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Review

Revisiting Wildland Fire Fuel Quantification Methods: The Challenge of Understanding a Dynamic, Biotic Entity

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Abstract: Wildland fires are a function of properties of the fuels that sustain them. These fuels are themselves a function of vegetation, and share the complexity and dynamics of natural systems. Worldwide, the requirement for solutions to the threat of fire to human values has resulted in the development of systems for predicting fire behaviour. To date, regional differences in vegetation and independent fire model development has resulted a variety of approaches being used to describe, measure and map fuels. As a result, widely different systems have been adopted, resulting in incompatibilities that pose challenges to applying research findings and fire models outside their development domains. As combustion is a fundamental process, the same relationships between fuel and fire behaviour occur universally. Consequently, there is potential for developing novel fuel assessment methods that are more broadly applicable and allow fire research to be leveraged worldwide. Such a movement would require broad cooperation between researchers and would most likely necessitate a focus on universal properties of fuel. However, to truly understand fuel dynamics, the complex biotic nature of fuel would also need to remain a consideration—particularly when looking to understand the effects of altered fire regimes or changing climate.

Keywords: bushfire; grassfire; flammability; forest fire; quantitative methods; wildland fire; vegetation dynamics

1. Introduction

Fire behaviour is the product of the weather, topography, human intervention and, importantly, the fuel properties at the time a fire occurs [1,2]. In the case of wildland fires, this consists of vegetative matter, both living and dead [3]. Wildland fires, while essential to ecosystem processes, impose costs on societies including the loss of life, productivity, property, infrastructure, and ecosystem services [4–7]. The management of the landscape to minimise these costs requires that fire and, by necessity, fuel, be understood [8–11].

Fuels have particular importance to managers as they are the only element of the landscape that can be modified to influence the behaviour of future fires [10–12]. Substantial efforts are put into the treatment of fuel for risk reduction [9–11,13,14] and parameterisations of fuel are a core component of fire prediction systems [12,15–17]. Dead fine fuels in particular, have long been a focus of fire managers and researchers as they respond to weather over short time scales [18,19] and so are important determinants of fire occurrence and behaviour [3,20–22].

Effective fire management before, during and after fire events demands an understanding of the properties of fuel that will contribute the greatest hazard to values of interest, and methods to quantify and represent these spatially [23,24]. While parameterisations of fuel for risk assessment and modelling purposes have been a chief focus of land managers over recent decades, recognition of the dynamic, biotic nature of fuel is also increasing [25–27] due to the magnitude of effects that changing vegetation composition can have on fire behaviour (e.g., [28,29]), particularly in the face of a changing climate [6,30–33].

The development of methods to describe, quantify and map fuels has occurred relatively independently between regions, leading to a wide diversity of approaches and standards, including multiple ways of describing the same fuel properties. In this paper, we provide a critical review of current approaches for wildland fuel description, summarization and mapping in use worldwide. To conclude, we make recommendations on future directions in methods for the evaluation of fuel that have the potential to increase accuracy, utility and our understanding of fuel dynamics.

2. Quantifying Fuel

At a fundamental level, wildfires are uncontrolled and sustained combustion reactions that spread between organic fuel elements in the landscape [3,34]. These elements have intrinsic and extrinsic properties that influence the occurrence, rate and intensity of combustion of fires. These properties include chemical composition, particle density, size, shape, arrangement (both vertical and horizontal) and moisture content [16]. Here, we refer to fundamental fuel properties as 'attributes' and measured abstractions used for modelling as 'parameters' sensu Hollis et al. [35]. The actual values used in models are referred to as 'arguments'. We use the term 'fuelbed' to refer to the entire live and dead fuel complex at a site including surface, shrub and canopy sensu Riccardi et al. [36].

The behaviour of a fire is a function of the components of a fuelbed, and fuelbed is a function of the vegetation community at a site, including species composition, condition, and structure [21,27,29]. The vegetation community itself is a function of complex processes including climate, geology, herbivory and disturbance [37–39]. Methodologies for representing fuelbed properties have predominantly been driven by a need to forecast and manage fire impacts rather than understand dynamic processes [3].

