



WIND SPEED REDUCTION INDUCED BY POST-FIRE VEGETATION REGROWTH

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ABSTRACT

In the current suite of operational fire spread models, wind speeds measured in the open environment (above the vegetation layer) are modified to represent wind speeds at 'mid-flame' height using adjustment factors. In general, these adjustment factors assume constant vertical wind speed profiles throughout the vegetation layer. However, empirical studies have shown that wind speeds beneath canopies can vary significantly with height above ground as well as with forest type and prevailing wind speed. Empirical wind reduction profiles have been developed for a number of different forest types in flat terrain using data collected across Victoria, Australia.

The present research aims to extend these empirical studies to better understand the impacts of topography and post-fire vegetation regrowth on the reduction of wind speeds beneath the canopy. Wind data collected over fire affected regions of rugged terrain in South Eastern Australia are used to analyse wind speed reduction induced by post-fire regrowth and complex topography. A secondary study is used to analyse wind speed reduction caused by Radiata pine plantation in undulating terrain.

Results of this study suggest that empirical wind reduction profiles perform well at the broader landscape-scale, i.e. ridge tops and valley floors. However, more complex topographical features appear to have a compounding affect on wind speed reduction within rugged terrain. Through better understanding of wind speed reduction beneath the canopy across landscapes from mountainous ranges through to flat plains, wind speed reduction models for bushfire spread prediction can be adapted to incorporate the variation observed in vertical wind speed profiles within the vegetation layer.



1 INTRODUCTION

Vertical wind profiles within the boundary layer are most often described using a logarithmic profile (Touma, 1977). This profile becomes disturbed near the surface due to roughness of varying lengths, from topographical scales down to vegetation (Finnigan, 2000; Belcher et al., 2012). These disturbances close to the ground, or at 'mid-flame height' are the wind patterns that drive surface bushfires beneath the canopy. In the current suite of fire spread prediction models, wind speeds measured in the open environment (with no vegetation or above the vegetation layer) are translated to predict wind speeds within forests or vegetation using adjustment factors. The 'wind reduction factor' (WRF) (Cionco, 1972; Rothermel, 1972) and 'wind adjustment factor' (WAF) (Andrews, 2012) are defined empirically for a number of structural vegetation features including crown ratios and vegetation age.

Both the WRF and WAF assume the wind reduction profile to be constant throughout the vegetation layer, whereas Moon et al. (2013) presented empirical wind speed profiles for different forest types, showing that wind speed profiles within the canopy were in fact non-constant. These wind profiles varied considerably with prevailing wind speeds as well as height above ground within the canopy. Cruz and Alexander (2013) noted that aside from topographical features, the principal drivers behind the behaviour of spreading fires are fuel moisture and wind speed; it can therefore be asserted that along-side the recognition by VanWagner (1989) that the prediction of surface fires may well be more difficult than that of crown fires due to the complexity of understorey fuels, the variation of wind fields within the vegetation layer adds further complications to the modelling of surface fires spreading beneath the canopy.

Since fire spread prediction models are not immune to the effects of error accumulation, and it has been noted that the main sources of errors in fire model predictions include input data error (Cruz and Alexander, 2013), it is within the interest of the fire research industry to better understand, and therefore model, the variability of wind fields within vegetation layers. Recent work (Moon et al., 2016) has shown that wind reduction profiles within the canopy depend upon open wind speeds and height within the layer. An empirical GAMS (general algebraic modelling system) model is under development to model wind reduction profiles under various conditions.

This new model for wind reduction profiles is based upon data collected in flat terrain areas, where the impacts of topography were intentionally minimised. Although there is a significant body of work on wind behaviour over topographical features such as hills, escarpments or wind breaks (Holmes et al., 1997; Glanville and Kwok, 1997; Cleugh, 2002; Allen, 2006), these studies focus on the wind behaviour and profiles above such features or in areas of minimal vegetation, rather than the impacts of such features on the wind fields experienced on the ground, especially within the vegetation layer.

This study aims to extend the work of Moon et al. (2013, 2016) to understand the impacts of vegetation regrowth on wind speeds experienced within the canopy over complex terrain. Wind data collected across sites in South-Eastern Australia are used to evaluate the applicability of the empirical wind profiles



described in Moon et al. (2013, 2016) to rugged landscapes, particularly valley structures within mountain ranges and ridge top spurs across undulating hills.



