BLACK SUMMER 2019–20 RESEARCH
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MAPPING SURFACE FINE FUEL MOISTURE CONTENT

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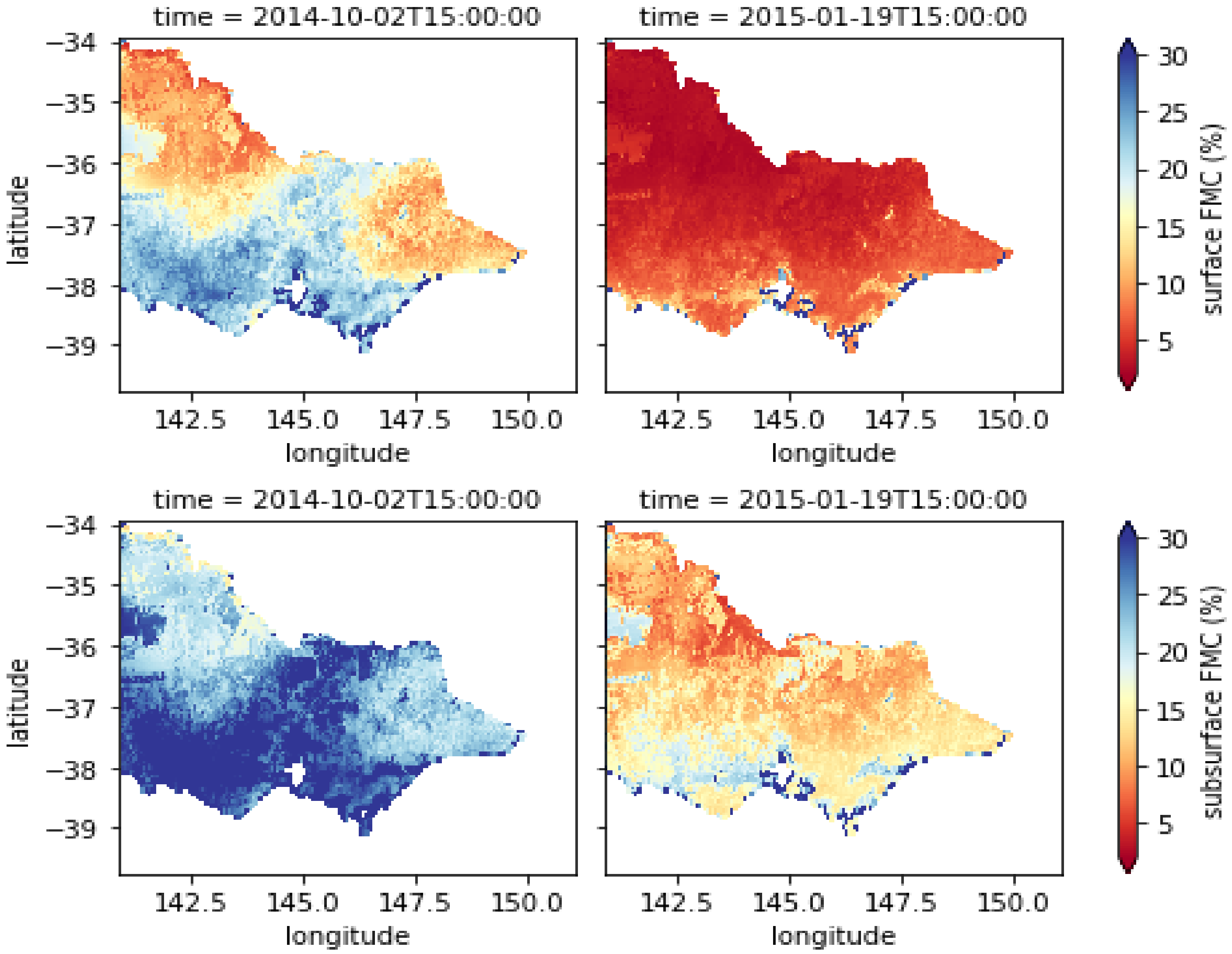

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Cover: Estimates of surface (left) and subsurface (right) FMC from the coupled model in Victoria on the 2nd of October 2014 (top) and the 19th of January 2015 (bottom).

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ACKNOWLEDGMENTS

Department of Environment, Land, Water and Planning (DELWP) for providing the data from the automated fuel stick sites, and for funding the field calibration component.

This research was part of the Bushfire and Natural Hazards Cooperative Research Centre's Black Summer research program, funded by the Australian Government and the CRC to investigate key issues from the 2019-20 bushfire season.

EXECUTIVE SUMMARY

Moisture content of dead fine fuel plays a decisive role in determining fire ignition and spread, and it is also an important input variable for many fire danger rating systems. Consequently, mapping dead fuel moisture content (FMC) is crucial and necessary for bushfire management but is not yet regularly accessible and available at a continental scale for Australia.

This report builds upon the research carried out by the team of the BNHCRC project "Mapping Bushfire Hazard and Impact". The earlier research involved developing new theory to couple vapour exchange and capillary flux from the soil to model litter fuel moisture content (FMC) and map dead fine FMC at 1h time steps and 5km spatial resolution for a pilot area in Victoria. In research reported here, soil moisture estimates were taken from the outputs of the BNHCRC project, "Mitigating the effects of severe fires, floods and heatwaves through the improvements of land dryness measures and forecasts", (also colloquially known as the JASMIN project, after the modelling framework developed within the project). The physics based Koba dead fine FMC model was used as the modelling framework. Results demonstrate the feasibility of mapping hourly dead fine FMC at 5 km resolution. The estimates of dead fine FMC were improved by our proposed coupled model, especially for subsurface litter where litter is in contact with the soil.

The methodology has the potential to be extended at a continental scale and delivered to stakeholders in a timely fashion via the Australian Flammability Monitoring System in future research. This information can help assist the development and improvement of a new national fire rating system and support Predictive services and Fire Behavior Analysts.

END-USER PROJECT IMPACT STATEMENT

Mike Wouters *Department for Environment and Water, SA*

"The development of improved methods for determining dead fuel moisture content (FMC) of fine fuel (a key variable in most of the current fire behaviour models) is a significant step forward for bushfire modelling and prediction. This project has demonstrated improved determination of dead FMC using outputs of the JASMIN model combined with the KOBA FMC model. This work has the potential to make bushfire predictions and modelling significantly more accurate, particularly in more remote parts of the Australian landscape, for a low cost.

