

Device for the standard measurement of shoot flammability in the field

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Abstract Fire ecology has been hindered by the lack of comparable, affordable protocols to quantify the flammability of whole plants over large numbers of species. We describe a low-tech device that can be carried to the field and that allows highly standardized measurement of the flammability of whole individuals or portions up to 70 cm long. We illustrate its potential with results for 34 species belonging to different growth forms from central Argentina. The device consists of an 85 × 60 cm half-cut metallic barrel placed horizontally and mounted on a removable metallic structure. It contains three parallel burners, a grill with an attached gauging thermometer and a blowtorch. Burners and blowtorch are connected to a propane–butane gas cylinder. Plant samples are placed on the grill and preheated with the burners for 2 min at 150°C. They are then ignited for 10 s with the blowtorch while the burners are kept on. Four parameters are measured for each sample: maximum temperature reached, burning time, burnt length and burnt biomass percentage. These parameters are used to construct a compound index of flammability for each sample that ranges between 0 (no flammability) and around 3 (maximum flammability). We obtained a wide range of values for flammability and all its components. Most of this variability was accounted for by differences between growth forms and species, rather than by differences at the level of replicates. This suggests that the device and protocol are sensitive enough to detect flammability differences among plants with different functional traits, and at the same time robust enough to produce consistent results among samples with similar traits. A major advantage is that plant architecture is kept almost intact, providing a flammability measure much closer to that of whole individuals in the field than those obtained by other standard protocols in use. The device and protocol presented here should facilitate the acquisition of comparable flammability data over large numbers of species from different floras and ecosystems, potentially contributing to several fields of research, such as functional ecology, evolutionary ecology and vegetation-atmosphere modelling.

Key words: comparative ecology, fire, plant architecture, plant functional trait.

INTRODUCTION

Fire is one of the most important factors shaping plant community structure and ecosystem processes worldwide (Bond 2005; Bowman *et al.* 2009; Pausas & Keeley 2009). The flammability – or capacity to burn – of dominant plant species strongly determines the overall tendency of vegetation to catch and carry fire, and is therefore a fundamental element in determining its ecological effects (Bond & Midgley 1995; Lavorel & Garnier 2002; Bond 2005).

Although most authors agree on broadly defining flammability as the capacity to burn, there is no universally accepted working definition. Flammability is a compound plant functional trait whose components vary among authors and disciplines. Current thinking suggests that flammability is composed of ignitability (i.e. how easily a fuel ignites), sustainability (i.e. how

long it continues to burn), combustibility (i.e. how rapidly it burns) and consumability (how much of it burns) (Anderson 1970; Martin *et al.* 1994; Hogenbirk & Serrazin-Delay 1995). The relevance of each of these components in assessing flammability, as well as the way in which the components are measured, are highly variable depending on the objectives and the scale of the experiment (e.g. small plant fragments, individuals, vegetation) (Gill & Zylstra 2005). For example, when measuring flammability of small fragments, ignitability is usually considered as a key parameter to be measured (e.g. Gill & Moore 1996; Valette 1997; Dimitrakopoulos & Papaioannou 2001). On the other hand, when working with whole plant shoots ignitability is much less relevant, as it is highly correlated with other parameters that are usually measured in these experiments. For example, the more ignitable the plant, the faster the burning rate (BR) (Fons 1946; Martin *et al.* 1994) because BR can ultimately be seen as a succession of ignitions in a certain period of time.

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Most studies are based on flammability measurements of small plant fragments such as leaves, small twigs, spines or litter in chambers in the laboratory (e.g. Valette 1997; Dimitrakopoulos & Panov 2001; Dimitrakopoulos & Papaioannou 2001; Behm *et al.* 2004; Scarff & Westoby 2006). Although this produces highly standardized results, the flammability of small fragments does not scale up well to that of whole shoots. This is because plant flammability in the field depends on physical, chemical and architectural characteristics of the whole shoot (Papió & Trabaud 1991; Bond & Midgley 1995; Schwilk 2003). Here the focus is on how the different plant parts (i.e. foliage, twigs, branches, main stem) affect heating by the fire source and each other during burning.

