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Testing and classification of individual plants for fire behaviour: plant selection for the wildland–urban interface

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Abstract. Knowledge of how species differ in their flammability characteristics is needed to develop more reliable lists of plants recommended for landscaping homes in the wildland–urban interface (WUI). As indicated by conflicting advice in such lists, such characterisation is not without difficulties and disagreements. The flammability of vegetation is often described as having four components (ignitability, combustibility, sustainability and consumability). No standards or generally recognised test procedures exist for evaluating these components in plants. Some measurements of flammability include times for ignition, rate of flame spread, flame height and heat release rate. Often, the fire behaviour characteristics of a plant are derived from its physical and chemical characteristics. Thermogravimetric analysis and other thermal analyses of ground samples have long been used to characterise the thermal degradation of vegetation. More recently, researchers have used the oxygen consumption methodology to measure the heat released due to combustion of the vegetation. Although oxygen consumption calorimetry is an improvement in characterising plant flammability, translation of laboratory results to field conditions can be problematic and tests can be expensive.

Additional keywords: calorimetry, flammability, oxygen consumption, vegetation.

Introduction

Fires in the wildland–urban interface (WUI) pose significant challenges to community leaders and incident managers. Although WUI fires are not new, the increased density of homes in wildlands and their increased risk to wildland fires are new. Initially, wildland homes were primarily low density (e.g. one home per 0.16 km^2 or 40 acres). As more individuals moved into wildlands, housing densities increased. Between 1990 and 2000, more than 6.5 million homes were built in the interface with 80% of them in medium to high density areas (Radeloff *et al*. 2005). Such densities were typical of the 2003 interface fires in southern California, USA. Because of these densities, we need to develop new wildland fire models and recommendations that account for the complexity of fire spread through an interface community.

The WUI is a complex fuel environment consisting of both vegetation and structure. This complexity entails the spread of fire from wildland vegetation to landscape vegetation (native and ornamental), vegetation to structure, structure to structure and structure to vegetation. Structurally, housing densities range from a single home to an entire community. At the low end of housing density, wildland fuels dominate fire dynamics. However, at the medium to high-end of housing density, structural fires can significantly affect fire behaviour and micro-weather patterns. Currently, many of the wildland fire behaviour models cannot account for the complexity of structures and vegetation across multiple scales (single residence, neighbourhoods and communities).

The intermix of native and ornamental vegetation as well as vegetation and structure creates unique spatial patterns that can affect fire spread. To minimise fire spread near structure, Firewise Communities planning (http://firewise.org/, accessed 15 December 2009) has proven to be an effective tool against structural ignitions. The complete clearing of vegetation 9 m (30 feet, or more when considering topography) can be draconic when considering other objectives for vegetation around houses and structures such as water conservation, aesthetics, wildlife habitat, privacy, noise reduction and energy conservation. The need for flammability information about plants becomes paramount when considering multiple usages that may be conflicting. For example, vegetation planted for privacy may be in conflict with wildfire risk reduction. A 'wall' of vegetation creates a visual barrier but may be a fire hazard because of ladder fuels. By knowing what plants have low flammability (remember, all vegetation will burn under certain conditions) and performing proper maintenance (e.g. irrigation and removal of dead material), home owners could reduce fire risk while achieving other objectives for vegetation.

Plant lists do exist for the home owner to select plants for particular reasons and conditions (e.g. Orange County Fire Authority 2001; Detweiler and Fitzgerald 2006). Plant lists for landscaping in the WUI, however, can be misleading because

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Table 1. Selected standard test methods for flammability and combustion properties of materials
ASTM, ASTM International, West Conshohocken, PA, USA (www.astm.org, accessed 16 December 2009); ISO, International Organization for Standardization, Geneva, Switzerland (www.iso.org, accessed 16 December 2009)

Common name	Organisation	Designation	Title of test standard
Oxygen bomb	ASTM	D 5865	Test method for gross calorific value of coal and coke
	ISO	1716	Reaction to fire tests for building products – determination of the heat of combustion
Ignition	ISO	5657	Reaction to fire tests – ignitability of building products using a radiant heat source
Mass loss calorimeter	ASTM	E 2102	Test method for measurement of mass loss and ignitability for screening purposes using a conical radiant heater
Oxygen Index	ASTM	D 2863	Test method for measuring the minimum oxygen concentration to support candle-like combustion of plastics (oxygen index)
Cone calorimeter	ASTM	E 1354	Test method for heat and visible smoke release rates for materials and products using an oxygen consumption calorimeter
	ISO	5660-1	Reaction to fire tests – heat release, smoke development and mass loss rate – part 1. Heat release rate (cone calorimeter method)
Full-scale calorimeter	ASTM	E 2067	Practice of full-scale oxygen consumption calorimetry fire tests
Furniture	ASTM	E 1822	Test method for fire testing of stacked chairs
Room/corner	ASTM	E 2257	Test method for room fire test of wall and ceiling materials and assemblies
	ISO	9705	Fire tests – full scale room test for surface products
Micro-calorimeter	ASTM	D 7309	Test method for determining flammability characteristics of plastics and other solid materials using microscale combustion calorimetry

they imply that species specific flammability is known. These lists often are based on anecdotal information, general knowledge of fire chiefs and landscape planners and responses of a congeneric. Lists are further compromised by the facts that there are no current standard for testing plant flammability and listing may have been based on other factors such as drought resistance.

In this paper, we address plant flammability. We review the different components of flammability as they apply to plants, look at different techniques to measure these components and discuss advantages and disadvantages of each technique, specifically oxygen consumption calorimetry because of its application for testing flammability of whole plants. Finally, we return to the issue of plant lists. Are they needed and if so, what form of standardisation may be needed to formalise lists.

Flammability

What is flammability?

Defining flammability has been a central tenet of fire research. What is it? What elements are important and how does one begin to measure it? When we think of flammability, the first criterion that comes to mind is the ease of or the delay of ignition.

Ignitability is often defined either as the minimum temperature or heat flux required for ignition or as how much time it takes a plant to ignite once it is exposed to an external heat source. Anderson (1970) defined ignitability as the ignition delay time and correlated this ignition delay time for different heat source intensity to the particular physical properties of density, specific heat and thickness. Behm *et al*. (2004*a*) associated ignitability with litter depth, height to lowest branch and foliar moisture content. Dimitrakopoulos and Papaioannou (2001) used time to ignition for a protocol to classify flammability of Mediterranean forest fuels. In their work on Australian vegetation, Gill and Moore (1996) used time to ignition to classify flammability of vegetation, but they also recognised, based on the work of Anderson (1970), the importance of combustibility and sustainability as components of flammability.

Combustibility reflects the rapidity with which a fire burns. The propensity to spread fire is a response often associated with flammability. In spread of flame tests, combustibility is reflected in the rapidity of the flame spread. Anderson (1970) suggested a correlation between combustibility and the specific burning time of a fuel, which was defined as the weight of the test sample divided by the maximum burning rate. Behm *et al.* (2004*a*) associated combustibility with energy content (i.e. heat of combustion), but the energy content itself does not provide an indicator of the rapidity of the combustion. In terms of fire tests, measurements of heat release and temperature as well as visual observations of the flames are all potential indicators of rapidity of combustion.

