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ORIGINAL PAPER

Flammability of some companion species in cork oak (*Quercus suber* L.) forests

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Abstract

• ***Key message*** **The high flammability of some companion species in *Quercus suber* forests, estimated in laboratory tests, could potentially generate an increase in fire vulnerability and in fire risk.**

• ***Context*** Recurrent wildfire is one of the main causes of forest degradation, especially in the Mediterranean region. Increased fire frequency and severity due to global change could reduce the natural resilience of cork oak to wildfire in the future. Hence, it is important to evaluate the flammability of companion species in cork oak forests in the particularly dry bioclimatic conditions of North Africa.

• ***Aims*** This study aimed to assess and compare flammability parameters at laboratory scale among ten companion frequent species in cork oak forests.

• ***Methods*** Fuel samples were collected in a cork oak (*Quercus suber* L) forest in the southern part of the mountains of Tlemcen (Western Algeria). A series of flammability tests were carried out using a Mass Loss Calorimeter device (FTT ®). A cluster analysis to classify flammability of the selected species was conducted using the K-means algorithm.

• ***Results*** The results revealed differences in the four flammability parameters (ignitability, sustainability, combustibility and consumability), in both fresh and dried fine fuel samples from *Quercus suber*, *Pinus halepensis*, *Quercus ilex*, *Quercus faginea*, *Erica arborea*, *Arbutus unedo*, *Pistacia lentiscus*, *Calicotome spinosa*, *Juniperus oxycedrus* and *Tetraclinis articulata*. Application of the K-means clustering algorithm showed that *C. spinosa*, *T. articulata*, *J. oxycedrus* and *P. halepensis* are highly flammable because of their high combustibility and sustainability.

• ***Conclusion*** The findings identify species that could potentially increase the vulnerability of cork oak forests to forest fires.

Keywords Fire risk · Fuel moisture content · Mass loss calorimeter · Mediterranean basin · Algeria

1 Introduction

Cork oak (*Quercus suber* L.) forests are a characteristic component of the Mediterranean region. They cover a total surface area of approximately 2.5 million hectares in the western Mediterranean Basin (Pausas et al. 2009), mainly in Portugal, Spain, Algeria, Morocco, France, Italy and Tunisia. Cork oak ecosystems play very important ecological and social roles in several Mediterranean countries (Pereira and Fonseca 2003; Bugalho et al. 2011), and they also support a large variety of animal, plant and fungal species, including

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Contribution of the co-authors B. Dehane carried out field work, experiments and wrote the first version of the paper; C. Hernando and M. Guijarro supervised experimental design and laboratory work and generated the last version of the manuscript; J. Madrigal coordinated the work, assisted on laboratory experiments, carried out experimental design and statistical analysis, and revised the manuscript

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many endemic species (Bernal 1999). Cork oak forests are especially valued for their cork, the basis of the cork industry. However, several factors such as pests and diseases, overharvesting, over-grazing and land use changes are endangering *Quercus suber* forests. Besides, shrubs understory which forms under abandoned or overgrown cork oak forests are sclerophyllous and accumulate large amounts of forest fuel biomass (Pasalodos-Tato et al. 2015). These threats, exacerbated by climate change, affect tree health and increase the vulnerability of stands to wildfire (WWF 2007). Recurrent wildfires are one of the major causes of forest degradation, especially in the Mediterranean region (Fares et al. 2017). The fires and burnt area within the European Union and in particular the Mediterranean region severely affect cork oak forests (Cardillo et al. 2007). For instance, in Portugal (the leading country in terms of *Q. suber* cover and cork production), 15–20% of *Q. suber* forests have been burned since 1990 (Catry et al. 2012). In Algeria, between 1963 and 2014, a total of 1.8 Mha of forest land was burned and over 40,000 fires were reported (Bekdouche 2009; DGF 2014).

Under these conditions and in the context of climate change, fire hazard will increase (Moritz et al. 2014) and the natural resilience of cork oak after wildfires may decrease in the future (Catry et al. 2012).

Fire hazard is directly related to fuel flammability and is a measure of the fire risk due to the fuel available for burning (WWF 2007). Consequently, the characterization of forest fuel flammability has a long history and classifications of species in terms of flammability are often requested (Fares et al. 2017). The interactions between species composition, canopy architecture, arrangement and size of fuel (including surface fuel or fuel loading), amount of dead-live fuel and fuel moisture content, affect ignition, fireline intensity, rate of spread and fuel consumption (Fernandes and Cruz 2012).

The concept of flammability still generates controversy (Schwilk 2015). In general, flammability can be defined as the capacity of plant biomass to burn, i.e. to ignite and sustain a flame (Pausas et al. 2017). According to Anderson (1970) and Martin et al. (1994), this process has four components: ignitability (the facility to produce ignition); sustainability (the ability of a material to maintain combustion and produce energy); combustibility (speed with which the combustion occurs); and consumability (the proportion of biomass consumed during combustion). In a recent study, Pausas et al. (2017) highlighted the failure to frame these components within a unified ecological and evolutionary context, and empirical evidence does not support viewing flammability components, sensu Anderson (1970) and Martin (1994), as independent axes. These authors suggested that flammability has three major dimensions: one associated with ignitability, another with flame spread rate (or rate of heat release) and another with heat released (standardized to fuel load). This new concept explains the chance of burning given an ignition, and the different ways in which plant biomass can burn (e.g. slow vs. fast and high intensity vs. low intensity). These major axes of variation are controlled by different plant traits and have differing ecological impacts during fire.

