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A new empirical approach to evaluating fire weather risk to severe-extreme wildfires

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Introduction

In a risk management framework, analysis of fire risk is based on:

- hazard (occurrence/probability and severity);
- impact (vulnerability x exposure to hazard)

In this paper we focus on the hazard aspects using historical exposure to severe-extreme fire weather to estimate likelihood of an event (severe-extreme bushfire) and its severity (duration of severe-extreme fire weather conditions) based on hourly fire weather data for at least 20-30 years, if not longer if the data can support the analysis. This is our objective we wish to understand.

To do this we analysed the exposure to such fire risk conditions using hourly fire weather records from representative weather stations in each region that have high quality weather records. Equilibrium fine fuel moisture content (EFFMC), average wind speed, and energy release component (ERC) are three key fire weather risk factors, derived using a suite of publicly available equations in the United States Fire Danger Rating System (USFDRS) (Deeming, Burgan et al. 1977), the Canadian Fire Weather Index (Van Wagner 1987) of the Canadian Fire Danger Rating System (CFDRS) and the Grassland Fire Danger index (GFDI) in the Australian Fire Danger Rating System (AFDRS) (Cheney, Gould et al. 1998). We applied these empirical relationships to the dominant most hazardous fuel type in a bushfire region. Secondly, we defined critical thresholds of the three factors into a new empirical relationship describing the historical hazard to severe-extreme fire environment conditions.

We applied this approach to estimating historical hazard three bushfire risk zones in south-eastern Australia 50x 50 km in size (Figure 1):

1. the Blue Mountains west of Sydney in the Sydney Sandstone region of NSW
2. the Yarra valley region east of Melbourne in southern central Victoria
3. Central Gippsland north of the Morwell-Traralgon basin

Bushfire zone 1 falls within eucalypt forest and woodland in the western central part of the Sydney Basin, comprising woodland and dry sclerophyll forest, and occasional heathland on dissected sandstone and siltstone plateaux and gorges. Bushfire zone 2 lies east of Melbourne in the southern foothills of the Great Dividing Range. The zone has a mosaic of dry, damp, and wet sclerophyll forest depending on aspect, soils, and elevation with higher mountain ranges in the north-east part of the zone up to 1200 m. Bushfire zone 3 occurs about 70-100 km further east of bushfire zone 2 in the southern part of the south-eastern highlands of Victoria. This is a cooler climate zone at higher elevations (500-1000 m) than in zone 2 (100-700 m) which supports a range of montane and sub-alpine eucalypt forest types found at these higher elevations.