Sustainability measures how well the fire will continue to burn with or without the external heat source. Anderson (1970) suggested that sustainability could be related to how stable the burning rate remains. Mak (1988) used oxygen index tests (Table 1) as indicator of ignitability and sustainability. In the oxygen index test, the minimum oxygen concentration needed to support the candle-like combustion of the specimen is determined. It is reasonable to associate the standard test as an indicator of sustainability because the criterion for changing the oxygen level is sustained flaming of the specimen once the igniter is removed. Behm *et al*. (2004*a*) associated the fuel bed bulk density with sustainability. In terms of a fire test, the durations of the elevated temperatures and heat release as well as the duration of visual flaming are indicators of sustainability. The surface area burned and the gross volume consumed in the test are other possible indicators because they reflect combustion away from the area initially ignited. Heat of combustion and total heat release (i.e. the amount of energy available) are indicators of the ability of a material to sustain a fire. For tests in

Table 2. Flammability components, their definitions and examples of fire test measurements
Flammability components and definitions from Anderson (1970) and Martin *et al*. (1994). Measurable test responses from fire testing of a plant sample

Components	Definition	Potential test responses
Ignitability	Time until ignition once exposed to a heat source	Ignition time Critical temperature Critical heat flux
Combustibility	Rapidity of the combustion after ignition	Visual flame spread rate or height Rate of temperature increase Rate of heat release Peak temperature and its time Peak heat release rate and its time
Consumability	Proportion of mass or volume consumed by combustion	Mass loss rate Residual mass fraction
Sustainability	Ability to sustain combustion once ignited, with or without the heat source	Duration of visual flaming Duration of elevated temperature Duration of heat release Area or volume consumed Total heat released Heat of combustion Oxygen index

which the external heat source is removed, the dimensions and geometry of the test specimen are likely to be significant factors in the sustainability of the flames.

Martin *et al*. (1994) added a fourth component – consumability, which is how much of the plant will be consumed by the fire. This is reflected in the proportion of the original mass consumed by the combustion. Behm *et al*. (2004*a*) associated fine fuel biomass and volatile solids with consumability.

As noted by Martin *et al*. (1994), the nature of vegetation flammability means that ignitability impacts the other three components of combustibility, sustainability and consumability. Without ignition, the other three components are irrelevant. The lack of independence between the four components of flammability adds to the complexity of quantifying flammability and using test results or other measurements to develop a classification scheme.

Etlinger and Beall (2004) pointed out that the technique used to quantify flammability depends on the components being evaluated. For example, both ignition and sustainability are temporal measurements (Table 2). Consumption can be measured from various perspectives: the evaluation of physical structure and weight loss. These components are straightforward and can be duplicated in different settings. However, measuring combustion is more problematic and is dependent on the techniques used. In the hope of standardising the testing and classification of individual plants for fire behaviour, we have listed potential test responses for these four components of flammability (Table 2).

Factors affecting flammability

As one might expect, flammability characteristics are affected by several factors which can be classified into two groups: (1) physical structure and components (e.g. branch size, leaf size and shape and retention of dead material); and (2) physiological or cellular elements (e.g. volatile oils and resins, moisture content, mineral content, lignin and waxes) (Table 3). From a physical perspective, surface area : volume ratio of fuel particles is often considered a significant factor in flammability (Fernandes and Rego 1998). Likewise, moisture content and the presence of flammable oils or resins significantly influence flammability components.

Doran *et al*. (2004) identified three levels of specimen: plant parts, whole plants and groups of plants. For whole plants, flammability depends on the physical arrangement of the plant biomass. Characteristics include branching patterns, deciduous *v.* evergreen, retention of dead biomass, foliage density and canopy volume (Table 3). The practical implication of the presence of flammable plants depends very much on the vertical and horizontal spacing, type of vegetation within groupings and the presence of other flammable material such as structures and mulches. Hence, flammability characteristics for a specific species are influenced not only by the species itself but also by the context of the environment containing it.

Realising the need to evaluate flammability characteristics more comprehensively, especially for landscape plants, Etlinger and Beall (2004) studied the characteristics for six species and identified that moisture content was the primary factor that influence flammability. Moisture content has been identified by other researchers as a key factor affecting flammability (see Albini 1980; Bilbao *et al*. 1996). Moisture content affects flammability, physically (increasing thermal capacity of the tissue) and chemically (inhibiting the flaming combustion process) (Etlinger and Beall 2004).

In a study on seasonal changes in flammability of Mediterranean species, Alessio *et al*. (2008) concluded that flammability strictly depended on the leaf water availability. Other influences included content and emissions of volatile terpenes. Although other authors (e.g. Gill and Moore 1996) observed mineral content to influence flammability, Etlinger and Beall (2004) saw no effect with the species they tested.

Table 3. Criteria associated with favourable and unfavourable characteristics when determining fire resistance of a plant
Compiled from Lubin and Shelly (1997), County of Los Angeles Fire Department (1998) and Orange County Fire Authority (2001)

Favourable characteristics	Unfavourable characteristics
Architecture and structure	
Easily maintained and pruned	Not maintained or pruned periodically
Drought tolerant	Accumulators of fuel including dead twigs, branches and leaves
Free of accumulating dead branches, needles or leaves	Production of copious amounts of litter
Thick, fleshy leaves or stems	Dry or dead undergrowth
Low growing, prostrate or creeping growth characteristics	Dry leathery leaves
Low volume of leaves and small twigs	Needle-like or very fine leaves
Difficult to ignite	Dense, compact form
Does not readily support open flames	Abundant, dense foliage
Broad leafed	Shaggy bark
Open, up-right	
Produces limited dead and fine materials	
Low foliage density	
Low surface area : volume ratio	
Physiological and cellular	
Low levels of volatiles oils or resins	High oil or resin content including gums and terpenes
High moisture content, succulent	Foliage with low moisture content
High ash or mineral content	

Measuring flammability

There are several issues to consider when it comes to measuring flammability of vegetation. First, does the species need to be tested? If heat yield is considered independent of species and flammability is considered largely a function of the density of the plant mass and other physical characteristics of the plant, then visual observations of the physical characteristic might be sufficient to evaluate the 'flammability' of a particular plant.

When fire testing is desired, there are a range of options. For example, Fonda (2001) visually observed flame spread and flame height to characterise flammability of pine needles. Slightly more sophisticated measures could include measurements of mass loss, the use of thermocouples to record temperatures, infrared cameras to record temperature structure of the fire plume (e.g. Sun *et al*. 2006) and photos of pre- and post-burning to record consumption. The development of oxygen consumption calorimetry has provided new technologies for measuring the behaviour of vegetation during a fire test.

Scale is another issue distinguishing different methodologies (Etlinger and Beall 2004). This is consistent with our earlier discussion of the three levels of factors affecting vegetation flammability: plant parts, whole plants and groups of plants. In general, small-scale fire testing largely addresses the flammability of the plant parts. Larger scale tests are used to evaluate whole plants and plant groupings.

Another factor is the plant itself. Both physical and chemical attributes of a species can vary with season, age and other environmental stresses (such as drought conditions). Physical attributes that can vary include crown density, the presence and quantity of dead materials, the distance from the ground to the lower limbs and the overall fuel volume (Table 3). Correspondingly, the irregular shapes of vegetation lead to questions even for the simplest of measurements. At the cellular level, moisture content is a major factor affecting the flammability of plants. Conditioning of the sample or watering of the plant before testing will likely have a major effect on the experimental results. Similarly, because of limiting rooting space, simulating drought conditions of whole plants in pots can be problematic when applying results to field conditions (see Etlinger and Beall 2004).

One critical aspect of any fire test method is the fire or heat exposure to the test specimen. The external fire exposure provides and sustains the ignition and combustion observed in the fire test. As such, it also affects the correlation between the results of fire tests and the behaviour observed in natural fires. For example, if a small ignition source is used to test vegetation with high moisture contents, little differences between species are likely to be observed. Likewise, a large ignition source, used in the testing of dry trees, will also fail to detect differences between species since the ignition source can cause rapid combustion regardless of any species differences.

Exposure involves one or more of the three mechanisms of heat transfer – conduction, convection and radiation. For many fire tests, the exposure is convection and radiation heat transfer from some type of source. In most cases, radiation is the main mechanism for the heat transfer and one must consider the presence, type and location of the piloted ignition sources. Several tests discussed in this paper use an electric heating element as the specific radiant heat source. Clark (1981) points out that there are other factors that affect exposure such as the spectral distribution of the radiation. Air flow across the specimen can introduce convective cooling of the test specimen.

