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Keywords

change, fuel, climate, fire, forest, behaviour, eucalypt

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Climate change, fuel, and fire behaviour in a eucalypt forest

Running title: Climate change, fuel, and fire behaviour

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Abstract

A suite of models were used to examine the links between climate, fuels and fire behaviour in dry eucalyptus forests in south-eastern Australia. Predictions from a downscaled climate model were used to drive models of fuel amount, the moisture content of fuels and two models of forest fire behaviour at a location in western Sydney in New South Wales, Australia.

We found that a warming and drying climate produced lower fine fuel amounts, but greater availability of this fuel to burn due to lower moisture contents. Changing fuel load had only a small effect on fuel moisture. A warmer, drier climate increased rate of spread, an important measure of fire behaviour. Reduced fuel loads ameliorated climate induced changes in fire behaviour for one model. Sensitivity analysis of the other fire model showed that changes in fuel amount induced changes in fire behaviour of a similar magnitude to that caused directly by sensitivity to climate. Projection of changes in fire risk requires modelling of changes in vegetation as well as changes in climate. Better understanding of climate change effects on vegetation structure is required.

1 Introduction

Fire is an important process in forested landscapes and, where fires encounter human habitation, presents a serious threat to life and property (Luke and McArthur, 1978). Fire behaviour is governed by weather, topography and fuel. Of these, weather and fuels are both susceptible to the effects of climate change (Bradstock, 2010). The potential for climate change to impact the occurrence of landscape fire has long been recognised (Beer et al., 1988; Flannigan et al., 2009b). The majority of studies investigating climate change and fire have used fire danger indices to predict changes in fire potential, as recently reviewed by Flannigan et al. (2009b, 2009a). These indices combine temperature, relative humidity, wind speed and a measure of long-term moisture deficit (through soil dryness or grass curing) to provide an assessment of the potential for fires to start and spread (McArthur, 1967; van Wagner, 1987; Burgan, 1988). Interactions between climate, fire and vegetation distribution have also been investigated using dynamic vegetation models in the USA (Malanson and Westman, 1991; Bachelet et al., 2003; Lenihan et al., 2008), Europe (Mouillot et al., 2002; Schumacher and Bugmann, 2006) and tropical savannahs (Hoffmann et al., 2002).

Studies to date in Australian forests have focused on changes in fire weather through fire danger indices, using the forest fire danger index (FFDI, McArthur 1967) and the grassland fire danger index (GFDI, McArthur 1966). Early studies (Beer and Williams, 1995; Cary, 2001; Williams et al., 2001) used climate model output to investigate a number of measures of fire danger, including distributions of daily values, monthly mean value and seasonal sum. These studies found fire danger to increase in the future in south-eastern Australia, largely as a result of increased temperature and reduced relative humidity.

More recent studies have used a variety of statistical methods to better understand the nature and uncertainty of predicted changes in fire danger. Hennessy et al. (2005) and Lucas et al. (2007) used simulations from a regional climate model nested within two global climate

models (GCMs) with high and moderate emissions scenarios to examine changes in FFDI for Australia capital cities and some regional locations. Rather than use model output directly, they modified observations from weather stations by linking changes in weather variable deciles to changes in global temperature using linear regression. They reported increases in fire danger, measured as monthly means and number of days above given thresholds, for most of south-eastern Australia, except southern Tasmania. Pitman et al. (2007) used a mesoscale climate model driven at the boundaries by a GCM to investigate changes in grass fire danger index in January in New South Wales for 2050 and 2100 under high and moderate climate change scenarios. To investigate changes in extreme values results were presented as probability density functions, in contrast to the means or sums used in other studies. Fire danger was found to increase under both scenarios in 2050 and 2100. Clarke et al. (2011) used four climate models to examine regional changes in four climatic zones in Australia. Results were presented as mean monthly fire danger, number of days per month on which potentially life threatening fire could occur and length of the fire season. In a development from earlier work, bootstrapping was used to establish uncertainty bounds for fire danger in present and future conditions. Small changes in fire danger in south-eastern Australia were observed in 2050, followed by large increases in 2100, with considerable variation between models. A different approach to describing fire danger was taken by Hasson et al. (2009), who looked at changes in the occurrence of synoptic weather patterns in southern Australia. They used the 850 hPa temperature gradient across south-eastern Australia to diagnose the passage of strong cold fronts, a pattern historically associated with destructive bushfires, in reanalysis data and climate model predictions. Under moderate and high climate change scenarios their analysis found an increased frequency of these synoptic systems.

All these studies predict increased fire danger due to climate change in south-eastern Australia, with some variation in the timing and magnitude of the changes, including

temporary decreases in some cases. While these studies have developed an increasingly sophisticated understanding of fire weather and climate change, the prediction of fire danger does not necessarily provide insight into the expected behaviour of fires burning under these conditions. This is because focus on fire weather does not allow for the effects of climate on the other major determinant of fire behaviour, namely fuels. Fuel amount and structure are an important determinant of fire behaviour. In addition to gross differences due to community structure (eg. grassland vs forest), differences in species composition, fuel age, amount and arrangement are also important (Gould et al., 2007). Climate change is expected to cause changes in both the extent of different communities and the composition of vegetation within communities (Bradstock, 2010). Sullivan (2010) first attempted to address this deficiency through application of the modified weather data of Lucas et al. (2007) to the behaviour of grassfires using the grassland fire spread model of Cheney et al. (1998). He found that maximum rate of forward spread of fires in natural pastures in southern Australia is predicted to increase by 10% by 2020 and 32% by 2050 and that the greatest increase will occur during the spring/early fire season period. However, this work did not take into account changes in grassland curing which may be affected by climate change (Gill et al., 2010).

In this study we extend previous work by examining the effect of changing fuels as well as climate on fire behaviour in forests. Also, we address limitations in the FFDI by using a physical fuel moisture model and by including a more sophisticated fire behaviour model (Gould et al., 2007). We use these models to examine two questions. First, what is the effect of changing climate on fuel amount, fuel moisture, or fire behaviour? Second, are the effects of climate change on fuel amount, and thus fuel moisture and fire behaviour, significant compared to its effects on fire weather? If these effects are significant, this implies that it is necessary to take changes in fuel into account when examining the effects of climate change on fire risk, in addition to the weather-based indices used in previous studies. Results are

presented for dry sclerophyll forest in the vicinity of western Sydney. This region is broadly representative of regions in the fire prone south east of Australia. Down-scaled climate change model outputs are available for this region, as are data on fuel accumulation in dry sclerophyll forests along relevant environmental gradients.

2 Methods

The effects of climate change on fire behaviour were examined using a suite of five models: a climate model, CSIRO's cubic-conformal atmospheric model (CCAM, McGregor and Dix 2008); a simple fuel accumulation model based on the Olson (1963) approach; an energy and water balance model of the moisture content of fuels on the forest floor (Matthews 2006); and two fire behaviour models, the Forest Fire Danger Meter model of McArthur (1967) and the Dry Eucalypt Forest Fire Model (Gould et al., 2007). Dependencies between the models is illustrated in Fig. 1. These models were applied to a location representative of forested areas in the vicinity of Sydney, Australia (34S, 151E).

