Laboratory characterization of firebrands involved in spot fires

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ORIGINAL PAPER

Laboratory characterization of firebrands involved in spot fires

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Abstract

• ***Introduction*** Wildfires are considered the most important disturbance in the Mediterranean Basin, and some are propagated over long distances due to lift-off and ignition of firebrands.

• ***Objectives*** To improve our knowledge of firebrands involved in spotting fires, flammability characteristics of eight types of firebrands commonly generated by wildfires in Southern Europe were determined under laboratory conditions.

• ***Results*** All the firebrands tested showed 100% ignition frequency but with a wide range of time to ignition and flaming duration. Weight loss during combustion was exponentially related to time, and there was a decrease in the ratio of the weight at temperature *T* to the initial weight with increasing temperatures. In our experimental conditions, there was a significant effect of fuel moisture content on time to ignition, flaming duration, combustion and thermal decomposition. On the basis of the characteristics analysed, three firebrand groups have been identified in relation to spotting: heavy firebrands with ability to sustain flames, efficient for long-distance spotting (pine cones); light firebrands with high surface-to-volume ratio, efficient for short-distance spotting (leaves and thin barks); and light firebrands with low surface-to-volume ratio, efficient for short and, occasionally, long-distance spotting (all the other types of firebands).

Keywords Firebrand · Fire behaviour · Flammability parameters · Wildfire · Ember

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1 Introduction

In the Mediterranean Basin, wildfires alter thousands of hectares of forest and shrubland ecosystems (JRC 2009). Some of these wildfires are propagated over long distances due to the spotting mechanism. Spotting is frequently related to crown fires; it complicates wildland fire control and is one of the main causes of loss of homes in wildland-urban interface areas. Spotting is a fire propagation mechanism which spreads fire by producing firebrands that are carried up in the rising convection column and then drift and fall on remote sites. Despite its important role in fire spread, spotting has rarely been modelled. McArthur (1967) produced an empirical model that predicts mean spotting distance for *Eucalyptus* forests. Albini developed several mathematical models to predict potential spot fire distance from torching trees (Albini 1979), a burning pile (Albini 1981) and a wind-driven surface fire (Albini 1983). Gardner et al. (1999) reviewed the main fire models and showed that most simulations do not include the influence of firebrands on fire pattern. Hargrove et al. (2000) developed a fire model (EMBYR) incorporating the effects of fuel moisture and wind on fire ignition and spread, including the role of firebrands in the spread and spatial pattern of crown fires.

Spotting comprises three phases: (a) the generation of firebrands from burning vegetation and structures, (b) their subsequent transport through the atmosphere by external and heat generated winds, and (c) potential spot fire ignition after the firebrand has landed. Production of firebrands from burning vegetation has rarely been studied (but see Manzello et al. 2007, 2008), whereas transport of embers has received more attention (e.g. Tarifa et al. 1967; Albini 1983; Woycheese et al. 1999; Himoto and Tanaka 2005; Anthenien et al. 2006). Research to quantify the transport of firebrands made of burning vegetation has mainly concentrated on spherical and cylindrical firebrands. Some experimental studies have also been conducted on the ignition of fuel beds due to firebrand impact (e.g. Waterman and Takata 1969; Ellis 2000; Pérez-Gorostiaga et al. 2002; Manzello et al. 2006a, 2006b; Ganteaume et al. 2009), but little empirical data are available on firebrands and their burning characteristics.

Firebrands lofted into the atmosphere may be carried by winds over long distances (up to several kilometres). So, knowledge of their physical characteristics is useful for improving models that deal with firebrand trajectories. Hot firebrands with a significantly long burn-out time can land on fuel sources far removed from the initial fire, resulting in spot fire ignition and increased rates of spread (Manzello et al. 2007). Thus, firebrand flammability characteristics such as ignitability (assessed by time to ignition or ignition frequency), sustainability (assessed by the duration of flames), combustibility (assessed by gross heat combustion) or thermal decomposition have been studied because of their importance in quantifying firebrand efficiency in the ignition of spot fires. Digital simulations of weight loss by the firebrands as a function of time (combustion) and of temperature (thermal decomposition) will be useful to assess the temperatures involved in the decomposition of the vegetation and to analyse variations between plant species that generate firebrands.

The aim of the present study was to assess the efficiency of firebrands commonly encountered in forest ecosystems of Southern Europe to ignite spot fires based on physical and flammability characteristics. This study was part of the experimental work conducted in the *SALTUS* Project, a more comprehensive research project on the mechanisms involved in spot fires (SALTUS 2001). It was based on the assumption that the selected firebrands are amongst those most commonly involved in spot fires in the study regions.

2 Materials and methods

Experiments on firebrand characteristics were carried out under laboratory conditions by three research teams (INIA and CIF in Spain; *Cemagref* in France). The three teams used similar methodologies for testing the most common species from each study region: Central and North-western Spain and Southern France (Quézel and Médail 2003).

2.1 Types and physical characteristics of firebrands

Eight kinds of firebrands from different parts of trees and of various shapes were studied: pine twigs (*Pinus halepensis* and *Pinus pinea*), pine bark plates (*P. halepensis, Pinus pinaster, P. pinea* and *Pinus radiata*), *Eucalyptus* bark (*Eucalyptus globulus*), leaves (*E. globulus* and *Quercus ilex*), pine cone scales (*P. halepensis, P. pinaster* and *P. pinea*), pine cones (*P. halepensis*), acorns (*Q. ilex*) and bark cubes (*Quercus suber*).

