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RESEARCH ARTICLE

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Assessment of crown fire initiation and spread models in Mediterranean conifer forests by using data from field and laboratory experiments

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Abstract

Aim of study: To conduct the first full-scale crown fire experiment carried out in a Mediterranean conifer stand in Spain; to use different data sources to assess crown fire initiation and spread models, and to evaluate the role of convection in crown fire initiation.

Area of study: The Sierra Morena mountains (Coordinates ETRS89 30N: X: 284793-285038; Y: 4218650-4218766), southern Spain, and the outdoor facilities of the Lourizán Forest Research Centre, northwestern Spain.

Material and methods: The full-scale crown fire experiment was conducted in a young *Pinus pinea* stand. Field data were compared with data predicted using the most used crown fire spread models. A small-scale experiment was developed with *Pinus pinaster* trees to evaluate the role of convection in crown fire initiation. Mass loss calorimeter tests were conducted with *P. pinea* needles to estimate residence time of the flame, which was used to validate the crown fire spread model.

Main results: The commonly used crown fire models underestimated the crown fire spread rate observed in the full-scale experiment, but the proposed new integrated approach yielded better fits. Without wind-forced convection, tree crowns did not ignite until flames from an intense surface fire contacted tree foliage. Bench-scale tests based on radiation heat flux therefore offer a limited insight to full-scale phenomena.

Research highlights: Existing crown fire behaviour models may underestimate the rate of spread of crown fires in many Mediterranean ecosystems. New bench-scale methods based on flame buoyancy and more crown field experiments allowing detailed measurements of fire behaviour are needed.

Additional key words: wildland fire; fire behaviour; *Pinus pinea*; small-scale experiment; bench-scale experiment; convection

Abbreviations used: CBD (Canopy Bulk Density); CBH (Crown Base Height); CFIS (Crown Fire Initiation and Spread); CFL (Crown Fuel Load); FMC (Fuel Moisture Content); ICFME (International Crown Fire Modelling Experiment); NFFL (Northern Forest Fire Laboratory); ROS (Rate of Spread); TFO (Time to Flame Out); TTI (Time to Ignition); t_r (Residence Time of the Flame)

Authors´ contributions: FRS conceived the field experimental work, obtained field data and co-wrote the manuscript. MG participated in data collection and paper writing and supervised the manuscript. JM designed the laboratory experimental work, obtained data, run data analysis and co-wrote de manuscript. EJ and JRM participated in data collection and analysis, and paper writing. CH supervised the work and is coordinating the GEPRIF Project. RV contributed to the conception of field experimental work and discussions with its expertise in forest fires fighting. JAV designed the small-scale experiment, supervised the work and coordinated the INFOCOPAS Project.

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Introduction

Crown fires display extreme fire behaviour (Werth *et al.*, 2016) as the fire spreads through both the surface and tree canopy fuel layers, with the surface and crown fire phases more or less linked (Alexander & Cruz, 2016). These fires are generally of high intensity, are difficult to suppress and can have severe ecological and socioeconomic impacts (Moreira *et al.*, 2011). However, despite the social, economic and ecological significance of crown fires, modelling of crown fire behaviour has not been adequately addressed from scientific and technical points of view, and it is far from being solved (Cruz & Alexander, 2010). There are two main reasons for the difficulties in modelling crown fires: (i) the extreme complexity of the physical phenomenon (Rothermel, 1991), due to the heterogeneous fuel involved and the multiple influencing factors such as wind, slope, relative humidity, fuel moisture, atmospheric stability and surface fire intensity; and (ii) the complexity of conducting experimental crown fires (Stocks *et al.*, 2004a). These difficulties are common throughout the world, including the most advanced countries where crown fire experiments have been carried out in a limited extension (for a review, see Alexander & Cruz, 2016).

Although current physical models (Linn *et al.*, 2005; Mell *et al.*, 2009) represent substantial advances in crown fire modelling, from an operational point of view, two main empirical approaches in predicting crown fire spread continue being the base of the commonly used crown fire prediction systems. The first approach is that used in the models proposed by Rothermel (1991) and Finney (1998), based on the relationship between the predicted rate of fire spread at the surface and the fire rate of spread observed in crown fires in the Rocky Mountains (North America). The second approach, used for active crown fires, is based on wind speed, canopy bulk density and the estimated fine dead fuel moisture content (Cruz *et al.*, 2005). Crown fires are serious and dangerous events for forest management, as fire suppression efforts are much more complex than for surface fires, due to high fire-line intensity, spread rate, smoke production, spotting and turbulent fire spread (Alexander & Cruz, 2016). In Spain, technical advances, available allometric equations and previous experience in tackling large fire in Andalusia have demonstrated the need for development of new approaches (Molina, 2015).

It must be taken into account that the most widely used crown fire initiation and spread models (Van Wagner, 1977; Rothermel, 1991; Finney, 1998; Cruz *et al.*, 2005) have an empirical basis developed and tested in boreal forests (Alexander & Cruz, 2016). The models of Van Wagner (1977) and Rothermel (1991) are integrated in prediction systems (www.fire.org) as well as in the widely applied FARSITE fire area simulation tool (https://www.firelab.org/project/farsite). Other fire area simulation systems (*e.g.* VISUAL-CARDIN® and WILDFIRE ANALYST®) also include these models. These tools are frequently used by forest managers to estimate fire risk (*e.g.* Bradstock *et al.*, 2012), to design fuel management treatments (*e.g.* Ager *et al.*, 2012) and fuelbreak networks (*e.g.* Oliveira *et al.*, 2016), and to prioritize firefighting strategies (*e.g.* Butler & Cohen, 1998) in a wide range of forest ecosystems. Crown fire behaviour modelling is also used within the framework of wildfire research to assess the efficacy of fuel treatments (*e.g.* Arca *et al.*, 2007; Duguy *et al.*, 2007; González-Olabarría *et al.*, 2012; Jiménez *et al.*, 2016; Oliveira *et al.*, 2016; Madrigal *et al.*, 2017). Nevertheless, crown fire models have not been tested by experimental burns in Mediterranean conditions and the predictions may therefore be misleading (Cruz & Alexander, 2010; Benali *et al.*, 2016), leading to the application of inappropriate forest and fire management activities.