2 DATA AND METHODS

2.1 CASE STUDIES

In this research, wind data were collected across two case studies. Davis Vantage Pro 2 Portable Automatic Weather Stations (PAWS) with cup anemometers were used to collect wind data at a height of 5 metres above ground level. These stations also collected data on temperature, relative humidity and solar radiation. In both case studies, the weather stations were located within vegetated areas.

In 2003, much of the mountainous region west of Canberra was devastated by bushfires. The fires spread rapidly from the Brindabella Ranges through to the edges of the city, exhibiting extreme fire behaviour which has been extensively documented (e.g. McRae, 2004; Sharples et al., 2012). The Flea Creek Valley (FCV) area (approximately 70km west of Canberra) was heavily burnt by the McIntyres Hut fire which ignited along the Goodradigbee River. The North-South valley runs approximately perpendicular to the dominant prevailing West-North-Westerly (WNW) winds.

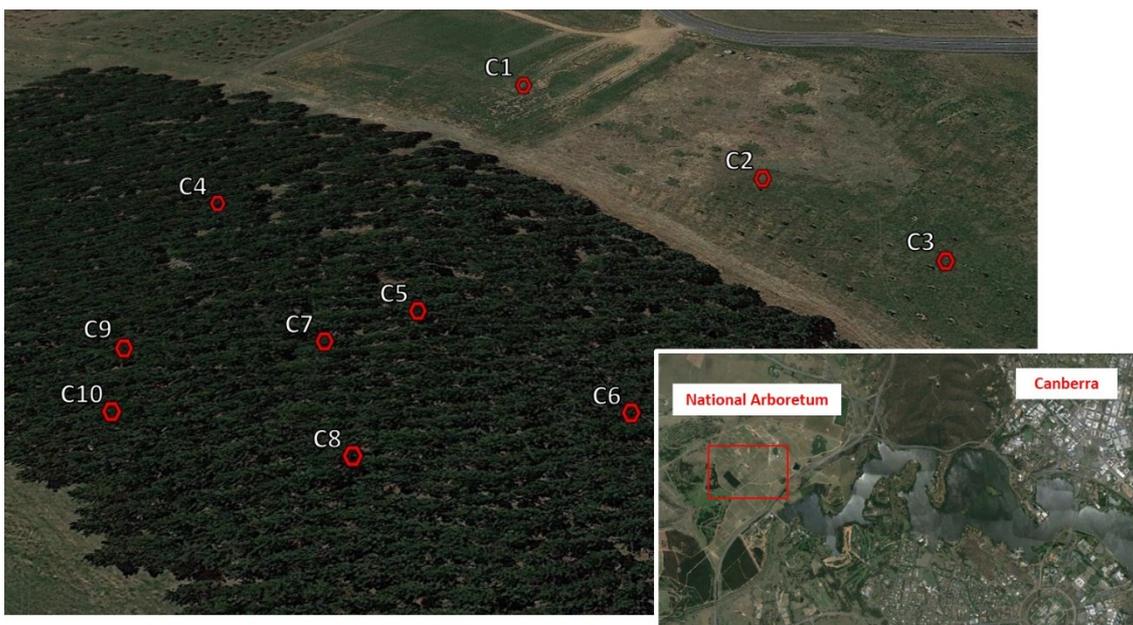
In 2007, after 4 years of post-fire regrowth, wind data were collected across a 3-4km East-West transect of the valley (Figure 1, A). Sharples et al. (2010) describes this data and the relationship between the wind behaviours observed and potential for extreme fire behaviours such as those experienced in 2003. In 2014, after 11 years of uninterrupted vegetation regrowth, wind data were collected along the same transect of Flea Creek Valley (Figure 1, B). Both data sets were collected over prolonged periods throughout each year; 9 months from January to October in 2007, and 9 months from April to December in 2014.

The vegetation observed in 2007 would be classed as 'open regrowth forest (30 year old)' as used in Moon et al (2016), or 'regrowth open forest' used in Moon et al. (2013). Whereas, the vegetation observed in 2014 would be more akin to the 'open regrowth forest (110 year old)' referred to by Moon et al. (2016), or the 'mature open forest' used in Moon et al. (2013). Both sets of data were collected in forests with average heights considerably lower than reported by Moon et al. (2016) (approximately 10 -15m, rather than 25 - 35m).



