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Research Article

Testing Vegetation Flammability: The Problem of Extremely Low Ignition Frequency and Overall Flammability Score

Zorica Kauf,[1] Andreas Fangmeier,[1] Roman Rosavec,[2] and Željko Španjol[2]

[1] *Institute of Landscape and Plant Ecology, University of Hohenheim, August-von-Hartmann Straße 3, 70599 Stuttgart, Germany*
[2] *Department of Forest Ecology and Silviculture, Faculty of Forestry, University of Zagreb, Svetošimunska 25, 10002 Zagreb, Croatia*

Correspondence should be addressed to Zorica Kauf; zorica.kauf@uni-hohenheim.de

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In the recent decades changes in fire regimes led to higher vulnerability of fire prone ecosystems, with vegetation being the only component influencing fire regime which can be managed in order to reduce probability of extreme fire events. For these management practices to be effective reliable information on the vegetation flammability is being crucial. Epiradiator based testing methods are one of the methods commonly used to investigate vegetation flammability and decrease in ignition frequency is always interpreted as a decrease in flammability. Furthermore, gathered information is often combined into a single flammability score. Here we present results of leaf litter testing which, together with previously conducted research on similar materials, show that material with very low ignition frequency under certain testing conditions can be extremely flammable if testing conditions are slightly changed. Additionally, our results indicate that combining measured information into one single flammability score, even though sometimes useful, is not always meaningful and should be performed with caution.

1. Introduction

In recent decades land use coupled with climate change led to changes in the fire regime making fire prone ecosystems more vulnerable to wildfires [1, 2], with further shift towards more devastating fire regimes being predicted in the future [3, 4]. Fire regime is the result of complex interactions between ignitions, weather, topography, and vegetation acting as fuel [5–7]. Even though vegetation is rarely the most influential factor, it is the only one that can be managed in order to reduce the probability of occurrence of extreme wildfires [8]. To achieve this goal correct and reliable information on vegetation flammability is being crucial, becoming one of the essential components of fire risk assessment and management planning [9, 10]. Even though there are numerous lists of species based on their flammability [11–13], the complexity of vegetation flammability makes such a ranking challenging and resulting lists unreliable and possibly misleading [10].

Flammability is comprised of (i) ignitibility—the fuel ignition delay once exposed to heat, (ii) sustainability—the measure of how well a fire will continue to burn with or without the heat source, (iii) combustibility—the reflection of the rapidity with which a fire burns [14], and (iv) consumability—the proportion of mass or volume consumed by fire (Martin et al. 1994). There is currently no validated method of integrating all flammability components into one single index of plant flammability [15]. Furthermore, vegetation fuels are highly variable; their flammability changes with genotype, age, season, location, and material tested [8, 16].

Due to rising importance of reliable vegetation flammability information numerous researchers worked on quantifying it with studies ranging from field burning experiments [17, 18] and burning tables/benches [19–22] to individual leaf testing [16, 23]. In this effort a high number of testing procedures and measured parameters were associated with vegetation flammability. Nevertheless, results of laboratory scale testing as well as vegetation flammability as a concept were challenged due to the discrepancy between laboratory testing results, field testing, and modelling outputs [24]. Simultaneously, they were defended as an opportunity to better understand the influence of fire as a selective evolutionary force [25] and being a useful tool for providing basic information for assessing fire risk despite the inability to directly transfer testing results to a bigger scale [26].

Epiradiator based methods are often criticized for their low reproducibility [27] and low heat flux used [24]. Nevertheless, due to low technical demands and presumably straight-forward interpretation they were often used [20, 28–35]. Up to now they are providing valuable information and are contributing to our better understanding of vegetation flammability [26, 36, 37].

Most of the authors refer to Valette's [38] work as to the reference epiradiator based vegetation flammability testing method. This method attributes flammability score ranging from 0 (the lowest flammability) to 5 (extreme flammability) based on combined information on average ignition delay (average time elapsed between placing a sample on the epiradiator surface and appearance of flame) and ignition frequency (percentage of tests in which flame occurred). Decrease in ignition delay leads to increase in flammability score, whereas decrease in ignition frequency leads to its decrease. If ignition frequency is lower than 50%, material can be assigned only 0 and 1 flammability score regardless of ignition delay. Even when alternative interpretation of data is given [26, 32] or alternative testing method is used [39], its final intention is to give a single flammability score.

Comparing our results to those previously published, we tried to answer two questions.

(i) Does low ignition frequency guarantee low flammability?

(ii) Is it always meaningful to combine gathered information into one single flammability score?

2. Materials and Methods

2.1. Samples Gathering and Storing. Sampling was performed in the coastal region of Croatia. Leaf litter was gathered on May 15, 2010, in the Trstenik area (42°54′N, 17°23′E) on the southwest coast of the Pelješac peninsula, where samples of *Arbutus unedo* L. (strawberry tree), *Ceratonia siliqua* L. (carob), *Laurus nobilis* L. (laurel), *Olea europaea* L. (olive), *Pinus halepensis* Mill. (aleppo pine), *Pistacia lentiscus* L. (mastic), *Pittosporum tobira* Thunb. (Japanese mock orange), and *Quercus ilex* L. (holm oak) were collected.

Samples of *P. tobira* and *P. lentiscus* originated from two and four individual plants, respectively. All the other samples were gathered randomly across the sampling sites and were composed of material originated from more than ten individuals. Only whole leaves and bigger leaf fragments which could be ambiguously identified as belonging to species of interest were gathered; thus only the upper leaf litter layer was sampled. Material was stored in open paper bags, on a storage table, at room temperature and humidity until further processing. Position of samples was occasionally changed.

