Modelling fuel moisture under climate change

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Abstract

Purpose – Fuel moisture is an important determinant of fire behaviour. Changes in climate will result in changes in fuel moisture and this will impact fire management by modifying the length and severity of the fire season and by changing opportunities for prescribed burning. This paper aims to examine the effect of climate on fuel moisture in Eucalypt forests.

Design/methodology/approach – A climate model is used to predict weather for five Australian cities from 1961 to 2100 under a high-emissions scenario. Time series are extracted from the model and used as boundary conditions for a process-based fuel moisture model. Fuel moisture predictions are used to examine two management variables: the number of days suitable for prescribed burning in spring, and the number of days when fire could burn in summer.

Findings – There were significantly more fire days in warmer-drier years. The number of days with extremely low fuel moisture was also higher in warmer-drier years. Variation in the number of burning days was narrower than for fire days but the number of burning days was lower in warmer-drier years. The lower number of burning days in warm years was due to a higher rate of fuel drying in these years.

Research limitations/implications – Analysis was limited to Australian locations. In future, the work should be expanded to include Eucalypt plantations on other continents.

Practical implications – The changes predicted will require changes to fire management practices, particularly the timing of prescribed burning.

Originality/value – This paper uses a new, physically based method to examine the effect of climate change on fuel moisture. It will be useful to fire managers seeking to adapt to a changing climate.

Keywords Fire, Fuels, Moisture, Forests, Australia

1. Introduction

The moisture content of forest litter is an important quantity in fire management because it affects the ignition and propagation of bushfires. Above some threshold moisture content fuel will not burn and fires cannot ignite (Catchpole, 2001). At the other extreme, very dry fuels ignite easily and this increases the likelihood of fires igniting or spot fires developing from already burning fires. Fuel moisture also plays an important part in prescribed burning because burns must be carried out when fuels are dry enough to sustain fire but not so dry that the fire is difficult to control. Fuel moisture

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is determined by short- and long-term weather patterns (Matthews, 2006) and is thus susceptible to climate variability and change. This paper examines the effect of climate on fuel moisture in Australian forests and the implications for fire management.

The effect of climate change on fire has previously been examined by using the output of climate models to examine changes in fire danger metrics (Beer and Williams, 1995; Brown et al., 2004; Cary, 2002; Hennessy et al., 2005; Williams et al., 2001). These studies have used operational fire danger indices, e.g. the forest fire danger meter (FFDM) that include empirical fuel moisture models (McArthur, 1967). These models are limited in that they assume that the relationships between daily weather observations and changes in fuel moisture do not change, in particular, the FFDM assumes a constant drying rate after rain, irrespective of weather conditions. This study addresses this problem by using a process-based fuel moisture model which can respond to changing weather sequences. Previous studies have compared fire danger under current and future climate but have provided limited insight into the mechanisms of change and variability. Because there is uncertainty about the magnitude and for some variables, direction of future change, this study uses a different approach. Rather than compare present and future climate scenarios, we use a climate model with a high emissions scenario to generate a wide range of weather conditions and then relate fuel moisture metrics to climate metrics. These relationships can then be combined with climate change scenarios to predict changes in fuel moisture.

We use the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Conformal Cubic Atmospheric Model (CCAM) to predict weather conditions for five Australian cities (Brisbane, Sydney, Canberra, Melbourne, Hobart) from 1961 to 2100. The climate model predictions are used to make fuel moisture predictions. The results are analysed in terms of two fuel moisture metrics: the number of days suitable for conducting prescribed burning in spring, and the number of days on which fire could burn in summer.

2. Methods

The climate dataset was created using the CSIRO CCAM (McGregor and Nguyen, 2009). CCAM was first run from 1961 to 2100 for the entire globe at 200 km resolution using sea surface temperatures from the CSIRO Mk 3.5 climate model. The CCAM predictions were then downscaled to 20 km resolution over southeast Australia (Thatcher and McGregor, 2009). Model runs were made under the Special Report on Emission Scenarios (SRES) A2 scenario (SRES, 2000). A2 is one of the higher emissions SRES scenarios, providing a large range of mean temperatures (Figure 1). Output from CCAM was stored...
in monthly files at 3-h (air temperature, rainfall, wind speed) and 6-h intervals (solar radiation, thermal radiation, specific humidity, soil temperature, soil moisture). Time series of surface variables were extracted from the nearest grid point to each selected location. The locations used in this study were: Brisbane, Sydney, Canberra, Melbourne, and Hobart. These cities were chosen to represent a range of climates in the fire prone south-east of Australia. All variables, except solar radiation, were transformed to 1-h intervals by linear interpolation. 1-h solar radiation was calculated by scaling a template curve by daily total solar radiation, to ensure the correct timing of dawn and dusk.