FIGURE 1 LOCATIONS OF DATA COLLECTION SITES AT FLEA CREEK VALLEY IN 2014 (A) AND 2007 (B).

In 2015, eleven weather stations were positioned on a spur along one of the highest ridge lines at the National Arboretum Canberra (NAC) for 9 months from April to December. The ridge line again runs approximately perpendicular to the dominant WNW prevailing winds experienced in the region. Three of the stations were located on a cleared area of the ridge line; one on the ridge itself and two on the leeward slope to the dominant prevailing winds (Figure 2, C1 to C3). The remaining eight stations were located within an adjacent Radiata pine stand (Figure 2, C4 to C10). Three of these eight stations were located along a parallel transect to those on the clear slope (C4 to C6). The vegetation at the National Arboretum is equivalent to the 'Pine plantation' class used by Moon et al. (2013, 2016), with average vegetation height around 15m as opposed to



23m.

FIGURE 2 LOCATIONS OF DATA COLLECTION SITES AT THE NATIONAL ARBORETUM CANBERRA IN 2015.



2.2 EMPIRICAL WIND PROFILES

Moon et al. (2013, 2016) describe the collection and analysis of wind data collected across seven different vegetation types in Victoria, Australia. Data were collected at heights of 1, 2, 5, 10 and 15m using guyed-masts with horizontal cup anemometers. At each site, average 30-minute wind speed measurements were taken between four closely located weather stations, with a fifth station located at a nearby 'open environment' site. Data were collected over approximate month long periods at each site.

To avoid the effects of topography, the stations were located in flat areas, and all stations were at least 20 times the vegetation height away from the vegetation boundary to avoid edge effects. To account for the accuracy of the cup anemometers, wind speeds below 1 km h^{-1} ($\approx 0.278 \text{ m s}^{-1}$) were excluded from the analysis presented in Moon et al. (2016). In this study, wind speed below 0.4 m s^{-1} ($\approx 1.4 \text{ km h}^{-1}$) were excluded, again to account for the accuracy of the instrumentation.

	$\geq 0.4 \text{ m s}^{-1}$	$\geq 2 \text{ m s}^{-1}$	$\geq 4 \text{ m s}^{-1}$
A1	1.2090	2.6781	4.4435
A2	0.5873	0.6480	0.7660
A3	0.9092	1.1160	1.5614
A4	0.6243	0.7307	1.0115
A5	0.7178	0.9981	1.3709
B1	1.2583	2.6655	4.2722
B2	0.8484	1.3801	2.5013
B3	0.9670	1.3848	1.8590
B4	0.8699	1.3225	1.5974
B5	0.8365	1.2587	1.6217
C1	3.8754	5.2196	6.5378
C2	2.7591	3.4209	4.2462
C3	2.2523	2.6587	3.1843
C4	0.5913	0.5921	0.5968
C5	0.8171	0.8215	0.8342
C6	0.6547	0.6545	0.6529

TABLE 1 AVERAGE WIND SPEEDS FOR EACH SITE ACROSS FCV (A AND B) AND THE NAC ©, AT OPEN WIND SPEED THRESHOLDS.

The reduction of wind speed induced by each forest type was calculated as the wind speed measured within the vegetation, U_v , divided by the wind speed measured at the nearby 'open' site, U_o , and terms Relative Wind Speed, **RWS** (Moon et al., 2013, 2016);



$$RWS = U_v/U_0$$

Relative wind speeds were calculated under increasing minimum prevailing wind speed thresholds (observed at the 'open' ridge top sites) to understand the changes in **RWS** as prevailing wind speeds increased; $T \geq 0.4 \text{ m s}^{-1} \approx 1.4 \text{ km h}^{-1}$, $T \geq 2 \text{ m s}^{-1} \approx 7.2 \text{ km h}^{-1}$ and $T \geq 4 \text{ m s}^{-1} \approx 14.4 \text{ km h}^{-1}$. Average wind speeds for each station, at each wind speed threshold are shown in Table 1. Relative wind speed results for each study site were compared to expected **RWS** values given in Moon et al. (2013, Fig. 3) for 10 to 20 km h^{-1} winds, as well as the wind speed profiles and results shown in Moon et al. (2016, Fig. 2 and 3).

