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Effect of woody debris on the rate of spread of surface fires in forest fuels in a combustion wind tunnel

A.L. Sullivan[a,*], N.C. Surawski[a,1], D. Crawford[a], R.J. Hurley[a], L. Volkova[b], C.J. Weston[b], C.P. Meyer[c]

[a] CSIRO, GPO Box 1700, Canberra, ACT 2601, Australia
[b] Department of Ecosystem and Forest Sciences, Faculty of Science, University of Melbourne, Water Street, Creswick, Victoria 3363, Australia
[c] CSIRO, PMB 1, Aspendale, Victoria 3195, Australia

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ABSTRACT

The treatment of the contribution of woody debris (WD, such as branches or small logs > 6–50 mm diameter) to the rate of forward spread of a fire in current operational forest fire spread models is inconsistent. Some models do not take into account this fuel at all (i.e. only consider the combustion of fine fuels (⩽6 mm diameter)), while others incorporate effects based on little or no data. An experimental programme utilising a large combustion wind tunnel investigated the effect of WD on the spread of fires burning through forest litter (surface fuel) beds of 1.0 kg m^{-2}. Fires spreading with (heading) and against (backing) the wind were investigated. Three treatments of WD load (0.2, 0.6 and 1.2 kg m^{-2}) and a control (0 kg m^{-2}) were studied using a single constant wind speed (1.0 m s^{-1}) and a narrow range of fine and woody fuel moisture contents (10.0–12.7% and 9.2–11.6% oven-dry weight, respectively) determined by ambient conditions. Presence of WD was found to approximately halve the overall rate of spread of heading fires relative to when no WD was present, regardless of the level of treatment. No effect of WD on rate of spread was found for backing fires. Potential explanations of these findings and implications for the use of operational forest fire spread models are explored, as are future research needs.

1. Introduction

A critical requirement in the operational management of a wildland fire (i.e. a forest or grassland fire) is knowledge of its rate of spread. Knowledge of the fire's speed is essential for effective decisions related to fire suppression planning and execution, firefighter safety, the assessment of the threat to life and property, and for the issuance of appropriate warnings (Sullivan et al., 2012; Cruz et al., 2015). Despite the extensive research that has been, and continues to be, devoted to this topic (e.g. Anderson, 1964; Byram, 1959; Curry and Fons, 1938; Rossa, 2017; Plucinski et al., 2017b), complete fundamental understanding of fire spread is still lacking (Finney et al., 2013). This situation stems from the complexity of the interactions and ranges of spatial and temporal scales involved in wildland fire (Sullivan, 2017a,b) and the fact that many physical mechanisms underpinning fire spread are still contested (e.g. Sullivan and Cruz, 2015). Empirical and quasi-empirical models (Sullivan, 2009a) derived from small and large scale experiments (e.g. Rothermel, 1972; Forestry Canada Fire Danger Group, 1992; Cheney et al., 1998) form the basis of all current operational systems due to their overall robustness and reliability (Sullivan, 2009b). Many of these models have undergone steady improvements or been replaced with improved versions over time, some have not (Cruz et al., 2018a).

The layers of forest vegetation and debris through which fire propagates is collectively called 'fuel' and can be classified according to various attributes in regard to their morphology, location, moisture loss or how they contribute to the behaviour of the fire via combustion (Byram, 1959; Agee, 1996; Scott and Burgan, 2005; Keane, 2016; Cruz et al., 2018b). Fine dead fuels, mostly comprising fallen leaf, bark and twig material 6 mm or less in diameter or living leaf and fine stems (⩽3 mm diameter) of shrubs and trees, are those fuels that respond rapidly to changes in their thermal environment due to their high surface area relative their mass (Rothermel, 1972), generally with a comparatively high surface area-to-volume ratio (SAVR) often > 50 cm^{-1} (Brown, 1970). These fuels are often described as 1-h fuels as this is their moisture response time to changes in the environment (Fosberg and Deeming, 1971). They ignite readily and are rapidly consumed by fire (Chandler et al., 1983, p. 10). Coarser dead fuel elements (i.e., those

* Corresponding author.
E-mail address: Andrew.Sullivan@csiro.au (A.L. Sullivan).
[1] Current address: School of Civil and Environmental Engineering, University of Technology Sydney, Ultimo 2007, Australia.

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>6 mm diameter), such as fallen branches, boughs and toppled stems (collectively known as down woody material or woody debris (WD)), have been shown to contribute significantly to total fuel load in most tropical, temperate and boreal forests (Hollis et al., 2011; van Leeuwen et al., 2014; Volkova and Weston, 2015). These fuel have a much reduced SAVR compared to fine fuels (generally < 50 cm^{-1} are often described as 10-h (>6–25.4 mm diameter) or 100-h (>25.4–75 mm diameter) fuels (Fosberg and Deeming, 1971)). However, the larger physical dimensions and masses of these coarser fuel elements mean that they take longer to ignite and combust.

Due to their relative ease of ignition and combustion, fine fuels have long been held to be the primary source of energy driving the behaviour of the flame front in a forest fire (McArthur, 1967; Rothermel, 1972; Rothermel, 1993), and changes in the way these fuels combust (particularly in regard to efficiency of energy transfer (Anderson and Rothermel, 1965)) affect the behaviour and spread of the fire front. In contrast, WD and larger live fuel elements generally ignite during or very soon after the passage of the flame front and can play a significant role in aspects of a forest fire other than the speed of the fire, particularly behind the fire front. For example, the contributions from WD elements have been found to significantly affect the total radiant heat flux behind the fire front and thus firefighter safety (Sullivan et al., 2002), the intensity, power, total energy release, severity, and burning depth (Agee, 1996; Hollis et al., 2011; Cruz et al., 2012), smoke production (Ward, 2001) and subsequent effects on human health (Weinhold, 2011; Reisen et al., 2011), and gaseous emissions (Bertschi et al., 2003) but also suppression difficulty (Proctor and McCarthy, 2015) and physical impact on soil and vegetation (Smith et al., 2017).