On the basis of the literature (e.g. Martin *et al.* 1994; Stephens *et al.* 1994; Hogenbirk & Serrazin-Delay 1995; Cornelissen *et al.* 2003; Behm *et al.* 2004; Etlinger & Beall 2004; Gill & Zylstra 2005) and for the purposes of designing a working definition that is both ecologically sound and feasible to be measured in a standard way on a large number of species, we defined flammability as the combination of maximum temperature reached (MT), BR (or the plant length burnt per unit time) and burnt biomass percentage (BB, or the percentage of the total plant biomass that burns before spontaneous fire die-off). MT and BR are both indicators of combustibility, while BB is a measure of consumability. Sustainability, on the other hand, is more difficult to define as it could be represented either by the burnt length or by the burning time, which are the two parameters measured to calculate BR in our study (see details in *Methods*). Burning time might be more appropriate in experiments with plant portions (e.g. leaves, twigs) and/or litter, as in most of these studies direction and distance of burning is not important. In contrast, when working with whole plant shoots, sustainability could be better defined in terms of whether or not fire would pass on through the plant (Martin *et al.* 1994). Therefore, burnt length would be more appropriate in such cases.

Few flammability experiments have been performed on whole plants in controlled environments. Some of them include Stephens *et al.*'s (1994) flammability measurements of air-dried mature junipers using a burning table, and Etlinger and Beall's (2004) experiment with six species using a biomass calorimeter. None of these studies included measures of ignitability, but rather different ways of assessing combustibility (e.g. heat released, mass loss rate and heat release rate), which is regarded by Martin *et al.* (1994) as the major driving force in fire behaviour measurements.

Other studies have focused on flammability at the community level and involved assembling model plant communities in large containers using whole shoots cut from the field, and placing them in experimental fire tunnels, where they burn while fire parameters are

recorded (Guijarro *et al.* 2004). These studies are considerably more realistic, but the large-scale facilities that allow whole plants to be included in a fire chamber are expensive, difficult to transport, and therefore impractical in many situations.

We designed a low-cost low-tech device that can be taken to the field with relative ease, does not depend on any source of power other than a small gas cylinder, and allows highly standardized measurement of all three flammability components on whole individuals or plant portions up to 70 cm long. The device has a double advantage. On the one hand, by preserving the basic architectural arrangement of the measured shoots, this method is considerably more realistic than the measurement of small fragments. On the other hand, by being transportable to the field, it allows carrying out experiments over large numbers of plant species without the deterioration of the canopy structure that unavoidably occurs when large numbers of shoots are transported to lab facilities from remote locations (such as our study area).

We present the technical details of the device and illustrate its potential with results from flammability measurements on 34 species of different growth forms (trees, shrubs, grasses and forbs) from central-western Argentina. The device offers the possibility to measure shoot flammability of a large number of plant species in a consistent, reliable way. This in turn allows flammability and its components to be incorporated into comparative plant trait databases useful for functional ecology (e.g. Pausas *et al.* 2004; Saura-Mas *et al.* 2009), evolutionary ecology (e.g. Schwilk & Ackerly 2001; Bond & Midgley 2003; Verdú & Pausas 2007) and vegetation-atmosphere modelling (Stich *et al.* 2003).