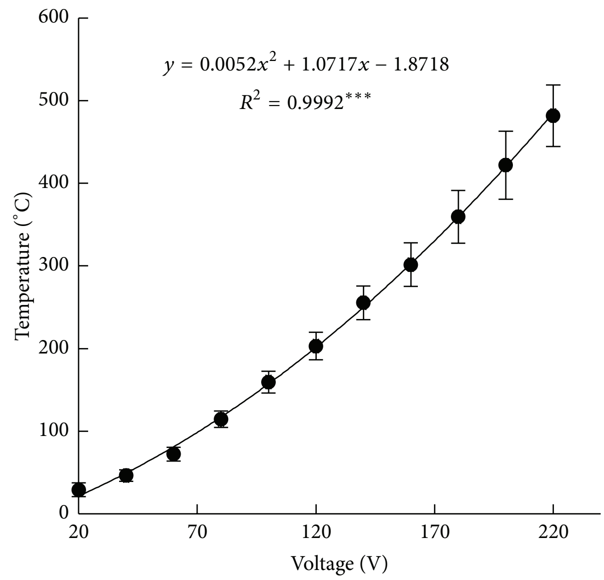

Figure 1: Relationship between input voltage and epiradiator surface temperature. Mean and standard deviation of 10 measurements per voltage input.

2.2. Flammability Testing. For flammability testing, a 500 W epiradiator with 10 cm diameter radiant disc and nominal surface temperature of 420°C was used as a heat source. It was connected to a variable voltage transformer allowing us to reduce and control surface temperature. While determining the voltage-temperature curve, it was observed that the actual temperature was higher than nominal temperature and varied substantially across the epiradiator surface (Figure 1). This was confirmed on three separated epiradiators, one being completely new. Thus, in order to ensure uniform start temperature, the same epiradiator (type 534 Rc2, Quartz Saint-Gobain) was used for all tests with its surface temperature being constantly measured and monitored at fixed point using a K-type temperature probe (GES 900, Greisinger) connected to a digital thermometer (GMH 3210, Greisinger). Additionally, during the process of determining the appropriate surface temperature-material amount combination, it was demonstrated that if the surface temperature rise during the test is substantial, the temperature does not drop back to the initial start temperature, regardless of the waiting time. To give an example for this effect: when testing 5 grams of leaf litter material at a start surface temperature of 500°C and waiting time between two consecutive tests sufficiently long for surface temperature to stabilise, after three successive tests the surface temperature stabilised at 590°C. Under these conditions, the ignition delay dropped from 5.65 seconds for the first test to 1.05 seconds for the third test, indicating that monitoring and stabilising the surface temperature is crucial for reducing systematic errors.

In order to capture the ignitability component of leaf litter flammability we aimed to achieve a higher ignition frequency than Petriccione et al. [34] and a longer ignition delay than Ormeño et al. [20]. Preliminary testing demonstrated that an increase in both epiradiator surface temperature and amount of material tested leads to an increase in ignition frequency; higher temperature results in shorter ignition delay and bigger amount of material tested in longer ignition delay.

After extensive pretesting we chose to test 3.0 ± 0.1 gram sample material at 400 ± 5°C epiradiator surface temperature, respectively. This combination led to 100% ignition frequency with relatively long ignition delay.

The chosen amount of test material formed a layer on the epiradiator surface for all the tested samples ensuring similar heat exposure despite varying surface temperature. After placement on the epiradiator surface samples surrounded the temperature probe, allowing us to use the same probe for measuring initial temperature of the epiradiator surface and temperature at the lower side of the leaf litter during a test. Samples were not additionally oven dried before flammability testing as final moisture content was attributed to intrinsic characteristics of materials governing their ability to retain moisture [40, 41].

The horizontal pilot flame was positioned 4.5 cm above the epiradiator surface. Four parameters were measured: (i) ignition delay (ID)—the time elapsed between placing a sample on the epiradiator surface and appearance of a flame, (ii) flame extinguish time (FET)—time elapsed between placing a sample on the epiradiator surface and end of the flaming combustion, (iii) ignition temperature (IT)—temperature measured at the moment of ignition, and (iv) max temperature (MT)—maximal temperature reached during the test. Flame residence time (FRT) was calculated as the difference between FET and ID, representing the duration of flaming combustion. ID is considered to be a measure of ignitability and FRT a measure of sustainability component of flammability [20, 36, 42]. FET is taken as an additional sustainability measure. IT was interpreted in relation to ID; MT, as it was measured at the bottom of the sample, could not be interpreted in light of flammability components, but provided limited information on heat transfer to the soil during wildfires. Flame intensity was not determined. Time variables were measured using a stopwatch.

Flammability testing was performed on September 5 and 6, 2010, with each sample being tested five times, once in every replication. Samples were tested in random order. Testing was performed in a closed room under a simple chamber, minimizing disturbance due to external air movement. The chamber was opened at the top to allow natural air convection and partially at one side to allow for sample manipulation.

2.3. Physical Measurements. Moisture content (MC), specific leas area (SLA), average area (AA), and average mass (AM) of the single particle are the physical parameters measured and reported. During flammability testing one or two subsamples per species, equal in size to the test samples, were taken. Their dry mass was determined by reweighting them after drying for 24 hours at 85°C and MC was expressed on dry weight basis [43]. After drying fragile leaf litter was soaked in warm tap water and flattened with cloths flatiron before its area was measured with a portable area meter. SLA was calculated by dividing leaf litter area by the corresponding dry mass; AM and AA were calculated dividing dry mass and area of the sample by the corresponding number of particles. An exception was made for *P. halepensis*, as needles were fragmented and the number of particles was difficult to count and it was estimated based on an even smaller subsample and set at 250.

2.4. Statistical Analysis. IBM SPSS Statistics 21 software was used for statistical analysis of gathered data. As all flammability parameters were normally distributed and had homogeneous variances on the species level one-way ANOVA was performed, followed by Duncan post hoc test in order to determine differences between species based on single parameters.

