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Measurement of topographic controls on the moisture content of surface fuels in south east Australian forests

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Abstract: Prediction of fuel moisture content (FMC) is important for estimating the rate of spread of wildfires, the ignition probability of firebrands, and for the efficient scheduling of prescribed fire. The moisture content of fine surface fuels varies dramatically at a range of spatial scales; at large scales (10's to 100's km) due to variation in meteorological variables (eg. temperature, relative humidity, precipitation), and at smaller scales (100's of metres) in steep topography due to factors that include differences in radiation due to aspect and slope, differences in precipitation, temperature and relative humidity due to elevation, and differences in soil moisture due to hillslope drainage position. Forest structure and canopy shading responses to these topographic influences adds further to the spatial variability in surface fuel moisture. Finally, it is likely that the interactions between these topographic influences, vegetation response and fuel moisture content will vary across climatic gradients, potentially creating a high level of complexity in the relationship between topography and fuel moisture. As a result of this complexity there have been few attempts to model FMC at smaller spatial scales that could assist fire managers in prediction and planning. In this study we aim to "untangle" these factors, and in particular answer the following questions i) How does fuel moisture vary with aspect? ii) How does fuel moisture vary with hillslope drainage position? iii) How do these topographic variables interact with vegetation structure to result in net FMC effects, and iv) How do these topographic and vegetation interactions change along a climatic gradient? To achieve the project aims, a new method was developed and validated to enable the monitoring of FMC over seasonal timescales. Microclimate stations were established in southeast Australian forests to monitor surface fine fuel moisture at 15-minute intervals using these newly developed instrumented litter packs, in addition to temperature and relative humidity measurements inside the litter pack, and measurement of precipitation and energy inputs above and below the forest canopy. Stations were established to monitor FMC and microclimate throughout a fire season across a gradient of aspect, drainage position, forest structure, and climate in order to address the research objectives. Preliminary conclusions from three months of data collection are that; 1) aspect effects on FMC are mostly due to secondary effects on canopy cover and shading, rather than the direct effect of aspect on incoming above-canopy radiation, 2) drainage position influences FMC due to the secondary effects on canopy cover and shading as well as the direct effect of drainage area on soil moisture, and, 3) as a result, both aspect and drainage position effects on FMC are strong when they result in significant change in canopy cover, and weak when they don't, resulting in highly variable topographic effects across a climatic gradient. These results based on an unprecedented field measurement campaign provide a major step forward towards the larger goal of constructing high spatial resolution models of FMC for implementation in complex landscapes.

Keywords: *Fuel moisture, bushfire, radiation, aspect, spatial variability, downscaling*

1. INTRODUCTION

The prediction of fuel moisture content (FMC) is important for estimating the rate of spread of forest fires, the ignition probability of firebrands, and for the efficient scheduling of prescribed fire (Matthews 2014). The moisture content of fine surface fuels varies spatially at large scales (10's to 100's km) due to variation in meteorological variables such as temperature, relative humidity, and precipitation (Schunk et al. 2013, Sullivan and Matthews 2013). At smaller scales (100's to 1000's of metres) in steep topography spatial variability is attributed to topographic influences that include differences in radiation due to aspect and slope, differences in precipitation, temperature and relative humidity due to elevation (not investigated here), and differences in soil moisture due to hillslope drainage position (Schunk et al. 2013).

Secondary effects of these variables on forest structure and canopy shading adds further to the spatial variability in surface fuel moisture (Nyman *et al.* 2015). Initial qualitative observations suggest that the magnitude of the effect of aspect and drainage position on FMC varies as a function of *aridity* (a function of average precipitation and radiation at a location). Aridity impacts on vegetation properties (Nyman et al. 2014, Nyman et al. 2015) which in turn affects the transmission of radiation to the forest floor. Models that predict the combined and interactive effects of topography and vegetation on radiation are available (e.g. Seyednasrollah and Kumar 2014) but have rarely, if ever, been implemented in fuel moisture research. This is a major limitation in the implementation of process-based FMC models at a landscape scale.