At Flea Creek Valley, the 2014 winds were considered relative to 2007 winds where vegetation already existed. Therefore, the expected relative wind speed between the two years was calculated by taking the ratio of **RWS** for the regrowth open forest and **RWS** for the mature open forest. For the normalised height of 0.3 (i.e. at 5m in 15m high vegetation), the relative wind speeds shown in Moon et al. (2013, Fig. 3) were both 0.11 for regrowth and mature open forest, for 10-20 km h^{-1} open winds. If height was read directly at 5m, the **RWS** values were 0.11 and 0.09 for regrowth and mature open forest, respectively. Thus, using this direct 5m vegetation height, the **RWS** from regrowth to mature open forest was approximately 0.82, while considering the normalised height the **RWS** was 1.00. In addition, when considering the results shown in Moon et al. (2016, Fig. 2), the **RWS** for both regrowth and mature open forests at a normalised height of 0.3 was approximately 0.15, giving a **RWS** value between the two forest types of 1.00. Moon et al. (2016, Fig. 3) also shows that the **RWS** between regrowth and mature forest is approximately 1.00.

At the National Arboretum Canberra, the 'open' wind speed was taken to be that recorded on the clear slope. The **RWS** was calculated between each weather station pair down the leeward facing slope, therefore maintaining similar topographical features between stations. Results from the NAC were directly comparable to results from the 'Pine plantation' class in Moon et al. (2013, 2016). From Moon et al. (2013, Fig. 3), relative wind speeds in mature pine forest at a normalised height of 0.3 (or a direct height of 5m) and a wind speed between 10 and 20 km h^{-1} , were around 0.035. Moon et al. (2016, Fig. 3) indicates a higher **RWS** value of approximately 0.1 for a normalised height of 0.3. Furthermore, Moon et al. (2016, Fig. 3), shows that after wind speeds over approximately 4 m s^{-1} ($\approx 14.4 \text{ km h}^{-1}$), the **RWS** stabilised at approximately 0.08. For lower wind speeds, however **RWS** values increase to approximately 0.2 for 2 m s^{-1} wind speeds, and up to 0.4 for wind speeds as low as 0.4 m s^{-1} .



3 RESULTS

Figure 3 shows the relative wind speed results from Flea Creek Valley. For the western ridge top pair (A1-B1), all **RWS** values at this site correspond well with the findings of Moon et al. (2013, 2016), after accounting for the relative change in vegetation, i.e. **RWS** values appear around 1.00 indicating that the increased vegetation between the two years has had very little impact on wind speeds experienced at this station.

Across the remainder of the valley, **RWS** values appear to decrease as the wind speed threshold increases. This concurs with the results shown in Moon et al. (2016, Fig. 3), but goes against the profiles shown in Moon et al. (2013). On the valley floor (A3-B3) and eastern ridge top (A5-B5), **RWS** values are at the lower end of the expected **RWS** range, indicating that the increased vegetation at these sites has induced higher levels of wind speed reduction than those observed by Moon et al. (2013, 2016).

Finally, on the walls of the valley, relative wind speeds appear considerably lower than those observed on flat terrain. On the predominantly windward slope (the eastern valley wall, A4-B4), **RWS** values are around 0.6, with increased wind speeds having limited impact on the **RWS** values. In contrast, on the predominantly leeward slope (or western valley wall, A2-B2), **RWS** values are approximately 0.7 for the lowest threshold, reducing to only 0.3 for the highest wind speed threshold. These results suggest that for increasing open wind speeds, greater reduction of wind speed beneath the canopy on the leeward slope is experienced. Indeed, when open wind speeds above 4 m s^{-1} , wind speeds experienced beneath the mature canopy in 2014 were only a third of the speed of those experienced under the sparse canopy of 2007.