Regression analysis was performed to determine if any of the physical parameters influenced flammability and to what extent different flammability parameters were related. Overall significance of the regression analysis was checked by ANOVA; regression coefficients were tested with t-test against null hypothesis. A relationship between flammability parameters was considered important in order to give appropriate interpretation to collected data, whereas relationships between physical parameters and flammability were reported but are not discussed in detail here.

In order to account for combined influence of all measured parameters on fire behaviour hierarchical cluster analysis was performed using squared Euclidean distances of standardised values (0-1) of measured flammability characteristics (ID, IT, FET, and MT) to determine within-group linkage and try to attribute an overall flammability score to leaf litters of different species.

3. Results and Discussion

When choosing sample mass-temperature combination for our testing procedure we were aware of the argument that masses larger than 1 gram should not be tested with epiradiator based methods as properties such as fuel height could influence the results [20] as well as criticism directed towards the laboratory flammability tests and their use of low heat fluxes [24]. Nevertheless, we consider our testing combination to be acceptable as Anderson [14] stated that there is a clear relationship between sample height and ignition when holding sample density and specific heat constant. If mass is held constant, difference in heights and densities will be present between materials, with both influencing flammability, but also being governed by particle geometry—an inherent characteristic of the material. Furthermore, Fernandes [24] stated that heat fluxes measured during wildland fires are several orders of magnitude higher than that used in laboratory studies, yet still ignition sources do not need to have big heat fluxes. If ignition source has low heat flux (e.g., cigarette butt, sparks, firebrands, not completely extinguished grilling amber, etc.), flammability together with other material properties can have a relevant role in determining whether or not ignition occurs and how fast initial combustion process proceeds, as shown in research made by Ganteaume et al. on reconstructed [22] and undisturbed [39] leaf litters tested with standardised firebrand.

3.1. Means, ANOVA, and Regression Analysis. All five flammability parameters showed statistically significant differences between tested species (Table 1), with the highest level of significance obtained for ignition related parameters: ID and IT. *P. lentiscus* and *P. halepensis* had the shortest ID and were considered the most ignitable of the tested species, whereas *C. siliqua* had by far the longest average ID and was the least ignitable species in this study. *C. siliqua* was followed by *Q. ilex*, *O. europaea*, and *A. unedo*, which formed a group of species with intermediate ignitability as all of the members were significantly different from *P. halepensis*. *L. nobilis* and *P. tobira* were designated as fairly ignitable species as they did not show any significant difference in comparison to *P. halepensis* but had significantly longer ID when compared to *P. lentiscus*. ID and IT grouping results were similar, as could be expected for two parameters measuring the same flammability component and had significant positive linear regression (Figure 2(a)). Nevertheless, the two species *L. nobilis* and *O. europaea* showed substantial difference in their ordering when comparing ID and IT (Table 1). Furthermore, same species showed a deviation from ID-IT regression line with *L. nobilis* having higher and *O. europaea* lower IT in comparison with species with similar ID (Figure 2(a)). These results suggest that in the same time period *L. nobilis* releases more energy and *O. europaea* less energy in comparison with other species involved in this study.

When comparing our ignitability results to those previously published it was observed that *P. lentiscus*, the species with the shortest ID and the highest ignitability in our study, had no positive flammability tests and was identified as species with "null flammability" (ignition frequency = 0) when 1 gram of leaf litter was tested at the epiradiator temperature of 250°C [34]. These contrary results together with the fact that in the research performed by Petriccione et al. [34] leaf litter of four out of fourteen species was considered to have "null flammability" challenge data interpretation with respect to the correlation between low ignition frequency and low flammability.

When taken into consideration that leaf litter is among the most flammable vegetation fraction [44], it is unreasonable for such a big number of species as reported by Petriccione et al. [34] to be "nonflammable"; as small, disturbed samples especially were tested and thus oxygen limitation due to dense packing of the material is highly unlikely.

Vegetation combustion does not start with the appearance of a flame; rather, materials undergo thermal degradation before the start of flaming combustion [45, 46] and complete combustion is possible without flames ever appearing [44, 47]. Therefore, interpretation of negative tests should be reconsidered and testing combinations which do not yield sufficient number of positive tests should be regarded as inconclusive as they do not guarantee low fire hazard. Lack of ignition tells us that critical mass flux of fuel vapours for piloted ignition was not reached, but it does not tell us the reason. A very small amount of highly ignitable material tested at low heat flux can lead to a lack of ignition as release of fuel vapours starts at low temperature and low release rates shortly upon positioning of the sample on the heater surface. As pyrolysis proceeds, mass flux of fuel vapours will increase, but the possibility of complete combustion before a critical mass flux of fuel vapours is reached cannot be excluded. In the same time heat resistant material tested under similar conditions can be completely combusted before a critical mass flux of fuel vapours is reached. In this case due to very slow pyrolysis and slow increase in fuel vapour mass flux. We suggest that tests with extremely low ignition frequency to be repeated under different testing conditions (e.g., higher fuel load and/or heater temperature/external heat flux) or characteristics other than the appearance of a flame are monitored as well [46, 48]. Depending on the purpose of the research and the material tested, different combinations might be appropriate with extra caution being necessary when interpreting and comparing results derived from different testing procedures.

When discussing appropriate fuel load-heater temperature (external heat flux) it should be noted that at low heat fluxes glowing combustion precedes ignition and is necessary for augmenting the radiation heating and enabling ignition [49]. Furthermore, with decreasing heat flux a bigger amount of material needs to be combusted in order for ignition to occur [50]. Thus, to avoid complete preignition combustion of a sample an increased amount of material should be considered at low heat fluxes. Epiradiator testing of leaf litter samples bigger than 1 gram is justified as leaf litter naturally occurs in layers, presenting more or less continuous fuel patches, which even in very fragmented state have mass bigger than 1 gram and a fuel load higher than that corresponding to testing 1 gram at epiradiator with 10-centimetre diameter [18, 22, 51, 52].

