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Review

Describing wildland surface fuel loading for fire management: a review of approaches, methods and systems

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Abstract. Wildland fuelbeds are exceptionally complex, consisting of diverse particles of many sizes, types and shapes with abundances and properties that are highly variable in time and space. This complexity makes it difficult to accurately describe, classify, sample and map fuels for wildland fire research and management. As a result, many fire behaviour and effects software prediction systems use a generalised description of fuels to simplify data collection and entry into various computer programs. There are several major fuel description systems currently used in the United States, Canada and Australia, and this is a source of confusion for many in fire management. This paper (1) summarises the challenges of describing fuels, (2) contrasts approaches (association, classification and abstraction) for developing fuel description systems and (3) discusses possible future directions in wildland fuel description and science to transition to a universal fuel description system. Most discussion centres on surface fuel loadings as the primary descriptive characteristic. This synthesis paper is intended to provide background for understanding surface fuel classification and description systems and their use in simulating fire behaviour and effects, quantifying carbon inventories and evaluating site productivity.

Additional keywords: fire behaviour, fire effects, fuel classification, fuel inventory, fuel models.

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Introduction

Fire management faces numerous challenges in the coming decades, including the build-up of surface and canopy fuel due to prolonged fire exclusion, the expansion of urban development into the world's wildlands and the skyrocketing costs of suppressing fire (McKetta and González-Cabán 1985; Berry *et al.* 2006). At the same time, future climates may be warmer and drier, which could result in substantial increases in fire size, severity, intensity and frequency for the world's fire-prone ecosystems (Cary 2002; Running 2006; Westerling *et al.* 2006). Fuel treatments are often proposed as a way to reduce fire intensity and severity, restore ecosystems, protect homes and lives, and mitigate adverse effects of unplanned wildfires, but these treatments are also costly, difficult and risky to implement (GAO/RCED 1999; GAO 2002; Reinhardt *et al.* 2008). Ironically, these same fire-prone forests are also being proposed to store carbon to offset human contributions to atmospheric carbon (Sampson and Clark 1995), even though they will probably burn long before they can become effective carbon sinks (Tilman *et al.* 2000). Fire management will need to develop new policies, strategies and tools to meet these future challenges and ensure the sustained health of people, ecosystems and landscapes. Central to the successful implementation of these actions will be a comprehensive, accurate and detailed description of wildland fuels (Sandberg *et al.* 2001; GAO 2007).

Wildland fuel is the one factor that fire management can directly manipulate to achieve management goals, but fuel treatments are difficult to implement without an accurate quantitative description of the fuels to be treated (Agee and Skinner 2005). Fuel-loading data are important inputs to the fire behaviour and effects models that are needed in all phases of fire management from planning (Hessburg *et al.* 2007) to wildfire management (Black 2005). In addition, fuel information is also needed to quantify dead and live carbon storage pools to evaluate the potential of ecosystems as possible carbon sinks (Finkral and Evans 2008), and to assess habitat for a wide diversity of organisms such as small mammals, insects and microbes (Bate *et al.* 2004).

To simplify fuel inputs, wildland fire science has developed several fuel description systems that catalogue fuelbed particles into unique categories called fuel components and then assign attributes to these categories (e.g. loading) based on the input requirements of fire software applications, such as fire behaviour and danger models, fire effects models and smoke emissions programs (e.g. Deeming *et al.* 1977; Anderson 1982; Sandberg *et al.* 2001; Arroyo *et al.* 2008). Most fire behaviour prediction systems developed for managers, for example, require fuel inputs to be represented by fire behaviour fuel models (FBFMs), which have woody fuel components differentiated by particle diameter ranges (Anderson 1982; Scott and

Burgan 2005). Characteristics of fuel components can be described by many variables, such as heat content, mineral content and density, but the most common variable used across most fire management applications is fuel loading or the biomass per unit area (Pyne *et al.* 1996). Fuel loads and related properties are required as inputs to nearly all fire applications (Burgan 1987; Fernandes 2009), and they are also important for other land management concerns, such as the quantification of carbon inventories (de Groot *et al.* 2007), site productivity (Neary *et al.* 1999) and wildlife habitat (Ucitel *et al.* 2003).

Several surface fuel description systems are currently used by land management agencies in the United States, Europe, Canada and Australia, and most of these systems have the same categories, components and description variables (Sandberg *et al.* 2001; Scott and Burgan 2005). For example, most describe surface fuelbeds using essentially the same fuel components (e.g. litter, 1 h down dead woody, shrub, herb) and the same attributes (e.g. loading). This is a source of confusion to many because the main distinction between the existing fuel description systems is more in the approach used to create them rather than their accuracy, application and implementation in fire management. Multiple fuel description systems are needed because each fire-modelling software application requires a specific set of fuel inputs. As mentioned, fire behaviour models often require FBFMs as input (Scott and Burgan 2005); fuel consumption and smoke emissions models require a description system based on the actual loading of fuelbed components (Reinhardt *et al.* 1997); and fire danger models use the National Fire Danger Rating System fuel models (Deeming *et al.* 1977; Forestry Canada Fire Danger Group 1992). The problem is that managers and researchers are somewhat frustrated by all these seemingly redundant choices and desire a single fuel description system that can be used across all software platforms and prediction systems. This would simplify (1) the sampling of fuels in the field, (2) the mapping of fuels across space and (3) the input of fuels into numerous fire management applications.

This paper is intended to provide background and understanding to those who use fuel description systems to plan and implement land management activities such as fuel treatments, ecosystem restoration and carbon manipulation and will discuss: (1) the peculiar properties of fuels that make their quantification difficult; (2) current approaches that are used to describe fuel for fire management with examples; (3) advantages and disadvantages of these approaches in fire management and (4) the future of fuel description including the creation of a single, universal fuel description system useful for all phases of natural resource management.