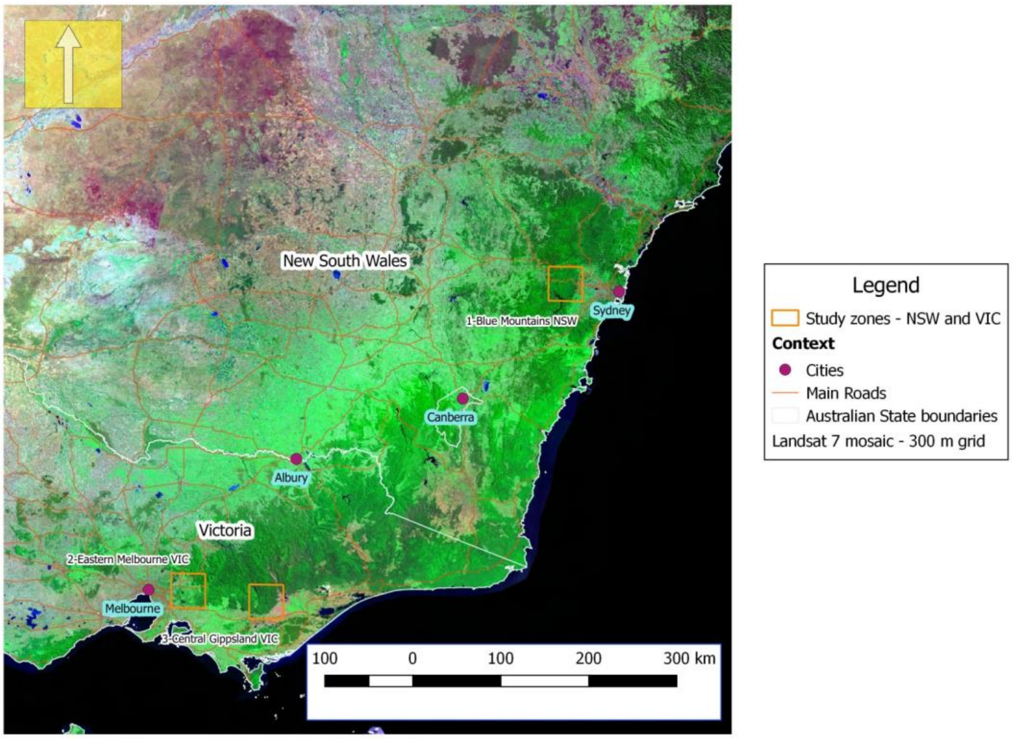

Figure 1: Locations of bushfire risk zones in south-eastern Australia. The boundaries of the bushfire risk zones are outlined as orange rectangles

Methods

We designed the method so that it can be applied to most countries in the world, once the user has available (1) the hourly weather data from remote automatic weather stations (station latitude, date, hourly time of day, rainfall, temperature, relative humidity, wind speed and direction, and solar irradiance) either measured at the station or inferred from these measurements, as well as (2) the fire history and fire footprints from existing fire record databases in fire agencies.

Step 1: Creating and cleaning the weather datasets

We identified the most representative weather station in each bushfire zone that had continuous and complete 0.5 or 1-h fire weather datasets from automatic weather stations.

The weather data for each bushfire zone was then imported into an Excel spreadsheet as 0.5 or 1-h (hourly) data. Missing data records for each of the key fire weather attributes were then infilled using either (1) averaging of the fire weather record the record before and after the missing data record where there was one missing record or (2) matching the fire weather records to a nearby weather stations if there were more than two successive empty weather records. For zone 1 we selected Richmond AWS. For zone 2 we selected Melbourne Airport and for zone 3 we selected Mount Moornapa.

Step 2 - Estimating Equilibrium Moisture Content (EMC) for 1-h, 10-h, 100-h, and 1000-h fuels

Table 1 summarizes the basic algorithms used to estimate EMC for 1-h, 10-h, 100-h, and 1000-h fuels. Estimation of EMC is a dynamic process involving wetting and drying of fine and coarse forest fuels. For the wetting process in 1-h surface dead fuels, we used the algorithms for wetting in the calculation of fine fuel moisture content (FFMC) in the Canadian Forest Fire Danger Rating System (CFFDRS) (Van Wagner 1993). For the drying process we adapted the Van Wagner (1993) algorithms but substituted Simard's EMC equations (1968) as these were found to more applicable to EMCs of eucalypt litter in eucalypt forests. In addition, the Byram and Jemison equation (Byram and Jemison 1943) for the effect of surface solar irradiance on heating eucalypt litter was used where there was data for solar irradiance in the AWS weather data. Surface solar radiation at right angles to the ground was estimated using using the Bird spreadsheet (Bird 1981) and index matched to each day within the 0.5 or 1-h weather data using Julian day number Solar irradiance was also adjusted using cloud cover when it was available for the full dataset.

EMC-1h was updated hourly or half-hourly using rainfall, temperature, relative humidity, and 10- m wind speed entered into the above equations to estimate EMC at any time of the day or night.

Estimation of Energy Release Component (ERC)

We also used the ERC as part of our new empirical approach to evaluating fire weather exposure risk (Deeming, Burgan et al. (1977)). To calculate the ERC a range of constant factors and variable factors are needed.