Assessment of flammability in the laboratory is limited by the scale of experiment (particle level or parts of plants, whole plants and stand scale, sensu White and Zipperer 2010) because the way in which plants are exposed to heat may not to be comparable to wildfire conditions (Fernandes and Cruz 2012), and outdoor experimental fires are often limited. Nevertheless the heat release rate estimated at laboratory scale is a good index to characterize fire hazard and it can be used to classify fuels (Babrauskas and Peacock 1992). Several studies have attempted to assess vegetation flammability at different scales (Etlinger and Beall 2004, White and Zipperer 2010) and great difficulties in evaluating the flammability of forest fuels have been reported (Madrigal et al. 2013): (1) most methods used to evaluate flammability are based on characterization of building materials, and they are only accurate for low moisture contents or for calculations made on an oven-dry basis; (2) the moisture content of forest fuels has a strong effect in reaction-to-fire tests, and it is therefore difficult to obtain repeatable results for a wide range of fuel moisture content (FMC); (3) sample dry mass has a strong effect on Heat Release Rate (HRR), so that the HRR values of live samples of different dry mass are not comparable; and (4) there is an interaction between the physiological state of a live plant, which determines the level of volatile compounds, and the moisture content. Some bench-scale studies have been carried out using different approaches and methods to characterize and compare the flammability of both live and dead fine fuel in Mediterranean species (e.g. Valette 1990; Alessio et al. 2008; Madrigal et al. 2011; Ganteaume et al. 2013; Pausas et al. 2015; Della Rocca et al. 2015; Jervis and Rein 2016). Comparison of the results obtained among studies is rather difficult, indicating that a standardized method for determining flammability must be developed and a common classification established for the test results (e.g. Weise et al. 2005; White and Zipperer 2010; Ganteaume et al. 2013). This fact has generated several rankings (e.g. Weise et al. 2005) and classifications of plants (e.g. Dimitrakopoulos 2001) and different approaches to link flammability with fire risk (e.g. Molina et al. 2017) but any universal classification of plants flammability is available (Fares et al. 2017). In addition, classifying species flammability taking into account heat release in order to link fire traits and flammability is mandatory (Schwilk 2015, Pausas et al. 2017).

In previous studies (Madrigal et al. 2011, Madrigal et al. 2013), the first attempt to rank Mediterranean forest fuel using heat release was developed using oven-dried and fresh samples of Mediterranean forest fuels. However, no such studies have been carried out in North Africa (Hachmi et al. 2011). Flammability classifications in dry bioclimatic conditions in the Mediterranean region could help to understand the effect of fuel moisture content and phenology on flammability properties of forest fuels in the future context of climate change (Fares et al. 2017). In addition, the characterization of flammability of companion species of these forests might help managers to prioritize treatments to reduce cover of high flammable species in order to reduce the vulnerability of cork oak to recurrent forest fires (Catry et al. 2012).

Living fuel is characterized by plant attributes that affect flammability. Flammability is strongly dependent on moisture, and many scientific studies have addressed this relationship. Numerous studies have examined the effects of fuel moisture content on ignition of several different fuels in the USA and in the Mediterranean region (chaparral) (e.g. Engstrom et al. 2004; Fletcher et al. 2007; Pickett et al. 2010;McAllister and Weise 2017). Although the findings confirm the importance of moisture content, some plant traits can enhance or reduce flammability at a given moisture level (Pausas et al. 2017). These traits include ecosystem-specific biomass, spatial arrangement and chemical composition (Fares et al. 2017). The chemical content of leaves is species-specific and determines different properties of flammability (Ciccioli et al. 2014). In this respect, Chetehouna et al. (2014) calculated that the amounts of Biogenic Volatile Organic Compounds (BVOC) emitted may lead to an accelerating wildfire especially when these compounds are volatilized at high temperatures and accumulate in canyons.

The aims of the present study are (i) to evaluate the flammability parameters, at laboratory scale, by means of a mass loss calorimeter in some frequent companion species in a cork oak (*Quercus suber* L.) forest in Algeria and (ii) to propose a new way to classify plant flammability in the particularly dry bioclimatic conditions of North Africa.

2 Material and methods

2.1 Study site and sampling

Fuel samples were collected in a cork oak (*Quercus suber* L.) forest in the southern part of the mountains of Tlemcen (West of Algeria). The area is characterized by a sub-humid climate with 27 °C of average annual temperature and 500 mm of mean annual precipitation. The altitude varies between 1000 and 1282 m and the slope between 1.1 and 9.1%. In addition to *Quercus suber* as the main tree species, the following companion species (shrubs and trees) were considered: *Pinus halepensis Mill.*, *Quercus ilex L.*, *Quercus faginea L.*, *Erica arborea L.*, *Arbutus unedo L.*, *Pistacia lentiscus L.*, *Calicotome spinosa L.*, *Juniperus oxycedrus L.* and *Tetraclinis articulata Vahl.*). These species are representative of the study area and frequent in cork oak forests and in the Mediterranean basin.

Fuel sampling was carried out during the fire season (September 2015) with the aim of assessing the effect of phenology on vegetation flammability and selecting low fuel moisture contents corresponding to high levels of fire hazard.

Samples (approximately 500 g) of live fine fuel (twigs Ø < 0.6 cm with foliage, according to Deeming and Brown 1975) were collected in five independent plots along one transect (34° 51′ 12.86″ N, 1° 21′ 07.99″ W) throughout the study area. In each plot, five trees and shrubs of each species were chosen at random. The samples were obtained with the aid of prune clippers and a telescopic saw.

