REPORT NO. A.07.02

BILLO ROAD FIRE

REPORT ON FIRE BEHAVIOUR PHENOMENA AND SUPPRESSION ACTIVITIES

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Front cover Picture: 10 December 2006 afternoon crown fire run in 15-year old radiata plantation with estimated fire intensity of ~20 000kW/m. Photo: Steve Cathcart

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SYNOPSIS

Billo Road Fire - Report on fire behaviour phenomena and suppression activities

Between the 10 and 14 December 2006 the Billo Road Fire burned an area of 10 866 ha (Fig. S1), 9526 ha being radiata pine (*Pinus radiata* D. Don) plantation in the Buccleuch State Forest (148°24'E, 35°13'S), 20 km east of Tumut, New South Wales (NSW). The fire started by arson during the night, and burnt under mild conditions before being detected at 0857 on 10 December. Within the first two days, three major fire runs characterized by a combination of crown fire propagation and surface fire with short distance spotting in recently logged or planted compartments burned 4700 ha at an average rate of 320 ha/hour (Fig. S2). Rates of spread in sustained crown fire runs varied between 20 and 40 m/min (1.2 to 2.4 km/h). Fire spread in the logging slash varied between 10 and 40 m/min (0.6 to 2.4 km/h) during the most severe burning conditions.

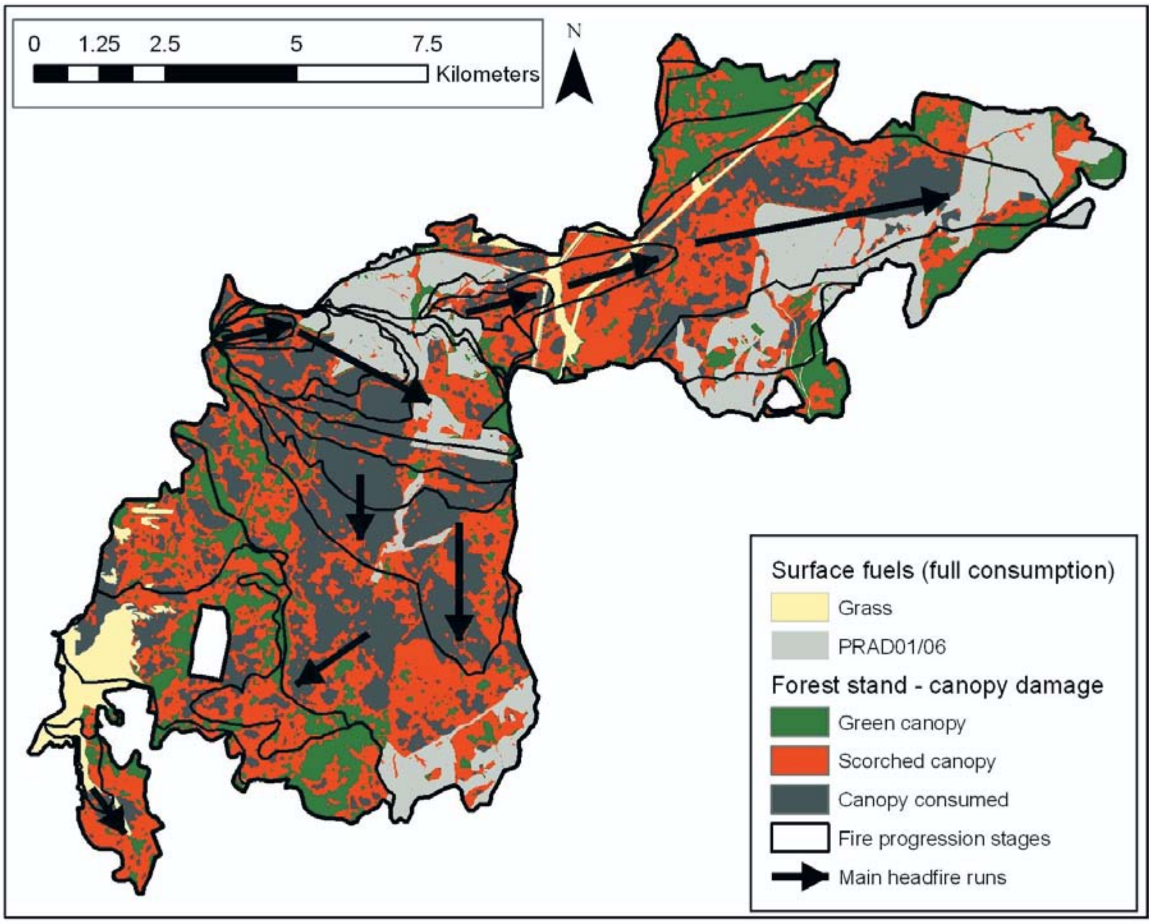

Figure S1. Progression of the Billo Road Fire perimeter highlighting the level of surface versus crown fire activity. Green canopy areas carried low intensity surface fire, scorched canopy sustained moderate to high intensity surface fire, and canopy consumed is associated with crown fire spread.

Significant factors in the propagation of the fire included the extreme dryness of surface fuels in recently logged or planted compartments, which contributed to abundant spotting activity, and the flammability of unthinned immature (10 – 15 year old) radiata pine stands. The vertical continuity between fuel layers in the latter fuel complex allowed the development of crown fire activity in moderate burning conditions, namely during a night run (Fig. S2). The spatial distribution of these two fuel complexes in the Buccleuch State Forest allowed the fire to propagate with extreme fire behaviour even under moderate wind speeds (< 20 km/h). Fire activity in the ensuing days (maximum Forest Fire Danger Index (FFDI) between 8 and 14) was moderate with occasional occurrence of short lived crown fire runs. The fire was contained to established fuelbreaks and burnout lines on the 14 of December.

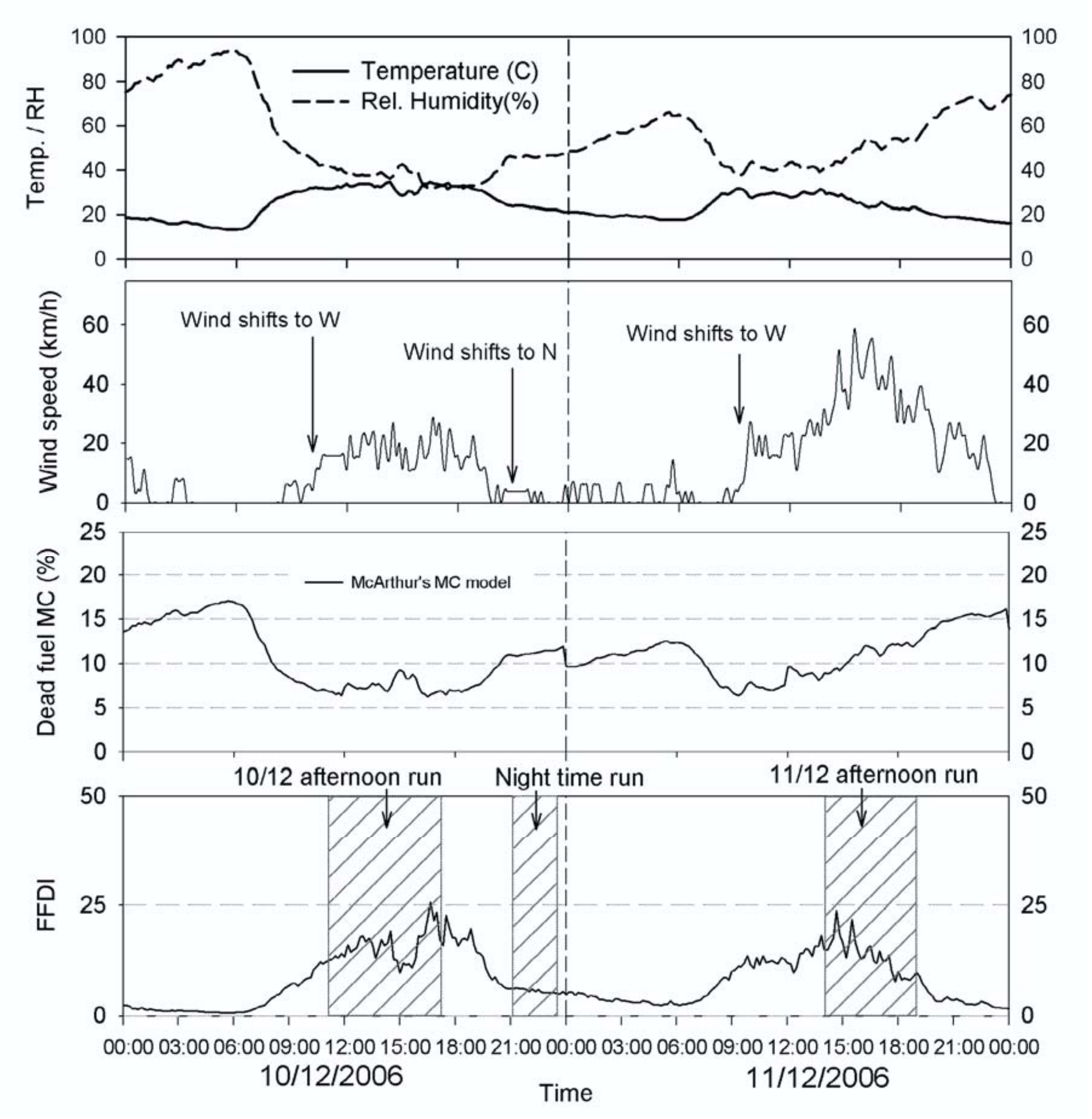

Figure S2. Diurnal trend of weather elements, fine dead fuel moisture content (MC) and the McArthur (1967) Forest Fire Danger Index (FFDI) for the 10 and 11 of December 2006. Weather data from Bondo weather station, operated by Forests New South Wales (Forests NSW).

The Billo Road Fire constituted a unique opportunity to acquire fire behaviour in pine plantations over a broad range of stand structures and fire environment conditions. This report focuses on the analysis of the weather, fuel and associated observed fire behaviour. Particular attention was given to (1) quantify the effect of fuel complex structure on fire behaviour, and its relation to fire propagation; (2) understand the effect of silvicultural operations on fire behaviour; and (3) evaluate the adequacy of fire behaviour models to predict fire spread and intensity in exotic pine plantations in Australia.

A smaller radiata pine plantation fire, the Mount David Fire, that burned 857 ha (721 ha plantation) within a few hours on the 19 December 2006 was also investigated within the scope of this study. This fire, burning in the Mount David State Forest (149°36'E, 33°53'S), Central Tablelands, NSW, spread under similar fire weather severity conditions to the main runs of the Billo Road Fire. Details into the propagation, fire behaviour and fire suppression of the Mount David Fire are included in this report as Appendix 1.

The analysis of the events of the Billo Road and Mount David fires, as well as other previous large plantation fires show a number of shortcomings on the current understanding of fire behaviour and fire management practices in this fuel type. A series of recommendations arose from this analysis and are presented.

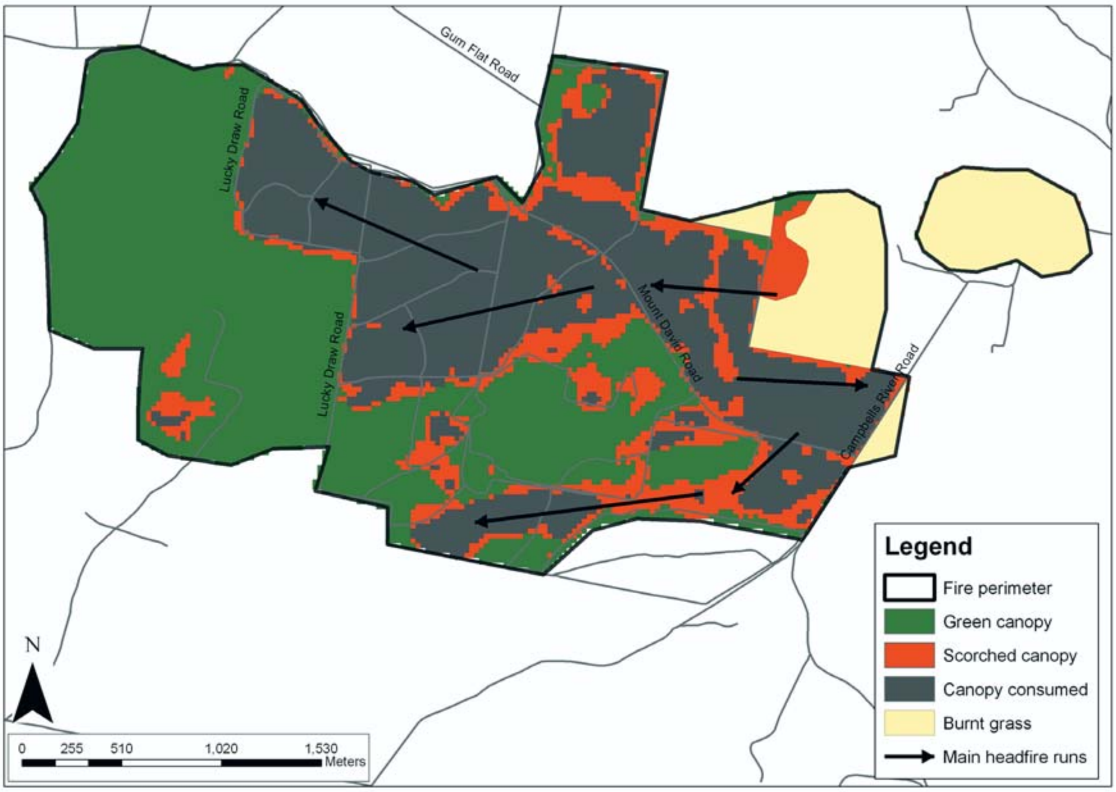

Figure S3. Progression of the Mount David Fire perimeter highlighting the level of surface versus crown fire activity. Green canopy areas carried low intensity surface fire, scorched canopy sustained moderate to high intensity surface fire, and canopy consumed is associated with crown fire spread.