METHODS

Flammability device description

The device consists of an 85 × 60 cm metal barrel cut in half, placed horizontally, with part of the remaining half used as removable wind protection, which is closed in the back-half and opened in the front-half, allowing the samples to be placed on the grill and observed during flammability measurements (Fig. 1 and Appendix S1). The wind protection creates a more homogeneous condition around the samples during burning, mostly preventing heat loss by convection. Inside the barrel, there are three parallel burners (80 cm long and 2.5 cm diameter) located 7 cm above the bottom of the barrel and separated from each other by 8 cm. The three burners collectively produce a maximum of 10 000 calories per hour. An 84 × 55 cm grill, made of an electrically welded mesh with a mesh size of 2.5 cm, is placed above the burners at an adjustable height (22 cm above the bottom of the barrel in our study). It includes a 45-cm-long thermometer attached along the grill, connected to a gauge on the outside

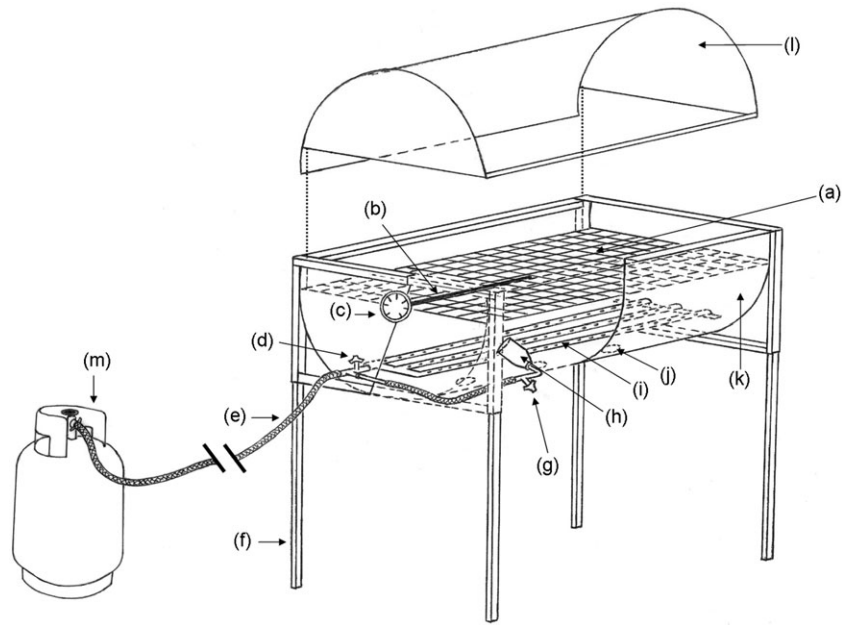


Fig. 1. General view of a device for measuring plant flammability in the field. (a) grill; (b) grill thermometer; (c) temperature gauge; (d) security valve; (e) connection to gas cylinder; (f) removable legs; (g) blowtorch valve; (h) blowtorch; (i) burners; (j) ventilation holes; (k) barrel; (l) removable wind protection; (m) gas cylinder. See main text for technical details.

of the barrel (Fig. 1). Both thermometer and gauge should have the capacity to measure temperatures of at least 600°C. A blowtorch is placed within the barrel, between the grill and the burners, and fixed to the front side at approximately 17 cm from the bottom. The bottom of the barrel has three 8-cm-diameter holes for ventilation. The whole structure is mounted on four 100-cm-long removable metallic legs. Both the burners and the blowtorch are connected to a propane-butane gas cylinder through a 10-mm-diameter metal-covered hose equipped with a security valve (Fig. 1). The total weight of the device is about 22 kg. The material cost of the device was about \$140 (September 2008), and its construction demanded approximately 2 days of work once the design was ready.

Plant species selection and sampling procedure

We selected species that dominate the canopy and understory of xerophytic woodlands and shrublands in central-western Argentina (31°17'–31°55'S, 65°12'–65°32'W). Phytogeographically this corresponds to the Western Chaco (Cabrera 1976), a biome which has been historically subjected to some burning (Morello & Saravia Toledo 1959) but for which there is no evidence of fire having been a strong natural selection pressure over evolutionary time (Cabido *et al.* 1992).

A total of 34 plant species (including two morphotypes of a single species – *Celtis ehrenbergiana* (Klotzsch) Liebm. – considered here as separate species in view of their distinct architecture) were selected on the basis of vegetation surveys carried out by Cabido *et al.* (1992). They included 15 taxonomic families and different growth forms (11 trees, 13 shrubs, 8 grasses and 2 forbs species) (Appendix S2).