The samples were placed in plastic bags, which were then sealed hermetically and transported to the laboratory in portable refrigerators, to prevent loss of water content and volatile organic compounds (VOCs). Once in the laboratory, one 100 g subsample of each fuel sample was used to determine fuel moisture content (FMC) by oven-drying the material in an oven at 100 ± 2 °C to constant weight (after approximately 24 h).

The remaining live fine fuel samples were stored in a refrigerated chamber (4 °C) until being tested for flammability, i.e. within 7 days of being collected. One subsample of each species was used to determine the flammability of fresh fuels (as a surrogate for live fuels) and another subsample was dried at 60 ± 2 °C (until the dry weight did not change) to constant weight, in order to reduce the variability in the results of flammability tests due to differences in water content. This temperature was selected in order to reduce losses of constitutive chemicals (Ciccioli et al. 2014).

2.2 Experimental procedure

Two series of tests were carried out using both fresh and dried fine fuel samples, from the ten selected species, according to the methodology proposed by Madrigal et al. (2013). A Mass Loss Calorimeter (MLC) device (FTT®) was used, as reported in previous studies concerning flammability of forest fuels (Madrigal et al. 2009; Madrigal et al. 2011; Madrigal et al. 2013, Della Rocca et al., 2015). This apparatus (Fig. 1a–c) is the complete fire model of the cone calorimeter, which has assumed a dominant role in bench-scale fire testing of building materials (more details in Madrigal et al. 2009). A specific holder adapted for forest fuels samples (Fig. 1d) was also designed to simulate rapid flaming combustion. The holder ($10 \times 10 \times 5$ cm^3) was made of stainless steel, with small uniformly sized holes over the entire outer surface (sides and bottom). These holes create an open space for inlet combustion gases to pass into the holder and through the fuel samples.

Tests were conducted at a radiant heat flux of 50 kW/m^2, simulating severe fire conditions (Cruz et al. 2011), and piloted ignition.

Paired samples were used in the experiment according to the method proposed by Madrigal et al. (2013): one to determine the FMC and the other one for flammability testing. Fuel

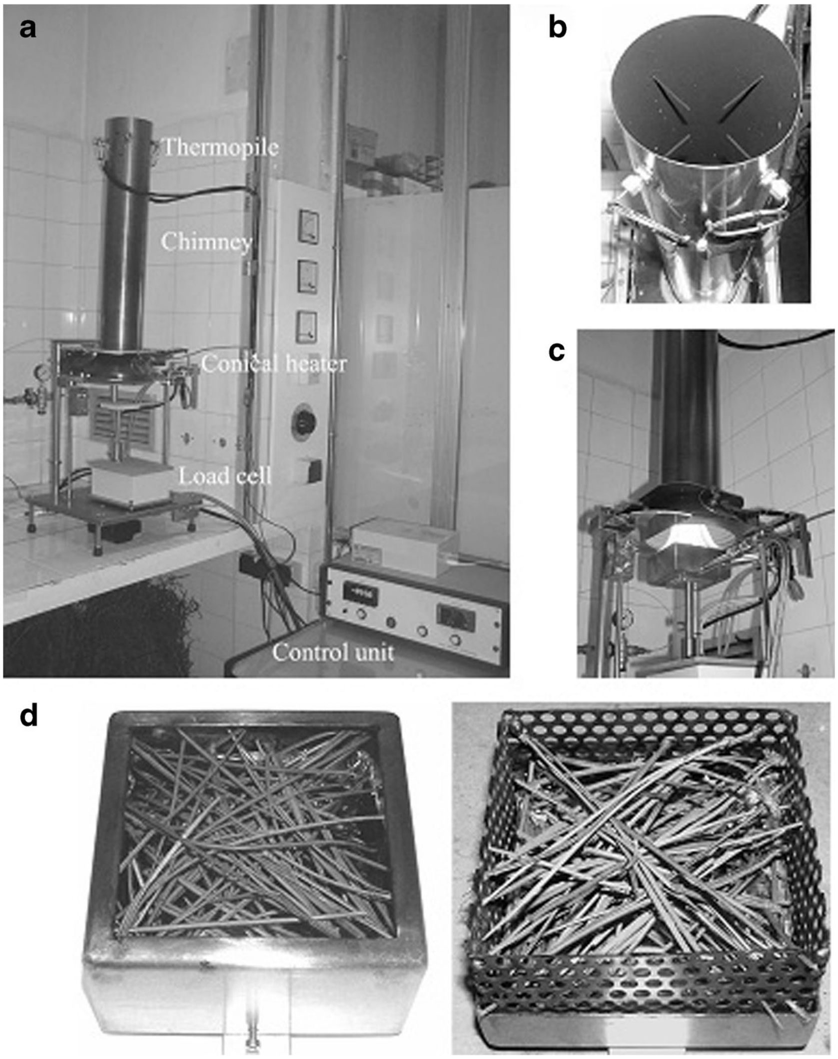

Fig. 1 **a** General view of the MLC device. **b** Detail of the sensor to estimate heat release rate, called thermopile. **c** Detail of methane burner used to calibrate the thermopile. **d** Standard holder (*left*) vs. porous holder (*right*) used in the series of tests immediately before a test

moisture content (FMC) was evaluated immediately before the tests by using a moisture analyser (Computrac MAX ®2000XL). The MLC sample weight was calculated from the FMC thus obtained and the fixed dry weight (10 g). The sample was then placed in the holder to obtain a bulk density of 20 kg/m^3 and was finally tested in the MLC. The combined use of the above-mentioned devices guarantees fixed conditions for conducting laboratory tests: constant bulk density and constant sample dry mass, to reduce the variability in heat release rate (HRR) due to dry mass and to enable evaluation of the effect of FMC and species on flammability (Madrigal et al. 2013).

