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Fire behaviour modelling in semi-arid mallee-heath shrublands of southern Australia

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ABSTRACT

Knowledge of fire behaviour potential is necessary for proactive management of fire prone shrublands. Data from two experimental burning programs in mallee-heath shrublands in semi-arid southern Australia were used to develop models for the sustainability of fire spread, fire type, i.e., surface or crown fire, forward spread rate and flame height. The dataset comprised 61 fires burned under a wide range of weather conditions. Rates of fire spread and fireline intensity varied between 4 and 55 m min^{-1} and 735 and 17,200 kW m^{-1} respectively. Likelihood of sustained fire spread and active crown fire propagation were modelled using logistic regression analysis. Fire spread sustainability was primarily a function of litter fuel moisture content with wind speed having a secondary but still significant effect. The continuity of fine fuels close to ground level was also significant. Onset of active crowning was mostly determined by wind speed. Rate of fire spread was modelled separately for surface and crown fires through nonlinear regression analysis with wind speed, litter fuel moisture content and overstorey canopy cover as significant variables. Flame height was modelled as a function of fireline intensity. A model system to predict the full range of fire behaviour in mallee-heath shrubland is proposed relying on a combined method that links the surface and crown fire rate of spread models. This model system was evaluated against independent data from large scale prescribed burns and wildfires with encouraging results. The best models for fire-spread sustainability and active crown fire propagation predicted correctly 75% and 79% respectively of the fires in the evaluation dataset. Rate of spread models produced mean absolute percent errors between 53% and 58% with only small bias. The models have applicability in planning and conducting prescribed fire operations but can also be extended to produce first order predictions of wildfire behaviour.

1. Introduction

Shrubland ecosystems in fire prone climates are renowned for their flammability. These include chaparral in southern California (Keeley et al., 1999), kwongan and mallee in south-west Western Australia (O'Donnell et al., 2011a, 2011b; Enright et al., 2012), fynbos in South Africa (Schwilk et al., 1997), and maquis and matorral in the Mediterranean Basin (Fernandes et al., 2000; Bilgili and Saglam, 2003). Shrubland fires can be fast moving and intense even under moderate burning conditions (Rawson, 1982; Catchpole et al., 1998), and have the potential to burn extensive areas under extreme conditions leading to severe impacts on human populations, water catchments and a broad range of environmental values (Pausas et al., 2008; Keeley et al., 2004; McCaw et al., 1992). Reliable fire behaviour models are needed to support fire management decision making in shrubland ecosystems including predicting the potential propagation, intensity and impact of wildfires, and to guide the planned use of fire for biodiversity conservation and other land management objectives (Parsons and Gosper, 2011; Clarke et al., 2010; Sandell et al., 2006).

Shrub vegetation form three-dimensional fuel complexes with fuel particles continuously distributed along its vertical dimension or stratified into vertically separated fuel layers. In open shrublands with stratified fuel layers fire transitions to an upper layer, e.g., litter to shrub overstorey, are associated with abrupt and drastic changes in fire behaviour (e.g., Catchpole, 1987; McCaw, 1995; Weise et al., 2005). These abrupt changes occur as a result of (i)

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increased wind speeds just above the stand canopy, (ii) increased efficiency of heat transfer into a taller and more porous fuel layer, (iii) increased amount of fuel involved in flaming combustion, and (iv) enhanced radiant heating owing to a taller and deeper flame front (Alexander and Cruz, 2011).

