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RESEARCH ARTICLE

Importance of fuel treatment for limiting moderate-to-high intensity fire: findings from comparative fire modelling

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Abstract
Context Wildland fire intensity influences natural communities, soil properties, erosion, and sequestered carbon. Measuring effectiveness of fuel treatment for reducing area of higher intensity unplanned fire is argued to be more meaningful than determining effect on total unplanned area burned.
Objectives To contrast the relative importance of fuel treatment effort, ignition management effort and weather for simulated total area burned and area burned by moderate-to-high intensity fire, and to determine the level of consensus among independent models.
Methods Published and previously unreported data from simulation experiments using three landscape fire models, two incorporating weather from south-eastern Australia and one with weather from a Mediterranean location, were compared. The comparison explored variation in fuel treatment and ignition management effort across ten separate years of daily weather. Importance of these variables was measured by the Relative Sum of Squares in a Generalised Linear Model analysis of total pixels burned and pixels burned with moderate-to-high intensity fire.
Results Variation in fuel treatment effort, from 0 to 30 % of landscape treated, explained less than 7 % of variation in both total area burned and area burned by moderate-to-high intensity fire. This was markedly less than that explained by variation in ignition management effort (0–75 % of ignitions prevented or extinguished) and weather year in all models.
Conclusions Increased fuel treatment effort, within a range comparable to practical operational limits, was no more important in controlling simulated moderate-to-high intensity unplanned fire than it was for total unplanned area burned.

Keywords Fire intensity · Ensemble modelling · Hazard reduction burning · Management · Prescribed burning · Planned burning · Simulation · Wildland fire

Introduction

Insights into the effectiveness of fuel treatment, via use of planned or prescribed fire, for limiting unplanned wildland fire exist for a range of vegetation

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types around the world (Boer et al. 2015; Price et al. 2015a). In some cases there is evidence that previous, planned fire limits the area of subsequent unplanned fire to a modest extent (Boer et al. 2009; Price and Bradstock 2011). Strong leverage, or ratio of area of prevented unplanned fire to area treated (Loehle 2004), of around one has been observed for the influence of early dry season prescribed fire on late dry season unplanned fire in tropical savannas of northern Australia (Price et al. 2012). Commonly, however, there is no measureable effect of prescribed fire on subsequent area of unplanned fire (Price et al. 2015b). Even in cases where simulated prescribed burning has some effectiveness in limiting area of unplanned fire, fuel treatment has been shown to be relatively unimportant when compared with other key factors including year-to-year variation in weather and the extent of effort aimed at either preventing or rapidly extinguishing bushfire ignitions (Cary et al. 2009).

Evaluation of fuel treatment programs on the basis of total burned area does not recognise their primary role in limiting area burned at higher levels of fire intensity (Reinhardt et al. 2008). Fuel treatment can reduce the intensity of unplanned fires (Fernandes and Botelho 2003) and this has formed a basis for advocating using prescribed fire to protect adjacent property (Calkin et al. 2014; Moritz et al. 2014), mitigate greenhouse gas emissions (Russell-Smith et al. 2013; North et al. 2015) and conserve biodiversity (Russell-Smith et al. 2013), in various landscapes. Therefore, studies into the effectiveness of fuel treatment in reducing area burned by higher intensity unplanned fire is critical for evaluating efficacy of fire management programs. Similarly, Fernandes (2015) argues that effects of fuel treatment on area burned with higher fire severity (Keeley 2009) is "…a more meaningful and objective measure of prescribed fire effectiveness than the decrease in wildfire area…", although in our study we focus solely on fire intensity.

Implications of fire intensity for ecological dynamics and gaseous emissions are widespread given that intensity-dependent outcomes occur at all burned points in a fire perimeter. Fire intensity, in combination with other factors like species attributes and soil properties, will influence a range of processes and states including the resilience and demography of organisms and resultant composition of natural communities (Morrison 2002; Vivian et al. 2008; Lindenmayer et al. 2013), soil physical, chemical and biological properties (Neary et al. 1999), post-fire erosion and sequestered carbon (Bowman et al. 2013). Thus, responding to challenges about evaluating effectiveness of fuel treatment via use of planned fire on the areal extent of higher fire intensities is critical for ecosystem management.

