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Corrigendum

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The authors wish to advise the original Figure 4 was incorrect, in part (*b*) the line for dry eucalyptus forest was shown as orange, where it should be brown. The correct figure is provided below. All data provided in the text and tables in the paper is correct.

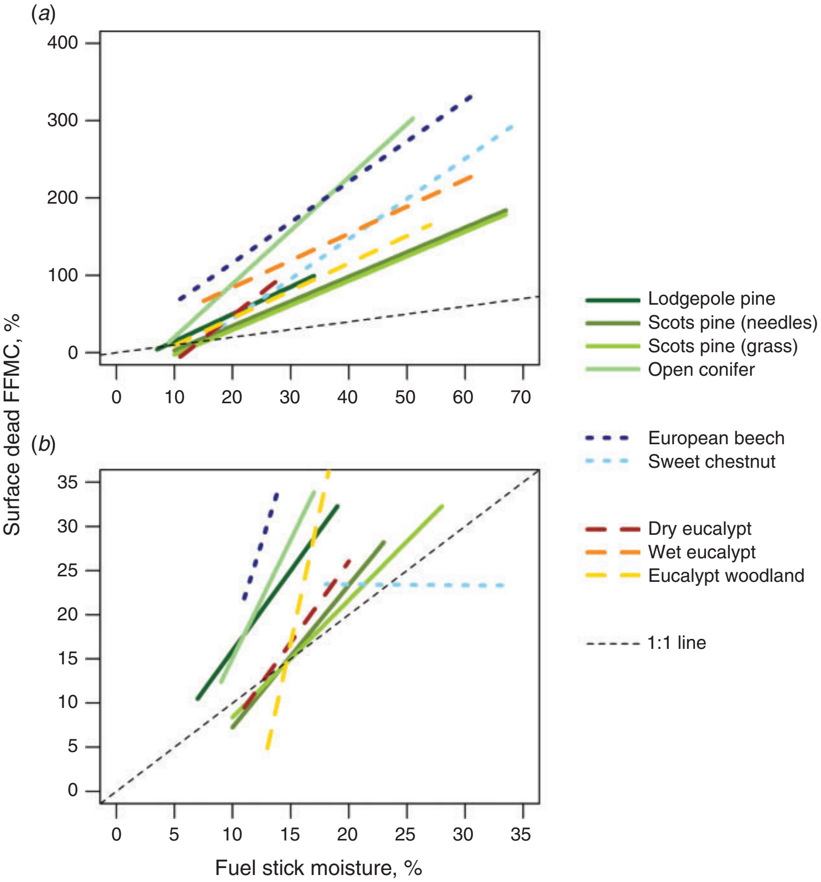

Fig. 4. Linear relationships between surface dead fine fuel moisture content (FFMC) and fuel stick moisture for (*a*) the full data range and (*b*) data where fine FMC is, 35%. Colours and symbols on the lines represent different forest fuel categories.

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Estimation of surface dead fine fuel moisture using automated fuel moisture sticks across a range of forests worldwide

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Abstract. Field measurements of surface dead fine fuel moisture content (FFMC) are integral to wildfire management, but conventional measurement techniques are limited. Automated fuel sticks offer a potential solution, providing a standardised, continuous and real-time measure of fuel moisture. As such, they are used as an analogue for surface dead fine fuel but their performance in this context has not been widely evaluated. We assessed the ability of automated fuel sticks to predict surface dead FFMC across a range of forest types. We combined concurrent moisture measurements of the fuel stick and surface dead fine fuel from 27 sites (570 samples), representing nine broad forest fuel categories. We found a moderate linear relationship between surface dead FFMC and fuel stick moisture for all data combined ($R^2 = 0.54$), with fuel stick moisture averaging 3-fold lower than surface dead FFMC. Relationships were typically stronger for individual forest fuel categories (median $R^2 = 0.70$; range = 0.55–0.87), suggesting the sticks require fuel-specific calibration for use as an analogue of surface dead fine fuel. Future research could identify fuel properties that will enable more generalised calibration functions.

Additional keywords: fire danger, fire risk, hazard stick, microclimate, response time, wildfire.

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Introduction

Dead fine fuel moisture content (FFMC) is a primary driver of wildfire behaviour. Numerous studies demonstrate its influence on fuel ignitability (Dimitrakopoulos and Papaioannou 2001; Fernandes *et al.* 2008), fire spread (Rothermel 1972; Burrows 1999), smoke emissions (Chen *et al.* 2010), fuel consumption (Knapp *et al.* 2005; de Groot *et al.* 2009) and spotting (McArthur 1967; Cruz *et al.* 2012). As such, dead FFMC is a key component of fire danger rating indices worldwide (McArthur 1967; Bradshaw *et al.* 1983; Van Wagner 1987). The worst fire days coincide with very low dead FFMC when large quantities of fuel across landscapes are dry enough to ignite and sustain burning (e.g. Keeley *et al.* 2009; Sullivan and Matthews 2013). Conversely, under more moderate conditions, sheltered parts of landscapes (gullies and polar-facing slopes) that are able to maintain higher dead FFMC act as a barrier to the spread of fire (Holden and Jolly 2011; Caccamo *et al.* 2012; Nyman *et al.* 2018).

The focus of this study is surface dead fine fuel, which we define as dead leaves, bark, twigs and dead grass less than 6 mm in diameter on the forest floor (as per Hines *et al.* 2010; Gould *et al.* 2011). Dead fine fuel is important to fire behaviour because it rapidly dries, ignites relatively easily and is consumed in the flaming front of the fire (Tolhurst and Cheney 1999; Keane 2015). The surface fuel layer is where wildfires typically ignite and where the spread of fire is typically sustained (Gould *et al.* 2011). Surface dead FFMC is sometimes considered separately for the upper litter layer (e.g. uppermost 5–10 mm) and full litter profile (e.g. Sneeuwjagt and Peet 1985; McCaw *et al.* 2012). The moisture content of the upper litter layer is more responsive to changes in atmospheric conditions (Slijepcevic *et al.* 2013) and has a large influence on ignitibility (Cawson and Duff 2019), rate of spread (Van Wagner 1987) and flame height (Gould *et al.* 2011). The average moisture content across the full litter profile is an important determinant of smouldering combustion, fuel availability and fuel consumption (Sneeuwjagt and Peet 1985; Van Wagner 1987; de Groot *et al.* 2009; Gould *et al.* 2011).

Surface dead FFMC varies both spatially and temporally as a function of microclimate and fuel properties. Microclimate (surface temperature, relative humidity, precipitation, wind and solar radiation) determines evaporative demand and the moisture vapour differential between the fuel and atmosphere and therefore the rate of moisture exchange (as reviewed by Viney 1991; Matthews 2014). The microclimate in turn depends on mesoscale weather, topographic position and forest cover (Schunk *et al.* 2013*b*; Cawson *et al.* 2017; Nyman *et al.* 2018). Fuel properties that influence its ability to uptake and loose moisture include fuel equilibrium moisture content and response time (Bradshaw *et al.* 1983). The equilibrium moisture content varies between fuel types as a function of fuel properties such as degree of decay and chemical composition (Van Wagner 1972; Anderson 1990*b*; Schunk *et al.* 2013*a*). Response time is how quickly the fuel dries under a set of environmental conditions. The response time of surface dead FFMC may vary with litter depth, litter composition, degree of decomposition and packing ratio (Simard 1968; Anderson 1990*a*).

Field measures of fuel moisture are needed by fire managers to assess fire danger (Bradshaw *et al.* 1983) and identify windows for prescribed burning (Tolhurst and Cheney 1999). Yet there are challenges with many of the current methods used to measure fuel moisture in the field. Measurement of fuel moisture by oven-drying is often considered the gold standard (Matthews 2010). However, this approach has limited value when continuous or real-time moisture information is needed or when monitoring needs to be done without personnel in the field. Another traditional method is the use of fuel analogues (i.e. hazard sticks or hazard bags) to track changes in moisture in a fixed location, which generates a moisture time series but requires manual measurement (Beck and Armitage 2004; Hardy and Hardy 2007). Alternatively, the Speedy Moisture Meter (Dexter and Williams 1976) or Wiltronics T-H Fine Fuel Moisture Meter (Chatto and Tolhurst 1997) can be used to obtain instantaneous measurements in any location but also require manual measurement. Soil moisture sensors have been trialled to continuously and automatically measure surface dead FFMC, but with mixed success (Condera *et al.* 2012; Wilson *et al.* 2014; Nyman *et al.* 2015; Schunk *et al.* 2016). This approach is under experimentation and cannot currently be used in operational fire management. Another increasingly popular approach is the use of automated fuel moisture sticks (Campbell Scientific CS506/26601), which collect and transmit moisture data, providing a real-time continuous measure that can be accessed remotely.

