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Flammability of litter sampled according to two different methods: comparison of results in laboratory experiments.

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Abstract.

In the laboratory, different types of litter samples (constructed *v.* intact) can be used in flammability experiments but the sampling method of these litters could affect litter flammability results. To assess this effect, samples of litters were collected in South-eastern France, according to two different methods previously used in other studies, one keeping intact the structure of the litter layers (non-constructed litter) and the other requiring the construction of the litter, using mainly the surface litter layer (constructed litter). The comparison of flammability results showed that the sampling method had a significant effect on litter bulk-density, rate of spread and rate of consumption, intact litter being more flammable than reconstructed litter that was artificially compacted. The type of vegetation had a significant effect on litter depth, ignitability, sustainability, consumability and combustibility (except on rate of spread) and the litter composition could explain in part this fire behaviour. The effect of the construction of litters on flammability parameters and its magnitude also differed according to vegetation types. Intact litter structure appeared to be an important driver of its flammability, especially of combustibility and consumability. The assessment of these flammability components will differ when using constructed litter samples instead of intact litter samples, especially according to vegetation types. Future research on litter flammability should take into account the bias due to the litter sampling method when the litter is constructed.

Additional keywords: litter composition, non-reconstructed litter, reconstructed litter.

1. Introduction

In Mediterranean-type regions, fires are a major disturbance for forest and shrubland ecosystems. Knowledge of fuels is a fundamental part of fire management, which is necessary to both conserve biodiversity and reduce the negative impact of wildland fires. Wildland fuel is any combustible material available for ignition and combustion, mainly live and dead organic matter. Surface fuels (such as litter) are crucial for the fire spread since they influence its transmission to the upper vegetation (Bradstock and Cohn 2002; Hogkinson 2002). Leaf litter is the primary component of the forest floor (Proksch *et al.* 1982; Petriccione *et al.* 2006) and the importance of this non-woody surface fuel in wildfire has been addressed in numerous studies in terms of the effects of its arrangement (Bradstock and Cohn 2002) and morphology (Scarff and Westoby 2006), for instance. Methods to assess and compare the flammability of litter vary (e.g. Valette 1990; Hernando-Lara 2000; Fonda 2001; Fonda and Varner 2004; Petriccione *et al.* 2006; Scarff and Westoby 2006; Ormeño *et al.* 2009; Pellizzaro *et al.* 2007; Engber and Varner 2012), some use different burning devices such as epi-radiators (for live fuel) or fire benches (for dead surface fuels).

Most of the time, constructed litter is used in flammability experiments (Fonda 2001; Fonda and Varner 2004; Scarff and Westoby 2006; Jappiot *et al.* 2007; Ormeño *et al.* 2009; Engber and Varner 2012), mostly calibrated (in term of biomass) samples of leaves of a given species (Fonda 2001; Kane *et al.* 2008; Petriccione *et al.* 2006), mixed litter beds of different species (Magalhães and Schwilk 2012) or masticated woody fuel beds (Kreye *et al.* 2011). Such works aimed at studying the litter flammability by testing the impact of different factors such as fuel moisture content (FMC), wind or bulk-density (Plucinski and Anderson 2008; Kreye *et al.* 2011), but also vegetation types (Fonda *et al.* 1998; Fonda 2001; Fonda and Varner 2004; Kane *et al.* 2008; Ganteaume *et al.* 2009a) or terpene content (Ormeño *et al.* 2009) on the flammability of a given species of leaf litter. There are very few works on the flammability of non-constructed (intact) litter which is hypothesized to represent the field conditions (in terms of structure, compactness, composition, etc.). Even if some authors worked in the field (Fernandes *et al.* 2008; Wenk *et al.* 2011; Ellair and Platt 2013), only very few worked with non-constructed litter samples

like Taylor and Fonda (1990) who, using Mutch's (1970) method, assessed the burning characteristics of reasonably intact litter samples mixing woody fuels with non-woody fuels. More recently, research using intact litter sampled in Southeastern France was carried out to assess the flammability of dead surface fuels keeping intact their structure and composition as in the field (Ganteaume *et al.* 2011; Curt *et al.* 2011) but the comparison of different sampling methods (constructed litter vs non-constructed litter) in terms of litter flammability results has never been made.

The aim of this research was to determine if differences existed between these sampling methods in terms of flammability results and to show how litter flammability was affected according to the type of sampling. As the type, size and proportions of the litter components affect flammability (Rothermel 1983; Ganteaume *et al.* 2011; Curt *et al.* 2011; Schwilk and Caprio 2011; Engber and Varner 2012), we also compared litter flammability according to the vegetation types. In other words, is the flammability of litter more influenced by its composition than by its structure?

2. Material and methods

2.1. Study sites

The study sites were located in Southeastern France (Provence) which is most affected by wildfires. The sampling sites were selected for their homogeneity in terms of physiographic conditions and a total of 28 study sites in Limestone Provence (Northwestern coordinates: 43.655°N, 5.495°E; Southeastern coordinates: 43.832°N, 5.672°E) and 21 sites in Acidic Provence (Southwestern coordinates: 43.177°N, 6.251°E; Northeastern coordinates: 43.374°N, 6.608°E) were selected between sea level and 486m elevation (this range of elevation covers most of the study area). In each site, live fuel and litter structure had been previously described (Ganteaume *et al.* 2009b; Schaffhauser *et al.* 2011) within a 400 m² georeferenced plot (20 m x 20 m). Litter was sampled in each one of these plots.

2.2. Vegetation types

Southeastern France includes a range of Mediterranean fire-prone ecosystems depending on the nature of the bedrock (alkaline or acidic) and the study sites were chosen according to the main fuel types of this study area. In the limestone region of Provence, *Pinus halepensis* (Aleppo pine) forest is one of the most frequently occurring vegetation types in forested areas (Quézel 2000) and mixed pine-holm oak/downy oak forests are often the pre-forest vegetation type before oak forests (Quézel and Médail 2003). In the acidic region of Provence, *Quercus suber* (cork oak) woodlands occupy the majority of the forested area, sometimes mixed with *Pinus pinaster* (maritime pine) and with *Q. pubescens* (downy oak) in mature stands. More than 100 000 hectares of the French Mediterranean region are occupied by shrublands either called “garrigue” on limestone-derived soils dominated by *Q. coccifera* (kermes oak) or “maquis” on acidic soils dominated by *Cistus monspelliensis* (Montpellier Cistus), *Calicotome spinosa* (thorny broom) or *Erica arborea* (tree heath). These vegetation types are representative of the sequences of post-fire succession on both types of soils and form a mosaic of vegetation in the landscape that is regularly reshaped by wildfires (Tatoni and Roche 1994).

Five vegetation types were selected in the sampling plan to account for the variability of the vegetation: (i) pure *Pinus halepensis* stands, (ii) mixed oak (*Quercus pubescens* or *Q. ilex*)-pine stands, (iii) mature *Quercus suber* stands, (iv) shrubland_garrigue and (v) shrubland_maquis (Tab. 1). Both types of shrubland differed in the shrub species and in the fuel structure. These vegetation types were chosen because they are also representative of the wildland fuel in the study area and constitute the dominant overstorey types found across the elevation range in which the sampling was carried out.

2.3. Sampling methods

The sampling occurred in the study plots already described (at levels of overstorey, understorey and surface fuels) by Ganteaume *et al.* (2009b) and Schaffhauser *et al.* (2011), in 49 study sites distributed throughout Provence between May and July 2006, 2007 and 2008 just before the main fire season and just after the peak of leaf/needle fall and before their decomposition, which occurs

in autumn–winter in the study area. To assess the impact of the sampling method on flammability, samples of litter were collected according to the sampling protocols already used in our previous works on constructed litter (Jappiot *et al.* 2007) and on intact (non-constructed) litter (Curt *et al.* 2011; Ganteaume *et al.* 2011). Intact litter samples were collected to avoid modifying the microstructure and bulk density of litters, which may affect their flammability (Plucinski and Anderson 2008). Both intact litter (taking into account all the litter layers and keeping intact the structure of litter layers, compactness and bulk-density) and constructed litter (sample constructed mainly using the top litter layers, disturbing its structure) were sampled, for each vegetation type, in the same study plot. The difference in sampling entailed that intact and constructed litters were different as the construction was not aimed at reproducing the intact litter. Thus, some litter parameters, such as mass load and bulk-density, differed from one type of sampling to the other one. This differed from other works carried out on constructed litters (Fonda *et al.* 1998; Fonda 2001; Kane *et al.* 2008; Ormeño *et al.* 2009) in which the litter samples were not compacted as they were not supposed to match field litter depth.

