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Evaluation of Forest Fuel Flammability and Combustion Properties with an Adapted Mass Loss Calorimeter Device

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ABSTRACT: An adapted bench-scale Mass Loss Calorimeter (MLC) device for evaluating forest fuel flammability and combustion properties is proposed. This fire test apparatus consists of an MLC fitted with a chimney containing a thermopile. After the thermopile output has been calibrated by use of a methane burner, these data are used to quantify heat release, as an alternative to the classical measurement of oxygen consumption due to combustion. The results showed good repeatability and reasonable approximation to HRR values obtained with a cone calorimeter, and also demonstrated that each variable analyzed was significantly affected by the species considered.

KEY WORDS: calorimetry, forest fuels flammability, heat release rate, rapid flaming combustion, porous fuels, thermopile.

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Los Angeles, London, New Delhi and Singapore

INTRODUCTION

COMBUSTION AND FLAMMABILITY studies have been carried out with different techniques and methodologies in order to characterize thermal degradation and heating value of forest fuels (e.g. [1–5]), to detect differences in flammability of species [6–10] and to evaluate the combustion process on different scales [11–13]. Such results may be useful for improving inputs to fire behavior models [14–16], and to assess fuel hazard [17,18].

Forest fuel combustion is a complex process with multiple interrelated components, some of which have not yet been measured. Consequently, theoretical modeling efforts for fire development are restrained by limitations in the understanding of the physical and chemical processes that take place during combustion [19].

From a scientific point of view, experimental data on ignition and combustion will serve to improve physical aspects of modeling of fire behavior and effects, which in turn will help the study of wildfire initiation, as well as other aspects of fire. From an applied point of view, these reference data on fuel flammability will be an important input to dynamic maps of ignition risk (www.fireparadox.org).

The Heat Release Rate (HRR) of a fuel is one of the most important characteristics for understanding the combustion process, fire characteristics and fire propagation rates [20]. This characteristic could be used by wildfire modellers to predict the spread and intensity of fire and hazard on the basis of results obtained for a particular species [14]. Bench-scale tests are the first step in understanding the combustion process in forest fuels. Calorimetry studies for measuring the amount of heat release have typically been carried out in an oxygen consumption calorimeter known as the cone calorimeter [21,22].

Anderson [23] divided the flammability process into three components: ignitability, sustainability and combustibility, to assist in understanding the process. Martin et al. [24] included a fourth component, consumability. According to Dibble et al. [9], these four components can be evaluated in a bench-scale calorimeter test. The ignitability is obtained by recording the Time to Ignition (TTI) of the test sample. The sustainability depends on the ignition characteristics of the fuel and the heat evolved in the combustion, which can be evaluated through the Average Effective Heat of Combustion (AEHC) and the Total Heat Release (THR). The combustibility is an indicator of the rapidity of the fuel combustion, and thus the Peak Heat Release Rate (PHRR) is an appropriate variable for evaluating this process. Finally, the consumability under specified test conditions can be evaluated by recording the Residual Mass Fraction (RMF).

The cone calorimeter is intended for testing commercial products in accordance with ISO 5660-1 standard [25], but there is no universally accepted methodology for forest fuels. Many approaches have therefore been evaluated for applying this device to the study of these types of fuels (see reviews in [9,11,12]).

Some method-related problems have been reported to affect the results [6,9,12], for example, confinement of the cone calorimeter sample holder, the incident heat flux selected, the sample structure, the sample surface exposed to the cone, the initial sample mass, the thickness of the layer of test material and the fuel moisture content. These studies illustrate many of the difficulties leading to inconsistent results in the analysis of wildland fuel flammability and combustion properties [20].

The aim of the present study was to propose an adapted bench-scale Mass Loss Calorimeter (MLC) device for evaluating forest fuel flammability and combustion properties. In this fire test apparatus, a chimney containing a thermopile was added to the MLC and used to quantify heat release, as an alternative approach to the classical measurement of oxygen consumption due to combustion. This is one of the most outstanding characteristics of the device.

The study was organized in the following stages: (i) Test of the accuracy of the adapted bench-scale methodology to demonstrate the influence of the sample holder confinement; (ii) Analysis of the effect of different species on the results, by use of a porous sample holder to obtain rapid flaming combustion.

This study is a part of a more comprehensive research on the flammability and combustion of European forest fuels (www.fireparadox.org).