Background

Wildland fuels are the dead and live biomass available for fire ignition and combustion (Albini 1976; Sandberg *et al.* 2001). Many fuel components comprise a fuelbed, and each component has unique properties that are be described by many characteristics, such as mineral content, specific gravity and heat content. This paper will confine its discussion to 'loading' or the dry weight biomass of fuel per unit area (e.g. kg m^{-2}) because it is the most common classification characteristic used in fuel description systems (Pyne *et al.* 1996). Common fuelbed components are dead or live, woody or non-woody, and surface or canopy fuels. Surface fuels (biomass <2 m above the ground) are often described in terms of the fuel components of downed, dead woody biomass by diameter size class, live and dead shrub and herbaceous material, duff and litter (Fosberg 1970; DeBano *et al.* 1998). Canopy fuels are burnable, aerial biomass (>2 m above the ground) primarily composed of tree branchwood and foliage, but also includes arboreal mosses, lichens and other hanging dead material (e.g. needles, dead branches) (Reinhardt *et al.* 2006). This present paper deals with only surface fuels because canopy fuels are often described by other quantitative measures, such as canopy bulk density, loading and height, so classification or description systems are often unnecessary.

This paper uses the term 'fuel description system' to represent any product that attempts to simplify the quantification of fuelbed properties into an application for fire management. The term 'classification' was used to represent those fuel description systems that actually classified fuels into groups using a systematic process (Sokal 1974). Classifications are typically comprehensive and the classes that comprise a classification are usually mutually exclusive; a change in a class means a significant change in the attribute(s) used to define the class (Gauch 1982). In general, most fuel description systems can be divided into those that were developed for fire effects simulations and those for fire behaviour predictions, although there are some that can be used for both, such as the Canadian Fire Behaviour Prediction (FBP) system (Forestry Canada Fire Danger Group 1992). Fire effects fuel classifications summarise fuel characteristics, most often fuel loading, across fuel components often based on vegetation type, biophysical setting or fuelbed characteristics (Reinhardt *et al.* 1997; Ottmar *et al.* 2007). Fire behaviour fuel inputs often require several other physical characteristics, such as mineral content, loading and heat content, for each model-specific fuel components, such as 1-, 10- and 100-h down dead woody fuels (Burgan and Rothermel 1984).

Describing and quantifying wildland fuelbeds are difficult because of the highly variable distribution and arrangement of fuel particles in space, and the dynamic changes in particle characteristics over time (Keane 2008*a*; Keane *et al.* 2012). The spatial and temporal variability of fuels directly influences fire behaviour (Frandsen and Andrews 1979; Bachmann and Allgower 2002; Parsons *et al.* 2011), controls fire effects (DeBano *et al.* 1998; Reinhardt *et al.* 2001), confounds fuel sampling (Sikkink and Keane 2008), confuses mapping efforts (Keane *et al.* 2001) and complicates fuel description and classification (Lutes *et al.* 2009). Fuel moistures, particle densities and, most importantly, component loadings are highly variable across space, and they can also be highly variable within individual fuel particles. This variability is scale dependent with variability of smaller fuel particles distributed over smaller scales than large fuels (e.g. twigs vary at smaller scales than logs) (Kalabokidis and Omi 1992; Habeeb *et al.* 2005; Hiers *et al.* 2009; Keane *et al.* 2012). Moreover, a single high wind or heavy snow event can dramatically increase surface litter and woody fuel loadings and change the entire structure of the fuelbed in a short time (Keane 2008*b*). Any fuel description system that does not incorporate this variability into its design

Table 1. A comparison of the three approaches used to develop wildland fuel classification for fire management

Approach	Description	Advantages	Disadvantages	Examples
Association (Fig. 1)	Fuels information is assigned to categories in extant classifications.	Existing vegetation classifications and maps can be used to describe fuels. Most existing classifications are widely used, well accepted and used in all phase of land management. Contain comprehensive keys to uniquely identify classes in the field.	Fuel properties are often uncorrelated with vegetation categories. Extant classifications are often too broad to describe subtle changes in fuels. Fuel properties can be redundant across the classes. Difficult to alter extant classifications to account for differences in fuel attributes.	US: Reinhardt *et al.* (1997), Ottmar *et al.* (2007). Canada: Hawkes *et al.* (1995). China: Wu *et al.* (2011). Russia: Volokitina and Sofronov (2000).
Classification – Direct (Fig. 2)	Fuel data are clustered into similar groups using statistical techniques.	Can control variation and limit redundancy across classes. Comprehensive keys can be developed to identify classes in field. Can design classification for any scale, area or fuel type. Easy to learn and use.	Data intensive and many fuelbeds may not be represented in data. Difficult to add new fuel types and new fuel components into the classification. Classification is complex and difficult to understand.	US: Lutes *et al.* (2009), Fahnestock (1970). Greece: Dimitrakopoulos (2001). Australia: Gould *et al.* (2011).
Classification – Indirect (Fig. 3)	Unique fuelbeds are identified and sampled in the field and the fuelbed is added as another category in the classification.	Represent real fuelbeds. Designed for fine scales. Can easily add new fuel types. Can easily add new fuel components.	Data intensive. Classes can be highly redundant. Infinite number of classes makes it difficult to learn and use. Many fuel types are missing because they are not yet sampled.	US: Ottmar *et al.* (2007), Vihnanek *et al.* (2009).
Abstraction (Fig. 4)	Fuels inputs to fire models are adjusted to match observed fire behaviour, and the adjusted fuel information becomes a category in the classification.	Match the resolution of the fire models. Widely used and accepted in fire management. Training widely available for managers.	Do not represent real fuel fuelbeds. Can't directly use sampled fuel loadings. Difficult to create, use and interpret. No keys are available to identify classes in the field. Only useful for the fire behaviour model for which they were developed.	Fire behaviour fuel models used as input to programs that contain the Rothermel (1972) model: Anderson (1982), Scott and Burgan (2005), Dimitrakopoulos (2002).

may be highly redundant , inaccurate and ineffective for desired fire applications.