Fewer differences with lower level of significance ($P > 0.001$) were found between species when examining sustainability related parameters. Regardless of the parameter used *L. nobilis* and *A. unedo* were shown to be the species with the lowest sustainability, whereas *P. tobira*, *O. europaea*, and *P. halepensis* were those species with the highest sustainability. Both parameters placed *P. lentiscus* and *Q. ilex* in-between these groups, but in case of FRT *P. lentiscus* was significantly different from the species with the lowest sustainability, whereas that was the case for *Q. ilex* with regard to flame extinguish time. Low sustainability of *L. nobilis* and high sustainability of *O. europaea* confirm that the former has fast energy release rate and the latter has slow energy release rate, as previously indicated by ID-IT results.

C. siliqua was the species that changed its order the most when comparing FRT and FET results. It was among the species with the lowest sustainability regarding FRT (ranking third) and among the species with the highest sustainability (ranking sixth) based on FET.

While similarities in grouping of species based on two different sustainability factors can be explained through their positive linear regression (Figure 2(b)), we were also interested in finding an explanation for differences in species ranking. When taking into consideration that a longer heating process results in an increase of ignition mass loss and ignition delay [53] it can be expected that larger differences in ignition delay will result in larger differences in masses still available for combustion at the moment of ignition. Thus, in cases where ID is relatively long and significantly different

Table 1: Mean values, standard deviations, results of ANOVA, and Duncan post hoc test for measured flammability parameters. Different letters indicating statistically significant differences at $P < 0.05$ level of probability.

	ID (s)			IT (°C)			FET (s)			FRT (s)			MT (°C)		
	Mean	St. dev.		Mean	St. dev.		Mean	St. dev.		Mean	St. dev.		Mean	St. dev.	
A. unedo	10.064	1.076	cde	402.8	2.59	abc	41.232	3.445	ab	31.168	3.637	ab	548.6	18.34	a
C. siliqua	14.758	1.481	f	419.2	13.14	d	47.458	2.977	bc	32.700	1.568	abc	556.2	15.45	a
L. nobilis	8.584	0.694	bcd	412.4	12.80	cd	37.084	3.359	ab	28.500	3.971	a	588.2	22.95	b
O. europaea	10.894	2.438	de	397.4	1.14	ab	49.622	7.970	c	38.728	6.616	bcd	557.4	20.38	a
P. halepensis	7.072	2.268	ab	396.6	8.08	ab	46.210	7.803	bc	39.138	7.018	cd	550.0	15.73	a
P. lentiscus	5.688	1.748	a	390.8	11.69	a	44.358	6.431	abc	38.670	7.134	bcd	545.2	9.76	a
P. tobira	8.172	1.997	bcd	398.2	5.93	ab	50.304	5.901	c	42.132	6.649	d	571.6	19.81	ab
Q. ilex	11.344	1.892	e	409.4	8.41	bcd	45.600	4.591	bc	34.256	4.469	abc	561.0	20.54	a
F		12.597			5.561			3.023			3.689			2.993	
P		<0.001			<0.001			0.015			0.005			0.016	