Samples were collected from six healthy-looking, sexually mature, randomly selected individuals of each species. In the case of trees and shrubs the samples consisted of 70-cm-long terminal branches. Samples of grasses and forbs consisted of whole shoots. In the case of grasses, sometimes it was not possible to cut off all the roots and at the same time preserve the integrity of the shoot architecture. In such cases, attached roots were reduced to a minimum and they were not considered in any of the flammability measurements. In the few cases in which grasses or forbs were taller than 70 cm, the tips that exceeded this distance from the base of the shoot were pruned. In all cases samples were collected and immediately brought to the device to perform the flammability tests.

The season and meteorological conditions during the few days previous to sampling are expected to significantly influence flammability. For example, plants are likely to burn differently depending on whether they have leaves on their branches, and on whether such leaves are dead or alive. The water content of leaves and branches depends both on the season and on the occurrence of rains in the days preceding the measurement. Therefore, the season of measurement, the time of the day and the weather conditions on the days preceding the collection and measurement should be standardized as much as possible. Because the measurement of flammability on the same species at different times of the year is often impractical, the best option is to collect and measure at the time of the year in which both meteorological conditions and the phenological stage of the plants are expected to be the most conducive to fire. In the case of our study, sampling and measurement was carried out during the time of the year with the highest occurrence of fires (PPMF 2007). No rain was recorded in the study area during the whole sampling period.

Flammability measurements

The experiment was conducted on 16–17 September 2008 at Villa Dolores Fire Station (Córdoba Province, Argentina, 31°56'57.40"S, 65°10'29.24"W). Ambient temperature, relative humidity and wind speed were recorded throughout the experiment using a Kestrel 3000 meteorological meter. A range of variation as small as possible is important to maximize comparability of measurements of different species. We achieved this by conducting all measurements between dusk and dawn. This also facilitated the visualization of small burning points in plant shoots, which can be difficult in full sunlight. Although we recommend taking these measurements at night, particularly in areas where high insolation produces sharp temperature changes during the day, they can also be conducted during daytime, provided temperature, humidity and wind speed are relatively stable and burning points in the shoots are easily visualized.

Measurements were conducted in each of the six individuals (replicates) of the 34 plant species. Experimental burns of species belonging to different growth forms were interspersed in time to avoid potential systematic error due to changing environmental conditions. The burners were turned on until the grill reached a temperature of about 150°C and kept on throughout the whole experiment. Each plant sample was then placed on the grill during 2 min for preheating (Appendix S3a). Samples are placed on the grill horizontally. In real fires in the field, the orientation of fuels vary from vertical to horizontal, depending on the circumstances and especially on the architecture of the plants involved. For example, while in our case grasses and forbs stand naturally in a vertical or oblique position, most of the branches of trees are placed in a horizontal position with respect to approaching fires. Therefore, we chose the horizontal position as the simplest option, sacrificing realism to some degree for the sake of standardization. Other studies measuring different parameters of flammability in whole plant shoots have also been performed placing the samples horizontally (e.g. Stephens *et al.* 1994; Atreya 1998; Weise *et al.* 2005). However, the device presented here can easily be adapted to place the shoots in different angles with respect to the fire source, if required by the objectives of a particular experiment. This can be achieved by removing two of the legs (whichever are necessary for the purpose of the experiment) and leaning the device on the floor (Appendix S4); different angles can be achieved by using legs of different lengths.

Preheating is considered an essential aspect of the protocol, as in nature plants facing an approaching fire get exposed to intense heat and dehydration well before the flames reach them. The blowtorch was subsequently turned on for 10 s to provide the plant with an ignition source (Appendix S3b). The flammability measurement (Appendix S3c) starts immediately after the blowtorch is turned off. Preheating time (2 min), grill temperature (150°C) and blowtorch ignition time (10 s) were decided on the basis of the literature (Stephens *et al.* 1994; Dimitrakopoulos & Papaioannou 2001) and trials by the authors, in which we searched for the best balance between logistic feasibility and ecological realism.