An exceptional form of discontinuous fire behaviour is observed in semi-arid environments where fuels are organized in discrete clumps separated by bare ground. Mallee-heath (McCaw, 1997) and hummock grasslands (Burrows et al., 2009) in Australia, big sagebrush (Neuenschwander, 1980; Brown, 1982), oak chaparral (Lindenmuth and Davis, 1973) and pinyon-juniper (Hester, 1952; Bruner and Klebenow, 1979) in the interior Western US are cases in point. Development of a self-sustained flame front capable of bridging gaps in these fuel complexes requires reasonably dry and windy conditions. Brown (1982) suggests a 16-km h^{-1} eye-level wind speed as a minimum to allow for fire to spread in sagebrush stands with marginal grass cover. Lindenmuth and Davis (1973) found a corresponding value of 12-km h^{-1} for oak chaparral. McCaw (1997) identified an 8% fuel moisture threshold to allow for fire propagation in Western Australia mallee-heath. In semi-arid shrubland fuel types it is not uncommon that the conditions required to support fire spread will lead to crown fire propagation and high rates of spread. Lindenmuth and Davis (1973) point out that fire in oak chaparral "either burns fiercely or does not burn at all – no gradation in between". Billing (1981) indicates a 10-m open wind speed between 15 and 20 km h^{-1} and an associated rate of fire spread of approximately 1 km h^{-1} (17 m min^{-1}) as lower threshold requirements for sustained propagation to occur in mallee-heath shrublands of Victoria, Australia. The narrow range of environmental conditions that separate non-sustained propagation from high intensity fire propagation constitute a challenge to fire practitioners aiming to apply prescribed fire as a land management tool.

Mallee-heath shrublands in southern Australia are significant for their biodiversity and maintenance of populations of a wide range of vertebrate and invertebrate species (Enright et al., 2012; Bradstock and Cohn, 2002). Extensive fires, typically >10,000 ha but surpassing 100,000 ha when spreading under extreme burning conditions (Rawson, 1982; McCaw et al., 1992; Sandell et al., 2006) have the potential to burn a high proportion of remnant vegetation in these landscapes and cause the local extinguishment of certain species (Bradstock and Cohn, 2002). Prescribed burning is an effective method of creating a mosaic of seral stages (and fuel ages) that will meet biodiversity conservation goals and constrain landscape-level fuel continuity and the likelihood of large fire occurrence.

One of the main constraints to broader application of prescribed burning in the management of mallee-heath shrublands is the limited quantitative understanding of fire dynamics in highly discontinuous and heterogeneous fuel complexes, albeit that a heuristic understanding of fire behaviour exists from a number of studies documenting fire propagation in mallee-heath and mallee-spinifex fuel types (e.g. Rawson, 1982; Noble, 1986; Bradstock et al., 1992; Bradstock and Gill, 1993; Billing, 1981; Sandell et al., 2006; McCaw et al., 1992; McCaw, 1997; Cruz et al., 2010). Prediction of fire behaviour in these fuel complexes follows a two-step process (Gill et al., 1995; McCaw, 1995). The first component requires determining the environmental conditions that will allow the development of a self-sustained flame front i.e., a flame front where the propagating flux is sufficient to bridge fuel gaps. Failure to meet these requirements will result in fragmentation of the flame front into discrete units that will fail to breach fuel gaps and eventually lead to self extinguishment. The second component concerns the prediction of fire behaviour quantities used to support operational decision making, e.g., rate of spread, flame geometry, fireline intensity and spotting characteristics.

In this paper we develop an empirically-based fire behaviour model for mallee-heath shrublands using data from two independent experimental burning programs in semi-arid southern Australia. The model reflects the transitional fire behaviour of mallee-heath shrublands and includes separate equations to predict: (1) likelihood of sustained fire propagation; (2) rate of spread of surface fires; (3) onset of crown fire propagation; (4) rate of spread of active crown fires and (5) flame height associated with each fire propagation regime.