Forecasting the progression of fires requires that methods be developed to describe, measure, summarise and map fuelbeds across the landscape. The methods selected to quantify and map fuel fundamental properties can have consequences on the applicability, accuracy, precision and compatibility of the modelled outcomes [40–45]. Creating fuel maps is a multi-stage process; it requires (A) having defined and measureable fuel parameters; (B) a method for assessment of parameters in the field; (C) a method to summarise or convert information to conform to model input argument requirements; and (D) a method for mapping summarised units [3]. These four steps and the implications of various approaches are discussed separately below.

2.1. Parameterising Fuel

Due to the need to manage fire, there is a long history of the assessment of fuels in wildland landscapes (e.g., [46] and [47]). However, a particular driver for the development of new fuel description and quantification methods was the advent and development of wildfire modelling in the 20th century [3], in which numerous models were created for a range of vegetation types, fuel conditions and regions [17,48,49]. To predict fire behaviour, it is necessary to parameterise the fuel attributes that are most influential over fire behaviour. However, the combustion of vegetation is a complex process [34,50] and there is no universal set of parameters common to all models. Fire behaviour is strongly determined by the properties of vegetation and consequently, features that are important in one system may be absent in another. Additionally, any parameterisation requires a degree of abstraction of the real world into something measurable; the degree of abstraction can vary, resulting in fuel parametrizations that vary along a spectrum from those thought to be fundamental to fire behaviour processes (as in the Rothermel Model [16]), to representations of vegetation type linked to fire behaviour through empirical observation (as in the Canadian Fire Danger Prediction System [51]). Some examples of operationally used models and the diversity of their key fuel input parameters are presented in Table 1. Further details of the contrasting inputs for the Australian models are presented in [52]. Although methods of quantification vary greatly, there are commonalities between approaches; operational fire models invariably include some form of consideration of the amount, physical characteristics and spatial configuration of fine fuels (<6 mm diameter [53]—the fuels that readily ignite in a flaming fire front).

Early fire models provided estimates of fire rate of spread for a defined set of conditions—they were inherently aspatial. To predict fire spread, their outputs had to be interpreted and mapped by hand [54–56]. To achieve this, maps of fuel were necessary to select the appropriate model to use and obtain the necessary fuel arguments. More recently, driven in-part by increasing computational power, models have been developed to be spatially explicit. Fire behaviour simulators are now routinely used operationally to solve large-scale real-time fire prediction problems to provide emergency decision support, e.g., FARSITE [57] and PHOENIX RapidFire [58,59]. Additionally, the applications of fire models are increasingly being extended, including applications such as strategic risk assessment [60,61], the assessment of ecological fire regimes [62,63] and carbon accounting [6]. In addition to modelling, fuel maps are also important for strategic purposes to enable managers to visualise fuels across the landscape relative to topography and vulnerable assets.

The development of spatial fire models has substantially increased demand for high quality maps of input arguments. Models developed for the management of fire risk typically require that predictions be made faster-than-realtime so wildfire spread can be forecast as they occur. As fires can be very large (i.e., 10's of square kilometres), this has influenced the practicality of data collection and affected the precision adopted in parametrising fuel. However, with increases in computer processing power, there has also been development of complex physical models that, while generally slower than real time, allow insight into the physical processes within fires, e.g., WRF-Fire [64], FIRETEC [65] and the Wildland Fire Dynamics Simulator [66]. The development of such models of fire poses additional challenges to fuel quantification as physical models require that the physio-chemical properties of fuel elements be known at the scale of the processes being emulated—these scales are typically much smaller than used in empirically models [49]. Furthermore, as empirical models are statistically fit, the fitting process can somewhat compensate errors in measurements—a luxury not afforded to physical models. Physical models are crucial to understanding fundamental combustion processes, so being able to accurately quantify fuels in the field to allow their verification and validation against real-world fire outcomes remains important.

To date, the development of fuel quantification and mapping systems has predominantly focused on providing arguments for specific fire models rather than representing the fundamental properties of fuel important to fire behaviour [67,68]. This means that the information collected is highly regional and focused on the limited number of parameters and methods specific to local vegetation types (e.g., Eucalyptus forests [69] or grasslands [70]).

