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Eco-hydrological controls on microclimate and surface fuel evaporation in complex terrain

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ABSTRACT

The micrometeorological factors driving variation in litter moisture (GWC_{lit}) at the landscape scale are poorly understood, particularly in areas with heterogeneous vegetation and complex terrain. In this research we seek to quantify how climate and eco-hydrology contribute to variation in litter moisture and potential evaporation at the forest floor. Research sites were established at 12 locations in southeast Australia with variable precipitation, solar exposure, and drainage position. We measured solar radiation, air temperature, relative humidity, litter moisture, and litter temperature. Spatial patterns of GWC_{lit}, examined during two drying phases, show that moisture in the litter and its rate of evaporation are closely linked to vegetation density, which is largely a function of aridity. This creates a pattern whereby aridity-related differences in vegetation structure controls the spatial variation in GWC_{lit}, with regional effects being driven by precipitation while local effects are caused by variation in solar exposure and drainage position. By parametrising a model of daily potential evaporation (E_p) at the forest floor we explore how vegetation and topography influence evaporative demand above the litter layer. The model shows that E_p is driven primarily by net radiation and that the role of vapour pressure deficit is almost negligible due to high moisture content within the sub-canopy air mass and high aerodynamic resistance. In dry forests the net radiation is directly related to shortwave radiation and E_p remains high despite low temperatures. In the tall wet forests, commonly found at high elevations, along drainage lines and on slopes with polar-facing aspects, the long-wave radiation (i.e. temperature) was just as important for E_p as the shortwave radiation. Low energy inputs to the forest floor in these tall forests means that a significant rainfall event results in surface fuels that remain wet for much longer than fuels in the dry open forest. This leads to a spatial pattern of flammability whereby surface fuels in densely vegetated areas are more often less likely to burn than those in the open forests. These wet compartments limit landscape-scale fire activity by creating dis-connectedness in the available fuel. Heatwaves and the duration of dry spells determine the degree with which these wet compartments persist as barriers to fuel connectivity through a fire season. Elsewhere in the landscape, however, the large inputs of shortwave radiation to the forest floor means that surface fuels reach flammable conditions within several hours or days after rainfall and are therefore flammable for much of the fire season.

1. Introduction

The litter layer (otherwise known as fine surface fuel) is an important component of fire regimes in forests (Catchpole, 2002; Viegas et al., 1992; Wotton, 2009). This layer of dead biomass can comprise a large component of the overall fuel load, and its amount and moisture status can determine fire ignition probabilities and fire behaviour (Duff et al., 2013; Gould et al., 2011; McArthur, 1967). Furthermore, this fuel source can often be managed effectively with prescribed burning (Birk and Bridges, 1989), so there has been much effort in developing tools for predicting its accumulation rates and moisture dynamics. After fire, the accumulation of fine fuel is a function of litter input from live biomass and decomposition, both varying with climate but typically following a negative exponential accumulation curve (Olson, 1963; Ossola and Nyman, 2017; Raison et al., 1983; Thomas et al., 2014). In temperate eucalypt forests of Australia, the accumulation of surface fuel after fire approaches an asymptote at about 5–10 years after burning, stabilising at loads in the range of 10–20 t ha^{-1} (Duff et al., 2013; Gould et al., 2011; Thomas et al., 2014), with values a function of system productivity.

The availability of surface fuels to burning depends on their moisture content (Plucinski and Anderson, 2008; Possell and Bell,

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2013), which is determined by the hydrological properties of the litter, precipitation and the microclimate above and within the litter layer (Matthews, 2006). In wet conditions when gravimetric water content of litter (GWC_{lit}) is above the fibre saturation point ($> \sim 0.35\,\mathrm{kg\,kg^{-1}}$), the temporal changes in moisture content are caused by drainage and evaporation of free water. In dry conditions when $GWC_{lit} < \sim 0.35\,\mathrm{kg\,kg^{-1}}$ the temporal changes in moisture content is caused by desorption and absorption of moisture as the litter approaches some equilibrium moisture content (EMC) with the surrounding atmosphere. The bulk of research on moisture contents of surface fuels has focused on representing changes in moisture of dry fuels when the assumptions underlying EMC models are applicable (Catchpole et al., 2001; Matthews et al., 2010; Resco de Dios et al., 2015; Sharples and McRae, 2011; Slijepcevic et al., 2013). Resolving variation in moisture contents in this low range of GWC_{lit} is important for predicting fire behaviour and ignition probabilities in a dry and flammable landscape when fuels are within the ignitable range.