Between 3 and 8 replicates were obtained in each series to yield 3 replicates that comply with repeatability criteria (Madrigal et al. 2009, 2013). In total, $n = 81$ replicates of fresh samples and $n = 42$ replicates of dried samples were obtained, finally yielding a database of $n = 30$ for fresh and $n = 30$ for dried samples (10 species and three values per species). For thorough representation of the four flammability components, sensu White and Zipperer (2010), the following parameters were measured: time to ignition (TTI, sec) for ignitability; Effective Heat of Combustion (AEHC, MJ/kg) for sustainability; peak heat release rate (PHRR, kW/m^2) for combustibility; and Residual Mass Fraction (RMF, %) for consumability. The mean value over three samples per species of each flammability parameter was used to generate a database of dependent variables.

2.3 Data analysis

Fuel moisture content (FMC) of fresh fuels and flammability parameters (TTI, AEHC, PHRR, RMF) in the different species were compared by one-way ANOVA (LSD test, $p < 0.05$; $n = 3$). The logarithmic and angular transformations were used when variables did not comply with parametric requisites. The effect of FMC on flammability parameters was evaluated using a non-parametric Pearson correlation matrix ($n = 10$). The flammability of the selected species was classified by cluster analysis, implemented using the K-means algorithm. This generalized method is robust when variables used for classification clustering are correlated (TTI, AEHC, PHRR, RMF) and present different metrics (Bishop 1995). Following the flammability classification proposed by Dimitrakopoulos (2001) in three typologies (low, medium and high flammability species), three clusters were used to classify species in main flammability groups. The process was carried out for both fresh and dried fuels (10 species, $n = 10$) to evaluate the effect of fuel moisture in flammability classification. K-means algorithm assigns three centres to represent the clustering of ten points (species). The points are iteratively adjusted (50 iterations was selected) starting with a random sample of species, so that each of the species is assigned to one of the three clusters and each of the three cluster is the mean of its assigned species (Bishop 1995). Standardize values of variables was used and Euclidean distances was selected.

The ANOVA analysis compares flammability components among species (e.g. Weise et al. 2005, Madrigal et al. 2013, Jervis and Rein 2016) and the representation of K-means cluster in different axes of the flammability parameters allows the evaluation of the new concept proposed by Pausas et al. (2017): three major dimensions, one associated with ignitability (TTI), another with flame spread rate (PHRR) and another with heat released (AEHC). Statistica 10.0 ® software was used to conduct ANOVAs and to generate flammability classifications.

3 Results

3.1 Effect of FMC on flammability parameters

Fuel moisture content (FMC) differed greatly among species collected on the same days (Table 1). The FMCs of trees such as *A. unedo* and *P. halepensis* were significantly higher than those of other tree species such as *Quercus* spp. (*Q. faginea*, *Q. ilex and Q. suber*) and *T. articulata*. The FMCs of understory shrubs such as *E. arborea*, *J. oxycedrus* and *P. lentiscus* were similar to those of *Quercus* spp. and *T. articulata*, and the lowest FMCs corresponded to *C. spinosa*.

The effect of FMC on flammability parameters was evaluated using a correlation matrix (Table 2). Surprisingly, FMC was not significantly correlated with TTI (ignitability) or RMF (consumability) and was weakly correlated ($p < 0.1$) with PHRR (combustibility) (Fig. 2a). However, FMC was strongly correlated ($p < 0.05$) with AEHC (sustainability) (Fig. 2b).

3.2 Flammability of cork oak forest species

The flammability variables determined in the fresh samples were compared (Table 1). Ignitability was higher (lower time-to-ignition), and combustibility (PHRR) and sustainability (AEHC) were lower in *A. unedo* than most of the other species studied, although consumability was similar (RMF). The ignitability of *C. spinosa* was moderate, but the levels of combustibility, sustainability and consumability were higher than those of the other species, and this was identified as the most flammable species. The FMCs of these species were respectively the highest and lowest of the series (Table 1).

Fewer differences were detected between oven-dried samples and fresh samples (Table 1). In this condition, the flammability characteristics of *A. unedo* and *Quercus* spp. were similar, although combustibility and consumability were still higher in *C. spinosa* than in the other species.

The ANOVA results indicate the need to use the four flammability components to describe and classify flammability properties of species (Pausas et al. 2017). Cluster analysis was carried out to classify species using the four selected flammability variables for both fresh and dried samples (Fig. 3). Clustering of fresh samples by applying the K-means algorithm (Fig. 3a, b) yielded three different groups: *Quercus spp.* and *A. unedo* (Cluster 1); *T. articulata*, *J. oxycedrus* and *C. spinosa* (Cluster 2); and *P. halepensis*, *P. lentiscus* and *E. arborea* (Cluster 3). Cluster 1 includes species characterized by high ignitability (low TTI) and low combustibility (low PHRR), low sustainability (low AEHC) and low consumability (high RMF). Cluster 2 is characterized by the species with the highest average value of TTI (low ignitability), but with a wide range of this flammability component and consumability (RMF) and very high combustibility and sustainability. Finally, Cluster 3 is characterized by species with intermediate values of the flammability parameters, between clusters 1 and 2 (Fig. 3a, b). However, the groups defined on the basis of analysis of fresh fuels are very different from those defined on the basis oven-dried fuels, showing the importance of physiological state and FMC in the results. The analysis based on oven-dried fuels (Fig. 3c, d) suggests three different groupings: *C. spinosa* (Cluster 1), *P. halepensis* (Cluster 2) and other species (Cluster 3).

