Attachment 3

Forest Ecology and Management 284 (2012) 269–285

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Anatomy of a catastrophic wildfire: The Black Saturday Kilmore East fire in Victoria, Australia

M.G. Cruz [a,*], A.L. Sullivan [a], J.S. Gould [a], N.C. Sims [b], A.J. Bannister [c], J.J. Hollis [a,d,e], R.J. Hurley [a]

[a] CSIRO Ecosystem Sciences and CSIRO Climate Adaptation Flagship, GPO Box 1700, Canberra, ACT 2601, Australia
[b] CSIRO Land and Water, Private Bag 10 Clayton S[th], VIC 3169, Australia
[c] Bureau of Meteorology, GPO Box 1636, Melbourne, VIC 3001, Australia
[d] University of New South Wales at the Australian Defence Force Academy, Canberra, ACT 2600, Australia
[e] Bushfire Cooperative Research Centre, Level 5, 340 Albert Street East Melbourne, VIC 3002, Australia

ARTICLE INFO

Article history:
Received 28 October 2011
Received in revised form 21 February 2012
Accepted 28 February 2012
Available online 31 August 2012

Keywords:
Megafire
Wildland–urban interface
Crown fire
Eucalyptus
Spotting
Pyrocumulonimbus

ABSTRACT

The 7 February 2009 wildfires in south-eastern Australia burned over 450,000 ha and resulted in 173 human fatalities. The Kilmore East fire was the most significant of these fires, burning 100,000 ha in less than 12 h and accounting for 70% of the fatalities. We report on the weather conditions, fuels and propagation of this fire to gain insights into the physical processes involved in high intensity fire behaviour in eucalypt forests. Driven by a combination of exceedingly dry fuel and near-gale to gale force winds, the fire developed a dynamic of profuse short range spotting that resulted in rates of fire spread varying between 68 and 153 m min^{-1} and average fireline intensities up to 88,000 kW m^{-1}. Strong winds aloft and the development of a strong convection plume led to the transport of firebrands over considerable distances causing the ignition of spotfires up to 33 km ahead of the main fire front. The passage of a wind change between 17:30 and 18:30 turned the approximately 55 km long eastern flank of the fire into a headfire. Spotting and mass fire behaviour associated with this wide front resulted in the development of a pyrocumulonimbus cloud that injected smoke and other combustion products into the lower stratosphere. The benchmark data collected in this case study will be invaluable for the evaluation of fire behaviour models. The study is also a source of real world data from which simulation studies investigating the impact of landscape fuel management on the propagation of fire under the most severe burning conditions can be undertaken.

1. Introduction

South-eastern (SE) Australia has a combination of climate, topography and vegetation that makes it prone to severe wildfires. Fires occur in most years but are generally most extensive and severe following extended drought, typically associated with El-Nino events (Sullivan et al., 2012). This region has a long history of severe fire events, some of which have significantly influenced wildland fire control and land management policy. In the past seven decades catastrophic fire events (defined here as fire in which at least a single day of high intensity fire behaviour occurs and generally results in large area burned with significant destruction of infrastructure and loss of life) have impacted SE Australia in 1939 (Black Friday), 1983 (Ash Wednesday), 2003 (Canberra) and 2009 (Black Saturday). These four fire events have burnt 7.68 Mha of land and caused 390 fatalities, predominantly in the state of Victoria.

The fires that occurred on 7 February 2009 (colloquially known as 'Black Saturday'), represent 44% of the fatalities. Of a total of 316 fires burning on this date, 13 developed into significant incidents (Fox and Runnalls, 2009) and five resulted in 173 fatalities. The Kilmore East fire was the most significant of these, resulting in 70% of the fatalities on the day. It burnt nearly 100,000 ha and destroyed over 2200 buildings in the first 12 h alone. The fire eventually merged with the Murrindindi fire, burning a combined area of approximately 400,000 ha over a period of 3 weeks.

Understanding the development and behaviour of the Kilmore East fire is important for a number of reasons. It is a critical step in identifying the factors that led to the scale of this catastrophic fire and its unprecedented impact on lives, livelihoods and ecosystem components. Despite the diverse adaptation of Australian ecosystems to fire (Gill, 1981a,b), large-scale fires can have detrimental impacts on ecological values. Such a fire converts biodiversity-rich, fine-scale mosaics at a range of seral states into a less diverse landscape, both in terms of species composition and vegetation structure (Adams and Attiwill, 2011). The sustainable management of SE Australian ecosystems requires a landscape level approach to

* Corresponding author. Tel.: +61 2 6246 4219; fax: +61 2 6246 4096.
E-mail address: miguel.cruz@csiro.au (M.G. Cruz).