The impact of the wide variety of external heat and energy sources on ignition in natural fires is discussed by Babrauskas (2003). Because of its well defined heat source, radiant heating can be used as an input for fire models, which require well defined fire exposures. In contrast to a solid product, the 3D aspects of a vegetation sample may introduce differences between convective and radiation heating in that the radiation mechanism requires a direct line of sight as defined by the view factors of the exposure. The flow of air and hot gases associated with convective heating affects the accumulation of the combustible gases required for flaming ignition.

The types of measurements and the methodology used in testing influence fire test results. Measurements include those of the sample before the test, during the test and post-test. Measurements before the test may include physical attributes – volume or area, mass, surface : volume ratio and height or thickness – and moisture content. An example of factors influencing measurements during the test is the placement of thermocouples. In whole-plant testing, for example, the placement of the thermocouple at the base, within or above the shrub will yield different measures of temperature. Likewise, the sensitivity of load-cells will influence measures of mass loss.

Finally, there is the question of interpretation of the laboratory test results as they apply to field conditions. Comparative data on the behaviour of the plants in natural fires is lacking. This reflects the lack of good documentation of the behaviour of individual plants in natural fires. Inconsistencies between test conditions and conditions commonly seen in natural fires often result in criticism of the extension of the test results to natural fires.

Need for standardisation

Unfortunately, there is a lack of standardisation of the methodologies for vegetation, particularly for 'flammability'. This lack of standardisation has been noted by several authors over the years (e.g. Weise *et al.* 2005). The lack of consensus on fire testing of vegetation also likely reflects a view that 'flammability' is a state of 'quality' rather than a quantifiable property. In this review, references are made to some of the standard test methodologies that are available for fire testing of materials that may have application to testing of vegetation (Table 1). In most cases, the standards were developed for fire testing and regulation of building materials and other commercial products (Apte 2006).

Standardisation of test methods also facilitates the scientific exchange of research results. For example, in the testing of building products, research on the fire resistance of structural elements in building fires has long benefited from small differences in test methods used worldwide. In contrast, research on the flame retardancy of building products has long been hampered by the wide diversity of test methods for flammability. A comparison of different methods used internationally to measure flammability showed a total lack of correlation even in the relative performance of different materials (Emmons 1974). This observation reflects the effect of test procedures on the flammability results (Clark 1981). Harmonisation within the European Union on flammability testing of materials was achieved only when a new test – the Single Burning Item test (EN 13823 of the European Committee for Standardization) – was developed. In addition to harmonisation, the international acceptance of the cone calorimeter as a research and development tool has significantly improved the scientific exchange of research results on new treatments for flame retardancy of building materials and other products.

To facilitate the effective use of any testing and classification of individual plants for landscaping in the WUI by regulatory authorities, insurance companies and home owners, it will be necessary to standardise test methodologies and the conversion of test results into a classification. Similarly, with the increased use of fire models to predict wildland fire behaviour, there have been increased efforts to develop and standardise fire tests that provide reliable and replicable test responses suitable for inputs into those models. In the following sections, we will review different methods to assess flammability characteristics of plants. We list different techniques – thermal analysis, oxygen bomb calorimetry, ignition tests and oxygen consumption calorimetry – that have been used to evaluate combustion and discuss their advantages and disadvantages with respect to landscape plants. For oxygen consumption calorimetry, we explore microscale combustion calorimetry, cone calorimetry and the whole-plant calorimetry.

Thermal analysis methods

The testing of small ground samples has long been used to measure thermal degradation and combustion characteristics of vegetation materials. While such testing does not consider the physical characteristics of the plant, it does provide information on the impact of chemical compositions on combustion characteristics. The methodologies are widely used to test other materials, the equipments are widely available and established test standards exist for various applications. Such methods include thermal gravimetric analysis (TGA) (Beall 1969), differential scanning calorimetry (DSC) (Susott 1982*b*) and differential thermal analysis (DTA) (Beall and Eickner 1970). As will be discussed later, one recent development in thermal analysis is microscale combustion calorimetry or pyrolysis–combustion flow calorimetry (Lyon and Walters 2004, 2007).

In addition to needing only small ground samples, advantages of thermal analysis methods include experimental results of a fundamental nature that are useful inputs into fire models. The heat exposure is generally well defined in term of a rate of heating (degrees temperature rise per minute). Thus, the observed results are a function of temperature. The different processes of drying, evaporation of volatiles, hemicellulose decomposition, cellulose decomposition and lignin decomposition can be associated with different time intervals of the thermal analysis graphs (Susott 1982*a*; Dimitrakopoulos 2001*b*; Liodakis *et al.* 2002). The scale of the test makes it easy to test the sample in nitrogen or air. Testing in nitrogen prevents oxidation of the sample during the actual test.

A disadvantage is that the results depend on the conditions of the experiment, such as specimen size and heating rate. While an advantage, the use of small ground samples is also a disadvantage in that the physical characteristics of the foliage or plant are not a factor in the results. For materials with complex degradation and combustion mechanisms, such as biomass, results from thermal analysis can be misleading. Instead of the pyrolysis gases passing through a heated char layer as would be the case in larger specimens, pyrolysis gases from the very small samples are immediately released into the surrounding environment. Because the results are of a fundamental nature, the experimental data and the extension of the results to natural fires require the incorporation of the results into a model.

As an illustration of thermal analysis data, we ranked eight species tested by Liodakis *et al.* (2002) (Table 4). Two results

Table 4. Ranking of eight plant species based on data from thermal analysis, heat of combustion and ignition tests
TGA, thermal gravimetric analysis. Rank of 1 for least flammable and 8 for most flammable based on data reported by Liodakis *et al*. (2002)

Species	Flammability rankings based on the test indicated			
	Percentage mass loss from 300° to 400°C in TGA tests[A]	Percentage residual mass at 600°C in TGA tests[B]	Heat of combustion from oxygen bomb calorimeter[C]	Delay in ignition for Temperature of 520°C[D]
Abies cephallonica	6	5	3	7
Arbutus adrachne	3	3	2	4
Cistus incanus	2	1	6	1
Cupressus semprevirens	4	4	1	5–6
Olea europaea	5	7	4	5–6
Pinus brutia	8	6	5	3
Pinus halepensis	7	8	8	8
Pistacia lentiscus	1	2	7	2

[A]Average results for the eight species ranged from 22 to 35% with the larger percentages associated with greater flammability (rank of 8).
[B]Average results for the eight species ranged from 22 to 36% with the smaller percentages associated with greater flammability (rank of 8).
[C]Average results of the eight species ranged from 20.2 to 22.2 with the larger numbers associated with greater flammability (rank of 8).
[D]Average results of the eight species ranged from 24 to 37 s with the smaller numbers associated with the greater flammability (rank of 8).

from TGA tests of the samples in a nitrogen atmosphere were reported by Liodakis *et al*. (2002) and correlated with flammability. The first result was the percentage mass loss from 300° to 400°C that was noted to be associated with cellulose degradation. Cellulose degradation largely results in volatile gases. The average results for the eight species ranged from 22 to 35%, with the higher percentages associated with greater flammability. The second result was residual mass percentage at 600°C. For the residual mass fraction, the lower percentages were associated with greater flammability. Greater residual mass fraction means less mass degraded to volatile gases. Average results for the eight species ranged from 22 to 36%. If the TGA tests had been conducted using air, the residual mass fraction would be near zero because of the oxidation of the char. Liodakis *et al*. (2002) concluded that the mass residue at 600°C and the 300°–400°C mass loss were directly related to ignition delay times obtained at different constant temperature exposures in a home-made apparatus (Table 4).

Oxygen bomb calorimetry

The adiabatic or oxygen bomb calorimeter is widely available because it is extensively used as an industrial tool in a variety of fields as well as an educational experiment. The experimental result is the gross heat of combustion of the material available for complete combustion. The low or net heat of combustion is the gross heat of combustion corrected for the gaseous state of the water products of combustion. The ASTM International test standard is ASTM D 5865 (Table 1).