The practical advantages of automated fuel moisture sticks have led to their use in fire management for routine measurement of fuel moisture (National Wildfire Coordinating Group 2014) and in fuel moisture research (e.g. Resco de Dios *et al.* 2015; Cawson *et al.* 2017; Schunk *et al.* 2017; Burton *et al.* 2019). Despite growing adoption, there has been limited systematic analysis of the performance of automated fuel sticks as an analogue for dead surface fine fuel (exceptions include Schunk *et al.* 2014 over a limited geographic range). Variations in canopy cover and the characteristics of surface dead fine fuel between forest types are likely to result in different relationships between surface dead FFMC and fuel stick moisture content, which need to be accounted for if the fuel sticks are to provide an accurate representation of surface dead FFMC.

Our aim was to evaluate automated fuel moisture sticks (Campbell Scientific CS505/10824, CS506/26601) as a method for estimating surface dead FFMC across a range of forest types worldwide. Specifically, we asked:

- How accurately do the automated fuel moisture sticks estimate surface dead FFMC?
- Does the relationship between the moisture of the automated fuel stick and surface dead FFMC vary by forest type?

We use the results of our study to evaluate the efficacy of automated fuel moisture sticks in wildfire management and to make recommendations for their future use.

Methods

We compiled a large dataset of concurrent automated fuel stick moisture observations and gravimetric surface dead FFMC measurements from 27 sites. These data were originally collected as part of separate fire research projects. The data were analysed using linear regression to determine relationships between fuel stick moisture and surface dead FFMC.

Site description

This study used data collected from three broad geographic regions: western Canada, central Europe and south-eastern Australia (Fig. 1). Some of the data have been published previously (Schunk *et al.* 2014; Bovill *et al.* 2015; Cawson *et al.* 2017; Schunk *et al.* 2017), but other datasets are unpublished or presented in theses (Gibos 2010). The dataset encompassed 27 sites across wide-ranging forest types typical of the different geographic regions, including boreal forest, lowland and alpine coniferous forests, deciduous broadleaf forest and temperate eucalypt forest. Data from the 27 sites were grouped into nine forest fuel categories based on geographic location, tree species, forest structure, type of dead surface fine fuel (needles, leaves or grass) and its depth (Table 1). The groupings resulted in one forest fuel category in western Canada (five sites), five forest fuel categories in central Europe (six sites) and three forest fuel categories in south-eastern Australia (16 sites).

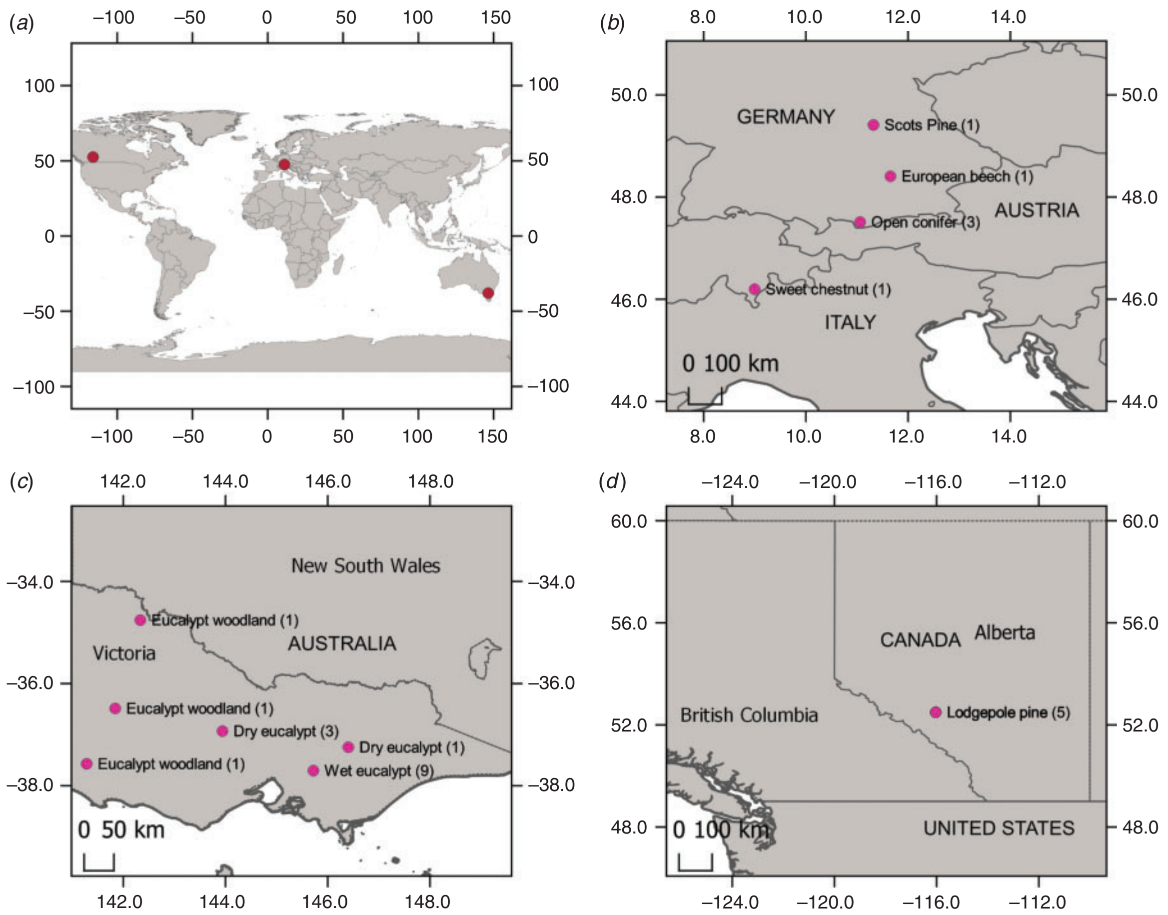

Fig. 1. Location of sites. (*a*) Worldwide map showing geographic regions and regional maps of (*b*) central Europe, (*c*) south-eastern Australia and (*d*) western Canada. For regional maps the site locations are marked with a red dot and labelled according to the forest fuel category. If the geographic distance between sites is too small to depict at the map's resolution, the number of sites is shown in parentheses.

Representative photographs of each forest fuel category illustrate the differences in surface fuel (Fig. 2). The categories are:

- Lodgepole pine – evergreen forest dominated by *Pinus contorta* in Canada with dead surface fuel comprising a shallow layer of pine needles
- Scots pine (needles) – evergreen lowland forest dominated by *P. sylvestris* in central Europe with dead surface fuel comprising a shallow layer of pine needles
- Scots pine (grass) – evergreen lowland forest dominated by *P. sylvestris* in central Europe with dead surface fuel comprising dead grass
- Open conifer – evergreen woodland and alpine forest dominated by either *P. mugo*, *P. sylvestris* or *Picea abies* in central Europe with dead surface fuel comprising dead grass
- European beech – deciduous lowland forest dominated by *Fagus sylvatica* in central Europe with dead surface fuel comprising a shallow layer of leaves
- Sweet chestnut – deciduous forest dominated by *Castanea sativa* in central Europe with dead surface fuel comprising a deep layer of leaves
- Dry eucalypt – evergreen open forest dominated by a variety of *Eucalyptus* species in south-eastern Australia with dead surface fuel comprising a moderately deep layer of leaves
- Wet eucalypt – evergreen tall open forest dominated by a variety of *Eucalyptus* species in south-eastern Australia with dead surface fuel comprising a deep layer of leaves
- Eucalypt woodland – evergreen woodland dominated by a variety of *Eucalyptus* species in south-eastern Australia with dead surface fuel comprising a shallow and patchy layer of leaves