0378-1127/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.foreco.2012.02.035

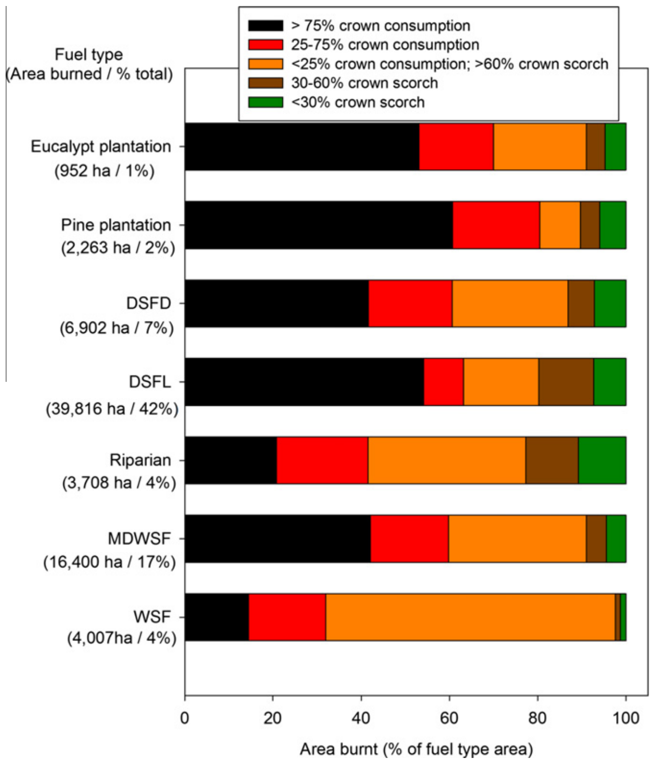

Fig. 9. Distribution of burn severity classes by selected fuel types.

4–7 is given in each figure caption. Fuel moisture estimates were considered to possess a rating of 3. Fuel characteristics data used was given a rating of 2.

The number of medium and long distance spot fires given in Figs. 4–7 should be seen as conservative. These were spotfires that were authenticated by one or more sources. A number of spot fires were not located and it is believed that there were a larger number of spot fires that were not detected. Spotfires were located with a precision of 100–500 m. For the scale of the fire, this precision corresponds to an error less than 10% for long distance spotting.

4.2. Spotting – short range

Eucalypt stringybark species (e.g., *E. obliqua*, *E. marginata* and *E. macrorhyncha*) are notable for their fibrous rough bark that can be easily ignited and decorticate from the trunk providing an optimum firebrand source for short-range spotting (Cheney and Bary, 1969). The presence of fibrous bark provides further vertical connectivity between fuel layers facilitating the transition from a surface fire to one involving the full fuel complex. The process of short-range spotting was exacerbated in the weather conditions driving the fire. The strong winds affecting the fires forced the transport of a profusion of burning embers through flat (rather than lofting) trajectories, delivering numerous firebrands up to 500 m ahead of the main fire front. The deep flaming fronts that arise from the coalescence of multiple short-range spot fires resulted in extensive crowning and further generation and transport of burning embers. McArthur (1967) describes this process as key to how a fire maintains overall rates of spread much higher than expected in the absence of spotting.

Key components for the maintenance of this process are the presence of high surface fuel loads (to induce ignition of bark fuels), long unburnt (>25 years since last fire in dry sclerophyll forest) eucalypt forest with a significant number of species with fibrous bark (the primary firebrand material), high wind speeds (causing flat ember trajectories) and low fuel moisture contents (increasing the likelihood of spotfire ignition). With fuel moisture contents <4%, the likelihood of spotfire ignitions increase significantly as the heat requirements for ignition are reduced. In this situation even tiny glowing particles had sufficient energy to start new spotfires (Albini, 1979; Ellis, 2011).

The observed short range spotting behaviour is consistent with McArthur's (1967) description of "showers of burning embers landing up to 800 m of the main fire front". A quantitative understanding of short range spotting dynamics, namely firebrand density distribution with distance from the fire front and how distinct fires coalesce in a high turbulent environment, is lacking. Field-based research into short range spotting such as that carried out in Project Vesta (Gould et al., 2007a; Box 1), provide benchmark data that can be used to parameterize firebrand transport and density models (e.g., Cheney and Bary, 1969; Sardoy et al., 2007). The validity of scaling up Gould et al. (2007a) observations to conditions similar to those driving the Kilmore East fire is nonetheless unknown.