One attempt to reduce this model-centric focus has been the development and implementation of the 'Fuel Characteristic Classification System (FCCS)' in the USA. Within this system, fuel beds are described in great detail with the aim of being able to provide inputs to a wide variety of models that operate at different scales and for different purposes [71].

Table 1. Selection of fire models used for operational faster-than-real-time fire behaviour prediction by landscape managers, and the fuel input arguments required for their computation *. The models presented utilise unique functions for deriving fire behaviour from fuel. Modelling systems that utilise these functions are not considered here.

Model	Region of Use	Intended Vegetation	Fuel Arguments
Anderson shrublands [1]	Australia, Europe	Shrublands	Vegetation height
Buttongrass model [2]	Australia	Buttongrass plains	Cover Fuel load % dead
Canadian FFDPS [3]	Canada, New Zealand	Various	Fuel type Grass curing
CSIRO Grass [4]	Australia	Temperate grasslands	Grassland structure Grass curing
CSIRO Tropical grass [5]	Australia	Tropical grasslands	Grassland type Grass curing
Mallee-Heath model [6]	Australia	Mallee Heath	Vegetation height Vegetation cover Near surface fuel load
McArthur [7]	Australia	Southern Australian forests	Fine fuel load Soil dryness / fuel availability
PHOENIX Rapidfire [8]	Australia	Various	Surface fine fuel load Near surface fine fuel load Bark fuel fine fuel load Shrub fine fuel load Grassland structure Grass curing Wind reduction factor
Rothermel [9]	USA, Europe	Various	Fuel load by size class and category Surface area: volume by class and category Fuelbed depth Dead fuel extinction moisture content Heat content of live and dead fuels
Vesta [10]	Australia	Southern Australian forests	Surface fine fuel load Near surface fine fuel load Shrub fine fuel load Bark fuel fine fuel load

* Short-term dynamic fuel properties (e.g., moisture content) are computed separately using weather data. [1] [72]; [2] [73]; [3] [51]; [4] [74]; [5] [75]; [6] [76]; [7] [12]; [8] [58]; [9] [16]; [10] [15].

2.2. Assessing Fuel Attributes in the Field

The effective spatial representation of fuel requires some level of assessment or verification in the field [77]. Extensive vegetation surveys are expensive, so invariably some form of sampling is required [78,79]. In designing a fuel inventory, the questions of what to measure within a sampling unit and how units should be sampled (including number and stratification) need to be resolved [3]. An ideal method for sampling within measurement units is one that can be completed efficiently and accurately with minimal expertise. As some fire model arguments are not easily measurable outside of a laboratory (e.g., fuel element energy, oil and mineral content) and others are time consuming to measure directly (e.g., bulk density and surface area to volume ratio), an alternative has been to undertake a number of simple measurements combined with visual estimates. This commonly involves textual descriptions combined with photos, keys and simple measurements (e.g., [77,80]) to approximate parameter arguments (or groups of parameter arguments) from a limited number of classes. Such class-based approaches can greatly increase the efficiency of field surveys; however, there is a cost in terms of the degree of accuracy and precision [81,82]. Additionally, error can be introduced due to variation in the way assessors interpret classification guidelines [83,84].

To understand fire behaviour processes from a scientific point of view, the ideal field assessments of fuel within a site would be comprehensive evaluations that quantify fuel element attributes in three dimensions to allow virtual fuelbed reconstruction. In addition, non-fuel details such as species composition, canopy cover and soil type would also be recorded as they can provide insight into the dynamics that result in particular fuel configurations [27,85]. Apart from the FCCS, such intensive fuel audits are rare outside research. However, recent developments in technology have the potential to improve the efficiency, accuracy and precision of highly detailed field assessments, in particular terrestrial LiDAR [86,87] and photogrammetry [88]. These enable the rapid quantification of structure in three dimensions, enabling sites to be digitally represented at extremely fine scales.

Fuels can have high levels of spatial variation [25] which can be important determinants of fire behaviour and impacts [43,44]. The capture of such variation necessitates a large number of sampling plots, resulting in trade-offs between the level of detail measured at a sampling unit and the number of sampling units that can be collected. To resolve this requires an understanding of the sensitivities of fire models to the relevant inputs (e.g., [89,90]), although ideally this would be driven by fundamental fire theory [91].