Laboratory experiments offer limited insight into forest fire behaviour (Fernandes & Cruz, 2012; Sullivan & Cruz, 2015); however, bench-scale and small-scale experiments can be designed in a partially controlled environment to help explain some physical and chemical aspects with a complex interpretation at full-scale (Finney *et al.*, 2015). In this sense, full-scale crown fire experiments can benefit from observations and data obtained in field experiments at smaller scale.

The aims of this paper are as follows: (1) to present the main results of the first full-scale crown fire experiment conducted in a Mediterranean conifer stand in Spain; (2) to compare the results obtained for crown fire initiation and propagation in Mediterranean conifer forests (*Pinus pinea* L. and *Pinus pinaster* Ait.) with current crown fire models by using data from field and laboratory experiments; (3) to obtain information on pine crown ignition in the absence of wind-forced convection; (4) to assess the flame residence time during crown fires in Mediterranean conditions. This work is part of a more comprehensive research project on the initiation, propagation and socio-economic impacts of crown fires in pine stands.

Material and methods

Full-scale crown fire experiment:"Las Traviesas" (Córdoba, southern Spain)

A young *P. pinea* (stone pine) stand (<40 years old) located in the Sierra Morena mountains in southern Spain (coordinates ETRS89 30N: X: 284793-285038; Y: 4218650-4218766) was selected as the study site for full-scale experiments (Fig. 1). *P. pinea* is one of the most important tree species in the Mediterranean region. It is patchily distributed all

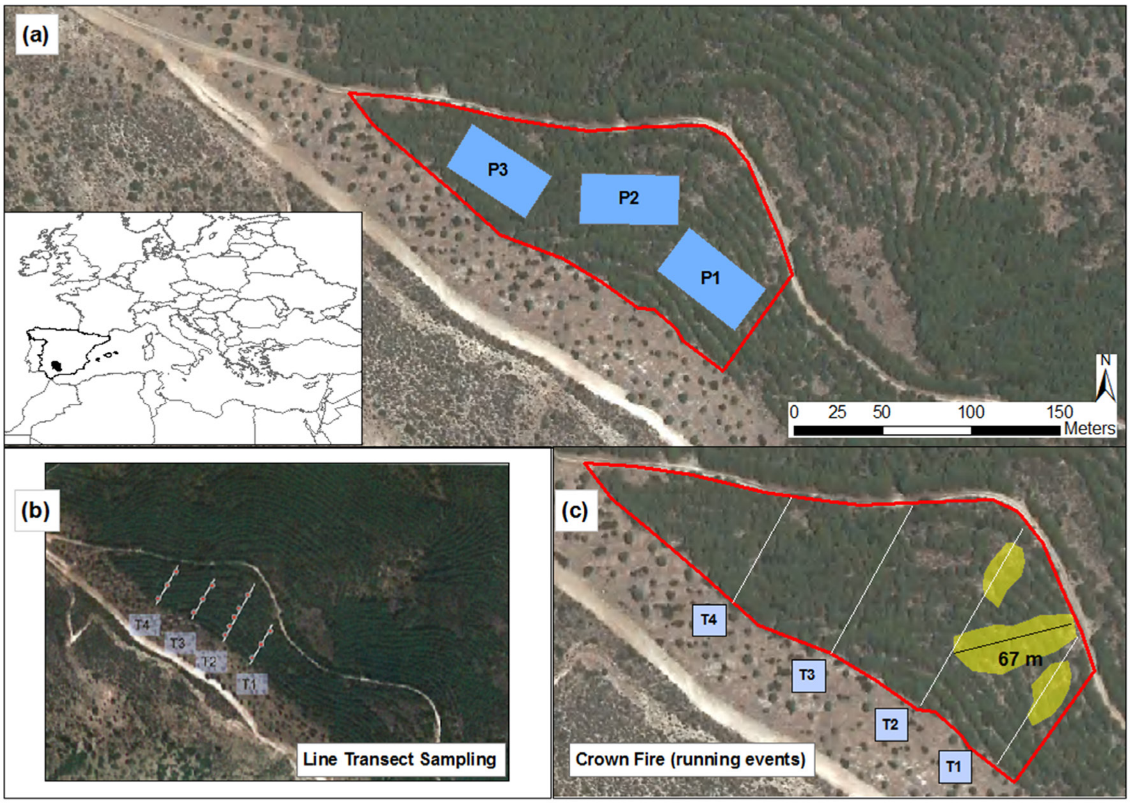

Figure 1. Full-scale crown fire experiment: (a) map showing location of the study area and photograph of the area (red line) and the experimental plots (blue rectangles), (b) transects for monitoring the fuels, and positions of the thermocouple stations (red points), and (c) positions of the crown fire events (indicated in yellow).

around the northern and eastern Mediterranean, from Portugal to Syria as well as along some coastal areas of the Black Sea, from sea level up to 500-600 m in the northern Mediterranean and up to 800-1400 m in the eastern Mediterranean (Fady *et al.*, 2004). In Spain, *P. pinea* occupies an area of approximately 480,000 ha in both natural and afforested stands (Bravo-Oviedo & Montero, 2008). For the present study, this species of pine was chosen for an opportunity reason. The area of burning is included in the priority areas of fuel treatment for the reduction of fire hazard planned by the Provincial Forest Fire Service. The selection was based on the annual fuel treatment planning and counted with the support of suppression teams and equipment for a fire escape contingency. In addition, the structure of the young stone pine stands is similar to that of other species of Mediterranean pines, and therefore it is possible to extrapolate the results to other species of pine associated with the model 7 of the Northern Forest Fire Laboratory (NFFL) System (Anderson, 1982). The climate in the selected area is classified as continental Mediterranean (mean annual precipitation, 492.92 mm; mean annual temperature, 15.47 °C; and mean temperature of coldest and hottest months, respectively, 6.62 and 26.31 °C). Altitude ranges from 664 and 716 m, with a mean slope of 34.25 %. The soils are siliceous with acid metasedimentary rocks.