Another factor complicating fuel descriptions is the diverse nature of fuelbeds, which are composed of many disparate fuel components, such as grasses, needles, twigs and logs, each having different sizes, shapes, densities and burning properties and which are arranged in infinite spatial patterns (Kalabokidis and Omi 1992; Van Wagtendonk *et al.* 1996; Nalder *et al.* 1999). Despite this diversity, most fuel descriptions consist of a simplified set of components that are differentiated by the objective of the wildland fuel application. For example, a description of fuels for fire behaviour prediction might require that the downed dead woody surface fuel loadings be stratified by particle size classes that are related to their rate of drying (Fosberg 1970). Three-dimensional (3-D) fluid dynamics fire behaviour models, such as WFDS (Baum and Mell 1998) and FIRETEC (Linn 1997), require that fuel data be distributed in three-dimensional space, which is completely different than those data used for input to one-dimensional (1-D) models that rely on the Rothermel (1972) spread model, such as BEHAVEPlus (Andrews and Bevins 1999) and FARSITE (Finney 1998). The following sections detail the primary approaches used in fuel description for fire management with summaries of the strengths and weaknesses of each approach.

Fuel description approaches

Because of the complex physical, ecological and technological reasons mentioned above, fire management has turned to generalised fuel descriptions to simplify fuel inputs to fire modelling applications. Most fire models use comprehensive fuel description systems to simplify the inputs for fuel information, but, again, the diverse number of components, wide variety of fuel types and high spatial variability of fuel characteristics makes accurate, comprehensive and consistent fuel description difficult (Sandberg *et al.* 2001; Riccardi *et al.* 2007*a*; Lutes *et al.* 2009). In the present paper, fuel description systems are detailed by three broad approaches based on the processes used to develop the description: (1) association; (2) classification and (3) abstraction (Table 1). Some fuel descriptions were created using a combination of approaches.

Association

Fuel information, such as loading, is often linked to the categories of other classifications commonly used in natural resource management. This is often accomplished by either summarising existing fuel field data or stratifying fuel sampling by extant classification categories (i.e. assign an average fuel loading to each classification category) (Fig. 1). For example, Reinhardt *et al.* (1997) simplified fuels input to the FOFEM model by averaging field-measured fuel loadings for eight input fuel components across the vegetation-based categories in both the Eyre (1980) forest cover type classification and the Shiflet (1994) range cover type classification. The Fuel Characteristics Classification System (FCCS) uses ecoregion, stand structure and site history classification variables as a basis for fuel description (Ottmar *et al.* 2007; Riccardi *et al.* 2007*a*), and McKenzie *et al.* (2007) mapped a set of default FCCS fuelbeds by linking them to vegetation and biophysical environmental

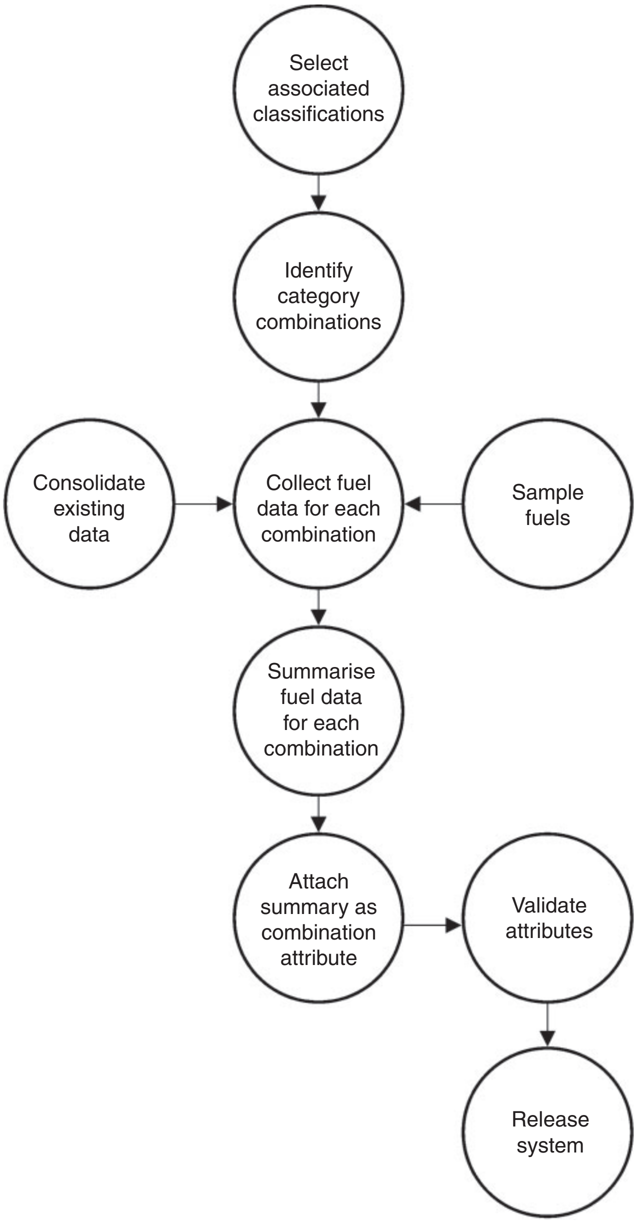

Fig. 1. An **association** process used to assign fuels information to vegetation classification categories.

classifications. In Canada, Hawkes *et al.* (1995) assigned fuel loadings to various categories of vegetation and timber types, and the Canadian FBP system contains fuel input types that are associated with major forest vegetation types (Forestry Canada Fire Danger Group 1992). Poulos *et al.* (2007) created vegetation composition and structure layers from environmental gradients, satellite imagery forest inventory data then scaled fuels information to the resultant biophysical classification for Texas fuelbeds, and Miller *et al.* (2003) sampled fuel loadings across vegetation and topography stratifications, and then assigned loadings to vegetation type categories using clustering techniques.