"The trial of this In Victoria is very positive. I am keen to progress further work In South Australia (along with partners from other areas) to develop a national-scale operational model for regular use in fire management."

INTRODUCTION

The Australian Flammability Monitoring System (AFMS) is a pre-operational near real-time flammability data service that provides estimates on live fuel moisture content (FMC) derived from the satellite-derived information and soil moisture from the JASMIN prototype. However, the AFMS (or other systems in Australia) does not provide spatial information on estimated dead fine FMC. Dead fine FMC (litter) plays a decisive role in determining fire ignition and spread, and it is also an important input variable for many fire danger rating systems (Matthews, 2014; Slijepcevic et al., 2015). Consequently, mapping dead fine FMC is crucial and necessary for bushfire management.

Although models ranging from empirical to physics-based have been developed to predict litter FMC, the spatial data provision of accurate predictions of dead FMC is challenging due to the complexity of dynamics at the interface of the atmosphere and the solid earth. Moreover, none of these models explicitly consider soil moisture dynamics in determining FMC, although soil moisture has been proposed to influence FMC (Hatton and Viney, 1988; Rothwell et al., 1991). Our BNHCRC research findings from the FMC simulation have shown soil moisture has a distinct influence on litter FMC when soil moisture is relatively high (Zhao et al., 2021). Our current research from field experiment analyses suggests that the influence of soil moisture could be through both vapour exchange and capillary flow (Zhao et al. Under review).

This project aims to map dead fine FMC by coupling soil moisture in a physics-based FMC prediction model (Koba model) proposed by Matthews (2006). The project represents scientific innovation in that the influence of soil moisture (both vapour and capillary flow from soil) is explicitly considered in the FMC simulation, and this helps to increase our understanding of the relationship between soil and dead fine moisture dynamics. In the long-term, future activities should focus on extending the modeling approach at the continental scale and the integration of fine dead FMC with the AFMS in real-time, which will provide the moisture estimations of both dead and live vegetation for strategic bushfire planning and response.

BACKGROUND

The underpinning Koba model, described in Matthews (2006), is the first fully physics-based model of fine dead FMC implemented in Australia. The model predicts dead fine (litter) FMC by accounting for energy and water continuity equations (Figure 1). Boundary conditions for the Koba model include air temperature, relative humidity, radiation, precipitation, and soil temperature.

Based on our BNHCRC research findings from FMC simulation and field experiments, we have developed theoretical underpinnings for improvements of fine dead FMC estimates by considering both vapour and capillary flow from soil. Soil moisture is then coupled in the Koba model (the coupled model) through both vapour exchange and capillary flux, to improve the predictions of litter FMC. The coupled model has been tested at our experimental field sites in the Australian Botanic Gardens. However, it has not been applied spatially.

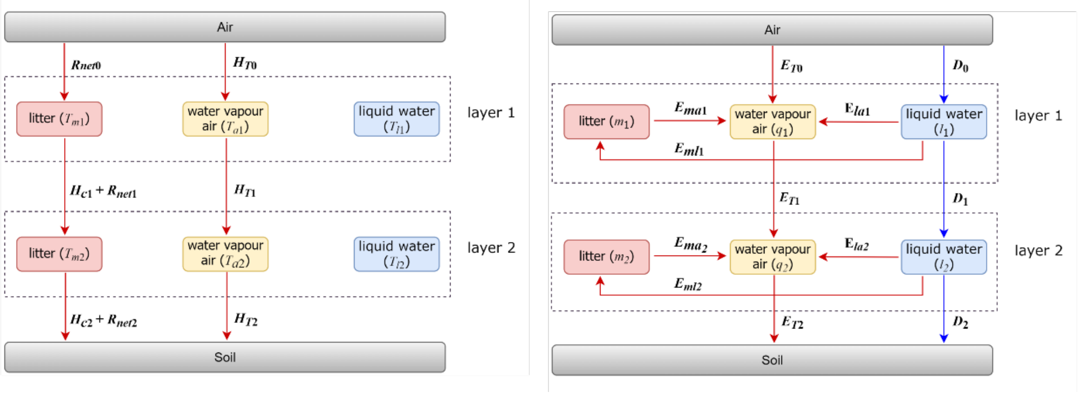


Figure 1 Representation of the energy balance (left) and water balance (right) in the Koba model (Zhao et al., 2021).

Therefore, this project aims to produce near real-time maps of surface fine FMC by coupling JASMIN soil moisture and the Koba model at a 5 km spatial resolution at an hourly temporal resolution for a study area in Victoria, Australia. There are five sites in the pilot area in Victoria, where Victorian Department of Environment, Land, Water and Planning (DELWP) installed automated equipment collecting FMC and meteorological data since July 2014 (Figure 2). The five sites cover different climate and vegetation conditions and they broadly fell into two groups: relatively dry sites with open vegetation (1, 2 and 3) and relatively wet sites with forest vegetation (4 and 5).

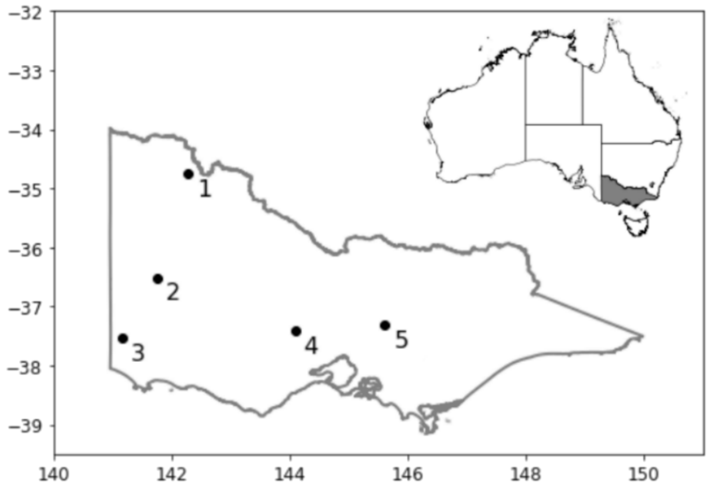


Figure 2 Location of five studied sites in Victoria, Australia.