2.3. Summarizing Fuel to Develop Maps

The process of summarizing measured fuel attributes at a site level and developing mapping methodologies is often concurrent, as site level classes are typically used as mapping units. During a site fuel survey, a diversity of attributes is independently considered. However, it is rare to map each attribute directly—values are usually first summarised using a single, exclusive site-level class. Attributes are given values that apply to the entirety of the assigned class. An example is the use of Fire Behaviour Fuel Models in the US to represent fuel loading, depth and moisture of extinction [92]. When assigning classes, there are three approaches that are used: association (using existing vegetation classifications), classification by fuel fundamental properties (using statistical or descriptive methods), and abstraction (grouping fuels based on a common secondary property such as fire behaviour). These approaches are comprehensively summarised in Keane [41].

Regardless of classification approach, the summarization of measurements into site level classes results in a loss of information if sites that have properties of more than one class are forced into a single class [93]. This effectively compresses information, resulting in approaches that do not represent the heterogeneity or potential range of values present in these systems. There is also an assumption that the site attributes consistently co-vary—i.e., that bulk density and crown base height are at consistent ratios for a particular vegetation class. This assumption may not be always valid as natural systems often have gradients of change [94] and high levels of independent variation occur in space and time in both species composition and fuel attributes [25,27,38,95]. The importance of considering this variation is particularly evident at the interface between wildlands and urban environments where vegetation is heavily modified (resulting in novel fuel configurations that are not well represented by existing classifications) and there are high concentrations of values at risk (so there are potentially greater consequences for errors) [96].

Variation within classes can be accounted for with the addition of intermediate classes [67,97]; however, large numbers of classes can provide additional challenges, such as difficulty in identifying or verifying them in the field [41]. This is a particular issue where fuels change rapidly post fire—fixed classifications have limited potential to represent the continuum of change that occurs as a forest recovers. One method that has been used to account for this is the adjustment of class attribute values to account based on other landscape properties. This approach is applied in Australia in systems where the forest overstorey typically survives fires and vegetation (and consequently fuel) re-accumulates after fire following a negative exponential pattern [27,53,98]. This pattern is used to moderate fuel loading from class equilibria based on time since last fire [59]. While this approach is unique to Australia, such patterns of recovery are not (e.g., [99,100]). Furthermore, with variation in post fire conditions [27] or fire severity [101,102] having the potential to influence vegetation recovery, using time since fire as the sole moderator of fuel properties may not necessarily deliver outcomes that meet manager's expectations. Additionally, fire is only one of many potential disturbances that can impact fuels—it may also be important to recognise other disturbances such as timber harvesting or drought.

The continuous and dynamic nature of vegetation through space and time means that high within-class heterogeneity and independent variation of attributes will remain a challenge with any fuel classification, necessitating monitoring or biophysical modelling to maintain reliability [3].

2.4. Creating Maps of Fuel

Mapping fuels at large scales faces challenges typical of mapping vegetation; practicality limits the proportion of the landscape that can be measured directly and high inherent heterogeneity limits the potential for interpolating between measured sites [103,104]. For broad-scale fuel mapping, there are three main approaches that can be applied; direct (where methods directly measure properties of interest—such as measuring canopy structure with LiDAR), indirect (where methods use the direct measurement of a proxy for the properties of interest—such as using images to create classes based on overstorey tree species as a proxy for fuel structure) or derived (where values are derived statistically from a range of sources including combinations of biophysical variables and indirect measurements—such as modelling fuel loading using climatic and vegetation community data) [23,105,106]. The methods available for mapping fuel are highly dependent on the ways fuel has been sampled and classified. Many of the parameters used in fire behaviour models (e.g., bulk density of fine fuels or surface fuel depth) are impractical to quantify with direct measurement so their values must be determined through other means.