For the intact litter, we worked with three layers of organic soil. Starting from the surface, these were the L, F and the upper part of the layer H (Fig. 1) whereas the constructed litter was only composed of the organic soil layer L and of the upper part of the layer F (Fig. 1). It was important to clearly differentiate between fuel layers to understand the scope of this study and its ability to be compared to other studies. L-layer (literally, the litter layer) is the surface layer on the forest floor consisting of freshly fallen needles, leaves, bark and fruits, etc. (Brown *et al.* 1982). F- and H-layers are defined as the fermentation and humus layers in the forest floor, including logs that are more than half buried, but not counting the freshly cast organic matter of the litter layer

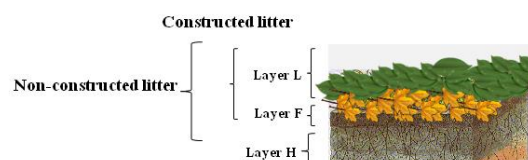


Fig. 1 : Description of the soil horizons collected during the litter sampling and sampling methods : constructed litter (A) and non-constructed litter (B)

Intact litter was sampled using an iron plate (40 x 40 cm) to cut all the litter layers without disturbing the litter structure (Fig.1A). Once cut, the sample of litter was carefully slipped from the iron plate into a cardboard box to protect it during transport to the laboratory. Four replicates were collected in each plot to account for the variability in litter depth (measured using a metallic ruler; see Ganteaume *et al.* 2009b). To approximate field conditions in terms of litter composition, the flammability of the whole forest floor was considered, including (i) plant material of variable sizes (leaf, needle, twig, cone scale, etc), (ii) different species, and also (iii) non-combustible particles. This type of sampling was an innovative method only previously used by Ganteaume *et al.* (2011) and Curt *et al.* (2011), improving the method of Taylor and Fonda (1990).

Constructed litter was sampled along a 20 m transect placed in the middle of each study plot according to the protocol used in Jappiot *et al.* (2007) in which a sub-sample of the upper litter (layer L and the upper part of layer F) was collected at 2-m intervals using a calibrated iron circle 0.2 m in diameter (Fig.1B). This procedure allowed us to take into account the variability within the plot. According to the protocol of Jappiot *et al.* (2007), one constructed litter sample of

0.11 m² surface area was formed from the ten subsamples collected per plot, with the same depth as the mean litter depth recorded in the plot during a previous fuel description. In the original protocol, the construction of litter was based on litter depth. To match this depth, the litter sample was artificially compacted and its depth was checked, using a metallic ruler, in five points spread over the sample before a fire was ignited. For the current study, even if other factors such as mass load would be easier to control, the same protocol was used as several works showed that depth had a significant influence on litter flammability and was also tightly related to bulk density (Ormeño *et al.* 2009; Ganteaume *et al.* 2011; Engber and Varner 2012).

A preliminary experiment was carried out in order to evaluate the relative effects of the construction of such litter samples, especially their compaction. For each vegetation type, litter samples were constructed following a gradient of compaction (litter depth ranging from 7 cm to 1 cm and bulk density ranging from 28 to 156 kgm⁻³) and burned according to our burning protocol.

2.4. Litter sorting

In order to test the effect of type and size of litter particles on litter flammability, one 50 g subsample of each litter sample was oven-dried and sorted in the laboratory to determine the proportions of the different litter components (Ganteaume *et al.* 2011; Curt *et al.* 2011). For sorting, eight classes of litter components were taken into account because of their specific flammability and of their abundance in the litter: (i) deciduous leaves (mainly large and lobed leaves of *Quercus pubescens*), (ii) evergreen leaves (mainly *Q. suber*, *Q. ilex*, *Q. coccifera* or *Cistus* leaves), (iii) needles, (iv) grass (mostly dead graminoids), (v) fine twigs and particles such as cone scales, bark, acorns, etc. (i.e. fine elements) and (vi) coarse twigs and particles (i.e. coarse elements), (vii) debris (defined here as unidentified plant material (it is worth noting that the class “debris”, corresponding to the organic soil layer H, was not found in the constructed litter samples, in which this layer was not collected) and (viii) non-combustible elements (stones, etc.). Twigs and particles were defined as fine when their thickness or diameter was less than 2 mm, and as coarse when these were more than 2 mm. For each sample, all the classes were weighed and their proportions were determined.

2.5. Sample preparation

As moisture content is known to be one of the most important factors to influence fire behaviour, litter samples, whose FMCs ranged between 3 and 8%, were oven-dried for 48 h at 60°C in the laboratory until the FMC value did not change (FMC < 2%). This protocol allowed us to control for different moisture retention capabilities of the different species composing the litter samples which would become a confounding factor in the analysis. This also allowed comparisons between all the burning experiments and was expected to mimic very low FMC predominating during periods of high fire risk in the study area. However, drying the samples entailed uniform moisture content throughout the litter profile that could differ from field conditions, in which there could be profile gradients (Matthews *et al.* 2007). The litter samples were quickly burned after drying to avoid any moisture content modifications.

The litter depth (cm) was recorded for each litter sample using a metallic ruler. The litter bulk-density (BD in kg m⁻³) was calculated for each sample by dividing the weight of the sample by the volume of sample litter (litter surface area multiplied by litter depth).

2.6. Burning experiments

Burning experiments took place under controlled laboratory conditions at the INRA Vignères facility (Avignon, France). They were conducted on a fire bench made of cellular concrete, on which the different litter samples were laid, forming round layers with a surface area of 0.11 m². This size allowed sufficient fire development to indicate sustainable ignition and the 0.19 m distance (radius of the sample), from the ignition point to one side of the sample was expected to allow sufficient fire spread to demonstrate flame sustainability (Plucinski and Anderson 2008) as we aimed at simulating the effects of a surface fire on heterogeneous litter. The fire bench (Fig. 2A) was placed on a scale (sensitivity 1 g) to measure weight loss during burning. Two vertical rulers calibrated in centimetres were placed on each side of the bench to enable visual assessment of flame height during the tests. A set of seven previously calibrated chromel-alumel thermocouples (thermocouple type k, 30µ in diameter) were positioned at each side (Fig. 2B) and

in the middle of the sample at three different heights (10 cm, 20 cm and 40 cm; Fig. 2A). They were connected to a computer to record variation in temperature during burning.

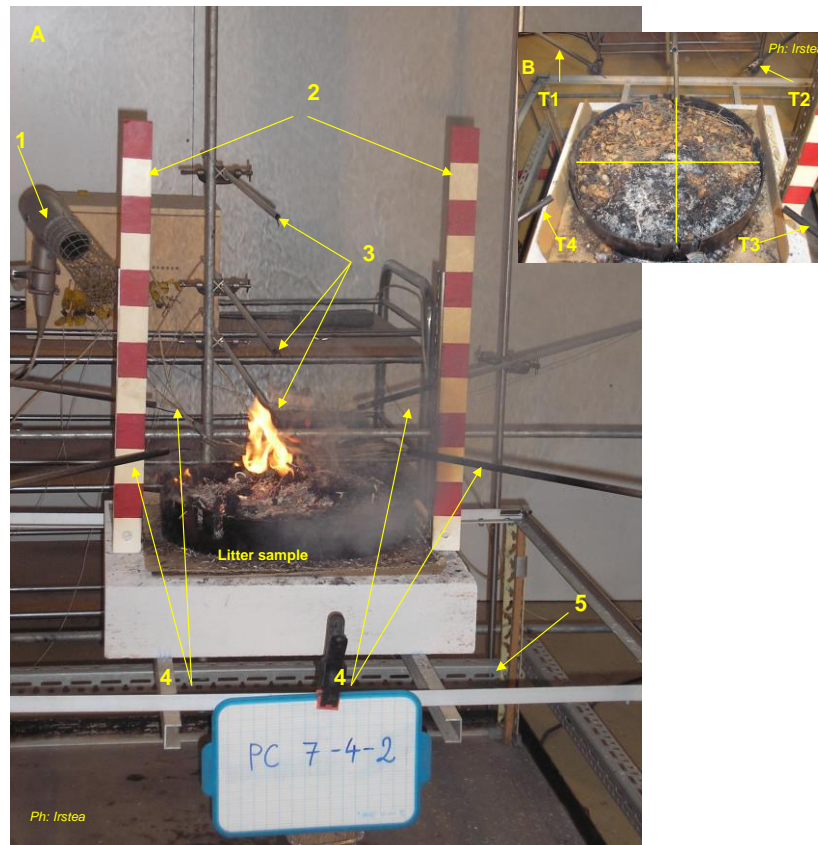


Fig. 2 The burning device (A) and a top view of a burned sample showing the 4 thermocouples (T) positioned around the sample that delineate the 4 edges used to assess the flame spread (B). (1: Domestic fan providing a 9.8 kmh^{-1} wind, 2: rulers for flame height assessment, 3: thermocouples positioned at 3 different heights in the centre of the sample for recording of flame temperature, 4 : thermocouples diametrically opposite around the sample for recording of flame temperature, 5: Scale for recording of weight loss)

A “standard” ignition source (“firebrand”) was used to ensure that the different litter samples ignited under similar conditions. The firebrands were made of *Pinus sylvestris* wood ($2 \times 2 \times 1 \text{ cm}$, mass= $1.44 \pm 0.05 \text{ g}$, FMC = 7%) and were ignited at a constant temperature of 415°C using a 500 W epiradiator which emitted a constant 7.5 Wcm^{-2} radiation (Standard NF P 92-509-1985), as described in Ganteaume *et al.* (2009a). Once the flaming phase ended, the glowing

“firebrand” was placed in the centre of the sample and the chronometer was switched on. For each litter sample, up to three successive ignition trials were performed until the sample ignited. A variety of definitions of ignition success exist in literature including the complete combustion of the sample (Frandsen 1997) or a minimum area burned (Lawson *et al.* 1996). In our study, ignition was considered successful if a flame lasted at least 10 s to ensure that ignition was sufficient to allow propagating flames. Variations in temperature were then recorded as along with the parameters that characterized the flammability of the litter samples as described in Ganteaume *et al.* (2009a). Previous works showed that flaming ignition of litter beds did not occur or was very infrequent with glowing firebrand and no wind (Curt *et al.* 2007; Ellis 2011) so our burning experiments were carried out in wind conditions. A domestic fan, fitted with grills and mesh filters to ensure an even flow across the burning area and fixed onto a stand, produced a hot (35 °C), oblique (45°) and constant wind speed of $9.8 \pm 0.1 \text{ km h}^{-1}$ (2.7 m s^{-1}) measured across the surface of the samples. An oblique and constant air flow was chosen because it was part of the experimental design developed in previous experiments (Ganteaume *et al.* 2009a, 2011; Curt *et al.* 2011). To which extent this mimics the real direction of air flow in the field has not been tested. However, our measurements of the wind speed in the field indicated that a value of $\sim 9.8 \text{ km h}^{-1}$ at the immediate vicinity of soil surface can be considered as high. During the experiments, the mean relative temperature was 24.0°C ($\pm 3.3^\circ\text{C}$) and mean relative humidity was 56.3% ($\pm 8.7\%$) but they did not affect flammability (Fisher’s LSD test, $p > 0.05$).