MATERIALS AND METHODS

Materials

Series of tests were conducted with the adapted bench-scale MLC device, to study a set of four forest fuels: *Pinus pinaster* Ait. (Maritime pine), *Pinus halepensis* L. (Aleppo pine), *Quercus coccifera* L. (Kermes oak) and *Pleurozium schereberi* (Brid.) Mitt. (Feather moss). Some characteristics of the forest fuels used for tests are shown in Table 1. The species are representative and very common in European Mediterranean (*Pinus* sp. and *Quercus* sp.) and Boreal (*Pleurozium* sp.) forests.

Table 1. Characteristics of forest fuel samples tested with the adapted MLC device.

Species names	Growth habitat	Plant parts collected	SAV[a] (cm^{-1})	GHC[b] (MJ/kg)
Pinus pinaster	Tree	Needle litter	47.4[c]	21.55
Pinus halepensis	Tree	Needle litter	81.7[c]	22.31
Quercus coccifera	Tree, shrub	Twigs and leaves	27.8[c] 59.2[c]	19.68[e]
Pleurozium schereberi	Moss	Carpet sample	115[d]	19.82[e]

[a]SAV = Surface area-to-volume ratio.
[b]GHC = Gross heat of combustion obtained by bomb calorimeter (CIFOR-INIA laboratory).
[c][26].
[d]Average value for non-vascular plants (mosses and lichens) [27].
[e]The difference between GHC are lower than the uncertainty , (0.15 MJ kg^{-1}), therefore we can assume the same value for the gross heat of combustion.

Description of the Device

The Mass Loss Calorimeter (MLC) is manufactured by Fire Testing Technology Limited (FTT®). This apparatus is the complete fire model of the cone calorimeter, which has assumed a dominant role in bench-scale fire testing of building materials. An introduction to and a description of cone calorimeter technology is provided by Babrauskas [22].

The MLC enables thermal exposure studies to be carried out under the same precise exposure conditions as those used in the cone calorimeter, whilst observing the sample reaction and measuring the mass loss changes at any heat flux condition defined within the internationally recognized cone calorimeter fire model [25]. The apparatus consists of two main components: (i) the cone assembly and (ii) the control unit (Figure 1):

(1) Stainless steel cone assembly, comprising:

- Conical heater with a variable heat flux of 10–100 kW/m^2
- 3-thermocouple sockets for cone control
- Heat shutter mechanism with hand operated lever
- Load cell with sample capacity of 500 g
- Adjustable specimen mounting for horizontal samples up to 50 mm thick
- Spark ignition assembly with hand operated lever
- Water cooling collar for cone
- Fluxmeter and housing

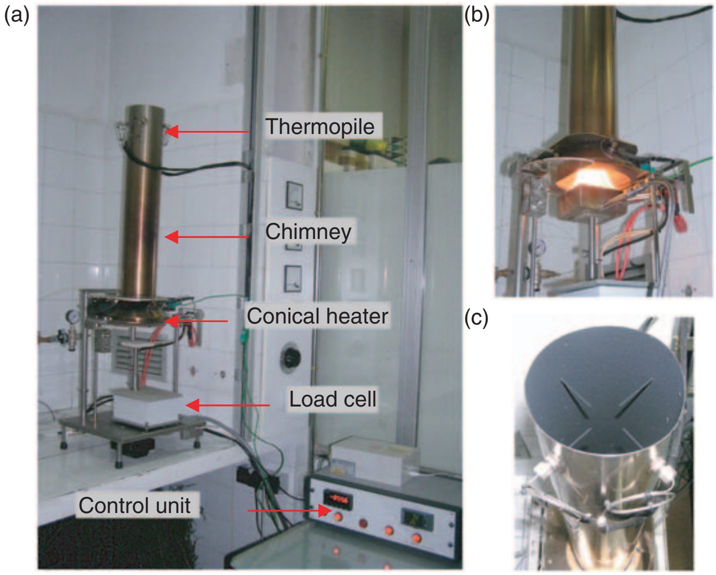

Figure 1. (a) General view of the experimental device, (b) detail of methane burner used to calibrate the thermopile, (c) detail of the thermopile.

(2) Control unit, comprising:

- Switches for power, ignition, load cell and conical heater
- Temperature controller with digital readout
- Load cell controller with digital readout and electronic tare

A chimney (Figure 1), manufactured from stainless steel (600 mm long × 114 mm inner diameter) and containing a thermopile of four mineral insulated inconel sheathed thermocouples (type K, 1.6 mm diameter), was added to the MLC (550 mm above the conical heater). The thermopile output is first calibrated by use of a methane burner and two flowmeters, and then used to quantify heat release [28].