Fuel moisture sampling

The fuel moisture dataset comprised concurrent measurements of gravimetric surface dead FFMC and automated fuel stick moisture. We used Campbell Scientific automated fuel moisture sensors (CS505/10824 and CS506/26601), which use time domain reflectometry with a reported operating range of 0% to 70% (Campbell Scientific 1998). It was beyond the scope of the current study to quantify the precision of the stick sensor, but previous research shows strong agreement ($R^2 = 0.981$) between the electronic measurements and real gravimetric stick moisture (Schunk *et al.* 2014). These fuel sticks are designed to emulate 10-h fuel (diameter 1.3 cm; length 50.8 cm). The sticks were mounted 30 cm above the forest floor using a mounting kit (except at eight eucalypt sites where they were mounted at 50 cm because of local project requirements). At a subset of sites, three

Table 1. Summary descriptors and statistics for each forest fuel category

Forest fuel category	Tree species or EVC[A] for Australia	Geographic location	Average latitude longitude	No. of sites	Monitoring period, year	Dominant type of surface dead fine fuel	PAI[B]	Litter depth,[C] mm	No. of concurrent samples	No. of subsamples per site visit[D]	Fuel sticks per site	Mean surface FFMC, %	Mean fuel stick moisture, %	Ratio of surface dead FFMC to fuel stick moisture
Lodgepole pine	*Pinus contorta*	Rocky Mountains, Alberta, Canada	52.49°N 116.04°W	5	3 months, 2009	Needles	4.3	1	80	4–8	1	37.9	16.6	2.3
Scots pine (needles)[E]	*Pinus sylvestris*	Middle Franconian Basin, Bavaria, Germany	49.41°N 11.32°E	1	7 months, 2013	Needles	1.1	1	84	3	1	44.0	23.0	1.9
Scots pine (grass)[E]	*Pinus sylvestris*					Grass	1.1	NA	56	3	1	36.6	22.3	1.6
Open conifer	*Pinus mugo* or *Pinus sylvestris* or *Picea abies*	Ammer Mountains, Bavaria, Germany	47.51°N 11.07°E	3	7 months, 2016	Grass	1.2	NA	41	3	3	107.9	22.7	4.8
European beech	*Fagus sylvatica*	Danube-Isar Hill Country, Bavaria, Germany	48.41°N 11.65°E	1	13 months, 2012–13	Leaves	3.1	16[3]	104	3	1	139.2	24.4	5.7
Sweet chestnut	*Castanea sativa*	Monte Carasso (Bellinzona), Switzerland	46.19°N 8.99°E	1	20 months, 2010–11	Leaves	–	40	53	6	1	79.9	27.0	3.0
Dry eucalypt	Box ironbark, shrubby foothill, herb-rich foothill forest	Central and Eastern Uplands, Victoria, Australia	37.01°S 144.56°E	4	6 months, 2015	Leaves	2.0	23	48	15	1	32.1	17.3	1.9
Wet eucalypt	Wet forest, damp forest	Eastern Uplands, Victoria, Australia	37.73°S 145.76°E	9	16 months, 2016–17	Leaves	3.7	44	37	5	1	100.1	24.5	4.1
Eucalypt woodland	Noorinen sands mallee, Lowan sands mallee	Murray Basin Plains, Victoria, Australia	36.27°S 141.82°E	3	6 months, 2015	Leaves	0.6	14	67	15	1	43.0	19.5	2.2

[A]Ecological vegetation class (EVC) refers to the vegetation type as mapped by the Victorian government (Department of Environment Land Water and Planning 2016). Within each vegetation class there are typically several dominant *Eucalyptus* species. [B]Plant area index (PAI) is a measure of all canopy elements intercepting radiation at a point. It differs from the leaf area index because there has been no correction to remove branches and stems. [C]Litter depth varies throughout the year. This measurement was taken shortly before leaf fall and hence likely represents the minimum depth. [D]Subsamples were often bulked in the field. [E]Scots pine (needles) and Scots pine (grass) sites are the same site with two different types of fine fuel measured.

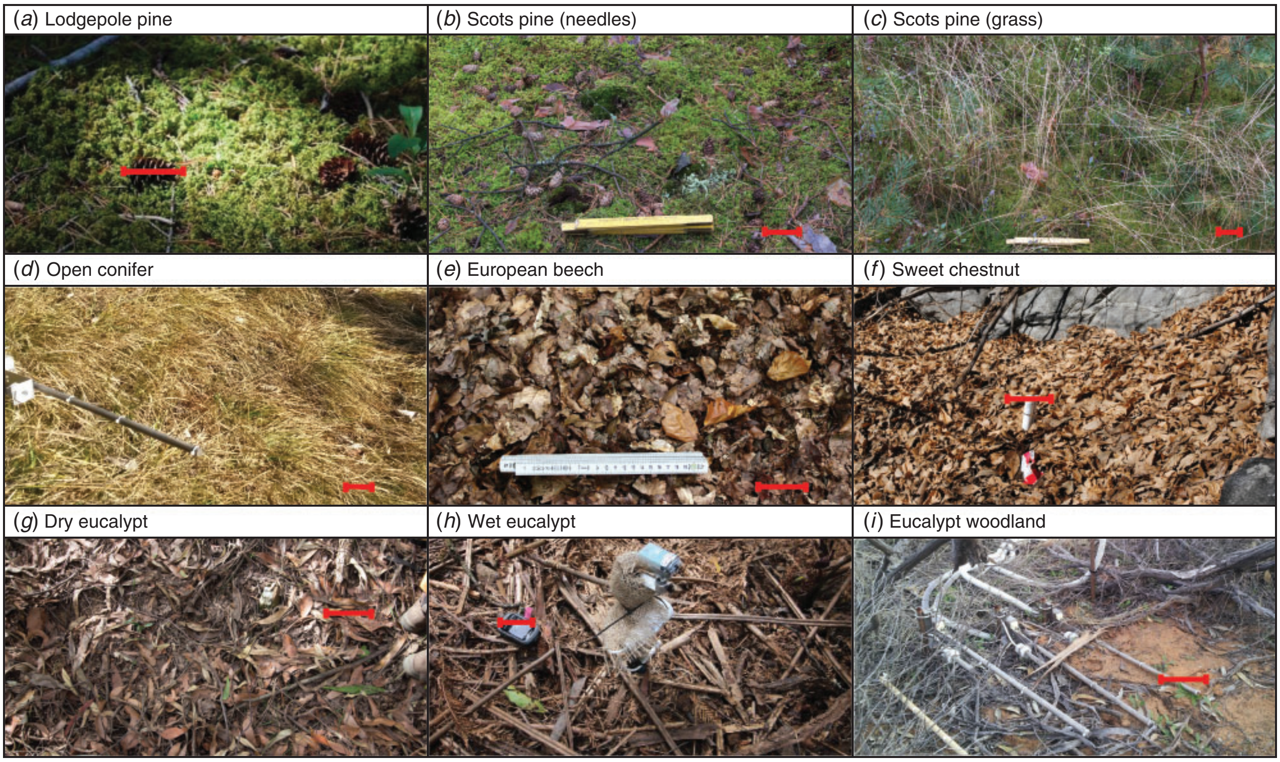

Fig. 2. Photographs depicting surface fine fuel in the nine forest fuel categories. (*a*) Lodgepole pine, (*b*) Scots pine (needles), (*c*) Scots pine (grass), (*d*) open conifer, (*e*) European beech, (*f*) sweet chestnut, (*g*) dry eucalypt, (*h*) wet eucalypt and (*i*) eucalypt woodland. Red scale bar = 5 cm.

fuel sticks were installed but for the purposes of this study only the mean values from those three fuel sticks are analysed.

To measure surface dead FFMC, surface fuel samples were collected into sealed containers from multiple locations within 20 m of the fuel sticks. The full litter profile was sampled down to the duff (or mineral soil where there was no duff); dead grass was sampled in the Scots pine (grass) and open conifer sites as it was the predominant dead surface fine fuel. Sample sizes varied between sites, depending on litter depth and study design, but typically exceeded 10 g in wet weight. Sampling was done at different times throughout the day and year to quantify a range of moisture conditions. The number of gravimetric subsamples taken at each site per sampling event varied from 3 to 15 depending on the design of the individual project. We only report the means for each sampling event as often the samples were bulked before drying. Samples were oven-dried at 105°C for at least 24 h until the sample achieved a constant weight. The moisture content was calculated as percent of oven dry weight. Gravimetric fuel moisture measurements were matched to the fuel stick measurements that had been recorded at the same time.