2. Methods

2.1. Data sources

2.1.1. Experimental sites

McCaw (1997) conducted 18 experimental fires in 200 × 200 m plots at the Stirling Range National Park in south-west Western Australia (WA) (34°31′S, 118° 15′E) between 1989 and 1992. This region experiences a dry Mediterranean climate with cool moist winters and warm dry summers. Annual average rainfall is 472 mm with monthly rainfall >50 mm during the five months from May to September and <25 mm from December to February. The experimental site was located on a broad plain at an elevation of 160 m above level, with brown sandy-gravel soil derived from laterite. The vegetation at the experimental site was mallee-heath with an overstorey stratum of *Eucalyptus pleurocarpa* and *Eucalyptus pachyloma*, an intermediate stratum up to 2.5 m tall of *Xanthorrhoea platyphylla*, *Hakea crassifolia*, *Banksia falcata* and *Banksia sessilis* (syn. *Dryandra sessilis*), and a species rich layer of dwarf shrubs up to 1 m tall comprised of *Banksia*, *Hakea*, *Isopogon*, *Beaufortia*, *Calothamnus*, *Calytrix*, *Chorizema*, *Daviesia* and *Jacksonia*. Vegetation was 20 years old (time since last fire) at the start of the experimental program.

Cruz et al. (2010) conducted a series of experimental fires at the Ngarkat Conservation Park (35°45′S, 140°51′E), South Australia (SA) between 2006 and 2008. A total of 27 experimental plots were prepared with sizes varying between approximately 250 × 250 m and 750 × 750 m. Annual rainfall of the area is 473 mm with a distinct annual cycle with a maximum of 63 mm in August and a minimum of 18 mm in February. The experimental site was approximately 130 m above sea level and located in a characteristic dune and swale system comprising large flat areas with relatively small dunes intermixed. Soils were aeolian sands of varying depth, overlying deep alluvial soils of the old River Murray delta (Specht and Rayson, 1957). Vegetation was characterized as open woodland with *Eucalyptus calycogona*, *Eucalyptus diversifolia*, *Eucalyptus incrassata* and *Eucalyptus leptophylla* as dominant overstorey species and an understorey *of Astroloma conostephioides*, *Adenanthos terminalis*, *Babingtonia behrii*, *Calytrix involucrata* and *Calytrix tetragona*. A ground layer of mixed grasses and sedges was also present. The vegetation had three age classes as a result of wildfires in 1958, 1986 and 1999.

Fig. 1 shows an idealized profile of the mallee-heath fuel complex representative of both experimental sites.

2.1.2. Fuel complex structure

Fuel load and structure were described using a combination of point intersect and destructive sampling (i.e., harvesting) methods. Destructive sampling was used to estimate fuel load in each layer (Fig. 1; litter, near-surface, elevated and overstorey; see Gould et al. (2011) for description of fuel layer definition), height, proportion of dead fuels and bulk density. Bulk density was calculated for each layer and aggregated to the fuel strata (surface and overstorey canopy) and fuel complex levels. Fuels were sampled on 1 m^2 or 2 m^2 quadrats systematically located along transects in experimental plots. Fuels were sorted and weighted in-situ with portable scales. After weighing, a subsample of each fuel category was taken in a sealed container for fuel moisture determination. Fuel moisture samples were oven dried at a nominal temperature of 100 °C for 24 h to determine their dry weight. A total of 300 and 308 sampling quadrats were sampled at the WA and SA sites respectively.

For the SA site fuels were also assessed using a visual fuel hazard scoring system that assigned numerical scores to the visually estimated cover and hazard of each fuel layer (Gould et al., 2011). These surrogates of fuel cover, load and arrangement provide a quantitative description of fuel hazard. The method has been used to describe fuel dynamics (accumulation through time) in dry sclerophyll eucalypt forests of the south-west WA (Gould et al., 2011). Numerical scores were able to explain fire behaviour such as fire rate of spread and flame height in this fuel type and predictive models were developed based on them (Cheney et al., 2012). The visual hazard scoring system was found to be robust (low observer bias) and to have a low implementation cost, making it a good alternative to other fuel sampling methods that are onerous and time consuming (e.g., destructive sampling). Hazard scores for the WA sites scores were interpreted from photographs.

2.1.3. Weather and fuel moisture

Air temperature and relative humidity were measured at 1.5 m above ground within 2 km of the experimental plots. For each WA experimental fire wind speed