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Generating a framework for fuel inputs to future fire behaviour models: reviews, recommendations and remote sensing

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Abstract

Land managers use models to understand potential fire behaviour, which provide insight into the social, economic and environmental implications of fire. Although combustion is a fundamental process, numerous fire behaviour models exist across the world, each with model-specific inputs and outputs. While these are useful for local-level fire management, vegetation- or country-specific fire behaviour models, they do limit knowledge-sharing between jurisdictions – largely because model inputs (particularly fuel arguments) and outputs differ, meaning they cannot be readily compared. At the same time, advancements in remote sensing techniques have resulted in accurate methods to estimate fuel for current fire behaviour models that have not been fully integrated.

This project has two key aims: a) to develop a comprehensive set of model parameters that can be used to universally characterise fuel attributes fundamental to fire behaviour, and b) based on knowledge gaps identified, undertake expert elicitation to identify fuel attributes for fire behaviour not currently utilised in models, and propose methods to estimate these values using remote sensing. To achieve this, we reviewed 25 fire behaviour models to identify similarities and differences in model inputs and outputs. We then subset model inputs to the fuel parameters and linked each to current remote sensing methods. Following the review, and in conjunction with an expert elicitation process, we developed a list of fundamental fuel attributes missing from current fire behaviour models. From this list, we developed novel fuel parameters that fully utilise information contained within remote sending datasets. The final step in this process is to validate the importance of each fuel argument using further expert elicitation and field burning experiments.

We found many common parameters across fire behaviour models. Most models require parameters that describe fuel, short- and long-term fuel moisture, temperature and wind variables, however, the physical fuel parameters are typically where models diverge. Models across the world use fuel inputs that describe the amount, horizontal and vertical arrangement of fuel, bark hazard and the importance of crown fuels. Preliminary expert elicitation identified shared and divergent opinions related to fuel characteristics that drive fire behaviour. While common parameters related to horizontal and vertical arrangement of fuel were important, gaps exist in our capacity to describe ladder fuels. From these results, we have developed novel remote sensing metrics to describe vertical and horizontal connectivity. Throughout 2022, we aim to validate these preliminary results through further expert elicitation and field observations of fire behaviour.

Through this work, we have developed a complete list of fuel parameters for fire behaviour and related these to remote sensing methods. This provides a framework for current models to shift to remotely sensed inputs, and a basis for future fire behaviour models. Overall, we argue that this work provides the foundation for a universal fuel assessment methodology to be developed, that is scalable and captures change over time, that can link physical fuel structure and remote sensing techniques to accurately capture fuel dynamics.

1. Background

In many regions across the globe, fires are becoming increasingly frequent and severe (Pausas & Keeley, 2021). With the effects of climate change likely to continue to amplify this pattern into the future, jurisdictions around the world model fire behaviour to make high-consequence decisions both during the response phase of wildfire management and for the estimation of risk by simulating a set of bushfires across the landscape and observing the associated environmental, economic and social impacts (Gazzard et al., 2020; Kramer et al., 2019; Ladds et al., 2017; Yu et al., 2020). Differences in vegetation across the world have led to independent fire behaviour models being developed (Sullivan, 2009a, 2009b). Consequently, descriptions and systems of measurement for fuel are also unique with the intention to characterise the necessary parameters for the associated model (T. Duff et al., 2017; Keane, 2013). Although this has been useful for local-level fire management, this has limited our capacity to share fire behaviour knowledge across different jurisdictions because the model inputs differ.

Remote sensing products derived from active sensors have been shown to provide an accurate, objective means of measuring fuel attributes. (Gale et al., 2021). Active remote sensing methods utilising LiDAR to measure the 3D structure of fuel have been the focus of the research (Calders et al., 2015; Cooper et al., 2017; Greaves et al., 2015; Kramer et al., 2014; Rowell et al., 2016; Wallace et al., 2016, 2017). A range of platforms have been used to derive measurements including terrestrial, Unoccupied Aircraft Systems (UAS), fixed wing and satellite (García et al., 2011, 2017; Hillman et al., 2021).. Limitations to using these approaches have been highlighted in the ability of these sensors to measure surface fuel characteristics (i.e. vegetation in contact with the ground) (Wallace et al., 2020) due to the inability of sensors to differentiate between ground and surface fuel. Despite this limitation, the information content within remote sensing products provides the ability to describe complex 3D attributes of fuel that are beyond those which are currently utilised in fire behaviour models (Hillman et al., 2021).

2. Knowledge gap

The fuel parameters that are used in current operational fire behaviour models are derived from research at the time of their development. Given advancements in both fire behaviour modelling and remote sensing techniques, there is a clear need for an extensive review of fundamental fuel characteristics that influence fire behaviour, combined with remote sensing techniques that can be employed to assist in the characterisation of complex fuel characteristics.