Indirect assignation of classes, in particular assigning estimated fuel attributes to existing classifications, has been common as it allows managers to apply existing maps—often of vegetation type—as fuel maps, reducing the need for extensive surveys or mapping programs [41]. However, the value of such maps will be dependent on (1) how well they represent existing vegetation type classes (as the accuracy of the derived fuel map cannot be greater than the vegetation map it is derived from); (2) how representative the existing classifications are of fuel attributes in space and time; and (3) how internally consistent the units are. Additionally, having a fuel map based on extant classifications means there is limited flexibility in adjusting values where there are known inconsistencies, such as those resulting from changing abundances of particular species that have unusual flammability properties (e.g., [28,29]).

Where there are site level classifications of fuel that can be discriminated aerially, remote sensing approaches can be used to directly assess and classify them [107]. While obscuration by tree canopies has provided a challenge for directly measuring many fuel properties [23], in recent years there have been rapid developments in technologies that allow the measurement of sub-canopy fuel properties, including airborne LiDAR [108], hyper and multi-spectral imagery [109], and radar [110]. These have the potential to yield detailed measurements of attributes that have been difficult to measure over large areas, in particular vertical and horizontal structure. Additionally, remote sensing approaches can now provide information on the status of fuels, including the degree of curing [111] and live moisture status [112–114].

Derived approaches are becoming increasingly available to allow attributes that are not so readily measurable remotely to be estimated using statistical approaches [115]. They have the strength of being able to use modelling to combine disparate sources of data to predict attributes in a parsimonious manner [23,27,116–118]. Advantages include the ability respond to dynamic changes (such as incorporating observations [119]) as well as being able to spatially quantify uncertainty around attribute values. Understanding uncertainty can be important for prioritizing the collection of data and for Monte Carlo style fire risk analysis [120].

The accuracies of fuel maps reflect the approaches used in their creation. There are a number of sources of error that may contribute to poor results. These include (1) inappropriate fuel sampling methods and designs; (2) improper classifications; (3) errors in the application of methods; (4) improper geo-registration; and (5) scale incompatibilities (both between fuel attributes at a site and between sampling scale and mapping scale) [3,95]. The level of error in using classes can be high: a review of the LANDFIRE fuel mapping products found that correlation between mapped units and fuel properties was relatively low (ranging between 5% and 85% correct, regardless of mapping approach) due to scale and resolution mismatches and the possible insensitivity of the attributes used [121].

3. Future Directions, Opportunities and Needs

3.1. Parameterising Fuel

It is important that the quality of fuel data is commensurate with the gravity of the decisions being made using them. Fuel maps are a key input in wildfire modelling systems; such systems are becoming increasingly important to land managers. Despite this, there are no universal standards used for quantifying and representing fuel worldwide. Single purpose methodologies are widespread, but incompatibilities in the parameters that are represented limits the ease at which models can be applied outside their development localities. This is because where one model is used operationally, the appropriate measurements for alternative models are rarely collected, necessitating unit conversion and approximation. The adoption of a more universal system would increase the applicability of fire models and research findings, foster collaboration and reduce research duplication by allowing findings to be generalised across regions [35,68,122].

While there is a great diversity of ecosystems prone to wildland fire worldwide, the fundamental processes behind combustion and fire propagation are common to all. As a result, fuel quantification systems that have a basis in fundamental fire properties will have a degree of universality by default. The adoption of a hierarchical system could provide for abstraction while allowing for base level fuel attributes to be reconstituted [25,123]. Such a hierarchy could be considered in terms of:

- Primary attributes; those that can be directly linked to fire behaviour (e.g., fuel element dimensions, chemistry, moisture content and spatial configuration);
- Secondary attributes; those that can measured in the field but require transformation to be linked to the primary attributes (e.g., plant species may be used as a proxy for element chemical composition);
- Tertiary attributes; those that summarise primary and secondary attributes (e.g., vegetation type may be used to describe the likely properties at a site) and can be used for mapping;
- Accessory attributes; those that are not directly related to fuel, but are important for understanding processes, such as species composition, site age and soil properties.

Due to the diversity in vegetation community properties worldwide, the development of a practical and functional system is a great challenge. However, by considering primary attributes as directly as possible and ensuring that any secondary attributes can be readily transformed into primary attributes, a basis for commonality can be maintained. A sample of measurable secondary fire behaviour attributes, their related primary attributes, and their effect on fire behaviour is presented in Table 2. One thing that is immediately evident from this table is the complexity of the problem—each secondary attribute may influence multiple primary attributes.