Simulation modelling is a well-established approach for exploring management effects on unplanned fire area (Keane et al. 2004). Ensemble modelling, involving multiple, independently developed models brought together within a standardised experimental design, is a powerful means of determining the level of consensus among different models with respect to model trends, compared to single model studies (Bugmann et al. 1996; Keane et al. 2013; Cary et al. 2015). Using an ensemble of simulation models, Cary et al. (2009) demonstrated that fuel treatment effort, defined as the percentage of simulation landscapes characterised by treated fuel, was relatively unimportant for explaining variation in total area burned compared to ignition management effort and the effect of variation in weather year. However, measuring the relative importance of these factors in determining area burned by higher intensity fire is required to provide further meaningful insights (Fernandes 2015) with specific relevance to landscape managers.

We conducted a comparison using data from three landscape-scale fire models incorporating woodland and forest in the temperate climate zone to evaluate the relative importance of fuel treatment effort, ignition management effort, and weather for both (i) total area burned and (ii) area burned by moderate-to-high intensity fire. Our focus was on broad-area patterns of fuel treatment, with the aim of understanding fuel treatment effects on landscape area burned by moderate-to-high intensity fire, rather than outcomes for specific, high economic values like houses (Gibbons et al. 2012) or high ecosystem value locations including significant and vulnerable vegetation types (King et al. 2006).

Our key objective was to determine the importance of fuel treatment effort, relative to the other factors, when considering area burned by moderate-to-high intensity unplanned fire, compared to an identical analysis involving total unplanned area burned. Evaluating the importance of fuel treatment effort, via planned burning, in combination with ignition management and weather, provides direct comparison with earlier comparative fire modelling studies (Cary et al. 2006, 2009) and an opportunity to further explore interactions between fuel treatment effort and other key determinants of fire area (Krawchuk et al. 2009).

Methods

We analysed data from simulation experiments using three landscape-scale models to determine the relationship of fuel treatment effort (FTE) to area burned by moderate-to-high intensity fire, compared with total area burned, in the context of other key factors. To achieve this, we analysed data from the three models included in Cary et al. (2009) that generate fire intensity for each pixel burned as an emergent property of simulations. The models were CAFÉ (shrubby dry sclerophyll forest/woodland; southeastern Australia), FIRESCAPE (*Eucalyptus* forest; southeastern Australia) and LAMOS-HS (generic vegetation; Mediterranean) (Table 1), noting that intensity data was not generated for SEM-LAND at the time that the Cary et al. (2009) study was conducted. The formulation of the models, application landscapes and weather data are described in Cary et al. (2009). Simulated data on total unplanned area burned was reported in Cary et al. (2009) whereas the data on area of moderate-to-high intensity unplanned fire, which was generated in the same model runs as the data on total unplanned area burned in the earlier study, has not previously been reported.

Each of the models (Table 1) explicitly simulates fire spread across landscapes composed of square pixels. Fire spread in FIRESCAPE and LAMOS-HS is determined by calculating rates of spread whereas CAFÉ invokes probabilistic fire spread. Fire ignitions in the Cary et al. (2009) study were incorporated in each model according to specifications of the original model implementations (Bradstock et al. 1998; Cary and Banks 2000; Lavorel et al. 2000). Simulated fires reduced fuel in burned pixels according to original model specifications, but since simulation length was limited to a single year, fuel accumulation or growth dynamics were not modelled. Given the strong consistency among a larger set of models regarding relative importance of fuel treatment effort for total area burned (Cary et al. 2009), we are confident that our comparison involving data from three models yields meaningful results.

A lower threshold for moderate-to-high intensity fire was specified for each model (Table 1). In the case of FIRESCAPE and LAMOS-HS, this threshold was 500 kW m^{-1} whereas in CAFÉ an index based on time since fire and weather, consistent with evidence from fire severity analyses in shrubby dry sclerophyll forests (e.g. Bradstock et al. 2010), was derived to approximate the intensity threshold used in the other models. This level of fire intensity is consistent with the suggested upper limit for low intensity prescribed burning (Luke and McArthur 1978) and the lower limit for complete crown scorch in most forests (Cheney 1981), but is above the 350 kW m^{-1} upper limit suggested for direct attack of fires with hand tools (Hirsch and Martell 1996).