Because particle geometry is an important factor in determining the transport and combustion of firebrands (Anthenien et al. 2006), their dimensions (in centimetres) and weights were measured. Dimensions were measured using a 10^{-4}-m accuracy micrometre. For pine twigs and cone scales, only thickness was measured. For the bark samples, a rectangular shape (2×3 to 5 cm) was chosen, but small cubes (roughly 1 cm^3) were cut in the *Q. suber* bark. To characterize the leaf surface exposed to hot gases and fire during combustion, leaf width and length were measured along the central vein (without taking the petiole into account) and leaf thickness was measured avoiding thick veins. To obtain relatively stable weight data, the samples were oven-dried at 60°C for 24 h. For all the firebrands, depending on their shape (cylindrical, rectangular or spherical), the surface of contact (in square centimetres) with the fuel bed, the total surface (in square centimetres), the volume (in cubic centimetres) and the total surface-to-volume ratio were calculated using geometrical formulae.

2.2 Ignition frequency, time to ignition and duration of flames

We assessed flammability of the firebrands using an experimental device partially based on the “flammability measurement method” (Delabraze and Valette 1974) used by other authors (Valette 1988; Hernando et al. 1994). The device consists of a 500-W electric radiator with a 10-cm diameter radiant disk; the surface temperature was 420°C at steady-state regime. After weighing and measuring, each firebrand was exposed to the heat source. Firebrands longer than the electric radiator were trimmed to fit it. Firebrand samples were in direct contact with the electric radiator, the surface of contact depended on their type (see Table 1). The surface touching the radiator was assumed to be close enough to the heat source to undergo heat transfer effects in a homogeneous way. Once samples were placed on the electric radiator, the time to ignition (TTI) and flame

Table 1 Characteristics of the firebrands and their classification according to Valette (1988)

Type of firebrand	W (g)	SC (cm^2)	TS (cm^2)	V (cm^3)	SVR (cm^{-1})	TTI (s)	FD (s)	Class
Twigs								
Pinus halepensis	0.67±0.32	2.46±0.6	7.72±1.87	0.99±0.46	8.74±2.26	22.23±10.66	29.92±15.12	Moderately flammable
Pinus pinea	0.39±0.15	2.39±0.90	7.50±2.03	0.76±0.39	11.16±3.00	13.95±5.22	15.59±5.84	Highly flammable
Bark plates								
P. halepensis	0.43±0.26	7.29±3.17	14.59±6.34	1.17±0.84	14.06±4.29	13.09±9.77	14.13±13.75	Highly flammable
Pinus pinaster	1.01±0.69	10.35±5.00	26.88±12.19	4.57±3.51	8.24 ±5.90	11.30±15.55	33.89±21.41	Extremely flammable
P. pinea	0.69±0.34	14.02±5.32	28.05±10.64	3.38±2.58	11.19±5.32	5.84±4.31	20.76 ±10.60	Extremely flammable
Pinus radiata	1.44±1.27	7.08±3.62	21.14±11.81	4.89±5.12	6.35 ±2.96	33.49 ±33.60	58.26 ±58.04	Flammable
Bark								
Eucalyptus globules	0.66±0.33	9.84±3.54	19.68±7.09	1.09±0.75	20.39±5.64	5.45±1.61	17.24±7.69	Extremely flammable
Leaves								
E. globulus	0.61±0.17	25.86±7.21	51.72±14.42	1.31±0.36	39.52±1.09	4.78±1.93	10.14±4.57	Extremely flammable
Quercus ilex (France)	0.12±0.04	10.62±3.01	21.25±6.01	0.35±0.13	64.31±14.35	4.20±1.21	4.18±1.20	Extremely flammable
Q. ilex (Spain)	0.14±0.04	9.27±2.34	18.55±4.68	0.46±0.13	40.85±6.96	3.15±0.87	4.22±1.02	Extremely flammable
Cone scales								
P. halepensis	0.22±0.04	2.66±0.52	4.92±1.19	0.70±0.24	7.79±3.19	18.13±6.61	18.35±3.78	Moderately flammable
P. pinaster	0.65±0.15	5.11±2.10	10.21±4.21	1.85±0.77	5.87±2.55	10.82±5.85	38.51±29.07	Extremely flammable
P. pinea	1.53±0.44	9.25±1.61	18.49±3.21	6.43±1.69	2.96±0.46	20.17±19.82	65.19±17.34	Moderately flammable
Cone								
P. halepensis	31.31 ±11.24	48.27±16.53	157.69±53.57	194.17±98.55	0.89±0.16	12.31±8.02	415.56±112.58	Extremely flammable
Acorn								
Q. ilex	2.37 ±0.75	3.93 ±0.90	14.54 ±3.46	5.32 ±1.90	2.85±0.34	8.03±3.30	165.61±75.54	Extremely flammable
Bark cube								
Quercus suber	0.71±0.26	2.04±0.56	10.37±2.53	2.26±0.86	4.88±1.46	21.37 ±19.42	71.51±26.67	Moderately flammable

Values are mean±standard deviation

W weight, *SC* surface of contact, *TS* total surface, *V* volume, *SVR* surface-to-volume ratio, *TTI* time to ignition, *FD* flaming duration extinction (enabling the calculation of the flaming duration (FD) of the firebrand) were recorded for each firebrand. The ignition frequency of the firebrand was calculated as the percentage of tests in which firebrands ignited. Each firebrand was classified according to its ignition frequency and its mean time to ignition following Valette's classification (Valette 1988): 0=very difficult to ignite; 1=difficult to ignite; 2=flammable; 3=moderately flammable; 4=highly flammable; and 5=extremely flammable. It should be noted that the above classification was established for tests performed with a heat source and a pilot flame while in the present study, no pilot flame was used. We nevertheless selected this classification because it enabled us to compare different firebrands.