3. Aims and Objective

This project has two key aims: a) to develop a comprehensive set of model parameters that can be used to universally characterise fuel attributes fundamental to fire behaviour, and b) based on knowledge gaps identified, undertake expert elicitation to identify fuel attributes for fire behaviour not currently utilised in models, and propose methods to estimate these values using remote sensing

4. Methods

To achieve the aims of this project, we firstly reviewed 25 fire behaviour models (empirical, semi-empirical and physical fire behaviour models) across the world. For each model we made note of the input parameters utilised and the outputs derived. For each fuel parameter we identified the scale, units of measure and the minimum levels of precision and accuracy required. Common parameters and outcomes were identified through this process.

Building on the considerable body of work completed by Gale et al. (2021) who reviewed remote sensing research in relation to the fuel attributes that influence fire behaviour, we directly identified the remote sensing research pertinent to each fuel argument identified in part one of this review.

A process of expert elicitation was then undertaken to review the current parameters utilised within fire behaviour models and identify attributes that are fundamental to fire behaviour but not currently measured. Three guiding principles were employed to develop novel metrics that leveraged the full capability of the remote sensing information. Firstly, the attributes had to provide an understanding of the vegetation at the time of measurement and be able to identify why things are changing over time. This builds on the concepts highlighted by Duff et al. (2012) and Keane et al. (2012). Secondly, a hierarchical system was used to describe the fuel attributes. Wherever possible primary fuel attributes that can be directly linked to fire behaviour were extracted. Thirdly, attributes had to be scalable with the associated remote sensing method able to provide the necessary precision and accuracy. By focussing on developing attributes that can be continuously mapped across the landscape, simulation models should be able to process the values directly.

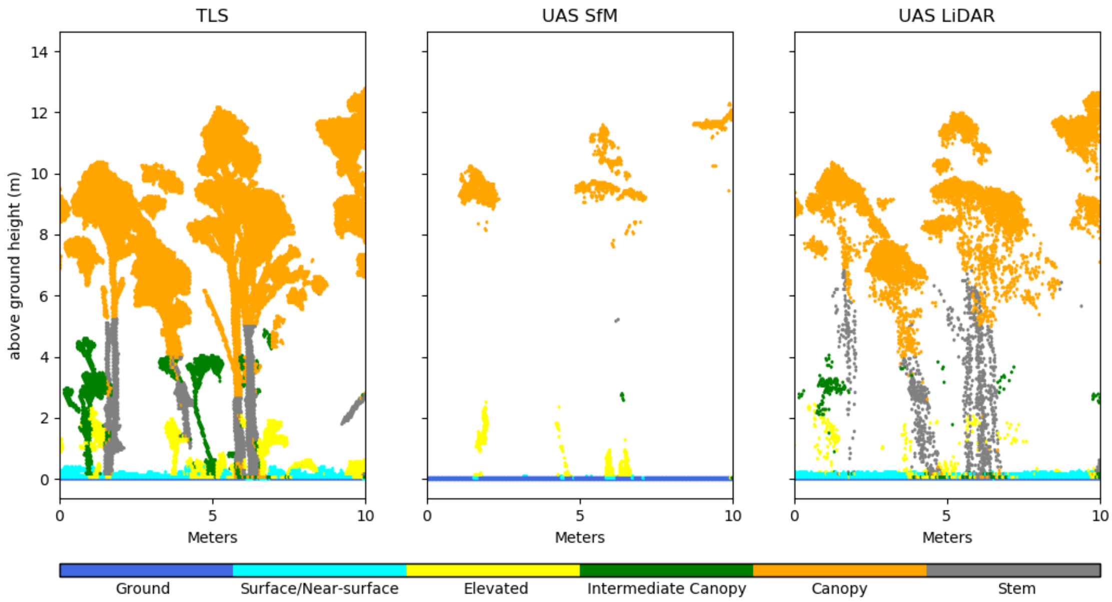

Figure 1. Side view transect through a section of a study area near Hobart, Tasmania demonstrating the capability of 3D remote sensing and novel classification approaches to automatically classify vegetation into canopy, stems intermediate canopy, elevated, surface/near-surface and ground layers (Hillman et al. 2021).

5. Results and Discussion

Preliminary results suggest that broad overlap in the inputs and outputs exist between empirical and semi-empirical fire behaviour models across the world. This is a logical outcome given the fundamental principles of fire behaviour. Most models utilise input arguments describing long term dryness, wind, temperature, short term fuel moisture (as temperature and relative humidity) and a fuel value. The main differences between models can be seen in the fuel parameters. Most models require parameters that describe the horizontal and vertical distribution of fuel at different strata in combination with the amount of fuel. Similar outputs from empirical and semi-empirical models include descriptions of the rate of spread and height, angle and the depth of flames at the head of the fire are observed across fire behaviour models. This contrasts with physical fire behaviour models which enable observations of fire behaviour in greater detail and consequences of multiple fire interactions and connectivity in vegetation to be analysed at the expense of longer running times.