The flammability of the litter beds was analysed following the definitions of Anderson (1970) and Martin *et al.* (1993) as the result of the following four components: ignitability (the amount of time until ignition once a material is exposed to a known ignition source), sustainability (how long the fuel continues to burn), combustibility (how rapidly or intensely a material burns), and consumability (the quantity of material that is consumed). Therefore, the main variables we recorded were (i) time-to-ignition (TTI, s) corresponding to the time necessary for the appearance of a flame after the firebrand had been placed on the sample (Anderson, 1970) as indicator of ignitability; (ii) flaming duration (FD, s) that stopped when flaming combustion finished as indicator of sustainability, (iii) flame spread calculated by the number of opposite directions

(called edges) of the round tray reached by flames (FS, 0–4) (Fig. 4B), (iv) rate of spread (ROS, cm s^{-1}) obtained from the mean value of the time required by the flame to reach the four edges of the fuel layer, (v) mean flame temperature (FT, $^{\circ}\text{C}$), which, in fact, was very often the mean temperature of the convection column¹, recorded by the seven thermocouples throughout the whole combustion process, (vi) maximum flame height (FH, cm) assessed visually every 2 s to the nearest cm using the graduated rulers as landmarks, as indicators of combustibility and (vii) rate of consumption (RC, %), as indicator of consumability, which was measured by calculating, for each sample, the weight loss (initial fuel weight minus final fuel weight) and dividing this weight by the sum of weight loss and residual litter weight. For the non-constructed sampling method (NC), each value given for the different flammability variables corresponded to an average of the four values obtained during the burning of the four replicates collected per plot.

2.7. Statistical analyses

In the preliminary experiment, the relationship between litter depth/bulk density (compaction) and the flammability variables recorded for each vegetation type was analyzed using linear regressions.

Two-way analysis of variance (ANOVA) performed on the flammability variables highlighted the most significant factor among those tested (sampling method and vegetation type) and one-way ANOVA was performed to assess the impact of vegetation types on the litter composition. In addition to the tests of overall significance with ANOVA, the least significant difference (LSD) test was used to check for significant differences between the different variables (Freedman 2005) and a significant relationship between the variables was assumed when the p-value was ≤ 0.05 . To test the effects of the sampling method and vegetation types on flammability and litter parameters, the variables except flame duration and rate of consumption were previously log-transformed to meet the two-way ANOVA assumption of normality and homoscedasticity. For the one-way ANOVA performed on the proportions of each litter component as a function of vegetation types, all the variables were log-transformed except the proportion of grass and of evergreen leaves and

¹ To be coherent with our previous works and for readability in figures, the name « Flame Temperature » was used instead of « Temperature of Convection Column ».

when the distribution of data did not follow the expected parametric pattern (proportion of grass), the non-parametric Kruskal-Wallis test was used instead of the Fisher test. For the comparison of the flammability of non-constructed and constructed litter samples, comparisons of mean, using Student's t-test, were performed on the whole set of data to test the influence of the sampling method on the flammability variables. Some variables (bulk density, time-to-ignition and rate of spread) were previously log-transformed to meet the assumption of normality and homoscedasticity. The non-parametric Wilcoxon-Mann-Whitney test was used when the distribution of data did not follow the expected parametric pattern (flame spread, flame height, litter depth). The same analysis was performed for the comparison of the flammability of non-constructed and constructed litter samples in each vegetation type because of the small number of data tested in each analysis (between 7 and 12 depending on the vegetation type), to evaluate a possible shift on the flammability of each vegetation types depending on the sampling method. These analyses were performed using Statgraphics Centurion XV (StatPoint Technologies).

Co-inertia analysis (Dolédéc and Chessel 1994), suited to large number of variables compared with small number of samples, was performed on the dependent variables (flammability and litter variables) and on the explanatory variables (proportions of the different components of the litter samples) to examine associations between litter composition and litter 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 et al. 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 correspondence analysis (CA) on the litter's characteristics and principal component analysis (PCA) was then performed 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.

For each type of sampling method, a hierarchical cluster analysis (R software, ADE-4 package) was used to rank the vegetation types according to their litter flammability. The main

aim of this analysis was to assign the different vegetation types into groups (clusters) in such a way that two types from the same cluster were more similar than two types from different clusters regarding their flammability variables. Thus, vegetation types presenting the same type of flammability will be grouped in the same cluster from the less flammable to the most flammable.

3. Results

3.1. Impact of the sampling method and vegetation types

Results of linear regressions showed that the construction of the litter samples significantly decreased maximum flame height, rate of consumption (both regarding bulk density) and flaming duration (regarding litter depth) of mixed oak-pine litter samples (correlation coefficients respectively equal to -0.71, -0.81 and 0.60) as well as maximum flame height (regarding litter depth) and rate of spread (regarding bulk density) of shrubland-maquis litter samples (correlation coefficients respectively equal to 0.72 and -0.63). On the contrary, the compaction significantly increased the flaming duration (regarding bulk density) in pure cork oak litter samples (correlation coefficient equals to 0.80). Taking into account all vegetation types as a whole, compaction entailed a significant decrease in rate of spread (regarding litter depth; correlation coefficient equals to 0.41), flame spread and rate of consumption (both regarding bulk density; correlation coefficients respectively equal to -0.41 and -0.44).

Results obtained in the flammability experiments (means and standard deviations of flammability variables and litter parameters), performed on litters sampled according to the two sampling methods in each vegetation type, are presented in Table 1. High standard deviation values showed within-sampling method (especially in the constructed samples) variability in some flammability results.

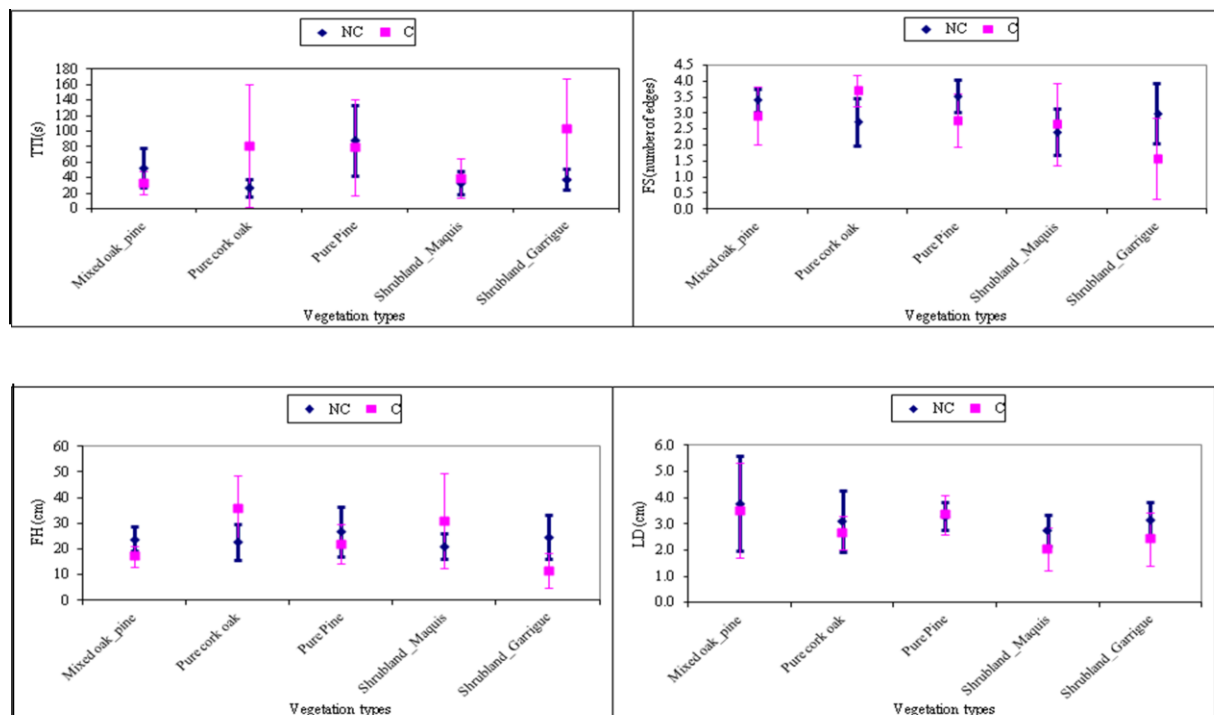
The comparison of non-constructed and constructed litter samples showed that rate of spread and rate of consumption were significantly higher in non-constructed samples than in constructed samples (respectively $t=3.58$, $p=0.0005$ and $t=3.14$, $p=0.002$) contrary to bulk density

($t = -4.01$, $p = 0.0001$) (Tab. 1) which was significantly higher in constructed litter samples. No difference in the other flammability variables (time-to-ignition, flaming duration, flame spread, flame height and flame temperature) was observed between the two sampling methods (Tab. 1).

