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Flammability of Some Ornamental Species in Wildland–Urban Interfaces in Southeastern France: Laboratory Assessment at Particle Level

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Abstract Assessment of the flammability of ornamental vegetation (particularly hedges) planted around houses is necessary in light of the increasing urbanization of the wildland–urban interfaces (WUIs) and the high fire occurrence in such areas. The structure and flammability of seven of the species most frequently planted as hedges in Provence (southeastern France) were studied at particle level. Spatial repartition of the different types of fuel particles within plants was assessed by means of the cube method. The leaf flammability was assessed using an epiradiator as a burning device, and measurements of foliar physical characteristics and gross heat of combustion (GHC) helped to explain the results of burning experiments. Co-inertia analysis revealed that species with thin leaves were quick to ignite (*Pyracantha coccinea, Phyllostachys sp.*) and species with high leaf GHC burned the longest (*Pittosporum tobira, Nerium oleander*). Species presenting high ignitability (*Photinia fraseri*, *Phyllostachys sp.* and *Pyracantha coccinea*) were characterized by high foliar surface area-to-volume ratio, and species presenting lower ignitability were characterized by high GHC (*Pittosporum tobira, Nerium oleander, Cupressus sempervirens*). Hierarchical cluster analysis of the flammability variables (ignition frequency, time-to-ignition and flaming duration) categorized the relative flammability of the seven species (including dead *Cupressus sempervirens*) in five clusters of species from poorly flammable (*Pittosporum tobira)* to extremely flammable (dead *Cupressus sempervirens*).This study provides useful information for reducing fire risk in WUIs in the study area.

Keywords Ornamental vegetation · Flammability parameters · Plant particles · Fire hazard · Wildland–urban interface

Introduction

Around the world, concerns about the impact of wildland fires are increasingly focusing on the wildland–urban interface (WUI), where their occurrence is high and where they can affect people and structures (Etlinger and Beall 2004). Fires in WUIs regularly destroy dwellings when fuel and weather are conducive to fire (Covington 2000), and human-caused fire ignitions are most common in these areas (Cardille and others 2001; Jappiot and others 2001; Lampin and others 2006a, b). As a result, WUIs are now considered as priority areas for controlling wildfire (Stephens 2005). In the Mediterranean region, the incidence of fire is often higher in WUIs and in wildland/network interfaces because of high urban pressure and accumulation of wildland biomass (Davis 1990; Vélez 1997; Cohen 2000; Leone and others 2003; de la Riva and Pérez-Cabello 2005; de la Riva and others 2006; Jappiot and others 2007; Lampin-Maillet 2009). Furthermore, the higher incidence of extreme climate events (very high summer temperatures, strong winds and drought periods) expected under climate change, together with the high flammability of Mediterranean fuels, implies higher probability of ignition (Valette 1990; Dimitrakopoulos and Papaioannou 2001).

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The presence of ornamental vegetation around houses is one of the major concerns regarding the vulnerability of structures as this vegetation can act as “ladder fuel” and ignite houses and other structures (Etlinger and Beall 2004). Therefore, less flammable species are recommended as ornamental plants (Monroe and others 2003). According to Dimitrakopoulos (2001) and Dimitrakopoulos and Papaioannou (2001), classification of fuel in relation to its expected flammability is an essential component of fire hazard assessment. Homeowners in WUIs are often advised to minimize or eliminate the use of highly flammable vegetation when landscaping their homes, and lists containing species that are appropriate for use in fire-wise landscaping are often requested. Reducing the fire hazard associated with vegetation can be accomplished by appropriate arrangement, maintenance and selection of species. However, Lubin and Shelly (1997) highlighted many discrepancies in the recommendations for plant selection by species, which often relied on anecdotal information with little scientific basis, largely because of the scarcity of scientific data on the flammability of ornamental vegetation. Nonetheless, there is an increasing demand from forest managers, fire managers and firefighters for scientifically based information about ornamental species for use in WUIs.

Although losses of WUI vegetation and structures are substantial and are increasingly common, studies on fire performance of ornamental plants, performed mainly in USA (White and others 1996; Irby and others 2000; Beall 2001; White and others 2002; Monroe and others 2003; Etlinger and Beall 2004; Weise and others 2005), have not been carried out in Europe. Some of the early studies sought to identify slow-burning plants that could survive in southern California, for example plants with high mineral content that could act as fire-retardant plants (Ching and Stewart 1962) and plant species with low fuel volume (Nord and Green 1977). More recent studies (Etlinger 2000; Etlinger and Beall 2004) have focused on the relationship between plant characteristics and flammability components as defined by Anderson (1970) and Martin and others (1994).

Plant flammability has been widely studied and experimentally assessed in the laboratory for various purposes, following several methods which took into account many different definitions and flammability parameters. Moreover, methods which allowed the assessment of vegetation flammability and the results obtained differed depending on the scale considered (Etlinger and Beall 2004; Madrigal and others 2012). However, the combination of different methods for assessing the flammability parameters of ornamental vegetation as well as the description of its structure has not been studied yet.

In WUIs, two types of fire ignition can occur regarding ornamental vegetation: (i) ignition of the vegetation directly subjected to the intensity of the flame front, as assessed in the present study (flammability at particle level) and (ii) in case of spot fire, ignition of the litter (ignition of dead surface fuel) by a glowing firebrand that lands at the foot of the plant. The flammability of dead surface fuels, that is litter, that could be ignited during a spot fire, has been assessed in a previous study (Ganteaume and others 2012).

The objective of this work was to compare the potential flammability of some ornamental plants that could be used as hedges for instance in Provence (SE France), taking into account the plant structure, some variables of flammability and the gross heat of combustion (GHC) of fine particles. According to the classical definition (Anderson 1970), flammability was considered as the result of ignitability (time until ignition), combustibility (rapidity of the combustion after ignition) and sustainability (ability to sustain combustion once ignited). Therefore, live leaf flammability was assessed by determining time-to-ignition (TTI), flaming duration (FD) and ignition frequency (IF).

Materials and Methods

Study Area and Selection of Species

Bouches du Rhône is one of the French “départements” which is located in eastern Provence (Fig. 1) and is one of the areas most seriously affected by wildfires in SE France (forest fire database Prométhée, www.promethee.com). The climatic conditions differ in the coastal fringe and in the inland part of the département (Météo France database, www.meteofrance.com); thus, the species planted as hedges will also differ depending on the location. Therefore, the study area was divided into two sub-areas (coastal and inland) for the purposes of sampling. To identify the main species used as ornamental vegetation, a survey of hedges was made in nine locations in both areas, taking into account a total of 117 hedges in four coastal locations and 110 hedges in five inland locations (Fig. 1).

A total of 20 species were recorded during the survey and were considered representative of the species planted in the whole study area. Seven of these species were chosen for the present study, either because they were the most frequent species planted as hedges (*Prunus laurocerasus*, *Pyracantha coccinea*, *Cupressus sempervirens*, *Nerium oleander, Photinia fraseri* and *Pittosporum tobira*) or because of their singularity, like *Phyllostachys sp.*, a type of bamboo, which may have particular flammability characteristics.