2.1 Climate change scenario

The model run used in this study was made under the Special Report on Emissions Scenarios (SRES) A2 scenario (Nakicenovic et al., 2000). A2 is one of the higher emissions SRES scenarios, driving a large range of mean temperatures. The A2 scenario was selected to provide a wide range of physically consistent weather conditions. The climate data set used in this study was created using the CSIRO Conformal Cubic Atmospheric Model (CCAM). As part of the South-east Australia Climate Initiative (McGregor and Nguyen, 2009) CCAM was first run for the period 1961 to 2100 for the entire globe at 200 km resolution using bias-corrected sea surface temperatures from the CSIRO Mk 3.5 climate model. The CCAM output was then downscaled to 20 km resolution over south-east Australia (Thatcher and McGregor, 2009). Predictions for the 4 grid cells covering western Sydney were averaged to

produce time series for this study. Comparison of simulations with climatology of rainfall and temperature for the period 1961–1990 found good agreement (McGregor and Nguyen, 2009; Watterson et al., 2009). For the study site biases were +0.2 °C in maximum temperature, +2.5 °C in minimum temperature and +78.5 mm (+10.8%) for annual rainfall.

Although climate models predict many meteorological quantities, most future scenarios have included temperature and rainfall as the most important and often only variables. More recent studies have also included solar radiation, wind speed and specific humidity, although the prediction ranges have in some cases been larger than the mean predicted changes (CSIRO and Australian Bureau of Meteorology, 2007). For this initial study we considered variables which are known to affect fuel moisture (Matthews, 2006) and fire behaviour (Gould et al., 2007): air temperature, rainfall, wind speed, humidity and solar radiation.

Fig. 2 shows modelled mean annual air temperature, rainfall, relative humidity, wind speed and solar radiation. As well as trends, there was significant annual and decadal variability in rainfall and relative humidity. There were significant trends of +4.2 °C century⁻¹ in air temperature, -90 mm century⁻¹ in annual rainfall and -4.5% century⁻¹ in relative humidity. Trends in wind speed and solar radiation were not significantly different from zero. The direction and magnitude of these trends were within the envelope of predictions for the CMIP3 models for eastern Australia (CSIRO and Australian Bureau of Meteorology, 2007). Annual averages of these variables were correlated (Fig. 3). Observations in south-eastern Australia show trends of +1 to +2 °C century⁻¹ in temperature (Nicholls 2006), -200 to -500 mm century⁻¹ in annual rainfall (Nicholls 2006) and 1.8±0.6 °C in dew point (Lucas 2010). The climate model trends in temperature and relative humidity were equivalent to a +3.1 °C century⁻¹ trend in dew point. Analyses for trends in solar radiation and wind speed are not available so it is not known whether all the correlations shown in Fig. 3 are present in reality.

2.2 Fuel Accumulation Model

A full understanding of the effects of climate change on fuels and fire behaviour would require understanding of changes in ecological communities, the response of species within communities and the processes that produce live and dead fuels (Specht and Specht, 1999). For fuels in south-eastern forests, key processes include litter (dead plant materials deposited on the forest floor including leaves, bark and twigs) production and decomposition (Raison et al., 1986) and growth of understorey herb and shrub species (Gould et al., 2011). In this study we used findings from field studies of litter dynamics to parameterise a litter accumulation model (Olson, 1963). The predictions of the litter model are used with the Forest Fire Danger Meter fire behaviour model (McArthur, 1967) which has litter load as its only fuel variable. Litter load in dry eucalypt forests varies during the year as material is deposited, particularly in early summer (e.g. Crockford and Richardson 1998), then decays throughout the year. To include some of this annual variation we used Olson's model to predict litter load, w (t ha^{-1}) at monthly resolution. We constructed the model following Olson's approach for accumulation with discrete annual litter fall:

- The model is initialised with equilibrium litter load, w_e (t ha^{-1}) based on climate conditions in the first year of the model data.
- Decay is proportional to the amount of litter present, i.e.

$$dw/dt = -kw \quad (1)$$

where k is a decay rate (y^{-1}).

- Each year on December 1st, an amount of litter, w_f (t ha^{-1}) is added.
- w_e , w_f and k depend on climate

This model is applied to a long unburned litter layer and thus the predictions reflect the effect of climate change on litter load absent of fire.

Fuel parameters were derived from seven published field studies in dry eucalypt forest sites in New South Wales and south-east Queensland below 400 m above sea level (Rogers and Westman, 1977; Birk, 1979; Fox et al., 1979; Lamb, 1985; Conroy, 1993; Hart, 1995; Bridges, 2005). These studies measured and classified litter in a variety of ways but for the present work measurements were adjusted to identify values for the Olson curve parameters for litter particles less than 6 mm in diameter (i.e. fine fuel). Fuels less than 6 mm diameter were used in the model as these are the fuels that determine rate of spread and intensity of moving fires (McArthur, 1967; Gould et al. 2007).

Stepwise linear regression was used to construct a model of annual litter fall and equilibrium load as a function of site annual rainfall and air temperature. Only rainfall was selected as an independent variable ($R^2 = 0.44$, $N = 7$)

$$w_f = -0.43 + 0.00385r \quad (2)$$

The dependence of decomposition rate on temperature and rainfall was modelled using the multiplicative approach of Moorhead and Reynolds (1991):

$$k = a(1 - e^{-bt})(1 - e^{-cr}) \quad (3)$$

Where r is annual rainfall (mm), T is mean temperature ($^{\circ}\text{C}$), $a = 1.16$, $b = 0.05$ and $c = 0.0004$ are parameters. Values for b and c were taken from Paul and Polglase (2004) and a was fit to the observations.

To initialise the model w_e was estimated as w_f / k (Olson 1963) using climate values from the first year of the model run. Equation 1 was integrated at 1 month intervals using annual rainfall values from CCAM to predict litter fuel load for the duration of the model run.

2.3 Fuel Moisture Model

Fine fuel moisture is determined by short and long term weather patterns (Nelson, 2000; Wittich, 2005; Matthews, 2006) and may depend on fuel load (Putuhena and Cordery, 1996; Sato et al., 2004; Matthews et al., 2007). Fuel moisture predictions were made using the Matthews (2006) model. The model represents fluxes of energy and water in a litter bed composed of three materials: litter, air and free liquid water on the surfaces of the litter. The litter bed is bounded above by the atmosphere and below by the soil. The heat and water budget of each of the three materials is calculated at five equally spaced nodes within the litter layer using equations for six quantities: litter temperature, the temperature of free liquid water on the litter surfaces, air temperature, litter moisture content (kg water per kg of dry litter), amount of liquid water on litter surfaces (kg of water per m of litter bed) and specific humidity.

The fuel moisture model was parameterised to represent dry eucalypt forest on flat ground with a varying fuel load, taken from the fuel accumulation model. The fuel load was updated annually in December. In order avoid violating conservation of mass in the water budget equations the fuel load was updated during the first time step for which no free water was present on the litter surface. The model was driven using CCAM output as boundary conditions. The CCAM variables were transformed from standard meteorological measurements to within-forest values using the methods described in Matthews et al. (2007). Additionally, for this project a Penman-Monteith scheme was used to simulate canopy interception of rainfall (Paul et al., 2003). The model equations were solved on a 1 h time step from January 1, 1961 to December 31, 2099. To examine the effect of large changes in fuel load on fuel moisture, the results of three further fuel moisture model runs were performed with constant fuel loads of 6, 12 and 18 t ha⁻¹, where 12 t ha⁻¹ was the mean fuel load from the Olson model described above.