1. INTRODUCTION

The documentation of wildfire behaviour constitutes an opportunity to obtain information into the propagation of fires and provide insight into fire phenomena under burning conditions that otherwise would be likely impossible to gather. The analysis of fire propagation under specified conditions allow fire management agencies to assess the suitability of current management practices under wildfire conditions, namely resource effectiveness and fuel management strategies, and constitute an unique component of fire suppression training (NWCG 1993). Aside from these applications, information derived from fire behaviour case studies have been used to develop and evaluate fire behaviour models (McArthur 1967, Forestry Canada Fire Danger Group 1992, Beck 1995) and provided insight into unknown fire phenomena (Dieterich 1976; Byram 1954). Hence, case studies constitute a knowledge basis and vehicle of dissemination for fire behaviour information. Alexander and Thomas (2003a and b) provide a review of the history behind wildfire case studies, their value and practical uses.

The importance of case studies as long been recognized in Australia, with reports such as McArthur (1965) and McArthur et al. (1966) on the 1962 Longford Fire in Victoria (VIC) and the 1958 Wandilo Fire in South Australia (SA) respectively highlighting the value of the case study approach to analysing high intensity fire behaviour in pine plantations. Other Australian pine plantation fire case studies worth referencing include Billing (1980) and Geddes and Pfeiffer (1981) on the 1978 Caroline Fire (SA), Alexander (1998) on the 1992 Toolara Fire in Queensland (QLD), and Burrows et al. (2000) on the 1994 Gnangara Fire in Western Australia (WA). Also in New Zealand several case studies in pine plantations provided valuable data to assess fire potential in this fuel type (e.g., Fogarty et al 1997).

The Billo Road Fire (10 866 ha) with 9 526 ha being radiata pine plantation was the largest single plantation fire on record in NSW. The fire constituted an excellent case study subject. Within the two first days of activity the fire burned over the full range of fuel complexes that characterize the radiata pine plantation rotation and exhibited fire behaviour covering its full range. With the aim of better understanding the factors that lead to the observed levels of fire behaviour and area burned, the Forests New South Wales (FNSW) Fire Management Branch commissioned Ensis – CSIRO Bushfire Research Group to conduct an investigation into the fire behaviour phenomena in the Billo Road and Mount David fires. Focus was given to the effect of fuel complex structure on fire behaviour and propagation, analysis of the effect of silvicultural operations on fire behaviour, and the adequacy of existent fire models to forecast fire behaviour in exotic pine plantations.

A list of the abbreviations used in this report is given in the very end.

2. METHODS

This investigation into the behaviour of the Billo Road Fire commenced about three weeks after the event; hence the investigation was focused on reconstructing fire behaviour and fire suppression actions. One member of the research team (M. Plucinski) was present during the last days of the fire as part of a Bushfire CRC project investigating aerial suppression effectiveness.

Reconstruction of fire behaviour was based on a detailed field survey combined with interviews of personnel involved in the suppression operations, analysis of radio logs, planning documents from the incident management team (IMT), analysis of digital still photos taken during the fire, and remotely sensed data, namely Landsat Thematic Mapper (TM) and high spatial resolution airborne digital camera imagery. It should be noted that due to incomplete and/or conflicting information, parts of the fire reconstruction are based on unverified evidence. Throughout the fire, no personnel were specifically assigned to monitor and document fire propagation and little information was available for some of the main fire runs, namely relative to fire front width, short range spotting and its effect on overall fire progression and behaviour along the flanks. Nonetheless, we feel that we were able to give a reasonably accurate description of fire behaviour for the main fire runs.

Two Landsat TM images, one pre-fire (16 November 2006) and one post-fire (19 January 2007), were obtained for this project. The post-fire image was captured 6 weeks after the fire. Bulk atmospheric and sensor errors were removed from the images using the ENVI (Environment for Visualising Images software) Landsat TM calibration tool, which accounts for gains and offsets in sensor calibration and illumination conditions. Further atmospheric correction was not considered necessary due to the high atmospheric clarity in this high-altitude region. In addition to the Landsat images, an airborne digital colour infra-red image was captured by FNSW on 28 December 2006. This image shows the burned area at 2m pixel spacing in 4 spectral bands: Blue, Green Red and NIR (Appendix 2, Fig A2.2). Compared to Landsat, this image contains less spectral information but increased spatial resolution, which proved invaluable in the post burn survey. Detailed descriptions of the methods used in the remote sensing image analysis are provided in Appendix 2.

The spatial distribution of forest type and plantation ages, from which fuel structure was derived, was provided from FNSW Geographical Information System (GIS) data. To better understand the effect of stand and fuel complex structure on the fire behaviour we quantified fuel structure according to different plantation ages. Fuels of selected stands covering the pine plantation rotation were sampled outside the burned area. Fuel inventory focused on surface fuel structure (load and height), existence of ladder fuels, canopy base height and canopy bulk density. We took 10 0.25 m^2 destructive samples of surface fuels per fuel complex stage. Fuels were partitioned by type (litter layer L, litter layer F and H (amorphous layer), woody material by size classes (round wood diameter (∅) < 6 mm; 6 mm < ∅ < 25 mm; 25 mm < ∅ < 76 mm; ∅ > 76 mm), live shrub, live fern, live herbaceous, pine cones and bark) and oven dried in the laboratory. Canopy fuel load was not directly measured but estimated based on a tree crown biomass study carried out by Forrest and Ovington (1969) in the same plantation. We did not quantify fuels on the eucalyptus stands and the grazing paddocks.

Climate and weather data was collected from nearby weather stations to describe fire weather potential along the fire season and during the fire event. Analysis of the build-up of fire potential leading to the fire was based on climate data from Wagga Wagga and Gundagai weather stations (Bureau of Meteorology, BoM) and from a FNSW weather station (WS) located on Bondo (Fig. 2). Although the weather conditions at the BoM weather stations locations might not represent the conditions present in fire area (located on a plateau 700 m higher), the use of BoM weather data was necessary as benchmark for comparative analysis of fire climate. No long term fire climate data was available for the Bondo WS.

Analysis of weather conditions in the days prior to the fire and during the fire was based on the Bondo WS, located within the area of the fire. An important note in this analysis was that this weather station does not follow the essential requirements for weather measurement in terms of positioning (WMO 1983). The anemometer was located on top of a roof and was unevenly surrounded by trees with dense canopy (Fig. 3). It was also indicated to us that the relative humidity sensor overestimated this quantity. Given the relevance of this weather station for the analysis of the fire, we produce a calibration for wind speed and direction based on measurements made at 10-m in the open on site. We were not able to produce similar calibration for the relative humidity sensor prior to its replacement; hence observations of relative humidity and estimation of fuel moisture content might be higher than what really occurred.

Figure 1. Location of Bondo weather station (WS) wind sensors on roof of building at the FNSW Bondo Ranger Station. Note row of dense canopy north of the sensor.

No fuel moisture samples were collected during the fire. Estimates of fine dead fuel moisture were obtained from a model published by Viney (1991) derived from tables contained in McArthur (1967). Given that this model is applicable to eucalyptus forest, and its adequacy to pine plantations is untested we also estimated fuel moisture content from Rothermel (1983) fuel moisture tables. This model characterizes fuel moisture in pine forests taking into account the temperature and relative humidity, plus solar radiation and its variation throughout the diurnal cycle. This is relevant to the present analysis as some of the fuels were unshaded, such as logging slash and recently thinned stands. Live fuel moisture of pine trees was derived from Pook and Gill (1993).

Fire climate and weather potential was analysed primarily through the Keetch-Byram Drought Index (KBDI) (Keetch and Byram 1968) to assess long term drought and its effect on fuel availability, and the Forest Fire Danger Index, FFDI (McArthur 1967). The FFDI was developed for eucalypt forests and its application to describe fire potential in pine plantations is open to question. Hence, we also assessed the influence of weather on fire potential through the Canadian Forest Fire Weather Index system (Van Wagner 1987). This option was justified as this system was developed from fuel moisture and fire behaviour data collected in mature pine stands. To analyse the influence of atmospheric instability on fire growth we derived the Haines index (Haines 1988) from charts produced by the Bureau of Meteorology based on the LASP model analysis of measured upper air observations. To further understand site specific fire dynamics we calculated rate of fire spread from: (1) the McArthur (1967) Forest Fire Danger Meter (FFDM) (Noble et al 1980); (2) the Forest Fire Behaviour Tables (FFBT) for WA (Sneeuwjagt and Peet 1985); and (3) the Canadian Forest Fire Behaviour Prediction System (Forestry Canada Fire Danger Group 1992).

Within the scope of the present study there was an initial interest to evaluate the adequacy of the model developed within Project Vesta (Gould et al. 2007) to pine plantation fuel complexes. The application of the Vesta model to describe fire behaviour would require taking the model beyond its range of validity, and perhaps yield misleading results. This led us to exclude the Vesta model outputs from the analysis. See Appendix 3 for a detailed explanation.

3. TOPOGRAPHY

The Billo Road Fire burned on the south western slopes of the Great Dividing Range. Elevation on the fire area ranges from 480 to 1100 m above sea level. The topography can be characterized as undulating, with gentle to moderate slopes over most of the fire area. Overall, the effect of topography on fire behaviour was moderate, with the three main runs occurring in undulating topography. Nonetheless, slope had a significant effect on the initial development of the fire due to the alignment with wind which was responsible for inducing crowning activity. Slope was also an important factor in short lived crown fire runs that occurred along steep drainages on the 12, 13 and 14 of December.

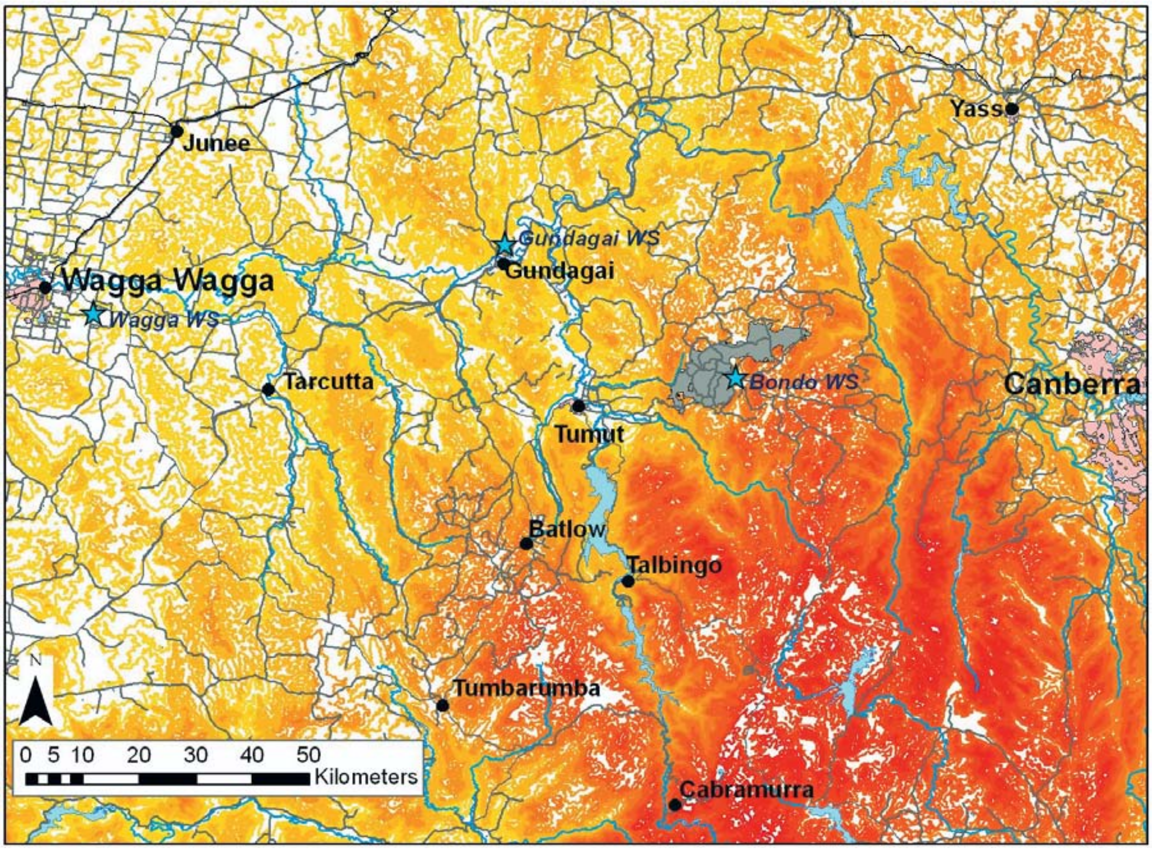

Figure 2. Location of the Billo Road Fire (shaded gray area) and weather stations used in the analysis of fire behaviour (Bondo, Wagga Wagga and Gundagai).