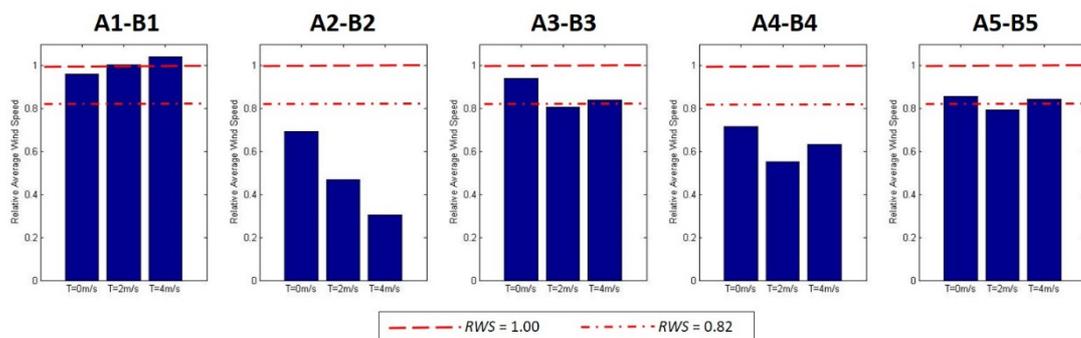


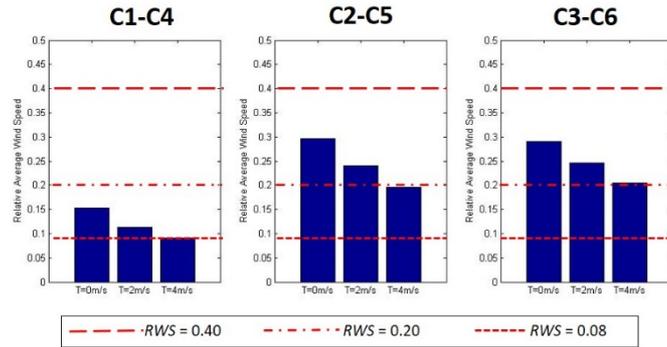
FIGURE 3 RELATIVE WIND SPEED OBSERVED BETWEEN 2007 AND 2014 ACROSS FLEA CREEK VALLEY. FINDINGS OF MOON ET AL. (2013, 2016) ARE INDICATED WITH THE RED DOTTED LINES.

Figure 4 shows the relative wind speeds between the parallel transects of the clear slope and the pine plantation slope at the National Arboretum Canberra. At the ridge-top stations (C1-C4), average wind speeds of 3.9 m s^{-1} , 5.2 m s^{-1} and 6.5 m s^{-1} are recorded for the three increasing open wind speed thresholds, respectively. At these wind speeds, it is expected from Moon et al. (2016) that the **RWS** values have reached stabilisation at 0.08. It is clear from Figure 4 that the observed **RWS** values approach this value as the wind speed threshold increases.

Down the predominantly lee-slope of the transect (C2-C5, C3-C6), **RWS** values are much higher, however average open wind speeds are lower; between 2.8



and 4.2 m s^{-1} for C2-C5 and between 2.3 and 3.2 m s^{-1} for C3-C6. At these lower open wind speeds, it is expected from Moon et al. (2016, Fig. 3) that RWS values



should be between 0.2 and 0.4. Clearly, results shown in Figure 4 agree with this expectation.

FIGURE 4 RELATIVE WIND SPEED OBSERVED BETWEEN CLEARED SLOPE AND RADIATA PINE STAND AT THE NATIONAL ARBORETUM CANBERRA. FINDINGS OF MOON ET AL. (20103, 2016) ARE INDICATED WITH THE RED DOTTED LINES.



4 DISCUSSION

Across Figure 3, results across sites representative of broader scale terrain or undulating landscapes (i.e. FCV ridge top and valley floor, or NAC transect) all show relatively good agreement with Moon et al. (2013, 2016) findings for the relevant forest types and wind speed thresholds (allowing for the relative change in forest type at FCV). On the leeward and windward slopes of Flea Creek Valley, wind speed reduction is much more significant between 2007 and 2014 than suggested by Moon et al. (2013, 2016). These results suggest that the terrain features have a compounding role to play in wind speed reduction caused by vegetation, and there is still further analysis required to better understand wind speed reduction beneath the canopy over complex terrain.