Cary et al. (2009) conducted their simulations on flat landscapes represented by a 1000 $\times$ 1000 array of

Table 1 Landscape-scale fire models, location for weather, vegetation type, fuel load levels for treated and untreated fuel (Cary et al. 2009), and lower threshold for moderate-to-high intensity fire

Model	Weather location (station name)	Vegetation	Fuel load (kg m^{-2})		Intensity threshold	Model reference
			Treated	Untreated		
CAFÉ	SE Australia (Ginnindera, ACT[a])	Shrubby dry sclerophyll forest/woodland	<0.8	>0.8	Upper bound of low index	Bradstock et al. (1998)
FIRESCAPE	SE Australia (Ginnindera, ACT[a])	*Eucalyptus* forest	0.4	1.4	500 kW m^{-1}	Cary and Banks (2000)
LAMOS-HS	Mediterranean (Venaco, Corsica[b])	Generic	0.5	1.6	500 kW m^{-1}	Lavorel et al. (2000)

[a] Statistically simulated weather from observations (Cary et al. 2006)

[b] Observed weather (Cary et al. 2006)

square pixels measuring 50 m per side, giving a total area of 250,000 ha. Fuel treatment effort (FTE) had four levels and varied from 0 to 30 % of simulation landscapes treated, ignition management effort (IME) had four levels and varied from 0 to 75 % of fires prevented or extinguished at the point of ignition, and weather year (WY) varied among 10 years of daily weather selected to represent variation in annual average maximum temperature and precipitation for simulation locations (Cary et al. 2009) (Table 2). Current fuel treatment rates in forested landscapes worldwide are typically much less than 5 % per annum (Bradstock et al. 2012; Price et al. 2015a), or approximately at this level (Boer et al. 2009), generally resulting in total treated area being below the highest simulated level of 30 % treated in total at any particular time. On the other hand, fire containment on initial attack can be higher than the highest simulated level of IME of 75 % (Arienti et al. 2006), which follows Cary et al. (2009) for direct comparison. Cary et al. (2009) conducted five replicate simulations for each unique combination of FTE, IME and WY (Table 2) using five replicate fuel maps generated by randomly assigning fuel load or age consistent with treated fuel (Table 1) in square, 625 ha patches across a landscape that otherwise consisted of untreated fuel (Fig. 1). Given four levels of FTE, four levels of IME, 10 distinct weather years (WY) and five fuel-map replicates, each model was used to generate 800, single-year simulations.

We analysed data on the total number of pixels burned and the number of pixels burned by moderate-to-high intensity fire (Table 1) in this design separately for each model. Consistent with Cary et al. (2009), for each fire model we measured the importance of FTE, IME and WY for determining total area burned and area burned by higher fire intensities by evaluating the variance in these measures that was explained by these factors and all of their interactions across the 800 single-year simulations in each case. Variance in area burned that was explained by FTE, IME and WY, and their interactions, was determined for each fire model as the Relative Sum of Squares (R^2) attributed to factors and their interactions in a

Table 2 Factors and their levels invoked in simulation experiments (Cary et al. 2009) with three landscape-scale fire models. Published and previously unreported data from the experiment was analysed to determine the relative importance of factors and their interactions in determining variance in total area burned and area of moderate-to-high intensity fire

Factor	Label	Levels	Description of levels
Fuel treatment effort	FTE	Four	0, 10, 20, 30 % of landscape treated
Ignition management effort	IME	Four	0, 25, 50, 75 % of ignitions prevented
Weather year	WY	Ten	10 distinct years of observed or simulated daily weather reflecting observed variability in mean annual temperature and precipitation in weather record for each location