The following measurements are made with the Mass Loss Calorimeter device:

- Time to ignition, TTI (s)
- Heat release rate, HRR (kW/m^2)
- Peak heat release rate, PHRR (kW/m^2)
- Total heat release, THR (MJ/m^2)
- Average effective heat of combustion, AEHC (MJ/kg)
- Residual mass fraction, RMF (%)

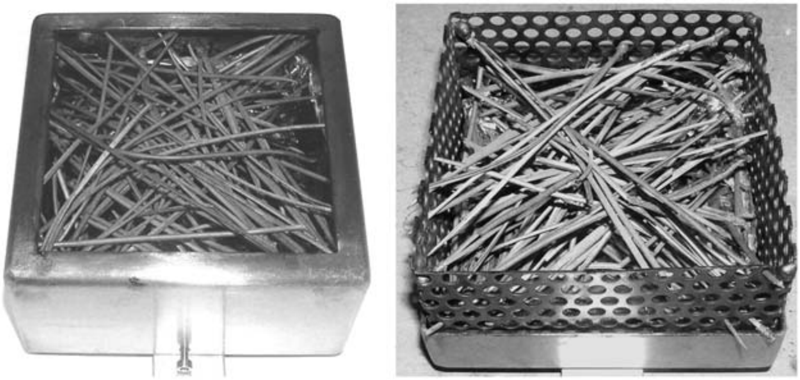

Figure 2. Standard holder (left) and porous holder (right) with samples of Pinus pinaster needles immediately before a test.

As mentioned in the Introduction, these are the most important properties in terms of wildfires because they are related to the four flammability components identified by Anderson [23] and Martin et al. [24].

The MLC standard sample holder contains low density ceramic wool to ensure the correct positioning of the samples, 25 mm from the conical heater and the sample is placed on aluminium foil. A specific holder adapted for forest fuels samples was also designed [20]. The holder ($10 \times 10 \times 5\,\text{cm}^3$) is made of stainless steel and has small uniformly sized holes over the entire outer surface (sides and bottom). These holes create an open space (63% porosity) for inlet combustion gases to pass into the holder and through the fuel samples (Figure 2).

Heat Release Rate Calibration

This procedure must be performed for each heat flux that will be used in the unit. In order to determine the response of the thermopile, a given flow of methane gas (99% purity) is burnt under the chimney and the thermopile signal recorder. Typically the HRR for methane is:

$$27.83\,\text{cm}^3/\text{s} = 1\,\text{kW} \tag{1}$$

The calibration is performed for 9 flows of methane corresponding to 5 kW, 4 kW, 3 kW, 2 kW, 1 kW, 0.75 kW, 0.5 kW, 0.25 kW, and 0 kW. With these calibration values, the average value of the thermopile signal outputs (mV) can be used as an approximation of heat release (kW) when performing tests on the apparatus. The calibration values of mV

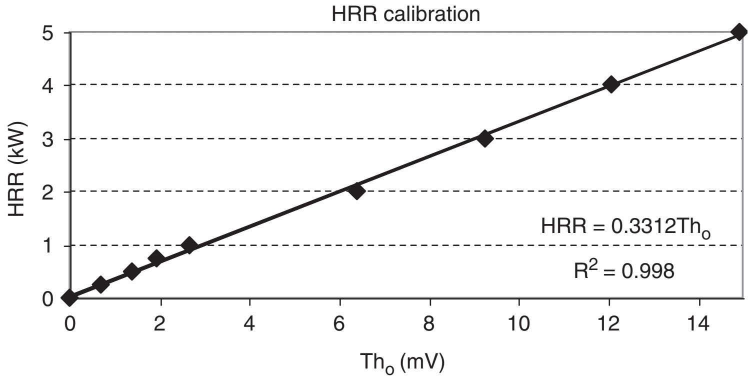

Figure 3. HRR calibration line for heat flux of 50 kW/m^2. Th$_o$ is the change in thermopile output relative to the baseline generated at a heat flux of 50 kW/m^2.

output should be checked periodically. A calibration line for a constant heat flux of 50 kW/m^2 is shown in Figure 3.

