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Development of a predictive model for estimating forest surface fuel load in Australian eucalypt forests with LiDAR data

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ABSTRACT

Accurate description of forest surface fuel load is important for understanding bushfire behaviour and suppression difficulties, predicting ongoing fires for operational activities, assessing potential fire hazards and assisting in fuel hazard-reduction burns to reduce fire risks to the community and the environment. Bushfire related studies and current operational activities have a common challenge in quantifying fuels, since the fuel load varies across the landscape. This paper developed a predictive model that efficiently and accurately estimates quantities of surface fuel in Australian southeast Eucalypt forests. Model coefficients were determined through a three-step process that attempts to evaluate how the spatial variation in surface fuel load relates to litter-bed depth, fuel characteristics, topography and previous fire disturbance. First, the forest surface fuel depth-to-load relationship was established; second, key quantitative variables of environmental factors were added; and third, important qualitative variables of fuel characteristics were included. The verification of model prediction was conducted through leave-one-out cross-validation (CV). Light Detection and Ranging was used to quantify forest structural characteristics and terrain features. The calibrated model had a R^2 of 0.89 ($RMSE = 20.7$ g) and performed better than the currently used surface fuel load models, including McArthur's ($R^2 = 0.61$ and $RMSE = 39.6$ g) and Gilroy and Tran's ($R^2 = 0.69$ and $RMSE = 36.5$ g) models. This study describes a novel approach to forest surface fuel load modelling using forest characteristics and environmental factors derived from LiDAR data through statistical analysis. The model established in this study can be used as an efficient approach to assist in forest fuel management and fire related operational activities.

1. Introduction

Fuel can be described by grouping vegetation communities into fuel types based on similar contribution to potential fire behaviour (Anderson, 1982). However fuel quantity and distribution are often not directly related to vegetation types; they may be extremely complex (Pyne et al., 1996). The variation in surface fuel load in eucalypt forests may be attributed to variability in species composition of overstorey and understorey vegetation, the extent and severity of previous disturbance events including fires and erosion, the site quality including soil quality, stocking rates and plant cover, the elevation, aspect and slope position which have impact on soil moisture and litter decomposition rates, and the moisture content of the leaf litter due to seasonal and diurnal changes (McCarthy, 2004; Tolhurst et al., 2008).

Determining surface fuel load traditionally involved collecting fine fuel from a defined sample area, sorting it to remove those fuel elements with a thickness greater than 6 mm, drying in an oven and then weighing to determine weight per unit area (McArthur, 1962; McCarthy et al., 1998). A landscape-scale fuel load was then estimated through extensive field inventories with sampling and statistical inference, which could be labour intensive and time consuming (Brown and Bevins, 1986; Burgan et al., 1998). A positive correlation between the depth of surface litter bed and the quantity of surface litter (depth-to-load relationship) proposed by McArthur (1962) has been used as a means of rapidly estimating fuel loads for fuel hazard-reduction burns in eucalypt forests (McCarthy, 2004). However the number of measurements taken in an area influences its accuracy, since large variation in surface fuel depth could be

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found at any given site within homogeneous vegetation (Gould et al., 2014). In addition, the fuel depth-to-load relationships vary between and across sites due to the high-degree of natural variability of overstorey and understorey vegetation species, topography, weather and previous fire severity and intensity (Birk and Simpson, 1980; McArthur, 1962).

The quantity of forest fuel after fire depends on the balance between rates of fuel accession and decomposition (Agee et al., 1973). When yearly decomposition equals yearly accession, fuel does not accumulate; when accession is more than decomposition, fuel builds up. Fuel accumulation models are used to estimate and predict quantities of fuel, which have been used to assist land management agencies in the decision making process (Gill, 1997; McCarthy et al., 1998). Fuel generally accumulates rapidly and steadily for a period of time after fires, and then the rate of accumulation reduces gradually to the level of equilibrium (Olson, 1963). This trend was described and modelled by several studies (Birk and Simpson, 1980; Burrows, 1994; Gould et al., 2011; Olson, 1963; Raison et al., 1983, 1986) using a general form of an exponential function rising to a steady-state fuel load (a maximum):

$$w_t = w_{ss}\left(1 - e^{kt}\right) \tag{1}$$

where w_t represents the weight of surface litter fuel accumulated at time t years since the last fire, w_{ss} is the weight of surface fuel accumulated under steady state conditions, k is defined as the decomposition constant. Given by the general form of the fuel accumulated model, years since last fire is the only independent variable to predict fuel load growth, and it therefore cannot be utilised to estimate spatial variation in fuel load within homogeneous vegetation. As a result, the pattern of fuel accumulation varies with vegetation species and environmental conditions (Birk and Simpson, 1980; Burrows, 1994; Chatto, 1996; Fox et al., 1979; Raison et al., 1983; Tolhurst and Kelly, 2003; Walker, 1981).