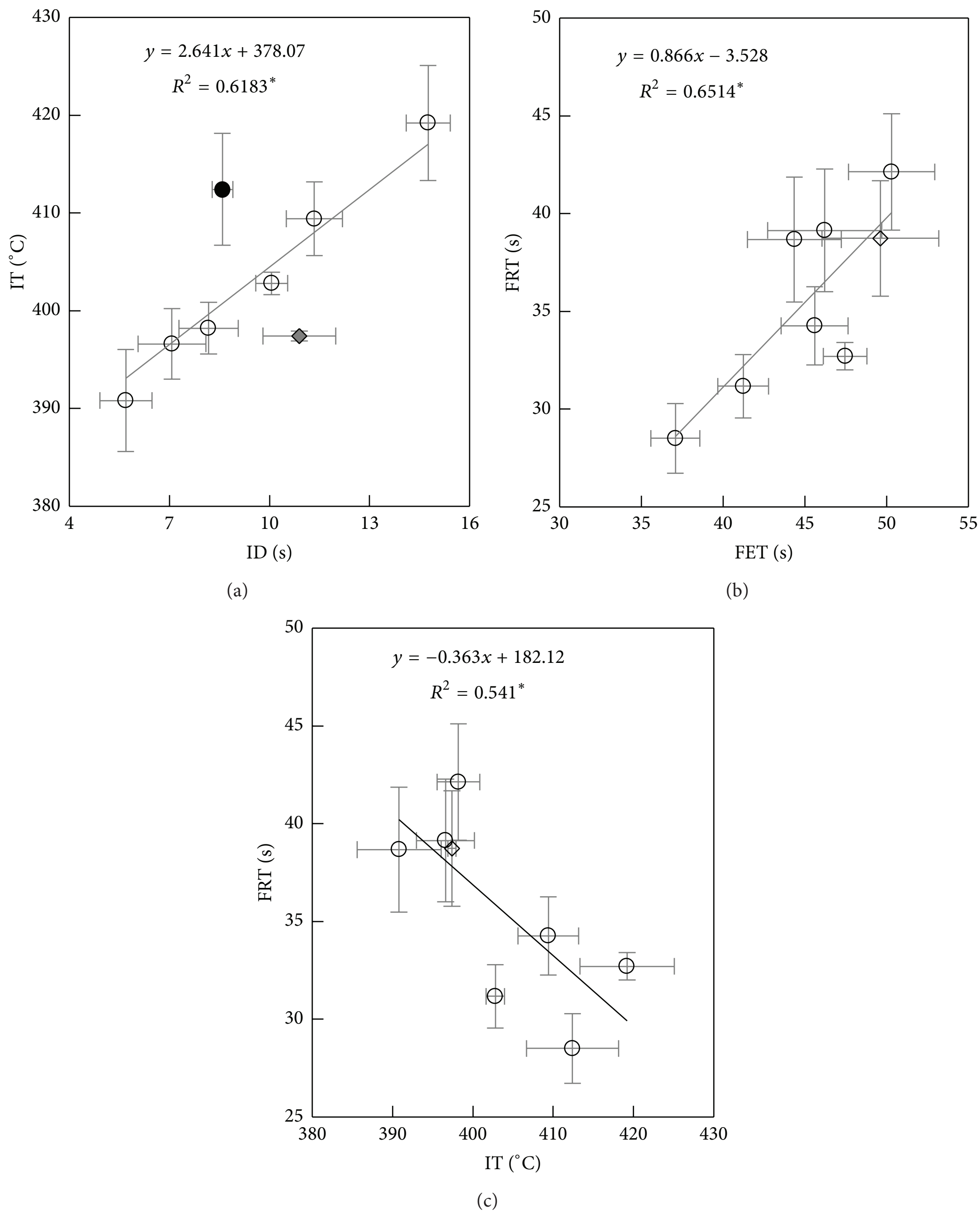

Figure 2: Significant liner regressions between flammability parameters. Points indicate mean values and error bars represent standard error. (a) Linear regression between ignitability related parameters ignition delay (ID) and ignition temperature (IT), with black data point indicating position of *L. nobilis* and grey data point indicating position of *O. europaea*. (b) Linear regression between sustainability related parameters flame extinguish time (FET) and flame residence time (FRT). (c) Liner regression between ignitability parameter ignition temperature (IT) and sustainability parameter flame residence time (FRT).

FRT might be distorted as a measure of sustainability and capture a portion of ignitability as well. This explanation is further reinforced by the significant negative linear regression between IT and FRT (Figure 2(c)), as mass needs to be combusted in order for temperature to increase. In our study the average ID of the species with the highest value was more than 2.5 times longer than that of the species with the shortest ID; thus differences in masses still available for combustion at the moment of ignition are very likely even when possible variations in energy release rate are taken into consideration. Nevertheless, in studies where ignition delays were short and there were no significant differences between them [20] the duration of flaming combustion might still be an appropriate measure of sustainability. In order to fully understand the influence of prolonged ID on FRT it might be useful to consider performing two series of epiradiator

Table 2: Physical parameters of tested leaf litter.

	SLA (cm^2/g)	AM (g)	AA (cm^2)	MC (%)
A. unedo	64.89	0.171	11.07	11.72
C. siliqua	72.19	0.232	16.75	13.03
L. nobilis	95.37	0.237	22.60	10.83
O. europaea	50.78	0.087	4.40	10.16
P. halepensis	33.43	0.011	0.36	11.47
P. lentiscus	61.15	0.023	1.43	9.55
P. tobira	74.51	0.095	7.05	9.77
Q. ilex	60.75	0.176	10.73	10.22

Table 3: Significant linear regressions between physical and flammability parameters.

Linear regression models $y = a + bx$					
y	a	b	x	r^2	P
SLA	522.121	0.587	MT	0.564	0.032
AM	41.387	−44.403	FRT	0.693	0.010
AA	40.479	−0.518	FRT	0.709	0.009
AA	393.198	1.092	IT	0.766	0.004

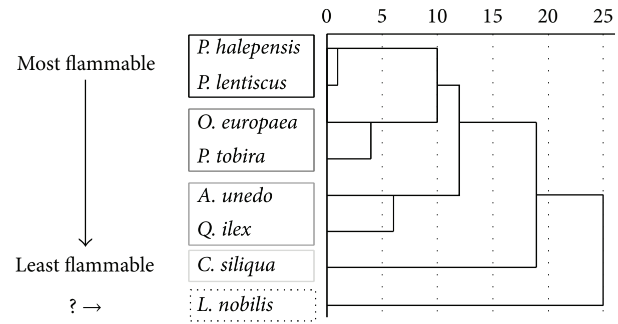

Figure 3: Hierarchical cluster analysis based on standardized measured flammability parameters: ignition delay (ID), ignition temperature (IT), flame extinguish time (FET), and maximal temperature (MT). Distances presented in the dendrogram are automatically rescaled by the SPSS software and thus the presented scale does not show the calculated distances.

tests for each material: one with prolonged ignition delay in order to capture the ignitability portion of flammability and another with extremely short ignition delay in order to capture sustainability while reducing the influence of differences in masses at the moment of ignition.

Out of the measured flammability parameters MT was the one that showed the least differences between species. It identified *L. nobilis* as the species that reached the highest maximal temperature. *P. tobira* did not significantly differ from any other species regarding maximal temperature reached. All the other species had significantly lower maximal temperature than *L. nobilis*, but no significant differences were found among them.

MC was the only physical parameter measured that had no significant influence on any of the flammability parameters (Table 2.). This can be attributed to the relatively small range of values with the minimum achieved for *P. lentiscus* being 9.55% and the maximum for *C. siliqua* being 13.03%. SLA showed a positive linear regression with MT (Table 3), whereas both AM and AA showed a negative relationship with FRT. AA also influenced IT, with an increase in single particle area leading to a higher ignition temperature.