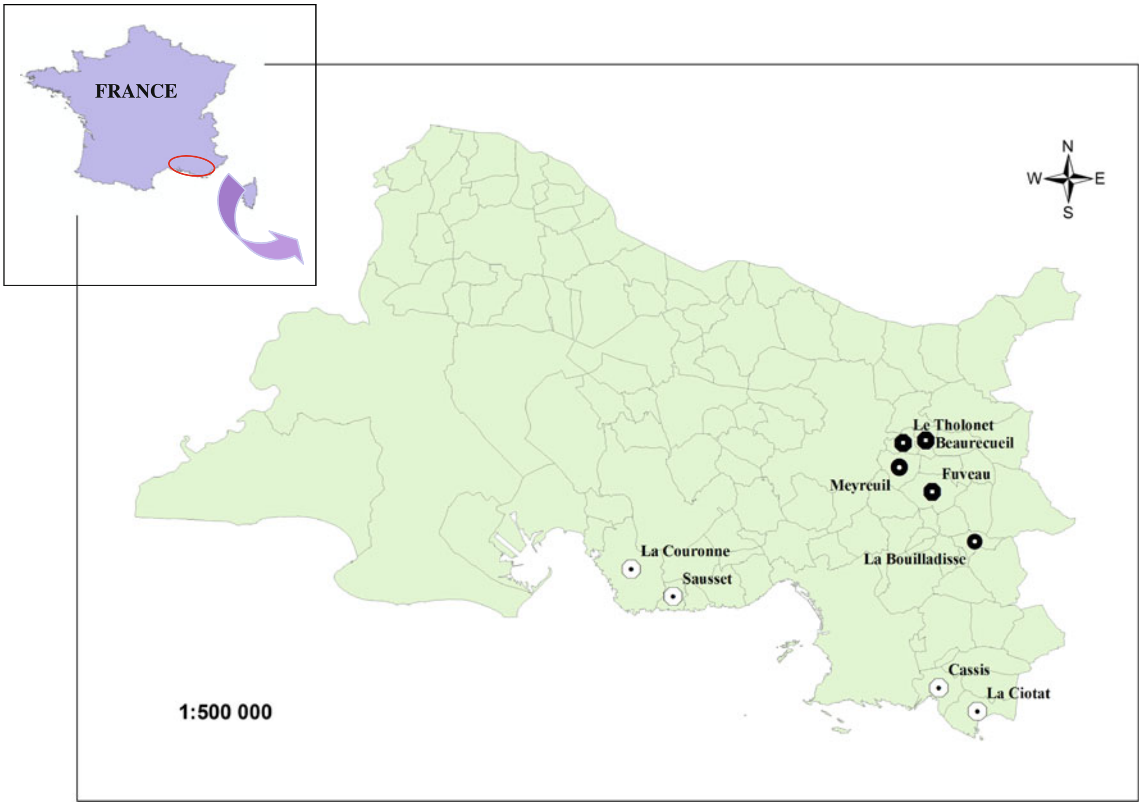

Fig. 1 Map of the study area (Département des Bouches du Rhône) in southeastern France showing where the hedges were surveyed (Source BD Carto. *Blue spots* coastal area, *red spots* inland area)

Field Samplings

The species were sampled in summer (between July and August 2011) during the fire season, when the fuel moisture content (FMC) is lowest and the fire risk is highest.

Fuel Sampling at Particle Level

The sampling of particles (mainly leaves and twigs) was performed according to the "cube method" (Cohen and others 2002). This method allowed us to determine the structure of the plant (proportion and spatial distribution of live and dead fuel particles of different sizes within the plant canopy) by use of a 0.008 m^3 cube (20 × 20 × 20 cm). The cube was placed on the plant, at breast height, at the base, the center and the top of the plant, and the biomass filling the cube was sampled (Fig. 2). For each species, the sampling was replicated in three different plants in the hedge.

Sampling of Leaves for Flammability Experiments

To characterize the flammability of the live fuel according to the protocol proposed by Valette (1990), the leaves of each species were sampled homogeneously, and only leaves of the same age and size were collected. Because of the high proportion of dead fuel sampled within the canopy of *Cupressus sempervirens*, dead leaves were also sampled for this species. To ensure that the FMC was minimal, in order to be in the worst-case scenario in terms of fire risk, each species was sampled in summer at the hottest time of the day (between 12 am and 2 pm) and the sampling was not carried out on days following rainfall events (Valette 1990). The leaves sampled were placed in plastic bags and stored in a cool box for transportation to the laboratory, minimizing changes in water content.

Before burning, the physical characteristics of the live leaves of the different species (mass, surface, volume and surface-to-volume ratio) were measured because of the importance of particle geometry in determining the combustion of fuel particles. To characterize the leaf surface exposed to hot gases and fire during combustion, leaf thickness was measured avoiding thick veins. Leaf surface area was measured using a 2400-dpi scanner and image analysis software. Particle thickness was measured using a 10^{-4} m accuracy micrometer.

Description of Laboratory Protocols

Sorting of Particles Sampled by the "cube method"

In the laboratory, the samples were oven-dried (48 h at 60 °C) until the dry weight did not change (FMC <5 %);

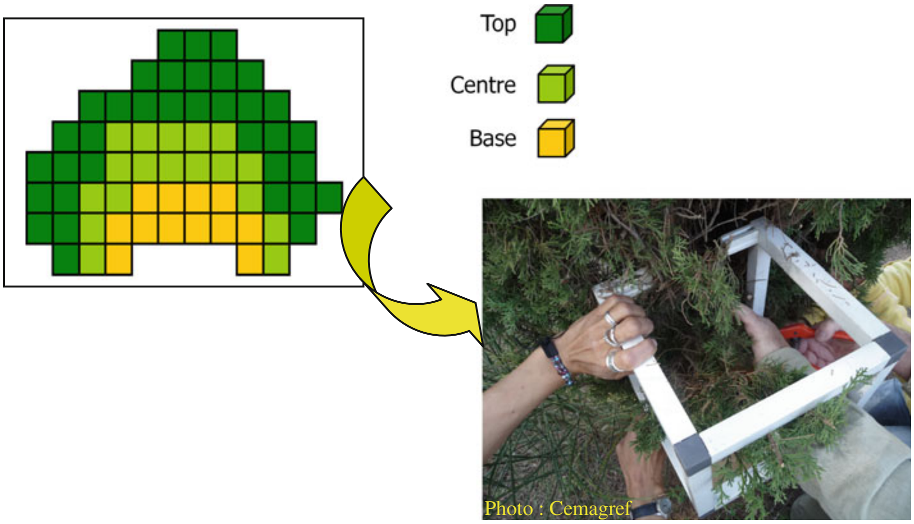

Fig. 2 Shape of the plant designed by three locations of cube (*top*, *center* and *base*) and biomass sampling in a Cypress "*top*" cube

then, the particles were sorted into four classes and weighed: (i) leaves, (ii) particles <2 mm in diameter, (iii) particles 2–6 mm and (iv) particles >6 mm. Particles were mainly composed of twigs and fractions of fruits. Very fine fuel was composed of leaves and particles <2 mm, and fine fuel was composed of leaves and particles up to 6 mm in diameter. Dead particles that may affect the flammability were separated from live particles in order to have available both proportions within a species. Bulk density was calculated as the dry weight of particles divided by the volume of the cube and expressed in kg m^{-3}. Bulk density was used to refer to the amount of fuel in a volume of airspace, for each class of particle, each cube location and each species.

