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Evidence for lack of a fuel effect on forest and shrubland fire rates of spread under elevated fire danger conditions: implications for modelling and management

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ABSTRACT

The suggestion has been made within the wildland fire community that the rate of spread in the upper portion of the fire danger spectrum is largely independent of the physical fuel characteristics in certain forest ecosystem types. Our review and analysis of the relevant scientific literature on the subject suggest that fuel characteristics have a gradual diminishing effect on the rate of fire spread in forest and shrubland fuel types with increasing fire danger, with the effect not being observable under extreme fire danger conditions. Empirical-based fire spread models with multiplicative fuel functions generally do not capture this effect adequately. The implications of this outcome on fire spread modelling and fuels management are discussed.

Keywords: dead fuel moisture contents, fire behaviour, fire propagation, fire spread modelling, fire weather, forest fuels management, fuel characteristics, fuel model, fuel type, wind speed.

Introduction

Catastrophic wildfire events over the past two decades, many of them involving a modern-day record number of fatalities amongst the local population (Tedim *et al.* 2020), have now more than ever highlighted the need for accurate fire spread prediction tools. Forecasts of fire propagation during wildfire events are required to assist decision making regarding the issuance of public warnings of an impending threat (Alexander *et al.* 2017). They are also needed to support safe and effective tactical and strategic wildfire suppression planning so that such actions are proactive and not reactive (Plucinski 2019*a*, 2019*b*; Neale and May 2020).

There is a general belief amongst some members of the wildland fire research community (e.g. Bessie and Johnson 1995; Parks *et al.* 2015) that as fire danger and (or) fire weather conditions become increasingly severe, the influence that fuel structural characteristics exert on fire propagation accordingly decreases. For example, when it comes to the spread of crown fires in coniferous forests, many experienced fire behaviour specialists, at least in the Canadian boreal region, commonly speak of simply 'trees' as being the prevailing type of fuel (M. E. Alexander, pers. obs.) – i.e. once a wildfire is crowning, the variation in the tree species and stand characteristics is not going to affect the outcomes in fire behaviour appreciably.

The term 'fuel effect' is used herein in a broad sense as the influence of the various physical characteristics of a fuel complex that directly affect fire behaviour (Sandberg *et al.* 2001; Keane 2014) – i.e. fuel load or quantity, fuel bed depth, height or thickness, bulk density or compactness, arrangement (vertical and horizontal continuity), composition or number of categories including their size/shape, condition (live and dead), cover and the number of strata involved (ground, surface, ladder and crown). It is exclusive of fuel moisture and chemical properties. A fuel effect implies that changes in fuel characteristics induce a change in observable fire behaviour characteristics. In contrast, the lack of a fuel effect implies no changes in the observed fire behaviour.

In this paper, we examine the influence that the fuel effect has on the forward rate of spread of wildfires under elevated fire danger (i.e. conditions that cause wildfires to propagate in the upper range of the fire behaviour). We begin by contrasting a number of current operational fire spread model outputs. We then look at the results from studies analysing wildfire occurrence data and observations of wildfire spread rates. Finally, we discuss the implications of this analysis within the framework of fire spread modelling and forest fuels management. Some familiarity on the part of the reader with the fundamentals of wildland fire behaviour and its impacts is presumed (Scott *et al.* 2014; Rego *et al.* 2021).

Operational empirical-based fire spread rate models

Fire spread rate models, both empirical (FCFDG 1992; Cheney *et al.* 1998, 2012) and semi-empirical ones (e.g. Rothermel 1972), form the basis of software tools used in the operational prediction of fire propagation, such as BehavePlus (Andrews 2014), Amicus (Plucinski *et al.* 2017), FARSITE (Finney 2004), Wildfire Analyst Pocket (Monedero *et al.* 2019), Phoenix (Tolhurst *et al.* 2008), Spark (Miller *et al.* 2015) and Prometheus (Tymstra *et al.* 2010). These operational tools are based on equations developed in part from the statistical analysis of the relationships between the observed rate of fire spread and components of the fire environment (i.e. fuels, weather and topography). Typically, the underlying sub-models include the effects of wind speed, fuel moisture content (or a surrogate), slope steepness and one or more physical fuel characteristics (Sullivan 2009; Cruz *et al.* 2015; Andrews 2018).