4.3. Spotting – long range

The occurrence of long-range spot fires (>5 km) contributed to the rapid extension of the fire zone. At 16:00 there were at least five spotfires occurring up to 33 km south-east of the main fire, approximately 40 km from its probable source. Comparable spotting distances have been verified on particular occasions in fires in southern Australia eucalypt forests (Hodgson, 1967; Cheney and Bary, 1969; McArthur, 1969). The process of long-range spotting can be seen as distinct from short-range spotting, requiring the presence of a specific different set of conditions. The firebrands responsible for long-range spotting are long

Table 4
Average rate of fire spread, area burned, fireline intensity (Byram, 1959) and heat release for selected burning periods (BP) in the Kilmore East fire.

BP	Main fuel type	Fire perimeter (km)	Average rate of fire spread (m min^{-1})	Hourly area burned (ha)	Average fireline intensity (kW m^{-1})	Energy released (GW)
1	Grass	1.3	–		–	1.1
2	Grass	10	71	239	6603	25.6
3	Grass, DSFL	21	73	1534	–	152.3
4	DSFL	30	68	1311	39,209	227.7
5	DSFL	50	153	4286	88,220	933.0
6	DSFL, MDWSF	106	–	10,068	–	2153.7
7	DSFL, MDWSF	143	–	9752	–	1794.4
8	DSFL	217	127	35,802	73,228	8554.8
9	MDWSF	311	90	12,626	82,677	2605.4
10	DSFL	487	–	6129	–	860.9

nd, not determined; DSFL, dry sclerophyll forest, low understory, MDWSF, mix dry-wet sclerophyll forest.

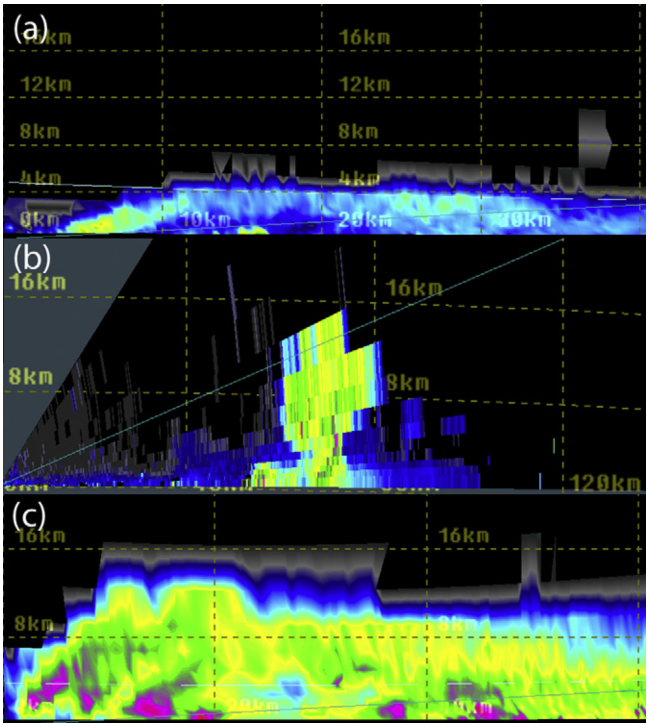

Fig. 10. Melbourne weather radar view of Kilmore East fire plume. (a) Profile of the plume through a NNW–SSE axis at 14:00. (b) Cross-section of the plume along a SW–NE axis at 19:30. (c) Cross-section of the plume along a SE–NW axis at 19:30.

streamers of decorticating bark that normally hang from the upper branches in certain smooth-barked eucalypt species such as *E. viminalis, E. globulus*, *E. delegatensis* (Cheney and Bary, 1969). The bark strips curl into hollow tubes that when ignited at one end can burn for as long as 40 min (Hodgson, 1967). The long combustion times coupled with its good aerodynamic properties (Luke and McArthur, 1978; Ellis, 2011) allows these firebrands to be a viable ignition source even when transported over long distances. Long-range spotting also requires an intense fire that maintains a strong upward motion in the buoyant plume to transport relatively large fuel particles several kilometres above the ground and high winds aloft to transport firebrands for extended distances downwind.