Three rectangular plots (60 m × 30 m) were established in the experimental site. Vegetation in Plots 1 and 2 (Fig. 1a) corresponds to the HPM5 surface fuel model (Rodríguez y Silva & Molina, 2012) and is characterized by a combination of litter, grasses and

Table 1. Characteristics of tree stand and canopy (*Pinus pinea*, fuel moisture content of needles = 140%) in the full-scale experimental crown fire in the "Las Traviesas" plots. Values are shown as means ± standard deviation.

Density (N)	525 (± 293) trees/ha
Diameter at breast height (DBH)	17.20 (± 4.49) cm
Mean height (H)	6.85 (± 1.77) m
Live crown base (LCB)	1.61 (± 0.49) m
Crown diameter (D)	4.08 (± 0.60) m
Crown fuel load (CFL)	1.239 (± 0.18) kg/m²
Crown bulk density (CBD)	0.236 (±0.04) kg/m³

shrubs under canopy. Plot 3 corresponds to model HR, litter under canopy, which is similar to model 9 in the NFFL System.

Litter, duff (humus) and understory fuel (vegetation under canopy) variables (average understory height and cover per species, litter and duff depth and cover) were characterized by continuous measurements made on two perpendicular transects across the plots. The fuel loads were determined by using destructive sampling in adjacent areas (30 quadrats of 0.4 m x 0.4 m for litter and duff and 28 samples of 1 m × 1 m for understory). Litter and understory fuel of thickness less than 6 mm was considered available fuel. The inventories were repeated in the plots after carrying out the experiment to estimate the fuel load consumed during burning.

Canopy and tree variables (diameter at breast height, height, crown base height, crown diameter) were measured in two circular plots (radius 10 m) in each rectangular plot (Table 1). Three representative trees were felled in an adjacent area. The fractions available for burning (branches and needles sorted by diameter size class <6 mm and 6-25 mm) were weighed and dried (100 ºC, 24 h) to enable calculation of the Crown Fuel Load (CFL, kg/m^2). The load over depth method (Van Wagner, 1977) was used to calculate Canopy Bulk Density (CBD, kg/m^3) (Table 1). This inventory was repeated after burning to estimate consumed fuel load by harvesting six trees.

In order to estimate the wind speed correction factor, micrometeorological parameters were measured by three weather stations placed under the canopy (at a height of 1.30 m) for 6 days before the experiment. An additional weather station was sited (at a height of 10 m) in an adjacent area as control (Tables S1, S2, S3 and S4 [suppl]). These automatic weather stations were used to monitor relative humidity, temperature, wind speed and wind direction throughout the experiment.

Samples of fine fuels (dead and live) were collected before the experiment and stored in hermetically sealed plastic bags for subsequent estimation of Fuel Moisture Content (FMC) in the laboratory within 24 hours.

In order to monitor the crown fire Rate of Spread (ROS) and temperatures reached during the experiment, 56 K type thermocouples (1 mm of diameter) were located at four different positions across four transects (Fig. 1b): (1) two thermocouples were placed at the Crown Base Height (CBH) level (roughly 2 m) in each tree: one in a windward (and upslope) position and the other one at an angle of 90º from the latter, and (2) two thermocouples were placed in the middle of the length of the crown (at a height of 4 m, in the same positions as before), *i.e* in the layer with highest canopy bulk density. The flame residence time t_r was estimated in (a) the passive crown fire events as the residence time of flame temperature (above 300 ºC), measured by thermocouples positioned in the same tree (2 and 4 m height), and in (b) the active crown fire events as the residence time of flame temperature (above 300 ºC), measured by thermocouples located in the crown (height 4 m) in two consecutively burned trees.

The fire was initiated with a dip torch. A fire line was established along the border of the experimental area and an upslope fire front was established. Crown fire events were monitored visually by three independent observers and automatically by thermocouples (see above). Passive crown fire events were observed along the fire line, and automatically-collected data were completed with visual observations of flame residence time. All field data were used as inputs to compare with the theoretical predictions from the most common crown fire propagation models.

In previous studies carried out in the Region of Andalusia (southern Spain), validation of crown fire models has relied on wildfires technical reports, cases study of large fires occurred and the experimental fires undertaken in the region. In these studies, comparisons between rates of fire spread observed in the field and their predictions have transmitted a certain degree of uncertainty, as the predictions did not yield similar behaviour parameters to those observed (Molina, 2015). A new approach to crown fire spread was developed on the basis of the models proposed by Rothermel (1991), Finney (1998) and Cruz *et al.* (2005), but with an integration parameter included in order to adapt the simulations to Mediterranean conditions. It was thus necessary to incorporate another two variables (wind speed and canopy cover) to explain real events (Eq. [1]). Information about the uncertainty (Ʋ) was important in testing and validating the new model for Mediterranean forest conditions. In this sense, the uncertainty measurement was lower for the new integrated equation (Ʋ = 43.19) than for approaches used by Rothermel and Finney (Ʋ = 74.70) and by Cruz *et al.* (Ʋ =58.49) according to some crown fire events (Molina *et al.*, 2013).

$$V_{UCO} = \frac{16.6 * V_{RF} * V_C}{(V_{RF} + 0.85 * V_C)^2 * V_{10m}^{\;0.298}} + \\ + 0.855 * (0.65 * V_{RF} + 0.35 * V_C) * CC^{0.35} \quad [1]$$

where "V_{UCO}" is the crown rate of spread according to the proposed new mathematical integration (m/min), "V_{RF}" is the crown rate of spread rate based on the approach used by Rothermel and Finney (m/min), "V_C" is the crown rate of spread according to the approach used by Cruz *et al.* (m/min), "V_{10m}" is the 10 m height wind speed (km/h) and "CC" is the canopy cover (expressed as parts per unit). This equation was also used in the present study to compare field data with modelling predictions.