The fuel effect on rate of fire spread assumes distinct forms in various predictive models. Some models incorporate the influence of fuel characteristics through a multiplicative effect, where a fuel factor (comprising one or more variables and associated regression parameters) is multiplied by the other components of the model (Marsden-Smedley and Catchpole 1995; Cruz *et al.* 2005; Fernandes *et al.* 2009; Cheney *et al.* 2012; Anderson *et al.* 2015). Other models consider the effect of fuel characteristics in a discrete form – i.e. there is an individual fire spread equation for a given fuel type with its characteristics being static (e.g. Forestry Canada Fire Danger Group (FCFDG) 1992; Cheney *et al.* 1998). A distinctly different, but commensurate fuel effect on rate of fire spread can also be seen using the Rothermel (1972) surface fire spread model while applying standardised fuel models (Anderson 1982; Scott and Burgan 2005) representing broad vegetation types or customised descriptions of particular vegetation types (e.g. Burgan and Rothermel 1984; Burgan 1987; Ascoli *et al.* 2015).[1]

Common to these modelling approaches is the fact that the fuel effect on fire spread rate is independent of the fire danger conditions. Fig. 1 illustrates this behaviour, showing how different empirical-based or semi-empirical fire spread rate models used operationally for shrublands and forests in Australia (Fig. 1*a, c*), the USA (Fig. 1*b*) and Canada (Fig. 1*d*), for example, respond to changes in fuel characteristics. This compilation shows that the increase in the potential for extremely fast rates of fire spread, as driven by an increase in wind speed (assuming an underlying low level of fuel dryness), results in a commensurate increase in the differences in predicted rate of fire spread within a fuel type or fuel model. In other words, for a given fire spread rate model, the higher the spread potential, the larger the differences between distinct fuel types or fuel models. Although the Canadian fire spread models for conifer forests assume a distinct functional form, where through a sigmoid function the rate of fire spread converges to a maximum rate of spread, the largest differences in predicted rate of fire spread between different fuel types are also attained at the most extreme of burning conditions.

The relationships between fuel characteristics and rate of fire spread in these models have typically been established under moderate burning conditions. Given this, the extrapolation of a fuel effect to elevated fire danger conditions needs to be accordingly verified.

Evidence from observational studies of landscape-scale analysis of wildfire occurrence

Several studies have attempted to quantify the effect of fuel characteristics on fire propagation under elevated fire danger conditions in certain vegetation types. Moritz *et al.* (2004), for example, found through the analysis of fire interval data in shrublands of coast central and southern California, USA, that extreme fire weather overwhelmed the influence of fuel age (a surrogate for biomass accumulation, arrangement and the quantity of dead fuels in shrubland fuel complexes) and the spatial patterns of fuels on area burned.

A number of studies in eucalypt (*Eucalyptus* spp.) forests in Australia have provided insight into the fuel effect over an explicit range of fire danger conditions. For dry sclerophyll forests in the Sydney region of New South Wales

[1]A ‘fuel type’ represents an identifiable association of fuel elements of distinctive species, form, size, arrangement and continuity that will exhibit characteristic fire behaviour under defined burning conditions (Merrill and Alexander 1987). The strata for the fuel types in the Canadian Forest Fire Behaviour Prediction (FBP) System are, for example, generally described qualitatively. In contrast, a ‘fuel model’ is a simulated fuel complex for which all the fuel descriptors required for the solution of the Rothermel (1972) mathematical rate of spread model have been specified (Deeming and Brown 1975).