4 Discussion

In the Mediterranean region, cork oaks are mixed with other species that display different levels of sensitivity to fire and fire traits (Pausas et al. 2016, 2017). The fuel moisture content (FMC) is recognized as the main catalyst for flammability (e.g. Valette 1990; Alessio et al. 2008; Madrigal et al. 2009; Dimitrakopoulos et al. 2013) and, for practical purposes, the moisture content must be taken into account in any method eventually proposed for estimating flammability (Babrauskas 2006). The mean moisture content for all samples was higher than 50% (FMC ranged from 53 to 131%) and was within the range reported for species in Mediterranean region (e.g. Viegas et al. 2001; Madrigal et al. 2013; Pausas et al. 2015). The moisture contents of *A. unedo* and *P. halepensis* were higher than those of the other species under study (Table 1).

Table 1 Fuel moisture content (FMC) and analysed flammability parameters for fresh (left, $N = 30$) and oven-dried (FMC = 0%) samples (right, $N = 30$) for each studied species. Average value and standard deviation are shown. Different letters show significant differences for each analysed variable (columns) among species (LSD test, $p < 0.05$)

	Fresh					Oven-dried			
Species	FMC (%)	TTI (s)	PHRR (kW/m^2)	AEHC (MJ/kg)	RMF (%)	TTI (s)	PHRR (kW/m^2)	AEHC (MJ/kg)	RMF (%)
Arbutus unedo	131 (2.1) g	26 (13.3) a	87.67 (11.28) ab	4.07 (0.42) a	3.61 (1.32) cd	8 (2.6) abc	219.10 (14.81) ab	13.30 (0.21) bcd	5.6 (0.57) b
Calicotome spinosa	53 (2.2) e	62 (7.2) bcd	204.25 (0.75) f	12.48 (1.02) e	1.53 (0.37) a	32 (5.3) e	340.81 (14.00) d	12.54 (0.99) bc	2.3 (0.57) a
Erica arborea	69 (2.1) ab	61 (1.5) bc	156.23 (8.56) e	9.48 (3.93) cde	2.07 (0.34) ab	13 (8.5) bcd	262.71 (14.09) c	13.97 (2.25) cd	6 (0.11) bc
Juniperus oxycedrus	64 (2.3) b	51 (11.3) ab	196.91 (8.41) f	10.08 (0.84) cde	2.44 (0.03) abc	16.3 (4.1) d	241.41 (21.60) bc	13.85 (0.30) cd	7.3 (1.52) cd
Pinus halepensis	102 (2.0) f	86 (11.1) de	162.17 (11.75) e	7.78 (1.02) bc	3.79 (0.75) d	6.6 (0.6) ab	311.07 (40.92) d	14.15 (0.75) d	5.6 (0.57) b
Pistacia lentiscus	74 (2.2) ac	86 (31.6) f	140.07 (12.93) d	8.86 (2.83) cd	2.01 (0.57) ab	11.3 (4.0) abcd	193.91 (40.62) a	12.22 (0.59) abc	8 (1.00) d
Quercus faginea	83 (5.7) d	13 (3.0) a	80.32 (3.80) a	4.62 (1.31) ab	5.74 (1.10) e	4.7 (0.6) a	223.27 (23.07) abc	10.98 (0.45) a	7.7 (0.57) d
Quercus ilex	69 (2.9) ab	33 (9.1) ab	114.75 (8.37) bc	8.46 (0.57) bcd	3.34 (0.29) cd	14 (7.9) bcd	198.33 (14.80) a	12.30 (0.28) abc	8.6 (0.57) d
Quercus suber	80 (7.5) cd	27 (15.1) ab	102.07 (4.56) bc	8.72 (2.52) cd	2.97 (0.27) bcd	6.7 (3.8) ab	251.12 (15.66) bc	12.75 (0.31) bcd	6 (0.10) bc
Tetraclinis articulata	74 (6.3) ac	109 (13.0) f	190.83 (5.13) f	11.59 (1.29) de	3.63 (0.84) cd	15 (1.7) cd	262.80 (18.07) c	13.05 (0.61) bcd	7.3 (1.52) cd

FMC fuel moisture content, *TTI* time to ignition, *PHRR* peak heat release rate, *AEHC* average effective heat of combustion, *RMF* residual mass fraction

The fire season in Algeria extends from May to October, a period characterized by a lack of rain and average daily temperatures higher than 30 °C, conditions which generate water stress in the vegetation.