Experimental Method

Checking the Device: HRR Repeatability Measurements and Effect of Holder Porosity

The implementation of the MLC was performed through a first series of tests conducted with *Pinus pinaster* Ait. dead needles, aimed at establishing the experimental procedure and testing the repeatability of the HRR measurements under different experimental conditions. A factorial design with two levels for each initial condition, fuel moisture content (FMC) and initial sample mass (ISM), was selected. In order to obtain significant differences between HRR curves, the two selected levels of FMC were fixed, as follows: samples were oven-dried at 60°C, or stored in a chamber at 23°C and 50% of relative humidity (standard conditions for fire tests of building materials). The resulting FMCs were ~0% and ~9% respectively. These values were calculated on the oven-dry basis, after drying the samples at 60°C to constant weight. This conditioning protocol was selected because full oven-drying of the samples at 100°C can result in the loss of volatile substances before the test. The two selected levels of initial sample mass were 8 g and 15 g. The resulting thicknesses of these initial masses of the samples were 1.3 cm and 1.8 cm respectively. In accordance with the holder surface (0.00884 m^2), these experimental conditions correspond to bulk densities of 70 kg/m^3 and 94 kg/m^3 respectively. Five replicates were tested for each condition, so that a total of 20 tests were included in the analysis. The electric conical heater was established to expose the samples to a constant heat flux of 50 kW/m^2. The MLC standard sample holder (0% porosity) was used in the tests. As *P. pinaster* needles are longer than the sample holder, they were trimmed to fill the holder, and uniformly covered its exposed surface area [29] (Figure 2). The initial mass of the sample was measured immediately before the sample was placed under the heater. The spark igniter was used to provide the piloted ignition.

A second series of tests was conducted with *Pinus pinaster* Ait. dead needles, in order to evaluate the influence of holder porosity on the results. The MLC standard sample holder (0% porosity) and the adapted design porous holder (63% porosity) were used. In this series, to avoid the effect of the factors (FMC and ISM) considered in the previous tests, only one value for each factor was selected: 10 g samples were oven dried at 60°C. Sample thickness was fixed at 5 cm, and therefore in accordance with the volume of the holder, these experimental conditions correspond to a bulk density of 20 kg/m^3. Enninful and Torvi [30] also proposed fixing the bulk density in order to compare HRR in different species.

The other test conditions and methodological procedures were exactly the same as described for the first series of tests. Five replicates were tested for each condition, so that a total of 10 tests were included in the analysis.

Effect of the Species on Flammability and Combustion Properties

A third series of tests was conducted with a set of four forest fuels: *Pinus pinaster* Ait., *Pinus halepensis* L., *Quercus coccifera* L. and *Pleurozium schereberi* (Brid.) Mitt. (Table 1), in order to analyze how the flammability and combustion properties were affected by the species considered. The adapted porous holder (63% porosity) was used in this series of tests.

Like *P. pinaster,* the samples of *P. halepensis* and *Q. coccifera* also had to be trimmed. In order to reduce the effect of initial sample mass and fuel moisture on the HRR results, the mass was fixed at 10 g and FMC was fixed at ~0% for all samples. In accordance with the volume of the holder, this mass corresponds to a bulk density of 20 kg/m^3. The rest of the test conditions and methodological procedures were exactly the same as described for the first and second series of tests. Five replicates were tested for each condition, that is a total of 20 tests.

Statistical Analysis

HRR Repeatability Measurements

According to the ISO 5725 guidelines [31], repeatability is defined as:

$$r = 2.8sr \tag{2}$$

The relative repeatability standard is defined as:

$$r_r = \frac{sr}{m} \tag{3}$$

Thus, the relative repeatability can be defined as:

$$r(\%) = 2.8\left(\frac{sr}{m}\right) \tag{4}$$

Where *r* is the repeatability, *sr* is standard deviation of the repeatability, *m* is the value analyzed and the factor 2.8 arises from the probability level of 95% specified. From the results of the interlaboratory trials, values of repeatability were calculated as a function of the overall mean replicates [22]. For this study, the results of the SBI round robin test series, conducted by 15 laboratories [32], were considered to analyze the reliability of the heat release rate measurements (relative repeatability for PHRR and THR must be lower than 16.8% and 10.3% respectively). Other uncertainty criteria for cone calorimeter round robin tests have been established by Janssens [14], who considered that the relative repeatability for PHRR and THR must be lower than 17% and 8% respectively. All criteria were applied here to evaluate the repeatability of tests series. At least three tests that comply with repeatability criteria were required for ratification of the results. This criterion is similar to that requested by other normalized laboratory tests, such as the standard test method for determining calorific value with a bomb calorimeter (ISO 1928 [33]; at least 3 replicates with a relative repeatability of 1%).