Flammability Experiments with the Epiradiator

The epiradiator device consisted of a 500-W electric radiator with a 10-cm-diameter radiant disk. The surface temperature achieved with the device at steady-state regime was 420 °C (Fig. 3). Fifty samples (each weighing 1 g) of live leaves of each species studied (and dead leaves of *Cupressus sempervirens*) were exposed to the heat source (Valette 1990). Use of larger fuel masses may increase the possibility that other fuel properties, such as fuel height on the epiradiator, would cause differences in flammability (Hernando 2000; Petriccione and others 2006; Pellizzaro and others 2007). The samples were in direct contact with the electric radiator, and the surface area of contact depended on the species. The surface in contact with the epiradiator was assumed to be close enough to the heat source to undergo homogeneous heat transfer effects. A pilot flame, which did not take part in decay of the sample, was located 4 cm above the center of the disk and allowed more regular ignition of the gases emitted during combustion of the leaf. The device was placed under a hood to prevent air currents perturbing the convection column and gas plumes. Once the leaf samples were placed on the electric radiator, TTI and flame extinction were recorded to enable calculation of the FD of the sample. The IF was calculated as the percentage of tests in which the samples ignited. Each species was classified according to its IF and its mean TTI following the classification outlined by Valette (1990) which combined IF ranging from <50 % to >95 % and time-to-ignition ranging from <12.5 s to >32.5 s and then rated the species from 0 to 5 (0 = slightly flammable; 1 = weakly flammable; 2 = moderately flammable; 3 = flammable; 4 = highly flammable; 5 = extremely flammable).

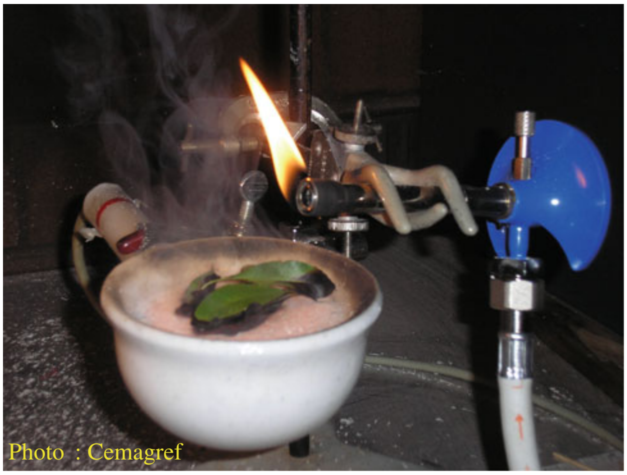

Fig. 3 Epiradiator used in the flammability experiments

Before the experiments, a 5-g sample (fresh weight) of each species was oven-dried for 24 h at 60 °C to enable calculation of the FMC according to the following equation:

$$\mathrm{FMC}\ (\%) = (\text{Fresh weight (g)} - -\text{Dry weight (g)}) / \text{Dry weight (g)} * 100$$

Gross Heat of Combustion of Very Fine Fuel

GHC of the very fine live fuel[1] (composite samples of leaves and particles <2 mm in diameter formed from all cubes collected within a species) was determined following Spanish Standard UNE 164001 EX (Asociación Española de Normalización y Certificación 2005). All fuel samples were ground individually to 5.10^{-4} m in a mill. A hand press was used to make the ground material into 1-g pellets, which were then oven-dried at 100 ± 5 °C for 24 h and weighed. Measurements were taken with an IKA®C5000 adiabatic bomb calorimeter with a platinum resistance sensor (PT-100). Both mill and hand press were also manufactured by IKA®. For each type of particle, the same measurements were taken on two samples. A third sample was included whenever the difference between the first two values was more than 2 % of the mean value.

Data Analyses

The effects of the species and of the cube location (sampled at the base, center or top of the plant) on the proportions of the different classes of particle and on the flammability variables (TTI, FD, IF) were analyzed by two-way and one-way (when nonparametric tests were used) analyses of variance (ANOVA). In addition to the tests of overall significance with ANOVA, the LSD test was used to check for significant differences between the different means. A significant difference between the variables was assumed when the P value was ≤ 0.05. Some of the variables were previously log-transformed to meet ANOVA assumptions of normality and homoscedasticity. In all cases, when the data distribution did not follow the expected parametric pattern or when a test condition provided insufficient data, a nonparametric Kruskal–Wallis test was used instead of a parametric Fisher's test. All species and cube locations were tested at random as well as their interaction. During the experiments, the mean relative temperature was 23.6 °C and mean relative humidity was 52 %, but these variables did not affect flammability (Fisher's LSD test, $P > 0.05$). All analyses were performed using Statgraphics Centurion XV.

Co-inertia analysis (Dolédec and Chessel 1994), suited to large number of variables compared with small number of samples, was performed on the dependent variables (flammability variables) and on the explanatory variables (leaf traits and leaf GHC) to examine associations between leaf characteristics and leaf flammability. The complete matrix of data was transferred to the statistical package under R 2.5.1 (R Development Core Team 2005) then analyzed using the ADE-4 package (Thioulouse and others 1997). Co-inertia is a statistical method commonly used to analyze the relationship between species and environmental variables (e.g., Moretti and Legg 2009). The first step of the co-inertia analysis (Ter Braak and Schaffers 2004) was to conduct a correspondence analysis (CA) on the leaf characteristics, then a principal component analysis (PCA) on the flammability variables. A factorial plane was thus created and enabled a new ordination of each data set. The statistical significance of each effect or combination of effects has been tested using a Monte Carlo permutation test with 1000 permutations using the 'coin' package on R. High sums of eigen values on the main axes indicate high correlation among datasets. Hierarchical cluster analysis of the flammability variables was performed to rank the seven species (including dead *Cupressus sempervirens*) according to their flammability. These multivariate analyses were performed with R software (R 2.11-1, ADE-4 1.5-1 package).

