuels and the canopy bulk density (Table 3). Although the 1-h timelag crown fuel is interesting in analyzing crown fire spread rates, it is easily dismissed because of estimation difficulties due to the time it takes and its destructive process. Therefore, an equation (Table 4) is presented as an immediate estimate to be used in forest inventories and forest fire prevention plans without the need for tree cutting.

The simulation of potential surface and crown fire has highlighted the effects of each of the treatments used. Crown treatments alone can not substantially change potential fire behavior or effects because torching and crowning indices are not significant changed after pruning or thinning (Stephens and Moghaddas, 2005). In our study area, pruning increases the threshold required for transition to crown fire («stands 2, 4, 5 and 6» in relation to «stands 1 and 3»), but may not be sufficient in preventing potential crown fire spread («stands 4, 5 and 6») (Table 6). Although crown thinning interrupts the continuity of the canopy, it is insufficient in itself in eliminating crown fire spread due to high surface fire intensity and low canopy base height («stands 1, 3, 4 and 5»). The potential for active crown fire in *P. pinea* polewood stands only decreases as the result of a combination action that causes, on the one hand, a decrease in the surface intensity by reducing fuel loads, and on the other, a rise in difficulty of crown transfer due to an increased distance between surface and crown fuels («Stand 2»).

Applying both crown fire spread models offers mixed results, with those from the Rothermel model (1991) being much lower than those from Cruz *et al.* model (2002, 2005, 2006) (Table 6). Stand differences in the Cruz *et al.* model are much more pronounced than in the Rothermel model because of the consideration of canopy characteristics. The Rothermel model's consideration of the vertical profile of stands associated with U.S. fuel model 10 (Anderson, 1982) appears to be largely responsible for these differences, even though the Cruz *et al.* model is also independent of the surface fuel model. Although both behavior models have been tested in different forest fires, Mediterranean forest characteristics such as the presence of high, dense and flammable understory, short distances between surface and crown fuels and low foliar moisture content, create special conditions for start and spread of crown fire. In this sense, crown fire spread models do not include these specific conditions and therefore require a thorough research in order to achieve a more consistent model of the fire spread typically occurring in Mediterranean forests.

Crown fires are at times so dangerous that they prevent any safe suppression efforts, proving nearly impossible to stop (Scott and Reinhardt, 2001; Cohen *et al.*, 2006). This situation is exacerbated in polewood stands where dense understory usually invades the lower layer of crown fuel, easing the transition to crown fire. Although stand treatments can be a very efficient solution in mitigating crown fire spread in mature *P. pinea* stands, in *P. pinea* polewood stands, brush is very dense and flammable being a trigger in itself for the transition and spread of crown fire. Following the evaluation of the effects of various treatments on crown fire behavior, we propose a joint surface-crown fuel treatment, similar to that of «stand 2», at landscape scale, so as to provide safe workplaces for firefighting forces and to increase the chances of fire suppression success.

Efficient fuel treatments lie not only in deciding what to do but in where and how to carry them out at the lowest cost (Smith *et al.*, 1997). Spatial optimization of joint surface-crown fuel treatments was performed using Geographic Information System (GIS) and using a cost-benefit analysis in relation to fire behavior and the cost of preventive silvicultural treatments. The available budget was set in basis of the treatment fraction (maximum area that can be treated) and treatment dimension (minimum fuelbreak width recommended). Unfortunately, surface treatment protection is short-term effective due to the dominance of colonizer species that are well adapted to these disturbances; in this case, the budget should include a regular maintenance of treated areas. Fuel treatments are therefore controversial and costly (Loehle, 2004), for which, to reduce the cost of the treatments planned, management for mitigating forest fire impacts and for pine nut harvesting should be integrated.

Current budget constraints limit fuel treatment to 20-30% of the study area based on cost increments imposed by the accessibility and topography of the foreseen treatments. Although some authors consider the fraction treated as small (Bevers *et al.*, 2004), as more areas are treated, the cost of completing maintenance on previously treated areas multiplies. Fire managers must choose between doing higher treated areas and maintaining areas that have received initial fuel treatments. The cost-benefit analysis using GIS permits defining the ideal block overlay that more effectively reduces the fire spread per unit area treated. While some authors propose standard widths for shade fuelbreak at 60-120 m (Green, 1977) or 400 m (Weatherspoon and Skinner, 1996), others believe they cannot be generalized (Agee *et al.*, 2000). This study supports this idea by using the «Rodríguez y Silva model» (Rodríguez y Silva, 1998; Rodríguez y Silva *et al.*, 2010) for calculating the width of each fuelbreak based on their specific characteristics in terms of surrounding vegetation and topographical features. Budget estimates based on the fraction treated, considering «stand 2» as the treated area, and on the costs of each joint surface-canopy fuel treatment in regards to topography and the