Comparison of Combustion and Flammability Properties

The results of the series of tests were analyzed by ANOVA. Models were fitted with least-squares means (LSD) calculated for each factor (the significance value used in all analyses was 95%). Results are the curves of HRR plotted against time (1 s frequency) and numerical results from these curves include PHRR and THR. The parameters selected as dependent variables in the third series of tests were TTI, PHRR, THR, AEHC and RMF. For results that are reported on a sample area basis (HRR, kW/m^2), the area opening of the standard holder frame ($0.00884\,m^2$) and porous holder ($0.01\,m^2$) were used in the calculations.

RESULTS

Testing the Device: HRR Repeatability Measurements and Effect of Holder Porosity

The repeatability of PHRR and THR results for the first series of tests is shown in Table 2. The values obtained for both variables comply with repeatability criteria. On the other hand, the effect of the selected factors on the variables were analyzed by two-way ANOVA. This analysis revealed significant differences in PHRR for the FMC factor ($F = 7.08$; $p = 0.0228$) and interactions between FMC and initial sample mass ($F = 4.11$; $p = 0.0772$). Significant differences in THR for the ISM factor ($F = 2011.30$; $p = 0.0000$) and interactions ($F = 7.93$; $p = 0.0226$) were also detected.

The second series of tests conducted to evaluate the effect of the holder porosity showed that the values of PHRR and THR comply with repeatability criteria for the standard holder; outliers were observed for

Table 2. Descriptive statistics and repeatability for Peak Heat Release Rate (PHRR, kW/m^2) and Total Heat Release (THR, MJ/m^2) in the first series of tests ($n = 20$).

Factors			Descriptive statistics					Uncertainty		
FMC (%)	ISM (g)		Mean	Max	Min	Range	*sr*	r_r[a] (%)	r[b] (%)	*r* limit[c]
0	15	PHRR	337.12	355.47	312.72	42.75	20.01	5.93	16.62	61.62
		THR	20.54	20.85	20.39	0.46	0.29	1.45	4.06	0.81
9	15	PHRR	292.63	309.91	282.38	27.53	15.05	5.14	14.39	37.96
		THR	20.06	20.40	19.50	0.90	0.49	2.45	6.86	0.67
0	8	PHRR	301.08	314.45	288.75	25.70	12.88	4.27	11.95	36.06
		THR	9.30	9.40	9.00	0.40	0.26	2.80	7.84	1.12
9	8	PHRR	295.07	310.00	281.54	28.46	14.28	4.83	13.52	39.98
		THR	10.20	10.30	10.00	0.30	0.17	1.69	4.73	0.47

[a]Relative repeatability standard limits from round robin tests are: 6% and 2.8% for PHRR and THR respectively.
[b]Relative repeatability limits from round robin tests are: 17% and 8% for PHRR and THR respectively.
[c]Repeatability definition from ISO 5725 [31].

the porous holder. The difficulty in fitting the holder to cover all the exposed surface area generates variability in TTI and HRR. However, we can remove tests to comply with repeatability criteria, and assume that the tests showing outliers are operational errors. Three tests that comply with repeatability criteria were therefore selected. A comparison between HRR curves obtained with standard and porous holders for *Pinus pinaster* samples with exactly the same FMC, ISM and Thickness (Figure 4) shows the important effect of the natural diffusion of air through the fuel bed. The porous holder allows rapid flaming, so that the values of PHRR and THR are significantly higher than those obtained with the standard holder.

Effect of Species on Flammability and Combustion Properties

The HRR curves for the third series of tests with the porous holder ($n = 20$) do not comply with the repeatability criteria when the five replicates were considered. Outliers were again observed in some tests with all species. As observed in the second series of tests, the difficulty in fitting the holder to cover all the exposed surface area and the sample heterogeneity generated variability in TTI and HRR. When the outlier tests were removed, HRR and THR complied with the repeatability criteria. Therefore, three tests for each species that comply with

