Plant flammability experiments offer limited insight into vegetation–fire dynamics interactions

Introduction

Flammability is the general ability of vegetation (fuel) to burn (Gill & Zylstra, 2005). The concept of flammability can be narrowed down to distinct aspects of combustion as gauged by a number of metrics (White & Zipperer, 2010). In this respect, Anderson (1970) proposed flammability to consist of ignitibility (ease of ignition), sustainability (how well combustion will proceed) and combustibility (velocity or intensity of combustion), and Martin et al. (1994) further added consumability, the amount of combusted fuel. Flammability is experimentally assessed by burning fuels in the laboratory, either in the form of discrete elements (e.g. a leaf, a twig) for which the concept has been coined, or as a fuel bed, a homogeneous or heterogeneous assemblage of individual units. In the real world (the community or stand level), flammability should be translated in terms of fire behaviour characteristics, for example, rate of fire spread and fire intensity (Anderson, 1970). However, because flammability is a broad, all-encompassing idea, its usage and appraisal know no scale boundaries and can even extend to the ecosystem level. It is notable that the scientific and practical relevance of vegetation flammability have been dismissed (Dickinson & Johnson, 2001), possibly because the term has been used less rigorously in fire ecology than in combustion science.

Flammability studies have been carried out for various purposes. A recent trend is to examine plant flammability descriptors as fire-adaptive traits (Schwik, 2003; Scarff & Westoby, 2006; Cowan & Ackerly, 2010; Saura-Mas et al., 2010; Pausas et al., 2012) in relation to the hypothesis that flammability has evolved to confer fitness in fire-prone environments (Bond & Midgley, 1995). None of these studies or, for that matter, any other flammability-related research thoroughly questions to what extent flammability experiments are adequate surrogates for real-world, full-scale fire behaviour and dynamics. White & Zipperer (2010) provide a thorough description and comparison of the methods used to assess flammability. Here we discuss the limitations of plant flammability tests regarding their ability to replicate real-world conditions, with an emphasis on shrub species.

Scale limitations of plant flammability experiments

A major shortcoming of flammability tests based on fuel elements is that these are taken out of the overall fuel context, that is, the fuel bed or complex (in this case the shrub canopy), as isolated and aggregated fuel particles have different burn properties. Combustion behaviour has been shown to vary with fuel particle mass (Fletcher et al., 2007; Cole et al., 2011), between single and paired shrub leaves (Pickett et al., 2009), and with shrub leaf orientation (Engstrom et al., 2004). An extreme illustration of decoupled flammability between fuel elements and their corresponding fuel beds is given by thin and small shrub leaves, which ignite easily as individuals but when organized as litter display low heat release rates as a result of poor ventilation (Scarff & Westoby, 2006). Ignition and combustion are directly affected by the intrinsic properties of fuel particles, but fuel-driven fire behaviour is mostly a function of the fuel complex, which essentially is defined by fuel loading, arrangement, size distribution and dead : live ratio (Chandler et al., 1983). In fact, because of their minor range of variation, reduced effect or lack of data, certain intrinsic fuel properties (specific gravity, mineral content, chemical composition) either are not used as inputs to fire spread models or are assumed constant, as in Rothermel (1972) and in sophisticated process models based on the solution of equations describing the conservation of mass, momentum, energy and species (Larini et al., 1998; Linn et al., 2002).

Fuel types dominated by shrubs can be structurally complex, which complicates the quantification of each fuel component and fuel metric contribution to flammability (Fernandes et al., 2000; Davies & Legg, 2011). The likelihood of fire spread is affected by wind speed, slope, fuel moisture content and fuel bed depth when live and implicitly discontinuous fuels predominate, which very often is the case in shrubland (Zhou et al., 2005; Yedinak et al., 2010). Hence, the ignition of fuel elements or even of individual shrubs is not synonymous with successful fire spread, as found by Anderson & Anderson (2010) in field experiments. Fire behaviour measured in shrub fuel beds reconstructed in the laboratory can be upscaled to match the results of field-based models (Marino et al., 2008). However, the flammability of shrub samples of foliage and branches was poorly correlated with whole shrub flammability in the laboratory studies of Weise et al. (2005) and Madrigal et al. (2011).