2.3 Loss of weight with time

The experimental device was the same electric radiator described above, but included simultaneously monitoring weight loss of the firebrands during combustion, measured at 1 s intervals. This test was only conducted on *P. halepensis* bark plates, *P. halepensis* cone scales and *Q. suber* bark cubes as the flaming combustion of needles and leaves was too rapid and the weight was too low to be monitored in the selected timeframe. For each firebrand, two levels of fuel moisture content (FMC) were selected: air-dried samples and oven-dried samples (dried at 60°C for 24 h).

For each firebrand and each FMC, 50 samples were tested and the following parameters were measured: TTI (time elapsed from the moment the firebrand was placed on the radiator to the moment of ignition), FD (time during which combustion of the firebrand continued with visible flame), combustion duration (CD; time during which combustion of the firebrand continued without flame, i.e. the glowing time of the firebrand), initial weight before ignition (M1), weight after combustion with flame (M2), weight after combustion without flame (M3) and weight losses (M1–M2)/M1 and (M1–M3)/M1.

2.4 Loss of weight depending on temperature

To study thermal decomposition, weight loss had to be analysed as a function of temperature. The furnace used in the experiment heated to 1,100°K. Thermal decomposition was measured on eight firebrands: needles of *Pinus eldarica*, *P. halepensis*, *P. pinaster* and *P. pinea*; twigs of *P. halepensis*; bark plates of *P. halepensis*; cone scales of *P. halepensis*; and bark cubes of *Q. suber*.

First, each sample was oven-dried at 60°C for 24 h, then weighed with a precision of 0.001 g (initial weight of 5 g). Five samples for each temperature were analysed without opening the furnace, i.e. without a supply of oxygen. Temperatures ranged from 373.15°K to 973.15°K, at 50°K increments. Changes in the MT/MI ratio (weight at temperature T/initial weight), which is a function of temperature where MT is the weight (milligrammes) at temperature T (°K) and MI is the initial weight (milligrammes), were analysed.

2.5 Gross heat of combustion

To estimate the gross heat of combustion of the firebrands, we used standard methods (Spanish Standard UNE 23103–78 and International Standard ISO 1716 of 1973). All fuel samples were ground individually to 5.10^{-4} m in a mill. From the ground material, pellets of about 1 g were prepared using a hand press, oven-dried at 100±5°C for 24 h and then weighed. Measurements were made with an adiabatic bomb calorimeter with a platinum resistance sensor (PT-100). Both mill and bomb calorimeter were manufactured by IKA® and were located in the Forest Fire Laboratory of INIA-CIFOR, Spain. For each type of firebrand, the same measurements were made on two samples. A third sample was included whenever the difference between the first two values was more than 2% of the mean value.

According to the classification proposed by Elvira and Hernando (1989), one class of forest fuel corresponds to each gross heat of combustion (GHC) measured: medium: 18,810 kJ kg^{-1}<GHC<20,900 kJ kg^{-1}, high: 20,900 kJ kg^{-1}<GHC<22,990 kJ kg^{-1} and very high: 22,990 kJ kg^{-1}<GHC.

2.6 Data analysis

As according to the Kolmogorov–Smirnov test, the data distributions were not normal, so a one-factor non-parametric analysis of variance (ANOVA; Kruskal–Wallis test) was used to test the significance of the relationship between the type of firebrands (predictor variable) and the response variables TTI, FD and MT/MI. In the combustion experiment, the distributions were not normal (Kolmogorov–Smirnov test), so means were compared using the Mann–Whitney non-parametric test, which tests the significance of the effects of the predictor variables "moisture content" and "firebrand type" on the response variables TTI, FD, CD, (M1–M2)/M1 and (M1–M3)/M1. As the gross heat of combustion experiments were carried out on two or three samples of each type of firebrand, a one-way non-parametric ANOVA (Kruskal–Wallis test) was used to validate the significance of the relationship between 'type of firebrand' (predictor variables) and 'gross heat of combustion' (response variable). A significant relationship between the variables was assumed when the probability was less than 0.05. The number of replicates of each test is shown in Tables SI and SII, available at www.afs-journal.org. Non-linear regression analysis (exponential model) was used to show the correlation between temperature and the ratio MT/MI during thermal decomposition of different firebrands. The firebrand thermal decomposition can be modelled using a non-linear statistical analysis of the following equation:

$$y = \exp^{(a+b^{*}x)} = \exp^{(a)}{*}\exp^{(-b^{*}x)}$$

where

y mean proportion of weight remaining (MT/MI)
x temperature
a intercept
b thermal decomposition loss rate.

Finally, to identify groups of particles or species with common characteristics in relation to spotting, a hierarchical cluster analysis was carried out by using Ward's method (Johnson and Wichern 1982). All analyses were performed using Statgraphics Centurion XV.

3 Results

3.1 Physical characteristics of firebrands

Mean and standard deviation of weight, surface of contact, total surface, volume and surface-to-volume ratio of the firebrands are presented in Table 1. Range is listed in Table SI, available at www.afs-journal.org. The cones of *P. halepensis* were the heaviest firebrands (31.31 g) used in the experiment and bark cubes of *Q. suber* were amongst the bulkiest (L=1.5 cm; w=1.3 cm; t=1.1 cm). The firebrand with the smallest surface area to volume ratio was *P. halepensis* cone (0.88 cm^{-1}); indeed, it presented the highest surface of contact (48.27 cm^2) and volume (194.17 cm^3). Results revealed high variability within each type of firebrand (see Table SI), but given the large number of samples (n>200), this variability may be due to ecological and physiological mechanisms.