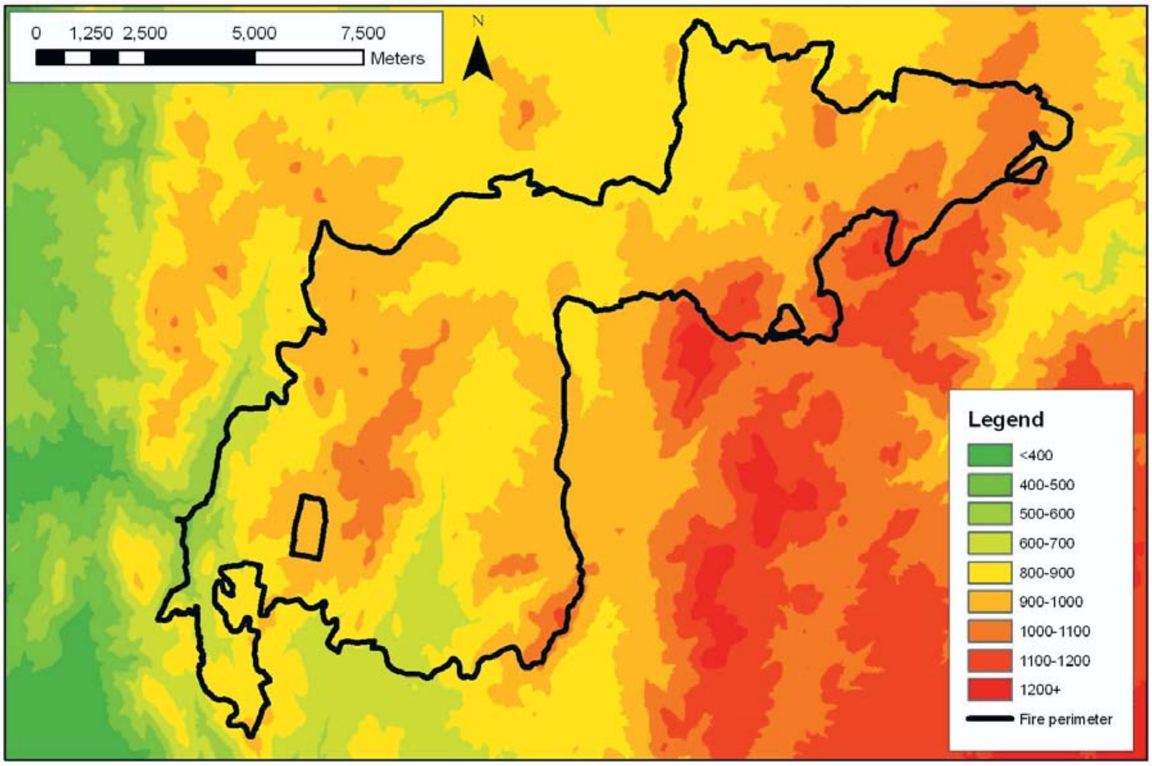

Figure 3. Elevation within and around the Billo Road Fire. Black line delimits extent of fire.

4. FUELS

The vegetation types within the area of the Billo Road Fire can be divided into three main fuel types: (1) dry sclerophyll eucalyptus forest; (2) grassland; and (3) radiata pine plantations of various ages (Table 1). The eucalyptus stands were dispersed throughout the fire area (Fig. 4), and did not have a significant impact on the overall fire propagation. The grasslands included pasture lands located outside the plantation area and small non continuous areas, such as swampy areas and powerline corridors, dispersed within the forest estate. The pasture lands were heavily grazed and limited fire propagation. The pine plantations were the main fire carrying fuel type and accounted for 88% of the burned area (Table 1).

Table 1. Burned area in the Billo Road Fire by fuel type

Fuel type	Burned area (ha)	% of total burned area
Dry sclerophyll eucalypt forest	1087	10%
Grassland	253	2%
Radiata pine forest (age classes)		
0 – 3 years	831	8%
3 – 8 years	1610	15%
8 – 13 years	1506	14%
13 – 20-years - unthinned	886	8%
13 – 20-years - thinned	339	3%
> 20 years	3097	28%
Logging slash	1256	12%

Dry sclerophyll eucalyptus forest

The eucalyptus stands were essentially located in low-lying perennially wet areas and a few dispersed islands (Fig. 4). This fuel type consisted of various eucalypt species with an average height around 20 m, with surface fuels consisting mostly of litter, bark, woody fuels and understorey vegetation. Understorey vegetation varied considerably with the location of the stand, and was typically thickest in riparian areas and low or absent on slopes and ridge tops. In some stands there was a significant understorey of pine wildings. Some of these stands were prescribed burned in the past but no information existed of the spatial extent of these burns, their location and when they occurred. From observation of non-burned areas within the Buccleuch State Forest it was estimated that fuel loads were characteristic of the dry sclerophyll eucalypt forest. Fuel sampling carried out during experimental burns in this fuel type near Tumbarumba (Fig. 2) indicates fuel loads between 12 – 16 T/ha (Gould et al. 2005). Post-fire assessment indicated that in this fuel type fire spread mostly as a surface fire. Only in a few upslope runs when the wind aligned with the slope did the fire crowned in the eucalyptus forest.

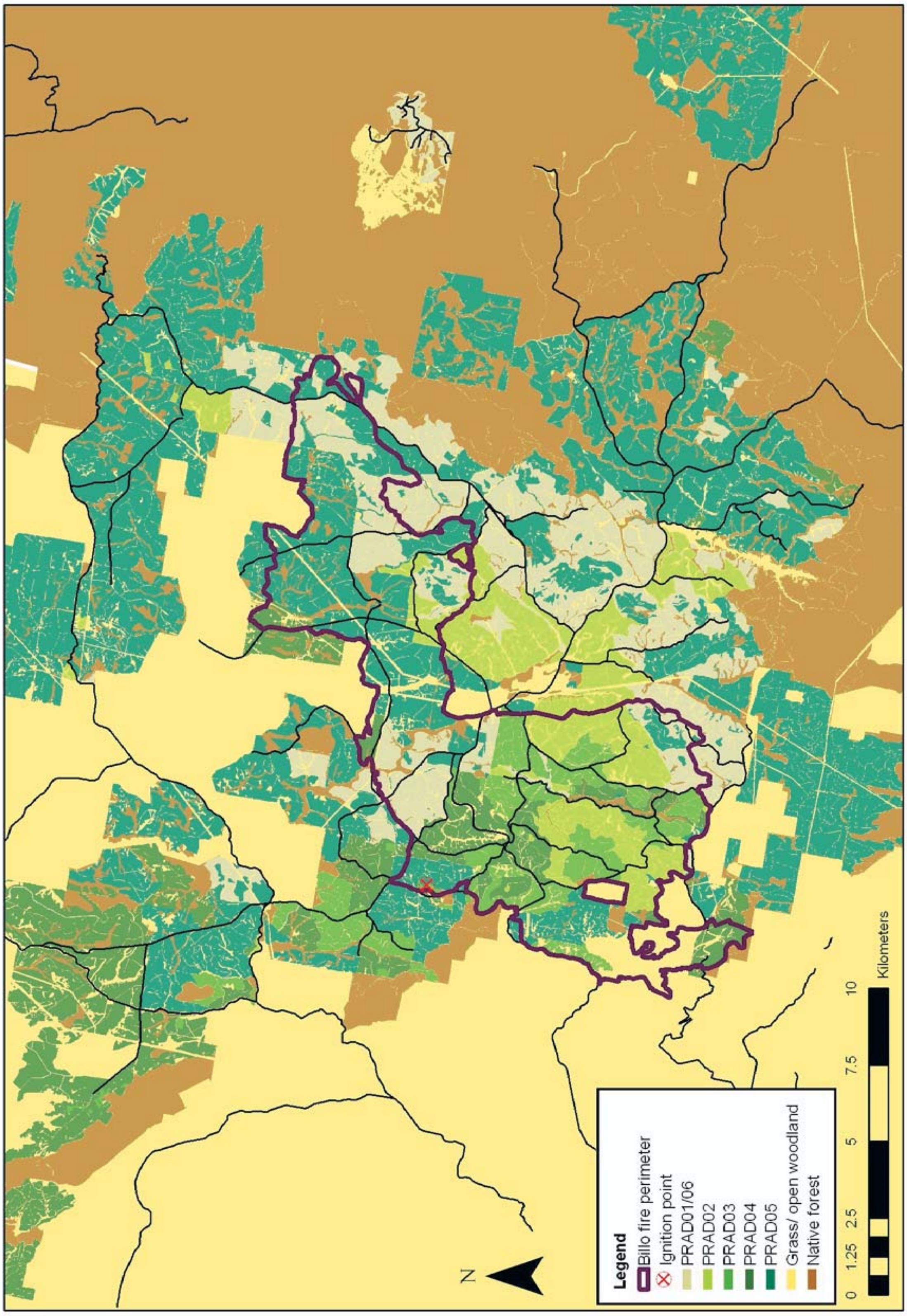

Figure 4. Spatial distribution of fuel complexes within and around the Billo fire. See Table 2 and 3 for fuel complex descriptions.

Grassland

The long term drought conditions of the fire area coupled with grazing resulted in a discontinuous cover of grass fuels with marginal fuel loads within the pasture areas. Fuel loads were estimated to be less than 0.2 T/ha with most pasture grasses grazed to around 1.0 cm in height. Fire in this fuel type was easily contained or self-extinguished. Higher fuel loads existed within the powerline corridors and some riparian areas. Grasses in the riparian areas were partially cured.

Radiata pine plantations

From a fuel classification standpoint, pine plantations can be characterized has having a dynamic structure, with significant changes in fuel continuity and fuel load occurring in relatively short time periods. Given the relevance of the radiata pine fuel complex structures and their spatial distribution on the propagation of the Billo Road Fire, we concentrated our fuel analysis on the variants of this fuel type. We classified the various fuel stages based on the fire potential (fuel hazard), or flammability, associated with a specific fuel arrangement. For this study we modified a classification proposed by Douglas (1964). Our classification divides the radiata pine plantation rotation into 6 fuel types or stages. The criteria to individualize each stage was based on the capacity of a fuel strata (surface and crown) to carry fire and the interaction between then, namely how the combustion of the surface fuels would support the spread of active crown fires. Therefore, each fuel stage has a particular combination of surface fuelbed structure (load and type), fuel strata gap (vertical distance between surface and crown fuel stratum), and canopy bulk density. Table 2 presents the qualitative description of each fuel stage. This description, and namely its dependence on age, is solely indicative, as differences in site quality, initial density and silvicultural system can anticipate, delay or prolong a stage.

Table 3 describes the physical characteristics of surface and canopy fuels as sampled and estimated (canopy bulk density) in selected radiata pine stands in the Buccleuch State Forest. The stands selected for sampling aimed at characterizing the fuels in each of the identified fuel complex stages. The values should be viewed with caution due to the limited number of sampled stands. Considering the dynamics of the surface fuel layer, the litter layer started to develop after canopy closure in PRAD03 (see Table 3 for fuel descriptors) and reaches a steady state in PRAD04 with a litter load slightly above 3 T/ha. The amorphous layer below the fresh litter (Layer F and H) showed a steady increase in load with age, reaching 8 T/ha at age 30. Canopy fuel load was derived from a published biomass study carried out in the same area (Forrest and Ovington 1969). In this study, these authors point out a build up of foliage at age 5, with a peak in foliage biomass of 12 T/ha at crown closure at age 7. After this stage foliage weight reaches a species and site dependent equilibrium and stabilises around 10 T/ha. They also found that the annual formation and shedding of foliage were in balance at about 3 T/ha, a value analogous to our samples of fresh litter. The live foliage biomass estimated by Forrest and Ovington (1969) were similar to other studies carried elsewhere -- 10.5 T/ha in 8-year old plantation in New Zealand (Madgwick 1983); 7.7 T/ha in 12-year old plantation in Victoria, (Williams 1976). After canopy closure the base of the live canopy follows tree height, increasing with time. In younger plantations after crown closure, a layer of dead needles suspended in the lower branches constitutes a ladder fuel layer that links the surface and crown fuel layers. As canopy base height is normally linked to the live canopy, we introduced the concept of the fuel strata gap (Cruz et al. 2004). Fuel strata gap is the distance between the top of the surface fuel layer and the bottom of the canopy layer. Fuel strata gap will equal canopy base height if there are no ladder fuels. A ladder fuel layer existed in PRAD03 but was almost absent in PRAD04. We did not sample the ladder fuels in the PRAD03 type. Williams (1976) reported a fuel load of 2.4 T/ha in a 12-year old unthinned plantation. In stage PRAD04, fuel strata gap equals canopy base height. Canopy bulk density was estimated from the ratio of canopy fuel load by canopy length. Canopy bulk density peaked at 0.21 kg/m3 in PRAD02 and decrease with time as the stand age. Thinning has a profound effect on canopy bulk density by removing tree canopies. The canopy bulk density value for PRAD04T is indicative only and considers that about one third of the trees were removed in the thinning operation.

We did not sample the PRAD01 and PRAD06 fuel complexes. Load and structure of logging slash, PRAD06, is a function of the original stand characteristics, logging method, maximum diameter left on site, and time since logging. The quantitative description of PRAD06 in Table 2 assumes the surface fuel layer of PRAD05 plus logging slash quantities given by N. Burrows "Slash burning guidelines" (undated manuscript on file).

Figure 5. General view of PRAD01 fuel complex. Reference mark is 1 m high.