The variations of the heats of combustion of most wildland fuels are within a fairly small range and the property is often treated as a constant. Behm *et al*. (2004*a*) obtained foliar gross heat of combustion for 12 southern USA species as part of a study of the flammability of species in pine flatwood and hardwood hemlock ecosystems. Foliar heat of combustion ranged from 19.42 to 21.48 MJ kg^{-1}. Dimitrakopoulos and Panov (2001) obtained gross heat of combustion values for leaves spines, stems or branches of 21 Mediterranean species. The mean values ranged from 18.5 to 23.6 MJ kg^{-1}. In a study of seasonal changes in chamise, Philpot (1969) found the heat of combustion was directly related to the ether extractive content.

The oxygen bomb calorimeter has the advantages and disadvantages of a small ground sample. It provides a quick and easy method to identify vegetation with high flammable resin or extractives contents. The well known properties of oxygen bomb calorimetry are used as input to vegetation fire models. The standardised fuels models used in the Rothermel's fire behaviour model use a net heat of combustion of 18.61 MJ kg^{-1} (8000 Btu lb^{-1}) and total mineral ash content of 5.55% (van Wagtendonk *et al*. 1998; Williamson and Agee 2002). In a study of three interior Pacific Northwest conifers, Williamson and Agee (2002) found that the net heat of combustion with ash did not vary much with species (species averages were 20.53 ± 0.06 MJ kg^{-1}), but variations in the ash content caused more of a difference in the net heat of combustion without ash (species averages were 21.48 ± 0.15 MJ kg^{-1}). Ash content is measured as a correction for the non-organic part of the fuel. Similarly, Hough (1969) reported heat of combustion data for a wide range of forest fuels from southern United States. Data were reported as sampled and on an ash-free basis.

The low or net heat of combustion values are multiplied by mass loss rate data to obtain estimates for the heat release rate, as done by Sun *et al*. (2006). As discussed by Babrauskas (2002*a*), this calculation should be done with effective heat of combustion values.

Combustion in natural fires is often incomplete and there is a char residue, whereas with the bomb calorimeter, the char is consumed. When combustion is incomplete, higher lignin content results in more char residue and less flammable gases. As a result, the effective heat of combustion is less. The combustion of higher lignin content and lower cellulose content increases the heat of combustion value for the plant material (White 1987). In addition to the TGA results, Liodakis *et al*. (2002) reported heat of combustion data (Table 4). The correlations of the rankings from the TGA results of 300°–400°C mass loss ($R^2 = 0.0006$), residual mass fraction ($R^2 = 0.0142$) and ignition delay times

Table 5. Ranking of 10 plant species selected from time-to-ignition data

Ten species selected from a group of 24 species reported by Dimitrakopoulos and Papaioannou (2001). Rank of 1 for least flammable and 10 for most flammable as reported by Dimitrakopoulos and Papaioannou (2001). Results are for tests of the vegetation samples with various moisture contents in an ISO 5657 apparatus. Data was fitted to a linear regression model ($y = \alpha + \beta x$) where y was the ignition time and x was the moisture content. Average results for the slope β of the regression model for the 10 species ranged from 0.149 to 0.687 with the smaller numbers associated with greater flammability (rank of 10). Average results for the intercept α of the regression model for the 10 species ranged from 4.09 to 18.16 with the smaller numbers associated with greater flammability (rank of 10)

Species	Flammability rankings based on the regression model parameter indicated	
	Slope β	Intercept α
Arbutus unedo	8	5
Cistus salvifoluis	3	3
Cistus creticus	4	7
Cupressus semprevirens	5	6
Eucalyptus camaldulensis	10	10
Juniperus oxycedrus	2	2
Olea europaea	9	4
Pinus brutia	6	9
Pinus halepensis	7	8
Tamarix smyrnensis	1	1

($R^2 = 0.024$) with the rankings from the heat of combustion data were all very small (Table 4).

Susott (1982*a*) found an average heat of combustion of 32 MJ kg^{-1} for the char samples, compared with 21.4 MJ kg^{-1} for the original uncharred fuel. Susott *et al*. (1975) and Susott (1982*a*) determined the effective heat of combustion or volatile heat of combustion for a variety of natural fuels by using the bomb calorimeter to measure the heat of combustion of the fuel, charred samples and ether extractives. Susott (1982*a*) concluded that, on average, ~60% of the total heat of combustion is available for flaming while the remaining 40% remains as char until released by glowing combustion. Shafizadeh *et al*. (1977) used thermal analysis techniques to determine the effective heat content and heat release rate of six species as a function of temperature. Based on tests of whole trees, Babrauskas (2006) obtained estimates for the effective heat of combustion. This study concluded that: (1) during a rapid flaming fire of vegetation, the effective heat of combustion is close to the heat of combustion of the volatiles alone; (2) effective heat of combustion of vegetation is a function of moisture content as a result of the moisture altering the combustion process; and (3) the effective heat of combustion during active flaming is significantly less than the heat of combustion obtained in the oxygen bomb calorimeter.

Ignition tests

As previously discussed, ignitability is often defined either as the minimum temperature or heat flux required for ignition or as how much time it takes a plant to ignite once it is exposed to an external heat source. Simplest of these experiments is to insert a sample in a furnace at different temperatures and observe the times for ignition (e.g. Montgomery and Cheo 1971; Liodakis *et al*. 2002). The rankings of eight species based on ignition delays for exposures in a furnace at temperature of 520°C (Liodakis *et al*. 2002) are in Table 4. As stated by Mak (1988), one drawback of such tests is the difference in the response of the samples depends on the severity of the isothermal conditions. A recurring problem with such experiments is the question of what temperature is actually being measured and how to transfer such data to other situations or test equipment.

Martin *et al*. (1994) argue that ignition delay is an insufficient measure of ignitability and that ignitability must include the heat flux at the surface required to bring a material to combustion under various conditions. Other complexities noted by Martin *et al*. (1994) include the type of heating (radiant, convective and fire brands), non-flaming combustion such as glowing and smouldering, piloted and non-piloted ignition and burning of vegetation as a series of ignitions of successive particles. Babrauskas (2003) reviews the literature on ignition of vegetation and discusses problems with some of the testing. Both piloted and auto-ignition experiments have been conducted. Other ignition experiments have been conducted pressing an object with a hot surface at a certain temperature against the vegetation sample and making observation of ignition.

More recently, radiant heating in standard test methods such as the ASTM E 1354 cone calorimeter and the International Organization for Standardization (ISO) 5657 ignitability test (Table 1) have been used to determine the times required for ignition. Dimitrakopoulos and Papaioannou (2001) used the ISO 5657 test method to obtain time to ignition of Mediterranean forest fuels. As with the cone calorimeter, the ISO 5657 method uses a conical heating element to provide the radiant exposure to the test specimen. Regression models were developed by Dimitrakopoulos and Papaioannou (2001) between the times for ignition and moisture content (Table 5). Dimitrakopoulos and Papaioannou (2001) advocated the use of the slopes from the regression model to rank the species, which is reasonable because it reflects the vegetation with moisture. For comparison, we have also included the ranking based on the intercept from the model, which reflects the results for oven-dry samples.

Alessio *et al*. (2008) used an infrared quartz epiradiator to provide the heat exposure and observed the time and temperature for the appearance of smoke, incandescence (pyrolysis) and flame. Ignition temperature data have also been obtained using thermal analysis techniques that measure the heat generated as the chamber temperature is increased. The exothermic peaks in the data are taken as the ignition temperature.

Oxygen consumption calorimetry

The oxygen consumption methodology is widely used in fire testing of building materials and manufactured products around the world. Oxygen consumption calorimetry calculates an estimated value of heat released from measurements of oxygen depletion. The methodology is possible because most materials containing carbon, hydrogen, oxygen and nitrogen have an average net heat release of 13.1 MJ kg^{-1} oxygen (Huggett 1980). It forms the basis for several standard test methods for such products. The measurement of the heat release from burning building materials has been of interests for many years (Janssens 2002).