Unlike fuel accumulation models, other studies used the influencing factors as predictors to estimate the spatial variation in surface fuel load. Agee et al. (1973) used basal area as an index of crown volume and plotted a polynomial relationship between basal area of *blue gum* (*Eucalyptus globulus*) and its dry weight of fuel, including duff, litter and large debris. The result shows that as basal area increases, the total dry fuel weight rises, which may also be explained from a fuel accession perspective, greater crown area and crown volume result in more fuel on the surface fuel layer. Bresnehan (2003) suggested that forest fuel type, canopy density and soil type may be used to estimate fuel load as an adjunct to the fuel accumulation models on the sites where years since last fire is not given. Canopy density directly impacts on fuel accession and elevation indirectly influences fuel productivities and decomposition rates due to its effect on temperature (Birk and Simpson, 1980; McArthur, 1962; McCaw et al., 1996; Schaub et al., 2008). A multiple regression analysis was applied in Gilroy and Tran (2006) to describe how the surface fuel load relates to more predictors, including years since last fire, fuel depth, canopy density, and average annual rainfall since fire. The model in their study suggests that years since last fire, fuel depth and canopy cover contribute more to surface fuel loading compared with the average rainfall in the study area. These authors suggested that their model could be enhanced by inclusion of other surface fuel load related predictors. Consequently, the development of such predictive models requires specific inputs.

The development of remote sensing technologies could potentially increase the accuracy and also reduce the time required to quantify fuels, by providing a continuous dataset from which to assess fuel conditions across large scales; it also has the potential to update fuel maps quickly and consistently in areas where conditions are dynamic due to disturbances caused by fires and other changes (Keane et al., 2001; López et al., 2002; Skowronski et al., 2007). Optical remote sensing (e.g. ASTER, Landsat, SPOT-HRV, and aerial photo) has been widely used in classifying canopy fuel type, estimating percentage canopy cover and foliage biomass (Arroyo et al., 2008; Saatchi et al., 2007).

Several studies used optical imagery - derived forest and environmental factors as explanatory variables in order to develop the predictive models to describe the spatial variability of forest fuel load (Brandis and Jacobson, 2003; Saatchi et al., 2007). In these studies, multiple regression was applied to determine which independent variables (e.g. spectral bands, forest class, structural stage, potential vegetation type, cover type, elevation, slope and aspect) have more significant impact on the response variable of interest - the fuel load. These models showed a range of 55%–72% of variability in prediction bias, the major limitation in estimating surface fuel derived from optical remote sensing being an inability to penetrate the canopy (Andersen et al., 2005; Lovell et al., 2003). Radar data has also been used to predict these canopy fuel attributes as well as crown bulk density (Saatchi et al., 2007). However, both satellite and airborne radar have limitations in estimating surface fuel load that requires very fine spatial resolution of cm or mm (Riaño et al., 2003).

Recently, Laser altimetry or Light Detection and Ranging (LiDAR) including airborne and terrestrial LiDAR has been used in estimating individual tree heights (Chen et al., 2006; Gougeon, 2000; Popescu, 2007), quantifying forest inventory (Maas et al., 2008; Næsset, 2004), leaf area (Béland et al., 2014), biomass (Lefsky et al., 1999a,b; Popescu, 2007; Tao et al., 2014), and safety zone identification for forest fire fighters (Dennison et al., 2014), with its ability to provide three-dimensional information to quantify forest structure with high spatial accuracies. Some studies have explored statistical distribution functions to represent the vertical profile of vegetation structure using full waveform LiDAR (Hermosilla et al., 2014; Lefsky et al., 1999a,b; Wagner et al., 2008), multi-echo LiDAR data (Lovell et al., 2003; Riaño et al., 2003), and terrestrial LiDAR data (Côté et al., 2011; Marselis et al., 2016), which indicates its potential for surface fuel load estimates (Jakubowksi et al., 2013; Skowronski et al., 2007).

Terrestrial and airborne LiDAR data were applied in this study to provide a continuity of spatial variation in surface fuel depth and cover, topography and canopy density. This study used the Upper Yarra Reservoir Park area as a case study area to model forest surface fuel load using multiple regression analysis. Unlike the fuel accumulation studies, it assessed how the spatial variation in fuel load relates to the separate and related influencing factors, including litter-bed depth, fuel types and environmental conditions. Comparing with the currently used models, the LiDAR-derived independent variables improved the efficiency and the accuracy in developing the predictive model of surface fuel load for eucalypt forests with high a spatial resolution. This study developed a novel approach to assist fire authorities in assessing fire hazards and guiding prescribed burns for bushfire risk mitigation.

2. Methods

2.1. Study area

The study was conducted in the Upper Yarra Reservoir Park in southeast Australia (Fig. 1a). It is located east of Melbourne, within the locality of Reefton (37°41′S, 145°55′E). The Reservoir Park is a eucalyptus open forest with a dense shrubby understorey, which has a large number of indigenous eucalypt species, including Manna Gum (e.g. *Eucalyptus viminalis*), Grey Gum (e.g. *Eucalyptus*