Results

Cube Method

The bulk densities of the most flammable classes of particles (leaves and particles <2 mm) sampled in each cube location for the seven species studied are shown in Table 1. Regarding live particles, the highest bulk densities were located in the top and center cubes. *Cupressus sempervirens* and *Prunus laurocerasus* presented the highest values (7.87 and 6.31 $\mathrm{kgm^{-3}}$ in total, respectively) contrary to *Pyracantha coccinea* and *Phyllostachys sp.* (0.96 and 0.93 $\mathrm{kgm^{-3}}$ in total, respectively). Regarding dead particles, *Cupressus sempervirens* presented huge amount of dead leaves, especially located in base cubes (10.36 $\mathrm{kgm^{-3}}$ for a total of 11.12 $\mathrm{kgm^{-3}}$). There was no dead fuel in the cubes sampled in *Nerium oleander, Photinia fraseri* and *Phyllostachys sp.*; bulk densities of dead particles were very low in the other species (<0.15 $\mathrm{kgm^{-3}}$ in total).

The species and the cube location significantly affected the proportions of live leaves, particles <2 mm and >6 mm; the proportion of 2–6 mm particles was only affected by the species. When it was significant, the cube location was the most important factor (two-way ANOVA, Table 2). Regarding live fuel, the proportion of leaves in *Pyracantha coccinea* was significantly lower than that in the other species, but the proportion of 2–6 mm particles was the highest in this species. The proportion of particles <2 mm in *Phyllostachys sp.* was significantly higher than that in the other species. The proportion of particles >6 mm was significantly higher in *Prunus laurocerasus*

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[1] The GHC of the very fine dead fuel was also measured for *Cupressus sempervirens* because of the high fraction of dead fuel recorded in this species.

Table 1 Bulk density (kg m^{-3}) of the very fine particles (leaves and particles <2 mm) in each cube location in the seven species studied

	LIVE			DEAD		
	Base	Center	Top	Base	Center	Top
Cupressus	0.44 (0.44)	3.72 (2.64)	3.71 (3.34)	10.36 (11.25)	0.70 (0.62)	0.053 (0.033)
Prunus	0.30 (0.36)	3.72 (1.26)	2.28 (2.42)	0.025	0.050	–
Nerium	0.80 (0.22)	0.82 (0.78)	2.51 (2.50)	–	–	–
Pittosporum	0.14 (0.11)	1.06 (0.69)	2.28 (2.42)	0.11 (0.11)	0.025	–
Pyracantha	0.18 (0.13)	0.19 (0.077)	0.59 (0.26)	0.012	0.037 (0.018)	–
Photinia	0.38 (0.54)	0.91 (0.93)	0.98 (0.62)	–	–	–
Phyllostachys	0.12 (0.098)	0.29 (0.11)	0.52 (0.24)	–	–	–

Mean (standard deviation)

Table 2 Results of the statistical analysis performed on the proportions of each class of particle compared across species and cube location (For the two-way ANOVAs, the <2 mm, 2–6 mm and >6 mm classes were transformed (log(x + 1) for <2 mm and >6 mm classes and square root (x) for 2–6 mm class

		Leaves	<2 mm	2–6 mm	>6 mm
Live particles	Species	F = 28.08, $P < 0.0001$	F = 35.04, $P < 0.0001$	F = 6.58, $P < 0.0001$	F = 5.85, $P = 0.0002$
Two-way ANOVA	Cube	F = 401.82, $P < 0.0001$	F = 42.41, $P < 0.0001$	*F = 3.19, P = 0.0512*	F = 52.61, $P < 0.0001$
	Interaction	F = 7.48, $P < 0.0001$	F = 4.26, $P = 0.0002$	F = 3.38, $P = 0.0017$	*F = 1.29, P = 0.26*
Dead particles	Species	KW = 46.29, $P < 0.0001$	KW = 25.02, $P = 0.0003$	KW = 20.89, $P = 0.0019$	KW = 15.66, $P = 0.015$
One-way ANOVA	Cube	KW = 1.46, $P = 0.48$	KW = 3.95, $P = 0.14$	KW = 8.54, $P = 0.014$	KW = 4.19, $P = 0.123$

Italic values refer not significant

and *Nerium oleander* than in *Phyllostachys sp*., *Cupressus sempervirens* and *Pyracantha coccinea* (Fig. 4). The proportions of leaves, particles <2 mm and >6 mm, significantly differed between the cube locations; top cubes presenting the highest proportions of leaves and particles <2 mm and base cubes the highest proportion of particles >6 mm. Center cubes presented higher proportion of 2–6 mm particles than the other location (Fig. 5). The proportions of live and dead particles that differed significantly between species are presented in Fig. 4, and the proportions of live and dead particles that differed significantly between cube locations are shown in Fig. 5. Regarding live fuel, the proportion of leaves was significantly higher in the top cubes, and regarding dead fuel, the proportion of very fine particles was significantly higher in the base cubes.

The interaction between the species and the cube location was significant in all the classes of particles except in the >6 mm class (two-way ANOVA, Table 2). Regarding live leaves, the effect of the cube location was not

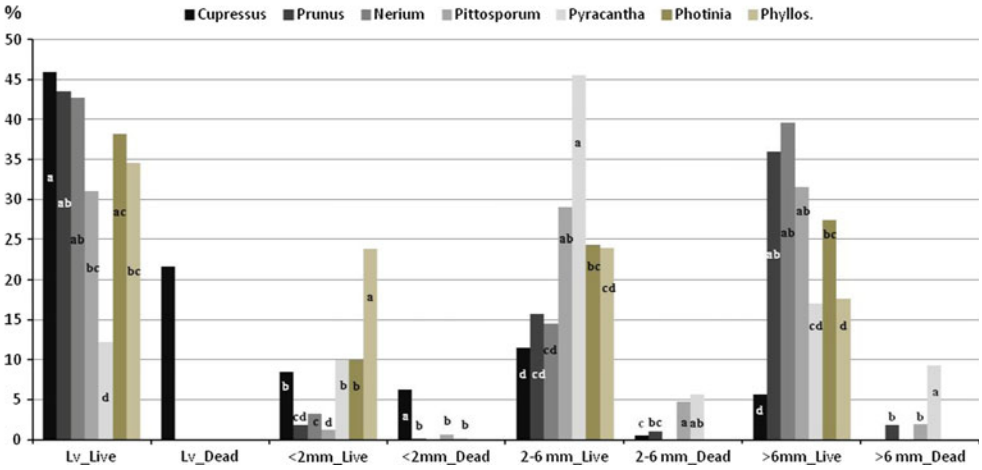

Fig. 4 Proportions of the different classes of particle in the seven species studied (Phyllo.: *Phyllostachys* sp.). *Different letters* on the *same bar* indicate significant differences according to two-way ANOVA Fisher's test for live particles and one-way ANOVA Kruskal–Wallis test for dead particles