Small-scale experiment: observing crown ignition without wind-driven convection in *Pinus pinaster*

This experiment, conducted in the field facilities of the Lourizán Forest Research Centre (Pontevedra, NW Spain), aimed to obtain direct information on *P. pinaster* crown ignition caused by the radiation from a high intensity surface fire front, spreading towards a clump of pine trees, simulating conditions in absence of wind-forced convection. A flat terrain and meteorological conditions with very low wind velocity were selected to minimize the effect of air of slope-forced convection on energy transport from the surface fire to tree crown. A plot of length 12 m and width 10 m was installed and surrounded by a fire break. A surface fuel layer made from a mixture of plants of the shrub species *Pterospartum tridentatum* (L.) Willk. and *Erica* spp., previously collected in the field and air-dried for several weeks, was constructed and used to carry a surface fire. This added material was weighted and homogenously distributed across the plot to obtain 9.4 kg/m^2 (oven-dry basis) of fuel load, with relatively low moisture content to enhance a high combustion rate and the development of a sustained high vertical flame and linear intensity. Twenty measurements of the shrub layer fuel height were systematically made. Eight *P. pinaster* trees (diameter at breast height from 8.3 to 11.8 cm, total height from 8.2 to 10.5 m, and height to live crown from 1.8 to 4.2 m) were felled in a nearby area and immediately placed in two rows at one end of the plot. The trees were inserted vertically, with the help of a small crane, in previously excavated cylindrical holes, which were filled with water to minimize foliar moisture loss. Eight samples of the added shrub fuel (1 m × 1 m) were collected and classified by size classes (1 h, 10 h and 100 h) and oven-dried in the laboratory for 24 h (100ºC) to determine pre-fire surface fuel load.

Wind direction and speed (2 m, 4 m and 6 m height), relative air humidity and air temperatures during the experiment were measured and recorded every second in a meteorological station installed in the nearby in the upwind position. Immediately before ignition, samples of shrub, trees needles and branches were collected to determine the fuel moisture content after oven-dried for 24 h (80ºC).

The fire was ignited along the edge of the plot opposite the trees rows. Fire behaviour was monitored during the experiment. Eight fine thermocouples were regularly located inside the shrub fuel area to determine fire rate of spread, and four thermocouples were installed in each tree crown at heights of 2 m, 4 m, 6 m and 8 m, on needles fascicles. The thermocouples were inconel-sheathed, type K (chromel-alumel), of 1 mm of diameter, with bared wires of 0.13 mm diameter with an exposed junction. Temperatures were recorded at 1-s intervals during the fire by dataloggers. Images of fire development and flame characteristics were recorded, at ground level, with one infrared thermographic camera and one video camera, and allowed estimate flames length. After flaming, a smouldering phase took place making it inadequate post-fire sampling to calculate fuel consumption during the flaming phase. Hence, linear intensity of the surface fire was calculated following two approaches. First, from the relationship between this parameter and flame length (Thomas, 1963). Second, according to Byram's equation (Byram, 1959), considering total 1 h material and half 10 h material as consumed fuel load during flame phase. A value of 19,500 kJ/kg was used for the heat content of the fuel complex.

Flammability bench-scale experiments: estimating flame residence time

Stocks *et al.* (2004b) and Taylor *et al.* (2004) reported that a physically-based model proposed by Nelson & Adkins (1988) yielded better cross-validations than the models developed by Rothermel (1991) and Finney (1998) during the International Crown Fire Modelling Experiment (ICFME) carried out in Canada (Stocks *et al.*, 2014a). This model (Eq. [2]) requires the value of residence time of the flame t_r to predict ROS:

$$ROS = \frac{0.39W^{0.25}U^{1.51}}{t_r} \quad [2]$$

where W is the fuel consumed and U is the wind speed. Due to the difficulties in measuring t_r in the field (visually and automatically observed, see above) a laboratory experiment was designed to enable comparison of full-scale and bench-scale tests and to determine the t_r value for its use in the model proposed by Nelson & Adkins (1988).

Sub-samples of material (500 g) were obtained from the crown of six *P. pinea* trees during collection of samples to estimate the FMC in the "Las Traviesas" experimental fire (see above). The samples were transported to the laboratory in hermetically sealed plastics bags and stored in a refrigerator chamber (4ºC). A series of mass loss calorimeter tests (N=10) was carried out during the course of one week by applying the method proposed by Madrigal *et al.* (2013) to produce at least 5 replicates that comply with repeatability criteria

Table 2. Surface fuel load and fuel consumed (mean ± standard deviation), for class size and type of fuel (dead and live) in the full-scale crown fire experiment. Live fuel comprised *Rosmarinus officinalis* (FMC[1]=193%), *Ulex parviflorus* (FMC=80%), *Pistacia lentiscus* (FMC=101%), *Quercus ilex* (FMC=98%) (total cover 86.79±9.83%, mean height 1.22±0.03 m).