Two-way ANOVA revealed that the sampling method had a significant effect on the litter bulk-density ($F = 18.32$, $p < 0.0001$) and on the rate of spread ($F = 20.02$, $p < 0.0001$) and rate of consumption ($F = 15.12$, $p = 0.0002$). The vegetation type had a significant effect on time-to-ignition ($F = 4.89$, $p = 0.0013$), flaming duration ($F = 2.67$, $p = 0.038$), flame spread ($F = 4.13$, $p = 0.004$), maximum flame height ($F = 3.85$, $p = 0.006$), mean flame temperature ($F = 3.31$, $p = 0.014$), rate of consumption ($F = 2.74$, $p = 0.034$) and litter depth ($F = 11.85$, $p < 0.0001$). There were significant interactions between vegetation type and litter sampling regarding the flammability variables only (Tab. 2). Regarding mean flame temperature and rate of spread, the effect of the sampling method was significant in all the vegetation types except in pure pine for the latter variable. Regarding flame spread and maximum flame height, this effect was significant in pure cork oak, garrigue and maquis whereas it was significant only in pure cork oak and garrigue for time-to-ignition and only in maquis for flaming duration. Regarding rate of consumption, the effect of the sampling method was significant in mixed pine -oak, pure pine and garrigue.

The comparison of both sampling methods for each vegetation type showed that the effect of the sampling and its magnitude differed depending on flammability variables and on vegetation type what was mainly a consequence of the interaction between vegetation types and sampling method (Tab. 1 and 3; Fig. 3). Time-to-ignition was significantly affected by the sampling method in litters sampled in *shrubland_garrigue*. This parameter increased by 173% for the litters sampled in this vegetation type (from 37.8 s to 103.4 s). However, the sampling method also had a significant effect on time-to-ignition in pure cork oak (increased by 122%) according to the interactions previously highlighted. Flame spread was significantly affected by the construction of litters sampled in *shrubland_garrigue* (decreasing from 2.98 to 1.57 edges of the sample reached by the flames). Rate of spread was significantly decreased by the construction of litters sampled in *shrubland_garrigue* (decreasing from 1.21 to 0.49 cm s^{-1}), *shrubland_maquis* (decreasing from 0.98 to 0.28 cm s^{-1}) and cork oak stands (decreasing from 1.08 to 0.48 cm s^{-1}). The construction of

litters had a significant effect on the mean flame temperature and the maximum flame height recorded in litters sampled in mixed pine-oak stands (decrease of flame temperature from 61.1 to 46.7°C and of flame height from 23.8 to 17.1 cm), shrubland_garrigue (decrease of flame temperature from 60.6 to 37.8°C and of flame height from 24.7 to 11.6 cm) and cork oak stands (increase of flame temperature from 40.1 to 57.7°C and of flame height from 20.5 to 35.8 cm). Flame temperature increased from 40.7°C for intact samples to 52°C for constructed samples collected in shrubland_maquis. Rate of consumption was significantly decreased by the construction of litters sampled in pure pine stands (decreasing from 85.2 to 56.2%) and mixed pine-oak stands (decreasing from 75.9 to 57.8%). Litter bulk density was significantly increased only by the construction of litters sampled in shrubland_garrigue (increasing from 37.5 to 70.2 kg m⁻³) and shrubland_maquis (increasing from 39.9 to 72.2 kg m⁻³). The sampling method had a significant effect on flaming duration of litter sampled in shrubland_maquis (increasing from 102.9 s for intact samples to 188.2 s for constructed samples (Tab. 1 and 3).



3.2. Role of the litter components in the litter flammability

As expected, intact samples collected in pine stands had high proportions of needles, fine particles and debris while samples collected in mixed pine-oak stands had high proportions of deciduous leaves, debris and grass. Mature cork oak stands were mainly composed of evergreen leaves, coarse (mostly twigs and pieces of bark >6 mm in diameter) and non-combustible particles (mostly stones). Samples collected in shrubland_garrigue had high proportions of evergreen leaves, fine particles, grass and debris whereas samples collected in shrubland_maquis had high proportions of fine and non-combustible particles (Fig. 4). One-way ANOVAs showed that the composition of litters (proportions of components) significantly varied between vegetation types (Tab. 4).

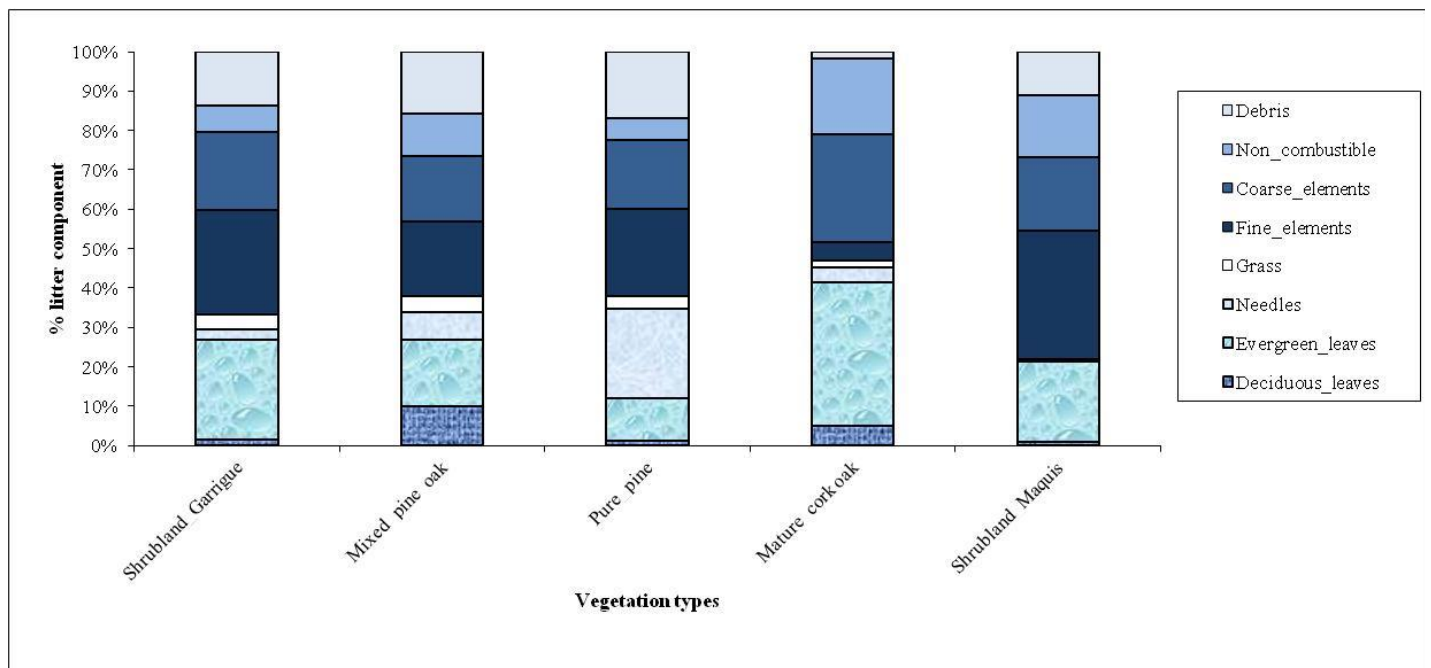


Fig. 4 Proportions of the different litter components according to the five vegetation types in non-constructed samples

The cloud plot extracted from the co-inertia analysis (Fig. 5) showed the positions of the dependent variables (flammability and litter parameters) and the positions of the explanatory variables (litter components). Axis 1 presented 73% of the explained variance and opposed non-constructed and constructed litter samples. This opposition also corresponded to a contrast between high values of litter depth, flame spread, rate of spread and rate of consumption on the

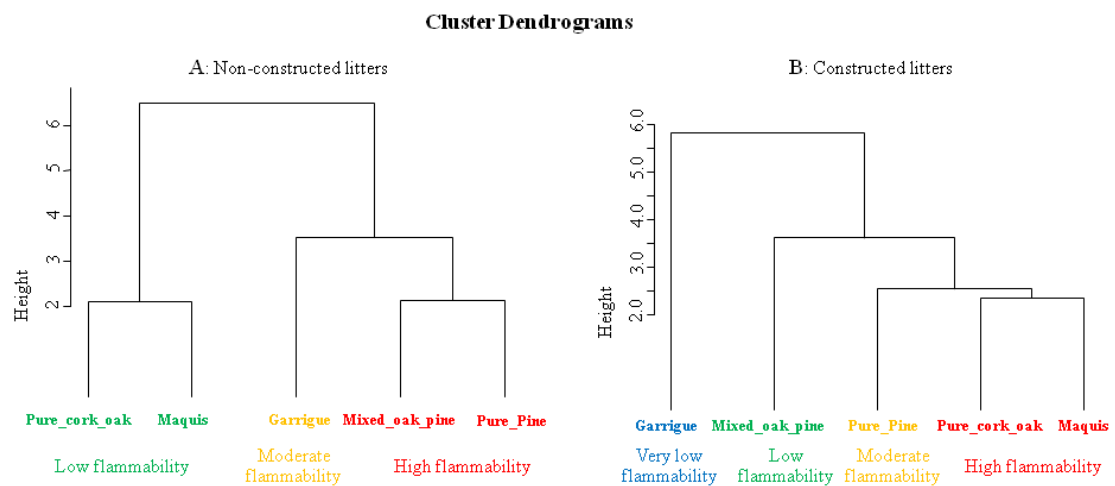
positive side of the axis 1 and high values of bulk-density, flaming duration, maximum flame height and time-to-ignition on the other side of the axis. These variables were characterised by the proportions of litter components. High values for debris characterised the non-constructed litter samples as this component was not present in constructed litter samples. This component was also linked to high values of rate of consumption and flame spread in intact litter samples, especially in pure pine and mixed pine-oak stands. High values of time-to-ignition and flame temperature were linked to the abundance of needles while high values of flame height, flaming duration and bulk density were linked to an abundance of fine particles especially in *shrubland_maquis* and *shrubland_garrigue*. On the contrary, low values of litter depth and rate of spread were linked to high proportion of non-combustible particles, especially in cork oak stands. High proportion of deciduous leaves, like in mixed pine oak stands, seemed to be linked to low values of rate of consumption and flame spread.