Quantification of the relationship between topography and vegetation on FMC variability will assist in the further development, parametrisation and testing of FMC models (eg. Matthews 2006, Slijepcevic et al 2013, Sharples and McRae 2011) for use in complex terrain. More specifically, time series of FMC is required to test models while data on forcing variables such as radiation, temperature and relative humidity are needed to parametrise the models. The overall project objective was to produce data that will provide a basis on which to model the moisture content of fine surface fuels in complex topography with heterogeneous vegetation. The specific aims were twofold:

i) To measure the effect of slope and aspect on FMC in different rainfall regimes.

ii) To measure the effect of drainage position on FMC on different topographic aspects.

Measurements were made across an *aridity* gradient, using an orographic rainfall gradient for the first aim, and an aspect-based radiation gradient for the second aim. The second aim used different drainage position to explore aspect-effects for different contributing areas. Interactions between these factors and vegetation cover were assessed.

2. METHODS

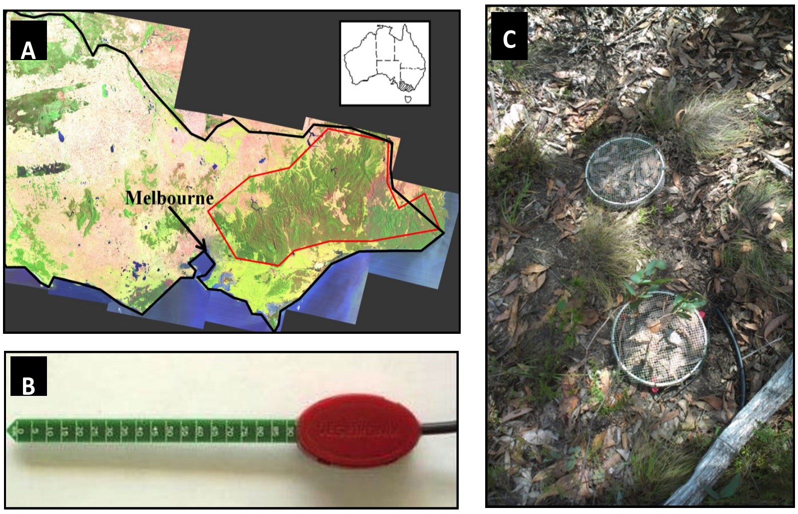

Figure 1. a) The location of the experimental area in Victoria, Australia, b) the litter fuel moisture sensors, and c) the instrumented litter packs with the sensors installed.

Experimental plots were located in south east Australia in the *Eucalyptus* forests of the Great Dividing Range (Figure 1a). Microclimate stations were established to monitor surface fine fuel moisture (every 15 minutes) using newly developed instrumented litter packs (Figure 1b&c), in addition to temperature and relative humidity measurements inside the litter pack, and measurement of precipitation, wind, and radiation inputs above and below the forest canopy. All sites were instrumented with four litter packs surrounding a central post on which the other sensors were mounted. Litter packs were made from plastic pipe (Figure 1c), (diameter=24cm, depth= 4cm) which were instrumented with three VH400 sensors (Vegetronix Inc) (Figure 1b), that were inserted horizontally through holes that had been drilled into the side of the pipe. The voltage output from the sensors was converted to FMC (%) using a calibration function which was obtained using manual gravimetric measurements of litter moisture (e.g. Nyman et al. 2015).

Leaf and stem area index (LSAI) was measured at each plot from 3 hemispherical photos. Aridity was obtained from calculations in Nyman et al. (2014). These values are based on spatially interpolated climate data and may not be representative of the exact conditions at each site. Site properties are listed in Table 1. Specific methods to achieve aims 1 and 2 are described further below.

Table 1. Properties of the fuel moisture monitoring plots.