3.2. Hierarchical Cluster Analysis. Based on hierarchical cluster analysis performed on four measured flammability parameters (ID, IT, FET, and MT) five separate clusters could be distinguished (Figure 3). *P. halepensis* and *P. lentiscus* formed the first cluster. On the single parameter bases they had the highest ignitability and intermediate to high sustainability in comparison to the other species tested (Table 1). A second cluster was formed by *O. europaea* and *P. tobira*, two species with the longest FET, which followed species from the first flammability group based on their IT and had a short to intermediate ID, indicating high sustainability and intermediate to high ignitability. *A. unedo* and *Q. ilex*, species from the third cluster, had intermediate to low both ignitability and sustainability. *C. siliqua* formed a fourth cluster with its relatively high sustainability when assessed by FET, the highest IT, and by far the longest ID—indicating species with remarkably low ignitability. All aforementioned species showed similar behaviour and it was possible to compare their flammability based on combined information and, if considered appropriately, attribute an overall flammability score with decreasing flammability from the first to the fourth cluster. Nevertheless, *L. nobilis* results were difficult to compare to the rest of the species. The most pronounced difference between *L. nobilis* and other species included in this study was its comparably faster energy release, which was shown through the shortest FET and FRT, highest MT, and higher IT in comparison to species with similar ID (Figure 2(a)). Combining this data we could conclude that *L. nobilis* was the least sustainable and intermediate to high ignitable species; but where does this information put *L. nobilis* in comparison to other species included in this research? Figure 3 shows that *L. nobilis* differs from any other species, but it does not tell us why and how this difference influences *L. nobilis* overall flammability score. This example raises a further question: can one single score describe the flammability of a material?

In our study we measured four flammability parameters, which could be attributed to two out of four components of vegetation flammability on small standardised samples of eight different leaf litters and were able to meaningfully compare seven species based on combined information. Ganteaume et al. [26], while performing epiradiator based testing of live vegetation, tested eight different materials and were able to attribute meaningful flammability scores to all the materials based on hierarchical cluster analysis that took into account ignition frequency, ignition delay, and flame residence time. Although the results of their analysis were meaningful and useful for the given situation, the included parameters did not account for all the flammability components.

In a different study which tested flammability of undisturbed leaf litters Ganteaumne et al. [39] also performed hierarchical cluster analysis based on four parameters (ignition frequency: IF, time to ignite: TTI, flaming duration: FD, and number of sides reached by the flame/flame spread: S). Even though we acknowledge the remarkable quality of the gathered data we disagree with its interpretation. In our opinion the clusters showed different relationship between flammability parameters which could not be transferred into single and comparable flammability score, similar to our own observations. For instance, in the mentioned work, the cluster containing *Prunus laurocerasus* L. was considered to be more flammable than that containing *Cupressus sempervirens* L. Nevertheless, when comparing values of the measured flammability parameters, only one out of four suggested this relationship between the species in question.

Hierarchical cluster analysis groups elements based on similarity of the measured parameters, maximising within group similarities and between group dissimilarities. Thus it can be expected that species in the same cluster will have similar fire behaviour and that the distance between clusters corresponds to differences in fire behaviour. Nevertheless, it does not tell us anything about the overall flammability score. Thus, attributing an overall flammability score depends strongly on the conclusions of the respective researcher and can only be done by taking into consideration the values of the input parameters on which the analysis is based.

If clustering or any other ranking based on combined information of different measured parameters is made, input parameters, limitations of the used method, and components of flammability taken into consideration should always be kept in mind when assessing output results. Furthermore, it can be expected that with every additional parameter and/or element (material, species, etc.) included into the analysis a meaningful interpretation of the combined results will be more difficult and more of the original information on the fire behaviour of material will be lost. Therefore, even though flammability assessment based on combined information can sometimes be useful, it should be performed with caution and should not be insisted upon.

4. Conclusions

The results presented here suggest that epiradiator testing with extremely low ignition frequency can occur in extremely flammable fuels if an inappropriate fuel load-heater temperature (external heat flux) combination is applied. The importance of these findings lies in the fact that wrongly identifying extremely flammable fuels as having low flammability can lead to misapprehension of vegetation characteristics influencing flammability and management practices with potentially adverse effects on the environment. It is our suggestion to treat tests with extremely low ignition frequency as inconclusive and retest materials yielding these results under different testing conditions or monitor characteristics other than the appearance of flame as well.

Performed clustering analysis showed that, even though sometimes useful, combining all the gathered vegetation flammability information into one single flammability score is not always meaningful. It should be performed with extra caution and should not always be insisted upon. In our study combining information of four measured parameters, which describe two out of four flammability components, allowed us to attribute comparable flammability scores to seven out of eight species included in this study. Nevertheless, in the case of *L. nobilis* we were unable to do so. As such, in this study, we preferred an explanatory comparison of species. Taking into consideration all the parameters in their original state allowed us to compare species based on their ignitability, sustainability, and energy release rates.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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References

[1] A. Badia, D. Saurí, R. Cerdan, and J. Llurdés, “Causality and management of forest fires in Mediterranean environments: an example from Catalonia,” *Environmental Hazards*, vol. 4, no. 1, pp. 23–32, 2002.

[2] J. González-Olabarria and T. Pukkala, “Integrating fire risk considerations in landscape-level forest planning,” *Forest Ecology and Management*, vol. 261, no. 2, pp. 278–287, 2011.

[3] J. Piñol, J. Terradas, and F. Lloret, “Climate warming, wildfire hazard, and wildfire occurrence in coastal Eastern Spain,” *Climatic Change*, vol. 38, no. 3, pp. 345–357, 1998.

[4] R. Marzano, E. Lingua, and M. Garbarino, “Post-fire effects and short-term regeneration dynamics following highseverity crown fires in a Mediterranean forest,” *IForest*, vol. 5, no. 3, pp. 93–100, 2012.

[5] R. C. Rothermel, “How to predict the spread and intensity of forest and range fires,” USDA General Technical Report INT-143, Intermountain Forest and Range Experiment Station, Ogden, Utah, USA, 1983.