To facilitate interpretation of model outputs, the model predictions of litter moisture content and amount of surface water were combined:

$$M_s = 100 \left(m_i + \frac{l_i}{\rho_b} \right) \quad (4)$$

$$M_p = 100 \left(\frac{1}{N} \sum_{i=1}^N \left(m_i + \frac{l_i}{\rho_b} \right) \right) \quad (5)$$

Where M_s is the total moisture content (%) of the top model layer (surface moisture content), M_p is the moisture content (%) of the entire litter layer (profile moisture content), m_i and l_i are the water content of the litter (kg kg^{-1}) and the free water content (kg m^{-3}) of the i^{th} model layer, ρ_b is the litter layer bulk density (kg m^{-3}) and $N=5$.

2.4 Fire behaviour models

Fire behaviour models take a number of forms, from purely physical in which all processes are explicitly modelled, through purely empirical, in which no processes are incorporated but their interactions parameterised through statistical regressions of input variables (Sullivan, 2009a). In all parts of the world, fire behaviour models used for operational purposes (for the purpose of fighting, controlling or warning of wildfires) are of empirical or quasi-empirical construction (Sullivan, 2009b). Here, two models were used. The Forest Fire Danger Meter model (McArthur, 1967), a model in widespread use in eastern Australian forests and the newer Dry Eucalypt Forest Fire Model (Gould et al., 2007) that is proposed to replace it nationally.

Forest Fire Danger Meter

The FFDM was developed from a series of experimental fires conducted over a 10-15 year period in various types of native forest around the country (McArthur, 1967). The majority of these experimental fires were conducted under low- to moderate- fire weather conditions and

were generally of small scale (<0.5 ha), lasting less than 1 hour from ignition to completion, augmented by ad hoc wildfire observations. The FFDM has been used in all studies that have examined fire danger and climate change in Australia. Despite its widespread use, this model has been found to under-predict the rate of spread of large fires or fires burning through forests with shrubby understorey or under high wind speeds (Rawson et al., 1983; Buckley, 1992; Burrows, 1999; McCaw et al., 2008). For the FFDM:

$$R=0.0012Fw \quad (6)$$

where R is rate of forward spread (km h^{-1}) and w is the amount (load) of fine surface fuel (t ha^{-1}). F is the forest fire danger index (FFDI), a meteorologically based index:

$$F=2\exp [-0.45+0.987\log (D)-0.0345H+0.0338T+0.0234U] \quad (7)$$

where, D is the drought factor (0–10), H is the relative humidity (%), T is the air temperature ($^{\circ}\text{C}$) and U is the wind speed at 10 m in the open (km h^{-1}). Two sets of predictions were made, the first using fuel load, w , from the litter load model, the second with constant fuel load of 12 t ha^{-1} .

Dry Eucalypt Forest Fire Model (DEFFM)

While also empirical this model differs from the FFDM in that it was developed under a broader range of weather and fuel conditions and utilised experimental fires that had attained a pseudo-steady rate of spread for the conditions (Gould et al., 2007). It is thus applicable to larger fires burning under summer conditions. The DEFFM rate of spread is calculated as:

$$R=0.0183 [30+3.102 (U-5)^{0.904} e^{0.279S_s+0.611N_s+0.013N_h}] M_s^{-1.495} \quad (8)$$

where R is the rate of forward spread (km h^{-1}), U is the mean wind speed measured in the open at 10 m above ground level (km h^{-1}), S_s is the surface fuel (i.e. litter) hazard score (0–4), N_s is the near-surface fuel hazard score (0–4), N_h is the near-surface fuel height (cm) and M_s is the moisture content (%). Near-surface fuel is dead material suspended close to the ground

with a significant horizontally oriented component, e.g. grasses and dead leaves and twigs suspended in low shrubs. 'Hazard scores' are categorical scales which describe the amount and arrangement of fuel present on the basis of visual assessment (McCarthy et al., 1999).

Information from a recent assessment of fuel hazard in the most common shrubby dry sclerophyll forest types in the Sydney region (Table 1) was used as the basis of fire spread modelling. While there is information on surface fuel load and the potential for a direct mapping of surface fuel load to surface fuel hazard for particular species (e.g. jarrah forests of Western Australia (Gould et al., 2007)), there is currently no robust general method of converting surface fuel load to hazard for other forest species or for determining the near-surface fuel hazard or height from such measurements, so we cannot apply the predictions of the fuel load model to the DEFFM model. As a result of this and the lack of knowledge about how fuel hazard in any particular vegetation type will be affected by climate change, a sensitivity-type analysis was conducted. The current fuel state was used as the basis for the analysis in which fuel hazard classes were changed by ± 0.5 hazard score and fuel height by ± 10 cm (Table 1). For the forest described by Table 1 a ± 0.5 change in surface fuel hazard score is equivalent to a change of approximately 25% in litter layer depth, a -0.5 change to the near surface hazard score would require a reduction in the fraction of dead material from 20-50% to <20% and an increase of +0.5 would require an increase in dead material to >50% and the presence of senescent understory vegetation. These changes should be measurable with careful monitoring but do not imply significant structural change to the forest. All fire behaviour predictions were made by applying eqns 6 and 8 using the outputs of the climate, fuel and fuel moisture models at an hourly timestep.

2.5 Data aggregation

The output of the five models presents a rich data set for investigation of potential changes in fire risk and fire behaviour in the future. Here we examine a limited number of measures:

- Mean monthly surface fuel moisture content as a measure of fuel flammability,
- The number of days per month on which fuels are dry enough to sustain fire for at least some of the day (fire days). This condition is defined as a day that has minimum surface moisture content, $M_s < 15\%$ and profile moisture content, $M_p < 20\%$. (McCaw, 1986; Plucinski and Anderson, 2003),
- Histograms of minimum surface moisture content for summer days, a measure of the potential for severe fires and spot fires,
- Monthly mean and monthly maxima of rate of spread calculated at 3PM local time each day.

The CCAM rainfall and humidity series have variances that are large relative to their linear trends (Fig 2). Although rising temperature with time will drive fire danger higher (Williams et al., 2001), simply comparing present to future climate using averages over the start and end portions of the model runs will not capture variability due to rainfall, which is known to affect fuel moisture (Matthews, 2006) and hence fire behaviour. So, rather than using a time-based analysis for these variables, we instead used a climate index to examine the effect of climate on the above measures of fire risk and behaviour. This index is based on the observation that climate variables affecting fire behaviour are correlated in the CCAM data set (Fig. 3). To take advantage of this correlation and simplify the presentation of results, principal components analysis (R Development Core Team, 2009) was used to reduce the number of variables. Principal components analysis was performed on centred, scaled, annual

values of air temperature, rainfall, relative humidity, wind speed and solar radiation. The first principal component was used as a climate index.