Table 1: Summary of the equations used to estimate EMC for 1-h, 10-h, 100-h, and 1000-h fuels

Variable	Abbreviation	Preferred	Alternative	Comments
Fuel temperature	T_f	Byram and Jemison (1943) (1943)	Wotton (2012)	Wotton's formula may contain some errors – does not calculate all values correctly. The Byram equation
Surface Irradiance	Irr_S	Bird (1981)		No readily published alternative
Moisture effect	P_{EFF}	Wotton (2009)		Used grassland moisture correction formulae as more applicable than boreal forest ones in CFFDRS
Equilibrium Moisture Content	EMC-1h	Simard (1968)	Nelson (1984)	Nelson's model does not work at extremes of moisture. Not suitable for a bookkeeping spreadsheet
	EMC-10h	Deeming, Burgan et al. 1977	Nelson (1984)	Nelson's model does not work at extremes of moisture.
	EMC-100h & EMC-1000h	Cohen (1985)	Nelson (1984)	We would prefer to use Nelson (1984) in the future
Desorption and Adsorption adjustments	K_D	Wotton (2012)	Van Wagner (1987)	These equations allow for an hourly adjustment for wetting and drying. This can make a 2%

				difference
Cloud Cover effect	CC_{EFF}	Black (1956)	Locally derived cloud cover effect models	See also Sarkar (2016). Because surface irradiance ranges from 0-1100 kW/m2

The constant factors are: (1) fuel type; (2) fuel loadings and weighted surface area to volume ratios for the 1-h, 10-h, 100-h, 1000-h fuel live shrubs; (3) for 1-h and shrub fuels; and (4) fuel bed depth

The variable factors are: moisture of 1-h, 10-h, 100-h, and 1000-h fuel calculated in a separate spreadsheet as per the previous section and carried over in the ERC spreadsheet.

Determination and application of fire weather risk thresholds

We examined the fire literature to find evidence of a set of trigger thresholds for determining the historical hazard risk to severe-extreme fires in a bushfire risk zone.

It became clear that the following set of fire weather and ERC thresholds could be used to determine this:

- EMC-1h< 3-4%
- 10-m wind speed >30-40 km/h
- ERC>0.8 of ERC kW/m^2 (Zone 1: > 50,000 kW/m^2; Zone 2: >53,000 kW/m^2; Zone3: > 100,000 kW/m^2)

Below 5%, we found that ember and firebrand spotting become the predominant fire spread propagation mechanism and potential loss and damage to human infrastructure and natural ecosystem function. We then filtered the fire weather data using the above criteria. We then introduced a further temporal filter of duration of number of hours when these criteria were exceeded on a day. The idea behind this is the higher the number of hours on a fire day, the higher is the potential exposure to a large bushfire. The data was then synthesized into a contingency table of true and false positives, and correspondingly combined true and false negatives.

Results

Table 2 shows the results of applying a combined set of fire weather and ERC thresholds for the three bushfire zones in south-eastern Australia.

Bushfire zone one 1 has the highest percentage of severe-extreme fire weather conditions at 0.14% in the 29-year period. In both zone 2 and 3, the percentages are three to five times lower than in zone 1. When the number of severe-extreme bushfire hours is expressed as a % of afternoon daylight hours, the percentage rises to 0.8% in zone 1, and in zone 2 and 3 to 0.16 and 0.31% respectively.

Table 2: Comparative number and percentage of severe-extreme fire weather conditions for each bushfire zone

Zone	No of Years	Total number of hours in period	Total no. of severe-extreme fire weather hours	% of total hours between 1994 and 2017	Duration of peak hour period (13:00-18:00)	Total no. of PM daylight hours	% of PM daylight hours
1	29	254,040	344	0.14%	6	42,340	0.81%
2	47	411,720	113	0.03%	6	68,620	0.16%
3	23	201,480	103	0.05%	6	33,580	0.31%

Table 3 summarizes the results using the applied fire weather risk thresholds of more than 3 hours duration of design conditions (EMC-1h <=4%, WS-10m>= 30 km/h; ERC>0.8 of maximum ERC). We find that there are 24 true positives (28% of 85 severe-extreme fire weather days in the period from 1994 to 2018) when a bushfire has occurred within the defined set of weather conditions. There were false positives (12.8% of severe-extreme fire weather days in the period from 1994 to 2018) when there were no recorded bushfires on the design days. There were 50 days (58.8%) of false and positive negatives when there were no severe-extreme bushfires in zone 1.