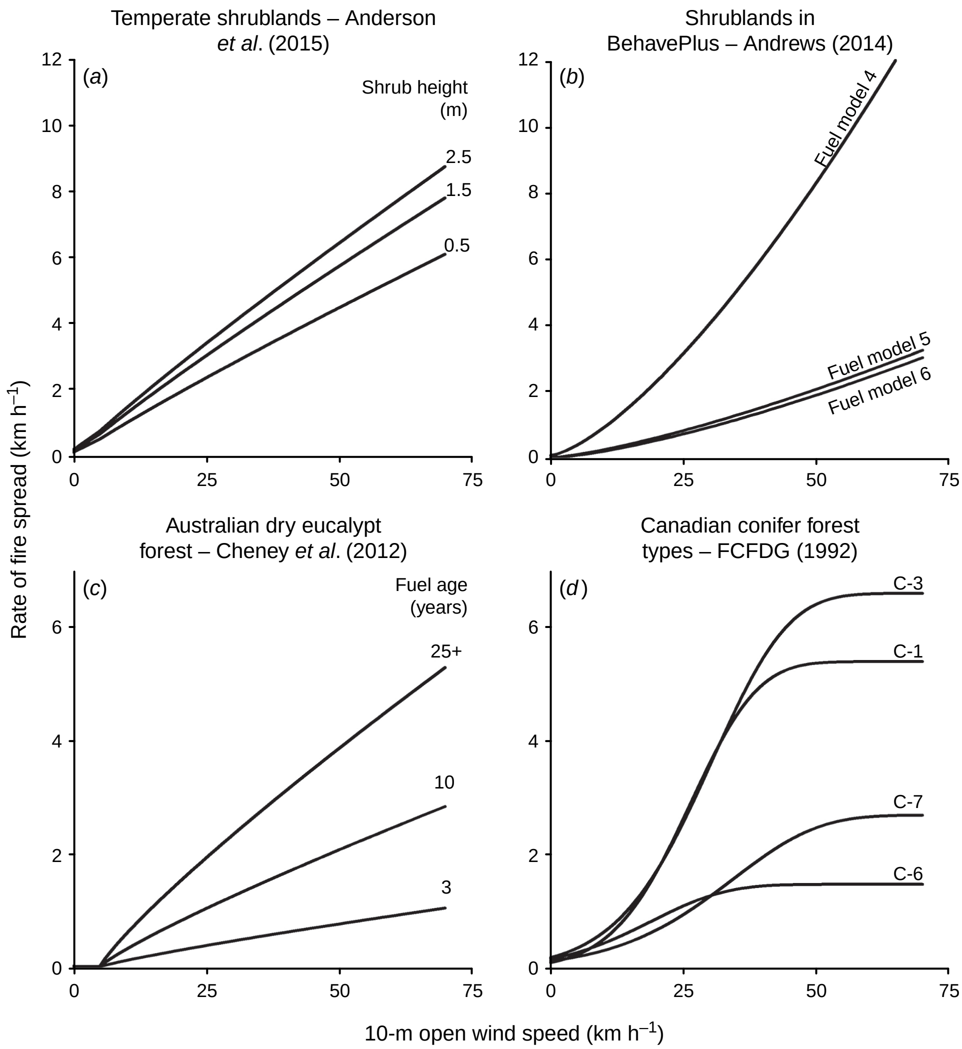

Fig. 1. Model predictions of rate of fire spread as a function of 10-m open wind speed on level ground for: (*a*) the Anderson *et al.* (2015) shrubland model for three different fuel heights; (*b*) the Rothermel (1972) model as implemented in the US BehavePlus Fire Modeling System (Andrews 2014) for three of the four Anderson (1982) shrubland fuel models (4, chaparral (1.8 m); 5, brush (0.6 m); and 6, dormant brush); (*c*) the Cheney *et al.* (2012) eucalypt forest fire spread model for three different fuel ages; and (*d*) four of the seven conifer forest fuel types (C-1, spruce–lichen woodland; C-3, mature jack or lodgepole pine; C-6, conifer plantation; and C-7, ponderosa pine–Douglas-fir) in the Canadian Forest Fire Behaviour Prediction (FBP) System (FCFDG 1992). All simulations assume a fine dead fuel moisture content of 6%. All BehavePlus simulations assume a live herbaceous fuel moisture content of 30% and a live woody fuel moisture content of 75%. All FBP System simulations assume the average Buildup Index (Van Wagner 1987) level assigned to each fuel type. A foliar moisture content of 97% was assumed for the fuel type C-6.

(NSW), Bradstock *et al.* (2010), for example, found the fire weather effect (extreme vs non-extreme) on the type of fire (understorey vs crown fire) to be much stronger than the fuel age effect. As fuel age varied between 5 and 20 years, with the latter considered a long-unburned condition in these forests, the fuel age effect on the type of fire was limited. The fuel age effect was found to be pronounced when fuels were younger (1–5 years), even under extreme fire weather conditions (as in McArthur 1967), but still small when compared with the weather effect. Price and Bradstock (2012) found comparable results in the burned areas associated with the 2009 Black Saturday fires in Victoria, with weather being the primary influence on fire severity, a surrogate for fireline intensity in this specific wildfire event. Price and Bradstock (2010), in another study in the Sydney region, also noted that under severe burning conditions (i.e. strong winds, low relative humidity and drought), the effect of young fuel-age areas in aiding