To examine the effect of climate on fires, the daily model outputs were then aggregated and related to the climate index:

1. The daily series were aggregated to calculate monthly means, maxima and counts.
2. Monthly values were assigned to bins by the annual value of the first principal component of the climate data set. Bins were defined as the bottom, middle and top third of values.
3. Bootstrapping with replacement for values within each bin was used to establish 90% confidence intervals (Clarke et al., 2011).

The result of this analysis is a set of time series curves representing fuel moisture and fire behaviour variables in 3 climate ranges.

3 Results

3.1 Climate index

The first principal component captured 65% of variance in the climate data set. Negative values corresponded to years which were cooler, more rainy, more humid, less windy and cloudier than the model mean, hereafter referred to as “cool-wet” years, while positive values were warmer, less rainy, windier and sunnier (Fig 3), “warm-dry” years. This index is specific to this model run and would be different for other models or locations which predict, for example, increasing temperature and increasing rainfall.

There was a statistically significant trend in the frequency of occurrence of warm-dry years for the western Sydney region (Fig 4) (p-value for slope of linear regression < 0.001). For the period 1961-2000, 30% of years are warmer and drier than the 140 year mean. For

2061-2100, 63% of years are warmer and drier. Thus, there is a substantial shift in the frequency of occurrence of warm-dry years as a consequence of the modelled climate change scenario. There is also an increase in the extreme values of the index, with 8 years in the period 2011-2099 having higher values than the highest value in the observational period (1961-2010).

3.2 Fuel Load

At a monthly time scale, the model predictions were dominated by the annual cycle of litter fall in December and decomposition during the remainder of the year (Fig. 5). At longer time scales, fuel load varied on a decadal scale with an overall downward trend of $1.8 \text{ t ha}^{-1} \text{ century}^{-1}$. This variability and trend reflects the rainfall and temperature values used to drive the model (Fig 2) and our assumptions linking litter dynamics to climate. As noted above, this relationship is an over-simplification. However, a similar relationship of declining litter load with lower rainfall and increasing temperature has also been observed in a space-for-time study (Williams et al., 2009) and at a long term monitoring site in NSW (Penman and York, 2010).

3.3 Fuel Moisture

A strong climate signal was observed in average moisture content (Fig. 6) and number of fire days (Fig. 7). In the cool-wet years, moisture content was higher and there were fewer fire days in every month of the year than in the warm-dry years, with intermediate results in other conditions. Without further analysis relating mean moisture content to fire occurrence it is not possible to define a threshold moisture value which defines a wet winter non-burning period, particularly as even the months with the highest moisture content have some fire days.

However, the shifting of the moisture curves between cool-wet and warm-dry years has two implications. Firstly, that the winter period with few fire days is shorter in warm-dry than in cool-wet years. Secondly, the gradients in moisture content spring and autumn are similar in all year types but shifted towards July in warm-dry years and towards December in cool-wet years. In Fig. 8 there is a higher probability of values below a given value in warm-dry years than cool-wet years, meaning that as well as there being more fire days, moisture content on those days is likely to be lower, with corresponding implications for fire behaviour.

Statistics for the varying fuel load run did not differ at all from the 12 t ha⁻¹ run. That is, the variations in fuel load modelled were too small to have any effect on fuel moisture. Similarly, increasing fuel load by 50% did not have a measurable effect on M_s (Fig. 9). In contrast, reducing fuel load by 50% led to a small but non-significant reduction in M_s , particularly in winter.

The similarity of the 12 and 18 t ha⁻¹ runs indicates that most rain events in the western Sydney region were sufficient to saturate the deeper litter layer and that the additional depth did not affect the drying of the surface of the layer. In contrast, the shallower 6 t ha⁻¹ litter layer did dry slightly more rapidly. It is possible that further reduction of the fuel load would lead to larger changes in fuel moisture. We did not model this possibility as such a large change in litter load would be expected to occur with a change in canopy species and possibly a transition from forest to open woodland structure.

3.4 Fire Behaviour

3.4.1 Forest Fire Danger Meter

The dependence of fire behaviour on climate was similar for both monthly mean 3PM and monthly maximum 3PM rates of spread, illustrating the change in expected fire behaviour throughout the year defining the fire season (Fig. 10). A strong dependence on climate was

observed for the length of the fire season. In warm-dry years, mean rate of spread began to increase from the winter minimum 1-2 months earlier than in cool-wet years and in warm-dry years the mean spring rate of spread was higher than in the summer of cool-wet years. Mean rate of spread in December in warm-dry years was 66% higher than in wet years, while maximum rate of spread was 14% higher. These two values reflect an increased number of fire days in warm-dry years along with the increase in peak rate of spread.

In cool-wet years the rate of spread calculated using fuel load from Figure 4 is higher than the rate of spread assuming a constant fuel load of 12 t ha^{-1} , R_f , because higher rainfall is associated with higher fuel loads (Fig. 11). This difference was greatest at the beginning of the year and decreases as the litter decays through the year. Similarly, R_v was lower than R_s in warm-dry years but the rate of change during the year is slower because fuels decay more slowly in drier conditions.

This result demonstrates the antagonistic interaction between the second-order effects of climate on rate of spread in this model through weather and fuel load. While weather, as affected by climate change, acted to increase rate of spread through decreased fuel moisture and increased wind speeds, a concurrent effect of climate change was to reduce surface fuels, thus reducing rate of spread. Using this fire behaviour model, these opposing effects were of similar magnitude.

3.4.2 Dry Eucalypt Forest Fire Model

The DEFFM rates of spread are approximately double those predicted by the FFDM (Fig. 12), reflecting the improved knowledge of behaviour of larger fires burning under less moderate conditions. The dependence of rate of spread on climate was similar to that observed for the FFDM, with a longer fire season and higher maximum rate of spread in warm-dry years. Mean December rate of spread showed similar dependence on climate to the

FFDM, with a 57% increase in warm-dry years compared to cool-wet years. Maximum rates of spread were more sensitive to climate in DEFFM than FFDM, with peak values in warm-dry years from the DEFFM modelling 46% higher than those in cool-wet years. This difference is larger than the effect of variable fuel load on modelled FFDM rate of spread (Fig. 11). Thus predictions of fire behaviour under a changed climate will differ somewhat depending on which fire behaviour model is used.

Changes in rate of spread due to fuel hazard were of similar magnitude to the direct effect of climate change. The DEFFM is most sensitive to changes in the near-surface fuel hazard component, with approximately +35%, -25% changes in monthly maximum 3PM rate of spread during the fire season with, respectively, a 0.5 increase in hazard score and a 0.5 decrease in hazard score (Fig. 13). These variations are asymmetrical because the hazard function in the DEFFM is non-linear (Eqn 8). Surface fuel hazard is the next most sensitive with +13%, -10% changes in monthly maximum 3PM rates of spread during the fire season with a +0.5 and -0.5 change in hazard score respectively. The model is relatively insensitive to changes in near-surface fuel height at the current value. The result of simultaneous increases to all fuel variables is about a 55% increase in rate of spread during the fire season (Fig. 13d). The result of the decreases to all fuel variables is about a 35% decrease in rate of spread during the fire season. During the fire season, there is very little variation in response between climate types. The largest effects are evident during the winter months where fire behaviour is more sensitive to changing fuel in warm-dry years than in cool-wet years.