Site	Aspect	Drainage area (ha)	LSAI	Aridity
Sugarloaf	North	0.1	1.73	2.4*
	South	0.1	2.08	1.8*
Maroondah	North	0.1	2.39	2.5
	South	0.1	2.68	1.9
Upper Yarra	North	0.1	3.1	2.2
		0.3	2.6	2.2
		2.0	1.97	2.1
	South	0.1	4.22	1.4
		0.3	5.31	1.5
		2.0	3.41	1.8
Woods Points	North	0.1	3.35	1.7
	South	0.1	3.78	1.5

*The actual aridity at this site is higher. Spatially interpolated rainfall data from the Bureau of Meteorology returns annual rainfall values that are too high for this location.

2.1. Aspect effects on fuel moisture content

FMC was monitored at 15-min intervals for 3 months at four paired north (more arid) and south (less arid) facing locations along a rainfall gradient from 800 to 1700 mm/year, while holding other factors as constant as possible. The forest types range from open dry woodlands (Peppermint and Box *Eucalyptus*) to wet montane forest (Alpine Ash).

2.2. Drainage position effects on fuel moisture content

FMC was monitored at 15-min intervals for 3 months at both north (more arid) and south (less arid) facing locations with drainage areas of 0.1, 0.3 and 2.0 ha, while holding other factors as constant as possible. The two smaller drainage areas were located on hillslopes on opposite sides of an east-west facing ridgeline. The plots in larger drainages areas were located in small convergent headwaters on a separate hillslope. The vegetation on the south aspects was dominated by Mountain Grey Gum and Mountain Ash. North facing slopes were dominated by Peppermint and Stringybark.

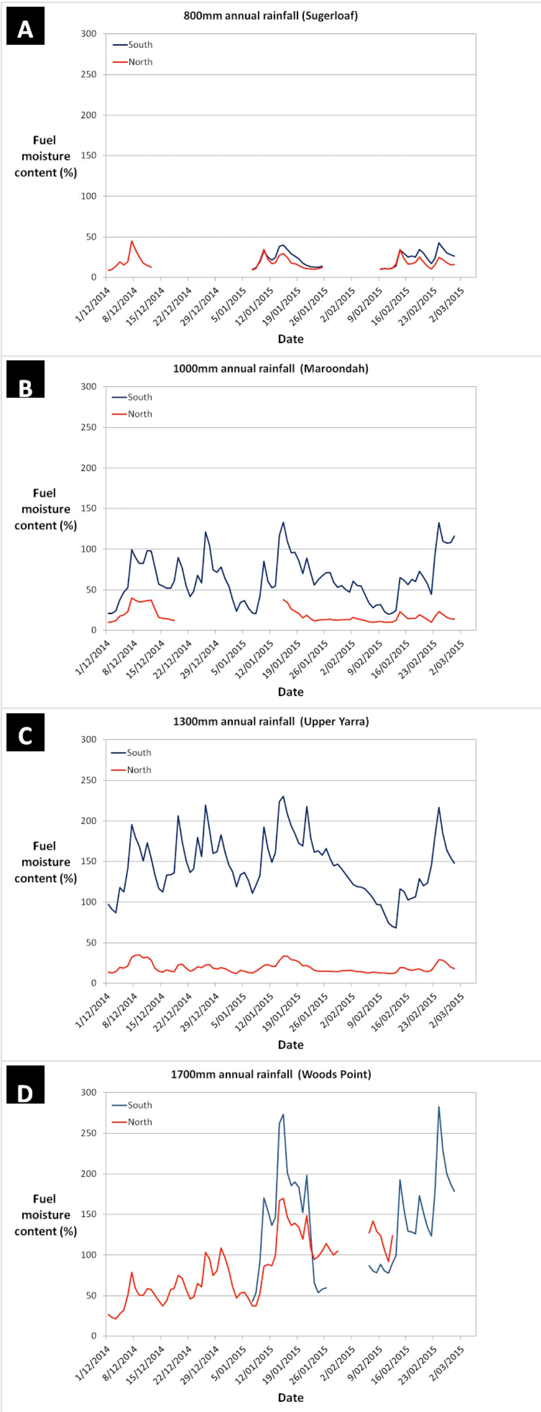

Figure 2. Measured differences in FMC for a three month period across north facing (more arid, red lines) and south facing (less arid, blue lines) aspects across four sites (Figures 2a to 2d) with different average annual rainfalls (800, 1000, 1300 and 1700 mm per annum). Time periods of missing data are due to sensor issues from lightning, faulty batteries and animal interference with wires.