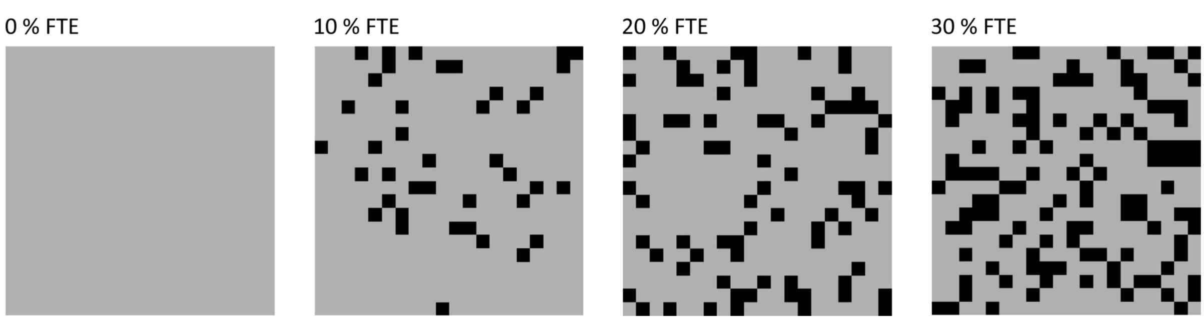

Fig. 1 Fuel map replicate one (of five) for each level of fuel treatment effort (FTE), ranging from 0 to 30 % of landscape treated, used in simulations of total area burned (Cary et al. 2009) and area burned by moderate-to-high intensity unplanned fire. Black squares represent 625 ha patches of treated fuel (Table 1) across a 250,000 ha landscape that otherwise consists of untreated fuel (Table 1) indicated in grey. Each of the five fuel map replicates (not shown) within each level of FTE was generated by Cary et al. (2009) by randomly allocating fuel treatment to meet the specified FTE level

Generalised Linear Model analysis of: (i) ln-transformed total pixels burned; and (ii) ln-transformed moderate-to-high intensity pixels burned. We focus on the importance of FTE, IME, WY and their interactions, rather than statistical significance, given that it is more meaningful to use statistical frameworks like GLMs to partition variance in simulated data among treatments than for significance testing (White et al. 2014).

We examined trends in ln-transformed area burned simultaneously against FTE, IME, and WY, for total pixels burned and moderate-to-high intensity pixels burned. In each case, independent rankings were made from lowest FTE effort (0 % treated), lowest IME (zero ignitions prevented) and highest area-burned WY, to highest FTE (30 % treated), highest IME (75 % ignitions prevented) and lowest area-burned WY, respectively.

Results

Moderate-to-high intensity fire accounted for 41 and 42 % of total area burned for FIRESCAPE and LAMOS-HS respectively, with 98 % of total area burned in CAFÉ experiencing moderate-to-high intensity fire, on average. The high proportion observed for CAFÉ reflects flammability characteristics of woodlands with tall, shrubby mid-storeys that typically burn with relatively high intensity under typical wildfire conditions (Bradstock et al. 2010).

Relative importance of FTE, IME and WY, and their interactions, were similar for area of unplanned moderate-to-high intensity fire to what was the case for total unplanned area burned for each model (Fig. 2). In each model, IME and WY were markedly more important than FTE in explaining area burned by moderate-to-high intensity unplanned fire, consistent with the result for total area burned (Fig. 2; Cary et al. 2009).

FTE was marginally less important in explaining area burned by moderate-to-high intensity fire when its relative importance as a main effect alone was considered in each model (Fig. 2). The cumulative importance of FTE, when considering the total variance explained by the main effect of FTE, and all of its interactions, was unchanged within individual models when comparing the outcomes for total area burned to area of moderate-to-high intensity fire (Fig. 2). Therefore, there is no evidence for a higher relative importance of FTE in controlling simulated area of moderate-to-high intensity fire than is the case for simulated total area burned.

Despite being the least important variable, increasing FTE reduced total unplanned area burned and unplanned area burned by moderate-to-high intensity fire in all models. On average, across all models, the highest FTE of 30 % of landscape treated resulted in a 40 % reduction in total unplanned area burned, being a reduction equivalent to 8.0 % of the area treated. Similarly, the highest level of FTE resulted in a 43 % reduction in area burned by unplanned moderate-to-high intensity fire. However, in all cases the magnitude of the effect of FTE in reducing area burned in total, or area burned with moderate-to-high fire intensity, was less than that resulting from IME and WY variations (Fig. 3).