Data analysis

We used linear regression to quantify the strength of relationships between fuel stick moisture and surface dead FFMC with all the data pooled and for each forest fuel category individually. We excluded concurrent measurements where the fuel stick moisture was >70% because the recommended operating range of the fuel stick is 0–70%. We performed an analysis of covariance (ANCOVA) to test for the effect of forest fuel category on the regression between fuel stick moisture and surface dead FFMC. The analysis was first done for the full range of gravimetric moisture values, which sometimes exceeded 200%. Next, the analysis was repeated for a subset of the data where gravimetric moisture was below 35% to evaluate the moisture sticks at the lower end of the fuel moisture spectrum when fires are more likely to occur. All analyses were performed using the R statistical programming language, version 3.6.1 (R Core Team 2019).

Results

The linear regression between surface dead FFMC and fuel stick moisture for the full dataset had a R^2 of 0.54 and a root mean squared error (RMSE) of 46 (Fig. 3; Table 2). In most cases the surface dead FFMC was much higher than fuel stick moisture – on average by a factor of 3 (Table 1), except at low moisture contents when surface dead FFMC was sometimes lower than fuel stick moisture. The magnitude of the discrepancy between fuel stick moisture and surface dead FFMC varied depending on forest fuel category, from a factor of 1.6 (Scots pine needles) to a factor of 5.7 (European beech). We performed a separate regression analysis for surface dead FFMC <35%. At this lower end of the fuel moisture spectrum, the model was weaker ($R^2 = 0.18$) than for the full range of data. The RMSE was 7, which is large given the narrow range of the data. The slope of the regression was lower and close to 1 for the model fitted to dead FFMC <35%.

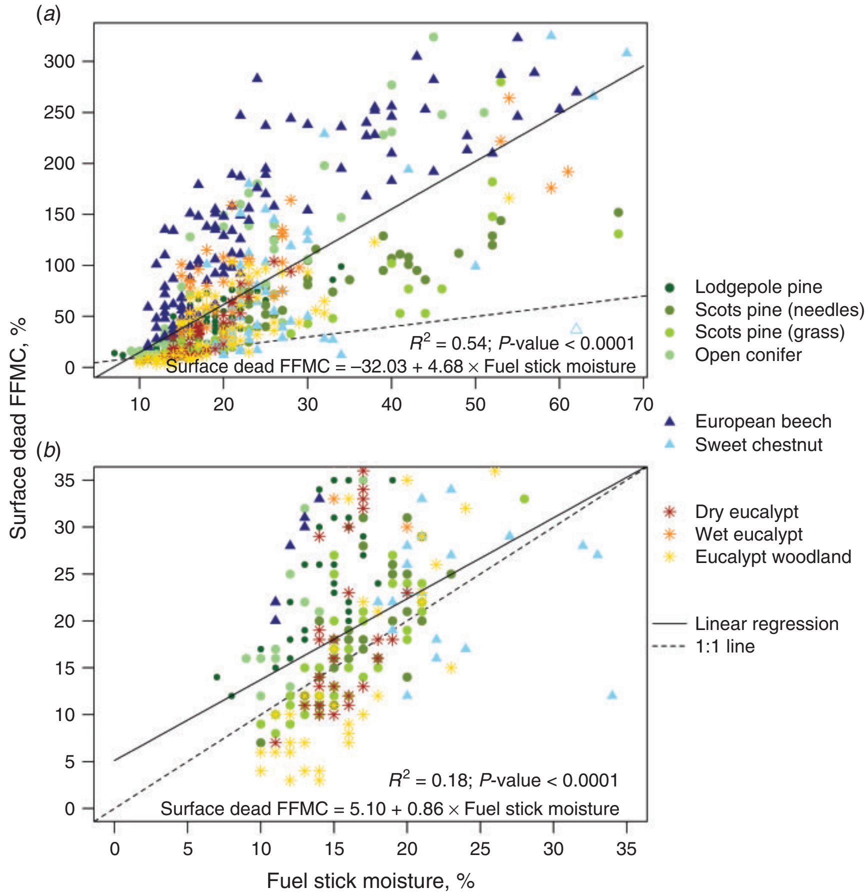

Fig. 3. Scatterplots comparing surface dead fine fuel moisture content (FFMC) with fuel stick moisture for (*a*) the full data range and (*b*) data below the fibre saturation point of ~35%. Colours and symbols for the data points represent different forest fuel categories. The solid black line is a linear regression of all data and the dashed line is the 1 : 1 line. The hollow blue triangle is an outlier in the sweet chestnut data that is displayed in the scatterplots but removed from the regression modelling.

Table 2. Summary of correlation coefficients and linear models fitted to datasets for individual forest fuel categories. *n* is the number of samples used to derive the models for each forest fuel category. Standard error of parameter estimates are given in parentheses. Significance of F-tests are as indicated: n.s. $P > 0.05$; $^*P \leq 0.05$; $^{**}P \leq 0.01$; $^{***}P \leq 0.001$; $^{****}P \leq 0.0001$. There is no regression for wet eucalypt when surface dead FFMC <35% because the sample size was too small. FFMC, fine fuel moisture content

	Linear models for full range of data						Linear models for data where surface dead FFMC < 35%					
Fuel category	*n*	y-intercept	Slope	R^2	F-test	RMSE	*n*	y-intercept	Slope	R^2	F-test	RMSE
All data	570	−32.0 (4.4)	4.7 (0.2)	0.54	****	46.3	237	5.1 (11.9)	0.9 (0.1)	0.18	****	7.1
Lodgepole pine	80	−20.6 (5.1)	3.5 (0.3)	0.64	****	49.9	44	−2.2 (4.5)	1.8 (0.3)	0.43	****	20.6
Scots pine (needles)	84	−29.0 (3.6)	3.2 (0.1)	0.87	****	57.4	51	−8.9 (3.0)	1.6 (0.2)	0.59	****	11.8
Scots pine (grass)	56	−34.2 (7.0)	3.2 (0.3)	0.72	****	60.2	41	−4.9 (2.6)	1.3 (0.2)	0.62	****	11.9
Open conifer	41	−49.0 (14.1)	6.9 (0.6)	0.80	****	60.8	12	−11.7 (8.3)	2.7 (0.7)	0.59	**	47.9
European beech	104	11.5 (9.3)	5.2 (0.3)	0.70	****	72.7	7	−24.4 (6.5)	4.2 (0.5)	0.92	****	77.6
Sweet chestnut	53	−60.5 (18.8)	5.2 (0.7)	0.55	****	49.7	20	23.6 (7.3)	0.0 (0.3)	−0.05	n.s.	18.7
Dry eucalypt	48	−70.4 (8.0)	5.9 (0.5)	0.79	****	49.5	29	−10.7 (10.4)	1.8 (0.6)	0.19	**	21.5
Wet eucalypt	37	14.5 (11.9)	3.5 (0.4)	0.65	****	52.2	2	Insufficient data				
Eucalypt woodland	67	−26.3 (8.4)	3.6 (0.4)	0.55	****	51.5	13	−72.7 (11.4)	6.0 (0.7)	0.78	****	16.8

Linear regressions between fuel stick moisture and surface dead FFMC for individual forest fuel categories generally had higher R^2 values than the regression for the full dataset (Table 2; Fig. 4; Fig. A1). The R^2 ranged from 0.55 (sweet chestnut and eucalypt woodland) to 0.87 (Scots pine needles), with a median of 0.70. The median RMSE was 52, which is slightly higher than