Similarly, Susott (1982*a*) used Evolved Gas Analysis (EGA) to analyse combustion products of thermal degradation and estimated heat release rates of forest fuels. The oxygen consumed in the combustion of the collected volatile gases was measured. Using a value of 14.0 ± 0.6 MJ liberated per kilogram of oxygen consumed, the gross heat of combustion for the volatiles was calculated from the measurements of oxygen consumed. Dietenberger (2002) re-analysed the data of Susott *et al*. (1975) and other data to obtain a value of 13.23 MJ per kilogram of oxygen consumed for the estimation of the net heat of combustion of biomass and wood products.

The ability to measure the heat released due to combustion simply by measuring the depletion of oxygen in the exhaust has greatly simplified and expanded the experimental capabilities to quantify the combustion characteristics associated with flammability. By constructing a hood that captures the exhaust gases from combustion, researchers were able to determine heat release for not only an entire object but also facsimiles of rooms from offices and homes. The ramifications of the technique were far reaching as it opened up a wide range of possibilities of testing, including entire plants. The application of oxygen calorimetry to whole plants was an important step towards quantifying flammability characteristics of different plant species under different growing conditions.

Unlike other calorimetry methods, oxygen consumption calorimetry is an open combustion system in which the air flow entering the system is not measured. Unlike heat release measurements based on temperature, the oxygen consumption methodology is measuring only the heat released due to combustion. The incoming air is assumed to be oxygen, carbon dioxide, water vapour and nitrogen. Likewise, the methodology assumes that there is complete combustion of the exhaust gases before the sampling of the exhaust gas such that these gases are also the composition of the exhaust. The primary measurements are the oxygen concentrations as measured with an oxygen analyser and the exhaust gas flow rate. If only the oxygen level is measured, the carbon dioxide is removed from the gas sample before the oxygen concentration is measured. To improve the heat release calculations if there is some incomplete combustion and avoid the scrubbing of the carbon dioxide, the carbon monoxide and carbon dioxide concentrations are often measured. Water vapour is removed before the oxygen, carbon monoxide and carbon dioxide measurements. Exhaust fans are needed to develop the measurable flow rates through the exhaust ducts. Additional information on the heat release measurements and calculations can be found in the annexes and appendices of ASTM International standards cited in Table 1 (e.g. ASTM E 2067, E 1822 and E 2257) and articles by Janssens (2002) and Babrauskas (2002*b*). ASTM E 2067 is a standard practice for full-scale oxygen consumption calorimetry. In contrast to fire tests limited to thermocouples, oxygen consumption calorimetry depends on gas concentration measurements that have significant response times that need to be measured and accounted for in the calculations of the heat release rates. As discussed in E 2067, the response times for each analyser need to be determined and include the lag time for the physical transport of the gases from the source to the gas analyser and the response time of the analysers themselves.

The primary results from oxygen consumption calorimetry are heat release rate curves as a function of time. In such tests, the loss of mass is often measured, the time for ignition is observed and other visual observations are recorded. As such, a set of results are obtained that reflects the different components of flammability. Ignitability is the observed times for ignition once the sample is exposed to the external heat or ignition source. Measurements that reflect sustainability include the total combustion time, the total heat released and the effective heat of combustion. Consumability is reflected in the results for the residual mass fraction or the total canopy loss. The heat release rate curve, particularly the peak heat release rate, provides the means to quantify the combustibility of the material. Smoke development is also often measured by the obscuration of light across the exhaust duct.

The oxygen consumption methodology can be used with different sizes of test samples. Most recently, the technique has been applied to small ground samples similar to those of thermal analysis techniques. The bench-scale cone calorimeter is the widely known test method that uses this technology. Finally, oxygen consumption calorimetry is used to measure the heat release of full-scale items such a whole plants. Test equipment associated with these three scales of test specimen will be reviewed as well as recent applications of the tests to vegetation. The application of the different test equipment to the testing of vegetation is not standardised.

Micro-calorimeter

Microscale combustion calorimetry is the application of oxygen consumption calorimetry to thermal analysis. The methodology was developed as a screening test to expedite the development of new materials for aircraft applications by allowing the testing to be conducted on milligram samples (Lyon and Walters 2007). It was recently approved as an ASTM International standard for plastics and other solid materials (ASTM D 7309; Table 1). Like traditional thermal analysis, the two modes of operation (thermal degradation with or without oxygen) allow the combustion characteristics of the volatile gases to be separated from those of the solid residue. Results are obtained for the amount, rate and temperature of the heat released under controlled heating. It can be used as an alternative to the traditional oxygen bomb calorimeter to obtain the net heat of combustion for the organic material (volatile gases and solid residue). As noted in ASTM D 7309, corrections for latent heat of evaporation or heat of solution of acid gas that are required in oxygen bomb calorimetry are not necessary with this method. At the present time, there has been no known use of the equipment to test vegetation.

As with traditional thermal analysis, a sample (1 to 50 mg) is heated in a pyrolyser in either a nitrogen or oxygen environment at a controlled rate of temperature rise of 0.2–2 $K s^{-1}$. The volatiles are extracted to an oxidising chamber in which they undergo complete combustion at 900°C. Similar to the EGA of Susott (1982*a*) and Lyon and Walters (2004), oxygen consumption calorimetry obtains the heat release rate associated with the combustion of the volatiles gases when the thermal degradation is done in the nitrogen environment. When the thermal degradation occurs in a high oxygen environment, the combustion of the solid residue is included in the heat release observed by the oxygen consumption calorimetry measurements.

As with other thermal analyses, one advantage of the milligram size of the specimen is that it allows the combustion characteristics of individual components (leaf, bark, stem, etc.) to be investigated. Another advantage is that the rising temperature exposure means the basic test results are a function of temperature and the temperatures for maximum heat release rate can be reported. Results with polymers have been encouraging in terms of correlations with other fire tests such as the cone calorimeter and limiting oxygen index test (Lyon and Walters 2007). The small specimen size is also its disadvantage for organic materials. The samples need to be representative of the organic material being evaluated. The application of the methodology to vegetation has not been investigated.

Cone calorimeter

The 'cone calorimeter' is the bench-scale test method that uses oxygen consumption to measure the heat release rate of a burning material exposed to a constant external heat flux (Babrauskas 1984, 2002*a*). Because the fire exposure is a constant heat flux, the ignition characteristic reported is the duration of heating required for ignition. The bench-scale size of the 100 mm^2 specimen used in the method is such that it can be used to evaluate the flammability of the plant parts. It has been used to test the foliage of different plants. The standards are ASTM E 1354 and ISO 5660-1 (Table 1).

The cone calorimeter name comes from the conical electric heater element used to provide the constant heat flux to the sample. In addition to the radiant heater, there is a spark igniter for piloted ignition. In addition to the heat release rate, measurements include time for sustained ignition, mass loss rate, effective heat of combustion and visible smoke development. These measurements are collected as a function of time. For reporting purposes, the results are often averaged over a specific time period, such as 60, 180 and 300 s after the observation of sustained ignition. The duration of flaming required for the observation of 'sustained' ignition is specified in the standard. The heat release rate and mass loss rate are generally reported on a per area basis using the area of the planar sample or the sample holder. The specimen orientation is generally horizontal, but the specimen can be tested in a vertical orientation. The constant incident heat flux imposed on the test specimen can be as high as 100 $kW m^{-2}$. The specimen is placed on a layer of refractory fibre blanket. The placement of the specimen in a retainer frame and the use of a grid over the specimen are options. The smoke obscuration measurements are done with a helium-neon laser to provide the beam across the exhaust duct and silicon photodiodes as the reference detectors. Load cell beneath the sample measures the mass loss.

Besides the heat release measurements, the advantages of the method include a well defined external heat source and the ability to test actual foliage in a green or dry state. The measured heat of combustion is the effective heat of combustion, which is consistent with natural fires. The sample also is the disadvantage. Cone calorimeter results are generally reported on a per area basis, which for foliage, is an ill-defined number. An alternative is to use a layer of ground material instead of pieces of actual foliage. The composition of the sample in terms of the different components of the whole plant is another consideration in the preparation of the sample and the interpretation of the results. The initial mass does affect some of the results, such as the time for sustained ignition. Because coverage of the sample holder also likely influence some results, it is difficult to maintain consistent initial mass when testing foliage.