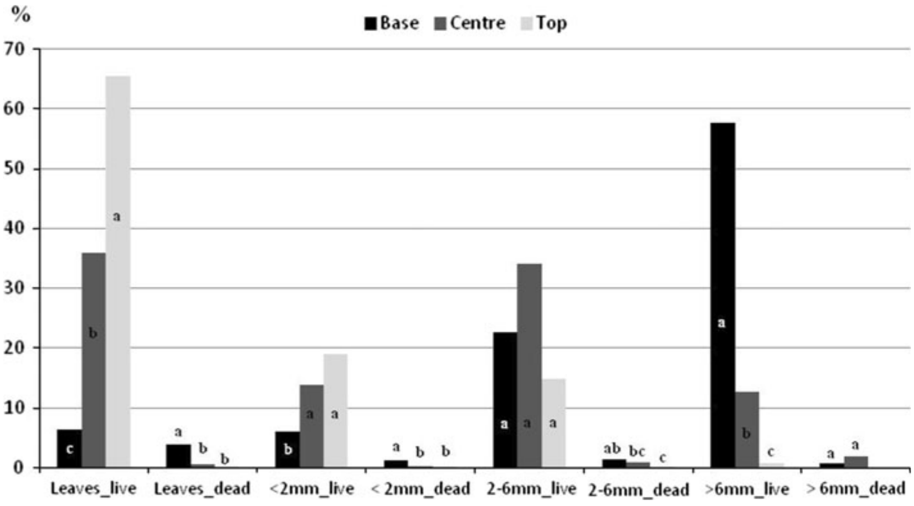

Fig. 5 Proportions of the different classes of particles in the three cube locations. *Different letters* on the *same bar* indicate significant difference according to two-way ANOVA Fisher's test for live particles and one-way ANOVA Kruskal–Wallis test for dead particles

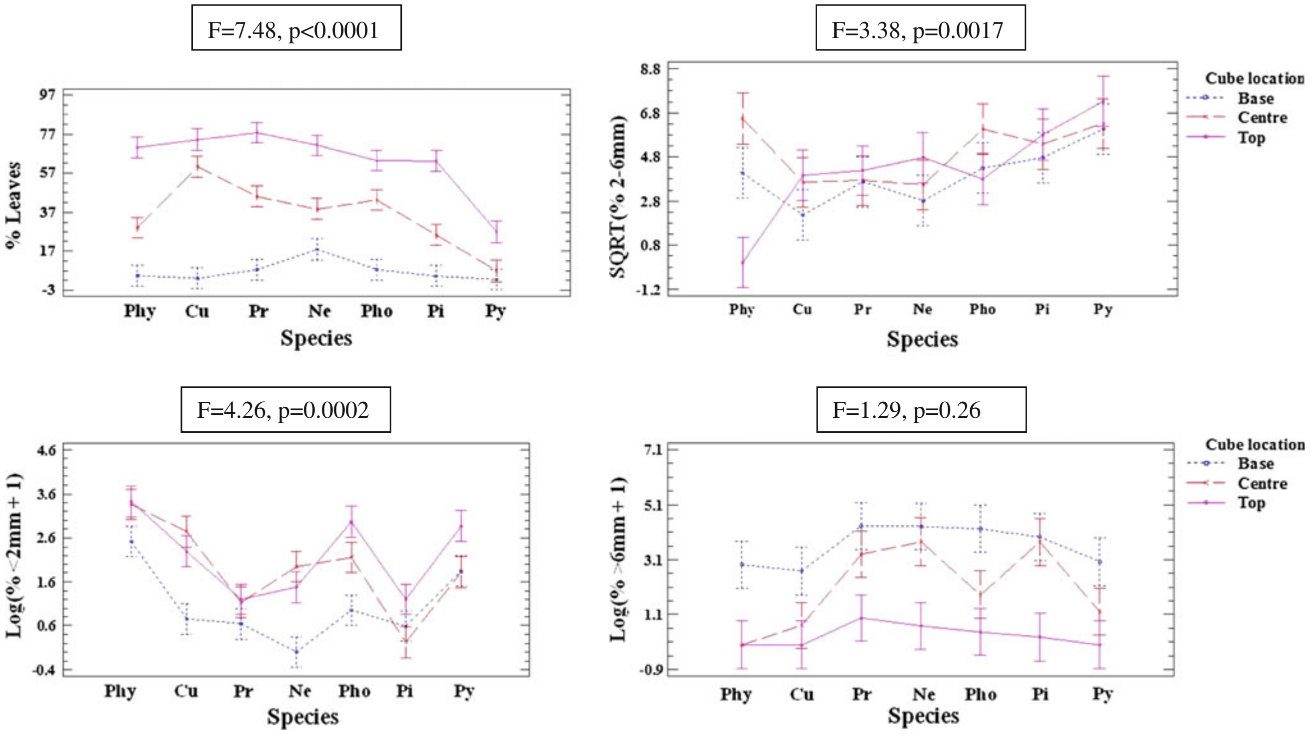

Fig. 6 Interactions and 95 % Fisher's LSD interval between cube location and species for the different classes of live particle (Phy: *Phyllostachys sp.*, *Cu*: *Cupressus sempervirens*, *Ne*: *Nerium oleander*, *Pho*: *Photinia fraseri*, *Pi*: *Pittosporum tobira*, *Pr*: *Prunus laurocerasus* and *Py*: *Pyracantha coccinea*)

significant for *Pyracantha coccinea* and *Cupressus sempervirens* and it was significant only for *Photinia fraseri* regarding the particles <2 mm. Regarding the 2–6 mm particles, the species significantly interacted with the top cubes only (Fig. 6).

The species had always a significant effect on the proportions of the different classes of dead particles, while the cube location significantly affected the proportion of 2–6 mm particles (one-way ANOVA, Table 2). Regarding dead fuel, cubes sampled in *Cupressus sempervirens* presented significantly higher proportions of very fine fuel (leaves and particles <2 mm) than the other species.

Flammability Experiments with the Epiradiator

The flammability experiments performed on the live leaves of the different species showed that *Phyllostachys sp.* and *Photinia fraseri* were the most flammable species (short time-to-ignition, high IF and FD), while *Pittosporum tobira* was the least flammable species (long time-to-ignition and low IF) according to Valette's classification (1990). Results also showed that, regarding live leaves, *Cupressus sempervirens* was among the least flammable species despite its high IF (Table 3), but the dead leaves of this species were the most flammable particles (IF = 100 %, TTI <3 s and FD >15 s), regardless of the flammability variables and of the species. Because of this, data on dead leaves have not been taken into account in the ANOVAs.