Maximum temperature reached by the burning shoot (MT, in °C) was recorded from a distance of 50 cm with a TES-1322A remote infrared thermometer with the capacity

to measure temperatures up to 550°C. The duration of burning (BT, in seconds) and the length of the burnt portion of the shoot (BL, in centimetres) were also recorded. BL was then divided by BT to obtain BR. Finally, BB was estimated visually and assigned to one of six categories: 1 = 1–10%, 2 = 11–25%, 3 = 26–50%, 4 = 51–75% and 5 = 76–100%. On the bases of these three parameters we calculated flammability. The values recorded for each sample for each of the three components (MT, BR and BB) were transformed to a proportional (0–1) scale, with the value 1 being assigned to a reference value. In the case of BB the value 1 was assigned to the maximum possible value for this component (i.e. 6), whereas for the other components, the reference value was based on the literature and the results of our experiments. Reference values are: MT = 500°C; BR = 1 cm s⁻¹. Standardized MT, BR and BB scores for each sample were then added to obtain a compound value of flammability that has a minimum possible value of 0 (no flammability) and a maximum value that would rarely exceed 3 (maximum flammability).

Although from an ecological point of view the relevant components of flammability are just MT, BR and BB, in this article we also report results on BL and BT (components of BR, rather than direct ecological indicators of flammability) for better illustration of the performance of the device.

Data analysis

Due to the lack of homogeneity of variance, the data were analysed through a mixed model using growth form as a fixed effect and species within growth forms as a random effect. To evaluate heterogeneity of the within-growth-form variance, a different random effect of species was specified for each growth form. The model selection was based on the Akaike criterion. The adjustment of the models was made using InfoStat as an interface of the *lme* routine from the *nlme* library of the R-package.

In view of their different architecture, and therefore expectedly different flammability, correlation analyses among all components of flammability were carried out both considering all species together and species grouped by growth form. All statistical analyses were performed using InfoStat Version 2009p (Grupo InfoStat, Facultad de Ciencias Agropecuarias, Universidad Nacional de Córdoba, Argentina).

RESULTS

Flammability device performance

During the experiment ambient temperature ranged between 16 and 23°C and relative humidity varied between 24 and 33%. Wind speed ranged between 1.1 and 6.0 km h⁻¹. The time needed to carry out an individual flammability measurement varied with the nature of the sample, especially with its BT. Average time over all 204 samples was 3–4 min per sample, including preparation and placing of the shoots on the

grill, preheating and the flammability measurements themselves. Heating of the grill to 150°C at the beginning of the experiment took about 5 min. When burnt samples raised grill temperature significantly (e.g. in the case of tussock grasses), extra time was spent waiting until temperature decreased back to the standard 150°C before placing the next sample on the grill. Conversely, increasing grill temperature after it had decreased beyond the standard limit was fast and easy through the regulation of the burners' gas flow with the security valve. Total gas consumed throughout the experiment was about 15 kg, or an average of 74 g per sample.

Some grasses reached temperatures near 550°C, where the measurement accuracy of the thermometer is unknown (personal communication by an expert technician; Ergio Controles, Córdoba, Argentina, 2009). Nevertheless, differences with other growth forms remained significant even if this was an underestimation. For more precision in experiments involving, for example tussock grasses, which might often exceed 500°C during burning tests, we recommend using a higher temperature thermometer. The main disadvantage is that thermometers measuring up to 850°C are 7–20 times more expensive than 500°C ones. A less expensive option is using a thermocouple connected to the infrared thermometer, which allows measuring temperatures up to 1333°C (for the ther-

mometer model used in our study). However, the thermal inertia of the thermocouple makes the measurements considerably slower.