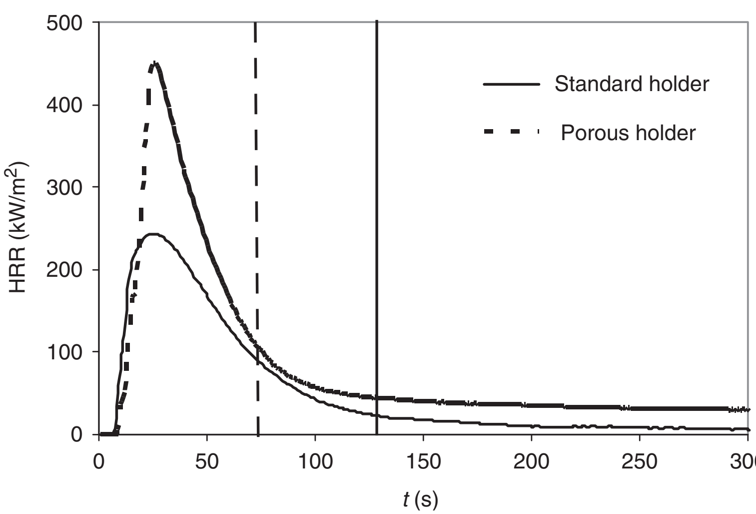

Figure 4. Comparison of HRR curves obtained for porous and standard holders in series of tests with Pinus pinaster (vertical lines indicate flameout).

repeatability criteria were selected ($n = 12$) for plotting the HRR curves (Figure 5) and carrying out ANOVA.

The results show that the species studied had a significant effect on each variable analyzed (Table 3). The PHRR differed most among species ($F = 193.61$; $p = 0.0000$).

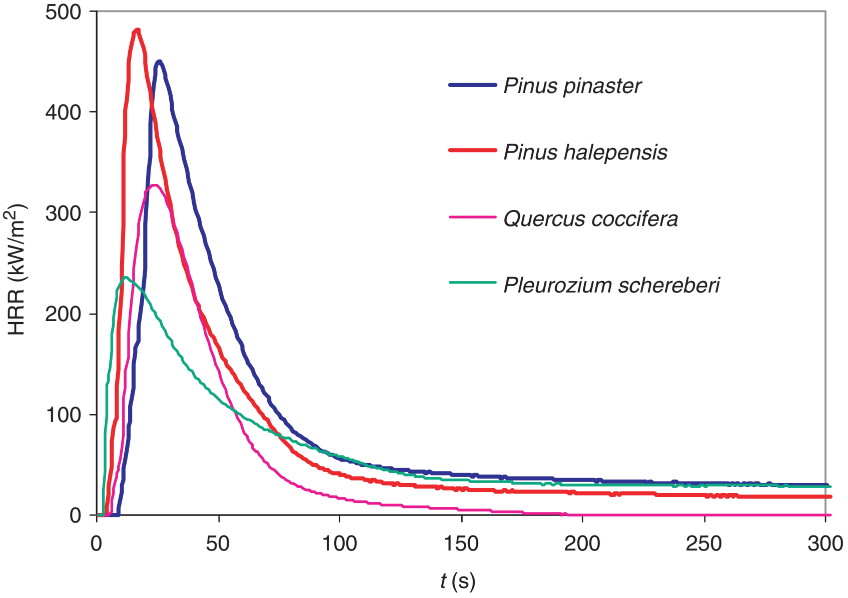

Figure 5. HRR curves for third series tests with a porous holder ($n = 12$).

Table 3. ANOVA results for TTI, PRHR, THR, AEHC and RMF for the third series of tests to characterize forest fuels (FMC 0%) with the porous holder ($n = 12$).

	TTI (s)	PHRR (kW/m^2)	THR (MJ/m^2)	AEHC (MJ/kg)	RMF (%)
P. pinaster	13.67[a] (5.85)a	472.53 (8.79)a	20.67 (0.55)a	17.90 (1.79)a	0.33 (0.04)a
P. halepensis	5.66 (3.05)b	488.02 (10.89)b	19.31 (0.53)a	19.26 (0.69) b	0.58 (0.09)b
Q. coccifera	7.67 (2.88)b	335.26 (20.11)c	10.79 (0.23)b	11.79 (0.25)c	0.40 (0.07)ac
P. schereberi	3.33 (2.51)b	236.02 (14.10)d	10.25 (0.20)b	14.91 (0.86)d	0.44 (0.13)abc
F	18.53[b]	193.61	120.46	30.72	11.82
p	0.0000[b]	0.0000	0.0000	0.0000	0.0002

[a]Mean values (repeatability standard deviation in brackets). Different letters indicate significant differences for dependent variables (LSD test at 95% confidence level).
[b]F-ratios (Type III sum of squares) and p-values from one-way ANOVA.