4 Discussion

Applying the changing rainfall scenarios from the climate model projections to models of fuel dynamics for the western Sydney region produced a declining, but variable, litter fuel load. The response of fuel mass to changing moisture regimes was slow and thus changes to

fuel loads as a consequence of climate change-induced changes to moisture regimes are unlikely to be detected in the coming decades. A strong climate signal was observed in fuel moisture, with a shorter winter period, lower fuel moisture levels and greater number of fire days in warm-dry years, in all months. Fuel load had only a weak effect on fuel moisture, with no effect at small fuel load changes and a slight decrease in fuel moisture for a 50% reduction in fuel load. Thus, a major decline in fuel mass as a consequence of climate change would be needed to induce a concomitant decline in fuel moisture. Changes to fuel moisture will be driven primarily by first order responses to climate change (i.e. the warming and drying) rather than by second-order changes via fuel mass.

The two fire behaviour models vary in their ability to incorporate changes in fuel moisture and load. The FFDM has only moderate capability of incorporating long-term first order weather effects but can incorporate first order fuel effects through existing models of surface fuel accumulation and decay. The DEFFM has greater scope to incorporate second order effects of weather and fuel, however there are no current methods for determining what the first order effects on fuel quantities (hazard scores and fuel height) will be. The models were directly sensitive to climate change, with an increase in the rate of spread during years characterised by increased temperatures and decreased rainfall. These results are broadly similar to previous studies which used fire danger index to examine climate change effects in eucalypt forests (Beer and Williams, 1995; Williams et al., 2001; Cary, 2001; Hennessy et al., 2005; Lucas et al., 2007; Clarke et al., 2011). However, variability in the climate index (Fig. 4) means that changes are likely to be manifest as a change in the frequency of severe fire seasons rather than a gradual shift in mean index values. As with the findings of Clarke et al. (2011) and Hasson et al. (2009) it remains to be seen whether these changes in frequency are measurable in coming years.

Both fire behaviour models used showed that climate induced changes in fuel amount will induce changes in fire behaviour that are of similar magnitude to the direct climate effects. Rate of spread was most sensitive to fuel hazard scores, while fuel height was relatively unimportant. If these changes reduce fuel load, as suggested by the simple fuel accumulation model, then this will act to partially ameliorate the direct effects of climate change. However, there is currently very little understanding of the likely effects of climate change on forest composition or fuel structure (Williams et al., 2009), so it is unclear in which direction fuel amounts and structure will respond. This should be an area of priority research and continued monitoring of fuel structure, as well as mass and changes in vegetation composition, will be a vital component of fire management in coming decades. Our approach is relevant to forests around the globe, but the main limitation at present is the lack of suitable models of fuel accumulation.

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Tables

Table 1: Fuel variables for western Sydney.

Variable	Current value	Pertubation
Surface fuel hazard	3.5	± 0.5
Near-surface fuel hazard	3.0	± 0.5
Near-surface fuel height (m)	0.35	± 0.10

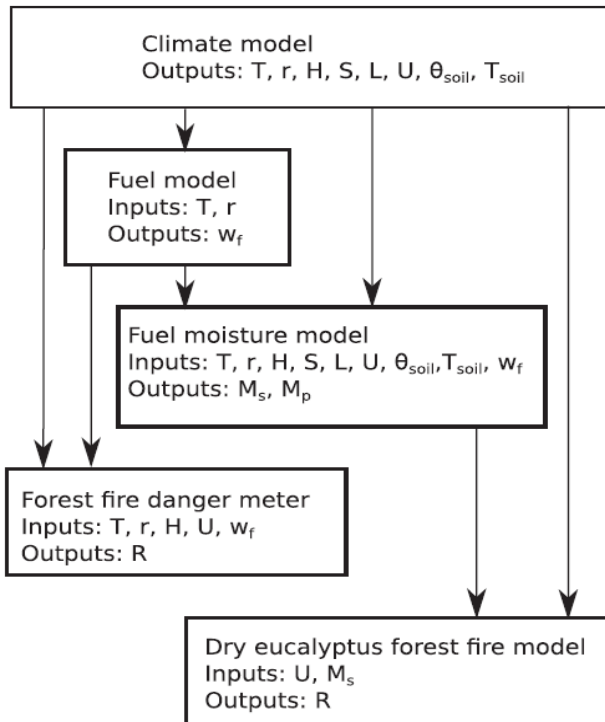


Figure 1: Relationships between models used in this study. Variables are: T , air temperature, r , rainfall, H , humidity, S , shortwave radiation, L , longwave radiation, U , wind speed, θ_{soil} , soil moisture, T_{soil} , soil temperature, w_f , litter fuel load, M_s , surface fuel moisture content, M_p , profile fuel moisture content and R , rate of fire spread.

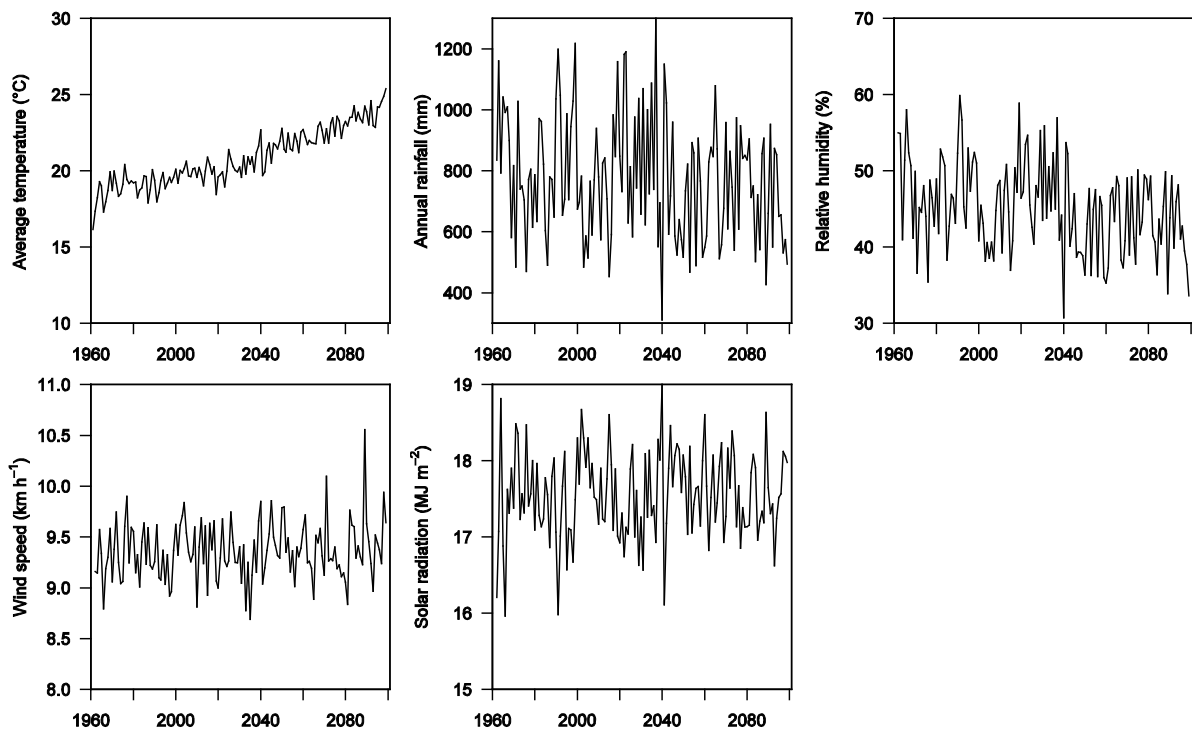


Figure 2: Annual temperature, rainfall, relative humidity, wind speed and solar radiation for western Sydney for the period 1960-2099 from CCAM.