[6] F. Moreira, O. Viedma, M. Arianoutsou et al., “Landscape—wildfire interactions in southern Europe: implications for landscape management,” *Journal of Environmental Management*, vol. 92, no. 10, pp. 2389–2402, 2011.

[7] P. M. Fernandes, “Fire-smart management of forest landscapes in the Mediterranean basin under global change,” *Landscape and Urban Planning*, vol. 110, no. 1, pp. 175–182, 2013.

[8] L. G. Fogarty, *A Flammability Guide for Some Common New Zealand Native Tree and Shrub Species*, Forest Research Bulletin no. 197, Forest and Rural Fire Scientific and Technical Series Report no. 6, New Zealand Fire Service Commission and National Rural Fire Authority, Wellington, New Zealand, 2001.

[9] A. P. Dimitrakopoulos, “Thermogravimetric analysis of Mediterranean plant species,” *Journal of Analytical and Applied Pyrolysis*, vol. 60, no. 2, pp. 123–130, 2001.

[10] R. H. White and W. C. Zipperer, “Testing and classification of individual plants for fire behaviour: plant selection for the

wildlandurban interface," *International Journal of Wildland Fire*, vol. 19, no. 2, pp. 213–227, 2010.

[11] S. Fitzgerald and A. J. Waldo, *Fire-Resistant Plants for Oregon Home Landscapes*, Forest Resource Note No. 6, Oregon State University Extentsion Service, Salem, Ore, USA, 2001.

[12] L. Lorenson and K. Callahan, *Firewise Plants for Western Nevada County*, Fire Safe Council of Nevada County, Grass Valley, Nev, USA, 2010.

[13] C. Lippi and M. Kuypers, *Making Your Landscape More Resistant to Wildfires*, Institute of Food and Agricultural Sciences, University of Florida, Bunnell, Fla, USA, 1998.

[14] H. E. Anderson, "Forest fuel ignitibility," *Fire Technology*, vol. 6, no. 4, pp. 312–319, 1970.

[15] A. L. Behm, A. J. Long, M. C. Monroe, C. K. Randall, W. C. Zipperer, and L. A. Hermansen-Baez, *Fire in the Wildland-Urban Interface: Preparing a Firewise Plant List for WUI Residents*, Circular 1453, Institute of Food and Agricultural Sciences, University of Florida and Southern Center for Wildland-Urban Interface Research and Information, Southern Research Station, USDA Forest Service, Gainesville, Fla, USA, 2011.

[16] A. M. Gill and P. H. R. Moor, "Ignitability of leaves of Australian plants," A Contract Report to the Australian Flora Fundation, Centre for Plant Biodiversity Research, CSIRO Plant Industry, Canberra, Australia, 1996.

[17] C. D. Grant, W. A. Loneragan, J. M. Koch, and D. T. Bell, "Fuel characteristics, vegetation structure and fire behaviour of 11–15 year-old rehabilitated bauxite mines in Western Australia," *Australian Forestry*, vol. 60, no. 3, pp. 147–157, 1997.

[18] D. P. Ellair and W. J. Platt, "Fuel composition influences fire characteristics and understorey hardwoods in pine savanna," *Journal of Ecology*, vol. 101, no. 1, pp. 192–201, 2013.

[19] F. Morandini, Y. Perez-Ramirez, V. Tihay, P. Santoni, and T. Barboni, "Radiant, convective and heat release characterization of vegetation fire," *International Journal of Thermal Sciences*, vol. 70, pp. 83–91, 2013.

[20] E. Ormeño, B. Céspedes, I. A. Sánchez et al., "The relationship between terpenes and flammability of leaf litter," *Forest Ecology and Management*, vol. 257, no. 2, pp. 471–482, 2009.

[21] P. Santoni, F. Morandini, and T. Barboni, "Determination of fireline intensity by oxygen consumption calorimetry," *Journal of Thermal Analysis and Calorimetry*, vol. 104, no. 3, pp. 1005–1015, 2011.

[22] A. Ganteaume, C. Lampin-Maillet, M. Guijarro et al., "Spot fires: fuel bed flammability and capability of firebrands to ignite fuel beds," *International Journal of Wildland Fire*, vol. 18, no. 8, pp. 951–969, 2009.

[23] J. D. Engstrom, J. K. Butler, S. G. Smith, L. L. Baxter, T. H. Fletcher, and D. R. Weise, "Ignition behavior of live California chaparral leaves," *Combustion Science and Technology*, vol. 176, no. 9, pp. 1577–1591, 2004.

[24] P. M. Fernandes and M. G. Cruz, "Plant flammability experiments offer limited insight into vegetation-fire dynamics interactions," *New Phytologist*, vol. 194, no. 3, pp. 606–609, 2012.

[25] J. G. Pausas and B. Moreira, "Flammability as a biological concept," *New Phytologist*, vol. 194, no. 3, pp. 610–613, 2012.

[26] A. Ganteaume, M. Jappiot, C. Lampin, M. Guijarro, and C. Hernando, "Flammability of some ornamental species in wildland-urban interfaces in southeastern France: laboratory assessment at particle level," *Environmental Management*, vol. 52, no. 2, pp. 467–480, 2013.

[27] S. Liodakis, T. Kakardakis, S. Tzortzakou, and V. Tsapara, "How to measure the particle ignitability of forest species by TG and LOI," *Thermochimica Acta*, vol. 477, no. 1-2, pp. 16–20, 2008.

[28] G. A. Alessio, J. Peñuelas, M. De Lillis, and J. Llusià, "Implications of foliar terpene content and hydration on leaf flammability of *Quercus ilex* and *Pinus halepensis*," *Plant Biology*, vol. 10, no. 1, pp. 123–128, 2008.