The correlation of the results from the cone calorimeter to tests of whole plants or natural fires has not been demonstrated. While the cone calorimeter has gained international recognition and use, it is more expensive and less available then equipment such the oxygen bomb calorimeter. A lower cost bench-scale alternative to the cone calorimeter for screening materials is the mass loss calorimeter (ASTM E 2102; Table 1). It uses the conical radiant heater and specimen load cell of the cone calorimeter. It is mainly intended to test for ignitability and to test fire retardant treated materials in which the effectiveness of the treatment reflects the residual weight of the sample. Optional heat release measurements can be made using thermopiles in a stack above the heater. In this simplified heat release rate equipment, there are heat losses that reduce the heat release reflected in the thermopile measurements.

The cone calorimeter has been used to investigate the combustion characteristics of vegetation in several recent projects. Enninful and Torvi (2005) used the cone calorimeter to investigate the effects of moisture and incident heat flux on smoke production and heat release rates of vegetation. The samples were needles, twigs and small branches of jack pine and balsam fir. In recent years, the USA Forest Products Laboratory (FPL) has used its cone calorimeter in various collaborative projects. In the initial study with Forest Service Riverside Forest Fire Laboratory, the seasonal differences in combustion characteristics of 10 Californian ornamental plants were examined (Weise *et al*. 2005). Three of the combustion characteristics measured were the peak heat release rate (PHRR), average effective heat of combustion (AEHOC) and the times for sustained ignition (TSI)

Table 6. Ranking of 10 plant species tested in the cone calorimeter

Rank of 1 for least flammable and 10 for most flammable based on Weise *et al*. (2005). Selected test results for vegetation samples obtained in August and tested in a cone calorimeter. Average results for the peak heat release rate (PHRR) for the green samples of the 10 species ranged from 4 to 127 kW m^{-2} with the higher numbers associated with greater flammability (rank of 10). Average results for the average effective heat of combustion (AEHOC) for the oven dry samples of the 10 species ranged from 11.6 to 17.4 MJ kg^{-1} with the higher numbers associated with greater flammability (rank of 10). Average results for the times for sustained ignition (TSI) for the green samples of the 10 species ranged from 99 to 292 s with the smaller numbers associated with greater flammability (rank of 10). No sustained ignitions were observed for four of the species and these were assumed to be 1 to 4 in the rankings

Species	Flammability rankings based on the cone calorimeter test result indicated		
	PHRR	AEHOC	TSI
Adenostoma fasciculatum	9	9	7
Aloe spp.	1	1	NSI
Atriplex halimus	3	2	NSI
Ceanothus 'Joyce Coulter'	6	4	6
Cistrus ladanifer	5	6	9
Cistus salviifolius	8	3	8
Heteromeles arbutifolia	7	7	NSI
Myoporum parvifolia	4	8	5
Olea europaea	10	10	10
Rhagodia spinescens	2	5	NSI

(Table 6). As part of this study, a sub-set of the cone calorimeter data was compared with the results of whole plants calorimetry tests. In cooperation with the State Fire Marshall of Minnesota, cone calorimeter tests were conducted on samples from Christmas trees (White *et al*. 1997). The results were compared with ignition experiments on whole trees that had undergone drying associated with indoor use and whole plant calorimetry tests. The combustion characteristics of vegetation common to the Colorado wildland–urban interface were obtained in a short preliminary study at Colorado State University (White *et al*. 2002). In a study with Agricultural Research Services, the impact of historic changes in CO_2 and elevation ecotype on the combustion characteristics of *Bromus tectorum* L. (cheatgrass) (Blank *et al*. 2006) was investigated. Samples from 42 plants found in the north-eastern United States were tested as part of a study with Forest Service Northern Research Station to examine the relative flammability of non-invasive plants and the invasive plants that are replacing them (Dibble *et al*. 2007).

Full-scale calorimetry

Because the measurements needed to implement the oxygen consumption methodology are all associated with the exhaust of the combustion gases, the methodology can be used to measure the heat release rate of any burning item that will fit under the hood. The size of the items is limited only by the size of the hood and the exhaust fans to handle the burning item and collect all the combustion products.

With the wide application of the methodology to different products, ASTM International developed a standard practice for full-scale oxygen consumption calorimetry fire tests (ASTM E 2067; Table 1). This practice specifically addresses the equipment needed to conduct oxygen consumption tests under a large hood. Some specific standards include room fire tests of wall and ceiling materials (ASTM E 2257 and ISO 9705) and fire testing of stacked chairs (ASTM E 1822; Table 1). Because an ignition source larger than an electrical heater is normally desired, propane or another gas with a known net heat of combustion is normally used to provide the external fire exposure. Because the combustion products from the gas burner are collected in the exhaust duct, the heat release of the burner needs to be subtracted from the heat release obtained from the oxygen consumption calculations.

Unlike for building materials and contents, no standards exist for testing whole plants. For example, what size plant should be burned? How will ignition occur and how long should the exposure be? Even with these challenges, whole-plant testing is giving researchers values for the components of flammability for different species.

To test a plant, several factors need to be considered. First, the size, shape, arrangement and condition the plant itself needs to be considered (Etlinger and Beall 2004). For example, one can vary plant size to determine the relationship between size and heat release. Similarly, one can vary shape and arrangement by pruning branches and removing leaves to evaluate how plant structure can influence fire behaviour. Finally, plant condition, referring to its health and moisture content, can be evaluated. Unlike the other attributes, this attribute is more difficult to control and replicate. If necessary, one could use, for example, USA Forest Service Forest Health Monitoring protocols (see http://science.nature.nps.gov/im/monitor/protocols/fhmproto.htm, accessed 18 December 2009) to define plant health. Likewise, moisture content may be modified through water stressing but it is difficult to replicate even with nursery-grown material (Etlinger and Beall 2004). As one might expect, there are endless possibilities when one considers the number of plants that need to be tested as well as accounting for their ages and seasonality.

In general, plants used in whole-plant analyses are from nurseries and are in excellent condition. They do not show symptoms of dieback disease, have no dead material contained within them and are relatively uniform in shape. These conditions are not frequently found under field conditions. The size of the calorimetry and budgets often dictate the size and number of plants to be tested. For example, some facilities, such as the National Institute of Standards and Technology, have a variety of hoods that allows researchers to burn plants ranging in size from 0.5-m shrubs to 3.5-m Norway spruces. The larger hood also creates the opportunity to expand beyond a single plant and explore fire behaviour with respect to the interactions among mulch, shrub, tree, and structure at one time.

Unlike for cone calorimetry, ignition source, duration of exposure and intensity of flame can vary. For example, Etlinger and Beall (2004) created a uniform flame front (150 kW) by forcing propane gas through 150 mm of sand with an exposure of 5 min to burn a sample of two to three plants. Because of air entrainment, the flame leaned at a 45° angle and penetrated the midsection of the plants. In contrast, Long *et al*. (2006) used a U-shaped burner (40 kW) at the base of a single plant with an exposure of 2 min. For comparability, it becomes imperative that detailed descriptions of plant material and ignition protocols are given within the study.