Increasing detail in the parameterisation of fuel is likely to exacerbate the issue where the standard site level classifications currently used for mapping are too coarse to represent the known variation between components of the fuel bed. It is regressive to discard detailed information (such as from LiDAR) to constrain fuel information to a fixed classification. An alternative could be to treat fuel attributes as independent continuous variables. While separate maps of each fuel parameter of interest may cause difficulties in human interpretation, simulation models should be able to process the values directly.

Table 2. Some commonly measured fuel attributes that are assessed at a site level (secondary attributes), the associated (primary) attributes of these that affect fire behaviour, and the fundamental fire behaviour processes they influence [16,34,50,77]. Processes may be associated with more than one primary attribute.

Secondary Attributes	Primary Attributes	Associated Fire Behaviour Processes *
Fuel element geometry	Size Shape Surface area to volume ratio	Heat transfer (including cooling) Ignitability Residence time
Fuel type (species) and condition	Stratum particle density Stratum bulk density Stratum packing ratio Species composition Moisture content Fuel availability Chemistry (Fats, Salts, Ash content, Carbohydrates, Sugars and other extractives) Proportion dead Decomposition state	Ignitability Energy balance Air: fuel mixture Reaction chemistry Heat transfer H_2O Latent heat absorption Combustible air: fuel mixture Heat conductivity Residence time Combustion efficiency Smoke production Proportion of fuel remaining unburnt
Horizontal continuity fuel continuity	Distance between fuel elements Distance between fuel clumps	Connectivity/sustainability thresholds (i.e., wind and flame properties) Heat transfer efficiency Combustible air: fuel mixture
Mass and location of fuel in different strata	Fuel element spatial configuration Stratum particle density Stratum bulk density Stratum packing ratio Wind adjustment factor Wind profile and turbulence Overall fuel load	Flame height/depth Energy output Ignitability Preheating of fuel Residence time Spread rate
Firebrand potential	Mass of loose material Nature of loose material Location of loose material	Number of viable embers produced Aerodynamic properties of embers Likelihood of lofting Sustainability of embers

Ideally, fuel quantification would be purely directed by fundamentals; however, areas of ambiguity remain as fire science is not settled. There is not yet a fundamental framework describing the process of wildfire spread [124], and there are clear challenges in transferring the concepts of flammability from the laboratory to landscape scales, as fire is more complex than a spreading flame front [125–128]. For example, the different dimensions of flammability (for example, ignitability and combustibility) take on different meanings at different scales, each of which may require particular fuel information in order to be understood [126]. Other processes, such as the spread of fire through spotting (considered in Australian fire models due to the nature of Eucalyptus bark) incorporate firebrand generation, transport and spot fire ignition [129]—this cannot be replicated in totality in a laboratory. Despite these issues, there are a number of attributes that are already currently common components of fire models including fuel element size, amount, spatial distribution and status (live or dead) that are already quantified and mapped in various forms. A review of these would be a potential starting point for considering a more universal system.

The adoption of a new set of universal model parameters would require unit conversion for the majority of existing fire models. Ideally, models would be updated to process primary attributes without the use of intermediate units—or alternatively, novel models could be developed to supersede the current ones. It is unlikely, due to the complexity of natural systems and the vastly different scales of processes (i.e., from molecular decomposition to terrain wind channelling), that any single model (or fuel quantification system) will meet all needs at all scales. However, in principle, a universal fuel quantification system could support the development of a universally applicable fire model. There are substantial benefits that could be realised from this—in particular, increased leverage of research and development, and greater availability of wildfire data for testing.

3.2. Cooperative Development

Many parts of the world subject to wildfire are likely to have fuel quantification systems currently in place based on contemporary fire models, as evidenced by the Canadian and US field assessment systems [130,131]. As moving to a new system would require investment, a compelling case needs to be made as to what the benefits would be. These are likely to include:

- The ability to share research and apply models developed elsewhere;
- The ability to adopt new systems as science progresses;
- The ability to combine fire behaviour and fire effects systems.