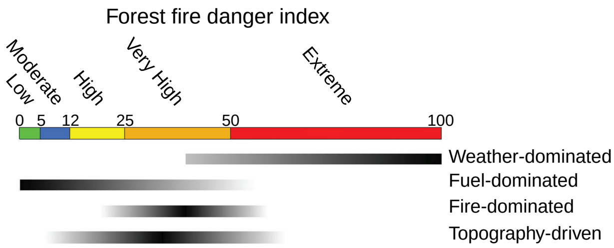

Fig. 2. The effect of different fire environment factors on eucalypt forest fire behaviour across a range of McArthur (1967) Forest Fire Danger Index values (adapted from Tolhurst and McCarthy 2016).

effective suppression was less effective than under moderated burning conditions. Similarly, Parks *et al.* (2015) found in distinct North American ecosystems that the effectiveness of recent wildfires acting as a fuelbreak diminished as the fire weather severity increased.

Tolhurst and McCarthy (2016) examined the effect of fuel reduction burns on wildfire severity in the southern Australia eucalypt forests of Victoria. They found that the reduction in severity and suppression assistance in fuel-treated areas declined substantially with an increase in the McArthur (1967) Forest Fire Danger Index (FFDI) above the 'Extreme' rating threshold (i.e. FFDI > 50), with wildfires becoming 'weather-dominated' and the effect of variation in fuel and topography becoming less important in fire propagation (Fig. 2); refer to Appendix 1 for a description of the FFDI and its calculation. Storey *et al.* (2016) looked explicitly at the variation of the effect of fuel age on wildfire severity across the FFDI spectrum over a broad range of eucalypt forests types in NSW, finding the overall fuel age effect to decrease with increasing FFDI.

Studies like the ones discussed in this section support the notion that as the severity of fire weather conditions worsen, the influence that fuels exert on fire propagation diminishes. Agee (1997) called this the 'weather hypothesis', where fires driven by extreme fire weather events burn very intensely regardless of the fuel condition, assuming the fuels present are not at such a low level (e.g. just after a fuel reduction treatment) that they would limit combustion processes. It is worth noting that none of these studies looked explicitly at the actual observed wildfire rates of spread.