3.2 Ignition frequency, time to ignition and flaming duration

All the firebrands showed 100% ignition frequency. Results of time to ignition and flaming duration (mean and standard deviation) of the firebrands are shown in Table 1. Range is presented in Table SI, available at www.afs-journal.org. Both TTI and FD showed a wide range of variability. The type of firebrand had a significant effect on TTI and FD, and this effect was independent of the part of the tree or the species from which the sample was taken (Kruskal–Wallis test: KW>100 and p<0.0001). *Q. ilex* leaves presented the shortest time to ignition and the shortest flaming duration. *P. radiata* bark plates had the longest TTI and *P. halepensis* cones the longest FD (Table 1).

3.3 Loss of weight with time

Firstly, it should be noted that temperatures reached in combustion tests were much lower than those observed in wildfires, but nevertheless enabled us to record the flammability parameters particular to each firebrand. Indeed, as fires are heterogeneous, sustained temperatures are rarely observed and can vary significantly over small spatial scales. In addition, if the particles land on fuels, lags in ignition will be important in determining fire behaviour.

The values recorded during combustion are presented in Table 2 and Table SII (available at www.afs-journal.org). The air-dried *Quercus suber* bark underwent the greatest weight losses (M1–M2)/M1 (0.86) and (M1–M3)/M1 (0.90). The oven-dried *P. halepensis* bark underwent the smallest weight loss after flaming combustion (M1–M2)/M1 (0.72) and the oven-dried *P. halepensis* cone scales underwent the smallest weight loss after glowing combustion (M1–M3)/M1 (0.83). It was not possible to record the weight loss of *Q. ilex* leaves as the initial weight of this firebrand was too light. Air-dried *P. halepensis* cone scales and bark presented the longest time to ignition (19.49 s and 16.76 s). The most ignitable firebrands were *Q. ilex* leaves (regardless of the FMC). *Q. suber* bark presented the longest flaming and combustion durations and *Q. ilex* leaves the shortest.

3.3.1 The effect of fuel moisture content

Regarding time to ignition, the effect of FMC was significant in all the firebrands tested (Mann–Whitney test: U>2.5 and p<0.01). With the exception of *Q. suber* bark (Fig. 1), time to ignition decreased with decreasing FMC. Regarding flaming duration, moisture content was significant only in *P. halepensis* bark, *Q. suber* bark and *Q. ilex* leaves (Mann–Whitney test: U>2.2 and p<0.05), flaming duration decreased with a decrease in FMC. An increase in fuel moisture resulted in an increase in flaming duration except in *P. halepensis* cone scales and needles (Fig. 1). Regarding combustion duration, only *Q. suber* bark and *Q. ilex* leaves showed a significant decrease in combustion duration at the lowest FMC values (Mann–Whitney test: U>4 and p<0.0001).

Regarding weight loss following flaming combustion, FMC had a significant effect on all the firebrands (Mann–Whitney test: U>2 and p<0.05). Regarding weight loss following glowing combustion, the effect was not significant in *Q. suber* bark cubes (Mann–Whitney test: U=1.55 and p=0.12).

Table 2 Weight loss depending on time for the different firebrands, at different moisture contents, air-dried or oven-dried

Firebrand	TTI	FD	CD	(M1–M2)/M1	(M1–M3)/M1
Quercus suber bark (oven-dried: FMC=0.07%)	10.07±5.34 (n=50)	83.24±23.95 (n=50)	151.80±68.59 (n=50)	0.85±0.83	0.89±0.85
Q. suber bark (air-dried: FMC=4.06%)	6.43±5.35 (n=50)	118.65±32.88 (n=50)	152.47±79.58 (n=50)	0.86±0.82	0.90±0.86
Pinus halepensis cone scales (oven-dried: FMC=0.17%)	10.77±4.08 (n=49)	17.23±2.50 (n=49)	43.46±22.77 (n=49)	0.82±0.80	0.83±0.83
P. halepensis cone scales (air-dried: FMC=6.65%)	19.49±4.85 (n=41)	17.13±3.58 (n=41)	45.56±24.51 (n=41)	0.83±0.85	0.85±0.86
P. halepensis bark (oven-dried: FMC=0.1%)	7.38±3.74 (n=48)	12.20±4.21 (n=48)	147.85±129.90 (n=50)	0.72±0.75	0.84±0.87
P. halepensis bark (air-dried: FMC = 14.57%)	16.76±10.71 (n=49)	14.62±6.06 (n=49)	149.12±79.93 (n=49)	0.77±0.74	0.87±0.82
Quercus ilex leaves (oven-dried: FMC=0.18%)	2.60±1.25 (n=47)	3.50±1.07 (n=47)	27.36±7.67 (n=50)	–	–
Q. ilex leaves (air-dried: FMC=6.77%)	3.36±1.49 (n=50)	4.54±1.40 (n=50)	29.81±7.28 (n=50)	–	–
P. halepensis needles (oven-dried: FMC=0.34%)	2.34±0.83 (n=50)	1.39±0.51 (n=50)	5.00±1.48 (n=50)	–	–
P. halepensis needles (air-dried: FMC = 7.03%)	2.83±0.75 (n=50)	1.32±0.52 (n=50)	4.68±1.34 (n=50)	–	–

Values are means±standard deviation

TTI time to ignition, *FD* flaming duration, *CD* combustion duration, *(M1–M2)/M1* and *(M1–M3)/M1* weight losses, *n* number of samples

3.3.2 The effect of the type of firebrand

In the case of air-dried firebrands, time to ignition differed significantly (Mann–Whitney test: U>2.23 and p<0.05) except between *P. halepensis* bark and *P. halepensis* cone scales (Mann–Whitney test: U=1.58 and p=0.11). For oven-dried firebrands, time to ignition differed significantly only between *Q. ilex* leaves and *P. halepensis* bark and between *P. halepensis* bark and *Q. suber* bark (Mann–Whitney test: U>3.8 and p≤0.0001).