Discussion

We found no evidence, among data from three independently developed models, that FTE was more important in influencing area of moderate-to-high intensity fire than it was for total area burned. Increasing FTE resulted in lower area of moderate-to-high intensity fire, however, the trend was similar to that for total area burned. In all cases, the overall effect of varying fuel treatment effort on area burned was small compared to the effect resulting from variation in IME and WY. In essence, the similarity of trends for total area burned and area burned by moderate-to-high intensity fire suggest that earlier studies, focused solely on the total area burned data (Cary et al. 2009), provide general and meaningful insights into the importance of fuel treatment for spreading fires, at landscape scales.

These findings were generated from single-year simulation replicates without invoking dynamic succession or fuel development processes. This allowed the relative importance of IME and variation in WY to be directly compared in a design that also tightly controlled the area of treated fuel, a key study objective. Keane et al. (2013) explored the importance of fire, vegetation succession, climate and weather on landscape dynamics across a suite of models using simulation lengths equivalent to the length of the vegetation 'succession cycle' inherent to each

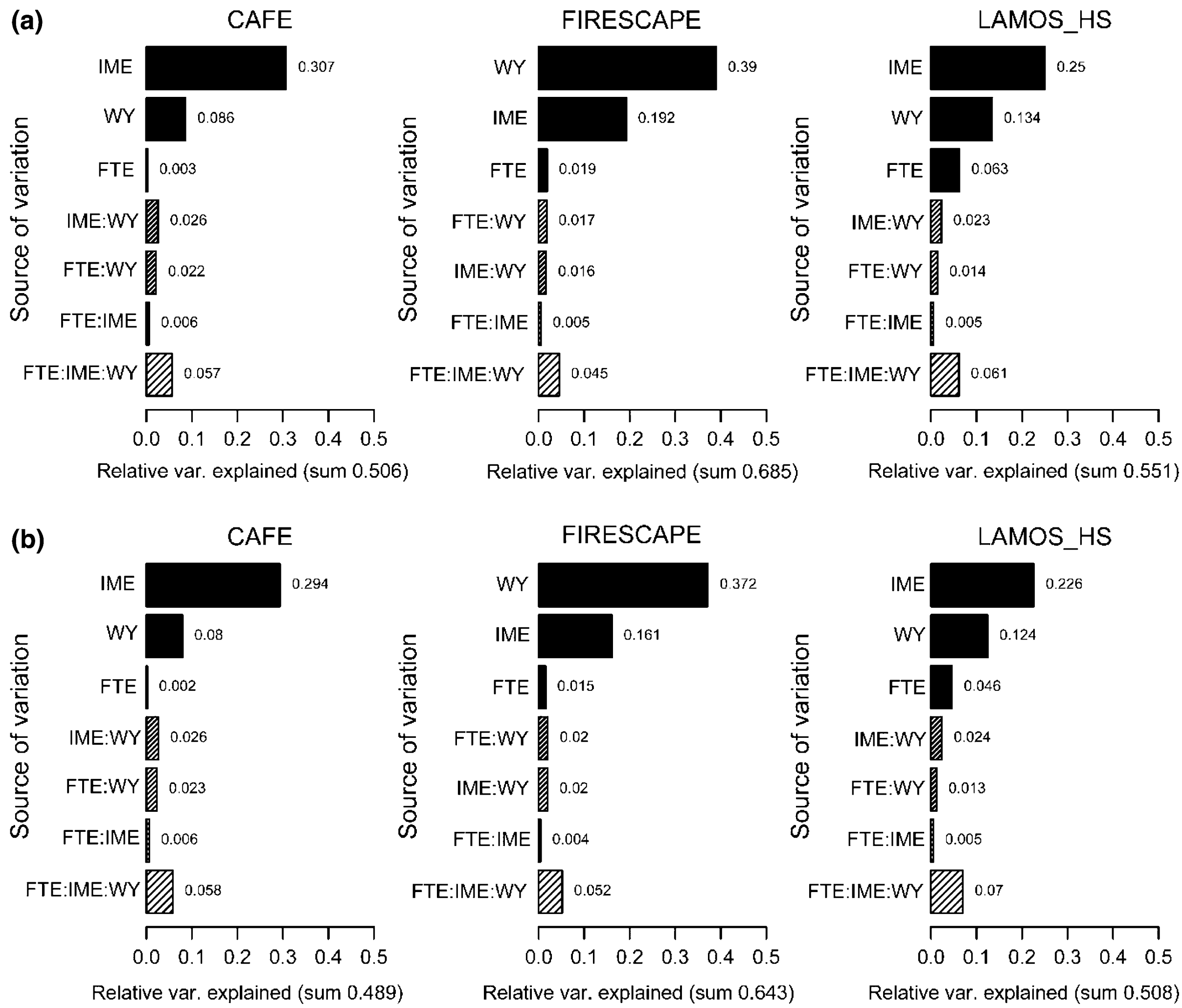

Fig. 2 Variance in ln-transformed, simulated area burned explained in three landscape-scale fire models by factors and their interactions in a Generalised Linear Model analysis of (**a**) total unplanned area burned and (**b**) unplanned area burned with moderate-to-high fire intensity. Factors are fuel treatment effort (FTE), ignition management effort (IME) and weather year (WY)

landscape modelled. They simulated successive, varying weather years, whereas in our data, variation in weather year was a key component of the original design (Cary et al. 2009). In our analysis, variation in area burned arising from year-to-year variation in weather was large compared to that arising from FTE for each model, but the importance of weather did not change much when analysing total area burned or area of moderate-to-high intensity fire.

We analysed data from a simulation design (Cary et al. 2009), which was orthogonal in relation to the key factors influencing area burned. This places our exploration of the degree to which management and weather influence moderate-to-high intensity fire directly within the context of the earlier study, thus allowing direct comparisons to be drawn with the results reported by Cary et al. (2009). With respect to the models, differences among the SE Australian model formulations and representations of fuel resulted in reversed ranking of IME and WY as the most important factor determining area burned, but FTE was ranked the least important influence by a considerable margin for each model. A key characteristic affecting simulated fire behaviour in CAFÉ,