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 model has one spatial dimension, height. The properties of the litter bed are assumed to be horizontally homogeneous and no horizontal transport is included. 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: \( T_m \), litter temperature (K), \( T_l \), the temperature of free liquid water on the litter surfaces (K), \( T_a \), air temperature (K), \( m \), litter moisture content (kg water per kg of dry litter), \( l \), amount of liquid water on litter surfaces (kg of water per m\(^2\) of litter bed), \( q \), specific humidity (kg of water vapour per kg of air). Physical processes that change these six quantities are represented in the model as fluxes of energy and water between the three materials at a given level, between levels within a given material, and between the litter layer and the atmosphere or soil. Fluxes of heat, water, and radiation between the litter layer and the soil or atmosphere were computed from boundary conditions: air temperature, wind speed, specific humidity, rainfall rate, solar radiation, thermal radiation, soil temperature, and soil moisture. To allow comparisons with field measurements of surface and profile fuel moisture the model predictions of litter moisture content and amount of surface water were combined:

\[
S = m_1 + \frac{l_1}{\rho_{bulk}}, \quad P = \sum_{i=1}^{N} \left( m_i + \frac{l_i}{\rho_{bulk}} \right), \quad A = 1 - \left( \frac{1}{1 + ae^{blP} + c} \right)
\]

where \( S \) is the total moisture content (kg kg\(^{-1}\)) of the top model layer, \( P \) is the moisture content (kg kg\(^{-1}\)) of the entire litter layer, \( A \) is the fraction of the fuel bed that is dry enough to burn (“Available fuel factor”) (Beck, 1995), \( m_i \) 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, \( \rho_{bulk} \) is the litter layer bulk density (kg m\(^{-3}\)), \( N = 5 \), \( a = 0.43e^{23S} + 2 \), \( b = -85S + 2.4 \), and \( c = 1.3S - 0.43 \).

At each site the fuel moisture model was parameterised to represent Eucalyptus forest on flat ground with a 30 mm deep litter layer, equivalent to 1.5 kg m\(^{-2}\) fuel load. This relatively heavy fuel load was selected to allow the model to respond to variation in drying conditions after rain. A very thin layer will always dry rapidly, and hence effects of variation in climate would not be seen. 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). The Matthews model was initialised in an arbitrary state and run from January 1, 1961 to December 31, 2099. The model equations were solved on a 1-h time step. The first two months of the run were not used in data analysis, to avoid
dependence on the initial conditions. The Matthews model, originally implemented in visual basic for applications within a spreadsheet, was rewritten as a Python script. The model run for each city took \( \sim 5 \) processor days.

3. Results

We present results for two important management variables: the number of days suitable for conducting prescribed burning in spring, and the number of days on which fire could burn in summer. A prescribed burning day is defined as having available fuel factor between 0.3 and 0.7 (Sneeuwjagt and Peet, 1998). A fire day is defined by surface fuel moisture < 15 percent and profile moisture < 25 percent. Fuel moisture can be combined with wind speed to calculate fire danger or with wind speed and fuel characteristics to predict fire behaviour. This analysis is beyond the scope of this paper.

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 projects have also included solar radiation, wind speed, and specific humidity, although the prediction ranges have been larger than the mean predicted changes (CSIRO, 2007). For this initial study we considered only two climate variables: mean temperature, and rainfall amount.

Average annual temperature increased at all sites by between 3.2 and 4.5°C century\(^{-1}\) (Figure 1). There was greater variation in rainfall but all sites recorded a negative trend in annual rainfall of between 83 and 141 mm century\(^{-1}\). Seasonal mean temperature, \(T\), and rainfall, \(R\), were correlated at all sites (Figure 2). The range of \(T\) and \(R\) in the later years of the model run (2009-2100) extended beyond the ranges simulated for current conditions (1961-2008) (Figure 1). To simplify presentation of results, and because \(T\) and \(R\) were correlated, principal components analysis was used to reduce the number of variables. The first principal component, PC1, axis for each season and site is shown in Figure 2. PC1 captured 71-80 percent of variance in spring and 61-76 percent of variance in summer. As shown in Figure 1, seasons with positive PC1 are relatively warmer and drier than seasons with negative PC1, so PC1 may be interpreted as an index of warm-dryness vs cool-moistness.

PC1 was significantly correlated with the number of summer fire days at all sites (\(R^2\) between 0.66 and 0.80), with more fire days in warmer-drier years. The largest variation was seen at Brisbane, which also had the widest range of rainfall totals, with the wettest years having 0 summer fire days and the driest 82. The remaining sites had at least 18 fire days in even the coolest-wettest years and 80-90 fire days in warmer-drier years. At all sites except Canberra (where some years have 90 fire days) there was an increase in the highest number of fire days from current to future climate. As well as variation in the number of fire days, PC1 was correlated with the fuel moisture on any given day (Figure 3). In warmer-drier years the frequency of moisture contents below 10 percent is higher than in cooler-wetter years, implying a higher number of days with at least a given level of fire danger, given equal wind speeds.