With respect to the alignment of remote sensing literature to describe fuel variables - consistent with previous findings of Gale et al. (2021) most research has focussed on extracting measurements describing overstorey and understorey variables. This suggests that fuel variables at the fuel assemblage scale which are currently utilised in operational fire behaviour models could be measured using remote sensing methods. However, factors which limit wider implementation of such technologies include the inability of active sensors to measure surface fuel properties in contact with the ground and the patchwork nature of these datasets. The incomplete coverage of datasets is also at odds with operational fire behaviour models which need to be run at a regional scale. Potential opportunities to bridge this gap have been demonstrated in recent research which has shown ability to scale up point-based measurements across the landscape (Jenkins et al., 2020; McColl-Gausden et al., 2020). It was also noted through this manuscript that remote sensing derived datasets have the ability to characterise complex 3D fuel attributes (Figure 1).

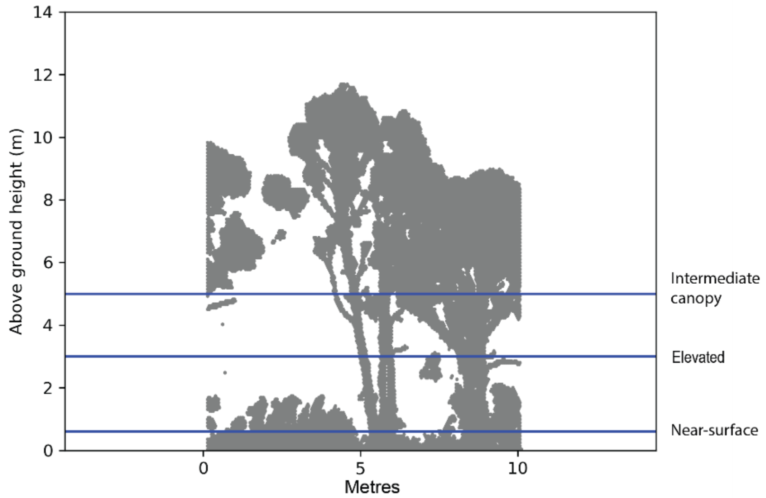

Figure 2. Height thresholds used to extract different fuel strata (based on Hines et al. (2008) and Gould et al. (2012)). Expert elicitation highlighted difficulties in the utilisation of remote sensing to extract vegetation at different strata due to the high variability of vegetation in different areas.

Preliminary results from the expert elicitation process highlighted shared and divergent opinions about the fuel characteristics that drive fire behaviour across the world. Consistent with current fuel inputs used in fire behaviour models, metrics that describe the horizontal and vertical arrangement of fuel are considered important to be measured. In contrast to current fuel hazard measurement systems, there were suggestions to move away from defined strata layers due to the complexities of defining strata using both in-field and remote sensing techniques (Figure 2). Instead, metrics describing the connectedness of fuel across the “ladder” was seen to be an area of opportunity for active 3D remote sensing. Work has begun on developing a metric to describe the vertical and horizontal connectedness of fuel from 3D remote sensing that will also allow changes in the arrangement of fuels to be observed through time. Further metrics of interest derived from the expert elicitation process include the development of an approach that allows for assessment of vulnerability of a site to stand-replacing fire and the fusion of structural and moisture information). Whilst the aforementioned fuel attributes are universal across fuel types, expert elicitation highlighted cases where fuel attributes that influence fire behaviour were unique to the vegetation type. An example of this, is the need to describe canopy fuel properties in coniferous and deciduous trees (e.g. canopy base height, canopy fuel load) which were observed to be of lower relevance in eucalypt dominated systems. Similarly, the properties of different bark types in eucalypt dominated systems were seen to be of great importance to potential fire behaviour and less important in deciduous forests. Future work completed as part of this project will validate the metrics developed through remote sensing with further expert elicitation and field observations of fire behaviour.

6. Conclusions

Overall, we make two key recommendations from this manuscript on the assessment of fuel attributes for fire behaviour in models used across the world. Firstly, we recommended that current operational models (e.g. PHOENIX, RapidFire, and FARSITE) undertake a trial to utilise fuel parameters derived from remote sensing approaches outlined in this manuscript and compare outputs from this approach with current input parameter outputs. Secondly, the complete list of fuel attributes derived from this manuscript are validated in their ability to represent fuel hazard in forest types around the world. This would enable greater confidence in the attributes ability to represent fire behaviour and identify fuel change over time. Overall, we argue that this work provides the foundation for a universal fuel assessment methodology to be developed, that is scalable and captures change over time and can link physical fuel structure and remote sensing techniques to accurately capture fuel dynamics. This work will be undertaken through a Fulbright exchange (Samuel Hillman with Rocky Mountain Research Station, Missoula, Montana).

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