This project aims for operational use, since once the estimates of litter FMC are validated in our pilot area in Victoria, and in the medium term, the modelling can be extended across the Australia continent and the product can be used by land managers and fire services, for example, to plan hazard reduction burning and as an input in fire behaviour models. This work will set the foundations for the provision of spatial dead FMC information in the AFMS which, with further funding, can be a new tool that can help assist the development and improvement of a new national fire rating system.

RESEARCH APPROACH, FINDINGS AND KEY MILESTONES

METHODS

Soil moisture was used as a boundary condition to the Koba model by considering both vapour exchange and capillary flux between soil and litter. The vapour interaction between soil and litter air spaces is quantified by Equation 1.

$$E_{soil} = -\,\rho_{air}\,\frac{\beta\,[q_{air} - h\,q_{sat}(T_s)]}{r_a}\,, \tag{1}$$

$$\beta = \begin{cases} \frac{1}{4}\left[1 - \cos\left(\pi \frac{\theta}{\theta_{fc}}\right)\right]^2 & \theta < \theta_{fc} \\ 1 & \theta \geq \theta_{fc} \end{cases}, \tag{2}$$

Where: E_{soil} (kg m^{-2} s^{-1}) is the vapour flux; ρ_{air} (kg m^{-3}) is air density; r_a (s m^{-1}) is aerodynamic resistance to water vapour transfer; q_{air} (kg kg^{-1}) is the specific humidity of the air; q_{sat} (kg kg^{-1}) is the saturated specific humidity at the soil surface temperature Ts (K) ; h represents the relative humidity of the air within the soil pore space where evaporation occurs and it was set as 1; β is a parameter varying from 0 to 1 to scale the effect of soil resistance on the evaporation and it can be represented as Equation 2; θ (m^3 m^{-3}) is volumetric soil moisture content; θ_{fc} (m^3 m^{-3}) is the value of θ at field capacity and a function of soil texture and structure.

Capillary rise from the soil is driven by capillary and adsorptive forces in the pore spaces, and capillary flux from the soil can be represented as the Darcy flow equation for unsaturated flow (Equation 3).

(3)

$$\Psi = \frac{\rho_w\,R\,T}{M_w}\,ln\,(RH) \tag{4}$$

$$K(\Psi) = K_{sat}\,\exp\,(\alpha\,\Psi) \tag{5}$$

Where: Q (mm/d) is the capillary rise from the soil; Ψ is negative water pressure head (mm), which is related to the relative humidity in the soil pores and can be expressed by the relationship between relative humidity and the corresponding matric potential in the soil (Equation 4), when a local equilibrium exists between liquid and vapour in the soil pores; z is the height above the soil surface; ∂Ψ/∂z is the negative pressure head gradient between soil and litter; ρ_w (kg m^{-3}) is liquid water density; R (8.314 J mol^{-1} K^{-1}) is the gas constant; T (K) is absolute temperature; M_w (18 g mol^{-1}) is the molecular weight of water; RH is the relative humidity in the soil pore space; K(Ψ) (mm/d) is the unsaturated hydraulic conductivity between soil and litter, which is usually a nonlinear function of moisture content or pressure head (Equation 5) (Gardner, 1958); K_{sat} (mm/d) is the saturated hydraulic conductivity; a is the empirical parameter.

The coupled model was first tested at five sites in Victoria with in-situ micrometeorological measurements and parameters required by the model were optimized at each site. Then the coupled model was spatially extended using gridded meteorological datasets to drive the model, and the required parameters were optimized uniformly for the studied area. Model performance was assessed by comparing modelled and observed FMC dynamics across all sites. Statistical measures of performance include mean bias error (MBE), mean absolute error (MAE), root mean square error (RMSE) (Willmott, 1982), and the Pearson's correlation (R) between predictions and observations. The simulations from the coupled model were also compared to that of the original Koba model (the uncoupled model), where the influence of soil moisture on litter FMC is not accounted for.

DATA

The coupled Koba model was applied to Victoria incorporating by 5 km gridded weather variables at 1h intervals from September 2014 to April 2015, which coincides with the fire season in Victoria where field measurements were also collected. The required input weather variables are air temperature, wind speed, specific humidity, rainfall rate, solar radiation, thermal radiation, soil temperature, and soil moisture. Among those variables, air temperature, specific humidity and solar radiation were derived from gridded daily 5 km × 5 km solar radiation data from the Bureau of Meteorology (BoM), which were downscaled to hourly temporal resolution. Wind speed was derived from McVicar et al. (2008) gridded daily 5 km × 5 km wind speed and soil moisture from gridded daily 5 km × 5 km soil moisture estimates from the JASMIN prototype. JASMIN is a comprehensive land surface modelling system that calculates soil moisture state at a spatial resolution of 5 km system. JASMIN is run with an hourly time step and output is stored at 00 UTC daily. The soil column in JASMIN is 3 m deep and is divided into four layers of 0.1, 0.35, 0.65 and 2 m depth from the surface. Soil moisture from the 0.1m depth was used in the coupled model reported here.

Air temperature was interpolated between observed daily maxima and minima based on the method of Beck and Trevitt (1989). Specific humidity was derived from linear interpolation between 9 am and 15 pm vapour pressure. Radiation was downscaled to hourly temporal resolution using the method of Whillier (1956). The interception of radiation was estimated from canopy openness which was a function of solar zenith angle following the hemispheric sampling in Victoria by Matthews et al. (2015). Wind speed was downscaled to hourly temporal resolution based on the method of Beck and Trevitt (1989) and wind speed from McVicar et al. (2008) was assumed to be the observations at 15pm. Soil moisture was linearly interpolated between daily estimates.

In addition to these, the downscaling of daily rainfall observations to hourly rate is challenging, as the time, duration and intensity of rainfall are hard to accurately predict. Therefore, rainfall required in the model was regarded as zero in the spatial model, which means the spatial model ignored the influence of rainfall and FMC estimates from the model would only focus on low FMC values (below 30%).