Contrary to most previous studies, FMC did not have a significant effect on TTI (ignitability) or RMF (consumability) ($p > 0.5$) (Table 2). White and Zipperer (2010) pointed out the difficulties in examining combustion characteristics of live fuels, and some studies have not successfully correlated flammability measures and moisture content. Fuel moisture content (FMC > 50%) generates a high level of variability in TTI (between 53 and 131 s) and RMF values (between 1.52 and 5.75%), and, therefore, it was not possible to identify differences among species. Indeed, the effect of FMC of live fuels on forest fire behaviour at high radiant heat flux is controversial (Madrigal et al. 2013). Some authors consider that under such circumstances, the effect of the feedback from the fire (Finney et al. 2015) and accumulation of VOCs may be stronger than that owing to FMC (Viegas and Simeoni 2011). Hachmi et al. (2011) confirmed that this is probably due to the presence of a high content of extractive compounds and volatilized aromatic essential oils in the foliage of the species in North Africa, especially in cork oak forests. The procedure in this study was designed to limit the evaporation of water and VOCs before the test. Emission of VOCs is favoured by evaporation of water due to transportation of such compounds by water molecules during the evaporation process (Chetehouna et al. 2009, Ormeño et al. 2009, Fares et al. 2017). However, the results of the tests showed a significant correlation between FMC and PHRR (combustibility, $r = -0.56$, $p < 0.1$) and a strong correlation between FMC and AEHC (sustainability, $r = -0.78$, $p < 0.05$) (Fig. 2a, b). Thus, as the water content (FMC) decreased, the speed of combustion (PHRR) and heat release (AEHC) increased. Indeed, these findings show the importance of these variables in describing the combustion process (Babrauskas and Peacock 1992) and the possible involvement of VOCs in accelerating combustion (Viegas and Simeoni 2011, Chetehouna et al. 2014). Although laboratory tests can provide detailed and quantitative information about biomass burned and gaseous emissions, results obtained from the analysis of live leaves are not definitive because there is a strong interaction among VOCs, FMC and radiant heat flux (Madrigal et al. 2013, Ciccioli et al. 2014). Under real field conditions, highly volatile isoprenoids are emitted as leaves are exposed to high temperatures (Fares et al. 2017).

As expected, characterization of the flammability of the studied species revealed significant differences between fresh and dried fuels (Table 1), and differences between species were detected for the same range of FMC (Madrigal et al. 2013). Weise et al. (2005) also observed differences in peak heat release rate and time to ignition in a cone calorimeter with intact green and oven-dried samples of foliage and branches

Table 2 Correlation matrix (Pearson non-parametric correlation) for analysed variables (*90% significance, **95% significance). Data (N = 10) correspond to 10 studied species (*Pinus halepensis*, *Quercus ilex.*, *Quercus faginea*, *Quercus suber*, *Erica arborea*, *Arbutus unedo*, *Pistacia lentiscus*, *Calicotome spinosa*, *Juniperus oxycedrus* and *Tetraclinis articulata*)

	FMC	TTI	PHRR	AEHC	RMF
FMC	1.000	− 0.223	− 0.571*	− 0.787**	0.478
TTI		1.000	0.726**	0.624**	− 0.365
PHRR			1.000	0.866**	− 0.596*
AEHC				1.000	− 0.690**
RMF					1.000

FMC fuel moisture content, *TTI* time to ignition, *PHRR* peak heat release rate, *AEHC* average effective heat of combustion, *RMF* residual mass fraction

and attributed the difference to moisture content. The results obtained for *A. unedo* (Table 1) confirmed the effect of the moisture on some flammability parameters (FMC = 131%, TTI = 25.66 s, PHRR = 87.67 kW/m^2, AEHC = 4.07 KJ/kg, RMF = 3.6%). *Arbutus unedo* is rich in tannins, polyphenols and catechin gallate (Minker 2013), which will interact at moisture component level (Chetehouna et al. 2009). Jervis and Rein (2016) and McAllister et al. (2012) observed differences in the ignition behaviour of live fuels that cannot only be explained by moisture content. Jervis and Rein (2016) suggested that volatile compounds were lost on drying the fuels, which contributed to the very different ignition behaviour of live and dried fuel. McAllister et al. (2012) examined the variation in the chemical composition of the live fuel to help explain the discrepancies. By contrast, analysis of both fresh and dried fuels revealed *C. spinosa* (Table 1) to be the most flammable species (FMC = 53%, TTI = 61.66 s, PHRR = 204.25 kW/m^2, AEHC = 12.47 MJ/kg, RMF = 1.42%; FMC = 0%, TTI = 32 s, PHRR = 340 kW/m^2, AEHC = 12.54, RMF = 1.1%).

The K-means clustering (where TTI, PHRR, AEHC and MLR are the variables used to classify studied species) revealed the existence of three different groups. Custer analysis of fresh samples showed that the group including oak species and *A. unedo* presented low values of the four flammability parameters (cluster 1; Fig. 3a, b): high ignitability but low combustibility, sustainability and consumability. The FMC was significantly higher in *A. unedo* than in the other species studied. By contrast, the fuel moisture content of *Quercus* spp. is significantly lower than that of other more flammable species (e.g. *P. halepensis*). Despite being highly flammable (due to its high surface area-to-volume ratio -Valette 2007- and low FMC in leaves), *Quercus* spp. do not store VOCs (Peñuelas and Llusia 2003) and have been described as less flammable than conifers (Pausas et al. 2015). This group of species can be considered as intermediate between "non-flammable" and "hot-flammable" under the new evolutionary concept defined by Pausas et al. (2017). For fresh samples, the second cluster (cluster 2; Fig. 3a, b) shows that the most flammable group is formed by three species: *C. spinosa*, *T. articulata* and *J. oxycedrus*. Among Algerian species, *C. spinosa* is the most lignified, has the lowest biomass and is rich in flavonoids (Larit et al. 2012; Mebirouk-Boudechiche et al. 2014). The species *T. articulata* and common cypress (*Cupressus sempervirens* L.) showed great similarities. Both species, which are closely related, displayed high values of TTI (low ignitability) and also of PHRR and AEHC (Della Rocca et al. 2015; Ganteaume et al. 2013). *Juniperus oxycedrus* is recognized as a highly flammable species in the Mediterranean