In further research, the compounding effects of topography may be characterised through the consideration of drag coefficients and streamlining (as noted by Moon et al., 2016). Consideration of vegetation structure and penetrability, as well as three-dimensional turbulence will also be relevant to this future discussion. As an immediate extension of this study, **RWS** could also be calculated between each NAC station within the vegetation (C4 to C10) and the station on the clear ridge top (C1). Differences between such results and those shown in Figure 4 would indicate any compounding effects of topography on **RWS**.

In this study, the average height of vegetation at both Flea Creek Valley and the National Arboretum Canberra was significantly less than heights reported by Moon et al. (2013, 2016). In addition, the vegetation structure was not quantified for both case studies, and it is important to consider where in the strata the 5 metre observations would sit. At the National Arboretum Canberra, within the pine stand, the 5 metre wind observations were within the dense pine canopy, but at Flea Creek Valley, within the open forest, it is possible that the observations were made within a secondary maximum in the wind speed profile. The comparison of normalised height results goes a considerable way to account for this with good agreement between results, but further quantification of vegetation structure would be necessary to progress this research and characterise the impacts of vegetation and topography on wind speed reduction.

It is noted by Moon et al. (2016) that the vegetation structure is itself dynamic, and varies over time. This variation is contemplated over long periods of time, with vegetation growth and interference due to human or natural causes. With shorter periods of data collection, i.e. less than one year, the seasonality of plant density, particularly through the open Eucalypt forest may have a significant impact on relative wind speeds. In this study, although data collection periods spanned considerably different time scales (9 months for the case studies compared to 1 month collected by Moon et al. (2013, 2016)), there was good agreement between results at the broader landscape scale. Further investigation into the impacts of seasonality on **RWS** is possible with this data set and it would be expected to further advance the discussion of drag effects and penetrability as areas for characterisation of the impacts of vegetation and topography on wind speed reduction. This could have



significant implications for the application of wind speed reduction factors or models in fire spread prediction.

This study is limited by the caveats of wind data collection in the 'real world'. Data were collected using low-cost Davis cup anemometers which have been reported to show a bias towards lower wind speeds (Moon et al., 2016). This form of data collection records horizontal wind speeds - limiting analysis to the horizontal while vertical wind flow is unaccounted for and may have significant impacts on fire spread below the canopy. More accurate data collection and more detailed analysis would be possible with three-dimensional sonic anemometers, as noted by Moon et al. (2016).

The possibility that edge effects at the NAC may play a significant role in the wind behaviour observed on both the clear slope and within the Radiata pine and thus needs to be also considered as a limiting factor in this study. Stations are at distances in the order of only a few times the height of the vegetation from the boundary of the pine stand, rather than 20 times the height of the vegetation as used by Moon et al. (2013, 2016). In light of this, it might be expected that the wind reduction observed at the stations would be less than that observed further away from the edge of the vegetation. However, in the results shown in Figure 4, this does not appear to be the case. Furthermore, analysis of wind direction across the NAC has shown that edge effects have minimal impacts on the wind fields experienced at the study sites.

Finally, it should be noted that reported wind speeds in this study were generally relatively low, but in application to fire spread prediction, high wind speeds are of most relevance in the context of extreme bushfire behaviour. Despite this, the focus here is on conditions driving surface fires beneath the canopy where conditions may be less extreme. Indeed, as noted by Moon et al. (2016), in cases of prescribed burns conditions are ideally mild, so understanding low wind speed interactions within the vegetation layer is important in the development of accurate bushfire spread models.



5 CONCLUSION

From this study, it is clear that observations over areas of broad scale topography or undulating terrain align well with the empirical wind profiles developed using data from flat terrain described by Moon et al. (2013, 2016). However, in amongst more complex landscape features, i.e. on valley walls and leeward slopes, the relative wind speeds observed were significantly lower than those shown in the empirical profiles constructed over flat terrain. This suggests that topographical features can have a significant compounding effect on wind reduction across complex landscapes. There is potential to study these data more closely to understand the processes behind this variation, and adapt developing wind reduction models to application in fire spread models.

Although the collection and analysis of 'real world' wind data has a number of caveats - perhaps leading to the lack of such data sets being available for model validation - results from this study show that the evaluation of models developed throughout the fire spread modelling process is a necessary step to reducing errors in the modelling process and improving fire spread predictions.



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