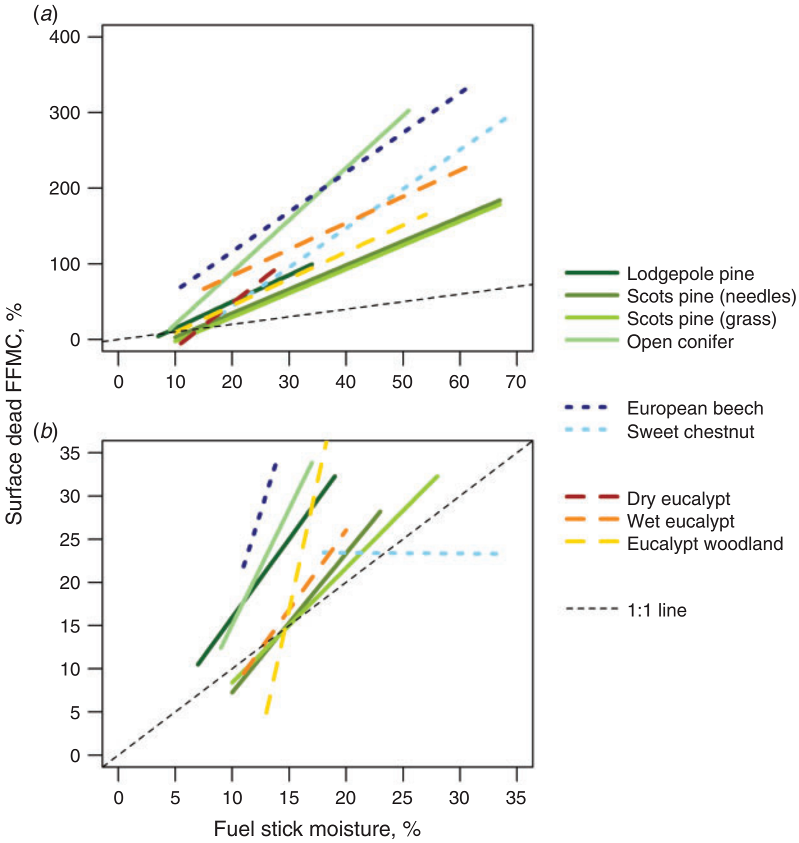

Fig. 4. Linear relationships between surface dead fine fuel moisture content (FFMC) and fuel stick moisture for (*a*) the full data range and (*b*) data where fine FMC is <35%. Colours and symbols on the lines represent different forest fuel categories.

the RMSE for the regression for the full dataset. Regression models fitted to surface dead FFMC <35% were generally weaker, with a median R^2 of 0.59 (Table 2; Fig. 4; Fig. A2). Exceptions were European beech and eucalypt woodland, which both had stronger models within this range (R^2 of 0.92 and 0.78 respectively). The model for sweet chestnut was non-significant and there was insufficient data to derive a model for wet eucalypt.

Results from the ANCOVA showed there was a statistically significant effect of forest fuel category on the relationship between fuel stick moisture and surface dead FFMC. For the dataset spanning the full range of moisture values, both the treatment effect (forest fuel category; $F = 90.11$, $P < 0.001$) and the interaction effect (forest fuel category × stick moisture; $F = 12.73$, $P < 0.001$) were statistically significant, meaning there was a significant difference between both the intercepts and slopes of the regressions. Slopes ranged from 3.18 to 6.90 and intercepts ranged from −70.43 to 14.49. Similarly, for the dataset with surface dead FFMC <35%, both the treatment effect (forest fuel category; $F = 28.13$, $P < 0.001$) and the interaction effect (forest fuel category × stick moisture; $F = 6.54$, $P < 0.001$) were statistically significant. For these regressions, slopes ranged from 1.3 to 4.2 and intercepts ranged from −72.7 to −2.2.

Discussion

Automated fuel sticks provided a reasonable estimate of surface dead FFMC in most cases, but only after forest fuel-specific calibration. They are best utilised as a coarse indicator of when surface dead FFMC reaches a threshold where it is likely to be ignitable, rather than as a precise estimator of moisture content. They provide a continuous, automated measure of fuel moisture that can be transmitted from remote locations, so they reduce the labour-intensiveness of obtaining field-based moisture information. Precision may be improved with future work.

Accuracy of automated fuel moistures sticks in estimating surface dead FFMC

Typically, surface dead FFMC was higher than fuel stick moisture content, except under dry conditions (moisture content <20%) in some forest fuel categories with a shallow litter bed. Resco de Dios *et al.* (2015) report a similar relationship between fuel stick moisture and profile dead FFMC in eucalypt woodland. This result may seem counterintuitive given the smaller diameter of the fine fuel particles (<6 mm) relative to the fuel sticks (1.3 cm). Fine fuels have a higher surface-area-to-volume ratio than fuel sticks, potentially enabling more rapid moisture exchange with the atmosphere and therefore more rapid dry-down (Fosberg *et al.* 1970). However, the location of surface fine fuel in a (sometimes deep) litter bed likely reduces the atmospheric exposure of most individual fuel particles, thus slowing the response time of the surface fine fuel relative to the fuel stick that is installed above the surface (Keane 2015). Additionally, surface fuels that are in contact with moist soil or duff may be less responsive to changes in atmospheric conditions (Hatton *et al.* 1988).

Some of the disparity between surface dead FFMC and fuel stick moisture may be related to sampling issues rather than to real differences in moisture content. The data used for the regression analysis (Figs 3, 4) were collected for a range of different purposes and thus sampling protocols differed between forest fuel categories and were not necessarily optimal for the purposes of the current study. One potential issue was the lack of spatial replication in fuel stick measurements; for most sites only one fuel stick was used. It is possible that the microclimate in the fuel stick locations (e.g. solar radiation and precipitation throughfall) were not representative of average site conditions. The amount of error introduced from this lack of replication likely varies by forest type depending on the spatial variability of the microclimate within that forest type. Similarly, the disparity between surface dead FFMC and fuel stick moisture may differ between forest fuel categories because of the varying number of fine fuel samples taken at each visit to a site (ranging from 3 to 15) or the total number of days when the fuels were sampled (ranging from 37 to 104). Within-site variability in surface dead FFMC was not quantified in this study.

Effects of forest fuel category

The relationship between fuel stick moisture and surface dead FFMC was reasonably strong for the full dataset ($R^2 = 0.54$), but typically strengthened when the analyses were performed within forest fuel categories (median $R^2 = 0.70$). Other studies report regression functions of similar strength; for example, $R^2 = 0.74$ in wet eucalypt forest (Burton *et al.* 2019) and $R^2 = 0.63$ in eucalypt woodland (Resco de Dios *et al.* 2015). Differences in the regression functions between forest fuel categories likely reflect differences in both fuel properties and forest structure. Fuel properties such as fuel particle type, particle thickness, packing ratio, state of decomposition and litter bed depth contribute to differences in the diffusivity, response time and saturation water content of the fuel (Simard 1968; Anderson 1990*a*). Forest structural properties such as canopy cover, tree height, tree density and understorey density influence the microclimate (i.e. in-forest temperature, relative humidity and wind) (Walsh *et al.* 2017; Nyman *et al.* 2018) and types of drying and wetting processes that the fuel stick and fuel bed are exposed to. Some fuel and forest structural properties may change seasonally, potentially weakening the regression functions (e.g. for sweet chestnut).

With so many different factors potentially contributing to differences in the regression functions, it is difficult to identify individual factors that explain the trends across the full dataset. For example, past research has shown that dead grass absorbs more water than needles (Simard 1968), but also has a faster response time (Anderson 1990*a*). This might explain the high slope of the regression function for the open conifer forest fuel category (grass-dominated) relative to the other fuel categories. However, the same explanation cannot be used to explain the results for Scots pine (grass), which had a slope equal to Scots pine (needles). A much larger dataset is needed to quantitatively determine which fuel and forest structural properties are having the greatest influence. In the absence of this knowledge, our results clearly demonstrate that calibrations for forest fuel categories are needed to improve the strength of the relationships between fuel stick moisture and surface dead FFMC.

Implications for fire management

Automated fuel sticks will be useful to fire managers as a method for estimating surface dead FFMC provided forest fuel-specific calibrations are derived. They should be used in conjunction with other methods because they are not highly accurate as an analogue for surface dead fine fuels, particularly at lower moisture contents. In the context of fire management, they could be used to track fuel moisture over time in a range of landscape positions without the need for regular site visits, providing an indication of topographical differences in moisture and drying rates following precipitation. Many of the moisture models used by fire managers do not adequately capture the effects of terrain or variations in canopy cover (Matthews 2014), so the fuel sticks will be valuable in this regard. The fuel sticks can be used to indicate when surface dead fine fuel is approaching a dry state in different parts of the landscape. At the drier end of the moisture spectrum, they should be supplemented by manual sampling using devices such as the Wiltronics T-H Fine Fuel Moisture Meter (Chatto and Tolhurst 1997) and moisture models that can reliably predict under dry conditions (Slijepcevic *et al.* 2015).

