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A fuel moisture content and flammability monitoring methodology for continental Australia based on optical remote sensing

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ABSTRACT

Fuel Moisture Content (FMC) is one of the primary drivers affecting fuel flammability that lead to fires. Satellite observations well-grounded with field data over the highly climatologically and ecologically diverse Australian region served to estimate FMC and flammability for the first time at a continental-scale. The methodology includes a physically-based retrieval model to estimate FMC from MODIS (Moderate Resolution Imaging Spectrometer) reflectance data using radiative transfer model inversion. The algorithm was evaluated using 360 observations at 32 locations around Australia with mean accuracy for the studied land cover classes (grassland, shrubland, and forest) close to those obtained elsewhere (r^2 = 0.58, RMSE = 40%) but without site-specific calibration. Logistic regression models were developed to generate a flammability index, trained on fire events mapped in the MODIS burned area product and four predictor variables calculated from the FMC estimates. The selected predictor variables were actual FMC corresponding to the 8-day and 16-day period before burning; the same but expressed as an anomaly from the long-term mean for that date; and the FMC change between the two successive 8-day periods before burning. Separate logistic regression models were developed for grassland, shrubland and forest. The models obtained an "Area Under the Curve" calculated from the Receiver Operating Characteristic plot method of 0.70, 0.78 and 0.71, respectively, indicating reasonable skill in fire risk prediction.

1. Introduction

The Fuel Moisture Content (FMC) of live bushfire fuel affects fire danger and fire behaviour, as it strongly influences the key components of flammability including ignitability, fire sustainability and combustibility (Anderson, 1970). 'Mega-fires' – extreme fire events with dramatic impacts on people and environment – generally occur after periods of moderate to severe drought (Stephens et al., 2014) in part due to drought effects on FMC. Therefore, spatially comprehensive and temporally frequent estimates of FMC should be a fundamental component of fire danger rating systems in support of a wide range of fire risk management and response activities, such as prescribed burning and pre-positioning firefighting resources.

In recent years, there has been considerable development in the estimation of FMC from satellite imagery. The literature is dominated by studies that apply either statistical (empirical) or physical model-based methods to coarse resolution data covering the visible, near infrared, and shortwave infrared regions of the electromagnetic spectrum (Yebra et al., 2013). Empirical relationships have the drawback of being sample-specific, but on the other hand, the selection and parameterization of physically-based algorithms is challenging. Previous studies mainly retrieved FMC in Mediterranean and Temperate ecosystems in Europe (Al-Moustafa et al., 2012; García et al., 2008; Jurdao et al., 2013b; Yebra and Chuvieco, 2009b), Western North America (Casas et al., 2014; Hao and Qu, 2007; Peterson et al., 2008) and south-eastern Australia (Caccamo et al., 2012; Nolan et al., 2016). Further research is needed to assess the full utility of FMC estimation across other fire-prone ecosystems (Yebra et al., 2013).

The conversion of FMC values into a Flammability Index (FI) can be an important additional step that facilitates the inclusion of FMC

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estimates into an integrated fire risk assessment system (Chuvieco et al., 2014). Research has produced several methods for this conversion based on (i) the concept of moisture of extinction, defined as the moisture threshold above which fire cannot be sustained (Chuvieco et al., 2004a); (ii) critical FMC thresholds derived from empirical statistical relations between FMC and fire occurrence (Dennison and Moritz, 2009; Nolan et al., 2016); and (iii) fitting a continuous logistic probability model between fire occurrence and FMC (Chuvieco et al., 2009a; Jurdao et al., 2012). However, so far none of these methods have been evaluated across a region as climatologically and ecologically diverse as Australia.

Through the use of remotely sensed data, this paper aims to derive the first continental-wide FMC and flammability monitoring methodology for Australia. The overarching objective is to contribute to the development of operational tools that can assist in better resources allocation in fire protection and response and improved awareness of fire risk to life and property.

2. Data

2.1. Live fuel moisture content measurements

Existing field FMC data had been collected at 32 sites across Australia as part of fuel remote sensing studies (Table 1, Fig. 1). All sites were selected to be sufficiently homogeneous to assume that the field measurements would be representative within a 2 × 2 MODIS 500 m pixels window. The data was collected between 2004 and 2014 by different research groups, during various time periods, and for different land cover classes, including grassland and crop (Newnham et al., 2011), shrubland (Caccamo et al., 2012) and forest (Caccamo et al., 2012; Nolan et al., 2016). These resulted in 3 to 37 observations over time per site (Table 1). Two of the heathland sites of Caccamo et al. (2012) were not considered here due to incomplete FMC data (their DNR site), and because of a geocoding anomaly (their LPF site). BCA2 location was also anomalous in Table 1 of Caccamo et al. (2012) but a revised longitude was provided by the authors (Table 1). Of the 25 grassland sites reported by Newnham et al. (2011), ten were not considered: four had no live FMC measurements, another four were represented by only one measurement, another one contained a geocoding anomaly and another one had unrealistically low values.

As part of this study, new FMC data were collected at one grassland and two forest sites in the Australian Capital Territory. Sample sites included a grassland site adjacent to Coppins Crossing Road and two forest sites in Namadgi National Park (Table 1).

At the grassland site, ten grass samples of about 80 g each were collected on 33 occasions between 17 November 2014 and 20 April 2016, along a 670 m transect where in-situ NDVI sensors were installed. Each sample was a mixture of live and dead but always standing material, and therefore FMC values lower than 30% were observed over some days during the summer periods. At each forest site, four samples were collected from each of three forest layers (canopy, elevated fuel and near-surface fuel) on 19–21 occasions between 19 October 2015 and 19 April 2016. Leaves from the canopy were collected using an arborist throw-line launcher following Youngentob et al. (2016). The collected samples were placed in a sealed bag and returned to the laboratory to weigh (m_f) and transferred into paper bags to be oven dried for 24 h at 105 °C (Matthews, 2010). Once dried, the samples were weighed again to determine dry weight (m_d). The FMC of each sample was calculated as the percentage difference of fresh and dry weight (Eq. 1).