Fig. 5 Co-inertia analysis comparing the distribution of the characteristics of the litter samples and their flammability variables. The main figure indicates the groups of plots having similar litter and flammability characteristics (PC: Limestone Provence, MC: Acidic Provence). The grey ellipses include 95% of the plots of a specific group. Abbreviations for litter characteristics, flammability variables and sampling methods (LD: litter depth, BD: litter bulk-density, TTI: time-to-ignition,

FD: flaming duration, S: flame spread, ROS: rate of spread, FH: max flame height, FT: mean flame temperature, RC: rate of consumption)

3.3. Change in flammability according to the sampling method

For the non-constructed litters, hierarchical cluster analysis assigned the different vegetation types into three clusters regarding their flammability variables (Fig. 6A) and into four clusters for the constructed litters (Fig. 6B). Non-constructed litters sampled in mixed oak-pine stands and in pure pine stands were the most flammable and those sampled in pure cork oak stands and in shrubland maquis were the least flammable; intact litters sampled in shrubland_garrigue were ranked moderately flammable. However, constructed litters sampled in pure cork oak stands and in shrubland maquis became the most flammable, those sampled in pure pine stands were ranked moderately flammable whereas constructed litters sampled in mixed oak-pine stands were ranked weakly flammable and those sampled in shrubland_garrigue were the least flammable.



litters)

4. Discussion

4.1. Effect of the artificial compaction of the constructed litter

Our results suggesting differences in flammability metrics caused by collection method have implications for future research. Fernandes *et al.* (2008) pointed out that retaining the fuel arrangement and using a large enough spatial scale to ensure some fire development could allow the assessment of the fire behaviour in laboratory conditions. However, constructed litter samples, mostly composed of leaves of a given species, were widely used in burning experiments (Fonda 2001; Petriccione *et al.* 2006; Kane *et al.* 2008; Ormeño *et al.* 2009; Ganteaume *et al.* 2009b; Engber and Varner 2012). The main advantage of these constructed samples, in addition to being easier and faster to collect, was the smaller variability in results which were therefore more suited to experiments requiring repetition. However, in our study, because of their heterogeneous composition, the constructed litter samples presented as much variability as the intact litter samples.

Statistical analyses showed, as a whole, that rate of spread and rate of consumption tended to be higher in non-constructed samples contrary to bulk-density. This result was also underlined by co-inertia analysis. The higher bulk density of the constructed samples was due to the sampling method as each sample was composed of ten sub-samples collected in each plot and to their compaction to match the litter depth recorded in each plot. The lower flammability (lower rate of spread and rate of consumption as previously highlighted in the preliminary study) recorded in these samples was more due to their artificial compaction (carried out in order to obtain the value of the mean litter depth recorded in each plot) than to the litter particle type as found in Plucinski and Anderson (2008). In the literature, different types of results were found regarding the effect of the bulk density on flammability according to the type of fuelbed. Working on compacted fuelbed composed of slash produced by mechanical mastication, Kane *et al.* (2009) assumed that the high bulk density of these fuelbeds may slow the combustion process however Kreyes *et al.* (2011) showed that the combustion duration was increased by high bulk density of this type of fuelbed. Regarding the flammability of fuelbed composed mainly of duff, bulk density (as well as mineral content) has been identified as primary determinant of duff consumption (Hartford 1989; Varner *et al.* 2005); the increase in bulk density decreasing the flammability by

reducing the amount of oxygen available but Garlough and Kreyes (2011) found that this parameter was not a significant factor for either ignition and consumption in duff samples.

In constructed litter samples, some authors showed that litter bed depth had a significant effect on flame temperature (Ormeño *et al.* 2009), flame height (Kane *et al.* 2008) and on rate of consumption (Kane *et al.* 2008; Ormeño *et al.* 2009). Ormeño *et al.* (2009) showed that litter bed depth was likely partially responsible for fire being self-extinguished by decreasing flame propagation and that flame height was clearly sensitive to fuel loads and their arrangements. As reported in different studies (Fernandes and Rego 1998; Bilandzija and Lindic 1993; Scarff and Westoby 2006), fuel structure, area-volume ratio and litter packing ratio were also involved in fire behaviour and the effect of leaf packing was greater than chemical factors such as oil or lignin content (Vines 1981; Parker and Levan 1989). Moreover, the work of Engber and Varner (2012) suggested that oak litter physical characteristics and fuel depth explained almost all the variability in flammability. Indeed, ventilated litter beds ensure a faster supply of oxygen to the fire leading to increased flammability. However, the litter component “debris”, only sorted in the intact litter samples, could also explain the fire behaviour recorded during the burning experiments. The shorter time-to-ignition obtained during the burning of non-constructed litter samples could be explained by a better contact of the heat source (glowing firebrand) with the dense and ignitable dry H layer due to the oven-drying. The higher rate of consumption of the intact litter samples would be due, in part, to the combustion of this dry H-horizon. However, even if the rate of consumption was highest in the non-reconstructed samples, it ranged between 57% (in maquis litter samples) and 85% at the highest (in pure pine litter samples) despite the low FMC of the dried litters.

It is worth noting that the results obtained for some of the flammability variables we recorded during the burning experiments differed from those found in other works; this may be due to the burning protocol but also to the litter sampling method. Indeed, the protocol used in our study differed from the sampling method and protocols (constructed litter samples only, different burning device and ignition source) used by Ormeño *et al.* (2009) or Kane *et al.* (2008), and was closer to the one (constructed litter samples only, same burning device and ignition source) used in

Ganteaume *et al.* (2009a). However, the constructed litter used in these latter studies was homogeneous, i.e. only composed of calibrated pine needles or oak leaves of a single species. In our study, the litter composition was heterogeneous regardless of the sampling method; including different particles (leaves, twigs, etc.) of different species. This heterogeneity could explain the high variability in the composition of the different litter samples and this resulting variability could in turn explain the variability in the flammability characteristics of litters. Because of the heterogeneous composition of our litter samples, there was a variability in flammability results within each modality (see table 3). Moreover, because of the different sampling methods we used, our experiments were conducted on litter of different bulk densities what could also increased the variability of flammability. The difference in composition of constructed litter between our study and previous ones (Kane *et al.* 2008; Ormeño *et al.* 2009) can explain for instance the longer time-to-ignition and lower flame height recorded in our burning experiments. Regarding intact litter, our results and those obtained in previous works (Ganteaume *et al.* 2011; Curt *et al.* 2011) that used the same litter sampling and the same burning protocol, the flammability variables were overall of the same order of magnitude.

4.2. Effect of vegetation types

The effects of vegetation types and of their litter composition on the flammability of intact litter were reported in previous works (Ganteaume *et al.* 2011; Curt *et al.* 2011). Contrary to Ganteaume *et al.* (2011), our results showed that flame height and flame spread significantly differed according to vegetation types. Five vegetation types were sampled in the current study instead of three in the previous one what could explain the difference. However, regarding time-to-ignition, in both studies, the highest values were recorded for pure pine stands. This lower ignitability could be explained by the high proportion of needles in pure pine stands and by the high proportion of fine particles (mainly twigs) in pure pine stands but also in both types of shrubland, increasing the packing ratio of the litter and so decreasing its aeration. Furthermore, this effect was magnified by the construction of litters collected in shrubland_garrigue which were already fuel-limited due to the frequent consumption during recurrent fires. In contrast, the construction only affected the

combustibility of the cork oak litters, positively or negatively according to the parameters, but overall, the flammability was increased, may be because of the lower bulk density of the samples. The rapid spread values we recorded for cork oak litters were consistent with the work of Curt *et al.* (2011) who worked on the flammability of litter samples of cork oak and maquis. According to Ganteaume *et al.* (2011) and Petriccione *et al.* (2006), the high ignitability of mixed pine-oak litters could be explained by the presence of deciduous leaves of *Quercus pubescens* which had high surface area to volume ratio. In our study, these litters also had higher flammability (high flame spread and rate of spread and long flaming duration) according to several other works (Papió and Trabaud 1990; Scarff and Westoby 2006; Kane *et al.* 2008) and large-leaved species have been hypothesized to drive the flammability of mixed litters (Magalhães and Schwilk 2012). However, some flammability variables (flame height, flame temperature and rate of consumption) were highly affected by the construction of litters which decreased the litter aeration, excepted for very compacted litters like those of pure pine. The burning of these litters released the highest temperature, regardless the sampling method and this result was consistent with the work of Ellair and Platt (2013). The negative relationship between rate of spread and flaming duration shown in the co-inertia analysis was consistent with other works dealing with mixed litters (Magalhães and Schwilk 2012); however, none of these variables varied significantly between vegetation types. Even though multivariate analysis showed that high proportion of fine particles in the samples was related to long flaming duration and that abundance of non-combustible particles, evergreen leaves and coarse particles in the samples were linked to low rate of consumption regardless of the sampling method. Ganteaume *et al.* (2011) found that *Pinus halepensis*, as an evader pine species (see Fonda 2001), had needles that burned for a long time with a high rate of consumption what was consistent with our results. The construction of litters less affected pure pine litters (decrease only in the rate of consumption). These litters were already very compacted (high bulk density due to the packing ratio of needles) when they were intact and the difference in litter consumption may come from the absence of debris in the constructed samples as shown in co-inertia analysis.