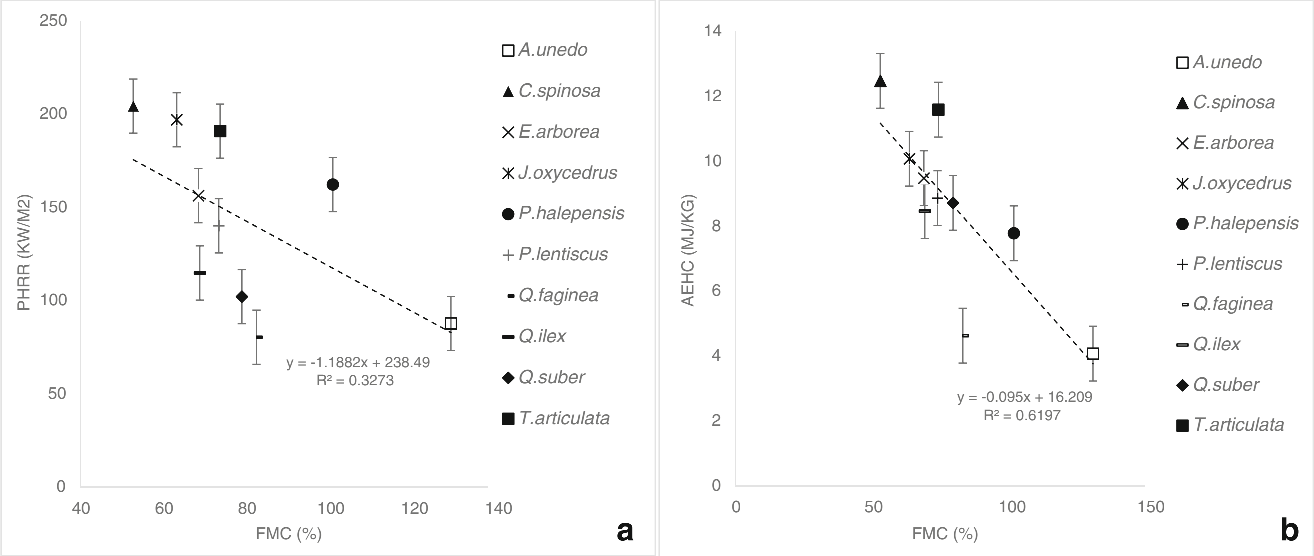

Fig. 2 Correlation between fuel moisture content (FMC, %). **a** Peak heat release rate (PHRR, kW/m^2). **b** Average effective heat of combustion (AEHC, MJ/kg). *Vertical bars* represent the standard errors for each flammability series of test

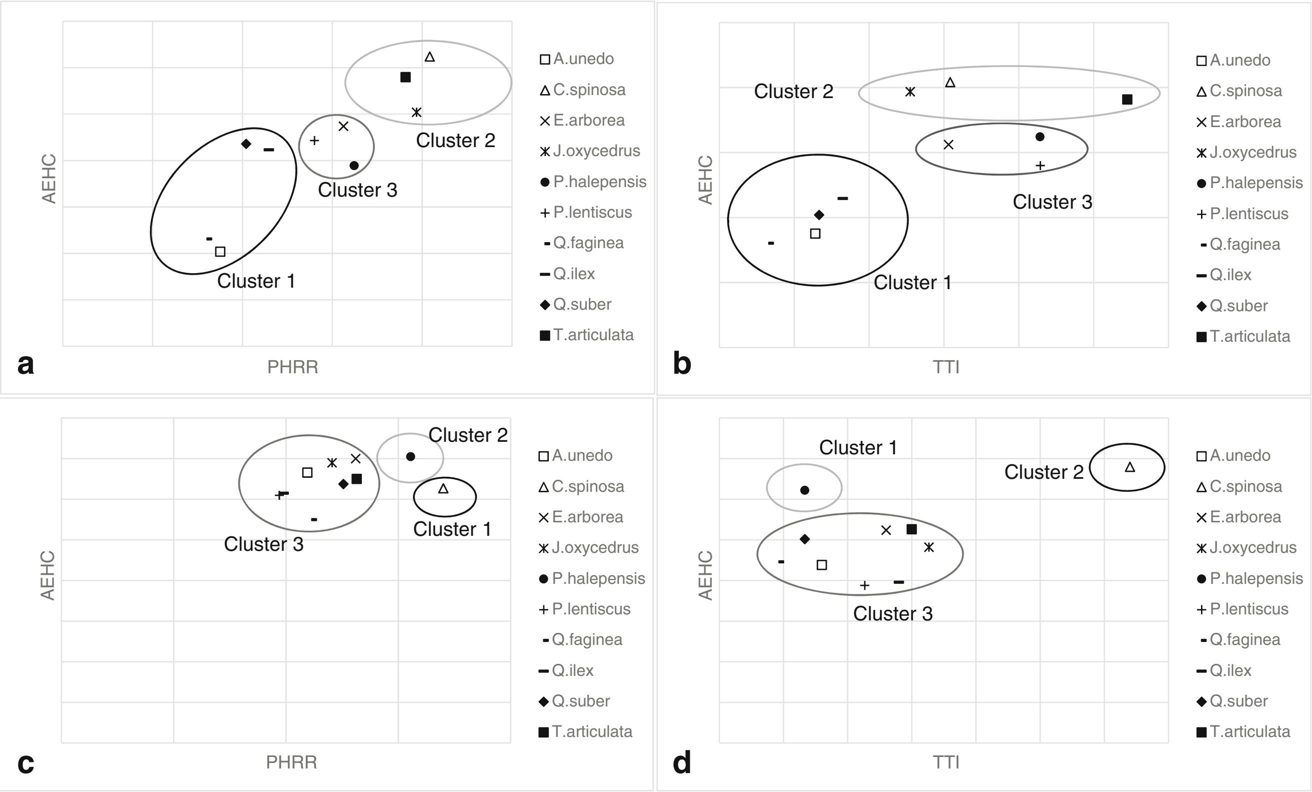

Fig. 3 Cluster analysis using K-means algorithm. **a**, **b** Fresh samples clustered by main flammability variables. **c**, **d** Oven-dried samples clustered by main flammability variables. *TTI* time to ignition (s), *PHRR* peak heat release rate (kW/m^2), *AEHC* average effective heat of combustion (MJ/kg)