Many studies have used extant vegetation and related biophysical classifications as the *de facto* fuels classification at multiple scales (Xiao-rui *et al.* 2005; Reeves *et al.* 2009). At coarse scales, Dimitrakopoulos (2002) summarised fuel loadings by the major vegetation types of Greece to build fuel models. Volokitina and Sofronov (2000) assigned fuel properties to the major vegetation types across Russia to simulate fire behaviour. In South Africa, Pool and de Ronde (2002) developed a broad regional fuel classification by using natural vegetation biome and land use classifications, and in north-eastern China, Wu *et al.* (2011) sampled fuels across all major vegetation types in the boreal forest and created fuel models that were then assigned to these vegetation types. At landscape scales, Stottlemyer *et al.* (2006) assigned field-sampled fuel loadings to categories of a landscape ecosystem classification that was based on vegetation, soils and physiography for the south-eastern USA. Maxwell and Ward (1980) assigned fuels to site types in drainages of the Pacific Northwest USA. And at stand scales, the photo series publications used extensively by US fire managers to estimate fuel loadings are an indirect associative classification (see Brown 1974) where representative stands of different cover types (Fischer 1981; Ottmar and Vihnanek 2000), stages of development (Stebleton and Bunting 2009), natural disturbance (Vihnanek *et al.* 2009) and treatments (Koski and Fischer 1979) are photographed, sampled and then assigned fuel loadings.

There are many advantages of linking fuels to vegetation-based classifications, which make this approach quite attractive to researchers and managers (Bailey and Mickler 2007). There are many well known vegetation and site classifications that have a long history of use in land management because they are easy to learn and contain proven keys for quick and objective identification of categories in the field. And vegetation characteristics, such as composition, structure and successional stage, are easily identified in the field with minimal training (Grime 1974; Oliver and Larson 1990). Moreover, a vast array of land management analyses can done by linking vegetation information with fuels data, such as predicting future fuel conditions using vegetation succession models (Cary *et al.* 2006; Davis *et al.* 2009), linking canopy fuels with surface fuels (Keane *et al.* 2006) and prioritising areas for fuel treatment (Hessburg *et al.* 2007).

There are also some major problems with the association of fuel characteristics to existing classification categories that may limit the application of this approach in the future (Table 1). First and foremost, fuel characteristics are rarely correlated with vegetation attributes and categories, especially at fine scales (Keane *et al.* 2012). Brown and Bevins (1986) found that fuel loadings did not correlate with cover type or habitat type and speculated that stand disturbance history had more influence on fuelbed loadings than vegetation. One reason for this lack of relationship between fuels and vegetation is that vegetation attributes, such as species cover and height, vary at coarser scales than wildland fuels. Keane *et al.* (2012) found that the spatial distributions of fine woody fuels varied at smaller scales ($<$10 m) than vegetation attributes ($\sim$500 m). As a result, many disparate fuelbeds may be represented within one vegetation type, and conversely, many vegetation types may have the same fuelbed description. This embedded redundancy is also related to the fact that the resolutions of most vegetation classifications do not match the resolution of fuelbed characteristics that foster unique fire behaviour and effects.

Fuelbed development is a result of complex interactions acting across many ecosystem processes and scales, some of which are related to vegetation, but others are related to important biophysical processes, such as soils, climate and disturbance (Harmon *et al.* 1986). Fuel deposition rates are governed by the size, species, phenologies and vigour of the vegetation that contribute material to the fuelbed as they interact with disturbances (e.g. wind) that act to detach fuel for deposition on the ground in unique patterns (Keane 2008*b*). Decomposition of the fallen fuel particles, however, is governed by the interaction of climate with vegetation to create moisture, temperature and nutrient regimes that facilitate micro- and macro-organism activity (Kaarik 1974; Millar 1974). Exogenous disturbances then modify fuelbed properties by consuming fuels (fire), opening canopies (insects, disease) and increasing deposition (wind, snow) (Kauffman and Martin 1989; Wooldridge *et al.* 1996; Pedlar *et al.* 2002; Jenkins *et al.* 2008). As a result, fuel properties are rarely static in time or uniform in space, so instantaneous fuel characteristics are seldom explained by broad vegetation or bioenvironmental classification categories.

Another problem with the association approach is that it is difficult to refine fuels descriptions to improve accuracies. Accuracies of classifications for which fuels are associated do not reflect the true accuracy of the fuel information; a 90% accuracy of a vegetation map does not translate into 90% accuracy for the fuels data. The associated fuels information must be compared with sampled field data to determine fuelbed accuracy, and often these analyses show poor agreement (Keane *et al.* 1998; Reeves *et al.* 2009). If classified fuel loading accuracies are low, there is little recourse to improve the accuracy without changing the original vegetation classifications by adding, modifying or deleting categories, or by adding additional classifications to the already complex associative approach. The addition of new classifications exponentially increases the amount of fuel data needed to cover all combinations of the merged classifications, and, as a result, many combinations might be missing valuable fuel data to quantify fuel information (Reeves *et al.* 2009).