Table 2. Qualitative description of fuel complex characteristics in the various aged radiata pine plantations

Fuel complex stage (Plantation age)	Surface fuel strata	Ladder fuels	Crown fuel strata
PRAD01 (0 – 3 years)	Absent or composed mostly of grasses/shrubs and/or compacted logging slash if plantation follows previous rotation.	Absent	Absent or incipient
PRAD02 (3 - 8 years)	Needle litter absent to incipient; Possibly moderate cover of shrubs and grasses.	Absent	Crown extends to ground; partial crown to crown contact at end of age class.
PRAD03 (8 – 13 years)	Crown closure leads to development of a light litter layer. Grasses and shrubs suppressed due to canopy closure; begins to form loose uncompacted dead layer.	Layer of dead branches and suspended needles connect surface and canopy layers.	Fully stocked stand with complete crown closure. Canopy base height from 3 to 5 m.
PRAD04 (13 – 20 years)	Continuous litter layer developing in depth.	Layer of dead branches and suspended needles connect surface and canopy layers.	Fully stocked stand with complete crown closure. Canopy base height from 5 to 10 m.
	--- Thinning or pruning ---		
	Continuous litter layer plus layer of woody material of moderate to high loading. Decomposition of woody material function of site characteristics.	Absent	Discontinuous canopy cover with gaps a function of thinning intensity. Canopy base height from 5 to 10 m.
PRAD05 (> 20 years)	Continuous litter layer with duff formation; development of a moderately dense low shrub understorey	Absent	Well stocked stand with good canopy cover. Canopy base height higher than 10 m.
PRAD06 Logging slash	Heavy and continuous (unless piled in windrows) harvest residue layer; red needles retained.	Absent	Absent

Table 3. Sampled and estimated surface and canopy fuel properties for selected fuel complex stages of radiata pine plantations, Buccleuch State Forest, Tumut, NSW.

Fuel complex stage	Fuel load (T/ha)						Canopy bulk density (kg/m^3)	Fuel strata gap (m)	Canopy base height (m)
	Litter L layer	Litter F - H layer	Other fine[1]	Live fuels[2]	Coarse fuels[3]	Canopy live fuels			
PRAD02 (7 years)	0.6	0	7.7	2.2	0	12	0.21	0.5	0.8
PRAD03 (10 years)	1.6	1.9	4.6	0	0	10	0.15	1.5	4.7
PRAD04 (15 years)	3.8	4.4	0.3	0	2.4	10	0.11	10.5	10.5
PRAD04T[4] (15 years)	3.8	4.4	3	0	13	6	0.07	10.5	10.5
PRAD05 (30 years)	3.3	7.7	0.6	0	5	10	0.1	16	16
PRAD06[5] (fresh)	3.3	8	14	0	27	-	-	-	-

[1] - Woody material with < 6 mm in diameter, dead ferns, herbaceous and shrub fuels.

[2] - Live ferns, herbaceous and shrub fuels.

[3] - Woody material with > 6 mm in diameter and pine cones.

[4] - The amount of thinning slash is a function of thinning density. We used Burrows (1980) tables assuming a commercial thinning removing 500 trees.

[5] - Data from Neil Burrows, Slash burning guidelines (undated manuscript).

Figure 6. General view of PRAD02 fuel complex. Reference mark is 1 m tall. Grassy fuels would have been mostly cured at the time of the fire.

Figure 7. General view of PRAD03 fuel complex. Reference mark is 1 m tall.

Figure 8. General view of PRAD04 fuel complex. Reference mark is 1 m tall.

Figure 9. General view of PRAD04T (recently thinned) fuel complex. Reference mark is 1 m tall.

Figure 10. General view of PRAD05 fuel complex. Reference mark is 1 m tall.

5. CLIMATE AND WEATHER CONDITIONS

5.1. FIRE SEASON

Analysis of the KBDI trace for the months preceding the fire reveal that the area had been subject to a prolonged drought. The drought index never decreased to values normally experienced during winter/spring, and at the beginning of December, the index levels were 100 points higher than the average for the period 1996/2006. The potential for the occurrence of severe fire events during the 2006/2007 season occurred several months earlier than they did during the regionally significant 2002/2003 fire season.

The months preceding the Billo Road Fire were characterized by prolonged drying periods with small episodic rainfall amounts (see decrease in KBDI in Fig. 11 and 12). For Gundagai, precipitation in August, September, October and November was less than one third of the 30-year climatological average. The yearly precipitation at Bondo up until the 10 of December 2006 was 440 mm, higher than the observed at Wagga Wagga (260 mm) and Gundagai (281 mm). Correspondingly, the KBDI at Bondo weather station was 98 on the 10 of December, about 50 points lower than Wagga Wagga (146) and Gundagai (160). Being that the KBDI is a surrogate for fuel moisture and fuel availability, the trends in Fig. 11 and 12 and the magnitude of the values are indicative that a large proportion of the duff layer and large woody fuels were available for combustion during the Billo Road Fire.

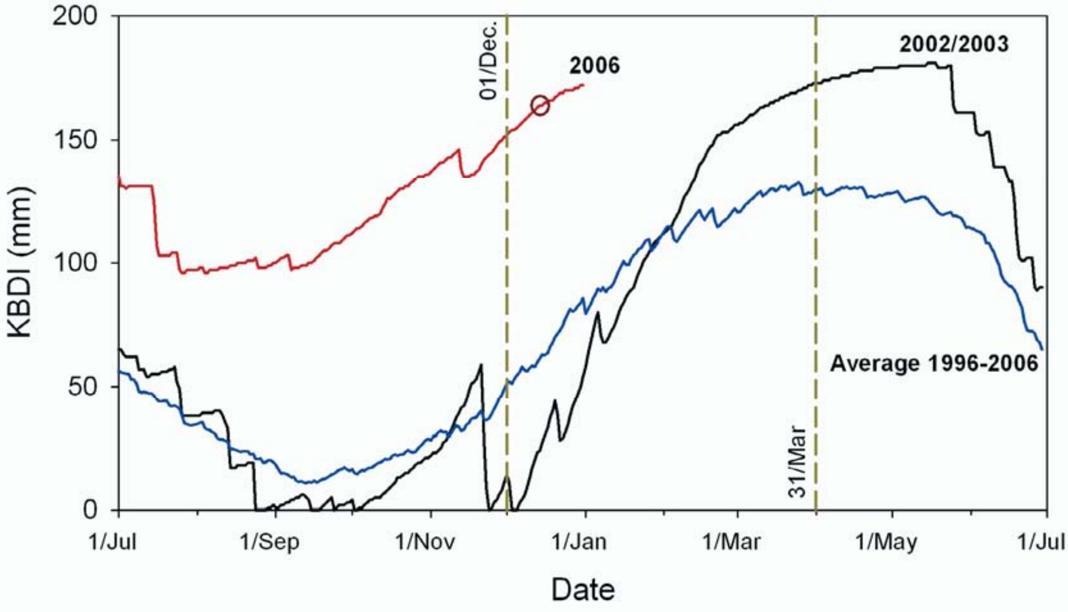

Figure 11. Seasonal variation in the Keetch-Byram Drought Index (KBDI) in 2006 (red), 2002/2003 (black) and 10-year average (blue) for Gundagai weather station (BoM). Red circle identifies the date of origin of the Billo Road Fire.

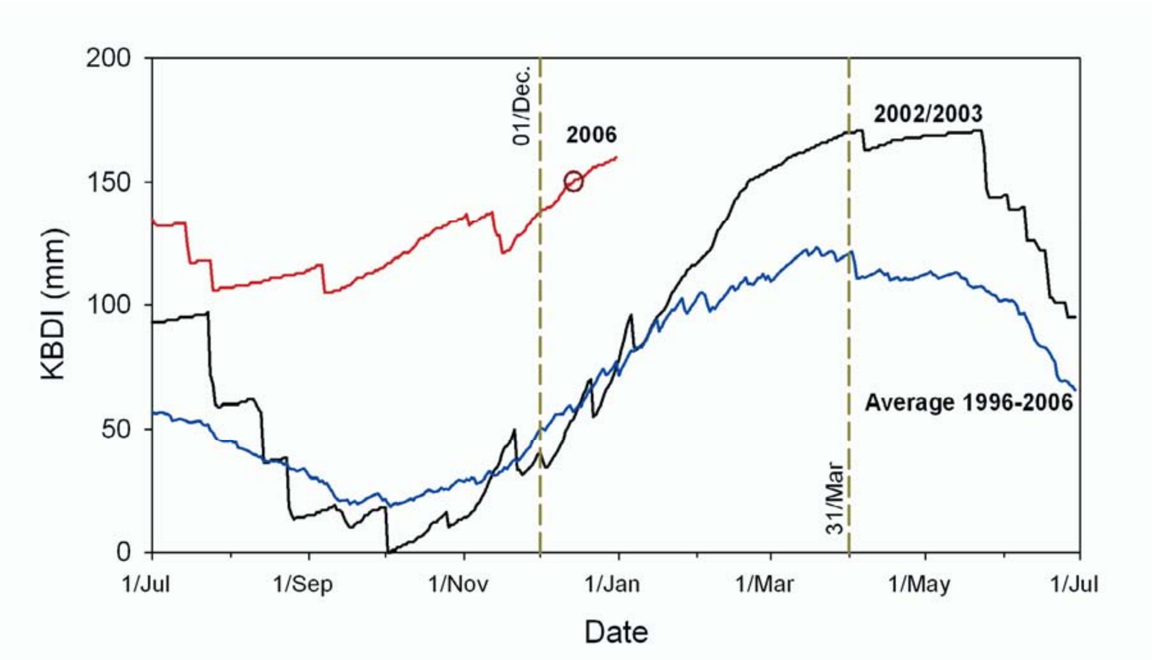

Figure 12. Seasonal variation in the Keetch-Byram Drought Index (KBDI) in 2006 (red), 2002/2003 (black) and 10-year average (blue) for Wagga Wagga weather station (BoM). Red circle identifies the date of origin of the Billo Road Fire.

5.2. SYNOPTIC SITUATION ANALYSIS AND OBSERVED WEATHER

The synoptic situation from the 9th to 15th of December was a typical summer time pattern for south-eastern Australia (Fig. 13 to 18). A series of high pressure systems moved eastwards across the south of the continent and out into the Tasman Sea. Between highs were paired troughs extending from tropical low pressure systems and cold fronts, a situation conducive to severe fire weather conditions. The high pressure systems directed warm, dry continental air over southeast Australia, resulting in very dry fuels and elevated fire danger levels. Conditions that prevailed on the 9 and 10 of December 2006 were a classic example of a critical fire weather situation from a synoptic standpoints in southeaster Australia, with temperatures in the high 30’s and very low humidity.

The fire danger under these conditions are frequently worsened by the subsequent passage of a cold front. Winds around the front are typically strong and gusty, leading to a potential change in direction of spread and a period of rapid fire propagation (e.g., McArthur 1965, Luke and McArthur 1978) as the front approaches and passes. Prior to the passage of a front, the associated trough brings tropical air southwards. If there is sufficient moisture in this north/northwest flow then rain may fall with the frontal passage, offering some relief. The dew points associated with the pre-frontal north/northwest winds during the first half December 2006 were notably low, as a consequence of the drought in central Australia. This meant that many fronts brought strong wind but no rain. The front that passed over the fireground on the 11 December night did not bring rain and contributed to the weather experienced during the Billo Road Fire.

The sequence of synoptic scale events and the corresponding weather conditions for the period 9-14 December 2006 are described below.

Saturday - 9 December 2006. Conditions at Buccleuch State Forest were dominated by a large high pressure system over the Tasman Sea (Fig. 13). The high directed hot, dry continental air over the fire area with afternoon conditions resulting in winds from the northeast in the morning gradually turning northwest by the evening, a maximum air temperature of 32°C, a dew point 18°C, and a relative humidity (RH) of 35%. The dew point fell to 12°C over night, with a minimum temperature of 13°C, and a near full recovery in the RH at 95% (weather observations from Bondo WS).

Sunday - 10 December 2006. The high moved further east but continued to dominate conditions over the fire area (Fig. 14). The high directed hot, dry continental air over the fireground with afternoon winds northwest at 20 km/h, gusting to 30 km/h, a maximum air temperature of 33°C, a dew point of 15°C and RH of 30%. Dew point fell to 10°C over night and coupled with a minimum temperature of 17°C, resulted in only a moderate recovery in RH (65% at Bondo WS).

Monday - 11 December 2006. The high over the Tasman continued to move east and a low pressure trough extended over NSW from a low situated over QLD (Fig. 15). A cold front passed over SE Australia during the day, bringing rain to Victoria but not NSW. The front passed over the fireground around 16:00. The area then came under the influence of a high over the Great Australian Bight. Conditions in the morning and early afternoon were: winds west at 20 km/h, gusting to 30 km/h, maximum temperature 30°C, dew point around 14°C, and RH falling from 45% at 08:00 to 40% at 14:00. Ahead of the front winds were very strong west at 40 km/h, gusting to 60, but dropping to SW at 20 km/h with gusts to 30 km/h behind the front, and falling to 10 km/h over night. The change in wind direction with the front was weak, with a gradual shift from west to southwest in the mid to late afternoon.

Dew point dropped a small amount with the passage of the front to 13°C. However, the night was much cooler than the previous night, with a minimum overnight temperature of 10°C. As a result, the RH rose to 100%.

Tuesday - 12 December 2006. The high in the Great Australian Bight moved eastwards over VIC, while a trough extended over NSW from a low situated above southern QLD (Fig. 16). The intrusion of the trough into the high in the vicinity of the fireground resulted in variable wind directions during the day. In late afternoon conditions stabilised with winds east-northeast at 15 km/h, gusting to 25 km/h. It was a relatively warm day, with a maximum temperature of 21°C, dew point rising from 10°C in the morning to 13°C by the afternoon, resulting in the RH falling to 65%. A cool night followed with the temperature dropping to 8°C and the RH rising to 100%.

Wednesday - 13 December 2006. The high over VIC moved east into the Tasman Sea and dominated weather conditions at the fireground (Fig. 17). Winds were NE at 20 km/h, gusting to 25 km/h, in the morning, becoming weaker and shifting to north-northwest at 15 km/h, gusting to 20 km/h, during the day. Dew point rose from 7°C to 17°C, with a minimum RH of 40%. This was followed by a cool night, with minimum air temperature and dew point 10°C and relative humidity rising to 100%.