Future research needs

There are several areas where research could be prioritised to further develop our ability to use fuel moisture sticks in wildfire management. First, there could be more work done to explore the utility of the fuel sticks to estimate dead FFMC across a range of fuel strata, including the uppermost litter layer and suspended dead fuel, which influence different components of fire behaviour (Gould *et al.* 2011). Fuel stick moisture may be more strongly related to the moisture content within these fuel strata compared with the full litter profile (as shown by Resco de Dios *et al.* 2015; Burton *et al.* 2019). Further research could also evaluate the fuel moisture sticks against widely used fuel moisture models. This analysis could be used to identify the moisture conditions for which the fuel sticks are most appropriate to use and when the models are a more reliable source of information. Finally, research effort could be directed towards the development of a generalised model linking fuel stick moisture to surface dead FFMC. Such models could include factors that contribute to fuel-specific effects (e.g. type of fuel particle, litter bed depth, decomposition) and forest-specific effects (e.g. leaf area index), eliminating the need for calibration functions for each forest fuel category. There may be opportunities to develop machine-learning routines to improve the accuracy of these generalised models over time. Despite the large dataset used in this study, it was too small to develop these more generalised models. Data would be needed from a larger number of sites and across a broader range of moisture conditions, particularly very dry conditions.

Conclusions

Our results indicate that typically the fuel stick underestimates surface dead FFMC, but the relationship can be modelled with reasonable accuracy for most dead surface fuels using forest fuel-specific linear calibration functions. The variation explained by those forest fuel-specific linear regressions ranges from 55% to 87%. Similarities in the regression functions for some forest fuel categories may be attributed to similarities in forest structure or surface fine fuel properties, including litter bed depth, packing density and degree of decay. Overall, our results demonstrate that automated fuel sticks can be used as an analogue for surface dead fine fuels for fuel moisture research, model development and fire management purposes, such as monitoring wildfire risk across landscapes and providing guidance about prescribed burning windows, but only if there are fuel-specific calibrations and if they are used together with other methods. Further research is needed to refine the calibration functions to improve precision and potentially devise a generalised model incorporating fuel properties across different forest types.

Conflicts of interest

The authors declare no conflicts of interest.

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References

Anderson HE (1990*a*) Moisture diffusivity and response-time in fine forest fuels. *Canadian Journal of Forest Research* **20**, 315–325. doi:10.1139/X90-046

Anderson HE (1990*b*) 'Predicting equilibrium moisture content of some foliar forest litter in the northern Rocky Mountains.' USDA Forest Service, Intermountain Research Station. (Ogden, UT, USA)

Beck JA, Armitage OB (2004) Diurnal fine fuel moisture characteristics at a northern latitude. In 'Proceedings of the 22nd Tall Timbers Fire Ecology Conference: Fire in Temperate, Boreal, and Montane Ecosystems.' (Eds RT Engstrom, KEM Galley, WJd Groot) pp. 211–221. (Tall Timbers Research Station, Tallahassee, FL, USA)

Bovill W, Hawthorne S, Radic J, Baillie C, Ashton A, Noske P, Lane P, Sheridan G (2015) Effectiveness of automated fuelsticks for predicting the moisture content of dead fuels in *Eucalyptus* forests. In '21st International Congress on Modelling and Simulation, 29 Nov to 4 Dec 2015. Gold Coast, Australia.'

Bradshaw LS, Deeming JE, Burgan JE, Cohen JD (1983) 'The 1978 National Fire-Danger Rating System: technical documentation.' USDA, Forest Service, Intermountain Forest and Range Experiment Station (Ogden, UT, USA)

Burrows ND (1999) Fire behaviour in jarrah forest fuels. 2: field experiments. *CALMscience* **3**, 57–84.

Burton J, Cawson J, Noske P, Sheridan G (2019) Shifting states, altered fates: divergent fuel moisture responses after high frequency wildfire in an obligate seeder eucalypt forest. *Forests* **10**, 436. doi:10.3390/F10050436

Caccamo G, Chisholm LA, Bradstock RA, Puotinen ML, Pippen BG (2012) Monitoring live fuel moisture content of heathland, shrubland and sclerophyll forest in south-eastern Australia using MODIS data. *International Journal of Wildland Fire* **21**, 257–269. doi:10.1071/WF11024

Campbell Scientific (1998) CS506 Fuel Moisture Sensor Instruction Manual, Campbell Scientific Inc, Logan, UT, USA. Available at https://s.campbellsci.com/documents/au/manuals/cs506.pdf [Verified 29 January 2020]

Cawson JG, Duff TJ (2019) Forest fuel bed ignitability under marginal fire weather conditions in Eucalyptus forests. *International Journal of Wildland Fire* **28**, 198–204. doi:10.1071/WF18070

Cawson JG, Duff TJ, Tolhurst KG, Baillie CC, Penman TD (2017) Fuel moisture in Mountain Ash forests with contrasting fire histories. *Forest Ecology and Management* **400**, 568–577. doi:10.1016/J.FORECO.2017.06.046

Chatto K, Tolhurst KG (1997) 'The development and testing of the Wiltronics T-H fine fuel moisture meter.' (Department of Natural Resources and Environment: East Melbourne, Vic.)

Chen LWA, Verburg P, Shackelford A, Zhu D, Susfalk R, Chow JC, Watson JG (2010) Moisture effects on carbon and nitrogen emission from burning of wildland biomass. *Atmospheric Chemistry and Physics* **10**, 6617–6625. doi:10.5194/ACP-10-6617-2010

Condera M, Brini M, Calabrese R, Ascoli D, Pezzatti GB (2012) Verifica sperimentale del Sistema FireLess2. *Sherwood* **18**, 25–31.

Cruz MG, Sullivan AL, Gould JS, Sims NC, Bannister AJ, Hollis JJ, Hurley RJ (2012) Anatomy of a catastrophic wildfire: the Black Saturday Kilmore East fire in Victoria, Australia. *Forest Ecology and Management* **284**, 269–285. doi:10.1016/J.FORECO.2012.02.035

de Groot WJ, Pritchard JM, Lynham TJ (2009) Forest floor fuel consumption and carbon emissions in Canadian boreal forest fires. *Canadian Journal of Forest Research* **39**, 367–382. doi:10.1139/X08-192

Department of Environment Land Water and Planning (2016) 'Native vegetation: modelled 2005 ecological vegetation classes (with bioregional conservation status).' (Victorian State Government: Melbourne) Available at https://discover.data.vic.gov.au/dataset/native-vegetation-modelled-2005-ecological-vegetation-classes-with-bioregional-conservation-sta [Verified 20 January 2020]

Dexter BD, Williams DF (1976) Direct field estimation of fine fuel moisture content. *Australian Forestry* **39**, 140–144. doi:10.1080/00049158.1976.10675649

Dimitrakopoulos AP, Papaioannou KK (2001) Flammability assessment of Mediterranean forest fuels. *Fire Technology* **37**, 143–152. doi:10.1023/A:1011641601076

Fernandes PM, Botelho H, Rego F, Loureiro C (2008) Using fuel and weather variables to predict the sustainability of surface fire spread in maritime pine stands. *Canadian Journal of Forest Research* **38**, 190–201. doi:10.1139/X07-159

Fosberg MA, Lancaster JW, Schroeder MJ (1970) Fuel moisture response: drying relationships under standard and field conditions. *Forest Science* **16**, 121–128.

Gibos KE (2010) 'Effect of slope and aspect on litter layer moisture content of lodgepole pine stands in the eastern slopes of the Rocky Mountains of Alberta.' (University of Toronto: Canada)

Gould JS, McCaw WL, Cheney NP (2011) Quantifying fine fuel dynamics and structure in dry eucalypt forest (*Eucalyptus marginata*) in Western

Australia for fire management. *Forest Ecology and Management* **262**, 531–546. doi:10.1016/J.FORECO.2011.04.022

Hardy CC, Hardy CE (2007) Fire danger rating in the United States of America: an evolution since 1916. *International Journal of Wildland Fire* **16**, 217–231. doi:10.1071/WF06076

Hatton TJ, Viney NR, Catchpole EA, De Mestre NJ (1988) The influence of soil moisture on *Eucalyptus* leaf litter moisture. *Forest Science* **34**, 292–301.