Evidence from studies of observed wildfire rate of spread

An analysis undertaken by Cruz and Alexander (2019) of published wildfire datasets (where n = sample size) from conifer forests (Alexander and Cruz 2006, $n = 57$), eucalypt forests (Cheney *et al.* 2012, $n = 29$) and shrublands (Anderson *et al.* 2015, $n = 32$), found the 10-m open wind speed (U_{10}, km h^{-1}) to largely explain the variation in the forward rate of fire spread when the U_{10} strength was above 30 km h^{-1} and the moisture content of fine dead fuels (*MC*) were at low levels (i.e. <7%). For these elevated fire danger conditions ($n = 24$), the authors found no statistical differences in the observed rate of fire spread across the three broad fuel types.

Cruz *et al.* (2020) extended this analysis of spread rates to two larger ($n = 350$) wildfire datasets (Kilinc *et al.* 2012; Fernandes *et al.* 2020) and obtained results consistent with the original Cruz and Alexander (2019) study. This analysis considered the application of the 10% wind speed rule of thumb to fires spreading at U_{10} levels >30 km h^{-1} with the *MC* < 7% and found no effect of fuel or broad fuel type (i.e. conifer forests, eucalypt forests or shrublands) on the distribution of residuals. This analysis, based on a larger dataset of wildfires spreading under elevated fire danger conditions ($n = 88$), found an *MC* of 5%, rather than 7%, to be a better threshold below which U_{10} largely determines rates of fire spread. It also constituted a case where the variation in fuel characteristics had a negligible effect on fire spread. The analyses by Cruz *et al.* (2022) using an extended dataset in eucalypt forests also found the rate of spread of fast-spreading wildfires not to be related to any fuel structure variables.

Interestingly enough, the >30 km h^{-1} U_{10} and <5% *MC* threshold levels equate to an FFDI of between 48 and 55 (Noble *et al.* 1980). Coincidently, this represents the onset of the 'Extreme' fire danger rating according to the McArthur (1967) FFDI, where Tolhurst and McCarthy (2016) suggested wildfires become weather-dominated (Fig. 2).

The evidence for a lack, or negligible, fuel effect on the spread rate of wildfires under elevated fire danger conditions as discussed above, coupled with the evidence of an observable fuel effect under moderate to high fire danger conditions (e.g. Fernandes *et al.* 2009; McCaw *et al.* 2012; Anderson *et al.* 2015) suggests that a fuel effect on fire spread rate varies with the burning conditions. From this, we contend that conceptually one should observe significant differences in fire spread rates between fuel complexes of distinct flammability under low- to moderate-severity burning conditions, but as the severity of burning conditions increases, the relative differences in wildfire rates of spread should diminish, up to a point where they would become indistinguishable (Fig. 3).

Implications for fire spread modelling

The reduction in the influence of fuel characteristics on fire spread rate with increasing fire danger or fire weather severity does not take place in most empirical-based fire spread models (Fig. 1) that underpin fire behaviour simulation tools and spatially explicit fire growth simulators. Such models are typically based solely on outdoor experimental fire data (e.g. Fernandes *et al.* 2009; Cheney *et al.* 2012; Anderson *et al.* 2015) or a combination of experimental fire

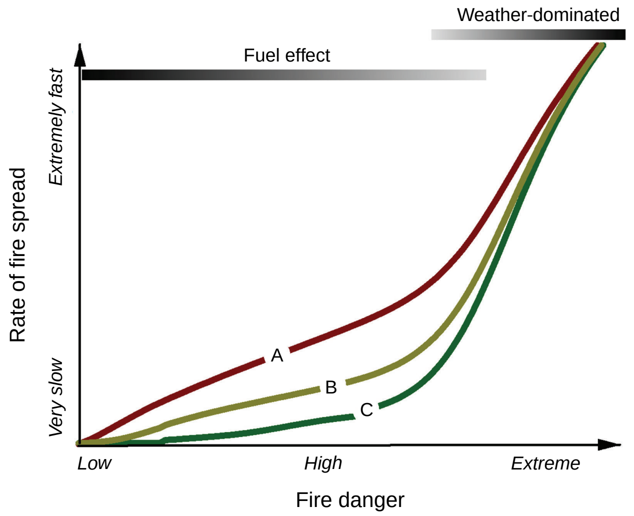

Fig. 3. Graphical representation of a conceptual effect of fuel condition on the rate of fire spread with increasing fire danger applied to three distinct forest fuel complexes. A, high flammability; B, intermediate flammability; C, low flammability. Flammability is a general term that describes the fire spread and intensity potential of a fuel complex.