Table 3 Leaf traits, flammability variables of live leaves and rating according to the classification of Valette (1990) for the species studied

Species	FMC (%)	Mass (g)	Contact surface area (cm^2)	Thickness (cm)	Volume (cm3)	Surface/Volume (cm^{-1})	N1	Ignition frequency (%)	N2	Time-to-ignition (s)	Flaming duration (s)	Rating
Cupressus sempervirens	150	0.42 (0.08)	6.9 (1.10)	0.093 (0.10)	0.51 (0.12)	13.82 (1.23)	50	94 (24)	47	35.55 (6.61)	6.51 (2.72)	1
C. sempervirens (dead)	6	0.23 (0.04)	6.0 (1.10)	0.075 (0.003)	0.35 (0.06)	16.94 (0.61)	50	100	50	2.58 (0.93)	15.52 (4.02)	5
Nerium oleander	213	0.96 (0.19)	23.4 (2.5)	0.044 (0.006)	1.03 (0.22)	23.36 (3.61)	50	86 (35)	42	23.67 (6.81)	8.14 (4.20)	2
Photinia fraseri	92	0.76 (0.20)	25.3 (2.4)	0.038 (0.002)	0.95 (0.13)	26.69 (1.71)	50	100	50	14.96 (2.09)	8.26 (3.13)	4
Phyllostachys sp.	117	0.094 (0.02)	10.6 (1.8)	0.027 (0.031)	0.28 (0.31)	37.89 (1.06)	50	96 (20)	48	10.71 (4.15)	8.75 (3.18)	5
Pittosporum tobira	178	0.43 (0.05)	13.2 (1.6)	0.032 (0.002)	0.43 (0.05)	31.09 (2.10)	50	46 (50)	23	29.56 (11.73)	8.96 (6.80)	0
Prunus laurocerasus	178	1.68 (0.27)	46.6 (7.5)	0.042 (0.003)	1.98 (0.41)	23.86 (1.73)	50	98 (14)	49	17.43 (4.27)	4.92 (2.04)	4
Pyracantha coccinea	108	0.069 (0.02)	4.3 (0.5)	0.016 (0.004)	0.07 (0.02)	64.81 (11.82)	50	88 (33)	44	15.86 (5.70)	7.11 (4.99)	3
Results of statistical tests								KW = 91.84, $P < 0.0001$		KW = 203.26, $P < 0.0001$	KW = 46.35, $P < 0.0001$	

Dead leaves of *Cupressus sempervirenswere* not taken into account in the statistical tests

Rating: *0* slightly flammable, *1* weakly flammable, *2* moderately flammable, *3* flammable, *4* highly flammable, *5* extremely flammable, *FMC* fuel moisture content, *N1* initial number of trials, *N2* number of trials with ignition

ANOVAs performed on the data recorded during these experiments showed that the species had a highly significant effect on flammability variables obtained with this experimental device, especially on time-to-ignition (Table 3). The IF of *Pittosporum tobira* leaves was significantly lower than that of leaves of the other species, while the IF of *Photinia fraseri* leaves was significantly higher than that of *Nerium oleander* and *Pyracantha coccinea* leaves. Furthermore, *Prunus laurocerasus* leaves ignited more frequently than those of *Nerium oleander*. The time-to-ignition was shorter for *Phyllostachys sp.* leaves than for the others, while *Cupressus sempervirens* leaves took the longest time to ignite. The time-to-ignition did not vary significantly between *Photinia fraseri* and *Pyracantha coccinea* or between *Prunus laurocerasus* and *Pyracantha coccinea*. *Prunus laurocerasus* and *Cupressus sempervirens* leaves burned significantly faster than those of the other species, but the FD of *Cupressus sempervirens* leaves was not significantly lower than that of *Pyracantha coccinea* leaves.

Gross Heat of Combustion

The GHC of very fine fuels (measured by calorimetry) was the highest in *Nerium oleander* and *Photinia fraseri* leaves and the lowest in *Phyllostachys sp.* leaves (Table 5). The GHC of twigs <2 mm in diameter in this latter species was the highest and it was the lowest in *Prunus laurocerasus*. The species had a significant effect on GHC of twigs <2 mm in diameter, but not on GHC of leaves (Table 4). GHC of twigs <2 mm in diameter did not differ between *Nerium oleander* and both *Pittosporum tobira* and *Prunus laurocerasus*, nor between *Pittosporum tobira* and *Prunus laurocerasus* as well as between *Photinia fraseri* and *Pyracantha coccinea*.

Classification of species

The cloud plot extracted from the co-inertia analysis (Fig. 6) showed the position of the dependent variables (flammability variables) and of the explanatory variables (leaf traits and GHC). Axis 1 explained 58 % of variance and differentiated species presenting high ignitability (*Photinia fraseri*, *Phyllostachys sp.* and *Pyracantha coccinea*), characterized by high foliar surface area-to-volume

Table 4 Gross heat of combustion (GHC, in kJ kg^{-1}) of very fine fuels in the seven species studied

Species	GHC_Lv_live	GHC_2 mm_live	GHC_Lv_dead	GHC_2 mm_dead
Cupressus sempervirens	19,819	19,108	19,265	19,223
Nerium oleander	20,067	18,172	NA	NA
Photinia fraseri	20,031	18,859	NA	NA
Phyllostachys sp.	18,704	19,676	NA	NA
Pittosporum tobira	19,929	18,134	NA	NA
Prunus laurocerasus	18,797	18,084	NA	NA
Pyracantha coccinea	19,358	18,905	NA	NA
Results of statistical tests	KW = 12.57, P = 0.0503	KW = 13.93, *P* = 0.0303		

Italic values refer not significant

Lv leaves, *NA* no data

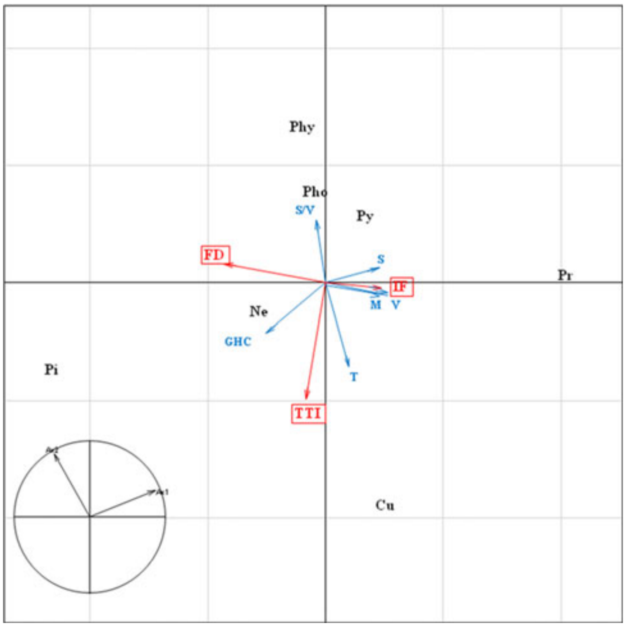

Fig. 7 Results of the co-inertia analysis performed on the leaf traits (*M* mass, *S* surface area, *V* volume, *S/V* surface area:volume ratio, *T* thickness) and gross heat content (*GHC*) values as explanatory variables and on the flammability variables (*TTI* time-to-ignition, *FD* flaming duration, *IF* ignition frequency) as dependent variables giving the position of species (*Phy*: *Phyllostachys sp.*, *Cu*: *Cupressus sempervirens*, *Ne*: *Nerium oleander*, *Pho*: *Photinia fraseri*, *Pi*: *Pittosporum tobira*, *Pr*: *Prunus laurocerasus* and *Py*: *Pyracantha coccinea*) on the co-inertia Factor 1 × Factor 2 plane

ratio, from species presenting lower ignitability, characterized by high GHC (*Pittosporum tobira, Nerium oleander, Cupressus sempervirens*). Axis 2 explained 42 % of variance and opposed species with short FD (*Cupressus sempervirens* and *Prunus laurocerasus*), characterized by thick leaves and low foliar surface area-to-volume ratio with species presenting higher sustainability and ignitability (*Photinia fraseri*, *Phyllostachys sp.*).