RESULTS

Dead FMC modelling using in-situ micrometeorological observations and local optimised parameters

The coupled model showed a slightly better performance than the original uncoupled model in the surface litter layer, with a slightly higher Pearson's correlation (R) and smaller errors (Figure 3 and Table 1). However, the difference between the coupled model and the uncoupled model was slight overall (Figure 3). In contrast, the subsurface FMC estimates were improved using the coupled model, which showed a higher R and smaller RMSE (Figure 3 and Table 1). According to Trevitt (1988), the errors of FMC predictions should be below 1% (MAE <1%) for FMC under 8% and below 2% (MAE <2%) for FMC above 8% to ensure accuracy of the rate of spread prediction within 50% in fire behaviour models. Therefore, when focusing on the percentage of FMC predictions with errors below 1% or 2%, the coupled model performed better overall, especially for subsurface litter at the wet sites (sites 4 and 5) (Figure 4). For example, when looking at the predictions from the coupled Koba model at site 5, 30% of the surface FMC predictions were within 1% or 2% of measured FMC, while 50% of subsurface FMC predictions were with the errors below 1% or 2% (Figure 4).

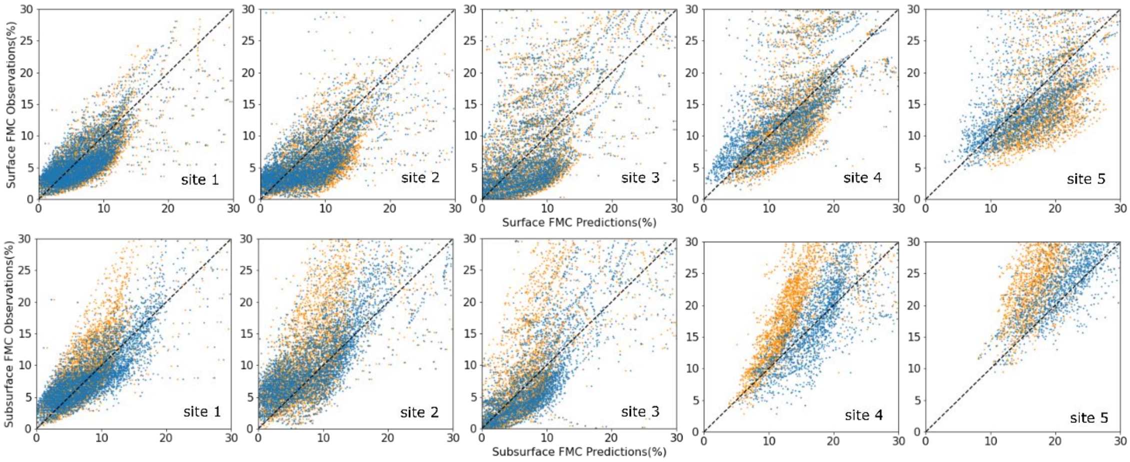


Figure 3 Observed versus predicted FMC for the surface (top) and subsurface (bottom) fuel at five sites in Victori (only FMC under 30% are considered). The dashed line indicated the 1:1 line. Orange points represent the results using the original uncoupled model; Blue points represent the results using the coupled model.

Table 1 Performance of predictions of FMC under 30% at five sites with in-situ micrometeorological observations and optimized model parameters at each site. Negative values of MBE indicate overestimation.

Site NO.	Litter Layer	R		MBE (%)		MAE (%)		RMSE (%)	
		Uncoupled Model	**Coupled Model**	Uncoupled Model	**Coupled Model**	Uncoupled Model	**Coupled Model**	Uncoupled Model	**Coupled Model**
1	Surface	0.74	**0.76**	-1.55	**-1.12**	2.98	**2.88**	5.50	**5.50**
	Subsurface	0.66	**0.77**	1.18	**-0.24**	2.92	**2.74**	4.97	**4.82**
2	Surface	0.72	**0.76**	-3.99	**-3.30**	5.30	**5.08**	9.98	**9.97**
	Subsurface	0.58	**0.74**	2.73	**1.42**	4.61	**4.07**	6.56	**5.90**
3	Surface	0.64	**0.67**	-1.77	-1.36	6.07	**5.92**	9.92	**9.85**

	Subsurface	0.61	**0.72**	0.58	-1.17	4.60	**4.34**	7.38	**7.09**
4	Surface	0.50	**0.58**	-1.05	**0.21**	4.57	**4.44**	7.64	**7.63**
	Subsurface	0.63	**0.68**	3.92	**-1.77**	5.53	**4.57**	7.17	**7.07**
5	Surface	0.46	**0.56**	-3.47	**-1.54**	5.29	**4.33**	7.18	**6.56**
	Subsurface	0.56	**0.72**	5.85	**0.68**	6.06	**2.71**	6.95	**3.58**

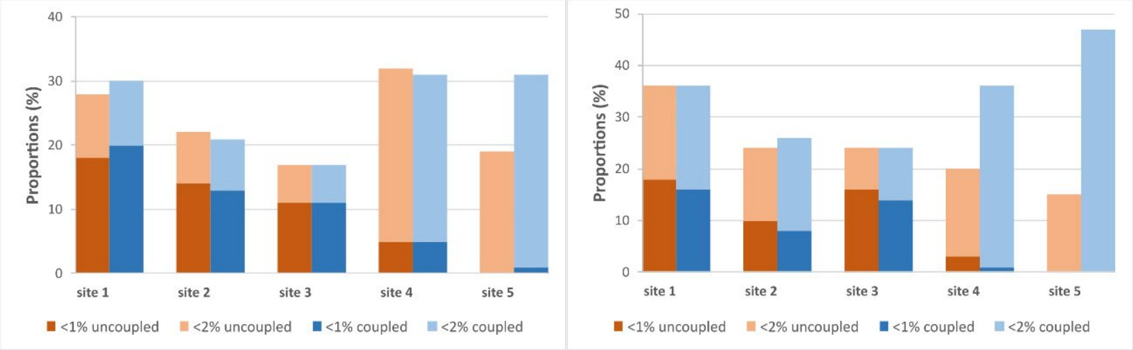


Figure 4 Percentage of surface FMC predictions (left) and subsurface FMC predictions (right) within 1% or 2% of measured FMC for the original uncoupled (orange bars) and the coupled (blue bars) Koba model, at five sites in Victoria, Australia.