Thursday - 14 December 2006. The high over the Tasman Sea continued to move east towards New Zealand (Fig. 18). Meanwhile a trough and cold front approach from the west. The front was at the NSW-VIC border at around 16:00 and crossed the fire ground during the small hours of the night.

Wind shifted to the northwest ahead of the front and strengthened to 35 km/h, with gusts of 50 km/h before easing to south-southwest at 20 km/h, gusting to 30 km/h, behind the passage of the front. It was a hot, dry day, with a maximum temperature of 31°C, minimum RH of 35% followed by a mild evening, with a minimum temperature of 13°C. Dew point rose from 7°C in the afternoon to 13°C during the night. In turn, overnight RH reached 100%. A total of 3 mm of rain was recorded at the Bondo weather station after the front passed.

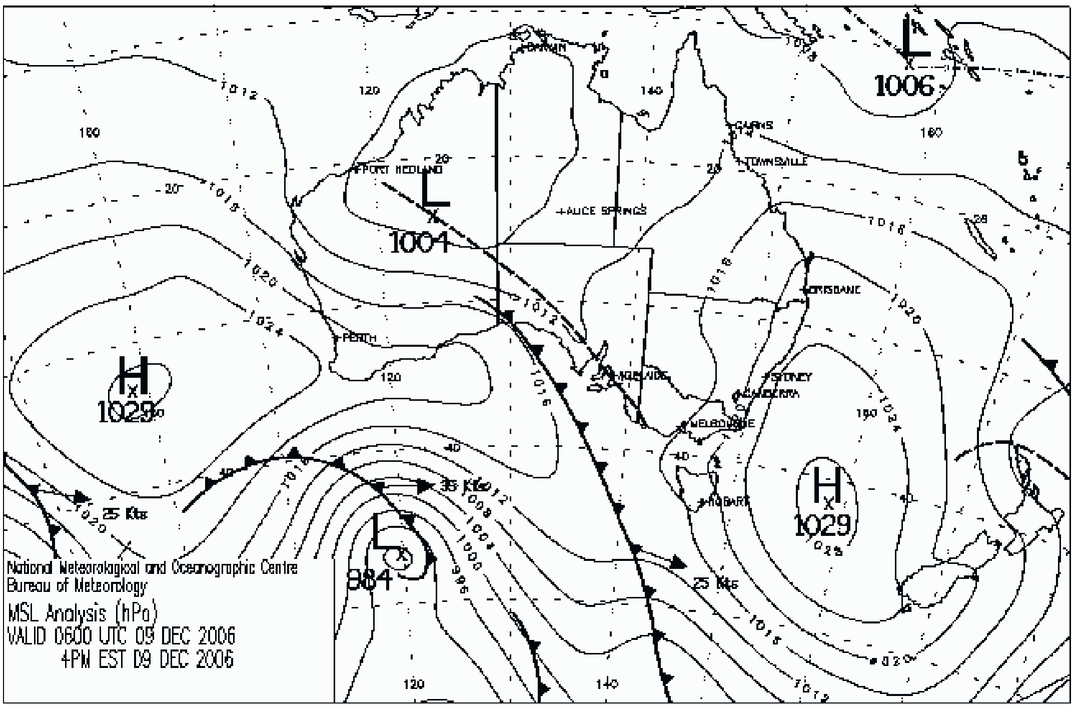

Figure 13. Mean surface level (MSL) analysis for Australia for 1600 EST on 9 December 2006. Source: Bureau of Meteorology.

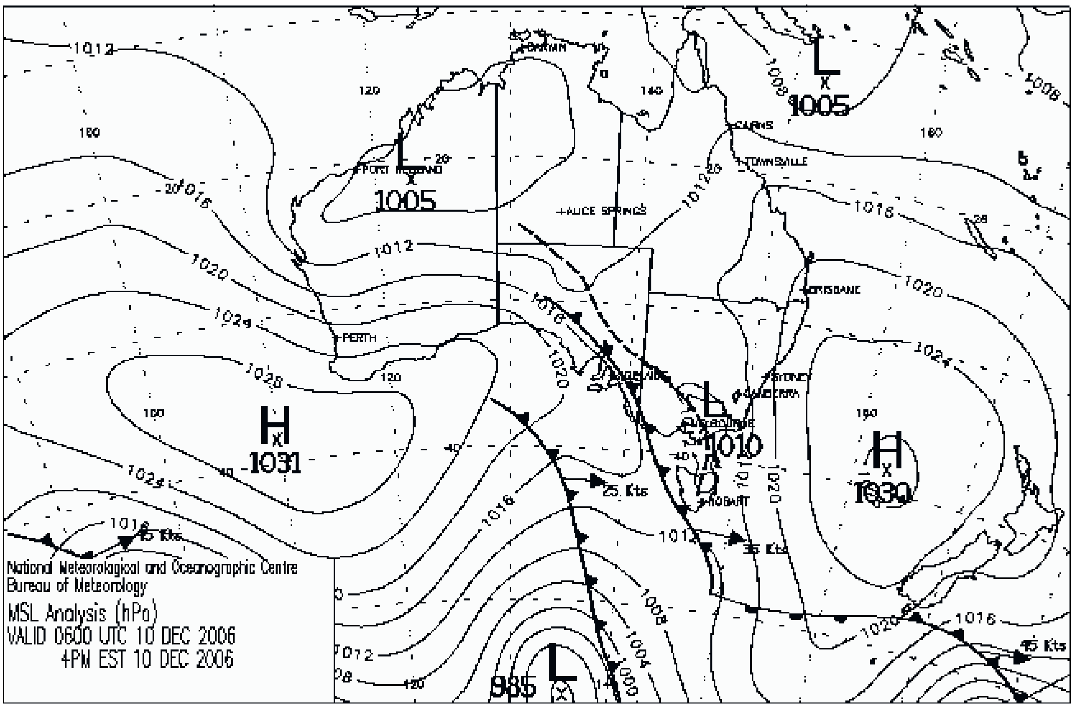

Figure 14. Mean surface level (MSL) analysis for Australia for 1600 EST on 10 December 2006. Source: Bureau of Meteorology.

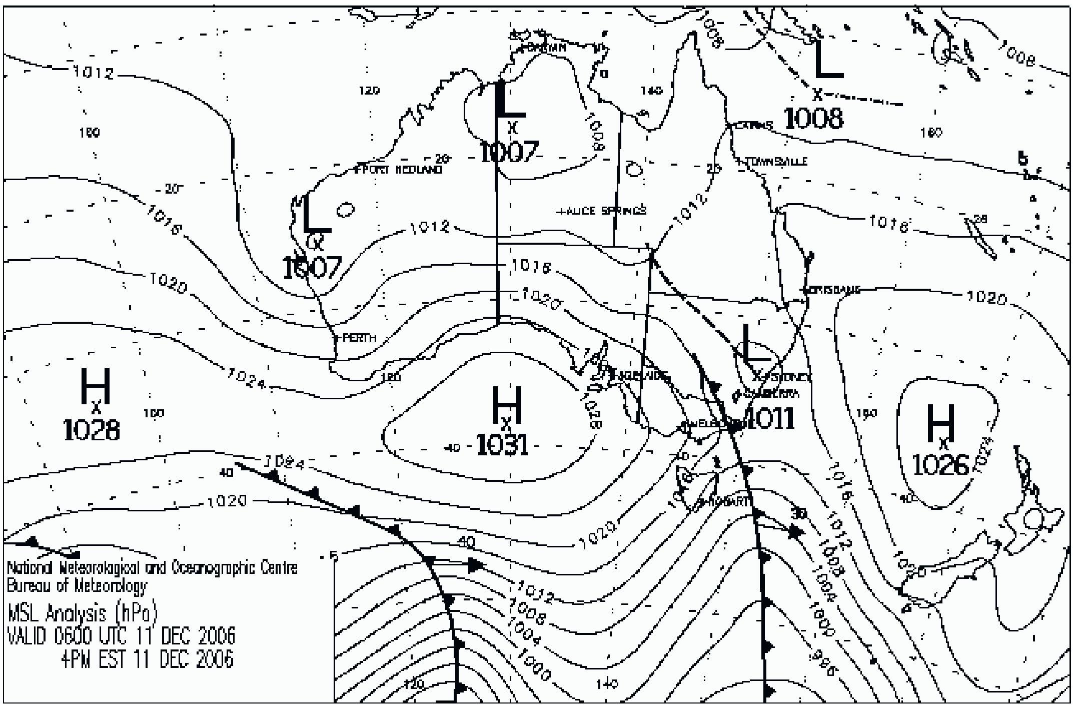

Figure 15. Mean surface level (MSL) analysis for Australia for 1600 EST on 11 December 2006. Source: Bureau of Meteorology.

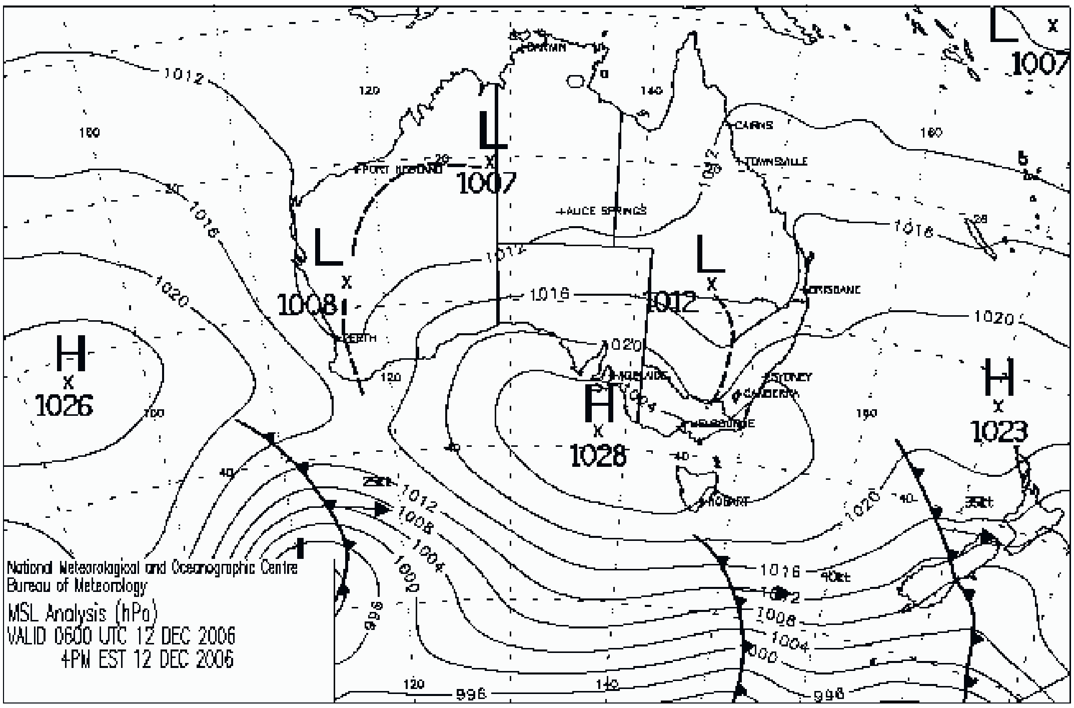

Figure 16. Mean surface level (MSL) analysis for Australia for 1600 EST on 12 December 2006. Source: Bureau of Meteorology.

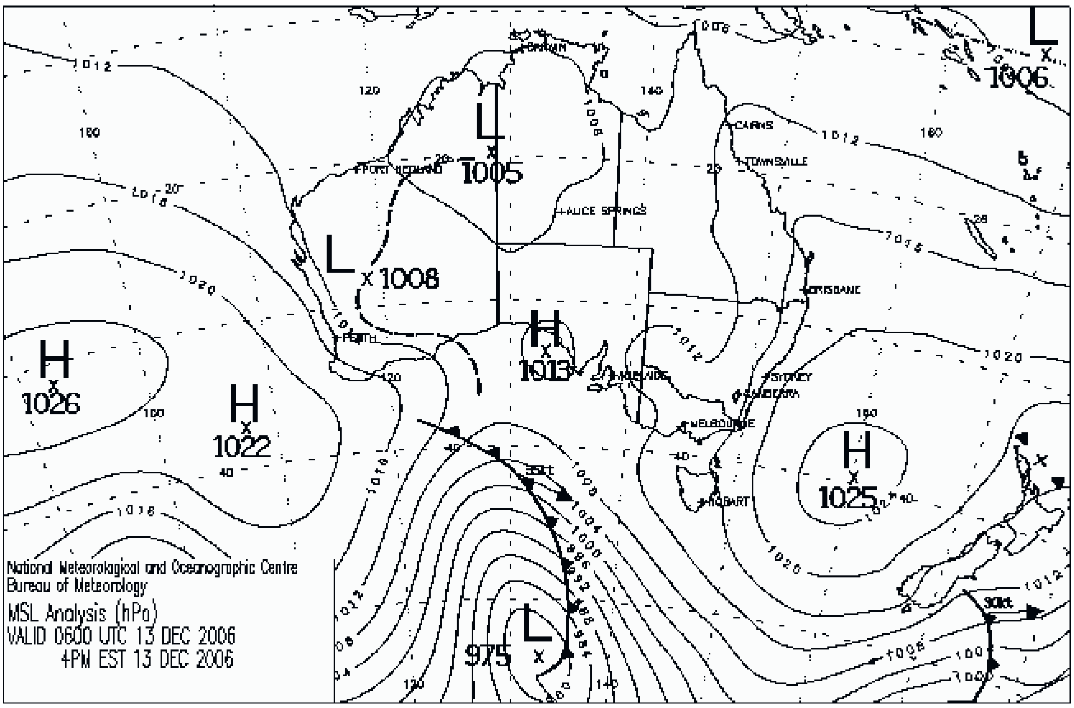

Figure 17. Mean surface level (MSL) analysis for Australia for 1600 EST on 13 December 2006. Source: Bureau of Meteorology.