DISCUSSION

HRR Repeatability Measurements and Effect of Holder Porosity

The accuracy of the MLC and repeatability of the device with the standard holder for forest fuels were very high, and therefore we can assume that the calibrated thermopile provides a good approximation to the HRR values, in accordance with cone calorimeter results for forest species [9,12,29]. On the other hand, the full test series with the porous holder show that repeatability is reasonably good when test conditions are fixed. Nevertheless, the difficulty in fitting the holder to cover all the exposed surface area generates variability in time to ignition, as also reported by White et al. [29]. It may therefore be necessary to increase the number of replicates in some species when the structure makes it difficult to fill the holder. Statistical analysis of cone calorimeter tests of vegetation in the Forest Products Laboratory (USDA Forest Service) recommended testing between three and six replicates [12]. The results of the present study show the need for a minimum of five replicates in order to obtain at least three replicates that comply with repeatability criteria.

The PHRR and THR are significantly affected by both initial sample mass and fuel moisture content [6,12]. The THR per unit mass depends on the amount of the sample that is consumed by combustion, and therefore this variable was significantly affected by mass and FMC. These results suggest that the variability due to these variables could be reduced by fixing the values of ISM and FMC, which would make the comparison among different forest fuels easier.

As regards comparison of the standard and porous holders, the results are consistent with the results of experiments carried out by Schemel et al. [20] with *P. pinaster* fuel beds. The confinement of the sample holder has important implications for HRR, because the standard holder does not allow the natural diffusion of air through the fuel bed. This affects the combustion process when the sample is considered as a 3-dimensional reality. In order to solve this problem, Schemel et al. compared the standard holder (0% porosity) with holders of different porosities (63% and 26%), in a fire propagation apparatus. The results showed that the magnitude of the HRR was significantly affected by the holder opening: 63% of porosity produced the highest PHRR value and 0% porosity the lowest HRR.

Effect of Species on Flammability and Combustion Properties

Time to ignition (TTI) differed significantly among species. We have already discussed the effect of the porous holder and the difficulty in fitting the holder to cover all the exposed surface area, which may generate variability in time to ignition (Table 3). Schemel et al. [20] analyzed this effect in *P. pinaster* and *P. halepensis* fuel beds and suggested that the variance in TTI was linked to the heterogeneous nature of the porosity of the fuel beds, thus the relative placement of the spark igniter with the localized heating and gas mixing may have resulted in variation in TTI. Nevertheless, TTI was ranked in accordance with Surface Area-to-Volume Ratio (SAV) rankings (Table 4), thereby confirming the effect of SAV ratio on forest fuel ignitability [10,23]. On the other hand, this ranking is totally consistent with the French INRA [34] and Spanish INIA [2] flammability classifications for Mediterranean species (*P. pinaster, P. halepensis* and *Q. coccifera*), obtained by radiant heater methods and TTI analysis of green and dead samples.

Peak heat release rate (PHRR) was significantly influenced by species, and was much higher when dead fuels (*P. pinaster* and *P. halepensis* needles) were compared with live fuels (*Q. coccifera* and *P. schereberi*). This is because the live fuels tested are less lignified than the dead ones, which in turn has a significant effect on the calorific value [2], as shown by the Gross Heat of Combustion (GHC) obtained in the bomb calorimeter (Table 1). One important objective of forest combustion and flammability studies is to compare HRR curves and PHRR among species. Even at an FMC of 0% (oven-dry basis, drying at 60°C to constant weight), PHRR as well as Total heat release (THR) differ among species. Furthermore, the PHRR values obtained with oven-dried samples reasonably preserve the bomb calorimetric rankings (Table 4), taking into account that the difference between the GHC of *Q. coccifera* and *P. schereberi* is not significant (Table 1). The important differences among species revealed by ANOVA suggest the use of oven-dried samples, in a first step, in order to reduce the confounding effect of moisture and plants [12]. The latter authors analyzed the rank of cone calorimeter-based mean peak heat release for ornamental vegetation by

Table 4. Comparison of rank values obtained in the characterization of forest fuels (SAV and GHC), with the rankings values obtained with the MLC device (TTI, PHRR, and AEHC).