Dead FMC modelling using gridded 5km data and uniform set of model parameters across sites

When extending the coupled model for Victoria using 5 km gridded data and a uniform set of model parameters across sites, the estimates of both surface and subsurface FMC were improved compared with the original uncoupled model (Figure 5 and Table 2). The coupled model showed a better Pearson's correlation (R) and smaller RMSE than the uncoupled model at the five sites (Table2). The improvements at the dry sites (sites 1, 2 and 3) were relatively small. However, the FMC estimates at the wet sites (sites 4 and 5) were distinct, especially for subsurface litter (Table 2 and Figure 5). When focusing on the percentage of FMC predictions with errors below 1% or 2%, the coupled model performed better overall, especially for subsurface litter at the wet sites (sites 4 and 5) (Figure 6). For example, approximately 20% of the subsurface FMC predictions from the coupled were within 1% or 2% of measured FMC at sites 4 and 5; while the proportions were no more than 5% when looking at predictions from the original uncoupled model at these two sites.

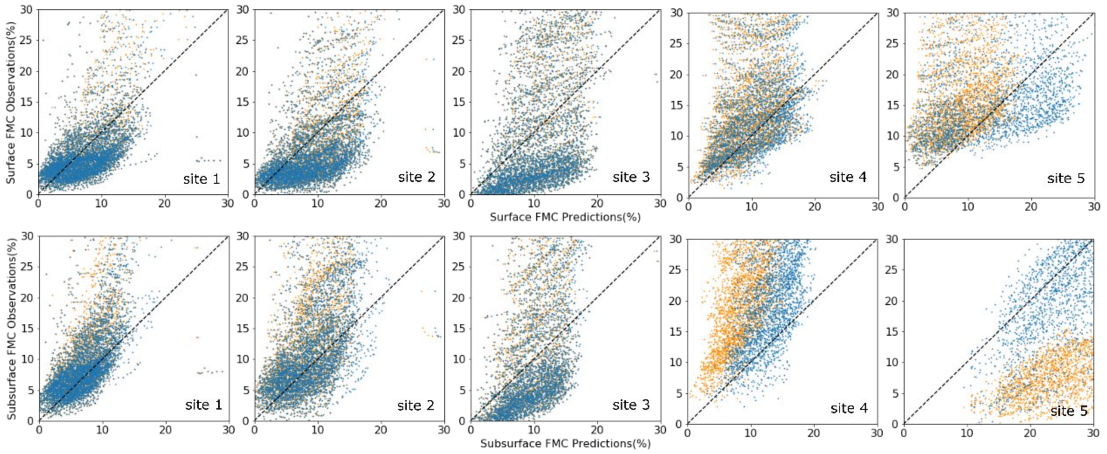


Figure 5 Observed versus predicted FMC for the surface (top) and subsurface (bottom) fuel at five sites in Victoria (only FMC under 30% are considered), when using 5 km gridded data and a uniform set of model parameters. The dashed line indicated the 1:1 line. Orange points represent the results using the original uncoupled model; Blue points represent the results using the coupled model.

Table 2 Performance of predictions of FMC under 30% at five sites using 5 km gridded weather data and a uniform set of optimized parameters across sites. Negative values of MBE indicate overestimation.

		R		MBE (%)		MAE (%)		RMSE (%)	
Site NO.	Litter Layer	Uncoupled Model	**Coupled Model**	Uncoupled Model	**Coupled Model**	Uncoupled Model	**Coupled Model**	Uncoupled Model	**Coupled Model**
1	Surface	0.53	**0.54**	-0.65	**-0.73**	3.18	**3.18**	4.21	**4.17**
	Subsurface	0.59	**0.64**	2.21	**1.93**	3.25	**3.05**	4.70	**4.39**
2	Surface	0.48	**0.50**	-1.81	**-2.03**	4.23	**4.30**	5.40	**5.46**
	Subsurface	0.53	**0.55**	2.85	**2.26**	4.59	**4.41**	6.22	**5.89**
3	Surface	0.41	**0.42**	-1.87	**-1.95**	6.47	**6.46**	7.74	**7.72**
	Subsurface	0.45	**0.48**	-0.59	**-0.85**	5.67	**5.62**	6.92	**6.8**
4	Surface	0.42	**0.54**	4.04	**3.06**	5.13	**4.90**	7.23	**6.82**
	Subsurface	0.59	**0.61**	10.10	**5.63**	10.12	**6.19**	11.34	**7.69**
5	Surface	0.35	**0.38**	6.41	**2.09**	6.67	**6.04**	8.56	**7.57**
	Subsurface	0.50	**0.53**	15.19	**4.57**	15.19	**5.96**	15.72	**7.80**

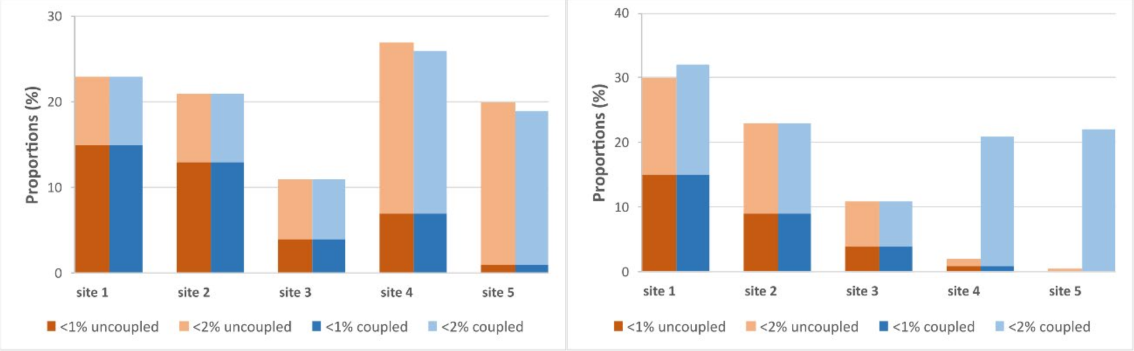


Figure 6 Percentage of surface FMC predictions (left) and subsurface FMC predictions (right) within 1% or 2% of measured FMC for the original uncoupled (orange bars) and the coupled (blue bars) Koba model, at five sites in Victoria, Australia.