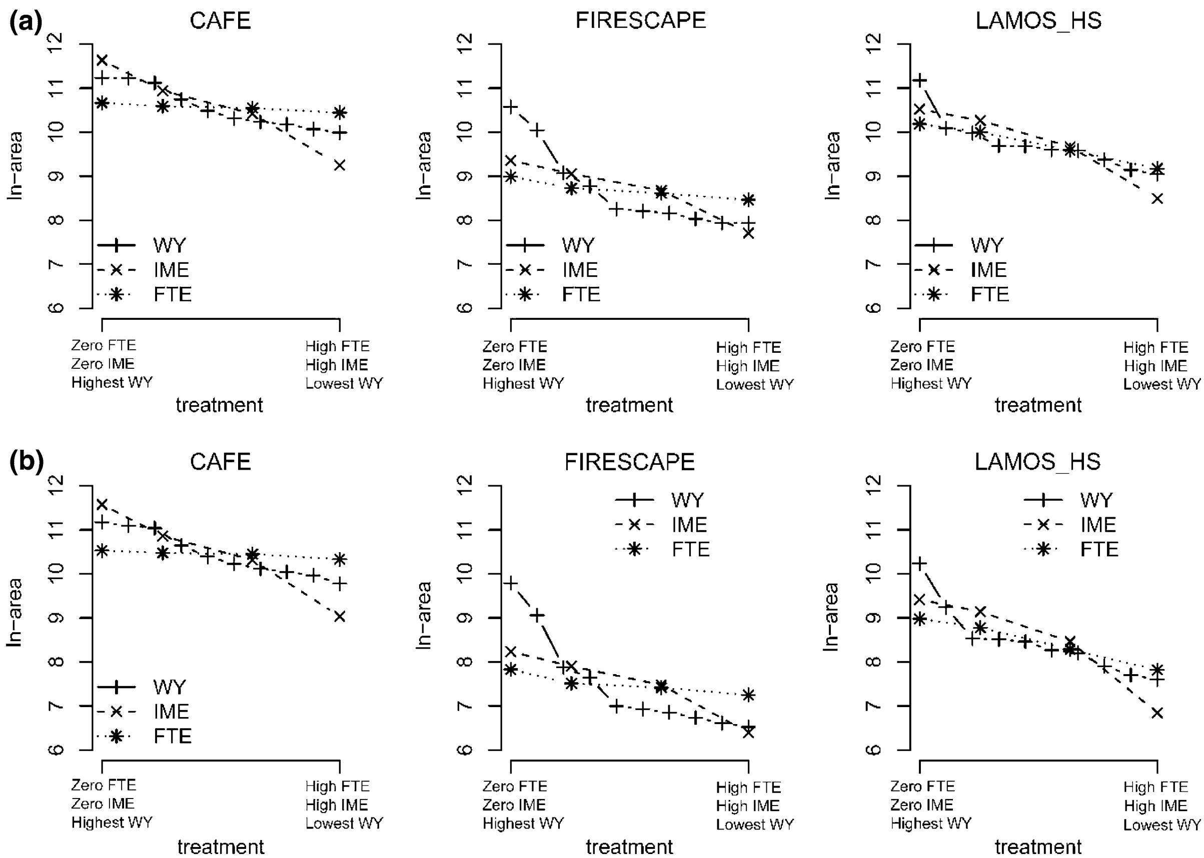

Fig. 3 Trends in ln-transformed, simulated area burned according to fuel treatment effort (FTE), ignition management effort (IME) and weather year (WY) in three landscape-scale fire models for (**a**) total unplanned area burned and (**b**) unplanned area burned with moderate-to-high fire intensity. In each case, factors are independently ranked from lowest FTE (0 % treated), lowest IME (zero ignitions prevented) and highest area-burned WY, to highest FTE (30 % treated), highest IME (75 % of ignitions prevented) and lowest area-burned WY

which results in almost all unplanned fire burning above the lower threshold for moderate-to-high intensity fire, means that the datasets for total area burned and area burned by higher fire intensity are essentially the same. This means there is little scope for differences in relative importance of FTE in limiting total area burned and area burned by moderate-to-high intensity fire, whereas for the other two models area burned with higher fire intensity was less than half of the total area burned.

Decisions on intensity thresholds dividing low and moderate-to-high intensity fire will always be arbitrary, to some extent, and it is reasonable to interpret these results in the context of ecological dynamics and operational firefighting. In this study, the lower limit for moderate-to-high intensity fire is 500 kW m^{-1} (FIRESCAPE, LAMOS-HS), or the upper bound of a 'Low' index based on time since fire and weather (CAFÉ), which is above the upper limit for direct attack of fires with hand tools (Hirsch and Martell 1996), represents an intensity where mechanised suppression begins to fail, and is the lower intensity threshold for complete crown scorch (Cheney 1981).

Upper fire intensity limits for fire suppression by ground-based forces might be in the order of 3000–4000 kW m^{-1} (Hirsch and Martell 1996; Fernandes and Botelho 2003). Loane and Gould (1986) indicate that the upper fire intensity limit for a "machine crew" (composed of a D6 bulldozer, a 4000 l four-wheel-drive water tanker, three four-wheel-drive utilities with small water tanks, two personnel vehicles and nine personnel) in Australian eucalypt forest is about 2000 kW m^{-1}. However, their analysis suggests that maximum and constant rate of fire construction occurs up to 500 kW m^{-1} but thereafter falls sharply to zero at 2000 kW m^{-1}. Therefore, in their case, a 500 kW m^{-1} threshold is the level that mechanised suppression begins to fail, as opposed to the higher intensity levels where suppression fails completely. Hirsch et al. (2004) report that according to estimates by fire crew leaders "fireline production rates" for initial-attack crews with pumps and hoses in Ontario would be lower for a 1500 kW m^{-1} fire intensity compared to rates when fire intensity is 500 kW m^{-1}. This further indicates that fire suppression begins to fail at intensity levels somewhat below the upper intensity limits which are usually quoted and which are presumably associated with total suppression failure.