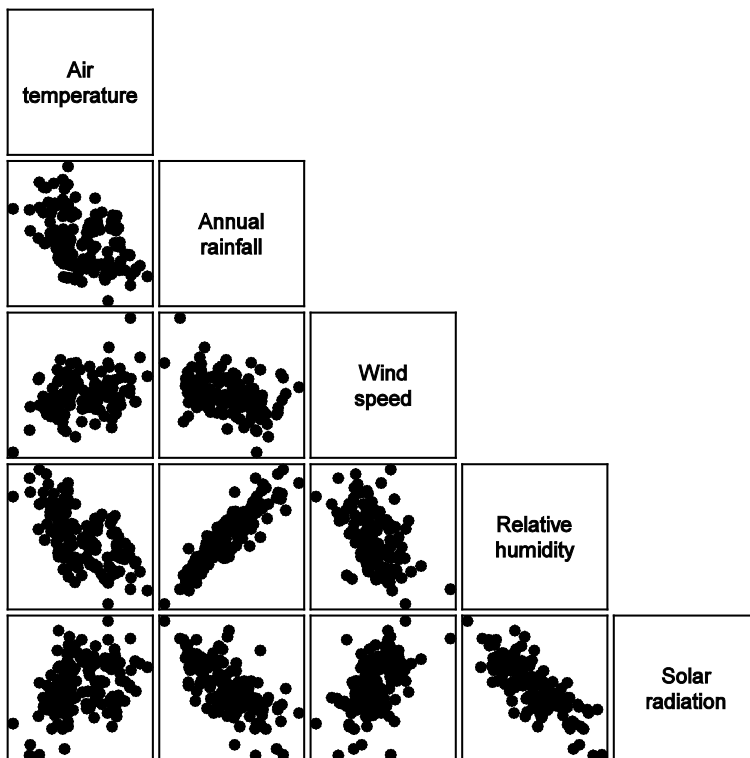


Figure 3: Correlation between major climate variables. Points are annual values plotted on arbitrary scales, positive to the right and upwards.

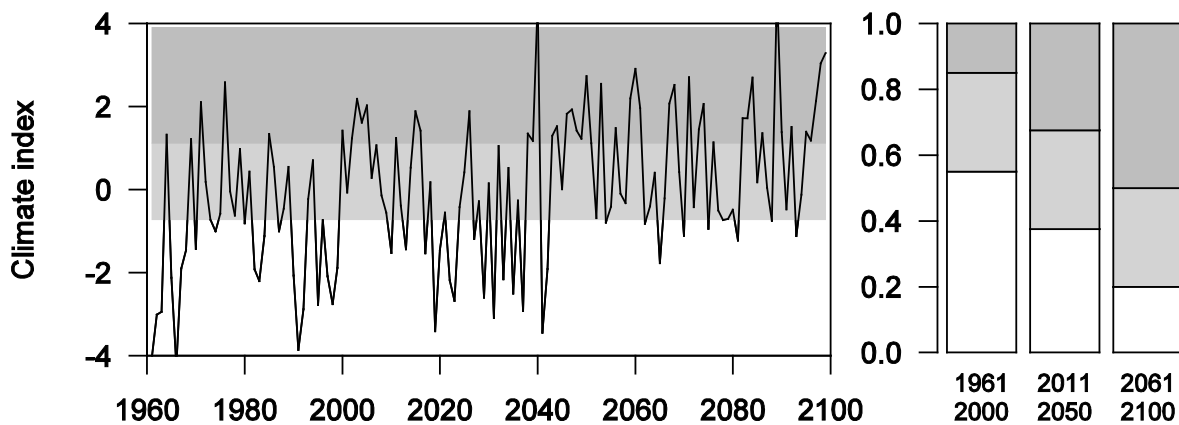


Figure 4: left) Time series of climate change index. Positive values are relatively warm, dry, sunny and windy, negative values are cool, wet, cloudy and calm. Shading shows the range of the lower (white, cool-wet), middle (light gray, intermediate) and upper (dark grey, warm-dry) third of values. right) Relative frequency of year types in 40 year ranges.

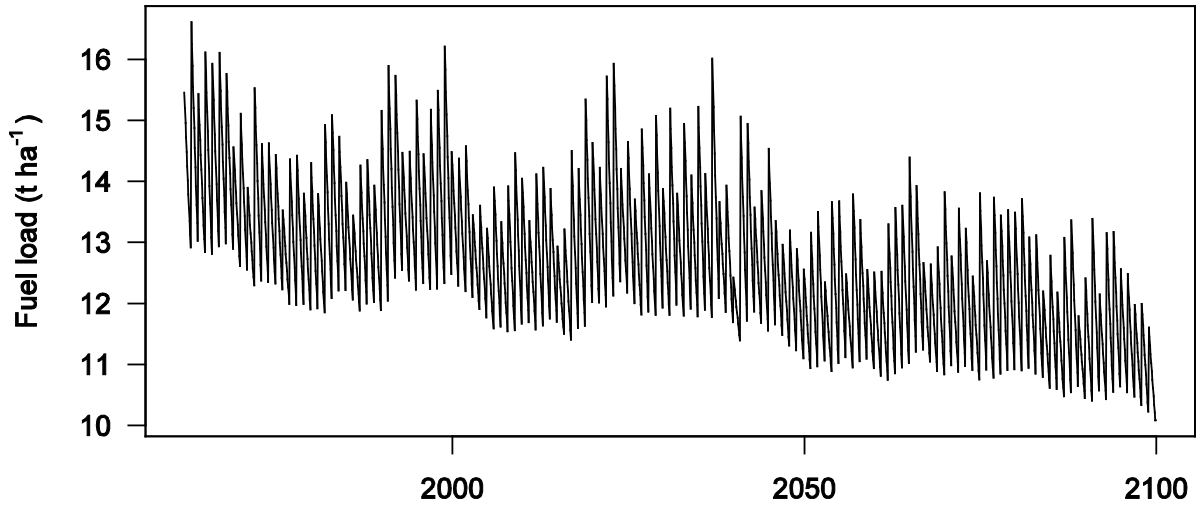


Figure 5: Monthly litter load predicted from CCAM annual rainfall and fuel accumulation curves.