Regarding litter flammability, the two methods of sampling were not linearly related as the rank of litters changed between the methods. According to the vegetation type, the construction

of litters entailed an increase or a decrease in flammability. Compaction and change in litter composition (absence of “debris”) mainly affected combustibility and consumability of litters, which decreased in litters of mixed oak-pine, pure pine and garrigue (highest proportions in debris) contrary to what happened in litters of pure cork oak (high proportion in coarse elements and evergreen leaves) and maquis (high proportion in fine elements and evergreen leaves). For constructed litters, our results showed that shrubland garrigue, whose litters were mainly composed of *Quercus coccifera*, an evergreen shrub oak with small unlobed leaves, was ranked the least flammable vegetation type. This is consistent with the work of Engber and Varner (2012) who ranked different oak species according to the flammability of their leaves (constructed samples). These authors also ranked oak species with large and lobed leaves (such as our *Q. pubescens*) as highly flammable and evergreen oak species with large and flat leaves (such as our *Q. suber* or *Q. ilex*) as moderately flammable contrary to our results. This difference could be due to the heterogeneous composition of our litter samples (especially in the mixed oak-pine samples) compared to the homogeneous samples (only leaves of a given species) of these authors.

Conclusions

Using different methods of litter sampling implies differences in litter flammability results. It was important to show how this flammability was affected by the type of sampling method but also if this effect varied according to the vegetation type. Only the rate of spread and the rate of consumption of litters burned in laboratory conditions were affected by the sampling method. These variables were lower when the litter samples were constructed because of the strong influence of the litter packing ratio and composition. This suggests that, even if the sampling of constructed litter is easier and faster, the construction of litters could not allow an assessment of flammability supposed to represent field conditions. However, to assess the flammability of only one type of particles (of a given species) as it is usually done in literature, none of our sampling methods are very accurate given the different types of particles and of species composing both types of litter samples.

Moreover, the rank of the vegetation types tested in this work, from the most flammable type to the least flammable type differed according to the sampling method. The least flammable type of non-constructed litter became the most flammable types once the litters were constructed. The effects of compaction and litter composition entailed an increase in flammability of pure cork oak and maquis samples and a decrease in flammability of the other vegetation types. These results, obtained in laboratory conditions, need to be confirmed by field experiments during prescribed burnings.

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References

- Anderson HE (1970) Forest fuel ignitability. *Fire Technology* 6: 312-319.
- Bilandzija J and Lindic V (1993) Influence of forest fuel structure on fire behaviour in aleppo pine stands. *Radovi – Sumarski Institut Jastrebarsko* 28: 215-224.
- Bradstock RA and Cohn JS (2002) Fire regimes and biodiversity in semi-arid mallee ecosystems. In “Flammable Australia: The Fire Regimes and Biodiversity of a Continent” (Eds RA Bradstock, JE Williams, AM Gill) pp. 238–258 (Cambridge University Press, Cambridge, UK).
- Brown JK (1974) Handbook for inventorying downed woody material. Intermountain Forest and Range Experiment Station, United States Department of Agriculture, Forest Service, General Technical Report INT-16 (Ogden, Utah).

- Brown JK, Oberheu RD, Johnston CM (1982) Handbook for inventorying surface fuels and biomass in the Interior West. Intermountain Forest and Range Experiment Station, United States Department of Agriculture, Forest Service, General Technical Report INT-129 (Ogden, Utah).
- Curt T, Ganteaume A, Alleaume S, Borgniet L, Jappiot M, Lampin C, Chandioix O (2007) Vegetation flammability and ignition potential at road-forest interfaces (Southern France). In: IVth International Wildland Fire Conference, 14-17 mai 2007, Séville (Espagne).
- Curt T, Schaffhauser A, Borgniet L, Dumas C, Estève R, Ganteaume A, Jappiot M, Martin W, N'Diaye A, Poilvet B (2011) Litter flammability in oak woodlands and shrublands of southeastern France. *Forest Ecology and Management* 261: 2214-2222.
- Dolédec S, Chessel D (1994) Co-inertia analysis ; an alternative method for studying species-environment relationships. *Freshwater Biology* 31: 277-294.
- Ellair DP, Platt WJ (2013) Fuel composition influences fire characteristics and understorey hardwoods in pine savanna. *Journal of Ecology* 101 : 192-201.
- Ellis PFM (2011) Fuelbed ignition potential and bark morphology explain the notoriety of the eucalypt messmate 'stringybark' for intense spotting. *International Journal of Wildland Fire* 20: 897-907.
- Ellis PFM (2011) Fuelbed ignition potential and bark morphology explain the notoriety of the eucalypt messmate 'stringybark' for intense spotting. *International Journal of Wildland Fire* 20: 897-907.
- Engber EA, Varner JM (2012) Patterns of flammability of the California oaks: the role of leaf traits. *Canadian Journal of Forest Research* 42: 1965-1975.
- Fernandes PM, Rego F (1998) A new method to estimate fuel surface area-to-volume ratio using water immersion. *International Journal of Wildland Fire* 8: 121-128.
- Fernandes PM, Botelho H, Rego F, Loureiro C (2008) Using fuel and weather variables to predict the sustainability of surface fire spread in maritime pine stands. *Canadian Journal of Forest Research* 38: 190-201.
- Fonda RW (2001) Burning characteristics of needles from eight pine species. *Forest Science* 47: 390-396.

- Fonda RW, Varner JM (2004) Burning characteristics of cones from eight pine species. *Northwest Science* 78 (4): 322-333.
- Fonda RW, Bellanger LA, Burley LL (1998) Burning characteristics of western conifer needles. *Northwest Science* 72: 1-9.
- Frandsen W (1997) Ignition probability of organic soils. *Canadian Journal of Forest Research* 27: 1471-1477.
- Freedman DA (2005) *Statistical Models: Theory and Practice*, Cambridge University Press.
- Ganteaume A, Lampin-Maillet C, Guijarro M, Hernando C, Jappiot M, Fonturbel T, Pérez-Gorostiaga P, Vega JA (2009a) Spot fires: fuel bed flammability and capability of firebrands to ignite fuel beds. *International Journal of Wildland Fire* 18: 951-969.
- Ganteaume A, Jappiot M, Lampin-Maillet C, Curt T, Borgniet L (2009b) Fuel characterization and effects of wildfire on limestone soils in southeastern France. *Forest Ecology and Management* 258S: S15-S23.
- Ganteaume A, Jappiot M, Lampin-Maillet C, Curt T, and Borgniet L, 2011. Effects of vegetation types and fire regime on flammability of non-constructed litters in south-eastern France. *Forest Ecology and Management* 261: 2223-2231.
- Garlough EC, Keyes CR (2011) Influences of moisture content, mineral content and bulk density on smouldering combustion of ponderosa pine duff mounds. *International Journal of Wildland Fire* 20: 589-596
- Hartford RA (1989) Smoldering combustion limits in peat as influenced by moisture, mineral content and organic bulk density. In 'Proceedings of the 10th Conference on Fire and Forest Meteorology Ottawa, Ontario'. (Eds DC Maciver, H Auld, R Whitewood) pp. 282-286. (Forestry Canada, Netawawa Forestry Institute: Chalk River, ON)
- Hernando-Lara C (2000) Combustibles forestales: inflamabilidad. In "La defensa contra incendios forestales, fundamentos y experiencias", vol. 6, Vélez Muñoz R. (Ed.) pp. 3-6 (McGraw-Hill).
- Hogkinson KC (2002) Acacia wooded landscapes: effects on functional processes and biological diversity. In "Flammable Australia: The Fire Regimes and Biodiversity of a Continent" (Eds.