Furthermore, increasing the breadth and applicability of fuel information has the potential to increase efficiency and reduce costs by avoiding duplication between localities and providing for research leverage. This is particularly important when considering the research of rare events, such as extreme fire behaviour, where small sample sizes are an issue.

Any move towards universality in fuel quantification systems would require the cooperation of a broad range of users in multiple jurisdictions to ensure all needs are considered. Unless a system is able to meet the majority of needs of potential users, there is the risk of merely introducing an additional competing system [132]. Ideally, such a system would proceed as part of broader fire management information sharing agreements, allowing ecological, fire behaviour and operational data to be pooled internationally [133]. Such a process would require consensus on how to quantify various attributes, data formats, minimum levels of precision and accuracy, and units of measurement to allow interoperability between jurisdictions. Open ended standards have the benefit over set specifications of allowing higher quality information to be integrated where available so they do not impede improvement as technology advances. For example, this issue is already apparent with recent developments in remote sensing—we are beginning to have more detailed data (e.g., describing the nature of ladder fuels to the canopy using LiDAR [134]) than existing fire models can utilise. The operational fire simulation models discussed in this paper (FARSITE, PHOENIX RapidFire and Prometheus) are all based on point rate-of-spread models that were developed in the previous century [57,59,135], and so are not able to directly utilise more detailed information as it becomes available. These models were constrained by the processing and informational limitations at the time. Ideally, as improved fuel information becomes available, so too does the potential to develop new fire behaviour models that can process such data directly.

There is precedence for multijurisdictional cooperative development in fire sciences—for example, within Europe, the Paradox project [136] and within the US the Joint Fire Science Program [137]. There are also examples of multidisciplinary approaches to model development—for example, the FIREX climate and air study [138]. Ideally, such programs could be used to provide a framework for developing a broader framework for unifying approaches in localities with wildfire problems worldwide.

While it would be expected that the initial focus would be on the subset of attributes currently being used for fire models, it would be ideal to agree on protocols for as broad a set of attributes as possible. Such an attribute set would provide for the development of new, improved models, would allow integration with other ecological modelling systems and would allow broader uses of the data such as the analysis of ecological processes and spatial patterning in three dimensions [123]. An enduring challenge with the development of such a system is that there are multiple needs that require the quantification of fuels, in particular:

- The need for quantifying the fundamental properties of fuel that contribute to fire behaviour;

- The need for estimating fire effects such as smoke, carbon loss or watershed impacts;
- The need to have methods for evaluating fuel hazard and model verification in the field; and
- The need for understanding how fuel properties relate to vegetation, climate, and environmental variation.

These needs have different requirements (Table 3) and the levels of detail required for each are not the same. For example, simplicity and efficiency are priorities when conducting field fuel hazard assessments; however, the data collected are unlikely to have suitable resolution, accuracy or precision for developing landscape fuel dynamics models. Currently, no system is available that is suited to all phases of fire management [41]. Due to the diversity of fire prone ecosystems worldwide, the assessment of secondary and tertiary attributes may require different assessment methods and no 'one-size-fits-all' approach is likely to be feasible for all uses. A fundamental fire basis for fuel quantification will greatly help understand *what* the current conditions are. To understand *how* and *why* they will change, we need to continue to develop our understanding of the ecological processes behind fuel development.

Table 3. Uses of fuel quantifications and key features required to fulfil desired use.

Use of Fuel Quantification	Features Required for Efficacy
Field identification of fuel hazard	Limited number of classes to select from Potential for rapid assessment with limited expertise Distinctive classes that can be field identified Ability to provide dichotomous keys
Modelling of fire behaviour	Element moisture content Element arrangement (vertically and horizontally) Element dimensions Element load (in relation to spatial arrangement) Element chemical composition Element bulk density
Modelling of fire effects	Fuel element fundamental properties (as above) Expected fire/fuel interaction (fire behaviour outputs) Fuel/impact relationships (e.g., fuel type/sediment flow) Properties of less flammable components (e.g., duff, logs)
Spatio-temporal fuel/vegetation models	
Spatial information	Species abundances and properties Community dynamics (co-occurring species, dominance other interactions) Species—fuel relationships Seasonal variation
Temporal information	Fuel condition (e.g., current status) Live: dead ratio or curing properties Life cycle properties Fire responses
Accessory attributes	Disturbance history (e.g., landuse, fire) Biophysical attributes (e.g., soil, climate)