Variability in flammability and its components

We obtained a wide range of values for flammability and all its components (Fig. 2, graphs and legend; Appendix S5 for values of flammability and its components of each plant species). Most of this variability was accounted for by differences between growth forms (Fig. 2) and species. Most of the variance within growth forms was observed at the species level rather than at the replicate level in almost all growth forms and components (Table 1). Only in the case of BL of grasses was the variance explained at the replicate level higher than that at the species level. Values of flammability and all its components were highly correlated when considering all species together (Table 2). When considering species grouped by growth form (Table 2), correlation coefficients remained high in most cases. In the case of BB of grasses, however, they were low and statistically not significant. This is expectable as most of the samples burnt completely. The other two non-significant correlations (BT–BR and MT–BT; $P = 0.09$ and $P = 0.07$, respectively;

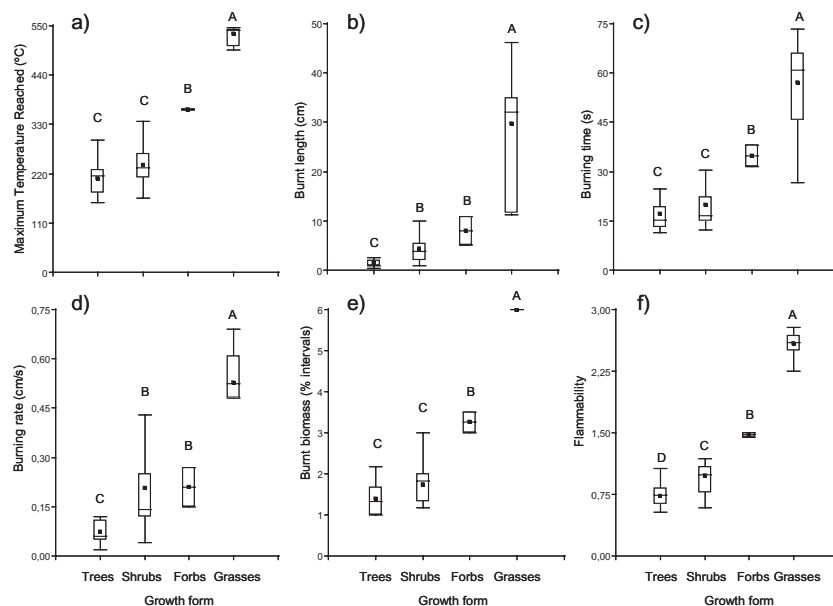


Fig. 2. Range of values obtained for each flammability component (a–e) and overall flammability (f) over the species grouped by their growth form. Box = interquartile range, containing 50% of values; line across box = median; black dot inside the box = mean; whiskers = extreme values (i.e. mean \pm 3 SD). Different (capital) letters indicate significant differences according to Di Rienzo, Guzmán, Casanoves (DGC) pair-wise comparison procedure ($\alpha = 0.05$) ($n = 11$ for trees, $n = 13$ for shrubs, $n = 8$ for grasses and $n = 2$ for forbs). Overall ranges for each component across all measurements were: maximum temperature reached: 156–546°C; burnt length: 0.4–46.3 cm; burning time: 11–74 s; burning rate: 0.02–0.69 cm s⁻¹; burnt biomass: 1–6 (intervals); flammability: 0.48–2.78.

Table 1. Analysis of the distribution of the total variance at the level of species and replicates, using a mixed model (see text for details)