Spatial maps of surface and subsurface dead FMC for Victoria

Timeseries of monthly and daily average FMC estimates from the coupled model for the whole of Victoria were extracted from September 2014 to April 2015 (Figures 7 and 8). This series shows the seasonal FMC trends over the summer-autumn period, with drier FMC following the summer days (November to February) and then fuel gaining moisture in autumn (March to May) (Figure 7). The dry-down of subsurface litter is consistent with that of surface litter, but the dries subsurface litter fuel occurred a bit later than the driest surface litter fuel, with the lowest surface FMC occurring in February while the lowest subsurface FMC occurring in November (Figure 7). This is reasonable as the response time of subsurface FMC to weather variables is supposed to be longer than that of surface FMC. The dry-down patterns of surface and subsurface fuel at a daily scale also show similar trends (Figure 8).

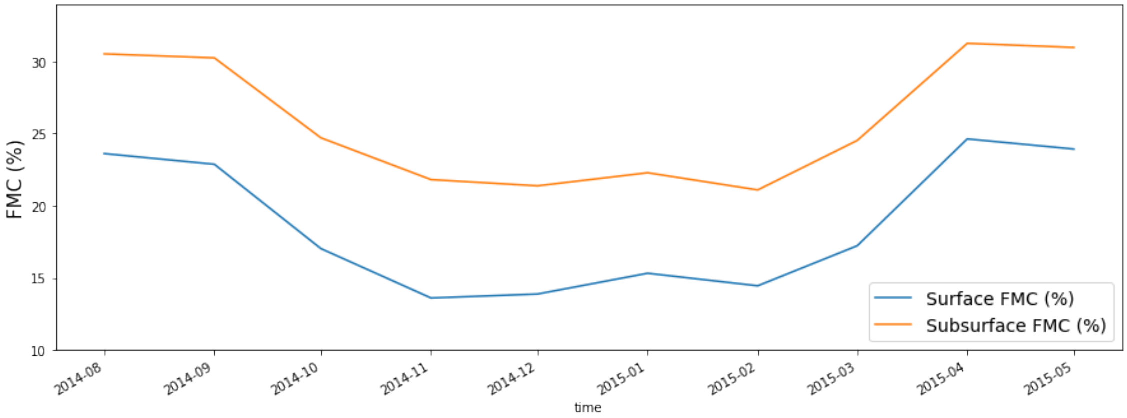


Figure 7 Timeseries of monthly average FMC in surface and subsurface litter layers for the whole Victoria from September 2014 to April 2015.

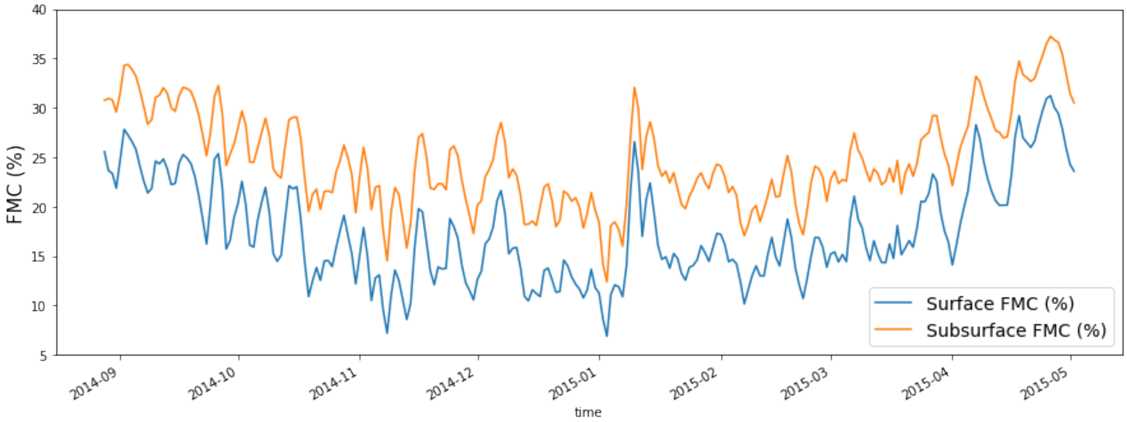


Figure 8 Timeseries of daily average FMC in surface and subsurface litter layers for the whole Victoria from September 2014 to April 2015.

Spatial maps of fine litter FMC estimates were produced from the coupled model at a 5 km spatial resolution and at an hourly time step (Figure 9). As examples, maps for the 2nd of October (beginning of fire season) and 19th of January (advanced fire season) are displayed in this report. Litter FMC (both surface and subsurface) on the 19th of January 2015 was lower than that on the 2nd of October 2014 (Figure 9). This can be explained by the higher temperature and lower relative humidity on the 19th of January

2015 (Figure 10). In addition, the sample maps show that litter in Northern Victoria is drier than that in Southern Victoria (Figure 9) given the hotter and drier weather conditions (higher temperature and lower relative humidity) in the north (Figure 10).