Limitations of laboratory-scale flammability studies are highlighted when contrasting results from these experiments with observations of fire dynamics in scaled-up outdoor experiments in shrub and forest fuel complexes. While live fuel moisture content has been identified as a key flammability variable (Alessio et al., 2008; Plucinski et al., 2010; Cole et al., 2011; Pausas et al., 2012), analyses of field experimental data failed to find a significant effect of this variable on fire spread and intensity in

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shrub ecosystems (Thomas, 1971; Lindenmuth & Davis, 1973; Van Wilgen et al., 1985; Catchpole et al., 1998; Vega et al., 1998; Fernandes, 2001; Bilgili & Saglam, 2003; Davies et al., 2009) and conifer forests (Van Wagner, 1998; Cruz et al., 2004, 2005; Fernandes et al., 2009). Likewise, Fletcher et al. (2007) were unable to find consistent correlations between moisture content and the ignition behaviour of shrub leaves exposed to field-like convective heat fluxes of 80–140 kW m$^{-2}$. The influence of live fuel moisture content on flammability is expected to decrease as the experimental heat source gets larger (White & Zipperer, 2010).

Laboratory flammability studies seldom replicate the heat transfer mechanisms and combustion processes driving fire propagation. Many studies employ a cone calorimeter (Weise et al., 2005; Madrignal et al., 2011) or epiradiator as the heat source (Pausas et al., 2012). Considering an epiradiator radius of 0.05 m and a surface temperature of 650°C, the fuel sample in Pausas et al. (2012) was heated by a constant radiative flux of 4.6 kW m$^{-2}$. Comparatively, measurements in shrubland fires yielded peak radiative heat fluxes between 36 and 150 kW m$^{-2}$ (Silvani & Morandini, 2009; Cruz et al., 2011). Values $c. 250$ kW m$^{-2}$ were measured in crown fires in conifer forests (Butler et al., 2004). In epiradiator experiments convection acts as a cooling mechanism after the fuel particle temperature surpasses the background temperature. Nonetheless, convective heat transfer mechanisms dominate fire spread in highly porous fuel complexes (Zhou et al., 2007; Yedinak et al., 2010). Measurements in moderate intensity wind-driven shrubland fires yielded peak convective heat fluxes between 40 and 61 kW m$^{-2}$ (Silvani & Morandini, 2009). Convective heat fluxes peaking at 150 kW m$^{-2}$ were measured in high-intensity crown fires (Butler, 2010). As such, the energy levels imposing fuel samples placed in cone calorimeters and epiradiators are two to three orders of magnitude lower than those observed in real fires. This has significant effects on the experimental conclusions as heating rates determine the rate, pathways and efficiency of pyrolysis of woody and nonwoody plant materials (Saastamoinen & Richard, 1996; Sullivan & Ball, 2012). Laboratory experiments that rely on realistic heat fluxes do provide key information to understand ignition processes at the leaf scale. However, only experiments that replicate not just the heat flux environment of outdoor fires, but also plant (fuel-complex) structure result in flammability metrics that are relevant to fire propagation in shrubland ecosystems.

**Flammability and physiological condition**

Live fuels are the subjects of many flammability studies, particularly those that test the behaviour of individual leaves or twigs (Engstrom et al., 2004; Fletcher et al., 2007; Alessio et al., 2008; Pickett et al., 2009; Pausas et al., 2012). However, retention of standing dead fuel in the lower to mid-canopy is a common feature in fire-prone shrubs, especially in mature and senescent populations (Fernandes et al., 2000; Baeza et al., 2006, 2011; Davies & Legg, 2011; Madrignal et al., 2011; Pausas et al., 2012). The main difference between physiologically active biomass and necromass in relation to ignition and combustion arises from substantially different water contents. Combustion of live fuels is often dependent on the combustion of dead fuels (Davies & Legg, 2011), which work as a catalyst releasing high amounts of energy that will lead to the sustained combustion of live fuels. Although the effect of dead : live ratio on shrubland fire behaviour remains to be experimentally quantified, testing live plant parts alone is a potentially misleading procedure when the objective is to characterize the flammability of species with high dead : live ratios. Likewise, the effect of minor differences in live fuel flammability is diluted and probably made irrelevant in the presence of high dead : live ratios, such as in the *Ulex parviflorus* study of Pausas et al. (2012).

**Fire modelling as a complement to flammability experiments**

Several authors infer flammability directly from fuel properties (Dimitrakopoulos, 2001; Behm et al., 2004; Cowan & Ackerly, 2010) or complement the results of flammability tests with fuel data (Saura-Mas et al., 2010; Pausas et al., 2012). This approach relies on personal judgement, is largely qualitative, and lacks the ability to weigh the role of each fuel property and the interactions involved. Fire behaviour modelling based on fuel characteristics provides a valuable, objective and quantitative supplement to flammability experiments.