Flammability component	Growth form	Species	Replicate	Mean	SE	CV
MT (°C)	Forbs	100	0	363	34	33
	Grasses	77	23	531	7	6
	Shrubs	82	18	238	13	34
	Trees	56	44	209	12	26
BL (cm)	Forbs	81	19	7.9	2.9	92
	Grasses	24	76	29.7	4.5	48
	Shrubs	70	30	4.4	1	119
	Trees	80	20	1.5	0.3	124
BT (s)	Forbs	100	0	35	7	66
	Grasses	56	44	57	5	36
	Shrubs	88	12	20	2	72
	Trees	61	39	17	2	60
BR (cm s ⁻¹)	Forbs	85	15	0.21	0.06	75
	Grasses	70	30	0.53	0.05	38
	Shrubs	63	37	0.22	0.04	97
	Trees	93	7	0.07	0.01	106
BB	Forbs	100	0	3.25	0.41	44
	Grasses	100	0	5.98	0.02	2
	Shrubs	53	47	1.73	0.14	39
	Trees	71	29	1.39	0.11	40
FL	Forbs	100	0	1.47	0.15	35
	Grasses	57	43	2.58	0.06	9
	Shrubs	57	43	0.98	0.08	42
	Trees	58	42	0.72	0.05	30

Results shown on Species and Replicate columns are percentages of the total variance accounted for at each level. Mean values, standard errors (SE) and coefficients of variation (CV) are shown in the last three columns. BB, burnt biomass; BL, burnt length; BR, burning rate; BT, burning time; FL, flammability; MT, maximum temperature reached.

Table 2) can be regarded as marginally significant considering that the number of species within this growth form was small ($n = 8$).

Differences among growth forms

The four growth forms analysed differed significantly in their flammability (Fig. 2f). The patterns found with respect to the different components of flammability (Fig. 2a–e) were very similar, as expected on the basis of the high correlation between them. Grasses were the most flammable (Fig. 2f), significantly differing from all other growth forms in all flammability components. The extremely low variability in BB among grasses was due to the fact that most samples burnt completely or almost completely, thus falling in the 76–100% interval. Trees and shrubs differed between themselves only in the cases of BL (Fig. 2b), BR (Fig. 2d) and flammability (Fig. 2f), but the tendency of shrubs to show higher values was maintained across all flammability components. The very small variation observed among forbs for all flammability components is possibly related to the fact that only two species were abundant enough in the study area to justify inclusion in this study.

DISCUSSION

The device and protocol described here provide the first standard method for measuring flammability of whole individuals or large plant portions in the field in a quantitative, and at the same time easy and inexpensive way. They combine precision with realism in a way that is ideal for flammability screening of large numbers of species. The method allows accurate data on flammability to be obtained from many individual samples in a short time. A major advantage is that plant architecture is kept almost intact as samples do not need any pre-processing or transportation to the laboratory. This reduces to a minimum the changes in moisture content of the samples in the period from collection to flammability measurement, as well as the crushing and flattening of twigs and the loss of leaves that are almost unavoidable during long-distance transportation of many samples. Hence, conducting the measurements close to the sampling site offers more realistic estimations of how plants would burn in real fires. Due to its very simple design, the device can also be adapted to various experimental needs, for example for measuring larger plant parts.

If required, ignitability could also be measured using the same device, for example by setting the burners at

Table 2. Spearman correlations coefficients among all the flammability variables considered in this study for 34 plant species of different growth forms in central Argentina (11 trees, 13 shrubs, 8 grasses and 2 forbs species)

	MT (°C)	BL (cm)	BT (s)	BR (cm s ⁻¹)	BB
All species (<i>n</i> = 34)					
BL (cm)	0.92***				
BT (s)	0.89***	0.88***			
BR (cm s ⁻¹)	0.85***	0.97***	0.79***		
BB	0.88***	0.93***	0.88***	0.88***	
FL	0.95***	0.99***	0.87***	0.96***	0.94***
Grasses (<i>n</i> = 8)					
BL (cm)	0.93*				
BT (s)	0.68 ^{ns}	0.81*			
BR (cm s ⁻¹)	0.82*	0.93*	0.64 ^{ns}		
BB	0.05 ^{ns}	0.19 ^{ns}	0.48 ^{ns}	0.19 ^{ns}	
FL	0.89*	0.98*	0.76*	0.98*	0.19 ^{ns}
Shrubs (<i>n</i> = 13)					
BL (cm)	0.73*				
BT (s)	0.64*	0.59*			
BR (cm s ⁻¹)	0.53*	0.89**	0.36 ^{ns}		
BB	0.63*	0.82**	0.57*	0.74*	
FL	0.75*	0.98**	0.48 ^{ns}	0.90**	0.81*
Trees (<i>n</i> = 11)					
BL (cm)	0.77*				
BT (s)	0.72*	0.95**			
BR (cm s ⁻¹)	0.67*	0.95**	0.83*		
BB	0.62*	0.77*	0.84*	0.72*	
FL	0.90**	0.90**	0.87*	0.85*	0.82*