Classification

Classification in this paper is the process of clustering items (fuelbeds) into unique groups based on various attributes (mainly loading by components). Usually this involves numerical clustering and complex statistical techniques that attempt to directly identify unique groups based on the variation of the attributes used to develop the classification (Orloci 1967; Sokal 1974; Gauch 1982) (Fig. 2). Once unique groups are identified, a comprehensive key based on the analysis variables (e.g. loading) can be devised to objectively identify the classification category for a field-assessed observation. This direct, top-down approach partitions the variation in the field data to reduce redundancy and produce a singular classification that can be used in the field. Few existing fuel description systems use a direct, top-down approach to generate a comprehensive fuel classification. In perhaps the first effort at directly classifying fuels, Fahnestock (1970) developed two keys that rated spread rate and crowning potential of fuelbeds based on general descriptive categories of particle size, compactness, vertical position and horizontal continuity, and each category combination was assigned specific fuel properties (particle density, loading, depth). Dimitrakopoulos (2001) created a fuels classification for Greece by clustering flammability variables, such as heat content, ash content and particle density, into unique groups using hierarchical cluster analysis and Canonical Discriminant Analysis for Mediterranean shrublands. Gould *et al.* (2011) took a different approach and used visual hazard rating classes for six fuel layers (overstorey, intermediate, elevated, near-surface, surface and soil) to key to fuel properties (loadings, depth, height and bulk density) for dry eucalypt forests in western Australia. The Fuel Loading Models (FLMs) of Lutes *et al.* (2009) are distinctive in that they used field-collected fuel-loading data to simulate smoke emissions and soil heating, and these results, along with loading, were used to cluster

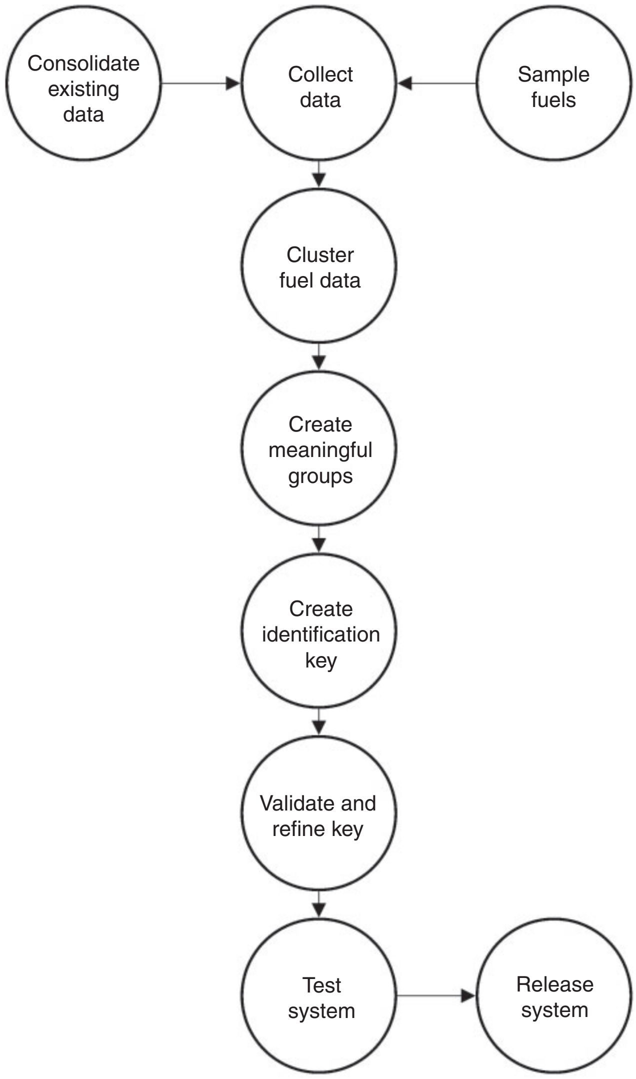

Fig. 2. The process involved in creating a fuel description system using **direct classification** techniques.

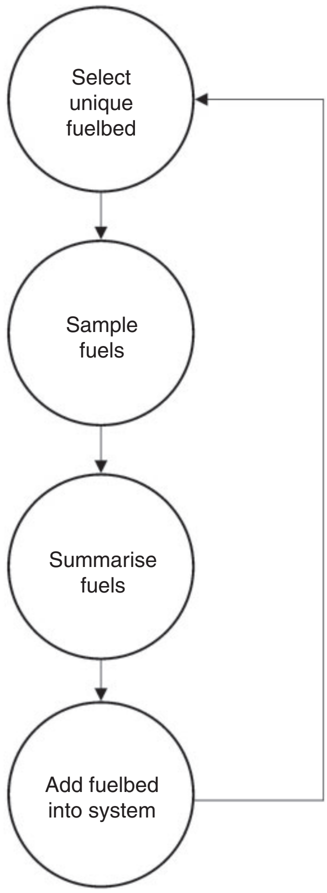

Fig. 3. Using **indirect classification** techniques to create a fuels description system.

field-sampled fuelbeds into unique classes using advanced clustering and regression tree statistical techniques. As a result, this classification effectively integrated the resolution of the fire models for which the FLMs would be used into the classification design.

Indirect classification approaches are also included in this section, and these techniques involve bottom-up methods where unique fuelbeds are qualitatively evaluated and selected for sampling in the field and the sampled fuelbed then becomes a category in the classification (Fig. 3). The FCCS is perhaps the best example of this indirect, bottom-up approach (Ottmar *et al.* 2007). In this ever-expanding classification, new and unique fuelbeds can be added into FCCS as they are identified by managers, scientists and resources specialists for local, regional or national applications (Berg 2007); new fuelbeds are sampled and these data become a class in the FCCS (Riccardi *et al.* 2007*b*). FCCS also contains its own fire behaviour model tuned for the FCCS fuel components (Sandberg *et al.* 2007). The next generation of photo series is also an example of this indirect approach (Ottmar and Vihnanek 2000; Vihnanek *et al.* 2009).