	Litter and humus layer	Dead fuel			Live fuel	Total
		<0.6 cm	0.6-2.5 cm	>2.5 cm		
Fuel load (kg/m^2)	0.64 (±0.009)	0.21 (±0.02)	0.46 (±0.08)	0.07 (±0.01)	0.986 (±0.13)	2.37 (±0.22)
Fuel consumed (%)	83.12 (±1.17)	95.89 (±19.82)	54.37 (±16.44)	9.27 (±4.08)	70.48 (±22.68)	83.87 (±19.81)

[1]FMC = fuel mtoisture content

Table 3. Canopy fuel load and fuel consumed during the full-scale experimental crown fire (mean±standard deviation). FMC=fuel moisture content

	Needles (FMC=140%)	Branches		Total
		<0.6 cm	0.6-2.5 cm	
Fuel load (kg/m^2)	0.56 (±0.16)	0.255 (±0.05)	0.424 (±0.05)	1.239
Fuel consumed (%)	100	51.5 (±19.51)	36.82 (±16.35)	64.85 (±15.04)
Fuel consumed (kg/m^2)	0.56 (±0.16)	0.131 (±0.03)	0.156 (±0.02)	0.847 (±0.17)

Table 4. Validation of crown fire rate of spread models for the main crown fire events (A, B, C) in the full-scale crown fire experiment.

Event	Slope (%)	DFMC (%)	U (km/h)	CDB (kg/m^3)	ROS[1] (m/min)	ROS (m/min)[2]		
						Rothermel-Finney	Cruz *et al.*	UCO
A	30	11	5.9	0.21	8	7.5	3.5	9.3
B	30	11	5.9	0.11	10	7.5	4	11
C	30	11	14.04	0.22	21	13.5	8.5	17.3

DFMC=dead fuel moisture content; U=wind speed; CBD=crown bulk density; ROS= rate of spread; [1] observed; [2] estimated with Rothermel and Finney, Cruz *et al.* and University of Córdoba (UCO) models.

Table 5. Fuel moisture values of fuel samples immediately before ignition in the small-scale experiment at the Lourizán Forest Research Centre.

Vegetation	Sample	Fuel moisture content (%)
Trees	Current needles	219
	One-year-old needles	164
	Two-year-old needles	157
	Branches (<0.6 cm)	122
Shrub	1 h (<0.6 cm)	17
	10 h (0.6-2.5 cm)	17

Figure 2. Images of crown fire events during burning in the fullscale crown fire experiment: (a,b) general view of study area, (c,d,e) crown fire events, (f) detail of a crown fire.

(Madrigal *et al.*, 2009). Samples were tested at an average of 130% of FMC (similar to the field-estimated FMC of 140%). A heat flux of 50 kw/m^2 was selected to simulate the crown fire combustion during the field experiments (Cruz *et al.*, 2006). A type K thermocouple (1 mm diameter) was sited at fuel level to measure the increase in temperature during the tests for comparison with field data (see previous section). Difference between Time to Flame Out (TFO) and Time to Ignition (TTI) of the samples was used as an estimate of t_r. The results of this series of tests were compared with the time dependent curve of temperatures during crown fire events determined in the full-scale experiment (see previous section). Different t_r values obtained in bench scale and full scale experiments were used to validate the model proposed by Nelson & Adkins (1988), considering the average values of W and U determined in the "Las Traviesas" experiment.

Results

Full-scale crown fire experiment: "Las Traviesas" (Córdoba, southern Spain)

Crown fire activity was only observed in Plot 1 and in the lower part of Plot 2 (Fig. 1). Surface fire spread was observed in Plots 1, 2 and 3. The average total surface fuel load consumed was 2.05 kg/m^2 (Table

2) and the estimated canopy fuel load consumed was 0.85 kg/m^2 (Table 3). Three crown fire events (A, B and C) were monitored in the "Las Traviesas" experiment (Fig. 1c, Fig. 2). Although wind speed was different in event C than in events A and B, the differences in the ROS between "events A and C" and "event B" seem to be due to differences in CBD (Table 4). Wind speed was moderate (5.9 km/h), but a mass fire (Finney & McAllister, 2016) was observed, generating an increase in local wind speed (14 km/h) detected by the meteorological station closest to the crown fire event C (Table 4). The signal recorded by the thermocouples located in the tree crowns (Fig. 3) indicated that ROS ranged between 8 and 21 m/min (Table 4). ROS of event C (21 m/min) differed from that of events A and B (8-10 m/min). Field ROS were compared with the theoretical predictions from the Rothermel-Finney approach, the Cruz *et al.* approach and the new mathematical integrated approach (Eq. [1]).

The most commonly used crown fire models (Rothermel, 1991; Finney, 1998; Cruz *et al.*, 2005) underestimated ROS relative to observed values (particularly the Cruz *et al.* approach) (Table 4). Although the best-fit for event A was yielded by the Rothermel and Finney model, the best-fit for events B and C was achieved with the proposed new integrated model (Table 4).

Small-scale experiment: observing crown ignition without wind-driven convection in *Pinus pinaster*

Shrub fuel load was 5.6 kg/m^2 for 1 h material (<0.6 cm of thickness) and 3.8 kg/m^2 for 10 h material

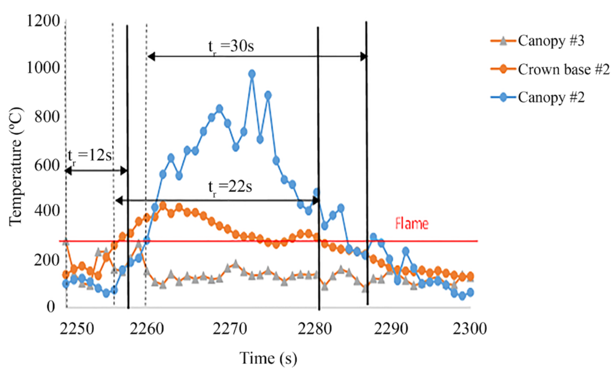

Figure 3. Full-scale crown fire experiment. Time-dependent temperature curves during the burning. Horizontal red line indicates assumed crown ignition threshold. Vertical lines indicate the residence time of flame (t_r). Minimum, average and maximum t_r are shown.