3. RESULTS AND DISCUSSION

3.1. Aspect effects on fuel moisture content

FMC differences across different aspects (ie. North vs South facing) were smallest at the wettest (1700 mm annual rainfall, Figure 2d) and driest (800 mm annual rainfall, Figure 2a) locations, and at a maximum at the intermediate (1300 mm annual rainfall, Figure 2c). The large observed aspect effect on FMC at intermediate annual rainfall values (Figure 2c) probably results from the interaction between radiation, water availability, canopy cover, shading, and FMC. In wet areas (Figure 2d) canopy closure is very high and small aspect related changes in radiation cannot change the already closed canopy very much. North and south facing areas therefore experience similar levels of shading, resulting in similar FMC's. In low rainfall areas (Figure 2a) the stand density is lower and the canopy is already very open, so small aspect related changes in radiation again have little effect on canopy closure. North and south facing areas again experience similar levels of shading, resulting in similar FMC's (although considerably lower on average here than at the wettest site). However for areas with intermediate rainfall (and aridity), small aspect related changes in radiation appear to result in large changes in canopy cover. As a consequence, north and south facing aspects have very different levels of shading, resulting in the large aspect related differences in FMC observed in Figure 2c.

3.2. Drainage position effects on fuel moisture content

On the north facing slope (Figure 3, right) the FMC varies systematically and tends to increase with catchment area, while soil moisture appears to be relatively insensitive to catchment area. However cumulative per-unit-area under-canopy radiation decreases as catchment area increases, suggesting the observed FMC differences are related to increased canopy shading.

In contrast, on the south facing slopes (Figure 3, left) there is no apparent systematic relationship between FMC and catchment area, and cumulative under-canopy radiation does not vary between the sites, indicating that canopy shading is not a key driver of FMC differences. It seems that high soil moisture on the mid-slope position (0.3 ha) is resulting in this plot having much higher FMC. The reason for the high soil moisture at this plot may be due to subsurface processes and a saturated soil profile. At the plot with the largest drainage area the soil was observed to be very water repellent and the soil moisture dynamics was therefore different to the other plots on the south aspect.