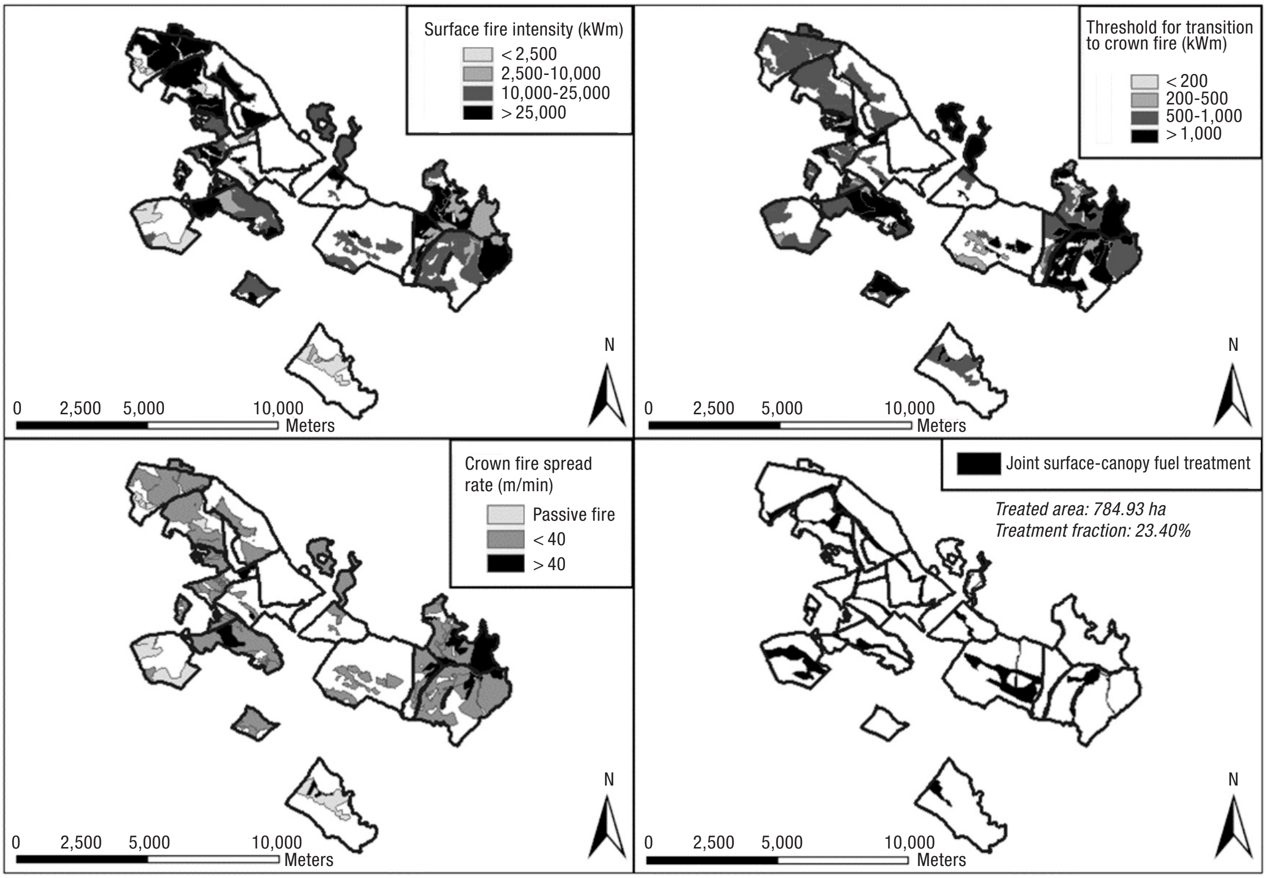

Figure 2. Optimization of joint treatment for the study area.

accessibility of each, can efficiently adjust the treated fraction to 23.40% of the total *P. pinea* area (Fig. 2).

Conclusions

P. pinea stands have a vital importance for the development of rural Mediterranean areas, providing not only tangible resources such as timber, or hunting game, but also environmental services and landscape goods. Given the numerous direct and indirect benefits of mature stands, polewood stands acquire a future importance, capitalizing on the investment carried out through reforestation efforts. The future sustainability of these forests, however, requires comprehensive action at the landscape level to mitigate the impacts of forest fires.

Given the current budgetary constraints, measures for economic efficiency acquire a prominent role. In this sense, a proposed equation to accelerate field inventories as well as a method for optimizing fuel treatments in accordance with their efficiency and the available budget provides various options that facilitate forest management decision-making. Applying a cost-benefit approach with GIS increases the methodology's simplicity and flexibility. This allows it to be extrapolated to any forest area by means of a previous characterization of the fuel and the evaluation of the effects of fuel treatments in the event of a transition to crown fire and its potential crown spread.

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