Regardless of the FMC, the flaming duration differed significantly among the firebrands tested (Mann–Whitney test: U>2.4 and p<0.05).

The combustion duration differed significantly regardless of the FMC (Mann–Whitney test: U>3.9 and p< 0.0001) except between *P. halepensis* bark and cone scales and between *P. halepensis* bark and *Q. suber* bark.

Regarding weight loss following flaming combustion, values differed significantly regardless of the FMC (Mann–Whitney test: U>8.2 and p<0.0001).

Regarding weight loss following glowing combustion, the values of the air-dried firebrands differed significantly (Mann–Whitney test: U>2.18 and p<0.05). Regarding oven-dried firebrands, the values of *Q. suber* bark differed significantly from the other firebrands (Mann–Whitney test: U=16.72 and p<0.0001).

The ranking orders of the different firebrands for both FMCs are presented in Fig. 1.

3.4 Loss of weight depending on temperature

For each type of firebrand, changes in the MT/MI ratio (%) are presented in Fig. 2. There was a decrease in the MT/MI ratio with an increase in temperature. The greatest weight loss occurred in *Q. suber* bark (MT/MI varying from 98.66% to 1.63%) and *P. halepensis* cone scales (from 97.69% to 0.54%). The type of firebrand did not have a significant effect on thermal decomposition (Kruskal–Wallis test: KW= 5.39, p=0.61). Moreover, firebrands such as needles of different *Pinus* species displayed similar behaviour in their thermal decomposition. *P. pinea* had the lowest MT/MI ratio (2.23%) at the highest temperature (973°K). This ratio was the highest amongst the pine needles when the temperature was the lowest (373°K). *P. pinea* underwent faster thermal decomposition than the other species. Variations were observed between different firebrands such as *P. halepensis* twigs, bark or bark plates. Cone scales underwent the fastest thermal decomposition, and needles the slowest (Fig. 2).

Non-linear regression analyses revealed that there was a strong negative relationship between temperature and weight loss (% MT/MI) for all the firebrands (Fig. 2). *P. elderica* needles presented the highest correlation (correlation coefficient=−0.989) and *P. halepensis* cone scales the