However, in landscapes with complex topography and variable vegetation, the range of GWC_{lit} at any particular point in time may be very large, resulting in fine surface fuels that are in different stages of drying depending on the attributes of the specific location (Cawson et al., 2017; Gibos, 2010; Nyman et al., 2015; Slijepcevic et al. (in press)). A wide range of GWC_{lit} can therefore co-exist in the landscape over relatively small spatial scales. For instance, in a study of topographic effects on litter moisture Nyman et al. (2015) found that the difference in moisture content as a result of slope orientation (aspect and slope gradient) meant that ~50% of the time during summer the assumptions associated with EMC models would apply to the equatorial-facing slope but not the polar-facing slope, limiting the predictive capacity of these models to only a fraction of the landscape. More shaded conditions on the polar-facing slopes meant that the dominant hydrological process controlling flammability of the litter was related to evaporation of free water and not desorption/adsorption processes associated with GWC_{lit} changes in dry fuel beds. In landscapes where a wide range of moisture contents co-exit, the rate at which water evaporates from fuels in wet and shaded parts of the landscape (when $GWC_{lit} > 0.35\,\mathrm{kg\,kg^{-1}}$) may be more important for ignition and fire spread across the landscape than the exchange of moisture within fuels that are already dry ($GWC_{lit} < 0.35\,\mathrm{kg\,kg^{-1}}$). High moisture contents in wet and shaded parts of the landscape promote patchiness in flammable surface fuel, thus reducing the likelihood of ignition sources (e.g. lightning) translating to active fire, and limiting fire spread in the event of a fire having started in a dry patch (Sharples, 2009). These factors related to spatial variation in GWC_{lit}, patchiness and connectivity of fuels are particularly important during benign fire weather (e.g planned burning) when fire behaviour and burn outcomes are most sensitive to flammability differentials (Bradstock, 2010; Bradstock et al., 2010; McCaw, 2013; McRae et al., 1979).

Existing process-based models for predicting GWC_{lit} take into account the full spectrum of hydrological processes underlying moisture dynamics in fuels in both wet and dry conditions (Matthews, 2006; Nelson Jr., 2000). However, the capacity to implement these models at the landscape scale is limited because we currently lack sufficient insight into the interactive effects of topography, climate and vegetation on the driving variables that control fuel moisture at the forest floor. Variation in vegetation structure with slope orientation and drainage position can be large (Gutiérrez-Jurado and Vivoni, 2013; Kirpatrick and Nunez, 1980; Nyman et al., 2015; Zhou et al., 2013), which in turn affects the local energy and water budget. And variation in vegetation structure with topography depends on climate. For instance, in a location with very high precipitation where is water not limiting, the vegetation structure is less dependent on aspect and drainage position than in a location where water is limiting. So changes in vegetation structure and the partitioning of energy into transpiration and evaporation across topographically complex landscape are sensitive to the amount of water that is available for plants to growth (Huxman et al., 2005).

Most of the recent efforts to measure and model the effects of vegetation on below-canopy microclimate have been aimed at improving predictions of snowmelt, which is function of the same variables that drive evaporation from fuels (Hardy et al., 2004; Moeser et al., 2014; Musselman et al., 2012; Reid et al., 2014; Seyednasrollah and Kumar, 2014). These studies and those from the fire literature (Schiks et al., 2015; Thompson et al., 2015; Walsh et al., 2017) have shown that microclimate on the forest floor is highly sensitive to forest structure. However, there are few studies that quantify the impacts of vegetation on microclimate more broadly across a landscape with complex terrain where eco-hydrological feedbacks result in complex patterns of spatial variability in vegetation, and where microclimate is subject to combined effects of terrain and vegetation. The paucity of research in this area limits our capacity to understand and model how surface fuel in forested landscapes dry out and become available to burn. How do the interactive effects of vegetation and topography play out in terms in spatial patterns of fuel moisture, microclimate and forest floor evaporation? What are the implication of these effects for predicting fuel moisture variation across complex landscapes? These questions are particularly pertinent in water limited environments where small changes in radiation and rainfall has large implications for eco-hydrology and fire regimes (Boer et al., 2016; Wang et al., 2014; Zhang et al., 2017a).

In this study we therefore aim to quantify the interactive effects of topographic position, aridity and vegetation cover on litter moisture, microclimate and potential evaporation above the forest floor. The work is set in context of fuel moisture dynamics and fire regimes but has application to hydrological processes and partitioning of evaporation and transpiration in these systems more generally. The aims are achieved by;

1 Monitoring litter moisture in different topographic positions across a rainfall gradient and examining the landscape-scale implications of the observed spatial variation.
2 Parameterising models of net radiation and potential evaporation below forest canopies in complex terrain using microclimate data from instrumented plots.
3 Using the models to identify major factors underlying variation in evaporation from the litter layer.

2. Methods

2.1. Overview

Data on microclimate and litter moisture were collected at 4 sites with different mean annual precipitation (MAP). At each of the 4 sites, experimental plots (20 × 20 m) were established in different positions with contrasting aspect and contributing drainage area. There are a total of 12 experimental plots. Data from these plots were used to i) quantify variation in litter moisture across the domain, and ii) parameterise a model of net radiation and potential evaporation (E_p) above the forest floor. The E_p model and the radiation terms within it were used to examine the interactive effects of topography, vegetation and aridity (the long term balance of precipitation and radiation) on microclimate in forests and evaporation from the litter layer. The methods first describe the field instrumentation (Section 2.2), the sensor calibration (Section 2.3), and finally the analysis (Section 2.4), with separate section on spatial-temporal patterns of variation in litter moisture (2.4.1) and models of E_p and net radiation (2.4.2).

2.2. Field experiments–sites and instrumentation

The sites are located in a region northeast of Melbourne in southeast (SE) Australia (Table 1, Fig. 1) with strong rainfall gradients, and encompass forests that are representative of a large proportion of the SE