- RA Bradstock, JE Williams, AM Gill) pp. 259-277 (Cambridge University Press, Cambridge, UK).
- Jappiot M, Curt T, Lampin C, Borgniet L, Vinet O, Louis S, Chandioux O, Estève R (2007) Characteristics and Flammability of French Mediterranean Dead Litter Fuels. In “4th International Wildfire Conference”, 13-17 may 2007, Seville, Spain.
- Kane JM, Varner JM, Hiers JK (2008) The burning characteristics of southeastern oaks: Discriminating fire facilitators from fire impiders. *Forest Ecology and Management* 256: 2039-2045.
- Kane JM, Varner JM, Knapp EE (2009) Novel fuelbed characteristics associated with mechanical mastication treatments in northern California and south-western Oregon, USA. *International Journal of Wildland Fire* 18: 686–696. doi:10.1071/WF08072
- Kreye JK, Varner JM, Knapp EE (2011) Effects of particle fracturing and moisture content on fire behaviour in masticated fuelbeds burned in a laboratory. *International Journal of Wildland Fire* 20: 308-317.
- Lawson B, Armitage O, Dalrymple G (1996) Wildfire Ignition Probability Predictor (WIPP). R&D Update, Canadian Forest Service (Pacific Forestry Center, Victoria, BC).
- Lawson BD, Armitage OB, Hoskins WD (1996) Diurnal variation in the Fine Fuel Moisture Code: tables and computer source code. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre. FRDA Report 245. Victoria, BC.
- Magalhães RMQ, Schwilk DW (2012) Leaf traits and litter flammability: evidence for non-additive mixture effects in a temperate forest. *Journal of Ecology*. 100 : 1153–1163.
- Martin RE, Gorden DA, Gutierrez ME, Lee DS, Molina DM, Schroeder RA, Sapsis DA, Stephens SL, Chambers M (1993) Assessing the flammability of domestic and wildland vegetation. In “Proceedings of the 12th Conference on Fire and Forest Meteorology”, October 26–28, Jekyll Island, Georgia, pp.130-137.
- Martin R.E., Gorden D.A., Gutierrez M.E., Lee D.S., Molina D.M., Schroeder R.A., Sapsis D.A., Stephens S.L., and Chambers M., 1993. Assessing the flammability of domestic and wildland

- vegetation. In: Proceedings of the 12th Conference on Fire and Forest Meteorology, Jekyll Island, Georgia, October 26–28, pp.130-137.
- Matthews S, McCaw WL, Neal JE, Smith RH (2007) Testing a process-based fine fuel moisture model in two forest types. *Canadian Journal of Forest Research* 37: 23-35.
- Moretti M, Legg C (2009) Combining plant and animal traits to assess community functional responses to disturbance. *Ecography* 32: 299-309.
- Mutch RW (1970) Wildland fires and ecosystems-a hypothesis. *Ecology* 51: 1046-1051.
- Ormeño E, Céspedes B, Sánchez IA, Velasco-García A, Moreno J, Fernandez C, Baldy V (2009) The relationship between terpenes and flammability of leaf litter. *Forest Ecology and Management* 257: 471-482.
- Papió C, Trabaud L (1990) Structural characteristics of fuel components of five Mediterranean shrubs. *Forest Ecology and Management* 35: 249-259.
- Parker WJ, LeVan SL (1989) Kinetic properties of the components of Douglas-fir and the heat of combustion of their volatile pyrolysis products. *Wood and Fiber Science* 21: 289-305.
- Pellizzaro G, Duce P, Ventura A, Zara P (2007) Seasonal variations of live moisture content and ignitability in shrubs of the Mediterranean Basin. *International Journal of Wildland Fire* 16: 633-641.
- Petriccione M, Moro C, Rutigliano FA (2006) Preliminary studies on litter flammability in Mediterranean region. *Forest Ecology and Management* 234S.
- Plucinski MP, Anderson WR (2008) Laboratory determination of factors influencing successful point ignition in the litter layer of shrubland vegetation *International Journal of Wildland Fire* 17: 628-637.
- Proksch P, Proksch M, Rundel PW, Rodriguez E (1982) Ecological significance of the chemistry of the leaf resin of *Elytropappus rhinocerotis*. *Biochem. Syst. Ecol.* 10: 49-53.
- Quézel P (2000) Taxonomy and biogeography of Mediterranean pines (*Pinus halepensis* and *P. brutia*). In “Ecology, Biogeography and Management of *Pinus halepensis* and *Pinus brutia* Forest Ecosystems in the Mediterranean Basin” (Eds G Ne'eman, and L Trabaud), p 1-12 (Backhuys, Leiden, NL).

- Quézel P, Médail F (2003) Ecologie et biogéographie des forêts du bassin méditerranéen. In “Impacts des perturbations anthropiques sur les forêts méditerranéennes” (Elsevier SAS ed. Paris).
- R Development Core Team (2005) R: A Language and Environment for Statistical Computing, Reference Index Version v. 2.5.1. R Foundation for Statistical Computing, Vienna, Austria.
- Rothermel RC (1983) How to predict the spread and intensity of forest and range fires. USDA Forest Service, Intermountain Forest and Range Experiment Station General Technical Report INT-143 (Ogden, UT).
- Scarff FR, Westoby M (2006) Leaf litter flammability in some semi-arid Australian woodlands. *Functional Ecology* 20: 745-752.
- Schaffhauser A, Curt T, Tatoni T (2011) Fire-vegetation interplay in a mosaic structure of *Quercus suber* woodlands and Mediterranean maquis under recurrent fires. *Forest Ecology and Management* 262: 730-738.
- Schwilk DW, Caprio AC (2011) Scaling from leaf traits to fire behaviour: community composition predicts fire severity in a temperate forest. *Journal of Ecology* 99: 970-979.
- Tatoni T, Roche P (1994) Comparison of old-field and forest revegetation dynamics in Provence. *Journal of Vegetation Science* 5: 295-302.
- Taylor KL, Fonda RW (1990) Woody fuel structure and fire in subalpine fir forests, Olympic National Park, Washington. *Canadian Journal of Forest Research* 20: 193-199.
- Ter Braak CJF, Schaffers AP (2004) Co-correspondence analysis: a new ordination method to relate two community compositions. *Ecology* 85: 834-846.
- Thioulouse J, Chessel D, Doledec S, Olivier JM (1997) ADE-4: a multivariate analysis and graphical display software. *Statistics and Computing* 7: 75-83.
- Valette JC (1990) Inflammabilités des espèces forestières méditerranéennes. *Revue Forestière Française* 42: 76-92.
- Varner, JM, Gordon, DR, Putz, E, Hiers, JK (2005) Restoring fire to long-unburned *Pinus palustris* ecosystems: novel fire effects and consequences for long-unburned ecosystems. *Restoration Ecology*, 13: 536-544.

Vines RG (1981) Physics and chemistry of rural fires. In "Fire and the Australian Biota" (Eds RM Gill, RH Groves, IR Noble), pp. 129-149 (Australian Academy of Science, Canberra).

Wenk ES, Wang GG, Walker JL (2011) Within-stand variation in understorey vegetation affects fire behaviour in longleaf pine xeric sandhills. *International Journal of Wildland Fire* 20: 866–875.

1 **Table 1** A: Flammability variables and litter parameters according to the sampling method and vegetation types
2 B: Comparison of the flammability and litter parameters of non-constructed and constructed litter samples.
3 Mean (standard deviation); N: number of plots in each vegetation type, TTI: time-to-ignition, FD: flaming duration, FS: flame spread, nb : number of edges ; ROS: rate of
4 spread, FH: max flame height, FT: mean flame temperature, RC: rate of consumption, LD: litter depth, BD: bulk-density; nb: number, NC: number of non-constructed
5 samples, C: number of constructed samples (For NC, values given for each parameter are an average of the 4 values obtained for the 4 replicates collected in each plot), t:
6 Student test, W: Wilcoxon test, p: p-value, p>0.05: non significant. BD, TTI and ROS were log-transformed

A. Vegetation types		TTI (s)	FD (s)	FS(nb)	ROS (cm s ⁻¹)	FH (cm)	FT (°C)	RC (%)	LD (cm)	BD (kg m ⁻³)
Mixed oak_pine	N=12	43.13 (22.65)	181.38 (72.94)	3.16 (0.71)	1.00 (0.67)	20.45 (5.47)	53.88 (10.09)	67.00 (18.28)	3.65 (1.28)	45.76 (17.54)
	NC=48	52.60 (25.30)	199.51 (62.89)	3.41 (0.36)	0.79 (0.44)	23.81 (4.75)	61.09 (7.32)	75.86 (14.69)	3.78 (1.80)	42.42 (16.69)
	C=12	33.67 (15.41)	163.25 (80.32)	2.92 (0.90)	1.20 (0.80)	17.08 (3.92)	46.67 (6.77)	57.84 (15.84)	3.52 (1.80)	49.09 (18.44)
Pure cork oak	N=10	58.81 (64.55)	158.83 (79.67)	3.21 (1.06)	0.78 (0.52)	28.14 (12.85)	48.94 (13.72)	70.25 (19.38)	2.62 (0.58)	45.25 (15.58)
	NC=40	36.50 (38.70)	129.60 (66.59)	2.70 (1.27)	1.08 (0.54)	20.50 (7.31)	40.15 (6.64)	67.37 (18.88)	2.60 (0.53)	43.84 (16.39)
	C=10	81.10 (78.71)	188.10 (84.04)	3.70 (0.48)	0.48 (0.27)	35.80 (12.83)	57.73 (13.48)	73.14 (20.44)	2.65 (0.65)	46.67 (15.48)
Pure Pine	N=9	83.96 (53.08)	207.08 (61.91)	3.16 (0.78)	0.88 (0.52)	24.27 (8.81)	56.87 (16.39)	70.73 (22.78)	3.33 (0.63)	56.62 (24.53)
	NC=36	88.36 (45.71)	213.60 (66.33)	3.54 (0.52)	0.91 (0.59)	26.65 (9.76)	62.64 (15.50)	85.22 (13.28)	3.30 (0.53)	46.33 (9.08)
	C=9	79.56 (62.08)	200.56 (60.42)	2.78 (0.83)	0.84 (0.47)	21.89 (7.79)	51.11 (16.00)	56.25 (21.32)	3.36 (0.75)	66.92 (30.95)
Shrubland _Maquis	N=11	37.99 (26.14)	145.54 (71.99)	2.19 (1.29)	0.63 (0.49)	23.93 (15.28)	46.37 (9.12)	60.08 (24.50)	2.05 (0.77)	56.04 (30.33)
	NC=44	36.70 (28.46)	102.90 (37.37)	1.70 (1.18)	0.98 (0.45)	16.90 (6.05)	40.75 (4.19)	56.85 (23.09)	2.10 (0.76)	39.92 (24.52)
	C=11	39.27 (24.94)	188.18 (74.07)	2.64 (1.29)	0.28 (0.15)	30.91 (18.62)	51.99 (9.36)	63.30 (26.54)	2.03 (0.81)	72.16 (27.55)