Table 1

Description of the field sites used in this study. NSW: New South Wales, ACT: Australian Capital Territory TAS: Tasmania, WA: Western Australia, VIC: Victoria, NP: National Park. $\overline{FMC}$, FMC_{std} and n are the mean, standard deviation and number of observations of the field FMC at each site (after spikes were removed). CV_{Sept} and CV_{Jan} are the NDVI coefficient of variation for September 2015 (spring) and January 2016 (summer) for a 40 × 40 Landsat-8 pixels window. *Indicate sites used for the calibration of Nolan et al. (2016)'s empirical model. Caccamo et al. (2012) used a 70% and 30% random sample for calibration and validation respectively.

ID	Name	Region	Fuel class	Latitude	Longitude	$\overline{FMC}$	FMC_{std}	CV_{Sept}	CV_{Jan}	n	Source
1	Majura	ACT	Grassland	−35.2778	149.1966	68	45	0.2	0.1	37	Newnham et al. (2011)
2	Tidbinbilla	ACT	Grassland	−35.4191	148.9506	95	64	0.1	0.1	33	Newnham et al. (2011)
3	Coppins crossing road	ACT	Grassland	−35.2787	149.0559	115	83	0.1	0.2	33	This study
4	Ballan	VIC	Grassland	−37.6352	144.2213	163	71	0	0.1	4	Newnham et al. (2011)
5	Caldermeade_Park	VIC	Grassland	−38.2257	145.5633	60	19	0.2	0.2	5	Newnham et al. (2011)
6	Kaduna_Park	VIC	Grassland	−38.0895	145.4307	93	23	0.2	0.2	5	Newnham et al. (2011)
7	Murrayville grassland	VIC	Grassland	−35.2414	141.2247	64	60	0.1	0.3	7	Newnham et al. (2011)
8	Murrayville wheat	VIC	Crop-non irrigated	−35.2405	141.2152	114	56	0.1	0.1	7	Newnham et al. (2011)
9	Parry lagoons	WA	Grassland	−15.5866	128.2338	65	27	0.1	0.1	12	Newnham et al. (2011)
10	Silent grove sandstone	WA	Grassland	−17.1309	125.3739	43	21	0.2	0.1	9	Newnham et al. (2011)
11	Silent grove black soil	WA	Grassland	−17.0629	125.2609	52	28	0.2	0.1	4	Newnham et al. (2011)
12	Mount hart sandstone	WA	Grassland	−17.0297	125.1159	55	30	0.1	0.2	9	Newnham et al. (2011)
13	Simcocks	WA	Grassland	−34.2170	116.3831	87	62	0.1	0.1	5	Newnham et al. (2011)
14	Lorna glen	WA	Grassland	−26.1629	121.5588	43	11	0.1	0.1	10	Newnham et al. (2011)
15	RNP	NSW	Shrubland	−34.1333	151.0667	102	12	0	0	15	Caccamo et al. (2012)
16	RNP2	NSW	Shrubland	−34.1667	151.0333	100	10	0.1	0.1	13	Caccamo et al. (2012)
17	RNP3	NSW	Shrubland	−34.1333	151.100	100	10	0.1	0.1	15	Caccamo et al. (2012)
18	TNP	NSW	Forest	−34.2167	150.5333	102	8	0.1	0.1	12	Caccamo et al. (2012)
19	BCA	NSW	Forest	−34.3167	150.4667	98	7	0	0.1	12	Caccamo et al. (2012)
20	BCA2	NSW	Forest	−34.2667	150.5000	98	6	0.1	0.1	11	Caccamo et al. (2012)
21	Cumberland plain woodland*	NSW	Forest	−33.6153	150.7237	106	34	0	0	19	Nolan et al. (2016)
22	Tumbarumba forest*	NSW	Forest	−35.6566	148.1517	156	20	0.1	0.1	8	Nolan et al. (2016)
24	Megalong	NSW	Forest	−33.6895	150.2342	102	7	0.1	0.1	5	Nolan et al. (2016)
25	Blue mountain NP (Ridge)	NSW	Forest	−33.6602	150.6177	107	1	0.1	0	4	Nolan et al. (2016)
26	Blue mountain NP (Gully)	NSW	Forest	−33.6578	150.6161	114	7	0.1	0.1	4	Nolan et al. (2016)
27	Blue mountains NP (open woodland)	NSW	Forest	−33.6107	150.6384	100	11	0.1	0.1	5	Nolan et al. (2016)
28	Blue mountains NP (denser canopy)	NSW	Forest	−33.7447	150.3900	108	12	0.1	0	4	Nolan et al. (2016)
31	Bago state forest	NSW	Forest	−35.6468	148.1483	164	27	0.2	0.2	3	Nolan et al. (2016)
30	Wombat forest*	VIC	Forest	−37.4215	144.0938	101	20	0.1	0.1	10	Nolan et al. (2016)
23	Tamboon state forest	VIC	Forest	−37.5679	149.1088	114	8	0.1	0.1	3	Nolan et al. (2016)
29	Namadgi National Park 1	ACT	Forest	−35.5979	148.8165	130	16	0.1	0.1	19	This study
32	Namadgi National Park 2	ACT	Forest	−35.6071	148.8657	137	11	0.2	0.1	18	This study