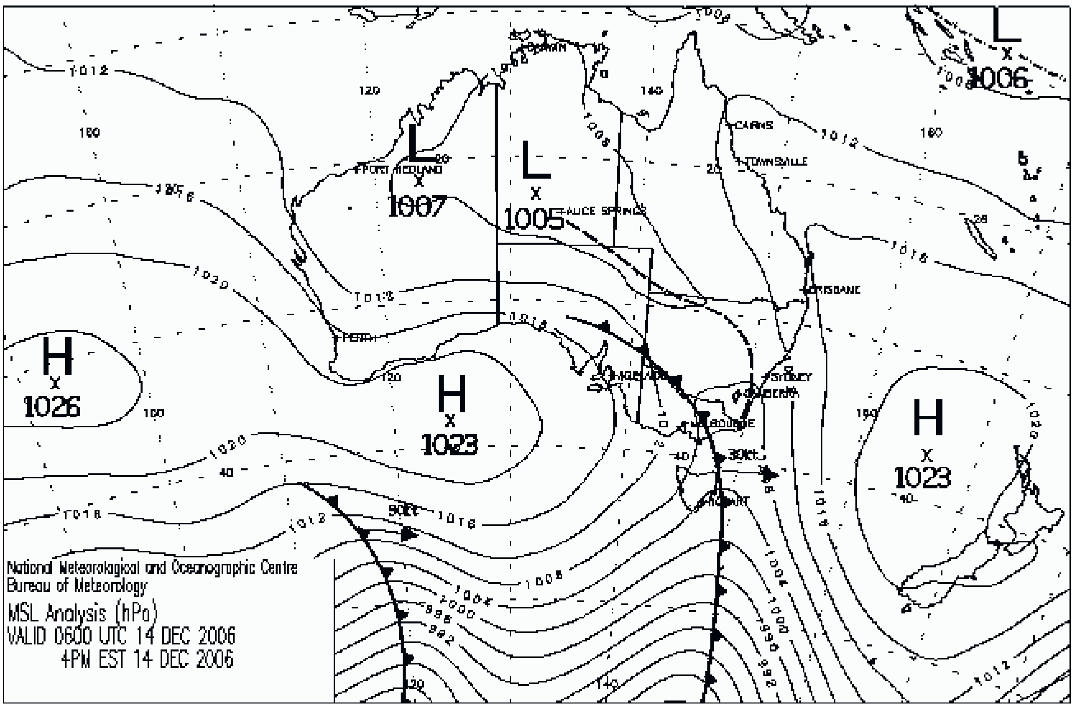

Figure 18. Mean surface level (MSL) analysis for Australia for 1600 EST on 14 December 2006. Source: Bureau of Meteorology.

5.3. FIRE WEATHER OBSERVATIONS AND FIRE DANGER RATINGS

Considering a shorter time scale relevant to the drying of fine and medium size fuels, the days that preceded the Billo Road Fire contributed significantly to increase the availability of these fuels for combustion (Fig. 19). The diurnal variation in temperature and RH on these days resulted in estimated fine dead fuel moisture contents (per the McArthur 1967 guide) of less than 5% at the peak burning period (3% on the 8 of December). The daily calculation of the McArthur (1967) FFDI at Bondo for these days indicates Moderate to High fire danger (FFDI between 9 and 14), although the diurnal calculation of the FFDI produces mid-afternoon peak values corresponding to Very High fire danger levels. Similarly, the Wagga Wagga weather station indicated daily FFDI values corresponding to Moderate and Very High fire danger levels for those days, with episodes of extreme FFDI values on the diurnal calculation (Table A3.2 in Appendix 4).

While the Billo road Fire was actively burning from the 10 to the 14 December 2006, the most significant fire events occurred on the 10 and 11 December. The calculated FFDI for 10 and 11 December at the Bondo weather station were 13 and 12 respectively (i.e., High fire danger). At Wagga Wagga, the FFDI for these two days were 51 (Extreme) and 46 (Very High) for the 10 and 11 of December, respectively. For these two days, the peak burning period (1300-1700) at Bondo were characterized by FFDI equivalent to High to Very High fire danger levels, with the minimum RH of 30 (at 16:30) and 39% (at 13:40) and maximum wind speeds of 29 and 59 km/h, respectively. The Haines Index, an indicator of the stability and moisture content of the lower atmosphere (Haines 1988), was 5 (Moderate) on the 10 December and 6 (High) on the 11 of December. It decreased to 2 and 3 for the 12 and 13 December respectively and then increase to High again on the 14 December.

Table 4. Daily 12:00 weather observations, McArthur (1967) Forest Fire Danger Index (FFDI), and the Keetch-Byram Drought Index (KBDI) for the Bondo weather station (FNSW). The Haines Index was derived from the Limited Area Prediction System (LAPS) model output (Courtesy of the Bureau of Meteorology).

Date	Air temp. (°C)	RH (%)	Wind speed (km/h)	Wind direction (°)	FFDI	KBDI	Haines Index
07/12/2006	28.9	36.3	15.8	229	14	90	5
08/12/2006	32.3	33.1	5.8	12	13	92	5
09/12/2006	31.7	43.4	3.9	115	9	95	6
10/12/2006	33.5	38.3	11.3	252	13	98	5
11/12/2006	27.5	43.4	22.6	246	12	101	6
12/12/2006	17.8	72.5	27.1	254	3	104	2
13/12/2006	27.8	51	5.8	330	6	104	3
14/12/2006	29.6	35	11.3	286	12	106	6

Several weather events are worth discussing. Significant to the observed fire behaviour were the low levels of relative humidity late on the 10 December and into 11 December and the lack of recovery in the fine dead fuel moisture to normal night values. At 23:00 on the 10 of December, RH was 46%, and estimated fine dead fuel moisture content was 9%. The extreme fire behaviour activity on the afternoon of the 11

December was the result of low fuel moisture contents coupled with the high wind speeds associated with a frontal passage.

Table 5. Daily 12:00 weather observations, McArthur (1967) Forest Fire Danger Index (FFDI), and the Keetch-Byram Drought Index (KBDI) for the Wagga Wagga weather station (Bureau of Meteorology). The Haines Index was derived from the Limited Area Prediction System (LAPS) model output (Courtesy of the Bureau of Meteorology).

Date	Air temp. (°C)	RH (%)	Wind speed (km/h)	Wind direction (°)	FFDI	KBDI	Haines Index
07/12/2006	32.1	12	21	270	40	142	5
08/12/2006	33.4	16	13	280	30	143	5
09/12/2006	33.1	21	13	360	25	145	6
10/12/2006	36.7	12	26	290	52	146	5
11/12/2006	32.1	17	35	240	46	148	5
12/12/2006	26.2	27	17	60	18	149	4
13/12/2006	27.6	23	24	10	25	149	4
14/12/2006	32.5	8	13	360	38	150	6

On the 11 of December, moisture brought by easterly winds in the late afternoon led to nighttime fuel moisture recovery (i.e., increase in fuel moisture content), and milder burning conditions on the ensuing days (Table 4). An additional peak in fire potential occurred on the afternoon of 14 December. Further discussion on the effect of weather variables on the observed fire behaviour is given in sections **6. Fire Chronology** and **7. Fire Behaviour Analysis** sections of this report.

The magnitude of the error introduced by the reported RH reading bias at the Bondo WS is unknown. Comparison between the weather at Bondo and at a weather station located in Laurel Hill (near Batlow, see Fig. S1) for the period of the fire produces a difference that can reach 10 percentage points in RH. If this was in fact an error in the sensor at the Bondo WS, we estimated that the calculated FFDI values could have been 6 to 12 points higher than what is being reported for this site. With the larger errors being associated with the higher FFDI situations.

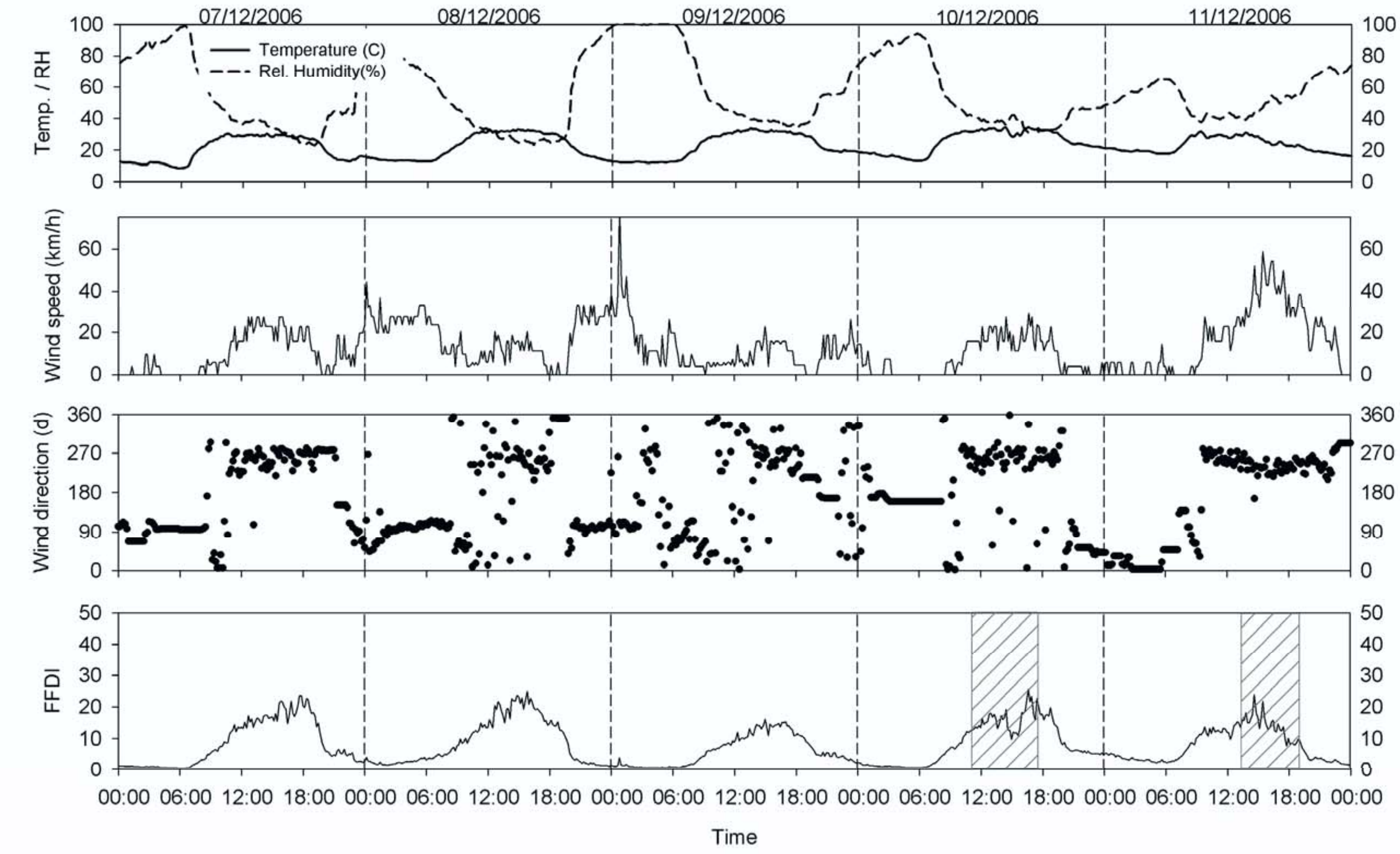

Figure 19. Diurnal pattern in fire weather observations and McArthur (1967) Forest Fire Danger Index (FFDI) from the 7-11 December 2006 at the Bondo weather station (FNSW). Shaded areas in the FFDI graph identify the periods associated with the main runs of the Billo Road Fire.