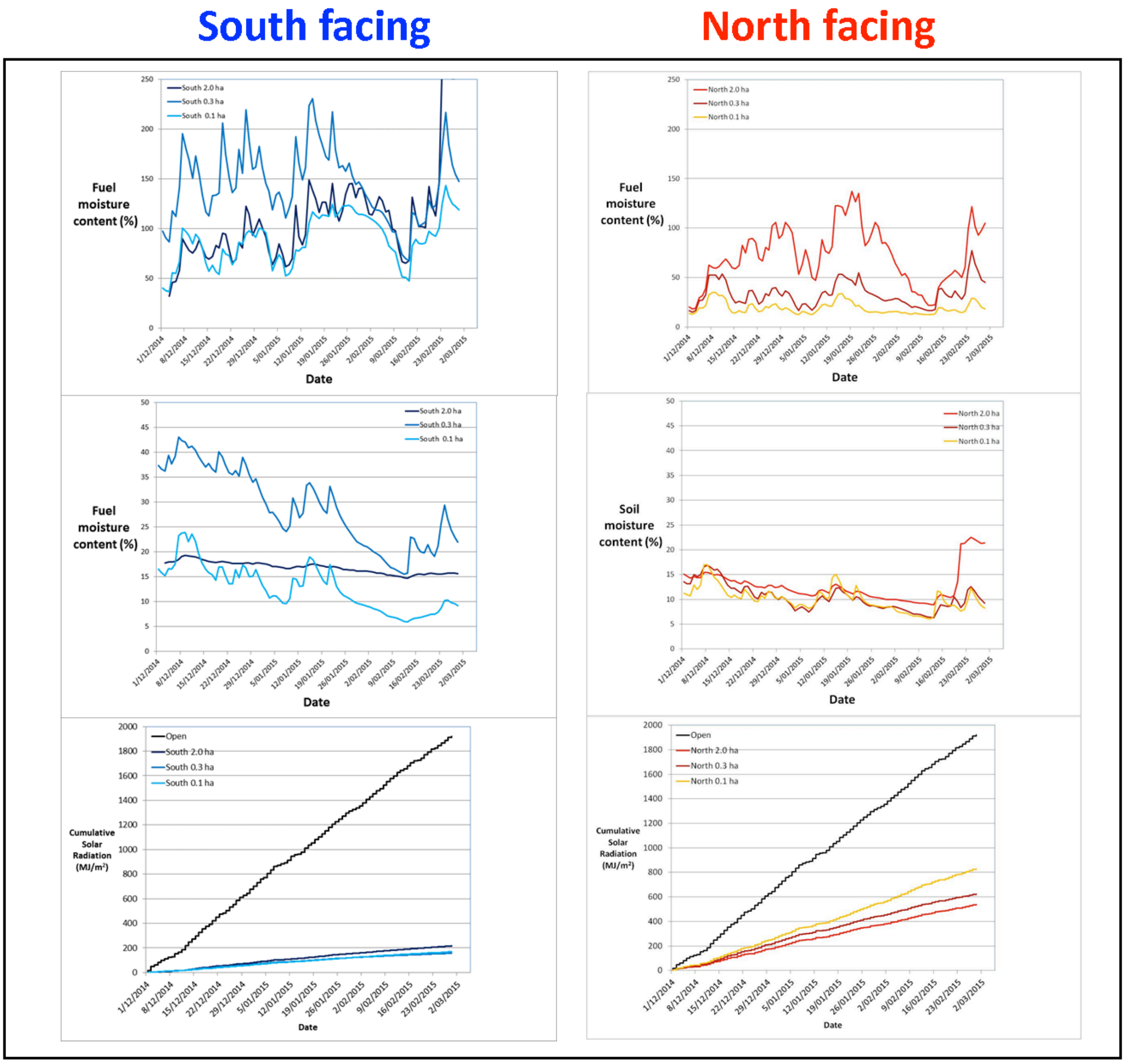

Figure 3. Fuel moisture content (top), soil moisture content (middle) and cumulative solar radiation (lower) for south facing (left) and north facing (right) sites over a three month period. Solar radiation is the horizontal component under the canopy. Differences between plots are therefore due to shading by vegetation and the surrounding terrain. Corrected radiation for slope orientation to get the incident radiation would results in even larger differences between north and south sites.

4. CONCLUSIONS

Preliminary conclusions from the data are that:

- Aspect effects on FMC are probably due to *secondary* effects on canopy cover and shading, rather than the *direct* effect of aspect on incoming above-canopy radiation.
- Drainage position influences FMC probably due to the *secondary* effects on canopy cover and shading, rather than the *direct* effect of drainage area on soil moisture. However, the increased soil moisture with increased drainage area may also be an important factor.
- As a result, both aspect and drainage position effects on FMC are strong when they result in significant change in canopy cover, and weak when they don't (a result consistent with the findings of Gibos 2010).

- These results suggest that understanding the interaction between topographic variables and canopy cover is critical for the development of high resolution models of FMC.

This work is ongoing, and current efforts are directed towards the development of a high resolution model of sub-canopy radiation and microclimate that can be used to drive mechanistic models of fuel moisture such as that of Matthews (2006).

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