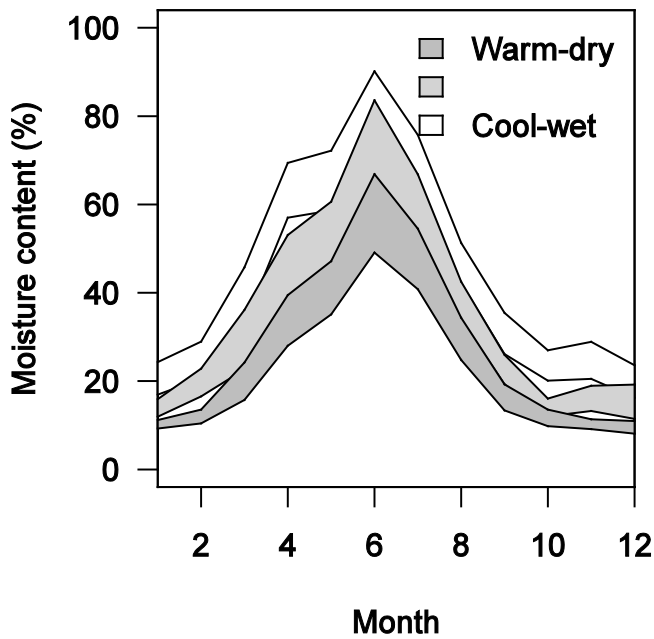


Figure 6: Average daily minimum fuel moisture content for years with different climatic conditions. Shaded areas are 90% confidence intervals for years in the climate change index bin shown in Fig. 4. 31

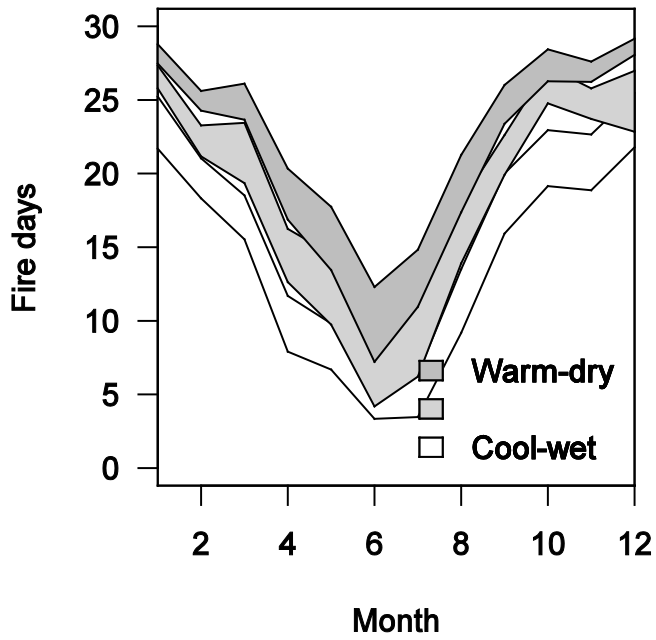


Figure 7: Number of fire days per month for years with different climatic conditions. Shading as per Fig. 5.

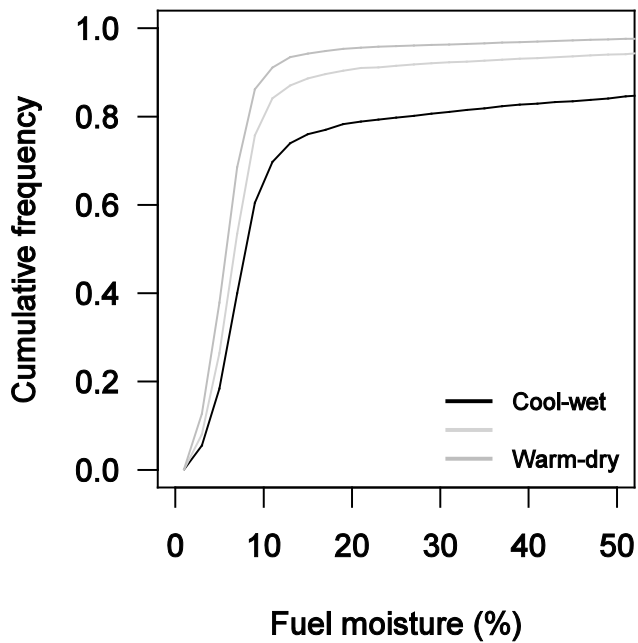


Figure 8: Surface fuel moisture fuel factor cumulative frequency histograms in summer for years with different climatic conditions.

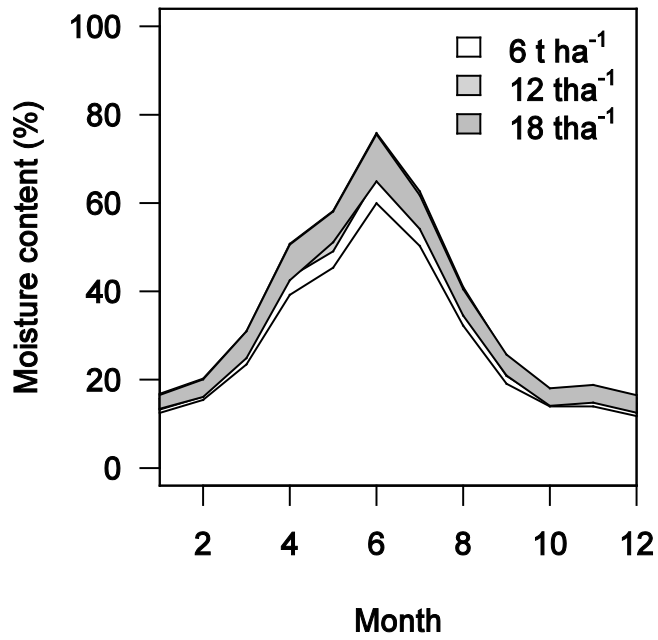


Figure 9: Average daily minimum moisture content for different fuel loads. 12 and 18 t ha⁻¹ lines are indistinguishable. Shaded areas are 90% confidence intervals for each fuel load.

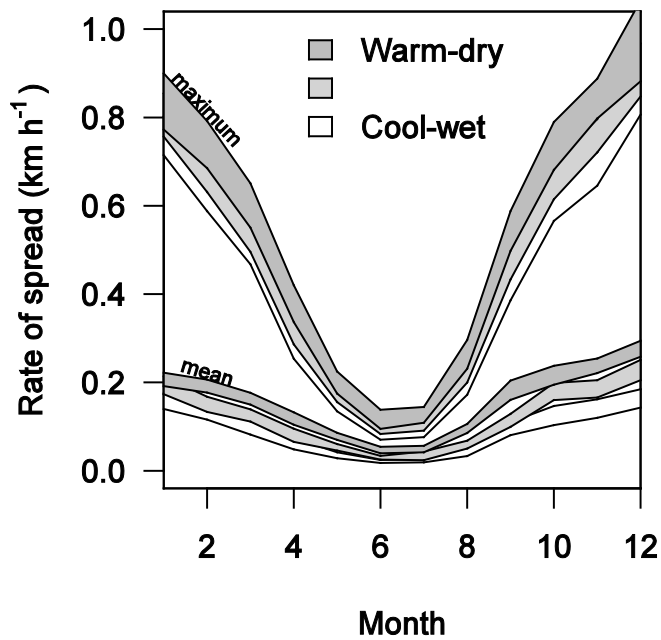


Figure 10: The monthly mean and maximum rates of spread for 3PM weather conditions using the FFDM. Shading as per Fig. 5.