Hierarchical cluster analysis of the flammability variables (IF, time-to-ignition and FD) categorized the relative flammability of the seven species (including dead *Cupressus sempervirens*) in five clusters of species (Fig. 7): (i) poorly flammable (*Pittosporum tobira),* (ii) not very flammable (live *Cupressus sempervirens*), (iii) moderately flammable (*Pyracantha coccinea, Nerium oleander* and *Prunus laurocerasus*), (iv) highly flammable (*Photinia fraseri* and *Phyllostachys sp.*) and (v) extremely flammable (dead *Cupressus sempervirens*).

Discussion

In this work, plant flammability was assessed through the measurement of physical characteristics such as the bulk density or the proportion of each class of particle composing the plant canopy and through the measurement of the gross heat content of these particles as well as through the measurements of the flammability variables (IF, time-to-ignition and FD) when leaves of each species were burned.

Effects of Species on the Proportion of Particles and on Their Size

A two-way ANOVA was used to assess the effects of the cube location and of the species on the proportions of the different classes of particles. These proportions were significantly influenced by the species and, except for the 2–6 mm class, by the cube location. However, there is evidence of a significant interaction between the two factors, except for the class of particles >6 mm. Thus, it is worth noting that, when it was significant, the cube location had an effect that varied between the different species.

The sorting of the cubes sampled in the three locations of the plant canopy showed that the amount of live particles, which were mainly located at the periphery of the canopy (top and center cubes), was much greater than that of dead particles, which were located more in depth in the canopy (base cube). Live fuel was mainly composed of leaves and particles <2 mm in diameter contrary to dead fuel which was mainly composed of particles >6 mm in diameter except for *Cupressus sempervirens* samples in which dead leaves dominated. Retention of fine dead fuel within the plant structure has been observed in several Australian fire-prone species (Specht and others 1958; Moore and Keratis 1971; Dickinson and Kirkpatrick 1985), in the European gorse, *Ulex europeus* (Baeza and others 2006) or in the American chamise *Adenostoma fasciculatum* (Schwilk 2003), and fire performance is affected by the fraction of dead fuel because of its low water content (Elvira and Hernando 1989; Babrauskas 2003), which in ornamental vegetation is related to the age, health and maintenance of the plants. Thus, the great amount of dead leaves within the canopy of *Cupressus sempervirens* would confer high flammability to this species. Moreover, several studies have shown that fuel size affects the potential amount of fuel that would combust in a wildfire, with fine fuel being more flammable than coarse fuel (e.g., Bond and Van Wilgen 1996; Baeza and others 2002) because fine particles ignite more readily and release their heat more quickly than do thicker particles of an equivalent total weight (Wilson 1992). As the bulk density of branches and leaves determines the rate of oxygen flow through the fuels as well as the heat transfer between fuel elements (Scarff and Westoby 2006), flammability mainly depends on the physical arrangement of the plant biomass (Doran and others 2004). Thus, flammability would be high for hedges composed of species such as *Pyracantha coccinea* or *Phyllostachys sp* which are the species with the lowest bulk densities of particles. It is worth noting that, except for *C. sempervirens* and *P. coccinea*, the species with high proportion of a given class of particle were not the species with high bulk density of this class.

Effect of Species on Flammability of Leaves

Flammability of live leaves (and of dead leaves of *Cupressus sempervirens*) was assessed by epiradiator tests. Live leaves of species presenting the higher moisture content had longer time-to-ignition (*Nerium oleander, Pittosporum tobira* and *Prunus laurocerasus)* and those presenting the lowest moisture content were the most flammable (higher ignitability and sustainability), especially live leaves of *Photinia fraseri* and *Phyllostachys sp*. and dead leaves of *Cupressus sempervirens*. Currently, there is no work on the assessment of the flammability of ornamental species using such a burning device. Data analyses showed that the species significantly affected the different flammability variables, partly through their leaf moisture content. In addition to the burning experiments, it would have been interesting to perform analyses of the volatile organic compounds of the leaves. Indeed, Brown and others (1982) showed that the flammability of fine fuel from different species may differ because of differences in physical and chemical attributes. Contrary to Alessio and others (2008), Ormeño and others (2009), who used the same burning protocol as ours, showed that the species significantly affected FD but not time-to-ignition and that ignitability was favored by high terpene content in contrast to FD. Theses authors worked on litter beds which had lower FMC than live fuels entailing shorter time-to-ignition values (between 2 and 4 s) which were in the same range as those of dead leaves of *Cupressus sempervirens* recorded in the present work. This was also the case with the work of Pellizzaro and others (2007) who compared the flammability of twigs of different species whose moisture contents were lower than that of leaves. Nevertheless, regarding time-to-ignition of live leaves, our results were in the same range as those of Valette (1990) who also worked on live leaves using the same burning protocol.

According to Valette's classification, which takes into account IF and time-to-ignition, the different species were ranked from slightly flammable (*Pittosporum tobira*) to extremely flammable (*Phyllostachys sp.*); *Nerium oleander* and, surprisingly, live leaves of *Cupressus sempervirens* were not ranked as very flammable (Table 4), even if they are known to contain great amount of volatile oils. These results agreed with those of Etlinger and Beall (2004) who also found that *Nerium oleander* was not a very flammable species, and it could therefore be recommended for planting in WUIs. In the present study, *Cupressus sempervirens* displayed the longest time-to-ignition (among the species tested), contrary to the results reported by Liodakis and others (2002), who found that this latter species was one of the most flammable (of the species tested) according to its short ignition delay. This different result could be explained, as the ignition device used in these authors' work differed from that used in the present study. Our results also showed that FD was shortest for *Prunus laurocerasus* leaves and highest for *Pittosporum tobira* leaves what was difficult to explain through the leaf moisture content as both species presented high foliar moisture content. In this case, analyses of the foliar chemical content could have given more information for explaining this latter result as, according to Behm and others (2004), chemical components may play a role in the fire sustainability of a plant.

Effect of Species on Gross Heat of Combustion of Very Fine Particles

Data analysis showed that the species had a significant effect on GHC of particles <2 mm in diameter, but not on the GHC of leaves. According to the classification proposed by Elvira and Hernando (1989), the GHC values obtained for leaves of the species studied were generally "intermediate" (18,810–20,900 kJ kg^{-1}), whereas the GHC values of the particles <2 mm in diameter were either "low" (16,720–18,809 kJ kg^{-1}) (*Prunus laurocesarus*, *Nerium oleander* and *Pittosporum tobira*) or "intermediate" (*Cupressus sempervirens*, *Pyracantha coccinea*, *Photinia fraseri* and *Phyllostachys* sp.). For each species, except for *Phyllostachys* sp., the GHC was higher for leaves than for particles <2 mm in diameter. A similar trend was observed by Dimitrakopoulos (2001) and Nuñez-Regueira and others (1996) in Mediterranean species, and it was attributed to the fact that leaves constituted sites for accumulation of essential oils in plants. However, the GHC of the ornamental species tested in our work was generally lower than that of common Mediterranean forest fuels (Madrigal and others 2011). The heat of combustion of leaves of *Cupressus sempervirens* (19,548 kJ kg^{-1}) given by Liodakis and others (2002), who worked on this species as a wildland species, was lower than that of other Mediterranean species but of the same order as those obtained in the present study (19,108–19,820 kJ kg^{-1}).