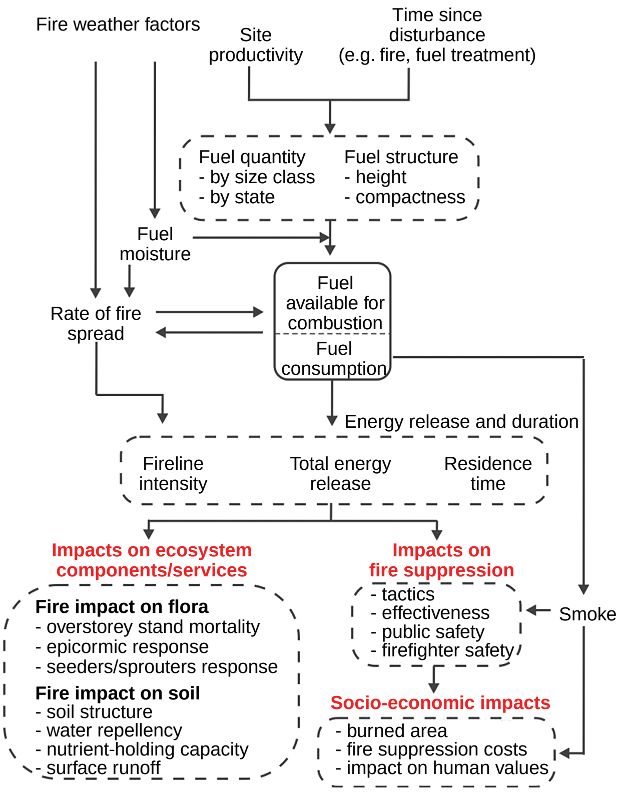

Fig. 4. Schematic diagram illustrating the primary processes involved in fire impacts in relation to fire behaviour in a forest fire environment.

and wildfire data (e.g. Rothermel 1972; FCFDG 1992; Marsden-Smedley and Catchpole 1995; Cheney *et al.* 1998). Because the fuel effect in these fire spread models arises from experimental field data in the lower portion of the fire danger spectrum, the effect is likely representative of that range and possibly not valid for higher-intensity wildfires. The careful choice of fuel inputs is necessary when operationally applying current empirical-based fire spread rate models under severe fire danger conditions. Under these conditions, the use of fuel inputs in the upper or lower extremes of their range of variability can potentially lead to noticeable over- and under-prediction errors. The use of mid-range fuel conditions, such as suggested by Cheney and Sullivan (2008) for grassfires, is possibly a good compromise with current fire spread models. Model systems that include linked surface and crown fire spread phases for conifer forests (e.g. Van Wagner 1993; Scott and Reinhardt 2001), with the crown fire phase being used for high-intensity fire propagation, will typically not show a strong effect of fuel variables on the rate of fire spread under elevated fire danger conditions.

The development of fire spread rate models that aim to be applied over a broad range of burning conditions should take into account the possibility of a non-linear fuel effect on fire propagation. For empirical-based models that rely on simple analytical equations (Sullivan 2009), this will require the use of distinct equations for different ranges in rate of fire spread (e.g. Cruz *et al.* 2022) and the inclusion of high-intensity fire spread rate data in the model development dataset (e.g. Stocks 1987; Storey *et al.* 2021; Cruz *et al.* 2022).