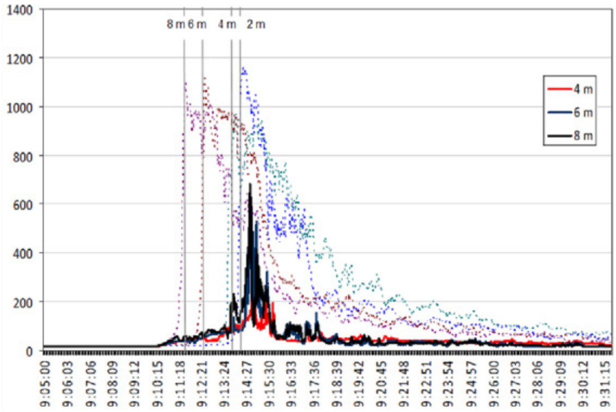

Figure 4. Small-scale experiment. Temporal variation (x-axis, s) in crown temperature (y-axis, ºC) at different heights (solid lines) and temporal variation in temperatures in surface fuel at different distances from the first trees line (dotted lines).

(between 0.6 and 2.5 cm). Shrub layer bulk density was 7.3 kg/m^3. FMC immediately before ignition of fuel samples is shown in Table 5. Air temperature was 20ºC and air humidity was 75%. Mean wind speed during the experimental fire was less than 1 km/h.

Despite low FMC, surface fire ROS was low (2.2 m/min), likely due to low wind velocity and high fuel compactness (more than twice the usual value for similar shrub species; Arellano *et al.*, 2016). Flames reached 7-12 m and were vertical during the fire run. This was likely due to high combustion rate (the heat generated was sufficient to partially melt some 20 mm diameter steel rods placed in the area to indicate the flame height), low wind velocity and fire front indraft, resulting in a high fireline intensity (9,500 kW/m following Thomas (1963) approach, and 5,363 kW/m following Byram (1959) approach). The maximum temperatures reached in the shrub layer ranged from 954 to 1,168 ºC, whereas in the tree crowns maximum temperatures ranged from 82 to 1,224 ºC.

Analysis of the information recorded by thermocouples (Fig. 4) and the images of the infrared thermography camera (Fig. 5) revealed that crowns did not start to ignite (temperatures higher than 300 ºC) until the distance between the fire and trees was less than 2 m. The average of t_r was 22 s (range between 12 s and 31 s). A crown fire simulation using the Crown Fire Initiation and Spread (CFIS) model (Alexander *et al.*, 2006) using the meteorological and fuel load information of the experimental fire predicted a probability of crown fire initiation of 61%, consistent with that observed in the experiment.

Table 6. Validation of Nelson & Adkins (1988) model considering different criteria for fuel consumed (W) and flame residence time (t_r) in the full-scale crown fire experiment. The best estimate of the observed rate of spread (ROS) is shown in bold.

Event	SFC (kg/m^2)	CFC (kg/m^2)	W (kg/m^2)	U (km/h)	ROS (m/min)	Nelson-Adkins (m/min)			
						t_r = 44 s	t_r = 30 s	t_r = 20 s	t_r = 12 s
A	2.05	0.847		5.9	8	1.46	2.14	3.21	5.35
B	2.05	0.423	SFC+CFC	5.9	10	1.40	2.06	3.09	5.15
C	2.05	0.860		14.04	21	5.42	7.95	11.93	**19.88**
A	2.05	0.847		5.9	8	1.07	1.57	2.36	3.94
B	2.05	0.423	CFC	5.9	10	0.90	1.32	1.98	3.31
C	2.05	0.860		14.04	21	3.99	5.86	8.79	14.66

SFC=surface fuel consumption; CFC=crown fuel consumption; U=wind speed

Flammability bench-scale experiments: estimating flame residence time

The Mass Loss Calorimeter experiments (Fig. 6) yielded a difference between TFO and TTI values of 44±10 s (average±standard error) as an estimate of t_r (range between 19 s and 71 s). This is consistent with visually observed values for passive crown fire during the "Las Traviesas" experiment (range, 12-30 s, and mean value, 22 s), small-scale experiments (range, 12-31 s, and mean value, 21 s) and is within the range obtained by Taylor *et al.* (2004) during the ICFME (range 29-37 s, and mean value, 34 s). Madrigal *et al.* (2013) reported an average t_r value of 30 s obtained during an experimental series of crown fire initiation tests in an outdoor wind tunnel. The prediction yielded by the Nelson & Adkins (1988) model using t_r = 30 s (Table 6) was similar to the rate of spread estimated by Cruz *et al.* (2005) model and was a poorer estimate than provided by the Rothermel-Finney model (Table 4).

Analysis of time-dependent temperature curve in the crowns during the full-scale experiment (Fig. 3) indicated a t_r of between 12 s and 30 s. The use of average values of t_r = 20 s observed during crown events in the full-scale and small scale experiments (t_r = 22s) and minimum values during bench-scale experiment (t_r = 19 s) yielded a better overall estimation of ROS but greatly underestimated the rate of spread (Table 6). The estimates closest to the observed ROS corresponding to t_r = 12 s for event C (considering the sum of consumed surface and crown fuel load as the fuel consumed *W* in the Nelson and Adkins equation) (Table 6).