Advantages of fuel descriptions created from direct and indirect classification approaches are that they are fully supported by the data that were used to create them, and therefore represent actual fuelbeds with measured loadings. As such, these classifications can be used as (1) inventory techniques to quantify fuel characteristics (Sikkink *et al.* 2009); (2) descriptors of unique fuel types to facilitate communication between managers, scientists and other professionals (Sandberg *et al.* 2001) and (3) map units in fuel-mapping efforts (Reeves *et al.* 2009). Direct fuel classifications contain dichotomous keys that can uniquely identify classification categories on the ground based on qualities of the fuelbed (Fahnestock 1970), and the loading information for that category can then be used in fire applications, such as simulating fire effects and validating fuel maps. And because direct fuel classifications have low redundancy between classes, class attributes can be used for populating fire models and identifying thresholds of fire behaviour and effects (Lutes *et al.* 2009). Indirect classifications have an advantage in that new fuel types and fuel components can be added to the classification with little effort providing there are appropriate methods to sample desired characteristics.

Direct classification approaches, such as that used for the FLMs, also have drawbacks that could limit their use across large areas. All fuel classifications, but especially direct classifications, are empirically driven and require extensive datasets to represent the diversity of fuelbeds in the analysis. As a result, the depth, scope and quality of the original dataset also describe the limitations in the classification. Although FLMs were developed using extensive data collected across the entire United States, the analysis was missing critical data from several major US fuelbeds that were unsampled at the time of FLM development, such as many non-forest rangelands, and these categories are missing in the classification (Lutes *et al.* 2009). The parameters used in the clustering algorithms, such as the desired number of clusters, are often subjectively quantified on the basis of previous experience and objectives of the analysis. And, to further complicate matters, it is difficult to modify, add or remove new categories in the direct classification as new data become available without completely redoing the entire classification.

There are also problems with the indirect classification approach. Few of these classifications can be used to uniquely identify a classification category in the field (Ottmar *et al.* 2007); most rely on the expertise of the fuel sampler to match the observed fuelbed conditions to the categories in the classification, or on the ancillary vegetation and site classification categories used to describe the fuelbed (e.g. photo series). The FCCS, for example, does not contain a key to directly identify a fuelbed; instead, it uses a set of ecological descriptions mostly based on vegetation and stand history to aid in fuelbed identification (Ottmar *et al.* 2007). And, as a result of this bottom-up process, there is often redundancy across many fuel classification categories; the properties of one fuelbed may be quite similar to those of other fuelbeds sampled in another part of the country for another vegetation type, especially for the fine woody debris components. Linking indirect classification categories to spatial data layer attributes is also problematic because it is difficult to consistently validate an assigned indirect class in the field because there is no key. Another problem is that because the variation across fuelbeds isn't incorporated into the indirect classification, there can be an infinite number of possible categories (fuelbeds) and, conversely, there can be many locally relevant fuelbeds that are missing in the final classification. Keane *et al.* (2006), for example, mapped FCCS categories across central Utah but found that over 30% of the land area had vegetation attributes that did not match sampled FCCS classes. This also makes learning indirect classifications somewhat difficult because it is always changing and new classes are always being added.

Abstraction

Most abstract fuel description systems characterise fuels using fire behaviour characteristics. Historically, Dubois (1914) and Hornby (1936) described western US fuelbeds using resistance to fire control and fire behaviour attributes. Now all US fire behaviour fuel description systems have categories that are referred to as fire behaviour fuel models (FBFMs) that are essentially an abstraction of expected fire behaviour. FBFMs are a set of fuel characteristics (e.g. loading, depth, surface area-to-volume ratios, mineral content, heat content) for each of the input fuel components required by the fire behaviour and danger models (Burgan and Rothermel 1984) that are quantified to represent 'expected' fire behaviour not actual fuel characteristics. This is because the inherent complexity of the mechanistic fire behaviour models of Rothermel (1972) and Albini (1976) makes it difficult to predict realistic fire behaviour from real fuel loadings (Burgan 1987). As a result, a somewhat complicated procedure must be followed to develop FBFMs where fuel loadings and other fuelbed characteristics are adjusted to achieve realistic and believable fire simulations based on observed fire behaviour (Burgan 1987) (Fig. 4). Because of this, many feel that FBFMs are actually classifications of expected fire behaviour, but they are included here because they describe fuelbeds but in different terms.

Most abstract fuel description systems today are FBFMs created for use in fire behaviour applications that contain the Rothermel (1972) spread model as implemented in BEHAVE (Andrews and Bevins 1999) and FARSITE (Finney 1998) systems. In the US, the most commonly used FBFM classifications are the 13 models described by Anderson (1982) and the 40+ models of Scott and Burgan (2005) for use as inputs to BEHAVE and FARSITE, and the 20 fire danger fuel models used in the National Fire Danger Rating System (Deeming *et al.* 1977). Reich *et al.* (2004) created several new BEHAVE custom fuel models using field loading data that were then mapped to a South Dakota US landscape, and Cheyette *et al.* (2008) created custom fuel models for the wildland urban interface lands around Anchorage, Alaska, using a supervised vegetation-based classification of 13 cover types. In Greece, Dimitrakopoulos (2002) created seven FBFMs by synthesising fuel data from 181 natural fuel complexes described by vegetation, and Mallinis *et al.* (2008) created a set of custom fuel models that were mapped across a large landscape using Quickbird imagery for input to the FARSITE model. In Corsica, Santoni *et al.* (2011) developed two fuel models for their own spatially explicit fire model built to simulate fire behaviour for maquis and juniper shrublands, whereas in Sardinia, Italy, Bacciu *et al.* (2009) used field loading data to create FBFMs for Mediterranean vegetation types for FARSITE simulations. To evaluate fire hazard in Portugal, Fernandes (2009) developed a suite of 19 fuel models based on the dominant vegetation structures and complexes in mainland Portuguese forests and Fernandes *et al.* (2000) created FBFMs for Mediterranean heathlands from extensively sampled plot data.