	SAV	GHC	TTI	PHRR	AEHC
P. pinaster	4	2	4	2	2
P. halepensis	2	1	2	1	1
Q. coccifera	3	4	3	3	4
P. schereberi	1	3	1	4	3

season and FMC, and found consistency between PHRR obtained in oven-dried conditions and undried (green) plant samples. Tests on real trees (as opposed to Cone Calorimeter samples) show that there is an effect on HRR of moisture content even beyond 100% [35]. Etlinger and Beall [11] reported that moisture had little effect on PHRR above moisture contents of 100% and a reduction in PHRR of 4 kW per 1% moisture content for moisture contents between 0% and 100%. Likewise, Weise et al. [12] suggested that there is an upper limit to the impact of even higher moisture, which decreased the variability in the PHRR results. Nevertheless, results of large-scale experiments [13] indicated that moisture alters the combustion process and therefore does not simply act as an inert diluent, and thus FMC has important effects on flammability and combustion variables.

Average effective heat of combustion (AEHC) values obtained with oven-dried samples maintained the bomb calorimetric rankings (Table 4), thereby confirming the important effect of species in the combustion process. The mean values obtained with the porous holder were 17.90 MJ/kg for *P. pinaster* and 19.26 MJ/kg for *P. halepensis*, both of which are in the range of reported values for the net heat of combustion of conifers (17.8–20.4 MJ/kg) and significantly lower than the gross heat of combustion (GHC in Table 1). The AEHC value obtained for *Quercus coccifera* (11.79 MJ/kg) is lower than AEHC value obtained by White et al. [29] for *Quercus gambelli* (14.2 MJ/kg) in cone calorimeter tests with standard holder. On the other hand, the values obtained for *Quercus coccifera* and *P. schereberi* (14.91 MJ/kg) are significantly lower than the bomb calorimetric value (19.67 MJ/kg and 19.82 MJ/kg respectively), although the rankings are maintained. Consequently, the present MLC study was able to detect differences in combustion properties in oven-dried samples (Table 4) although the GHC did not differ significantly between species such as *Q. coccifera* and *P. schereberi* (Table 1). These results confirm the effect of fuel structure on combustion properties. The proposed methodology also enables comparison of flammability and combustion properties among species by fixing bulk density [30] and thus preserving the forest fuel sample structure.

Residual mass fraction (RMF) values were significantly affected by species, which suggests that the consumability also depends on species characteristics, even on an oven-dry basis and with high combustion efficiency (RMF ranged between 2.5% and 5.8% with standard holder and between 0.28% and 0.58% with the porous holder). The combustion effectiveness has important implications for some flammability properties such as AEHC and THR [36].

CONCLUSIONS AND FUTURE WORK

The present results demonstrate the usefulness of a new approach to measure and compare flammability and combustion properties of forest species. The MLC equipment is easy to manage and the results provided by the thermopile showed good repeatability and reasonable approximation to HRR values obtained with a cone calorimeter. The adapted device, with a mass loss calorimeter and porous holder, showed reasonably good repeatability when the initial conditions were fixed. These results represent a preliminary attempt to develop a methodology to characterize forest fuel flammability and combustion with a cone calorimeter, fire propagation apparatus or mass loss calorimeter equipment. One interesting feature to explore is the possibility of the implementation of a Fourier-transform based (FTIR) spectroradiometer in the open-path configuration to measure *in situ* concentration of the gaseous by-products just at the end of the chimney [37]. This is an alternative way to measure these concentrations, because in a standard cone calorimeter the gases are conducted to the analysis equipments.

It is important to emphasize that it is essential to determine the flammability of forest fuels under field conditions in forest research. Therefore more research is needed in order to test live and dead fuels to establish the effect of FMC and season on flammability and combustion properties. It is also necessary to solve operational problems such as how to fill the holder with the samples, and the type of materials to include in the holder [9]. We consider that the use of a porous holder and a fixed bulk density are appropriate in a bench-scale approach. This is a first step in future research on the effect of the sample structure on forest fuel flammability and combustion. More studies are required to design suitable porous holders that simulate natural porosity conditions. Nevertheless, the present approximation to a rapid flaming combustion may be similar to real fire combustion.

On the other hand, some preliminary tests to compare average effective heat of combustion with gross heat of combustion obtained in bomb calorimeter have been carried out. The good results obtained suggest that further research should be carried out on this topic, which includes comparative calorimetry results and gross heat of combustion [9]. Such research would provide information to modellers and forest managers to enable them to improve wildland fire models, flammability databases including HRR data [14], and fire hazard indexes.

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