region (Madrigal et al. 2011) because of its very high surface area-to-volume ratio and low FMC during the summer (Valette 1990; Elvira and Hernando 1989). In addition, *T. articulata* and *J. oxycedrus* both belong to the *Cupressaceae* fam., characterized by the accumulation of VOCs (Della Rocca et al. 2015). The other species (cluster 3; Fig. 3a, b) displayed moderate flammability (*P. halepensis*, *P. lentiscus* and *E. arborea*) corresponding to a high FMC for *P. halepensis* and a moderate FMC for *P. lentiscus* and *E. arborea* (Table 1). The species in clusters 2 and 3 (*J. oxycedrus*, *T. articulata*, *E. arborea*, *P. halepensis*, *P. lentiscus* and *C. spinosa*) are phenologically and physiologically very similar and can be considered "hot flammable" under the new evolutionary concept defined by Pausas et al. (2017). They are characterized by a very poorly lignified leaf, generally growing in southern areas on limestone and rocky ground. These results also confirm the significant effect of species on combustion (Madrigal et al. 2013) and the need to consider all variables for classifying the forest fuel flammability (Pausas et al. 2017), including the physical structure of components and physiological or cellular elements (Ciccioli et al. 2014).

The classification based on the K-means algorithm for dried fuels highlights *C. spinosa* (cluster 1; Fig. 3c, d) as the most flammable species, thus confirming the results for fresh fuels. The classification of dried fuels also shows that *P. halepensis* is more flammable than the other species (cluster 2; Fig. 3c, d). The resin and essential oil (terpenoids) contents of *P. halepensis* tend to be very high, making this species extremely flammable (Dimitrakopoulos et al. 2013). These compounds and other flammable VOCs are stored in leaves and emitted during combustion and pyrolysis processes, thus enhancing the flammability relative to other dried fuels (Ciccioli et al. 2014; Yashwanth et al. 2015a and b). Terpenoids are described as one of the main drivers of combustion of vegetation during wildfires (Chetehouna et al. 2009, 2014). The present findings confirm this effect not only for fresh samples, but also for dried fuels (Ormeño et al. 2009). This appears consistent with other Mediterranean flammability classifications and rankings (Madrigal et al. 2011). The third cluster (cluster 3; Fig. 3c, d) comprising all other species, except *P. halepensis*, seems obvious. Most of these species have previously been studied and are classified as moderately flammable, except for *Q. suber and Q. ilex*, which are considered highly flammable (Papió and Trabaud 1990; Valette 1990; Elvira and Hernando 1989; Liodakis et al. 2008; Hachmi et al. 2011).

The K-means clustering highlighted flammable shrub species such as *C. spinosa* and *J. oxycedrus* and the high combustibility and sustainability of tree species such as *T. articulata* and *P. halepensis* ("hot flammable species" sensu Pausas et al. 2017).

The results of this study suggest that mixed forests of *Q. suber* with *P. halepensis* and/or *T. articulata* present a very significant risk to cork production in scenarios with increased fire occurrence (Bouhraoua 2003). In addition, the high flammability of *C. spinosa* (both fresh and dried samples) suggests the need to prioritize fuel management of this species in order to increase the resistance of cork oak ecosystems to fire. Clearing this species from areas around cork oak trees could greatly reduce the probability of lethal temperatures being reached in living tissues during wildfires (Dehane et al. 2015), thus increasing the probability of the species surviving after fire and of the cork regenerating (Pausas et al. 2009). Proposed classification of some companion species of cork oak forest could potentially be used as predictors of the actual risk of fire in these stands. A recent proposal (Molina et al. 2017) shows that flammability rankings can improve fire risk indexes. As well Fares et al. (2017) stated that the use of flammability classifications, including the natural dynamics of live fuels, might enhance fire risk indexes in the Mediterranean region. The new flammability evolutionary concept proposed by Pausas et al. (2017) opens the possibility to study potential links between biology, physiology and flammability (Schwilk 2015) to improve flammability classifications.

5 Conclusions

The high flammability of species is described for the Mediterranean-type climate ecosystems and is recognized as a fire adaptive trait. The study findings highlight those species whose presence could potentially increase the vulnerability of cork oak forests and cork production to forest fires. Results suggest the need of fuel management in order to reduce the presence of some high flammable companion species such as *Calicotome spinosa*.

The proposed methodology could be a first step to develop new metrics to characterize the main flammability parameters that link fire traits and flammability (Schwilk 2015, Pausas et al. 2017).

The results also indicate the need for future research to clarify important points such as the interaction between FMC in both fresh and dried fuels, volatile compounds and radiant heat flux. This would facilitate fire risk mapping, mainly in already managed forests with known ecological association units and plant flammability strategies.

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