4.4. Rate of fire spread and intensity

The fire exhibited three distinct spread phases between 12:00 and the arrival of the wind change around 18:00, even though average fire weather conditions stayed relatively constant (Table A2). These changes in spread dynamics were driven by fuels, topography and fire-atmosphere interactions. Between 12:00 and 15:00 the fire spread in a mosaic of fuel types, ranging from grazed paddocks intermixed with open woodland to dry sclerophyll eucalypt forest, and attained average rates of fire spread varying between 68 and 73 m min^{-1} (Table 4) and fireline intensities approaching 40,000 kW m^{-1}. In the next burning period, 15:00–16:00, the rate of fire spread doubled to an average of 153 m min^{-1}. This increase could be attributed partially to a gradual decrease in fine dead fuel moisture content (Table A2) but also to the fact that the fire transitioned into more complex topography with a mix of dry and wet sclerophyll forests. Upslope runs in this area might also have contributed to an increase in the overall rate of fire spread. The denser and more productive forests of this area contributed with higher available fuel loads that resulted in a peak in fireline intensity (85,000–90,000 kW m^{-1}) and strengthened the plume. This escalation in fire activity between 15:00 and 16:00 extended into the subsequent burning periods with dramatic effects. From 16:00 to 17:00 the fire increased in area from 7400 to 17,400 ha, corresponding to an elongation of the main axis of fire propagation from 23 to 47 km. Nonetheless, this was not due to the spread of a single flame front but the result of multiple new ignitions due to medium and long range spotting. At 17:00 substantial areas remained unburnt behind the leading edge of the fire but in a broad sense, considering fire spread at the landscape scale, one could say that the fire spread 24 km in an hour.

The passage of the wind change was followed by very high rates of fire spread in the northeast direction, 127 m min^{-1} between 18:00 and 19:00 and 90 m min^{-1} between 19:00 and 20:00. Such fast spread rates were maintained by profuse short-range spotting dynamics in dry and mixed dry-wet sclerophyll forest. Fireline intensities associated with this post wind change period varied between 70,000 and 85,000 kW m^{-1}. This extreme fire behaviour cannot be explained by the prevailing weather conditions at the Kilmore Gap and Coldstream AWS where the Forest Fire Danger Index (FFDI; McArthur, 1967) dropped to values below 20 (Table A2). Although the post-change cool and moist air mass caused an overall drop in fire potential at the various AWSs outside the fire area, it is unknown how much this air mass was able to influence the fire environment, particularly the moisture content of fine forest fuels, downwind of the fire perimeter. As the southwest winds pushed over the broad fire area (Fig. 10c), advection of heated products from residual combustion likely resulted in hotter and drier air in the fire path than recorded at the AWS peripheral locations. This advected heat mechanism allowed the maintenance of vigorous fire behaviour in the immediate hours following the wind change.

The observed rates of fire spread and associated fireline intensities are at the top end of the known fire behaviour spectrum in dry sclerophyll eucalypt forests (Cheney, 1991; Gill and Moore, 1990). To the authors' knowledge, there are no other published detailed case studies in eucalypt forests showing comparable rates of spread and fireline intensities. This is not to say that other fires in the past did not exhibit similar or more severe fire behaviour. The growth of past fires such as the 1952 Mangoplah fire (300,000 ha in 8 h) and the 1965 Chatsbury fire (260,000 ha in a 72 km long run in 8–10 h; McArthur, 1969) are clear evidence that commensurate fire behaviour have occurred in the past.

5. Conclusions

On the 7 February 2009, a date later named 'Black Saturday', history repeated itself. Under a synoptic situation typical of extreme fire weather potential in south-eastern Australia (Sullivan et al., 2012) the Kilmore East fire exhibited rates of fire spread and intensity at the top end of the fire behaviour spectrum. An area of approximately 100,000 ha burned in less then 12 h and a total of 121 people were killed during this period. Spotting dynamics dominated fire propagation. Prolific short range spotting linked with crown fire propagation in eucalypt forest allowed for exceedingly fast rates of spread, typically higher then 70 m min^{-1} and peaking at 150 m min^{-1}. The extreme fireline intensities, varying between 70,000 and 88,000 kW m^{-1} throughout most of the afternoon, combined with the strong winds aloft allowed for the development of a strong convection plume and the transport of firebrands at long distances. Spot fires occurred 33 km ahead of the flame front. These spotting distances corresponded to firebrand transport distances of approximately 41 km.

The high amounts of energy released by this fire resulted in a pyrocumulonimbus cloud with a top height of at least 13 km. This resulted in the injection of smoke and other combustion products