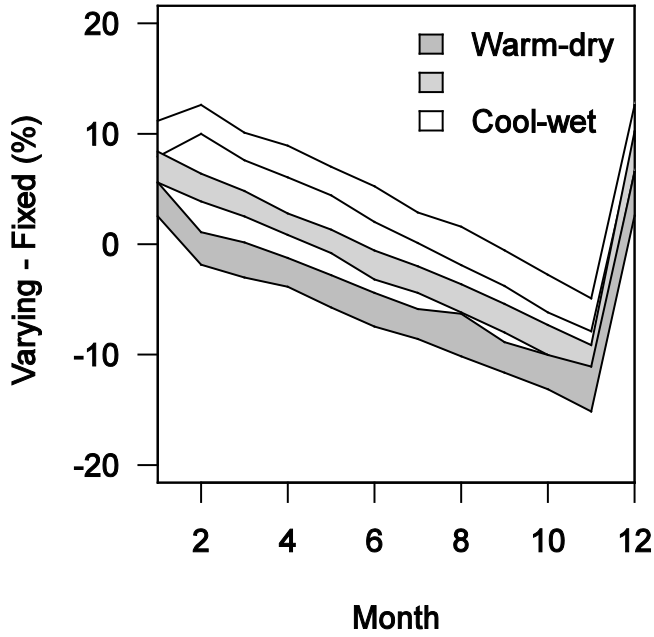


Figure 11: Percentage difference between modelled rates of spread using different fuel inputs to the FFDM. Shaded areas are 90% confidence intervals of the percentage difference between the monthly maximum 3PM rate of spread calculated using the Olson-derived fuel load data and the monthly maximum 3PM rate of spread calculated using a fixed fuel load of 12 t ha⁻¹.

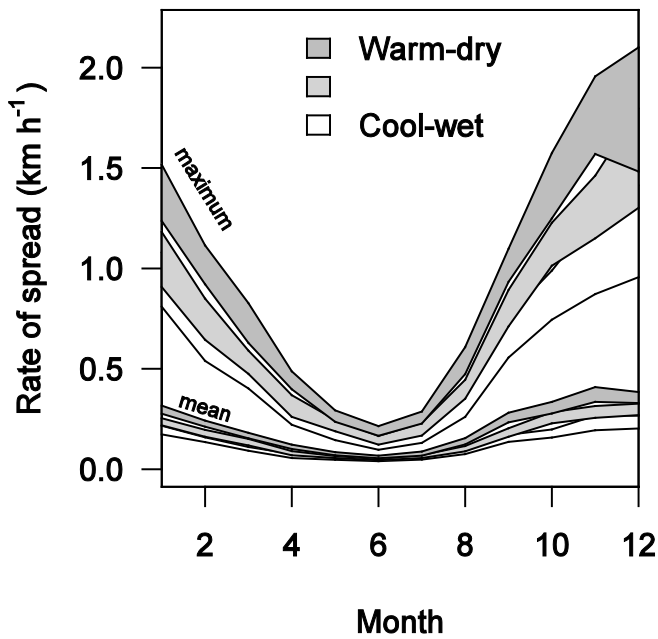


Figure 12: The monthly mean and maximum rates of spread for 3PM weather conditions using the DEFFM. Shading as per Fig. 5.

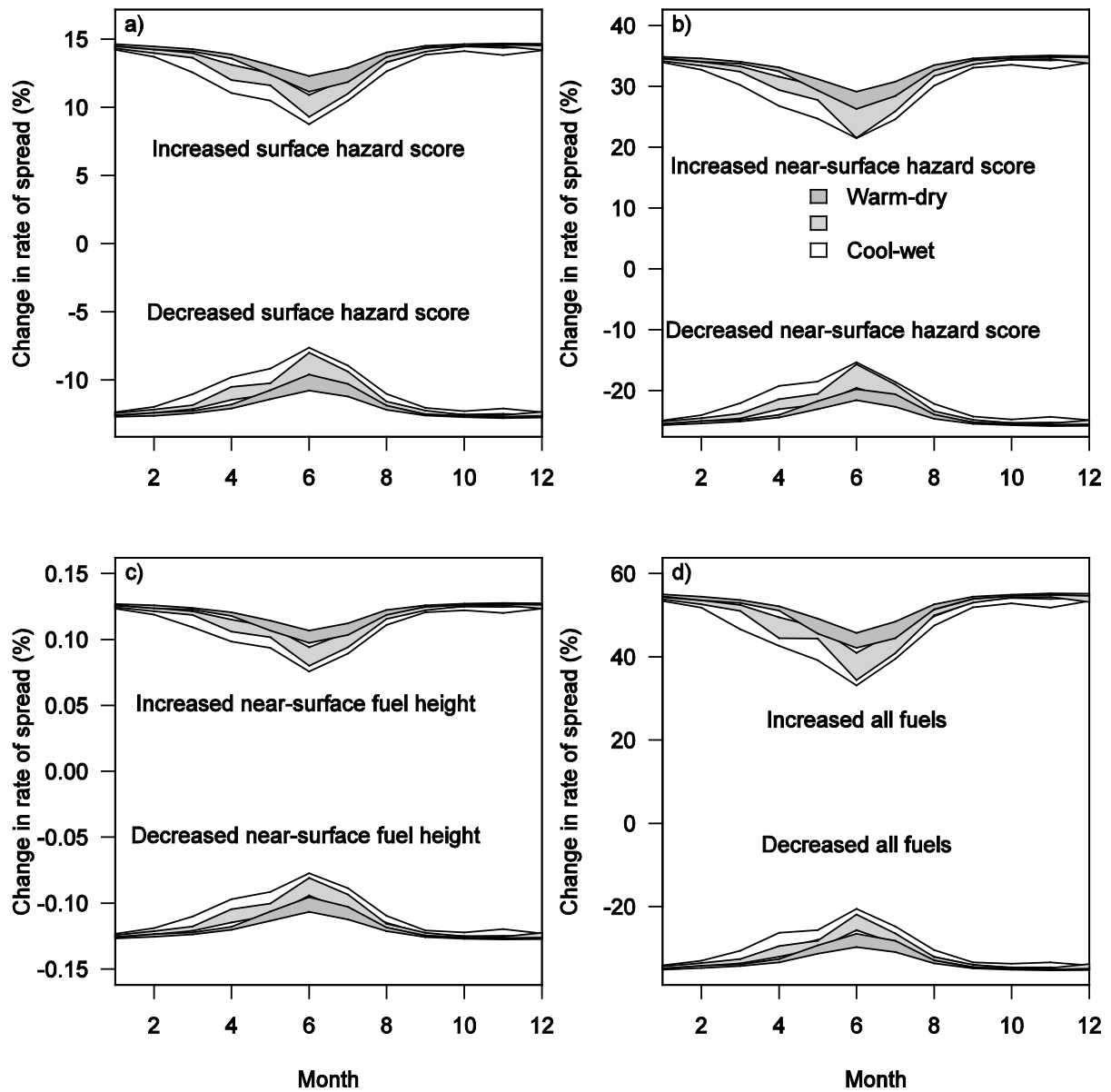


Figure 13: Percentage change in 3PM maximum rate of spread as a result of changing fuel variables in the DEFM. (a) Surface fuel hazard with ± 0.5 change in hazard score. (b) Near-surface fuel hazard with ± 0.5 change in hazard score. (c) Near-surface fuel height with ± 10 cm change in height. (d) All fuel variables increased or decreased simultaneously. Shading as per Fig. 5.