Hines F, Tolhurst KG, Wilson AAG, McCarthy GJ (2010) 'Overall fuel hazard assessment guide', 4th edition. (Fire Management Branch, Department of Sustainability and Environment Report No. 82: Melbourne, Vic.)

Holden ZA, Jolly WM (2011) Modeling topographic influences on fuel moisture and fire danger in complex terrain to improve wildland fire management decision support. *Forest Ecology and Management* **262**, 2133–2141. doi:10.1016/J.FORECO.2011.08.002

Keane RE (2015) 'Wildland fuel fundamentals and application.' (Springer International Publishing: Switzerland)

Keeley JE, Safford H, Fotheringham CJ, Franklin J, Moritz M (2009) The 2007 Southern California wildfires: lessons in complexity. *Journal of Forestry* **107**, 287–296.

Knapp EE, Keeley JE, Ballenger EA, Brennan TJ (2005) Fuel reduction and coarse woody debris dynamics with early season and late season prescribed fire in a Sierra Nevada mixed conifer forest. *Forest Ecology and Management* **208**, 383–397. doi:10.1016/J.FORECO.2005.01.016

Matthews S (2010) Effect of drying temperature on fuel moisture content measurements. *International Journal of Wildland Fire* **19**, 800–802. doi:10.1071/WF08188

Matthews S (2014) Dead fuel moisture research: 1991–2012. *International Journal of Wildland Fire* **23**, 78–92. doi:10.1071/WF13005

McArthur AG (1967) 'Fire behaviour in eucalypt forests.' (Department of National Development, Forestry and Timber Bureau Canberra)

McCaw WL, Gould JS, Cheney NP, Ellis PFM, Anderson WR (2012) Changes in behaviour of fire in dry eucalypt forest as fuel increases with age. *Forest Ecology and Management* **271**, 170–181. doi:10.1016/J.FORECO.2012.02.003

National Wildfire Coordinating Group (2014) 'Interagency wildland fire weather station standards and guidelines.' (NWCG: Boise, ID)

Nyman P, Metzen D, Noske PJ, Lane PNJ, Sheridan GJ (2015) Quantifying the effects of topographic aspect on water content and temperature in fine surface fuel. *International Journal of Wildland Fire* **24**, 1129–1142. doi:10.1071/WF14195

Nyman P, Baillie CC, Duff TJ, Sheridan GJ (2018) Eco-hydrological controls on microclimate and surface fuel evaporation in complex terrain. *Agricultural and Forest Meteorology* **252**, 49–61. doi:10.1016/J.AGRFORMET.2017.12.255

R Core Team (2019) 'R: A language and environment for statistical computing.' (R Foundation for Statistical Computing: Vienna, Austria) Available at https://www.R-project.org [Verified 29 January 2020]

Resco de Dios V, Fellows AW, Nolan RH, Boer MM, Bradstock RA, Domingo F, Goulden ML (2015) A semi-mechanistic model for predicting the moisture content of fine litter. *Agricultural and Forest Meteorology* **203**, 64–73. doi:10.1016/J.AGRFORMET.2015.01.002

Rothermel R (1972) 'A mathematical model of predicting fire spread in wildland fuels.' USDA Forest Service, Intermountain Forest and Range Experiment Station (Ogden, UT, USA)

Schunk C, Leutner C, Leuchner M, Wastl C, Menzel A (2013*a*) Equilibrium moisture content of dead fine fuels of selected central European tree species. *International Journal of Wildland Fire* **22**, 797–809. doi:10.1071/WF12105

Schunk C, Wastl C, Schuster C, Menzel A (2013*b*) Forest fire danger rating in complex topography: results from a case study in the Bavarian Alps in autumn 2011. *Natural Hazards and Earth System Sciences* **13**, 2157–2167. doi:10.5194/NHESS-13-2157-2013

Schunk C, Leuchner M, Menzel A (2014) Evaluation of a system for automatic dead fine fuel moisture measurements. In 'Advances in forest fire research.' (Ed. D Viegos.) pp. 1115–1123. (Coimbra University Press: Coimbra, Portugal)

Schunk C, Ruth B, Leuchner M, Wastl C, Menzel A (2016) Comparison of different methods for the in situ measurement of forest litter moisture content. *Natural Hazards and Earth System Sciences* **16**, 403–415. doi:10.5194/NHESS-16-403-2016

Schunk C, Wastl C, Leuchnera M, Menzel A (2017) Fine fuel moisture for site- and species-specific fire danger assessment in comparison to fire danger indices. *Agricultural and Forest Meteorology* **234–235**, 31–47. doi:10.1016/J.AGRFORMET.2016.12.007

Simard AJ (1968) 'The moisture content of forest fuels. II: comparison of moisture variations above the fiber saturation point between a number of fuel types.' (Forest Fire Research Institute, Department of Forestry and Rural Development: Ottawa, Canada)

Slijepcevic A, Anderson WR, Matthews S (2013) Testing existing models for predicting hourly variation in fine fuel moisture in eucalypt forests. *Forest Ecology and Management* **306**, 202–215. doi:10.1016/J.FORECO.2013.06.033

Slijepcevic A, Anderson WR, Matthews S, Anderson DH (2015) Evaluating models to predict daily fine fuel moisture content in eucalypt forest. *Forest Ecology and Management* **335**, 261–269. doi:10.1016/J.FORECO.2014.09.040

Sneeuwjagt R, Peet GB (1985) 'Forest fire behaviour tables for Western Australia', 3rd edition. (Western Australian Department of Conservation and Land Management: Perth, WA)

Sullivan AL, Matthews S (2013) Determining landscape fine fuel moisture content of the Kilmore East 'Black Saturday' wildfire using spatially-extended point-based models. *Environmental Modelling & Software* **40**, 98–108. doi:10.1016/J.ENVSOFT.2012.08.008

Tolhurst KG, Cheney NP (1999) 'Synopsis of the knowledge used in prescribed burning in Victoria.' (Department of Natural Resources and Environment, Fire Management: East Melbourne, Vic.)

Van Wagner CE (1972) 'Equilibrium moisture contents of some fine forest fuels in Eastern Canada.' (Canadian Forestry Service, Petawawa Forest Experiment Station: Chalk River, Ontario)

Van Wagner CE (1987) 'Development and structure of the Canadian forest fire weather index system.' (Canadian Forestry Service: Ottawa, Ontario)

Viney NR (1991) A review of fine fuel moisture modelling. *International Journal of Wildland Fire* **1**, 215–234. doi:10.1071/WF9910215

Walsh SF, Nyman P, Sheridan GJ, Baillie CC, Tolhurst KG, Duff TJ (2017) Hillslope-scale prediction of terrain and forest canopy effects on temperature and near-surface soil moisture deficit. *International Journal of Wildland Fire* **26**, 191–208. doi:10.1071/WF16106

Wilson TB, Kochendorfer J, Meyers TP, Heuer M, Sloop K, Miller J (2014) Leaf litter water content and soil surface CO2 fluxes in a deciduous forest. *Agricultural and Forest Meteorology* **192–193**, 42–50. doi:10.1016/J.AGRFORMET.2014.02.005