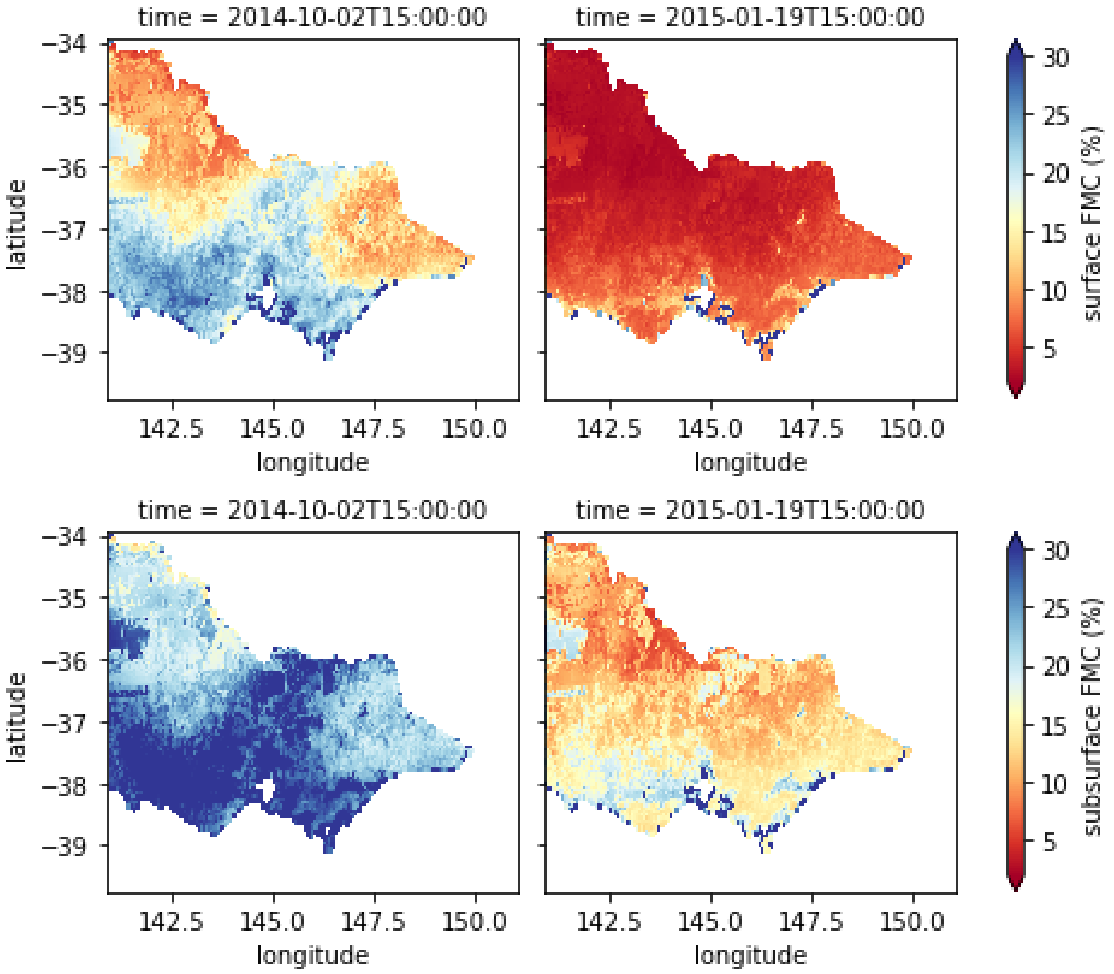
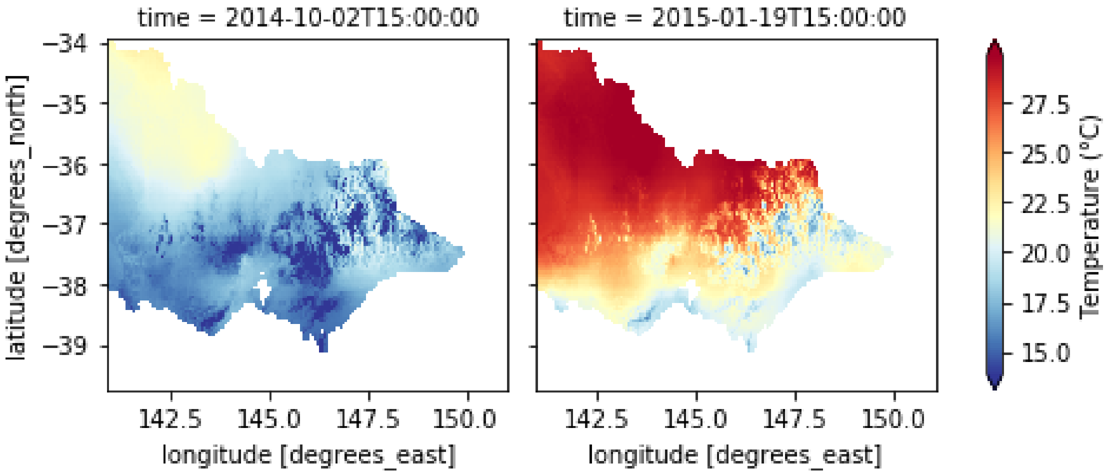


Figure 9 Estimates of surface (left) and subsurface (right) FMC from the coupled model in Victoria on the 2nd of October 2014 (top) and the 19th of January 2015 (bottom).



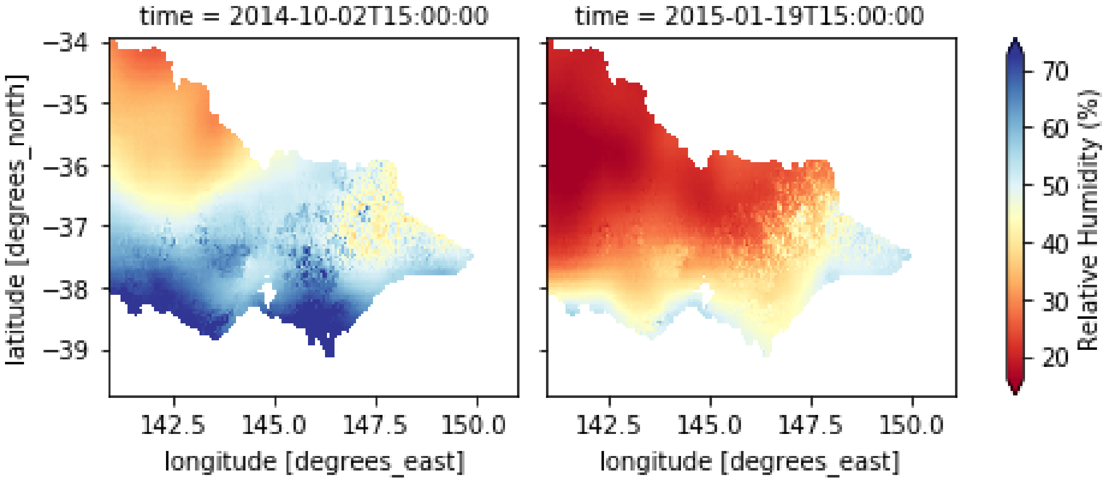


Figure 10 Temperature (top) and relative humidity (bottom) maps for Victoria on the 2nd of October 2014 (let) and the 19th of January 2015 (right).

UTILISATION AND IMPACT

Given the tight timeframes of the project, there has not been time for operational uptake of the project work. However, this research demonstrates the capability to map litter FMC at large spatial scales (Victoria state) and contributes to increase our understanding of the relationship between soil and litter moisture dynamics. In the long-term, future activities should focus on applying the modelling framework at a continental scale and the integration of litter FMC with the AFMS in real-time, which will provide the moisture estimations of both dead and live vegetation for strategic bushfire planning and response.