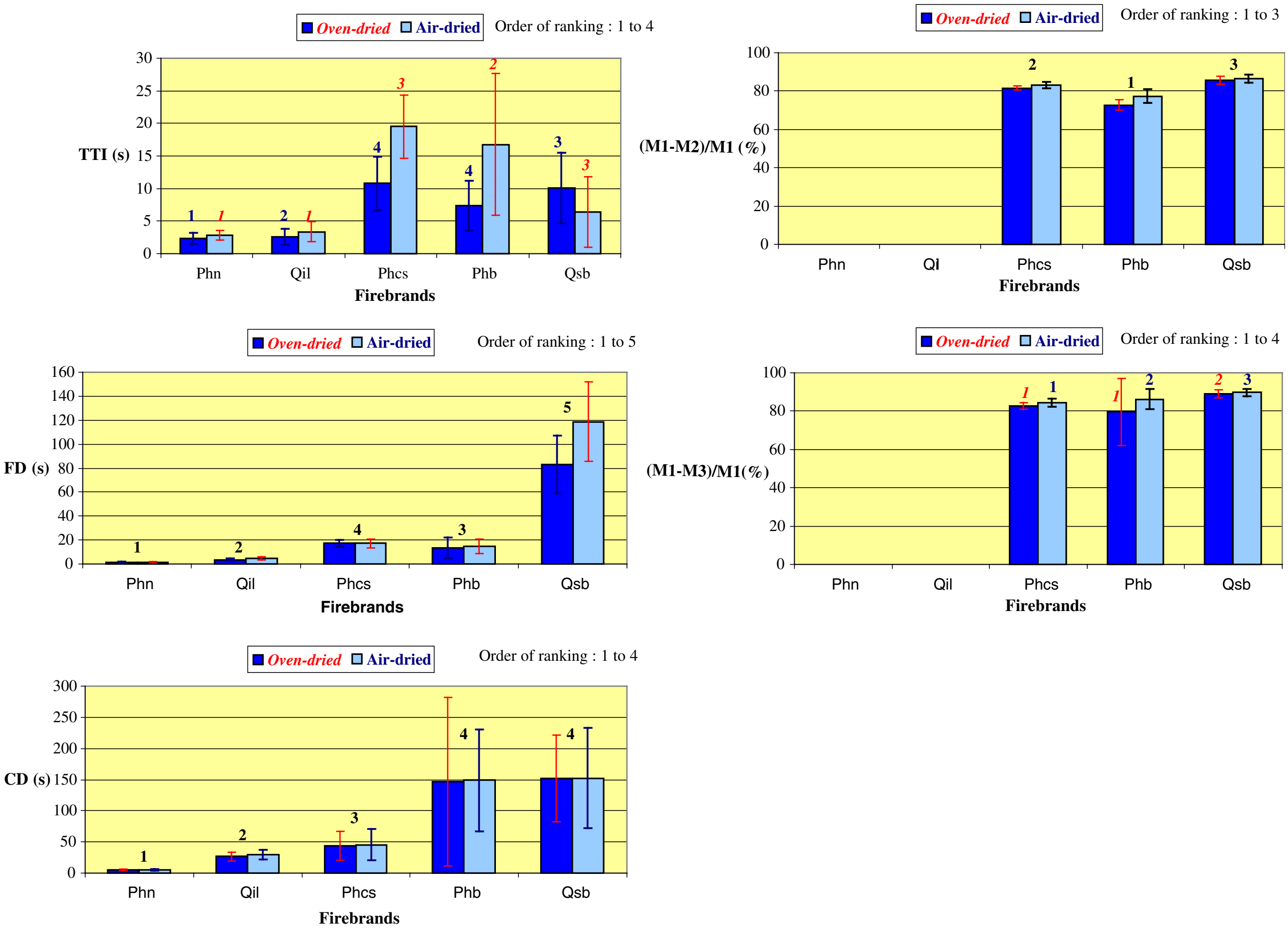

Fig. 1 Time to ignition, flaming duration, combustion duration, weight loss following flaming combustion and weight loss following glowing combustion according to the type and moisture content of firebrand (*Phn Pinus halepensis* needles, *Qil Quercus ilex* leaves, *P. halepensis* cone scales, *Phb P. halepensis* bark, *Phcs* pinus 17 halepensis cone scales, *Qsb Quercus suber* bark, *TTI* time to ignition, *FD*, flaming duration, *CD* Combustion duration, *(M1–M2)/M1* weight loss following flaming combustion, *(M1-M3)/M1* weight loss following glowing combustion)

lowest correlation (correlation coefficient=−0.956) (see equations that give the loss of the weight (y) depending on temperature (x) for each type of firebrand, in Table SIII, available at www.afs-journal.org).

3.5 Gross heat of combustion

The gross heat of combustion of each type of firebrand (average of two or three samples) as well as the class of forest fuel is presented in Table 3. The type of firebrand had a significant effect on gross heat of combustion (GHC; KW=37.15, p=0.0007) and the bark cubes of *Q. suber* had the highest value (GHC=27613 kJ kg^{-1}). When only bark and cone scale were tested, the plant species had a significant effect on GHC (KW=10.58, p=0.032, maximum GHC for *P. radiata* and KW=6.25, p=0.044, maximum GHC for *P. halepensis*). Plant species and geographical origin of *Q. ilex* leaves had a significant effect on GHC (KW=6.25, p=0.044, maximum GHC for *E. globulus* leaves). The GHC of *Q. ilex* leaves from Spain and France differed significantly (Table 3).

3.6 Cluster analysis

The hierarchical cluster analysis based on the values of the physical characteristics of firebrands, and their **time to ignition** and flaming duration identified three groups (see Fig. S1, available at www.afs-journal.org): (1) *P. halepensis* cone, (2) leaves of *E. globulus* and *Q. ilex* and bark of *E. globules* and (3) all the other types of firebrands.

4 Discussion

The burning characteristics of the different types of firebrands tested in this study address important aspects of their flammability and hence their capability to ignite spot fires (Ganteaume et al. 2009). Physical characteristics such