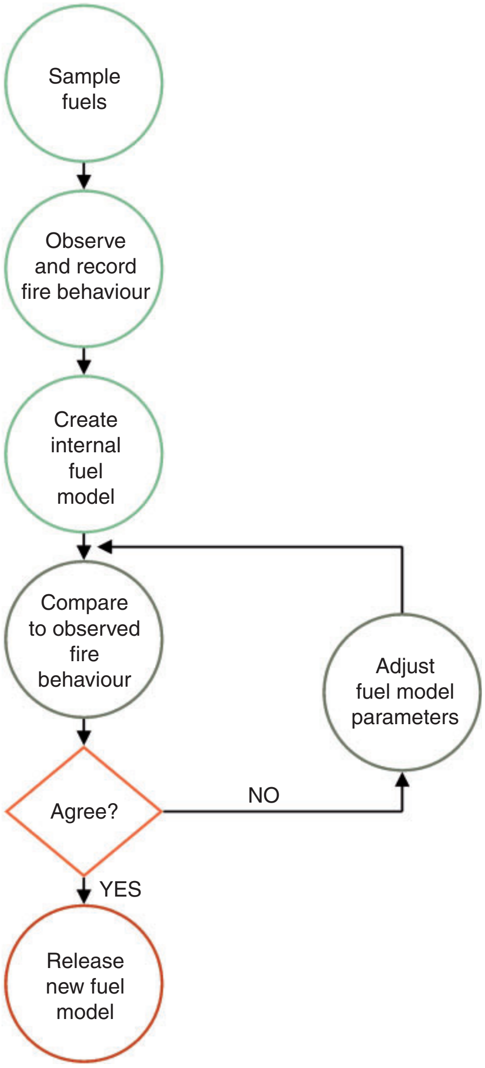

Fig. 4. An example of the **abstraction** approach used to create a fuels description system for fire behaviour modelling.

The main advantage in creating abstract fuel description systems is that the resultant fuel models match the resolution of the fire models for which the models will be used as inputs. This means that the uncertainty and error in model predictions will be minimised from inaccurate and inappropriate fuel inputs because the fuel models were calibrated to actual fire behaviour observations (Burgan 1987). Another advantage is that new fuel models can be developed for unique local situations (Burgan and Rothermel 1984) or for broad use across large regions (Burgan and Hardy 1994). US fire behaviour fuel models have been used for over 30 years and have been broadly accepted by managers as a viable method of describing fuels for fire behaviour modelling. The development and use of FBFMs are taught to fire managers in a wide variety of fire management courses throughout the US.

The biggest drawback to the abstract FBFMs is that without prior knowledge of fire behaviour in local fuel types, it is nearly impossible to accurately and consistently use and interpret most FBFMs. The identification of FBFMs in the field is highly subjective because it is based on an individual's perception of how fire will burn the fuel complex under severe weather conditions, rather than on actual measurements of fuel loadings. There are no standardised keys to consistently identify FBFMs for either the Anderson (1982) or Scott and Burgan (2005) fuel model classification systems. So, because abstract classifications are inherently subjective and difficult to use, most fuel mapping efforts must rely on expert knowledge and past experience in all phases of the mapping process (Keane and Reeves 2011). FBFMs are also difficult to create because their development requires a delicate balance of parameter adjustments to match observed fire behaviour (Fig. 4) that should only be done by experienced analysts and fire managers (Burgan 1987). These limitations may preclude the use of FBFMs in the future as new fire behaviour models are developed, as novel fuelbeds are created from innovative fuel treatments, and as abundant fuel input data become available for describing fuelbeds.

There are other limitations to this abstract approach. Most fuel descriptions created using abstraction approaches can be used only for the purpose of their development and they rarely have uses outside of fire management. FBFMs, for example, were specifically designed to predict fire spread and therefore don't include vital information on some major fuel components, such as logs and duff, that are essential for computing smoke emissions, simulating post-frontal combustion and evaluating wildlife habitat. FBFMs can be used only in the fire behaviour model for which they were created; it is inappropriate to use existing fire behaviour or danger fuel models in other fire simulation systems. And similar to indirect classification approaches, there can be an infinite number of abstractions to account for an infinite number of possible fire behaviours, making FBFMs that represent unique fire behaviours difficult to build, especially given the coarse resolution of the fire models. And because fuel models indirectly represent the resolution of the fire behaviour prediction systems, it is difficult to evaluate the effect that subtle changes in fuel characteristics brought about by fuel treatments have on fire behaviour, especially if there are only small changes in fuel loadings.

The future of fuel description

This paper has outlined numerous reasons why the fuel description systems mentioned in this paper do not have sufficient scope, quality, resolution and accuracy to serve as the primary fuel description system desperately needed by fire management to perform all phases of current and future fire analyses. All of the discussed systems have desirable qualities that can be integrated into a universal fuel classification, but they also have major flaws that may preclude their adoption by fire management at this time. For example, fire behaviour fuel models are a poor national system because they lack major fuel components and don't represent actual fuel loadings, whereas FLMs are poor because, among other reasons, they can't be input to commonly used fire behaviour prediction systems. All fuel description systems discussed in this paper have great value to fire management, and, as long as fire managers are aware of their strengths and limitations, they can be used together in the various fire models with great success. The main barrier in the adoption of one fuel description system is that none of the current systems can be used in all phases of fire management, such as predicting fire danger, estimating emissions and calculating flame length. There needs to be several major advances in technology and research before a universal fuel description system can be created.