CONCLUSION

Our developed theoretical insights into estimating litter FMC by coupling vapour exchange and capillary flux from the soil were developed and validated in the pilot area in Victoria, Australia. The resulting coupled JASMIN and Koba model were used to successfully estimate fine dead (litter) FMC at a spatial scale in Victoria at a 5 km spatial resolution and 1h temporal resolution. The estimates of fine dead FMC were improved by our proposed coupled model, especially for subsurface litter which is in contact with the soil. The improvement on litter FMC is distinct when soil moisture is relatively high. Our results should help to describe litter FMC dynamics better in operational fire management applications and in the longer term to provide near-real time estimates of litter FMC at a continental scale.

NEXT STEPS

The coupled JASMIN and Koba model have been applied in the pilot area in Victoria at a 5 km spatial resolution and an hourly step. However, the model has the disadvantage of requiring relatively large computing resources and the challenge of parameterising in an operational context. Consequently, there might be a need to simplify and improve the coupled model for better operational use at continental scale in future research. Besides, another limitation would be the spatial input data to drive the model at a continental scale as the model requires hourly input data, which is still challenging to acquire across Australia now. Therefore, incorporating hourly spatial weather models will also be of potential interest for future research.

PUBLICATIONS LIST

PEER-REVIEWED JOURNAL ARTICLES

1 ZHAO, L., YEBRA, M., VAN DIJK, A. I. J. M., CARY, G. J., MATTHEWS, S. & SHERIDAN, G. 2021. The influence of soil moisture on surface and sub-surface litter fuel moisture simulation at five Australian sites. Agricultural and Forest Meteorology, 298-299.

2 ZHAO, L., YEBRA, M., VAN DIJK, A. I. J. M., CARY, G. J., Hughes, D. 2021. Controlled field experiment clarifies the influence of soil moisture on litter moisture content (under review).

CONFERENCE PAPERS

1 ZHAO, L., YEBRA, M., VAN DIJK, A. I. J. M., CARY, G. J. (August 2020). *Coupling litter and soil moisture models to forecast surface fuel moisture content -- Field experiment* [Abstract]. The 20th Annual Australasian Fire and Emergency Service Authorities Council (AFAC2020).

TEAM MEMBERS

RESEARCH TEAM

Marta Yebra

Associate Professor at the ANU Fenner School of Environment & Society and the School of Engineering and Project Leader. Marta's research combines field measurements with on-ground sensor networks, airborne and satellite observations and high-performance computing technology and modelling to monitor, quantify and forecast vegetation and landscape processes, with applications in natural resources management, natural hazards, and ecosystem function at local, regional and global scale.

Geoff Cary

Associate Professor in Bushfire Science at the ANU Fenner School of Environment & Society. Geoff's research interests include evaluating fire management and climate change impacts on fire regimes using landscape-scale simulation and statistical modelling, ecological investigation of interactions between fire and biota from genes to communities, empirical analysis of house loss in wildland fire, and laboratory experimentation of fire behaviour.

Li Zhao

PhD candidate at the ANU Fenner School of Environment & Society. Li is under the supervision of Marta Yebra, Albert van Dijk and Geoff Cary. She is working on the forecasting of dead FMC. While performing this work she was finalizing her PhD and acting as a postdoctoral fellow.

END-USERS

End-user organisation	End-user representative	Extent of engagement (Describe type of engagement)
ACT Parks	Adam Leavesley	Project scoping, discussion results
SA DEW	Mike Wouters	Project scoping, discussion results
NSW-RFS	Stuart Matthews	Project scoping, discussion results

REFERENCES

BECK, J. & TREVITT, A. 1989. Forecasting diurnal variations in meteorological parameters for predicting fire behaviour. Canadian Journal of Forest Research, 19, 791-797.

GARDNER, W. 1958. Some steady-state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil science, 85, 228-232.

HATTON, T. J., VINEY, N. R., CATCHPOLE, E. & DE MESTRE, N. J. 1988. The influence of soil moisture on Eucalyptus leaf litter moisture. Forest Science, 34, 292-301.

MATTHEWS, S. 2006. A process-based model of fine fuel moisture. International Journal of Wildland Fire, 15, 155-168.

MATTHEWS, S. 2014. Dead fuel moisture research: 1991–2012. International Journal of Wildland Fire, 23, 78-92.

MATTHEWS, S., LOVEDAY, S., HURLEY, R. & ROXBURGH, S. 2015. Modelling fuel moisture across the landscape for fire management.

MCVICAR, T. R., VAN NIEL, T. G., LI, L. T., RODERICK, M. L., RAYNER, D. P., RICCIARDULLI, L. & DONOHUE, R. J. 2008. Wind speed climatology and trends for Australia, 1975–2006: Capturing the stilling phenomenon and comparison with near-surface reanalysis output. Geophysical Research Letters, 35.

ROTHWELL, R., WOODARD, P. & SAMRAN, S. The effect of soil water on aspen litter moisture content. 1991. Society of American Foresters.

SLIJEPCEVIC, A., ANDERSON, W., MATTHEWS, S. & ANDERSON, D. 2015. Evaluating models to predict daily fine fuel moisture content in eucalypt forest. Forest Ecology and Management, 335, 261-269.

WHILLIER, A. 1956. The determination of hourly values of total solar radiation from daily summations. Archiv für Meteorologie, Geophysik und Bioklimatologie, Serie B, 7, 197-204.

WILLMOTT, C. J. 1982. Some comments on the evaluation of model performance. Bulletin of the American Meteorological Society, 63, 1309-1313.

ZHAO, L., YEBRA, M., VAN DIJK, A. I. J. M., CARY, G. J., MATTHEWS, S. & SHERIDAN, G. 2021. The influence of soil moisture on surface and sub-surface litter fuel moisture simulation at five Australian sites. Agricultural and Forest Meteorology, 298-299.

ZHAO, L., YEBRA, M., VAN DIJK, A. I. J. M., CARY, G. J., Hughes, D. 2021. Controlled field experiment clarifies the influence of soil moisture on litter moisture content (under review).