Recent studies with whole plant calorimetry include studies to investigate the fire growth characteristics of Christmas trees as the ignition source to a structure fire. Damant and Nurbakhsh (1994) tested nine used Christmas trees (Douglas-fir (*Pseudotsuga menziesii*)) and 'Noble pine'. Ignition source for the tests included 0.23 to 0.5 kg of polyester fibre batting beneath the tree or a single paper match to a lower branch. For the four dry trees with initial weights of 5.3–11.8 kg, the peak heat release rate ranged from 786 to 1667 kW. A partially dried tree weighing 5.9 kg was not ignitable with the paper match and required the polyester batting to ignite and achieve a peak heat release rate of 831 kW. The fresh Douglas-fir tree did not ignite even with the 0.23 kg of polyester batting providing the fire exposure. As with the test of Damant and Nurbakhsh (1994), Stroup *et al*. (1999) were not able to achieve sustained ignition of a Scotch pine tree, kept fresh with water, even with application of a propane torch. In the seven tests of dry Scotch pine trees (initial weights of 9.5–20 kg), Stroup *et al*. (1999) recorded peak heat release rates of 1600–5200 kW per tree. The ignition source was 'electric match' (paper match wrapped with wire to which current is applied) placed on a lower branch. Natori *et al*. (2006) analysed the data of Stroup *et al*. (1999) and Damant and Nurbakhsh (1994) to obtain design fire curves for Christmas trees. To make the design curves applicable for variable sizes, the peak heat release rate was correlated with the surface area of the tree as calculated from an assumed circular cylinder. The total heat release rate was regressed with the total mass. In three tests of used Christmas trees (initial weights of 4.5–13.1 kg), White *et al*. (1997) obtained peak heat release rates of 469–1250 kW per tree. The ignition source was 0.22 or 0.45 kg of shredded paper and 100 mL of methanol. Babrauskas (2002*b*) identified four main variables that govern the heat release rate of Christmas trees: (1) moisture content of the needles; (2) mass of the tree; (3) species; and (4) ignition source used. In an extensive series of tests of Douglas-fir, Babrauskas (2002*b*) found that the peak heat release rate per unit mass ($\dot{q}$/mass, kW kg^{-1}) is:

$$\dot{q}/\text{mass} = e^{5.84-0.017M} \tag{1}$$

where M is the moisture content of the needles on a dry basis. The effective heat of combustion of the trees was 13.1 MJ kg^{-1}. Babrauskas (2002*b*) concluded that a small flame was not able to ignite the Douglas-fir tree if the moisture content was greater than 50–60%. The effect of moisture content on the ignition of Christmas trees is further discussed by Babrauskas (2003). Särdqvist (1993) included heat release curves for three spruce (*Picea excelsa*) Christmas trees (6.5–7.4 kg) in a compilation of heat release data. The ignition source was an isopropanol tray standing on the floor under the undermost branches.

More recently, whole-plant calorimetry has been used to address the behaviour of vegetation in the wildland–urban interface. Stephens *et al*. (1994) tested 11 mature Tam junipers (*Juniperus sabina* var. *tamariscifolia*). Fifteen-second exposure to a natural gas wand was used to ignite the shrubs. For the 10 specimens that ignited, the peak heat release ranged from 165 to 2130 kW. One plant that was tested the day after being harvested and had moisture content of 105% did not ignite. The moisture contents of the 10 plants that did ignite ranged from 31 to 92%, and the low peak heat release was for the plants with the higher moisture contents.

As part of research at NIST on physics-based modelling of WUI fires (Evans *et al*. 2004), nine Douglas-fir trees of three different sizes were tested to obtain information on peak heat release rate, flame height, radiant heat flux and burn time (Baker and Woycheese 2007). The ignition source was a 5 to 15-s application of a propane torch with two flames for simultaneous ignition of the crown on opposite sides of the stem. All nine trees regardless of size obtained their peak heat release rate in ~30 s.

Etlinger and Beall (2004) examine flammability characteristic of six species as part of a water-stressed experiment to simulate drought condition and identify what plant variables affected heat release performance. The ignition source was a 150-kW sand burner for 5 min placed so the flame leaned into the plants such that the full width of the plants was exposed to the flames. They observed that moisture content and foliar mass were the two primary attributes that affect peak heat release. Through their analysis, they reclassified *Cistus purpureus* from being acceptable in high fire hazard areas to being unacceptable. Similar tests were done at the University of California on five species of potted plants in conjunction with the cone calorimeter study (Weise *et al*. 2005).

Long *et al*. (2006) examined 34 species of plant to determine their flammability characteristics. The igniter was a U-shaped, natural gas metal pipe burner that was placed around the base of the plant and produced 100-mm flames for 120 s. Their primary objective was to classify species based on their flammability for creating a plant list. Using principal component analyses and cluster analyses, they were able to identify three groups of species based on flammability – low, moderate and high. The variable accounting for most variation was peak heat release performance. With this information, they made recommendations as to the application of a species to firewise planning.

As part of a study on firebrand production (Manzello *et al*. 2007), nine Douglas-fir trees were tested. The trees were ignited at the base with a 15-s exposure from a circular (800-mm diameter, 30-kW output) or hexagonal (1220-mm diameter, 130-kW output) natural gas burner. For trees with moisture contents of 50%, no firebrands were produced and the tree only partially burned. Firebrands were produced when the moisture contents were 30% or less.

Plant lists

Plant lists have become a component of many regulatory and educational efforts to promote the creation of defensible space in the wildland–urban interface. An important question to ask is how functional and accurate are these lists? To address this question, one can take two perspectives: (1) scientific and (2) policies and home owners. From the scientific perspective, plant architecture and geometry, structure and moisture content are the primary components that determine a plant's flammability (Pyne *et al*. 1996). Likewise, if moisture content of a plant is sufficiently low, it will burn regardless of its structure and geometry. Further, density also plays an important role in fire dynamics. Lists contribute minimally to understanding fire dynamics and behaviour because they generally do not provide sufficient information about physical and chemical attributes.

From the policy and home owner perspective, however, plant lists are guidelines for choices and recommendations. Without lists, home owners will be unable to select desirable species that reduce fire risk around their homes, and policies and regulations would be harder to write and enforce. Yet, lists are fraught with problems and most plants will burn in a high-intensity fire.

As part of its projects on wildland–urban interface fire safety, the University of California conducted an extensive survey of many published lists and compiled a list of 598 species (Lubin and Shelly 1997). Their examination of the lists found numerous conflicting recommendations and little scientific basis for them. Fifty three species were identified as having conflicting recommendations. Based on a criterion of three or more references, 147 plants were listed with favourable fire performance and 17 had unfavourable ratings. Characteristics identified to be associated with plants with unfavourable ratings included: (1) high surface area : volume ratio; (2) low moisture content; and (3) high percentage of dead matter or debris. The individual summaries of the references provided information on the criteria used (Table 3).

One problem with using such lists is that the basis for inclusion and exclusion of a plant has often been lost to the users. Likewise, many lists are just compilations from other lists and reasons for inclusion or exclusion are not evident. Similarly, other justifying factors, such as drought resistance, have been used for inclusion rather than any information on actual flammability characteristics of the plant. Another problem with lists in general is that there are many more species, variations and related species than there are species on such lists. It is impossible to test all the plants used in landscaping; yet, the selection of a plant that is even a slight deviation from the specific plant listed can be ill advised. Plants need to be identified precisely and clearly. If known, plants with similar names or groupings but with different fire performance characteristics need be identified too. Long *et al*. (2006) observed that species in the same genus do not always have the same flammability characteristics. Another factor that needs to be considered is what region the list was developed for. Because of regional climatic differences and species responses, flammability characteristics of a species in one location may be quite different for another location or elevation. Hence, application of plants lists from different regions should be used with caution. Further, because flammability can vary by season, flammability characteristics should be listed by season. Unfortunately, the amount of time, energy and cost to develop such an extensive list is prohibitive.