3.3. Rethinking Fuel–Fuel as an Ecological Entity

While fuels can be parameterised solely in terms of their potential contribution to fire behaviour, in order to understand their properties through time, it is important to also recognise that they are biological products that are a product of complex and dynamic processes [3,27,123]. To date, there has been a tendency to consider fuel separately from the vegetation it is derived from; however, to be truly understood, the biotic nature of fuel needs to be taken into consideration. Importantly, what is thought of as 'fuel' by land managers is, in essence, potential fuel—it only acts as fuel when it is involved with combustion; otherwise, it is vegetable matter. At broad scales, the occurrence of wildfires is dependent on a suitable combination of climate, weather, vegetation and ignitions [139–141]. Furthermore, climate is a key driver of the composition of plant species at a particular location (combined with other environmental tolerances, competition and disturbance [142]). With a changing climate, range shifting species and communities have the potential to alter fuel properties at a landscape level, resulting in changes in the relative distribution of fuel hazard through space and time by altering flammability [33,126,143]. Additionally, altered fire regimes driven by increased fire weather have the potential to cause abrupt shifts in vegetation communities, potentially resulting in rapid changes [39,144,145]. Even within communities, changing abundances of individual species may result in changes to flammability at the landscape scale [28,146,147]. The ecological aspects of wildland fuels are also strongly evident in the way fuel recovers after fire or other disturbances. The rate of vegetation recovery and the composition of a community is a function of the weather conditions before, during and after a fire—weather affects both the severity of a fire and resources available for growth [27,30,32,101]. The severity of a fire could also be considered in terms of the fuels that do not burn in a fire—understanding the availability of the lesser flammable fuels (logs, duff, soil etc.) to burn under particular conditions is important for predicting how a system recovers after fire in terms of fuel and important ecosystem services (carbon storage, faunal habitat, water quality). Other non-fuel properties of vegetation communities can also influence short-term fuel dynamics, for example, the overstorey of a forest plays a role in defining the understorey microclimate, influencing the water available for both plant growth and fuel moisture dynamics [148,149]. In the face of changing climates, understanding the interactions between plant ecology, fuel properties and fire regimes [150–153] will be critical for understanding future fire. A focus on processes can provide insight into fuel properties as they exist today and provide an indication of what may change with different forms of disturbance [145,153,154] or changing environmental conditions [155,156].

Due to ecosystem complexity, finding the best way to incorporate ecological processes and fuel quantification methods is likely to remain an enduring challenge. To begin to understand such relationships, the first step would be to begin to consider fuel data collection in a holistic manner and ensure that information about ecosystem properties are collected in conjunction with fuel surveys (for example, including assessing species abundances, their structural roles and site properties under which they occur). While such information may not add immediate value to a survey intended to provide a snapshot of the current fuel status, ultimately, consideration of ecosystem processes (i.e., looking at fuel types and components through an ecological lens) can both assist in the development of more appropriate and accurate sampling techniques and support the development of dynamic fuel models that improve estimates of fuel properties through time [41].

4. Conclusions

There is currently a wide variety of practices used in measuring wildland fuels worldwide. This has resulted in challenges in applying research findings and models outside of their development regions, limiting collaboration and resulting in duplicated efforts. Methods could potentially be focused in a hierarchical manner using the universal fundamental physical processes of wildfire behaviour as a basis. Additionally, it remains important to appreciate that fuel is of biotic origins—while it can be described in terms of fundamental fire properties, it can only be understood by ensuring that the complex biological processes are also recognised.

The movement towards a more universal approach to fuel quantification would require a deliberate concerted effort from many parties. A new system would be disruptive to many existing management systems; however, the benefits could be expected to be substantial. There have been regional scale multijurisdictional and multidisciplinary programs in fire science—the challenge now is to gain support for such an approach internationally.

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