Implications for fuels management

The results of the current investigation need to be discussed within the context of fuels management (Omi 2015). Some might read the evidence for a weak fuel effect on fire propagation under severe burning conditions as a reason to discount or dismiss the need for fuel mitigation measures, namely the use of prescribed burning as a landscape-scale fire management tool (Leavesley *et al.* 2020). There are, however, a number of benefits of fuel mitigation to wildfire management operations, ecosystem health and sustainability that go beyond the effects of a change in fuel flammability on rate of fire spread (Fig. 4).

Fire spread rate is but one of the dimensions of fire behaviour and its impacts. Fire behaviour characteristics that quantify or relate to its heat energy output rate, and hence to its effects on people and the environment (Rego *et al.* 2021), are directly dependent on the fuel quantity available for combustion (Cheney 1981; Alexander 1982). Fireline intensity, representing the rate of heat release per unit length of the fire front, is related to flame length (Byram 1959). These descriptors determine whether a wildfire can be controlled by direct attack or not (Plucinski 2019*a*). They are also important determinants of surface-to-crown fire transition (Van Wagner 1977) and spotting characteristics (Gould *et al.* 2007), and are correlated to the fire effects on aboveground vegetation, namely overstorey crown scorch and damage (McArthur 1962; Alexander and Cruz 2012).

Fireline intensity is directly proportional to fuel consumption (Alexander and Cruz 2020), which offers a straightforward and authoritative rationale for fuel reduction practices. Prescribed burning removes surface and ground fuels, such as duff and coarse woody debris, that are often unappreciated from a fire hazard perspective but that can exacerbate certain extreme fire behaviour phenomena and the negative impacts of wildfires. These fuel components increase the duration of flaming combustion and depth of the active fire front, as well as post-frontal combustion, and thus their reduction is expected to diminish convective heating and in turn the onset of crowning (Finney 2016). Overall, a fuel load reduction across the landscape implies less energy available in the system and is relevant for minimising scaled-up fire behaviour under common, but not critical, burning conditions and in turn the likelihood of fire–atmosphere interactions.

Fireline intensity can vary by one order of magnitude around a fire's perimeter length (Catchpole *et al.* 1992), meaning that a fuel load reduction expands the extent of the fire front that can be subjected to safe and effective direct or parallel attack (Luke and McArthur 1978). As the work to contain a growing wildfire perimeter usually proceeds from the rear of the fire to its head, this constrains flank fire spread and in turn the head fire width, hence the spread rate (Cheney *et al.* 1993) and ultimately the fire size. Likewise, fuel reduction enlarges the fire weather window for effective fire control operations, namely during initial attack (McCarthy and Tolhurst 2001). But a wildfire's resistance to control depends on other factors besides fireline intensity (Page *et al.* 2013). Fuel reduction assists with fire suppression operations in multiple ways: facilitating access (or escape routes), increasing resource productivity, decreasing holding time and the amount of retardant or suppressant needed, and improving the conditions for back-burning and mop-up operations (Plucinski 2019*a*). Thus, fuel reduction is expected to increase the strategic and tactical options available for suppression, provided that the required resources are in place, and the likelihood that they will be successful (e.g. Collins *et al.* 2018; Plucinski 2019*b*).

Often the focus of fuel treatment effectiveness is on fire severity and ecosystem resilience to wildfire, rather than an expanded fire suppression capability and a reduction in the extent of wildfires (Reinhardt *et al.* 2008), which can be a poor surrogate for fire-caused damage (Moreira *et al.* 2020). By recognising the inevitability of fire and its ecological role, this point of view focuses on the consequences of fuels management in terms of heat release. Thus, a decrease in fuel quantity lessens the potential burn severity of a fire by reducing its downward and upward heat energy fluxes, which are dominated by smouldering and flaming combustion, respectively. Less fuel available to burn potentially lowers the impacts on soils, vegetation and associated ecosystem services (e.g. carbon storage), thereby modulating post-fire response, and thus minimising post-fire restoration needs (Burrows *et al.* 2021).