[29] D. Alexandrian and E. Rigolot, "Sensibilité du pin d'Alep à l' incendie," *Forêt Méditerranéenne*, vol. 13, no. 3, pp. 185–198, 1992.

[30] P. Delabraze and J. Valette, ""The use of fire in silviculture ," in Proceedings of the Symposium on Dynamics and Management of Mediterranean-Type Ecosystems; June 22–26, 1981; San Diego, CA, pp. 475–482," General Technical Report PSW-GTR-058, USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif, USA, 1982.

[31] A. Ganteaume, M. Guijarro, M. Jappiot et al., "Laboratory characterization of firebrands involved in spot fires," *Annals of Forest Science*, vol. 68, no. 3, pp. 531–541, 2011.

[32] M. Hachmi, A. Sesbou, H. Benjelloun, N. El Handouz, and F. Bouanane, "A simple technique to estimate the flammability index of moroccan forest fuels," *Journal of Combustion*, vol. 2011, Article ID 263531, 11 pages, 2011.

[33] C. Moro, "Inflammabilité, matériels et méthodes," INRA's methodology, Internal report, Version 26/10/94, modified 27/01/04, French Mediterranean Forest Research Institute, INRA, Avignon, France, 2004.

[34] M. Petriccione, C. Moro, and F. A. Rutigliano, "Preliminary studies on litter flammability in Mediterranean region," in *Proceedings of the 5th International Conference on Forest Fire Research*, D. X. Viegas, Ed., ADAI, Figueira da Foz , Portugal, 2006.

[35] S. Saura-Mas, S. Paula, J. G. Pausas, and F. Lloret, "Fuel loading and flammability in the Mediterranean Basin woody species with different post-fire regenerative strategies," *International Journal of Wildland Fire*, vol. 19, no. 6, pp. 783–794, 2010.

[36] M. Blackhall, E. Raffaele, and T. T. Veblen, "Is foliar flammability of woody species related to time since fire and herbivory in Northwest Patagonia, Argentina?" *Journal of Vegetation Science*, vol. 23, no. 5, pp. 931–941, 2012.

[37] J. G. Pausas, G. A. Alessio, B. Moreira, and G. Corcobado, "Fires enhance flammability in Ulex parviflorus," *New Phytologist*, vol. 193, no. 1, pp. 18–23, 2012.

[38] J. Valette, "Inflammabilités des espèces forestières méditerranéennes. Conséquences sur la combustibilité des formations forestières," *Revue Forestière Française*, vol. 42, pp. 76–92, 1990.

[39] A. Ganteaume, M. Jappiot, and C. Lampin, "Assessing the flammability of surface fuels beneath ornamental vegetation in wildland-urban interfaces in Provence (south-eastern France)," *International Journal of Wildland Fire*, vol. 22, no. 3, pp. 333–342, 2013.

[40] J. K. Kreye, J. M. Varner, J. K. Hiers, and J. Mola, "Toward a mechanism for eastern North American forest mesophication: differential litter drying across 17 species," *Ecological Applications*, vol. 23, no. 8, pp. 1976–1986, 2013.

[41] H. E. Anderson, "Predicting equilibrium moisture content of some foliar forest litter in the northern Rocky Mountains," USDA Forest Services Research Paper INT-429, Intermountain Research Station, Ogden, Utah, USA, 1990.

[42] A. Ganteaume, J. Marielle, L. Corinne, C. Thomas, and B. Laurent, "Effects of vegetation type and fire regime on flammability

of undisturbed litter in Southeastern France," *Forest Ecology and Management*, vol. 261, no. 12, pp. 2223–2231, 2011.

[43] N. C. Turner, "Techniques and experimental approaches for the measurement of plant water status," *Plant and Soil*, vol. 58, no. 1–3, pp. 339–366, 1981.

[44] L. F. DeBano, D. G. Neary, and P. F. Ffolliott, *Fire's Effects on Ecosystems*, John Wiley & Sons, New York, NY, USA, 1998.

[45] L. Trabaud, "Inflammabilité et combustibilité des principales espèces des garrigues de la région méditerranéennes," *Oecologia Plantarum*, vol. 11, no. 2, pp. 117–136, 1976.

[46] M. Bernard and N. Nimour, "Inflammabilité des vegetaux Méditerranéens et feux de forêts: rôle de l'eau sur exothermicité de leur réaction," *Science Technique Technologie*, vol. 26, pp. 24–30, 1993.

[47] P. Delabraze and J. Valette, "Inflammabilité et combustibilité de la végétation forestière méditerranéenne," *Revue Forestière Française*, vol. 26, pp. 171–177, 1974.

[48] G. Massari and A. Leopaldi, "Leaf flammability in Mediterranean species," *Plant Biosystems*, vol. 132, no. 1, pp. 29–38, 1998.

[49] J. G. Quintiere, *Fundamentals of Fire Phenomena*, John Wiley & Sons, Chichester, UK, 2006.

[50] A. Atreya, "Ignition of fires," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 356, no. 1748, pp. 2787–2813, 1998.

[51] T. Curt, A. Schaffhauser, L. Borgniet et al., "Litter flammability in oak woodlands and shrublands of southeastern France," *Forest Ecology and Management*, vol. 261, no. 12, pp. 2214–2222, 2011.

[52] A. L. Behm, M. L. Duryea, A. J. Long, and W. C. Zipperer, "Flammability of native understory species in pine flatwood and hardwood hammock ecosystems and implications for the wildland-urban interface," *International Journal of Wildland Fire*, vol. 13, no. 3, pp. 355–365, 2004.

[53] J. L. Consalvi, F. Nmira, A. Fuentes, P. Mindykowski, and B. Porterie, "Numerical study of piloted ignition of forest fuel layer," *Proceedings of the Combustion Institute*, vol. 33, no. 2, pp. 2641–2648, 2011.