An example of a plant list being part of regulatory requirements is the plant list of Orange County, California (Orange County Fire Authority 2001). Grading and building permits require the submittal of a fuel modification plan to the fire department. The fuel modification zone is 'a strip of land where combustible native or ornamental vegetation has been modified and partially or totally replaced with drought tolerant, fire retardant, plants'. As noted in the guideline (Orange County Fire Authority 2001), the many variables involved with fuel modification make precise regulations impractical. Vegetation within the fuel modification zones needs to be drought tolerant and fire resistant. The guideline document lists plants with characteristics that makes them of such high flammability that their removal from any of the fuel modification zones is required. Included in the list of 26 undesirable fire-prone species are species of *Eucalyptus*, *Pinus* and *Juniperus*, and *Adenostoma fasciculatum* (chamise), and *Artemisia californica* (California sagebrush). (See Table 3 for examples of undesirable characteristics.) In addition to the list of fire-prone species, there is a second 'fuel modification zone plant list' of 286 species that are coded as permitted. Permitted plants are limited to those on the list. The list coding includes: (1) species prohibited in wet and dry fuel modification zones adjacent to reserve lands but acceptable on all other zones; (2) species appropriate for use in wet fuel modification zones adjacent to reserve lands and other wet or irrigated zones; (3) native species acceptable in all locations; (4) species acceptable on a limited basis in wet fuel modifications zones adjacent to reserve lands; and (5) species acceptable on a limited use basis per an approved plant palette that places species-specific restrictions on spacing, height and width of individual plants and number of plants per cluster. The desirable plant list is described as a 'list of plants exhibiting characteristics of low fuel volume, fire resistance, and drought tolerance which makes them desirable for planting in areas of high fire danger'. Drought tolerance is defined as 'the ability of a plant or species to survive on little water'. Fire resistance is described as a '. . .comparative term relating to the ability of a plant to resist ignition'. Fire retardance is defined as a 'relative comparison of plant species related to differences in fuel volume, inherent flammability characteristics, and ease of fire spread'. Performance requirements for submittal of additions to the list of acceptable plants are not provided. A similar fuel modification plan guidelines document has also been issued by Los Angeles County (County of Los Angeles Fire Department 1998). The document includes a desirable plant list, which is 'provided as a suggested guideline (not exclusive) for fuel modified landscapes within Los Angeles County' (Table 3).

An example of a plant list in educational materials is the list in a publication of the East Bay Municipal Utility District (Baptiste 1992). The list of recommended plants is a list of drought tolerant plants with notations of those plants with 'some fire resistance'. The list of highly flammable plants includes notations of plants considered to be 'pyrophytes'. Such plants were high in oils or resins (pines, junipers and *Eucalyptus globulus*). In the discussion of plant selection, it is advised to select plants that are low growing such as ground covers or have low fuel volumes (rock-rose (*Cistus*) and lavender cotton (*Santolina*)). The examples of fire-resistant plants that burn slowly were Toyon (*Heteromeles*) and mock orange (*Pittosporum*).

Most, if not all, literature including plant lists also advocates the creation of defensible space and the importance of the maintenance of the landscaping. A defensible space advocates the placement and maintenance of plants to reduce fire risk. Maintenance includes watering regularly, maintaining vertical and horizontal separation among landscape plants, removing dead materials from the plant and bed and regular pruning to create an open and loose branching pattern.

An alternative or supplement to plants lists is the listing of key plants characteristics associated with favourable or unfavourable fire resistance. This is the approach taken by Doran *et al*. (2004) for the selection of plants for the defensible space. The key plant characteristics are discussed at the three levels of plant parts, whole plants and groups of plants. Characteristics of the leaves and small branches are: (1) moisture content; (2) size and shape of leaves; and (3) presence of oils, resins, waxes or other chemicals. Key characteristics of whole plants include: (1) branching patterns; (2) deciduous *v.* evergreen; and (3) retention of dead leaves and branches. Beyond the performance of individual plants, Doran *et al*. (2004) discuss the importance of plant arrangements on the overall flammability of a landscape.

Given the possible need to consider conflicting characteristics and obtain species-specific data for the identified characteristic, lists remain the easiest method to convey information on desirable plants. Consequently, standard protocols with scientific vigour are needed for the creation of such lists. While extensive work has been done on characterising overall wildland fuel beds (Sandberg *et al*. 2001), there are not obvious agreements as to what should be included in such protocols of individual plants. When plant lists are used in the regulatory arena to regulate permitted plants in the required defensible space around structures, the protocols used to develop the lists must be defendable to legal challenge.

One protocol for the establishment of a plant list is a step-by-step process in which the judgments are based on the physical characteristics of the plant (Behm *et al*. 2004*b*). The proposed dichotomous key links the knowledge of the scientific and management perspective with that of the needs of the home owner. For example, the key starts with a simple identification: tree, palm, shrub, vine or herb (including grasses). Depending on the selection, the user progresses through a series of questions which include considerations on structure and management activities. When applicable, the key identifies ways to reduce fire hazard. For example, for conifers the key acknowledges the need to reduce accumulation of needles on the ground and reduce ladder fuels. Based on the number of 'hits', the home owner can determine whether the selected plant has low, moderate or high flammability. With this information, the home owner can then determine where to plant the specimen. The key itself may minimise the need for plant lists. Unfortunately, this process can be time consuming if one has a large number of plants to test and is probably not simplistic enough for public use; thus, further necessitating the need for lists.

A flammability plant list in New Zealand was obtained through surveys of fire managers in which the fire managers were asked to assign the specific species to a series of flammability classes based on their experience (Fogarty 2001). The survey results were collated and statistically analysed to obtain the 'state of our knowledge' compilation for use by homeowners and fire managers.

A classification methodology developed by Dimitrakopoulos (2001*a*) was based on multivariate statistical methods and uses the pyric properties (Dimitrakopoulos and Panov 2001) of the species. The characteristics included in the model were heat of combustion, total and silica-free ash content, surface area : volume ratio and fuel particle density for the species. The direct relationships of these characteristics to flammability are discussed by the authors. For example, the fuel particle density affects the thermal conductivity of the fuel and therefore its ignition time. Besides the net heat of combustion, particle characteristics included in the flame spread model of Rothermel (1972) include surface area : volume ratio, moisture content, total mineral content, dry density and the moisture content of extinction for the particles of the fuel. The application of various statistical methods, as demonstrated by Dimitrakopoulos (2001*a*) to a wider array of characteristics and test results would likely provide the further insight needed to develop more scientifically sound classification methodologies. Principal component analysis was used to examine relationships between test results obtained with the cone calorimeter (Dibble *et al*. 2007).

A task group within ASTM International Committee E-5 on Fire Standards is working on the classification of vegetation for use in wildland-urban interface. As an initial step in that direction, current effort is to develop a standard on whole-plant calorimetry testing. It is part of several standard development activities within Subcommittee E5.14 on External Fire Exposure Tests that are intended to address the unique aspects of the wildland–urban interface (Anonymous 2005).

Concluding remarks

Although plant lists can be fraught with inaccuracies, their demand will only increase in the future as more people move into the wildland–urban interface. However, the plant list should not be a home owner's first line of defence against a wildfire. Home owners should focus on creating a defensible space around their home and then determine within this space, where and where not to create landscape bed, what species to plant and how to arrange plantings. Maintenance also is paramount. By removing dead biomass, maintaining proper distances between vegetation through trimming and pruning and watering adequately, the potential of fire hazard can be greatly reduced.

To improve upon plant lists, lists should contain something like a metadata file, but in paragraph form. This meta-paragraph should at least list sources of information, criteria for classification, plant architecture and geometry, regional applicability and contact information. As the demand for lists increases, the criteria used to classify plant flammability need be standardised.

The protocols established to define flammability for California should be applicable to Florida. Likewise, this standardisation needs to move beyond just defining the ease of ignition but also the other elements of flammability – consumption, combustion and sustainability. To accomplish this objective, standardisation among scientific techniques used to quantify and test flammability must occur. For example, as stated in this article, there is currently no standardisation for the type of exposure, duration of exposure and the amount of heat flux needed for ignition. This is true especially with whole-plant testing. Without this standardisation, results from different studies may not be comparable.

Beyond standardisation, there is a need to relate results among the various methods used in oxygen consumption calorimetry. Each technique has its advantages and disadvantages. By establishing how results are correlated, techniques can augment each other. For example, cone calorimetry provides for heat release values for the individual plant parts. Whole-plant calorimetry provides values for the entire plant. By establishing the relationship between heat release for individual parts and the whole plant, one can begin to simulate management actions, such as pruning, on fire behaviour without conducting laboratory testing, thus saving time and funding. As we understand the relationship between results among different techniques, this information will need to be 'scaled-up' to field conditions and translated into plants lists usable by homeowners and regulators.

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