Considering ecological effects, canopy scorch heights associated with a 500 kW m^{-1} fire are around 8–10 m for Australian eucalypt forest, which is close to the median scorch height expected for this fire intensity in fire-prone forests around the world (Alexander and Cruz 2012). The degree of crown scorch is critical for determining mortality or persistence of plants in fires, with non-sprouter species defined as those where "plants in the reproductive phase just subject to 100 % leaf scorch by fire die" (Gill 1981).

Therefore, it is reasonable to conclude that, at the landscape level, increasing fuel management effort did not further reduce, compared with the reduction in total area burned, the area of moderate-to-high intensity fire that (i) is beyond control by remote fire crews equipped with hand tools, or is beyond a fire intensity that can be optimally controlled by mechanised fire attack crews and (ii) can cause complete crown scorch in most low forests, being an outcome that is critical for determining the persistence or mortality of non-sprouting trees in forest fires.

These models do not explicitly model extended fire attack, an activity that is receiving greater attention recently from a methodological perspective but is difficult to simulate mechanistically (Duff and Tolhurst 2015). While IME will include the effect of rapid initial attack of fires at the point of ignition, there is scope to further incorporate extended suppression capability (e.g. indirect attack) into model comparison experiments. Some fires will self-extinguish as a result of lower intensity in the relatively large (625 ha) areas of fuel treatment, and thus represent a further, indirect effect mimicking some aspects of fire suppression. Nevertheless, in the Sydney region of south-eastern Australia, where fire suppression resources are relatively plentiful, the chance that an unplanned fire will be stopped by a low fuel-age patch is less than 10 % in the situation where there is no road (Price and Bradstock 2010). Therefore, incorporating data from models with extended fire attack may have had potential to enhance the effectiveness of FTE in limiting moderate-to-high intensity fire at the landscape scale, but probably only to a marginal extent, and possibly to no greater extent than for total area burned.

Our insights on effects of broad-area fuel management are most relevant in an ecological context, given the effects of higher intensity fire on natural values (Moritz et al. 2014). Constructed assets, on the other hand, may be better protected with highly strategic fuel management approaches (Bradstock et al. 2012; Penman et al. 2014). Irrespective of the level of fuel management effort within feasible constraints, considerable area of moderate-to-high intensity fire will remain an integral component of the ecological systems that were modelled. Our findings suggest that the extent of moderate-to-high intensity fire cannot be more substantially limited by fuel reduction programs than is the case for total area burned. Perhaps of greater significance are the shorter intervals between fires, and the reduced variation in fire interval, that would result from the additional prescribed burning intended to reduce unplanned fire. For example, shorter intervals have been demonstrated to reduce species richness in some systems (Morrison et al. 1995)—due to a range of mechanisms (Enright et al. 2015)—but not in others (Wittkuhn et al. 2011), whereas reduced variation in fire interval may also reduce plant species numbers in some vegetation assemblages (Cary and Morrison 1995).

The greater sensitivity of area burned to variation in ignition management effort and weather variability suggest that human demographic and climate variability aspects of global change (Flannigan et al. 2009; Bradstock 2010; Cary et al. 2012) will influence this aspect of future fire regimes more than changes in efforts directed at broad-area fuel treatment. Given these insights, a key component for optimising future outcomes could be achieved by avoiding particularly adverse combinations of residential development within bushland environments (Price and Bradstock 2014; Syphard and Keeley 2015). This would help to reduce bushfire ignitions and separate constructed assets from wildland areas that are vulnerable to some extent of higher intensity fire, irrespective of the level of fuel treatment applied, within operational limits.

Our analysis found that increased fuel treatment effort, within a range comparable to practical operational limits, was no more important in controlling the area of moderate-to-high intensity unplanned fire, which has been suggested as a more meaningful and objective measure of the effectiveness of prescribed burning programs (Fernandes 2015), than it was for total area burned. While recognising there is scope for considerable further insights from empirical and analytical studies, the multi-model approach underpinning our findings contributes some consensus on insights about the effectiveness of management influences aimed at treatment of ignitions and fuel (Cary et al. 2015) in fire-prone landscapes.

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