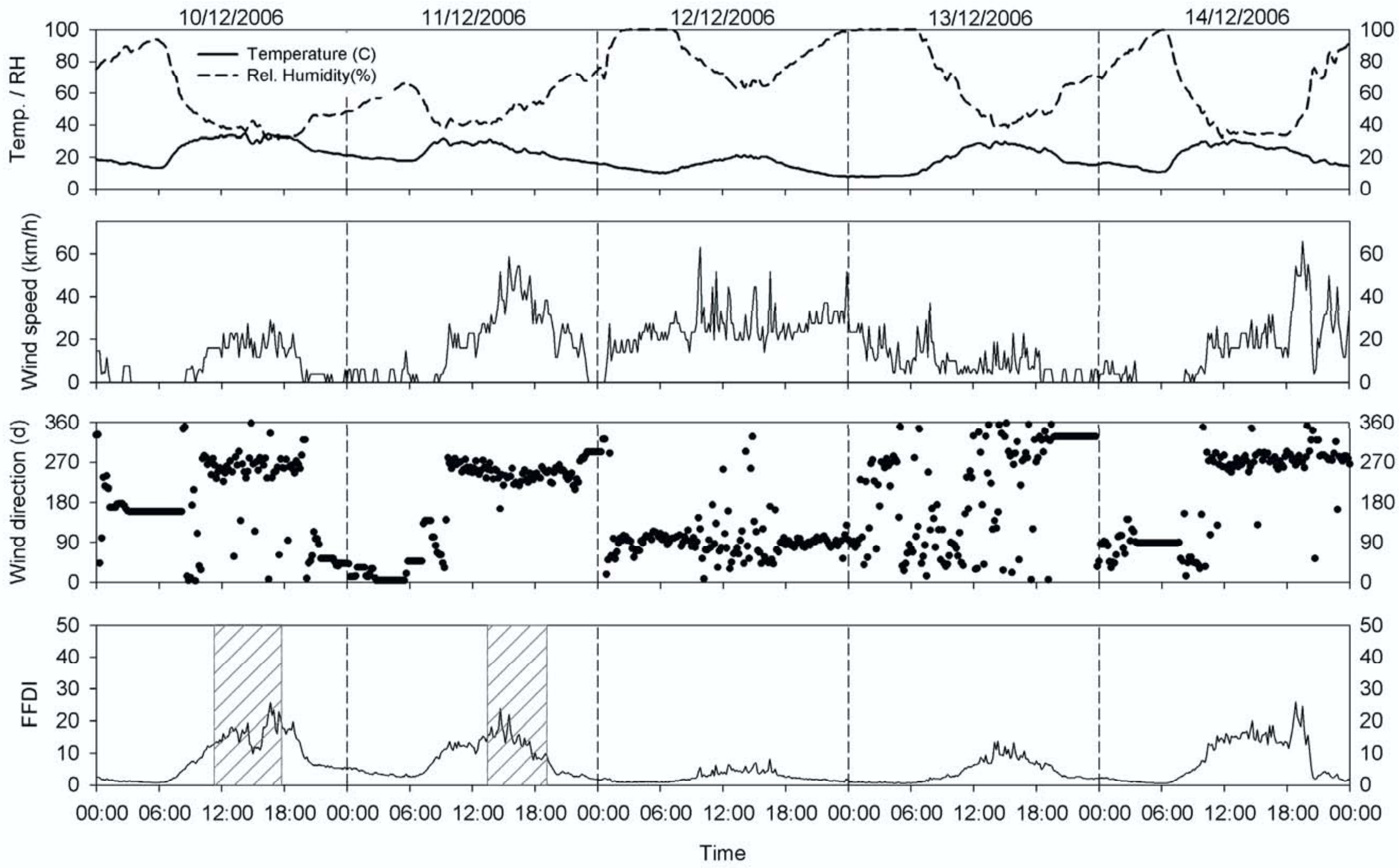

Figure 20. Diurnal pattern in fire weather observations and McArthur (1967) Forest Fire Danger Index (FFDI) from the 10-14 December 2006 at the Bondo weather station (FNSW). Shaded areas in the FFDI graph identify the periods associated with the main runs of the Billo Road Fire.

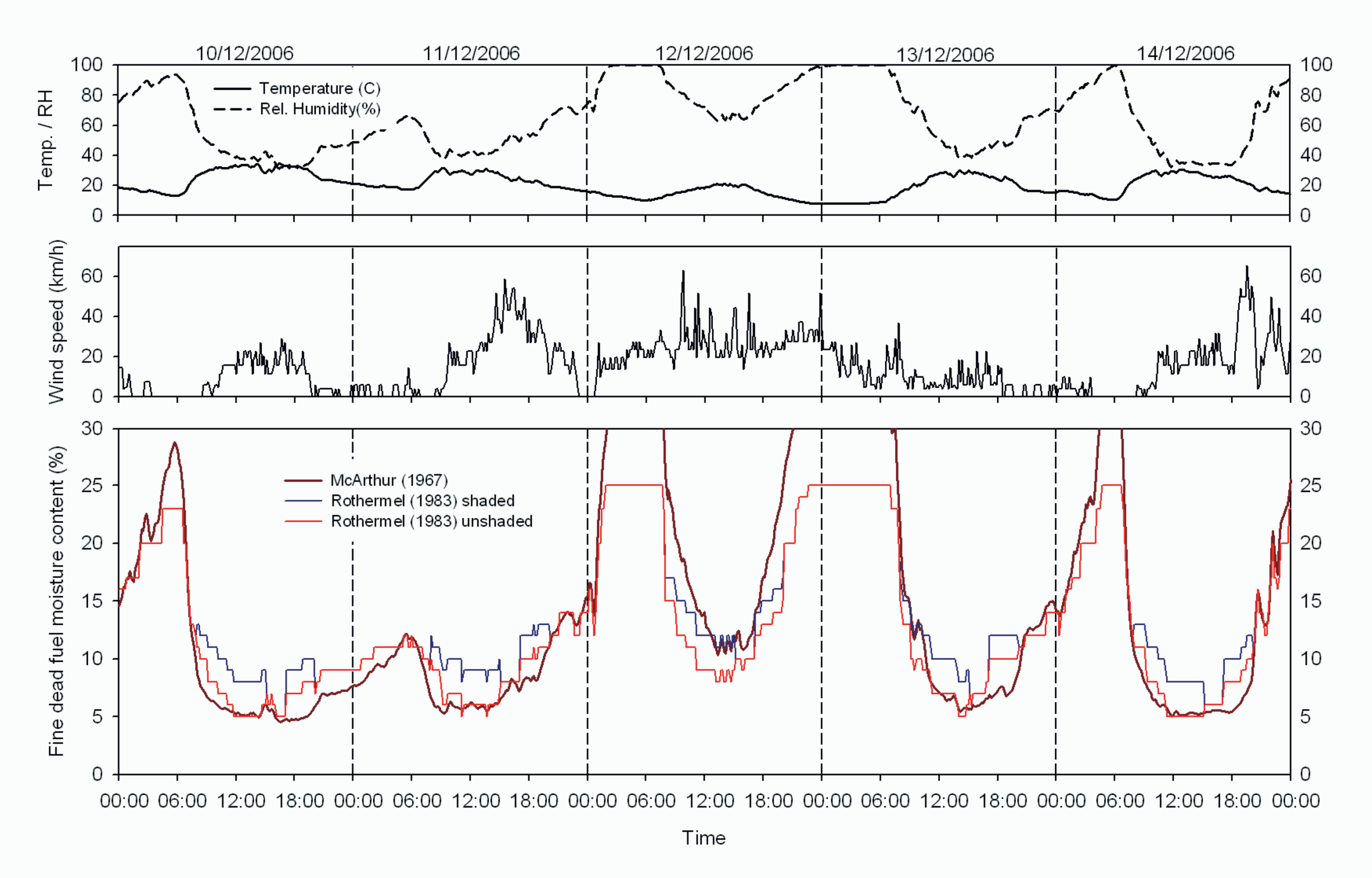

Figure 21. Diurnal pattern in fire weather observations and estimated fine dead fuel moisture content for the period 10-14 December 2006 at the Bondo weather station (FNSW).

5.4. PREDICTION OF FUEL MOISTURE CONTENT

No fuel moisture samples were collected during the fire. Estimation of fine dead fuel moisture contents driving the fire propagation relied on Viney (1991) model based on McArthur (1967) dead fuel moisture table and some degree of uncertainty exists. The main sources of uncertainty were: (1) the adequacy of the model to describe fuel moisture of litter fuels in radiata pine plantations; (2) its validity to nighttime conditions (it was parameterized for daytime drying and wetting cycles); and (3) its inability to characterize moisture content of fuels fully exposed to solar radiation, such as occurred in PRAD01 and PRAD06 fuel complexes. To explore the effect of solar radiation in the drying of the PRAD01 and PRAD06 surface fuels we used Rothermel's (1983) estimation procedures.

McArthur's model predicted fuel moisture contents between 19 and 5% at the 10 of December and between 15 and 5% on the 11 of December (Fig. 21). On the 10 of December fine dead fuel moisture content was predicted to reach 5-6% at 12:00 and stay at that level until 19:00-20:00. Nighttime fuel moisture recovery was minor in the early hours of 11 December. On this day a 5-6% fine dead fuel moisture content level was reached early in the morning and lasted until 16:00-17:00. The model identified a recovery in fuel moisture content during the nights of the 12 and 13 of December, with fine dead fuel moisture content reaching 30%. On the 14 of December, the diurnal trace in fuel moisture content was similar to that of the 10 of December.

The predictions from Rothermel (1983) guide show smaller amplitude of fuel moisture content variation with a differential between exposed and shaded fuels reaching 3% at the peak burning period of the 10 and 11 December. With this model, the lower levels of fuel moisture content were attained between 12:00 and 15:00, and these low fuel moisture periods were shorter than predicted by the McArthur (1967) guide. The two guides predicted similar results on the night of the 10-11 of December, with the maximum fine dead fuel moisture content reaching 11-12% at 06:00. On the remaining nights, the Rothermel (1983) guide predicted recovery of fuel moisture content to 25%. The Rothermel (1983) unshaded simulation tended to approximate the McArthur (1967) guide results, mainly at the peak burning period of the first two days of the fire when the dead fine fuel moisture content was at its lowest (i.e., 5-6%).

As with the FFDI computations, the possible error in RH measurements would have affected the assessment of fine dead fuel moisture content. An error of 10% overestimate of RH would translate into an over prediction of fine fuel moisture of 1.3 and 1 moisture content points, respectively for the McArthur (1967) and Rothermel (1983) guides for estimating fine dead fuel moisture.

No samples of live foliage fuel moisture were taken during the fire. Based on the results of Pook and Gill (1993) we assume that radiata pine foliage had an average moisture content of 110%.

6. FIRE CHRONOLOGY

9 December 2006

21:00 to 24:00

Air temperature: 19°C; RH 54 - 74%; 10-m wind speed: 7 - 26 km/h (direction S); FFDI: 2 - 6

Ignition most likely occurred sometime within this period or in the early hours of 10 December 2006. Ignition source was a stolen car set alight on an internal plantation firebreak near the Billapaloola Road picnic area (Fig. 22).

10 December 2006

00:00 to 09:00

Air temperature: 13 - 30°C; RH: 50 - 94%; 10-m wind speed: 0 - 15 km/h (S); FFDI: 1 - 7

Fire crept with low intensity through the night in 10- and 16-year old plantation fuels. The estimated burned area at the end of this period was 6 ha.

09:00 to 11:00

Air temperature: 28 - 32°C; RH: 31 - 50%; 10-m wind speed: 11 - 16 km/h (WNW); FFDI: 7 - 12

Initial report of a fire burning within the Billopoola State Forest was given by a local resident driving along Billopoola road. Initial attack started around 09:20. A combination of direct and indirect attack strategies were used at this stage in an attempt to contain the fire. Initial reports state that the fire was holding on breaks to the west and south and the main concern was upslope propagation towards the east, with reported flames up to 6 m in length.

11:00 to 18:00

Air temperature: 28 - 35°C; RH: 31 - 42%; 10-m wind speed: 11 - 29 km/h (WNW); FFDI: 10 - 26

At around 1110 the head fire intensity on the flame front spreading eastward increased with occasional torching of groups of trees and short range spotting in PRAD05 fuels. At this stage, the fire's intensity prevented direct suppression action at the head of the fire.

The high definition aerial photograph of this area shows evidence that the episode of torching activity was followed by bursts of sustained crown fire propagation, with the head fire spreading in an ENE direction (Fig. 22). This crown fire run continued for about 1 km, spreading downhill in a 14-year old, unthinned and unpruned stand and reaching Cotterills Road at 12:12. At this stage the fire was spotting profusely, with spot fire ignitions developing north and south of Rosettes Road, in PRAD01 and thinned PRAD04 fuels. Crews attempted to contain these new ignitions on the eastern side of Cotterills Road but were overcome by the number of spots and subsequently retreated to a safe zone.

Once the fire had crossed Cotterills Road it spread on both sides of Rossettes Road. The compartments on the northern side of Rossettes Road contained slash rows (Fig 25) that had been burned[1] six months before

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[1] The process of burning slash residue in the rows is carried out through a prescription that while allowing the combustion of a large proportion of the fuels in the rows, limits the consumption of inter-row space fuels which are retained for erosion control and nutrient retention.

the fire, some with new plantings. While these areas were open, and spot fires were visible to crews, the slash rows impeded access. On the southern side of Rosettes Road the fire spread through 17 year old thinned stands with intermittent crowning.

By this time a second head fire had developed, originating from the southern flank around 250 metres southeast of the ignition point, with two significant up-slope crown fire runs. The southern most of these runs continued spreading as down slope crown fire aided by area ignitions from mass spot fire coalescence.

Between 14:30 and 15:30 there were a number of spot fires reported up to 3 kilometres in front of the fire. Most of these were suppressed using tankers and dozers. The head fire reached Brindabella Road at 1558 as a crown fire (Fig. 26) and Sandy Creek Road at 1618. Throughout this period, the wind was shifting from west to northwest.

18:00 to 23:59

Air temperature: 21 - 33°C; RH: 32 - 48%; 10-m wind speed: 0 - 23 km/h (NNE); FFDI: 5 - 20

At 18:00 the wind speed decreased and direction shifted to the north. The northeast part of the fire burnt as a flank fire, predominantly in logging slash with the southeastern perimeter constituting the most active part of the fire at this stage. The fire spread in a combination of logging slash and mature plantation. Photographs taken during this period of the fire revealed strong indrafts into the fire's convection column (Fig. 27).

The fire spread southwards under the influence of the northerly wind, reaching an area of unthinned young plantation (9-year old) at around 18:30. Although the fire weather potential had been decreasing for the previous few hours (Fig. 20 and 21) the fire crowned again in this fuel type, propagating with moderate rates of spread (Fig. 23). Crown consumption patterns suggest that through the following hours the fire burned as an intermittent crown fire. The flame front crossed Webbs Road at 21:10, and continued to propagate as a crown fire in 8-9 and 5-6 year old pine plantation fuel complexes (i.e., PRAD03 and PRAD02 respectively), crossing Boyds Road at 23:40. The highest fire severity was identified in the 8-9 year old pine stands. This southern run was too intense for direct suppression and crews concentrated on putting in backburns along Masons Road and Boyds Road. The backburn on the western side of Masons Road paralleled the fires southward run, and provided a barrier to the plantations to the east.