Discussion

The fit for the new integrated model was validated in the "Las Traviesas" experiment. Variations in fire spread predicted by the models proposed by Rothermel-Finney and by Cruz *et al.* and actual field behaviour can be observed (Table 4). The new integrated equation (Eq. [1]) yielded better results for the mean absolute error and standard deviation (14.62±4.06) than obtained by the approaches used by Rothermel (1991) and Finney (1998) (23.11±16) and by Cruz *et al.* (2005) (58.59±2.04) and also provided a reasonable fit for observed values of ROS in the three events analysed during the full-scale "Las Traviesas" experiment (Table 4). Although Molina (2015) obtained overestimates for wind speeds, the most commonly used models (Rothermel 1991, Finney 1998, Cruz *et al.*, 2005) underestimated the ROS. This may be due to the low wind speed during the experiment (Table 4). Stocks *et al.* (2004b) obtained underestimations of Rothermel (1991) and Finney (1998) models but a reasonable fit from Cruz *et al.* (2002). The model proposed by Cruz *et al.* (2002) was developed in boreal forests characterized by low surface fuel load and lower CBD than in the *P. pinea* stands under study here (at least for events A and C, Table 4). This crown biomass structure is typical in the Mediterranean area (Molina *et al.*, 2013) and could be extrapolated to other young conifer stands arising from afforestation or post-fire natural regeneration in Spain (Montero *et al.*, 2005; Ruiz-Peinado *et al.*, 2011). Taking into account that meteorological conditions during the full-scale experiment were moderate relative to summer conditions in southern Spain, underestimation of the spread rate is expected if these models are applied during suppression activities in the study area.

Although crown fire is a very frequent phenomenon in pine wildfire, detailed records of temperature in crown flaming during experimental fires are extremely scarce. Our data are a first contribution, referred to the Mediterranean conifers, and show temperature peak values and transient responses fairly similar to those

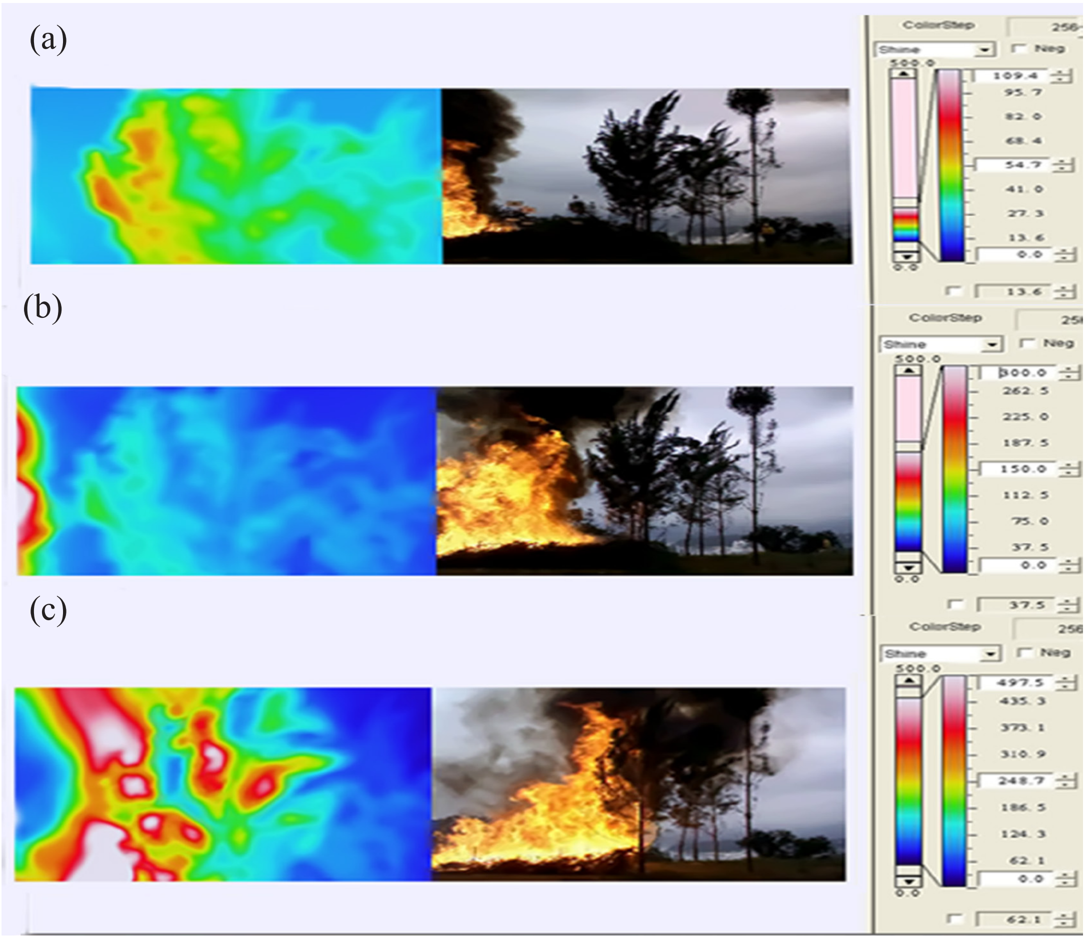

Figure 5. Small-scale experiment. Simultaneous images taken withan infrared thermography recording camera (left) and with a video camera (right), showing the flameat a distance of (a) 6 m and (b) 2 m from the tree crowns, and (c) in contact with the crowns and just when the ignition of them is starting.

observed in boreal forests (Taylor *et al.*, 2004; Butler *et al.*, 2004b; Butler, 2010). Although the limitations of the thermocouples to reflect the true values of temperature in the flaming area are well known (*e.g.* Pitts *et al.*, 2002; Shannon & Butler, 2003; Bova & Dickinson, 2008), the errors when fine thermocouples are used can be considered as to relatively be minor for peaks temperatures (Butler *et al.*, 2004b). Still, in our study, temperature records were primary used to determine fire spread in the full-scale experiment and the distance between fire front and crown to initiate a passive crown fire in the small-scale experiment. Moreover, both in the field and bench experiments, thermocouples records supplied values for flaming residence time in different conditions of heat transfer and assuming a common ignition threshold (573 ºK). The measured time were quite similar among them, consistent with data referred by Despain *et al.* (1996), obtained from video records in the Yellowstone fire (1988) and those measured in the above referred crown fire experiments.