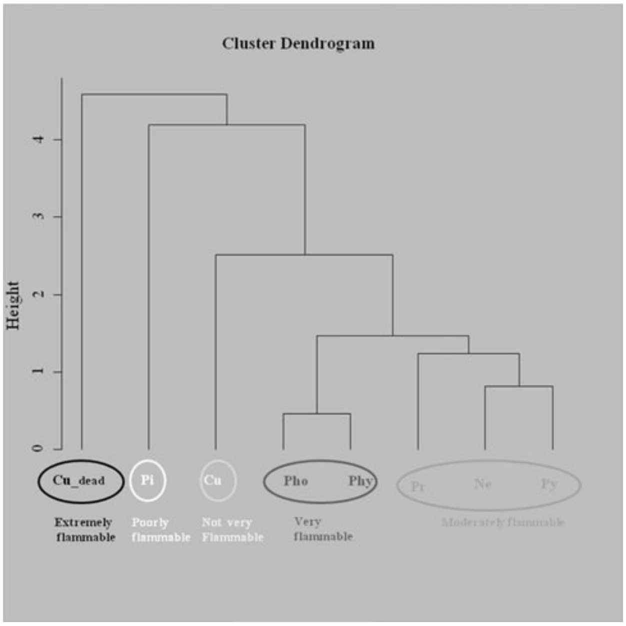

Fig. 8 Dendrogram of hierarchical cluster analysis based on the leaf flammability variables (time-to-ignition, flaming duration, ignition frequency) of the seven species studied (*Pi*: *Pittosporum tobira*, *Phy*: *Phyllostachys sp.*, *Ne*: *Nerium oleander*, *Cu*: *Cupressus sempervirens*, *Py*: *Pyracantha coccinea*, *Pho*: *Photinia fraseri*, *Pr*: *Prunus laurocerasus*)

Classification of Species

Co-inertia analysis revealed that species with thin leaves were quick to ignite (*Pyracantha coccinea, Phyllostachys sp.*) and species with high leaf GHC burned the longest (*Pittosporum tobira, Nerium oleander*). This result is consistent with the findings of Behm and others (2004), who reported species as highly consumable when they have high energy content. Usually, flammability characteristics mainly affected by either physical structure or physiological or cellular elements. From a physical perspective, foliage characteristics, especially the foliage mass, foliar moisture content and surface area-to-volume ratio of fuel particles are often considered significant factors in flammability (Fernandes and Rego 1998; Etlinger and Beall 2004). However, because we used a radiant disk (epiradiator) as burning device, foliar mass and volume should not be considered key variables for fire performance contrary to leaf surface area and thickness. Hierarchical classification revealed that *Pittosporum tobira* was the least flammable species according to the flammability variables (IF, time-to-ignition and FD). Dimitrakopoulos and Papaioannou (2001) ranked *Nerium oleander* as a low flammability species according to its time-to-ignition. In our experiment, this species also presented a long time-to-ignition but it was ranked as moderately flammable in the hierarchical analysis which combined its long time-to-ignition, intermediate IF and long FD.

In their fuel classification, Dimitrakopoulos and Papaioannou (2001) highlighted four clusters of species according to their ignitability as a function of their foliage adaptations to prevent water loss. Contrary to our results, these authors ranked *Cupressus sempervirens* in the cluster of flammable species because of its short time-to-ignition due to high foliar surface area-to-volume ratio which facilitates heat absorption. Moreover, for these authors, high flammability was linked to richness in flammable volatile essential oils, what was not the case in the present work as none of the highly flammable species (*Photinia fraseri* or *Phyllostachys sp.*) are known to be aromatic plant species. According to the classification system described by Valette (1990), which takes into account only IF and time-to-ignition of leaves, and according to the results of the hierarchical classification, live leaves of *Pittosporum tobira* and *Cupressus sempervirens* were the least flammable (respectively rated 0 and 1, Table 4 and Fig. 7), particularly because of their longer time-to-ignition. However, dead *C. sempervirens* was the most flammable, regarding both classifications. Thus, according to this last result, flammability within a species can strongly vary according to the type of fuel tested (dead or live). This is confirmed by the work of Ganteaume and others (2012) who assessed the flammability of the litters (dead surface fuels mainly composed of leaves) of the same ornamental species. These authors ranked litters of *Cupressus sempervirens* as moderately flammable (probably because of their high compaction), of *Prunus laurocerasus* as very flammable and of *Phyllostachys sp* as not very flammable, whereas they were ranked, respectively, as not very flammable, moderately flammable and very flammable in the current work Fig. 8.

Conclusion

In the present work, the flammability of seven ornamental species was assessed by their description at particle level and by the measurements of flammability variables during burning experiments on leaves. GHC and foliar physical characteristics helped to explain the flammability, and these species were ranked in five clusters according to the ignitability and sustainability of their leaves. *Pittosporum tobira*, ranked as poorly flammable species, can be considered a fire-wise species, while *Phyllostachys sp.* and *Photinia fraseri* ranked as highly flammable, should not be planted in WUI. Regarding the flammability of its live leaves, *Cupressus sempervirens* was not very flammable; however, because this species had the greatest amount of dead material which was ranked extremely flammable, this ornamental species should be avoided in WUI, especially close to the houses. Further experiments, especially burning experiments of whole plants, are needed to confirm the present results and to make them more widely applicable. Moreover, protocols for determining flammability must be standardized, and a common classification must be established for the test results as stated by several works (Weise and others 2005; White and Zipperer 2010).

Although laboratory experiments help improve our knowledge of the effects of live and dead fuel properties (species, moisture content and other physical and chemical characteristics) on flammability, the results obtained cannot be used directly to describe or predict the flammability of fuels under natural and real conditions; they represent basic information that is useful for assessing the fire risk of Mediterranean ornamental vegetation planted as hedges for instance. Moreover, White and Zipperer (2010) showed that flammability characteristics for a particular species were influenced not only by the species itself but also by their maintenance (watering, pruning, trimming, removing dead biomass, etc.) what could reduce the potential fire hazard. Indeed, routine irrigation, allowing the increase in FMC, has been shown to reduce plant flammability in wildland and WUIs (Narog and others 1991; Doran and others 2004), and pruning of dead wood decreases fire temperature and heat release (Schwilk 2003), indicating that plant flammability can be manipulated by horticultural practices.

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