Appendix

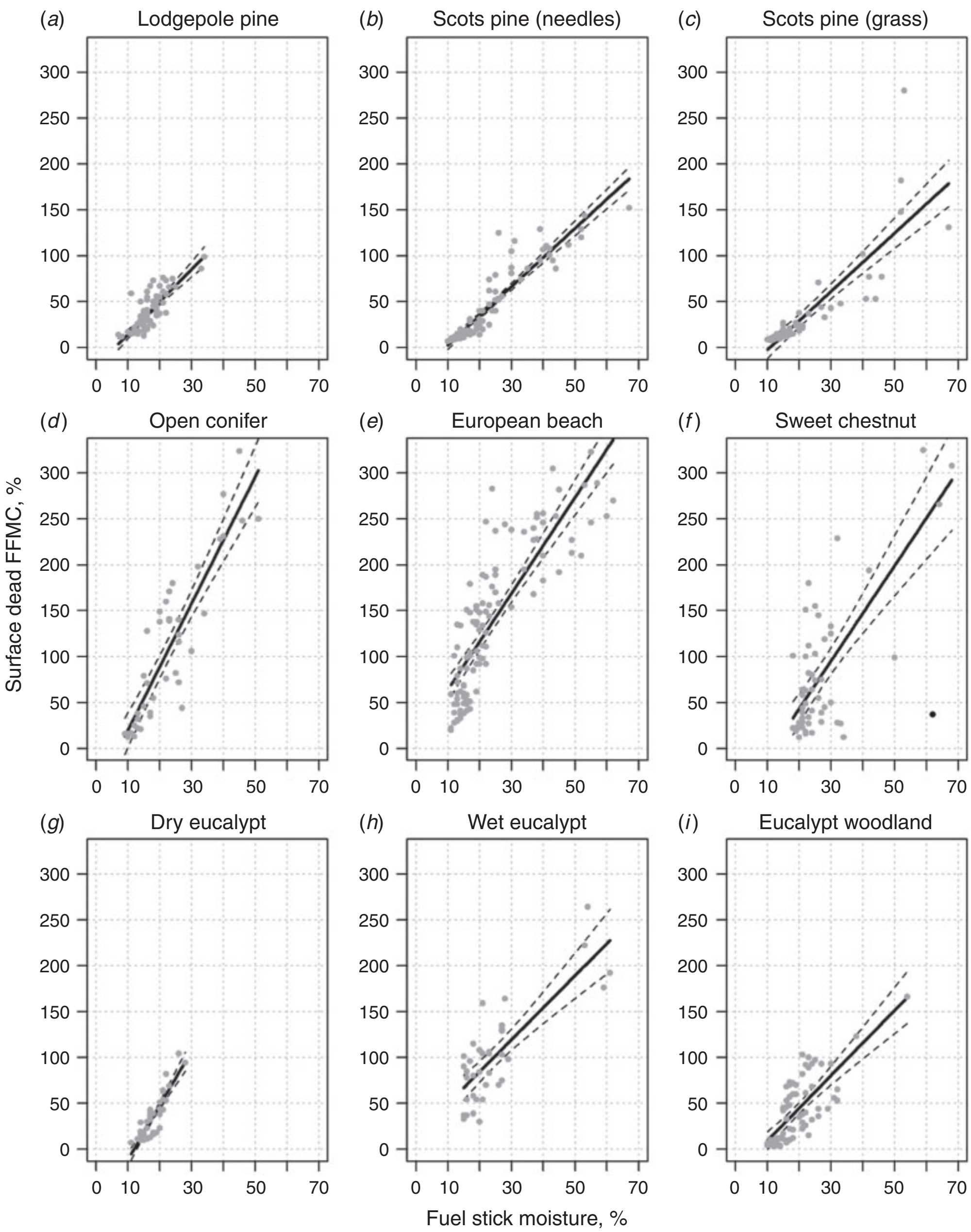

Fig. A1. Scatterplots comparing fuel stick moisture with surface dead fine fuel moisture content (FFMC) for each forest fuel category for the full data range. (*a*) Lodgepole pine, (*b*) Scots pine (needles), (*c*) Scots pine (grass), (*d*) open conifer; (*e*) European beech, (*f*) sweet chestnut, (*g*) dry eucalypt, (*h*) wet eucalypt and (*i*) eucalypt woodland. The solid black lines are linear regressions and the dashed lines denote the 95% confidence interval for the predicted mean. Data points used in the regressions are grey dots; the black dot for sweet chestnut is an outlier excluded from the regression analysis.

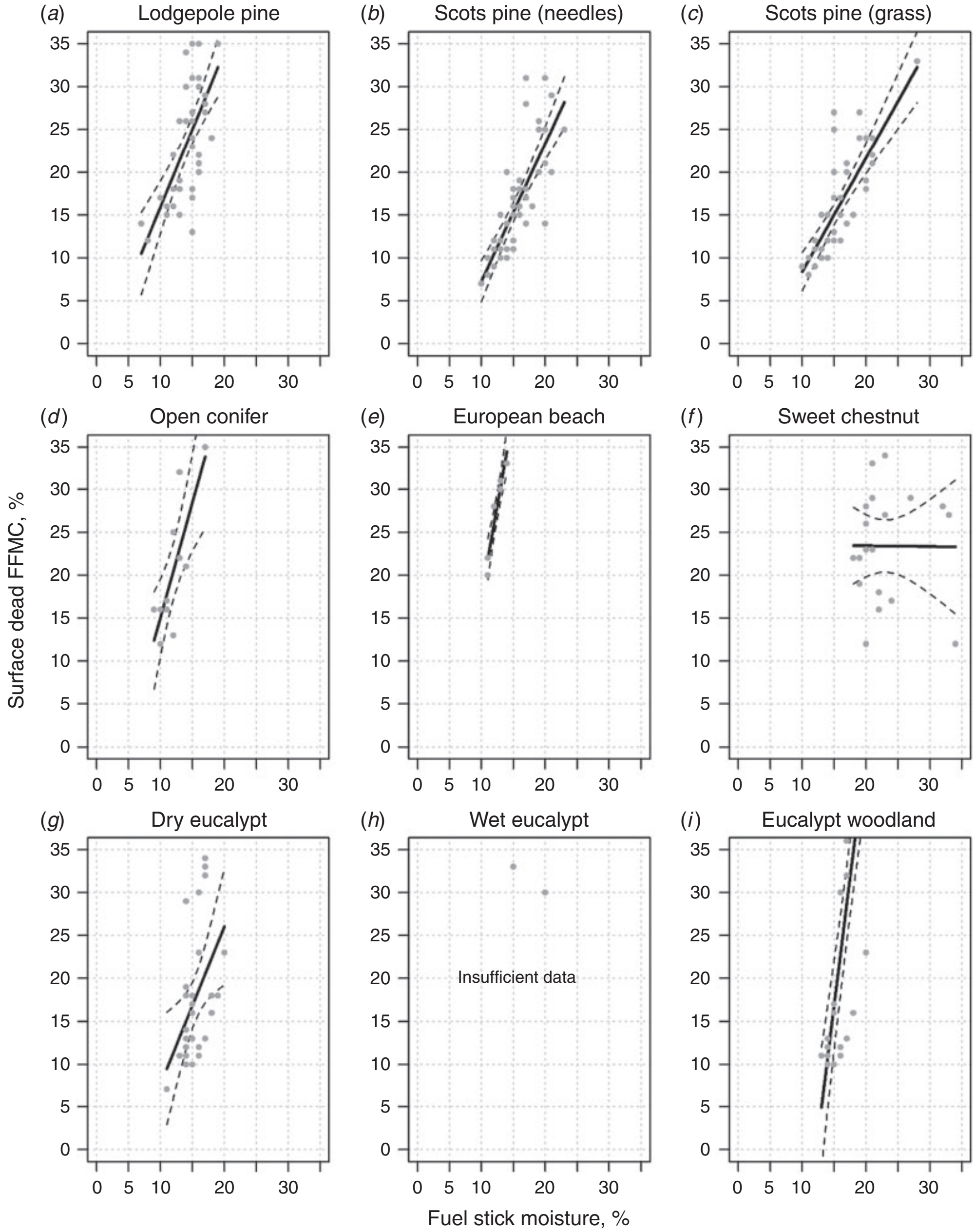

Fig. A2. Scatterplots comparing fuel stick moisture with surface dead fine fuel moisture content (FFMC) for each forest fuel category when surface dead FFMC data < 35%. (*a*) Lodgepole pine, (*b*) Scots pine (needles), (*c*) Scots pine (grass), (*d*) open conifer; (*e*) European beech, (*f*) sweet chestnut, (*g*) dry eucalypt, (*h*) wet eucalypt and (*i*) eucalypt woodland. The solid black lines are linear regressions and the dashed lines denote the 95% confidence interval for the predicted mean. Data points used in the regressions are grey dots. There was no regression for wet eucalypt because the sample size ($n = 2$) was too small.