Wildfire severity reduction in cases of extreme burning conditions in fuel-treated areas in the dry conifer forests of the western USA is well documented (Fernandes 2015; Lydersen *et al.* 2017). There is growing evidence of the ecological resilience to extreme wildfire events that fuels management in those ecosystems affords (Stevens-Rumann *et al.* 2013; Stevens *et al.* 2014; Waltz *et al.* 2014). Prescribed burning also mitigates the severity of extreme wildfires in the temperate eucalypt forests of southern Australia, but the effect tends to be much more short-lived (Price and Bradstock 2012; Tolhurst and McCarthy 2016; Hislop *et al.* 2020). This is possibly a result of such factors as plant adaptations to fire (e.g. resprouting trees and shrubs) and their fast response to it (Clarke *et al.* 2015).

As with fire suppression, mitigation of wildfire severity as an outcome of prescribed burning implies that the decrease is high enough to reach a threshold with practical significance. For example, decreased fire severity in the forest overstorey is contingent on whether the fuels guarantee that fireline intensity will be low enough to avoid crowning or crown scorching. Still, the aforementioned Australian studies (e.g. Price and Bradstock 2012; Tolhurst and McCarthy 2016) are based on remote sensing data of eucalypt canopy conditions and as such are unable to capture the full contribution of prescribed burning to decreasing wildfire severity, and namely the effect of reduced fuel quantities on understorey development and soil characteristics. Martinson and Omi (2013) note that fire severity assessments based on components other than aboveground vegetation remain subjective and poorly quantified.

Concluding remarks

The aim of this paper was to assess and discuss our current understanding of the effect of fuels on the forward spread rate of wildfires under elevated fire danger conditions. Our analyses suggest a lack of a fuel effect on rate of fire spread in forest and shrublands under extreme fire danger conditions. Coupled with the existing evidence of a fuel effect on fire behaviour under lower fire danger conditions (e.g. McCaw *et al.* 2012; Anderson *et al.* 2015), one can expect this effect to diminish with increasing fire danger conditions, up to a point where the effect is not discernible. The observed lack of a fuel effect on rate of fire spread under extreme fire danger conditions should not be viewed as a reason to disregard the importance of forest fuels management in mitigating the negative impacts of wildfire on human and ecosystem related values.

Forest fuels management, and namely the application of prescribed burning over large areas, has been shown to increase the opportunity as well as the effectiveness and overall success of fire suppression operations under common summer-time burning conditions, which eventually leads to a reduction in the number and extent of unwanted wildfires occurring across the landscape (Burrows and McCaw 2013). Prescribed burning operations will also lead to a reduction in fire severity and impacts on ecosystem components, such as soil and above-ground vegetation characteristics, even under extreme fire danger conditions (Outcalt and Wade 2004; Prichard *et al.* 2010). This will in turn lead to more sustainable ecosystems under the pressures of the increased length and severity of fire seasons as a result of the impacts of global warming.

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Appendix 1.

The McArthur Forest Fire Danger Index (FFDI) is a relative number indicating the degree of fire danger in Australian eucalypt forests in terms of suppression difficulty and rate of fire spread potential (McArthur 1967). The FFDI combines a record of short- and long-term fuel dryness with wind velocity.

The FFDI is currently calculated using the Mk 5 version of the McArthur Forest Fire Danger Meter as parameterised by Noble *et al.* (1980):

$$\mathrm{FFDI} = 2\exp(-0.45 + 0.987)\ln(D) - 0.0345RH + 0.0338T + 0.0234U_{10} \quad \text{(A1)}$$

where D is the McArthur (1967) Drought Factor, which ranges between 1.0 and 10.0, RH is relative humidity (%), T is air temperature (°C), and U_{10} is the 10-m open wind speed (km h^{-1}).

The term D is determined on the basis of the Keetch and Byram (1968) drought index, number of days since rain and amount of precipitation in the last rain event. For further information on the FFDI and D, consult Cruz *et al.* (2015).