Results for spring burning days were less pronounced. The range in burning days was narrower than for fire days (0-23 across all sites). Number of burning days decreased at all sites as warmer-drier years, but correlation with PC1 was weak, \(R^2\) were between 0.07 and 0.24. Available fuel factor histograms show a majority of days are either wet, \(A = 0\) or dry, \(A = 1\), with a minority in the burning range, 0.3 to 0.7. While the number of wet and dry days varies with PC1, the slope of the cumulative frequency curves in the
Figure 2.

Notes: Left column, number of spring burning and summer fire days; negative PC1 is cool-wet, positive is warm-dry; black dots are simulated current climate (1961-2008), coloured dots are future climate (2009-2100); right column, seasonal mean temperature and rainfall; lines are PC1 axis.
Modelling fuel moisture

Notes: Left column, available fuel factor cumulative frequency histograms in spring for binned PC1 values; black is cool-wet, pink is warm-dry, bins are 1 unit wide, centers from −2.5, to +2.5; right column, as left for surface fuel moisture in summer.
burning range does not. Because burning days occur in the drying phase after rain, this result indicates that during a wetter/drier spring there are longer/shorter wet periods but that number of drying cycles does not vary systematically with seasonal rainfall. Figure 4 shows the seasonal average rate of change of A per day. In warmer-drier years the rate of change is greater than in cooler-wetter years, although the correlation is weak for Melbourne and Hobart. This indicates that drying cycles are shorter because the fuels dry more rapidly, and not because rain is less effective in wetting the fuels.

4. Discussion/conclusions
Fuel moisture at five Australian sites was modelled by using a climate model and a process-based fuel moisture model. The climate model simulations provided a set of physically consistent weather conditions that extend beyond the ranges of temperature and rainfall under current climate. Climate model output was used to drive the process-based fuel moisture model, generating 140 years of fuel moisture predictions. This large set of prediction enabled us to investigate sensitivity of fuel moisture to climate, something which has not previously been possible as observational data sets for Australia have been less than six months long (Matthews et al., 2007). Full analysis of the climate and fuel moisture data sets produced for this was beyond the scope of this paper and is deferred for future study. Here, we presented results for two important management variables: the number of days suitable for conducting prescribed burning in spring, and the number of days on which fire could burn in summer.

During warmer-drier years there were more days on which fires could burn and the frequency of low moisture contents was higher than in cooler-wetter years. If Australia’s climate continues to warm and dry, then our results predict that there will be greater potential for more frequent and more severe fires than under current climate. In warmer-drier years this occurs through an increase in the upper limit of fire days per season and through increased frequency of low moisture contents. Although there was a weak correlation between the number of burning days in spring and rainfall and temperature, our results for prescribed burning were dominated by variability. Thus, it is not clear from analysis of simple climate variables such as mean temperature and seasonal rainfall what future changes can be expected.

The results presented here for summer are similar to those found in studies that modelled fire danger (Hennessy et al., 2005). However, the data sets generated in this study provide the basis for a more detailed investigation of fuel moisture, e.g. burning conditions, and examination of the variation of physical processes, particularly drying after rain. Although Eucalyptus species are endemic to Australia, some are grown as plantation species in Europe, Africa, and the Americas. As such, the results of this study will also apply to fire in those locations if they also experience warming and drying in the future. Further modelling would be required for locations where rainfall is predicted to increase, e.g. the tropics.

This study has two main management implications. First, an increased number of fire days is likely to require greater fire suppression effort. Second, opportunities for spring prescribed burning are expected to decrease in future. Because fuel management is one of the main strategies available to reduce fire risk, fire managers should seek to adapt their practices to maintain adequate levels of prescribed burning in spite of reduced opportunities. This might be achieved by exploiting marginal burning conditions on days which would be considered ‘too dry’ in this study, e.g. late in the afternoon. Alternatively,
Figure 4. Seasonal average rate of change of fuel availability, A per day, for days with A < 1

Notes: Left column, spring; right column, summer
increased resources could be used to conduct more burns on the reduced number of suitable days.

The analysis presented here is only a very simple overview of the climate and fuel moisture data set created. Further work will be required to look more deeply at the relationships between climate and fuel moisture. This analysis can also be extended by combining the fuel moisture results with wind speed to predict fire danger.

References


About the authors
S. Matthews is a Research Scientist with CSIRO Sustainable Ecosystems. His work investigates fuel moisture physics, and modelling the effects of climate change on fuel moisture and fire danger. His recently completed projects include: development of a process-based model of fine fuel moisture, testing this model in Australian forests, a comparison of fire danger rating systems in Australian conditions, and derivation of a new operational fuel moisture model for fire managers for dry Eucalyptus forests. S. Matthews is the corresponding author and can be contacted at: stuart.matthews@csiro.au

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