Fuel bulk density describes the mass of fuel per unit volume and is a common descriptor of fuel bed porosity, which determines convective and radiative heat transfer through the fuel bed, combustion efficiency and heat release rates. Empirical and theoretical analysis suggests that fire spread is inversely proportional to bulk density in some shrublands and dense conifer fuel types (Thomas, 1971; Butler et al., 2004). The relationship of combustion rate with bulk density is not straightforward and has been described through a parabolic curve, for example, by Wilson (1982). In the fire spread model of Rothermel (1972) bulk density acts as an heat sink, which implies that fire spread rate can decrease when fuel loading increases for a given fuel depth.

We will resort to the fuel bulk density data in Pausas et al. (2012) to exemplify the potential of fire modelling in flammability studies. Pausas et al. (2012) tested if previous exposure to fire had increased the flammability of the Mediterranean shrub *U. parviflorus*; two fire regimes were considered, highly frequent fire (HiFi) and absent fire (NoFi). *Ulex parviflorus* plants from the HiFi regime had higher bulk density than plants from populations without a prior history of fire. We used the BehavePlus 5.0 fire-modelling software (Heinsch & Andrews, 2010) based on Rothermel’s (1972) model to quantify how the bulk density difference between the NoFi and HiFi populations translates into fire behaviour. The required fuel data were sourced from Viegas et al. (2001), Baeza et al. (2006, 2011), Santana et al. (2011) and Pausas et al. (2012). Two simulations were carried out for typical Mediterranean climate summer moisture conditions: for a no-slope and no-wind setting and for a combination of 30% slope and 10 km h$^{-1}$ midflame wind speed.

Table 1 indicates that NoFi populations are more flammable than HiFi populations on average, as the simulated fire spread
rate and fireline intensity are substantially higher, especially under the influence of slope and wind. This reflects distinct relative packing ratio values between NoFi and HiFi, respectively, of 0.614 and 1.109. The relative packing ratio expresses the ratio of actual to optimum packing ratio for heat transfer and combustion efficiency. Hence, HiFi fuel structure is near optimal for combustion velocity, although this does not correspond with increased spread rate and intensity of the flame front (Rothermel, 1972). Rothermel’s model does have a number of problems, especially in relation to mixed-size and live fuels, to which the model has been mathematically extended. Nevertheless, its prediction of higher flammability when the bulk density of fine fuel beds decreases is corroborated by fire experiments in different shrubland types (Thomas, 1971; Fernandes et al., 2000; Davies et al., 2009).

This example of fire modelling was simple. Recent advances in the understanding of fire processes at fine scales allow for the use of more sophisticated, physical-based models to investigate the flammability of particular vegetation assemblages (Linn et al., 2002; Zhou et al., 2005; Parsons et al., 2011), provided that kinetic parameterization of ignition and combustion processes with field or laboratory data is possible.

**Conclusion**

The assessment of flammability in the laboratory is limited by various factors, mostly related to the scale of experimentation. Individual elements or fuel beds that do not replicate the natural fuel-complex structure and composition are often the subjects of flammability trials. Plant exposure to heat in flammability experiments is frequently not comparable to wildfire conditions. If the heat transfer processes that operate in the real world cannot be realistically reproduced in the laboratory then the correspondent flammability metrics and their interpretation should not be extrapolated beyond the experimental setting.

Various configurations for flammability experiments are possible. As a minimum requirement, the reconstructed fuel complex should emulate natural fuel structure as close as possible. The heat fluxes used in laboratory experiments should approximate the quantities observed in free-spreading flame fronts, as in the experimental setup of Engstrom et al. (2004) and Fletcher et al. (2007). Finally, flammability metrics should have field correspondence to enable scaling up, comparison and linkage with fire behaviour models. Reconciling these requirements may well be quite difficult, and laboratory flammability may, after all, remain a poor surrogate for full-scale, properly instrumented experimental fires. Nonetheless, outdoor experimental fires are often limited by operational, safety and cost constraints. As an alternative or supplement to experimentation, fire behaviour simulation based on detailed fuel characterization is useful to examine how flammability changes with the properties of fuel elements and complexes. Such a research approach is particularly promising to foster cross-disciplinary collaboration and to further increase our understanding of fire potential associated with specific vegetation types.

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