The first step in creating a common fuel description system is to fully understand the ecology of wildland fuels. Future fuel research should explore the processes that govern fuel dynamics, such as deposition, decomposition and accumulation, to understand how fuel characteristics, such as loading, density and heat content, change over time and space. Intensive research into the chemical, kinetic and physical properties of fuel particles is needed to determine how fuelbeds should be classified, described and quantified in the future (Van Wagtendonk *et al.* 1996). Fundamental ecological research must be done to determine the size and shape distributions of fuel particles on the plants and on the ground across all ecosystems and vegetation assemblages, and across landscapes. Down woody fuels, for example, must be better represented than the four size classes (1-, 10-, 100- and 1000-h size classes) used in conventional fire models because the uneven and broad diameter ranges make an accurate estimation of loading difficult (e.g. 100-h woody class has diameters that range from 2.5 to 8.0 cm, spanning an order of magnitude in loading). And last, spatial distributions and variabilities of different fuel components and properties must be described so that the appropriate sampling methods can be developed to estimate fuel properties with minimal bias (Keane *et al.* 2012) and the appropriate mapping techniques and technologies can be designed to match the scale of fuel variation.

It will be difficult to develop any new fuel description system without knowing what the new fire models need for fuels inputs. While the next generation of fire behaviour and effects simulation models are being developed, it is critical that new fuel classification systems be built to balance ecological understanding of fuel dynamics with the new input model requirements to allow for the input of real fuels information in a format that accounts for a suite of fuel properties such as kinetics, morphology and spatial distribution (Reinhardt *et al.* 2001; Parsons *et al.* 2011). It is also critical that future fire behaviour models be implemented in three dimensions to account for the spatial distributions of fuel and its effect on fire behaviour, especially those models used in fire research (Krivtsov *et al.* 2009). Fuel description systems for these 3-D fire models will be completely different from current fuel models because they will contain information on several fuel characteristics such as spatial distribution (clumpiness, pattern, variability), physical properties (density, heat content), moisture dynamics (depletion rates, storage) and size class distribution (particle shape, size) for several fuel components. And each of these characteristics must have an associated sampling method for accurate quantification and these methods must account for the wide diversity of fuel particles comprising the fuelbed (Riccardi *et al.* 2007*b*). And because the next generation of mechanistic fire models will probably be exceptionally complex so that a wide range of fire dynamics can be explored, there will need to be a synthesis of results from the complex 3-D models into a simple 1-D model for use in fire management, and new fuel inputs to the new 1-D model must be synthesised so that they remain simple to use, easy to sample and make ecological sense.

Quantifying wildland fuel characteristics in an ecologically appropriate and useful manner is the next step (Conard *et al.* 2001). Comprehensive sampling methods and protocols must be developed so that fuel components are sampled at the right scale and at the right level of detail for both old and new fire-modelling systems. Then, if these new methods are too complicated or too costly to implement for managers, simplified methods must be created to ensure fuel information is being collected at accuracies, resolutions and scales that match the resolution of management decision-making. Contemporary fuel inventory methods, such as photo series (Ottmar and Vihnanek 2000), planar intersect (van Wagner 1968; Brown 1971; Lutes *et al.* 2006) and photoloads (Keane and Dickinson 2007), must be revised to provide new critical information needed in the future by research and management, and new methods must be developed to describe how the sampled fuels are distributed across stands (Keane *et al.* 2012). Innovative sampling techniques must balance the level of resolution needed by fire models with accuracy needed by other fuel applications such as estimating smoke emissions, carbon inventories and smouldering combustion for both research and management.

And, last, the development of new comprehensive fuel classifications will need high-quality data across large geographical areas, diverse ecosystems and complex fuelbeds (Lutes *et al.* 2009). A comprehensive fuel inventory and monitoring program that collects extensive field data using the innovative and standardised methods developed above, and stores these data in readily available databases is critically needed for fire management (Conard *et al.* 2001; Krivtsov *et al.* 2009). New inventory techniques developed from basic wildland fuel ecological research can be integrated for this effort, along with the information needed to convert legacy fuels data to newer formats. Geo-referenced fuels inventory data are important not only for classification development, but also for map creation and validation, simulation model initialisation and parameterisation, and fuel treatment planning, implementation and monitoring (Reeves *et al.* 2009). The US Forest Service Forest Inventory and Analysis program has started collecting critical fuel information in many parts of the US and this represents a significant step forward in developing comprehensive fuel datasets for future fire management applications.

Today's fuel description systems have seen extensive use in fire management and it would never be prudent to advocate for their elimination. However, if fire management desires a single fuel description system for the next generation of fire applications, the development of the new system should probably look to the future instead of the past. It may be more efficient and effective to conduct basic research in wildland fuel science and fire behaviour modelling to design new and innovative fuel descriptions than to select one of the existing fuel classification systems and try to modify it to fit other applications and as new fire science technologies are developed. Moreover, wildland fuel science should never be done in a vacuum – fuel specialists must collaborate with fire modellers, ecologists and managers to more effectively design fuel description systems and their associated sampling protocols for tomorrow's fire management applications. And for building future fire modelling systems, ecologists, physicists and engineers must work together to design fire models that accept fuel inputs that are acceptable for modelling combustion, ecologically appropriate and measureable, and to design sampling methods that quantify input fuel variables at accuracy levels that work across all disciplines. Physicists, for example, will likely want precise quantification of many variables but field crews are unlikely to have the time, expertise or funding to sample at that level of intensity. A universal wildland fuel description system will be possible only if all fields of wildland fire sciences collaborate together to create the next generation of fire research and management models.

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