Shrubland_Garrigue	N=7	70.62 (56.33)	148.92 (67.38)	2.27 (1.30)	0.85 (0.60)	18.12 (10.15)	49.19 (18.05)	54.82 (30.73)	2.78 (0.92)	53.86 (31.42)
	NC=28	37.82 (13.44)	156.56 (37.14)	2.98 (0.94)	1.21 (0.43)	24.68 (8.78)	60.63 (18.57)	76.19 (21.69)	3.14 (0.71)	37.49 (7.48)
	C=7	103.43 (64.69)	141.29 (91.22)	1.57 (1.27)	0.49 (0.53)	11.57 (6.78)	37.76 (7.04)	33.44 (22.59)	2.43 (1.02)	70.22 (38.20)
B. Litter types										
Non-constructed		50.21 (36.67)	160.00 (69.32)	2.86 (1.11)	0.98 (0.49)	22.24 (7.78)	52.47 (14.80)	72.43 (22.22)	2.97 (0.85)	42.16 (16.38)
Constructed		63.00 (56.69)	177.63 (77.37)	2.80 (1.14)	0.68 (0.60)	24.10 (14.06)	49.66 (12.24)	57.76 (23.95)	2.82 (1.24)	60.07 (27.35)
Statistical test		t= -1.03	t= -1.19	W=1171.5	t=3.58	W=1146	t=1.02	t=3.14	W=980	t= -4.01
		p=0.30	p=0.24	p=0.84	p=0.0005	p=0.70	p=0.31	p=0.002	p=0.11	p=0.0001

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9 **Table 2** Effects of sampling method and vegetation types on the flammability and litter parameters. TTI: time-to-ignition; FD: Flaming duration; FS: Flame spread; ROS:
 10 Rate of spread; FH: max Flame height, FT: Flame temperature, RC: rate of consumption, LD: litter depth; BD: bulk-density, ML: mass load. TTI, MANOVA: F: Fisher test,
 11 p: p-value, p>0.05: non significant

	logTTI	FD	logFS	logROS	logFH	logFT	RC	logLD	logBD
Sampling method	F=2.63, p=0.11	F=1.28, p=0.26	F=0.02, p=0.89	F=20.02, p<0.0001	F=1.05, p=0.31	F=2.87, p=0.09	F=15.12, p=0.0002	F=2.21, p=0.14	F=18.32, p<0.0001
Vegetation types	F=4.89, p=0.001	F=2.67, p=0.038	F=4.13, p=0.004	F=1.77, p=0.14	F=3.85, p=0.006	F=3.31, p=0.014	F=2.74, p=0.034	F=11.85, P<0.0001	F=1.56, p=0.19
Interactions	F=3.67 p=0.008	F=3.17 p=0.017	F=5.61 p=0.0005	F=6.22 p=0.0002	F=8.48 p<0.0001	F=13.68 p<0.0001	F=5.38 p=0.0006	F=0.89 p=0.48	F=1.67 p=0.16

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14 **Table 3** Comparison of the flammability and litter parameters of non-constructed and constructed litter samples in each vegetation type. TTI: time-to-ignition; FD: Flaming
 15 duration; FS: Flame spread; ROS: Rate of spread; FH: Max flame height, FT: Flame temperature, RC: rate of consumption;, LD: litter depth; BD: bulk density; t: Student test,
 16 W: Wilcoxon test, p: p-value, ,p>0.05: non significant, M: magnitude of the change from non-constructed to constructed litter (in bold, significant results)

Vegetation types	TTI	FD	FS	ROS	FT	FH	RC	LD	BD
Mixed oak- pine	W=38, p=0.05	W=49, p=0.19	W=46.5, p=0.14	W=94, p=0.21	W=9, p=0.0003 M= -24%	W=17, p=0.002 M= -28%	W=26, p=0.009 M= -24%	W=40, p=0.07	W=90, p=0.31
Cork oak	W=71, p=0.12	W=71, p=0.12	W=74.5, p=0.05	W=13, p=0.006 M= -56%	W=88, p=0.005 M= 44%	W=85, p=0.009 M= 75%	W=55, p=0.73	W=51, p=0.97	W=59, p=0.52
Pure pine	W=32, p=0.48	W=28.5, p=0.31	W=19.5, p=0.06	W=39, p=0.05	W=22, p=0.11	W=26, p=0.22	W=7, p=0.003 M= -34%	W=42, p=0.93	W=59, p=0.11
Maquis	W=63.5, p=0.87	W=101, p=0.009 M= 83%	W=86.5, p=0.09	W=4, p=0.0002 M= -71%	W=103, p=0.006 M= 28%	W=87.5, p=0.08	W=71, p=0.51	W=55, p=0.74	W=89, p=0.02 M= 81%
Garrigue	W=49, p=0.002 M= 173%	W=24.5, p=0.95	W=8.5, p=0.046 M= -47%	W=7, p=0.03 M= -60%	W=4, p=0.01 M= -38%	W=8, p=0.04 M= -53%	W=9, p=0.05	W=14.5, p=0.22	W=49, p=0.002 M= 87%

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18 **Table 4** Results of the one-way ANOVA performed on the proportions of each litter component as a function of vegetation types. Different letters in the same column
 19 indicate statistically significant difference between vegetation types. F: Fisher test, KW: Kruskal-Wallis test, p: p-value, p>0.05: non significant

Litter component	log Deciduous Leaves	Evergreen. Leaves	log Needles	Grass	log Fine Elements	log Coarse Elements	log Non Combustible	log Debris
Statistical test	F=7.22	F=16.33	F=10.38	KW=33.33	F=24.75	F=5.59	F=7.6	F=12.79
	p=0.0002	p<0.0001	p<0.0001	p<0.0001	p<0.0001	p=0.0005	p<0.0001	P<0.0001
	Garrigue ^{AB}	Garrigue ^B	Garrigue ^B	Garrigue ^{AB}	Garrigue ^{AB}	Garrigue ^{BC}	Garrigue ^{BC}	Garrigue ^A
	Maquis ^B	Maquis ^{BC}	Maquis ^B	Maquis ^C	Maquis ^A	Maquis ^A	Maquis ^A	Maquis ^A
	Mixed oak-pine ^A	Mixed oak-pine ^C	Mixed oak-pine ^B	Mixed oak-pine ^A	Mixed oak-pine ^B	Mixed oak-pine ^C	Mixed oak-pine ^B	Mixed oak-pine ^A
	Pure pine ^B	Pure pine ^D	Pure pine ^A	Pure pine ^{AB}	Pure pine ^{AB}	Pure pine ^{BC}	Pure pine ^C	Pure pine ^A
	Cork oak ^A	Cork oak ^A		Cork oak ^{BC}	Cork oak ^C	Cork oak ^A	Cork oak ^A	Cork oak ^B

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FIGURE CAPTIONS

Fig. 1 : Description of the soil horizons collected during the litter sampling and sampling methods : constructed litter (A) and non-constructed litter (B)

Fig. 2 The burning device (A) and a top view of a burned sample showing the 4 thermocouples (T) positioned around the sample that delineate the 4 edges used to assess the flame spread (B). (1: Domestic fan providing a 9.8 kmh^{-1} wind, 2: rulers for flame height assessment, 3: thermocouples positioned at 3 different heights in the centre of the sample for recording of flame temperature, 4 : thermocouples diametrically opposite around the sample for recording of flame temperature, 5: Scale for recording of weight loss)

Fig. 3 Comparison of constructed and non-constructed litters according to vegetation types (C: constructed, NC: non-constructed, TTI: time-to-ignition, FS: flame spread, FH: max flame height, LD: litter depth)

Fig. 4 Proportions of the different litter components according to the five vegetation types in non-constructed samples

Fig. 5 Co-inertia analysis comparing the distribution of the characteristics of the litter samples and their flammability variables. The main figure indicates the groups of plots having similar litter and flammability characteristics (PC: Limestone Provence, MC: Acidic Provence). The grey ellipses include 95% of the plots of a specific group. Abbreviations for litter characteristics, flammability variables and sampling methods (LD: litter depth, BD: litter bulk-density, TTI: time-to-ignition, FD: flaming duration, S: flame spread, ROS: rate of spread, FH: max flame height, FT: mean flame temperature, RC: rate of consumption)

Fig. 6 Hierarchical cluster analysis based on the flammability variables recorded during the burning of the litter of the vegetation types studied (A: Non-constructed litters and B: Constructed litters)