* $P < 0.05$; ** $P < 0.005$; *** $P < 0.0005$. Forbs species were not analysed separately because only two of them were sampled. BB, burnt biomass; BL, burnt length; BR, burning rate; BT, burning time; FL, flammability; MT, maximum temperature reached; ns, non-significant.

the required temperature using the gas valve, then placing the sample on the grill and finally recording the time for the sample to ignite. The distance between the grill and the burner could also be modified to achieve a higher temperature if necessary.

Differences in flammability among growth form found in this pilot study were in accordance with the literature, and the lower variance among grasses than among woody species is consistent with the smaller architectural variability of the former. This, and the fact that growth form and species levels rather than replicates explained most of the variance in almost all cases, suggest that the device and protocols are sensitive enough to detect flammability differences among plants with different functional traits, and on the other hand robust enough to produce consistent results among samples with similar traits.

The correlation analysis showed that despite the significant differences in flammability and its components, grasses and woody species present a similar trend in most of the components.

Further studies will allow determining how the easy-to-measure flammability components used in our experiment are related to more complex parameters that are usually measured in the laboratory, such as mass loss rate, heat release rate and energy content.

For example, per cent consumption (equivalent to our BB) was significantly related to mass loss rate (mg s⁻¹) in 17 California oak species ($r^2 = 0.51$; $P < 0.001$) (E. Engber pers. comm. 2009). Furthermore, Weise *et al.* (2005) reported values of 'rate of spread' between 0.33 and 0.65 cm s⁻¹ (in tests with no slope and no wind) in a laboratory experiment with fuel beds of different chaparral shrub species. These results are comparable with the BR values obtained in grasses in our study, which ranged from 0.26 to 0.49 cm s⁻¹.

The lack of comparable flammability data over large numbers of species from different floras and vegetations types has hindered understanding of the mutual influences between land cover and fire. The construction of flammability datasets over large number of species should allow the incorporation of flammability characteristics to the analysis of recurrent trade-offs and syndromes of plant traits, including links between flammability traits (e.g. Bond & Midgley 1995; Schwilk & Ackerly 2001, 2005; Lavorel & Garnier 2002), fire-survival traits (e.g. Bond & Midgley 2003; Pausas *et al.* 2004; Paula *et al.* 2009) and resource-economy traits (Diaz *et al.* 2004; Wright *et al.* 2004; Saura-Mas *et al.* 2009).

From a modelling perspective, standard flammability data should improve fire models, because they

relate the variables used in the models with an actual measurement of flammability that considers the natural architecture of the plants. In this way, flammability of each species, weighted by its relative abundance in the vegetation should lead to more accurate modelling than common approaches that simply pool species into 'types of fuel' (e.g. Finney 2003; Leonard 2009). This could contribute to better wildfire prevention and management across a wide range of spatial scales (Keane *et al.* 2001; Stich *et al.* 2003; Pausas & Bradstock 2007; Bowman *et al.* 2009). In summary, the device and protocol presented here represent a step forward towards the production of standardized flammability data of a large number of species, which could be used at the level in specific locations and also in wider-scale comparisons. To what extent these flammability data explain the flammability of real vegetation plots would be the next stage of research.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

- Appendix S1.** More views of the device.
Appendix S2. Plant species included in this study.
Appendix S3. Illustration of measuring procedure.
Appendix S4. Measuring flammability at an angle.
Appendix S5. Flammability values for 34 species.