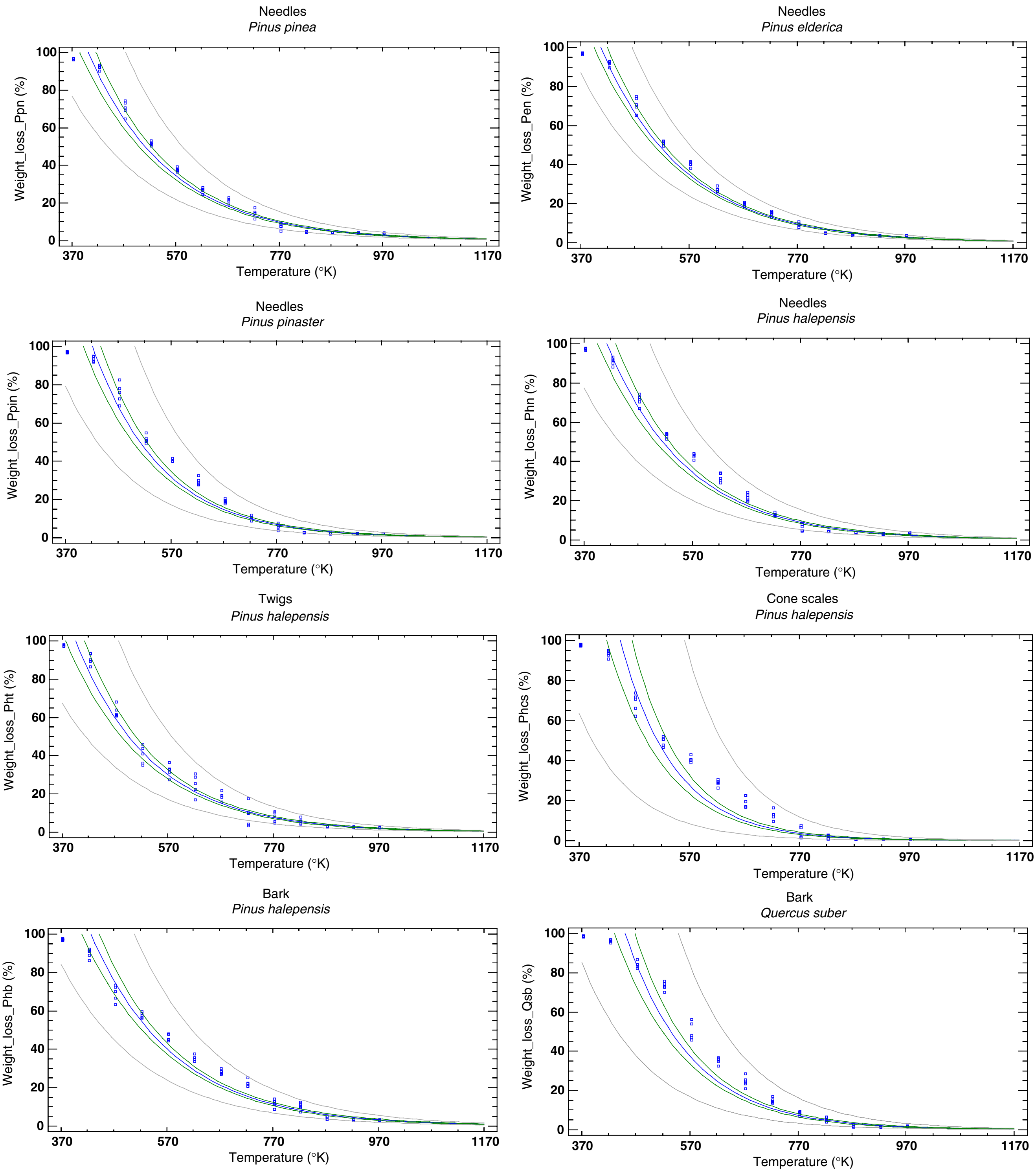

Fig. 2 Non-linear regression of weight loss (%MT/MI) of different species of firebrands as a function of temperature (*Ppn Pinus pinea* needles, *Pen Pinus eldarica* needles, *Ppin Pinus pinaster* needles, *Phn Pinus halepensis* needles, *Pht P. halepensis* twigs, *Phcs P. halepensis* cone scales, *Phb P. halepensis* bark, *Qsb Quercus suber* bark

as firebrand weight, surface-to-volume ratio or surface contact revealed differences in the flammability characteristics of these firebrands.

Of all the firebrands, *P. halepensis* cones were the heaviest and had the lowest surface-to-volume ratio. These characteristics may explain flammability parameters such as

Table 3 Gross heat of combustion of firebrands (average of two or three samples and standard deviation) and forest fuel class

Type of firebrand	Gross heat of combustion (kJ kg^{-1})	Class
Needles		
Pinus halepensis	22,940	High
Twig		
Pinus pinea	20,183 (98.91)	Medium
Bark plates		
P. halepensis	19,469 (35.76)	Medium
Pinus pinaster	20,548 (94.56)	Medium
P. pinea	20,040 (8.80)	Medium
Pinus radiata	21,583 (17.96)	High
Bark		
Eucalyptus globulus	18,870 (118.4)	Medium
Leaves		
E. globulus	22,665 (44.4)	High
Quercus ilex (France)	20,690 (105.09)	Medium
Q. ilex (Spain)	19,345 (135.34)	Medium
Cone scales		
P. halepensis	20,962 (106.91)	High
P. pinaster	20,537 (29.60)	Medium
P. pinea	20,153 (285.95)	Medium
Cone		
P. halepensis	20,650 (63.34)	Medium
Acorn		
Q. ilex	19,067 (118.40)	Medium
Bark cube		
Quercus suber	27,654 (262.90)	Very high

n=2 or 3

their long flaming duration compared with the other firebrands. The average flaming duration of this type of firebrand (415 s) is within the range (207 to 740 s) recorded for burning characteristics of cones from eight American pine species (Fonda and Varner 2004). Because of their ability to sustain flames, *P. halepensis* cones were thought to be one of the most efficient firebrands in a spotting fire. This was confirmed in laboratory tests (Ganteaume et al. 2009). However, a field study (SALTUS 2001) showed that conifer cones are not a very common firebrand. Conversely, in our study, *Q. ilex* leaves were the lightest firebrands with a high surface-to-volume ratio and burned the most rapidly. Generally speaking, in our experiments, regardless of their FMC, needles and leaves burned most rapidly but for the shortest time because of their low weight and high surface-to-volume ratio. Because of their short time to ignition, these firebrands were the most ignitable, the thinnest leaves being the most ignitable (Montgomery and Cheo 1971). According to Alessio et al. (2008), the ignitability of *Q. ilex* leaves and *P. halepensis* needles was of the same order. These firebrands did not sustain flames (very short flaming and combustion durations) and even if they had a high gross heat of combustion, they were too rapidly consumed to be efficient firebrands for long-distance fire spotting. Kane et al. (2008), analysing the burning characteristics of oak leaves from southeastern USA, found flaming durations ranging from 50.4 to 91.4 s and combustion durations ranging from 216 to 399.8 s. These values are much higher than those we found for *Q. ilex* leaves in our study, mainly because the burning methods used in the two studied were different. Kane et al. (2008) followed the method outlined in Fonda et al. (1998) and Fonda (2001) and burned samples of litter bed (15 g of oven-dried leaves) in a 35× 35-cm grid formed by eight xylene-soaked cotton strings, whereas in our experiment, only one leaf per trial was burned on an electric radiator. In our study, *P. halepensis* needles had short flaming and combustion durations (at the most 1.39 and 5 s) due to the direct contact of the needle on the electric radiator whereas Fonda (2001) found much longer durations for eight American pine species (respectively, 63.5 to 195.4 s and 69.9 to 360.1 s) certainly due to the increased packing ratio of the needles. This difference in flaming durations was, indeed, mainly due to the above-mentioned difference in experimental methods. In Mutch's (1970) study of the burning duration of *P. ponderosa* needles, in which the author found an intermediate value (16.7 s), a different experimental method was also used. In his work, Mutch conducted laboratory combustion tests on 45.4 g fuel samples placed in wire mesh baskets and ignited by xylene-dipped string. In our study, using an epiradiator, the time to ignition of *P. halepensis* needles was very short (less than 3 s). This result was also highlighted by Ormeño et al. (2009), who also used an electric radiator as burning device.