Operational forest fire spread prediction systems (e.g. Behave (Andrews, 1986) and BehavePlus (Andrews, 2014) based on the model of (Rothermel, 1972), the McArthur Forest Fire Danger Meter (McArthur, 1967), the Western Australia Forest Fire Behaviour Tables (FFBT) (Sneeuwjagt and Peet, 1985), the Canadian Forest Fire Behavior Prediction System (CFFBPS) (Forestry Canada Fire Danger Group, 1992) and the Dry Eucalypt Forest Fire Model (DEFFM) (Cheney et al., 2012)) are generally designed to predict the quasi-steady rate of forward spread of a fire using estimates of prevailing fuel, weather and topographic conditions. Some models, such as the McArthur, FFBT and DEFFM systems are purely empirical and directly consider only the contributions to fire spread from the combustion of fine dead fuels on the forest floor. Others, such as BehavePlus and the CFFBPS, integrate various degrees of quasi-empirical modelling based on physical considerations and allow the incorporation of the contribution of the combustion of other fuels, such as coarser dead fuels and fine live fuels, to total heat release and thereby fire propagation.

In the Rothermel model, mass of WD, weighted non-linearly by the SAVR of each fuel size class (the higher the SAVR, the greater the contribution), contributes to the overall fuel load and thus reaction intensity and propagating flux ratio but also to bulk density and total heat required to ignite the fuel (the heatsink). As a result, the influence of WD on rate of spread is quite complicated and not readily interpretable (Burgan and Rothermel, 1984). Increases to fuel bulk density and the heatsink generally result in decreases to rate of spread that overwhelm potential increases as a result of increased reaction intensity. In the CFFBPS, WD mass directly contributes to the rate of forward spread calculation through the Build-up Effect related to a Build-up Index as a function of surface fuel (both coarse and fine) consumption. In neither case does it appear that the methods by which the effects of WD on rate of spread are incorporated are based on data. Both McAlpine (1995) and Van Wagner (1998) point out that in a dataset of over 400 experimental fires no statistical evidence could be found to support an effect of Build-up Index on rate of spread, perhaps due to limitations of the data; instead a conceptually satisfying arbitrary function was incorporated into the system. As a result, the manner in which the effect of WD on rate of spread is included in operational systems around the world is inconsistent, ranging from not at all (e.g. McArthur and DEFFM) to arbitrarily, not based on data (Rothermel and CFFBPS).

Little is known about the characteristics of the particulate and gas emissions from the combustion of many types of WD, particularly WD found in the dry eucalypt forests of south-eastern Australia. As part of a larger research project attempting to characterise emissions released by combustion of WD under prescribed burning conditions (Cope et al., 2018), the opportunity was taken to investigate the effect WD on the forest floor has on fire behaviour, in particular rate of spread and flame dimensions, in the controlled conditions of a large combustion wind tunnel. Fallen branch material in the range 6–50 mm in diameter laid over a continuous fine litter fuel bed was used to test the hypothesis that the rate of forward spread of a fire is unaffected by the presence of WD in the fuel bed. Such an approach enables the ignition and combustion of WD via free-burning fire spreading through a surface fuel layer as would be found in nature, rather than burning pieces of WD in isolation from an external heat source as has been done in other studies (e.g. Albini and Reinhardt, 1995, 2001).

2. Methods

2.1. Experimental design

The design of this experiment focused on two variables: the amount (or load) of WD and the fire spread mode (i.e. whether the fire burns with the wind (heading fire) or against the wind (backing fire)). All other burning conditions (wind speed, fine fuel moisture content (MC) and surface fuel load) were either non-varying (wind speed and surface fuel load) or variation was limited as much as was practical (e.g. surface fuel MC). The values of these experimental factors were chosen to represent typical prescribed burning conditions for a dry eucalypt forest in central Victoria (Tolhurst and Cheney, 1999). Table 1 summarises the variables, factors and the range of values used in the study. The order of experimental treatments and replicates were randomised using a random number generator and were conducted over a three week period.

Table 1
Summary of variables and treatments in the design of the experimental burning programme. Fine and WD fuel loads were on a dry matter basis with fine fuels static at 1.0 kg m^{-2}. WD were distributed randomly within 1.5 m^2 sections of the fuel bed. Hyphenated quantities indicate the range (minimum-maximum). Wind speed was set to 1.0 m s^{-1} in all experiments.

WD treatment	Fire spread mode	WD load (kg m^{-2})	No. of replicates	Fine fuel MC (% ODW)	Woody debris MC (% ODW)
A	Heading	0	3	11.7–12.5%	9.2–11.6%
B	Heading	0.2	4	11.2–12.4%	9.2–11.6%
C	Heading	0.6	3	11.1–12.0%	9.2–11.6%
D	Heading	1.2	4	10.2–12.6%	9.2–11.6%
A	Backing	0	1	10.0%	9.2–11.6%
B	Backing	0.2	1	11.9%	9.2–11.6%
C	Backing	0.6	2	11.0–11.1%	9.2–11.6%
D	Backing	1.2	2	11.9–12.7%	9.2–11.6%