Table 3: contingency table of number of true and false positives (>=4 hours duration of design conditions) in the three bushfire zones, compared to true and false negatives (less than 4 h duration of design conditions)

Bushfire Zone	Total no. of severe-extreme days	True positives		False positives		No. (<4 h) both positive & false negatives	% of defined days
		No.	% of defined days	No.	% of defined days		
1	85	24	28.2	13	12.8	50	58.8
2	113	5	4.4	15	13.3	93	82.3
3	39	3	7.7	3	7.7	33	84.6

For zone 2 we found that there are 5 true positives (4.4% of 113 severe-extreme fire weather days in the period from 1971 to 2018) when a severe-extreme bushfire has occurred within the zone. There are 15 false positives (13.3 %) when there were no recorded bushfires. For zone 3 we found a similar trend to that in zone 2 although we had almost double the percentage (7.7%) of true positives and almost half the number of true negatives (7.7%) and a similar percent of true and false negatives (84.3 and 82.3% in zone 3 and zone respectively). Within both of these zones we find that using the filter of 4 hours or more of severe-extreme weather conditions to be very effective in identifying the potential days for severe – extreme bushfires. Within bushfire zone 1 the potential fire weather exposure risk is 4-7 times that of zones 2 and 3.

Discussion

Instead of a single value from a fire danger rating system, our alternative empirical approach can drill the data for potential combinations of EMC-1h, WS-10m, and ERC based on any criteria be it for extreme fire weather or prescribed burning conditions. This approach has two aspects: first, the detailed 0.5 or 1-h fire weather record; and the second is the duration of these 'design' conditions on any given fire weather day through out a given fire weather record. This creates distinct combinations of EMC-1h, WS-10m, and ERC, which can be compared to the whole of the historical weather record.

The data in Table 3 also provides the likelihood of a fire starting under a severe-extreme set of fire weather conditions in the different bushfire zones. In zone 1 within the Blue Mountains, a large bushfire is 4-7 times more likely to occur than in zones 2 and 3 in Victoria. Secondly, the fire weather conditions in zones 2 and 3 need to be more extreme and later in the fire season for an extreme bushfire to occur. This fits in with the concept of 'tipping' points used in climate science.

The next step in this empirical approach is to produce area growth statistics for bushfires in each of the bushfire zones 1, 2, and 3. Cursory inspection of the fire growth data suggests that the area growth is very much dependent on WS-10m once EMC-1h are below 3–4%. There are two separate fire scenarios: (1) the rate of fire growth with WS-10m of 30-40 km/h in dry sclerophyll forest can be 1300–1500 ha/h in all bushfire zones; (2) the rate of fire growth can increase to 3,500–4,500 ha/h when the wind is in excess of 45-50 km/h (2009 Kilmore East in zone 2 or 2013 State Mine bushfire in zone 1).

Conclusions

We have managed to develop a proof in concept empirical approach utilising hourly or half-hourly fire weather data to define a key part of historical hazard (exposure to severe-extreme fire weather) in three bushfire zones in south-eastern Australia. Because of its generic approach, the method can be used anywhere in the world. This method will clearly be largely improved by examining the link between the probability of occurrence and likely fire sizes, in order to get bushfire hazard characterisation (probability x severity).The benefit of this approach is that we optimally use the basic underlying values of fuel and fire weather conditions that drives large fires and captures their large variations at hourly scale in a fire day, and the approach provides a common risk assessment framework that enables equal comparisons of exposure to severe-extreme fire weather between any fire regions in the world.

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Presenter's bio:
Nic Gellie is a contract fire and vegetation scientist with a background in field fire research, vegetation and fire ecology, and fire management. He has worked with the Forestry Commission Tasmania, the National Parks and Wildlife Service of NSW, and the Department of Sustainability and Environment in Victoria. He completed a Masters of Philosophy in Science in 2009 at the Australian National University on the topic of Landscape Susceptibility to Large Landscape fires. He has prepared reports on the fire behaviour of extreme wildfires on Black Saturday 2009 in Victoria; reconstructed the spread of many different wildfires in different fire environments in south-eastern Australia; analysed the impact of prescribed burns on the spread and behaviour of extreme fires, and more recently analysed fire weather risk factors in producing severe-extreme fires.