Even with a bad ignitability but with a good sustainability, *Q. suber* bark cubes underwent the greatest weight loss with time at both fuel moisture contents (air-dried and oven-dried). Consequently, this firebrand would not be very efficient in igniting a spot fire over long distances. Conversely, *P. halepensis* bark had the lowest weight losses with time, with a short flaming duration but very long combustion duration. Regarding thermal decomposition, *P. halepensis* bark was also the most efficient firebrand amongst the species studied; its ability to sustain combustion would enable it to be effective even after being lofted over greater distances. In our experimental conditions, most of the thermal decomposition followed a charring combustion pathway that would not occur in these fuels in natural conditions.

As can be seen in Table 3, only *Q. suber* bark presented a very high gross heat of combustion; this characteristic should favour its efficiency as a firebrand. *P. halepensis* needles and cone scales, *P. radiata* bark and *E. globulus* leaves showed a high gross heat of combustion, whereas that of the other firebrands was medium. The high GHC recorded with *P. halepensis* needles could be attributed to its higher production of essential oils and resins (Liodakis and Kakardakis 2006). Núñez-Regueira et al. (1996) predicted the risk of wildfire for different geographical zones in Galicia (NW Spain) using the different heat of combustion values of different species over a year. The values we obtained with *E. globulus* bark as well as with the bark plate and cone scale of *P. pinaster* are in the range of the values measured by these authors over a period of a year (17,539 to 20,760 kJ kg^{-1} and 19,481 to 20,659 kJ kg^{-1}). However, *E. globulus* leaves presented higher GHC (22,665 kJ kg^{-1}) than the values obtained by the previous authors. Using ground samples of needles collected during the dry season, Liodakis and Kakardakis (2006) found a lower GHC for *P. halepensis* than the value obtained in our experiments (20,841 versus 22,940 kJ kg^{-1}).

On the basis of these results and of the cluster analysis (Fig. S1), three firebrand groups could be distinguished in relation to spotting:

1. Heavy firebrands with ability to sustain flames. This type of firebrands is more difficult to transport through the atmosphere, but they have a high potential to ignite spot fires after they have landed. Therefore, they would be efficient firebrands for long-distance spotting. Pine cones, as *P. halepensis* ones, are included in this group.
2. Light firebrands with high surface-to-volume ratio and low ability to sustain flames. This type of firebrands is easy to transport in the second phase of spotting, but they are rapidly consumed. So they would only be efficient for short-distance spotting. This group comprises leaves and thin barks (e.g. *E. globulus* and *Q. ilex* leaves and *E. globulus* bark). It must be noticed that *Eucalyptus* bark is classically considered to be an effective firebrand (Pyne et al. 1996), because it is easily lifted from the trees and the curled shapes gives it aerodynamic features that allow it to be carried out for long distance. But in our study, this aerodynamic characteristic has not been analysed.
3. Light firebrands with low surface-to-volume ratio and higher ability to sustain flames. This type of firebrands has intermediate characteristics between groups 1 and 2, but they are closer to group 2. They would be efficient for short and, occasionally, long-distance spotting. All the other types of firebrands, different from the pine cones, leaves and thin barks, are included in this group.

5 Conclusions

To improve our knowledge of firebrands involved in fire spotting, physical (weight, surface of contact, total surface, volume and surface-to-volume ratio) and flammability characteristics (ignition frequency, time to ignition, flaming duration, combustion, thermal decomposition and gross heat of combustion) of several types of firebrands commonly encountered in Southern Europe were determined in laboratory conditions. The firebrands studied showed an exponential loss of weight with time and a decrease in thermal decomposition as a function of temperature.

On the basis of the characteristics analysed, three firebrands groups have been identified in relation to spotting: heavy firebrands with ability to sustain flames, which would be efficient firebrands for long-distance spotting (pine cones); light firebrands with high surface-to-volume ratio, which would be effective for short-distance spotting (leaves and thin barks) and light firebrands with low surface-to-volume ratio which would be efficient for short and, occasionally, long-distance spotting (all the other types of firebands).

Fire spotting results from a complex interplay between the numbers of firebrands produced, firebrand dispersal distances, ignition probabilities of the recipient fuel class, and the spatial arrangement of fuel types at the landscape scale. The number of firebrands produced by each fuel type and the probability of ignition may have compensating effects on spotting behaviour; greater numbers of less-successful firebrands may produce the same pattern as fewer, more-successful ones (Hargrove et al. 2000).

Therefore, no strict recommendations could be derived from the results obtained in this study. Nevertheless, these results provide complementary information for potential spotting analysis in forest and fuel management plans and community wildfire protection strategies. Spotting potential, combined with forest structure data and fuel modelling, would improve fire hazard assessment (Fernandes 2009).

In future works, the results presented in this paper could be used as inputs for models describing the capability of firebrands to be carried up in the rising convection column or their capability to ignite secondary fires.

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