Despite the high intensity of the fire developed during the small-scale experiment and the substantial radiant surface from a well-developed “flames wall” of the surface fire, crown torching did no occurred until flames were very close to the trees crowns (Fig. 5). The images recorded do not suggest a piloted ignition of pyrolisates from radiation, but by buoyancy with strong turbulent convection in concordance with observations in the full-scale experiment and data from other crown fires (Clark *et al.*, 1999; Coen *et al.*, 2004; Taylor *et al.*, 2004). Therefore, it would seems to question the ability of just radiation to explain crown fire (Butler *et al.*, 2004a) and support the need to consider the role played by convection (Finney *et al.*, 2013, 2015). Measurements in scanty crown fire experiments (Frankman *et al.*, 2012) show that relative contribution of convective and radiative energy transfer can be highly variable from a fire to another. That suggests that likely models considering a more flexible contribution of convective and radiative components could be more realistic (Finney *et al.*, 2015). Both the full and small-scale experiments, with light-moderate wind and absence of wind respectively, showed the apparent need for contact between the flame and the crowns to generate crown fire.

Stocks *et al.* (2004b) and Taylor *et al.* (2004), from observations during the ICFME carried out in a boreal forest dominated by *Pinus banksiana* Lamb. with a minor *Picea mariana* Mill. component, suggested the need of a mean flame duration of at least 30 s for crown ignition. That time was assessed in the bench-scale experiments (Fig. 6) and through observations of the occurrence of passive crown fire events in the border of the field plots in the full-scale experiment. The values measured with thermocouples placed in the crowns (Fig. 3) and the validation of the Nelson & Adkins (1988) model (Table 6) indicate t_r required to generate a crown fire much shorter (12 s) in young stone pine stands than in boreal stands. The results also show that bench-scale tests, based on radiation heat flux, offer limited insight into what actually occurs in full-scale phenomena (Fernandes & Cruz, 2012; Sullivan & Cruz, 2015), thus highlighting the urgent need to develop new bench-scale methods based on flame buoyancy (Finney *et al.*, 2015).

Our initial results obtained at different scales suggest that flame buoyancy and likely air-forced convection are determinant for the ignition and fire propagation process in crown fires (Finney *et al.*, 2015). Furthermore, the reasonable estimation of ROS using the total fuel (surface and crown) consumed in the fire run C relative to runs A and B (better fit using only crown fuel), during fuel-scale experiment (Table 6) suggests interactions between both fuel layers and between fuel consumed and wind speed. This therefore suggests the need to develop specific fuel vegetation models that include the effect of fuel vertical structure and the simultaneous description of surface and crown biomass (Arellano *et al.*, 2016). This initial work calls for developing additional experiments with measurements of convective and radiative heat transfer components to confirm these first observations and help to shed some light on those questions.

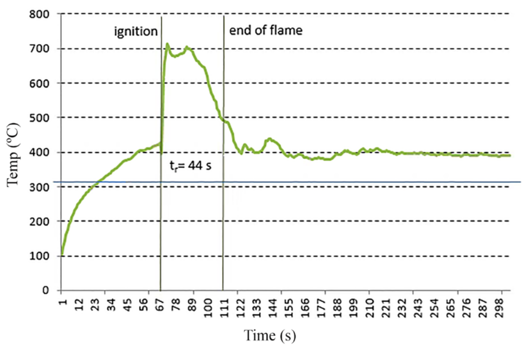

Figure 6. Flammability bench-scale experiment. Mean temperature curve (green) for pine needles (FMC 130%) during the Mass Loss Calorimeter experiments (N=10). The blue line represents the baseline temperature from the radiant heater (Heat flux 50 kW/m^2, piloted ignition). The grey lines represent the time to ignition and time to flame out; difference between both times is used as an estimation of flame residence time (t_r)

Conclusions

The results of the first crown fire full-scale experiment in a Mediterranean conifer stand in Spain indicate that the current crown fire behaviour models may underestimate the rate of spread of crown fires in many Mediterranean ecosystems. In spite of the particular crown shape of *P. pinea*, we think that the results of the current study could be likely extrapolated to other Mediterranean conifers in their young stage. In this stand stage, fuel complex structure is very similar, in terms of understory and canopy fuel layers, to other pine species, and arguably, a similar response in relation to the transition from surface fire to crown fire and the crown fire spread can be expected, although that requires complementary research.

The findings also suggest that empirical crown fire models developed in boreal ecosystems must be calibrated in Mediterranean conditions in order to minimize the observed discrepancies. Evaluation of crown fire behaviour in Mediterranean forests is urgently required and more experimental fires must be conducted to enable development of new models or to calibrate available models under Mediterranean conditions. The new integrated model proposed in this study may be useful for optimizing prevention activities and for addressing difficulties in fire suppression. Nonetheless, that new model needs to be improved as new data become available. The new model programming carried out with Visual Behave software (Rodríguez y Silva *et al.*, 2010) is a simple tool for predicting crown fire behaviour in Mediterranean environments, which is urgently needed by fire managers to help in preventing and extinguishing forest fires.

These initial results confirm the complexity of crown fire behaviour (Alexander & Cruz, 2016) and reinforce the idea of Finney *et al.* (2015) regarding the critical importance of convection and contact between flame and the crowns for crown fire initiation.

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