After crossing Boyds Road, the fire's intensity decreased as a combination of younger fuels (5-year old), and the fire spreading downslope into a downwind sheltered area.

11 December 2006

00:00 to 13:00

Air temperature: 18 - 32°C; RH: 38 - 66%; 10-m wind speed: 0 - 27 km/h (N); FFDI: 2 - 15

Between midnight and mid morning on the 11 of December, no major fire activity occurred as the fire continued spreading into the unbounded areas in the southwestern parts of the fire's perimeter. Several backburns carried out throughout the night confined the fire within established firebreaks.

The morning of the 11 of December was characterized by an increase in fire potential, with the lowest fuel moisture contents occurring between 12:00 and 14:00 (Fig. 21).

13:00 to 19:00

Air temperature: 22 - 31°C; RH: 39 - 55%; 10-m wind speed: 23 - 59 km/h (W); FFDI: 8 - 24

From 12:00 there was a steady increase in burning conditions (Fig. 20 and 21). At 13:50, coinciding with an increase in wind speed (above 30 km/h), the fire spotted into heavy fuels on the northeast section of the fire. By 14:40 spot fires were developing in slash, mature pine stands and native forest. Bursts of crowning activity were observed in both mature pine stands and the native forest.

At 15:00 the fire crossed a 200 m wide fuel break and spread in an east-northeast direction into mature pine stands (Fig. 28). Post-fire evidence indicates that at this stage the fire was spreading mostly as a high intensity surface fire in mature pruned and thinned stands, with short range spotting and occasional episodes of crown fire activity. The spot fires did not contribute to an increase of the overall rate of spread of the fire, as they were normally overrun by the main front, but allowed the fire to cross a series of fuelbreaks, including clearings and roads.

At 16:00 the fire crossed Cockatoo Road, and continued to spread mostly through two distinct fuel complexes: (1) mature pine stands (PRAD05) and (2) logging slash (PRAD06)/young plantation with logging slash (PRAD01). The fire spread with great intensity in the logging slash, with the main mechanism of propagation being mass ignition followed by the coalescence of multiple spot fires (Fig. 29). This kind of fire dynamics leads to deep flame fronts with large fuels being consumed during flaming combustion (Fig. 30). The post-fire evidence suggests that even though the fire was spreading concurrently in the mature pine stands by intermittently crowning, it lagged behind the advancing flame front in the slash fuels.

Detailed information on the fire’s progress during this period was scarce. The head fire was estimated to be approximately 500 m in width with the flank fires burning intensely. Short crown fire runs were associated with positive slopes and breakaway fingers of the fire at its flanks.

Some long distance spot fires did occur during this period. Two spot fire ignitions over 4 km in distance to the northeast of the fire were observed between 17:00 and 19:00. Most of these spots were burning in recently logged and planted areas, and were promptly extinguished.

In its final stages this east-northeast run of the Billo road Fire burned as a surface fire through mature pine plantation. The decrease in fire intensity at this stage can be attributed to the combination of lower flammability in the fuel complexes involved and a decline in burning conditions (Fig. 20 and 21). At around 19:00 the fire front reached Wee Jasper Road. No other major fire runs occurred on the 11 of December. The large eastern flank that developed from the previous night’s burning had been contained through backburning along Masons Road, although there were a large number of spot-overs that were contained.

19:00 to 23:59

Air temperature: 16 - 23°C; RH: 55 - 73%; 10-m wind speed: 0 - 38 km/h (NW); FFDI: 0 - 10

Nighttime operations were dominated by backburning to contain the day’s expansion and spot fires east of Wee Jasper Road, as well as consolidation of the southern perimeter along Argalong Road.

12 December 2006

00:00 to 23:59

Air temperature: 8 - 21°C; RH: 63 - 100%; 10-m wind speed: 0 - 63 km/h (E); FFDI: 1 - 8

Throughout the 12 of December much of the fire activity occurred along the southwest section of the fire, starting in the early hours of the morning under the influence of an easterly wind. The easterly wind caused much of the uncontained fire edge on the south-western perimeter to spread in a westerly direction. The northern most of these runs caused the staging area near the intersection of Billopoola, Brindabella, and Bombowlee Creek Roads to be relocated. This area was burned over soon afterwards. Most of this run burnt as a surface fire in 23 year old thinned and pruned pine.

Much of the documented fire runs were surface fires of moderate intensity, with episodic slope driven crown fire runs. Fire spread potential on the 12 of December was lower than in the previous days, mainly due to an increase in fuel moisture content. Various backburns were conducted along the western edge of the fire and around the Ballards property (house and structures), making it difficult to determine what areas burned as a result of backfires or the original fire growth.

13 December 2006

00:00 to 23:59

Air temperature: 8 - 30°C; RH: 38 - 100%; 10-m wind speed: 0 - 37 km/h (variable); FFDI: 1 - 14

The 13 of December was characterized by a combination of moderately low fuel moisture contents and low wind speeds. The southwestern corner of the fire was again the area of greatest concern from a suppression standpoint, with crews most active with property protection around Ballards and Culbura properties. The increase in fire behaviour in this area resulted in spotting to the south of the main fire and crown fire activity around 16:00 in 18-year old pine plantation.

14 December 2006

00:00 to 23:59

Air temperature: 11 - 31°C; RH: 32 - 100%; 10-m wind speed: 0 - 66 km/h; FFDI: 1 - 26

The fire was essentially contained by the overnight backburning and perimeter widening. Suppression forces were used to deepen containment lines, patrol the perimeter and conduct fill- in burning operations.

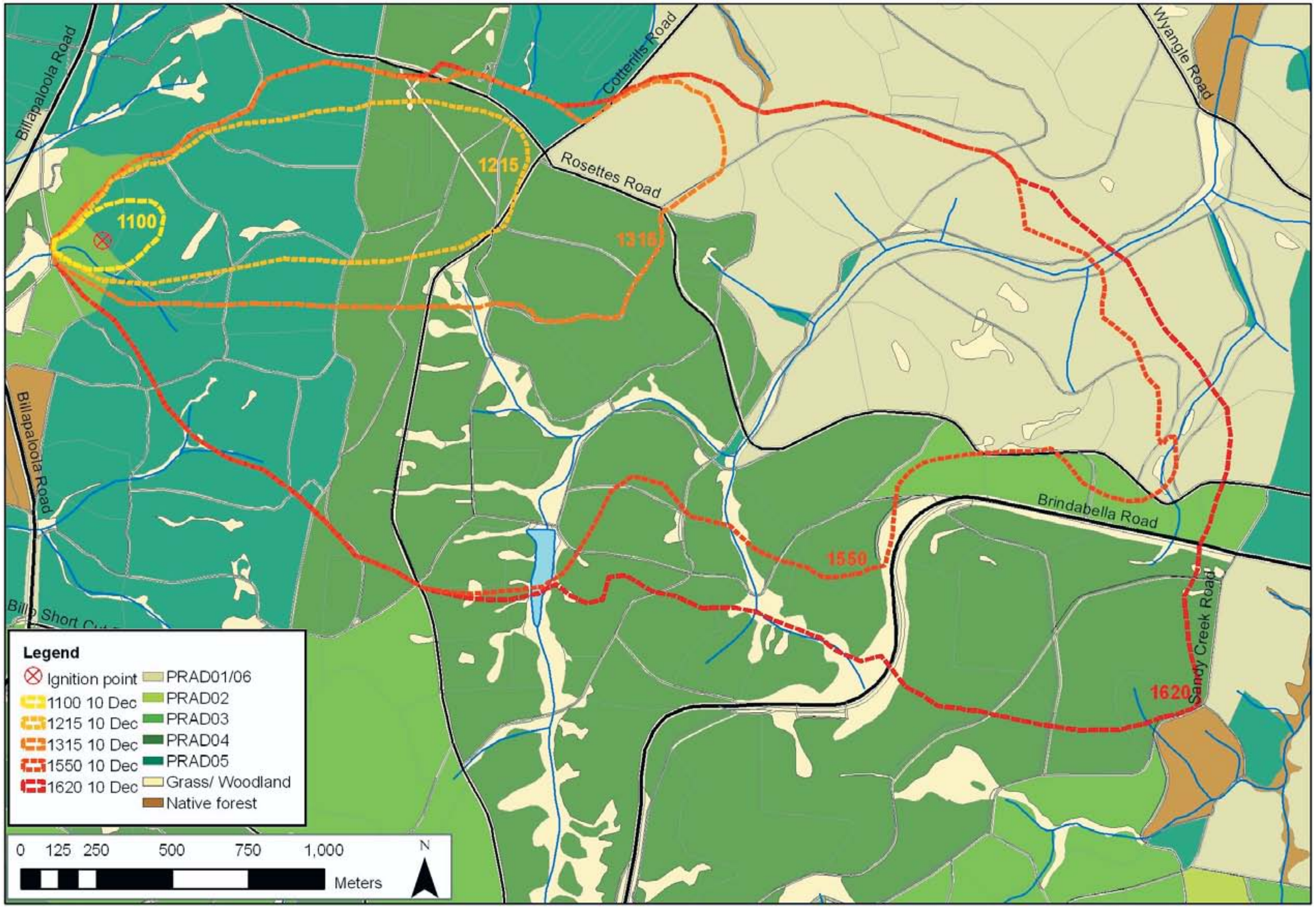

Figure 22. Map of fuel complexes and progression of fire perimeter from the origin of the Billo Road Fire up to 16:20 on 10 December 2006.

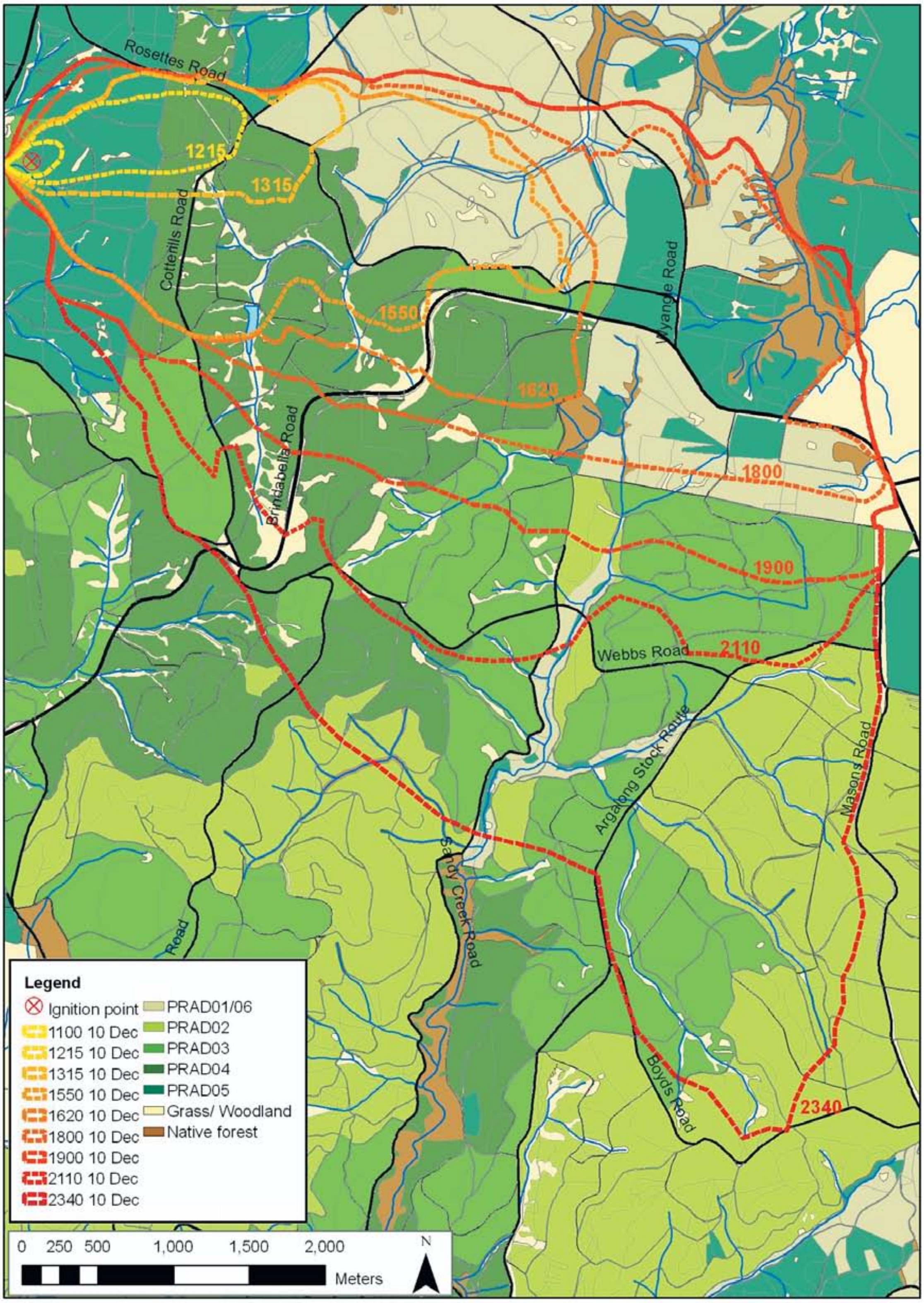

Figure 23. Map of fuel complexes and progression of the fire from ignition of the Billo Road Fire up to 23:40 on 10 December 2006.

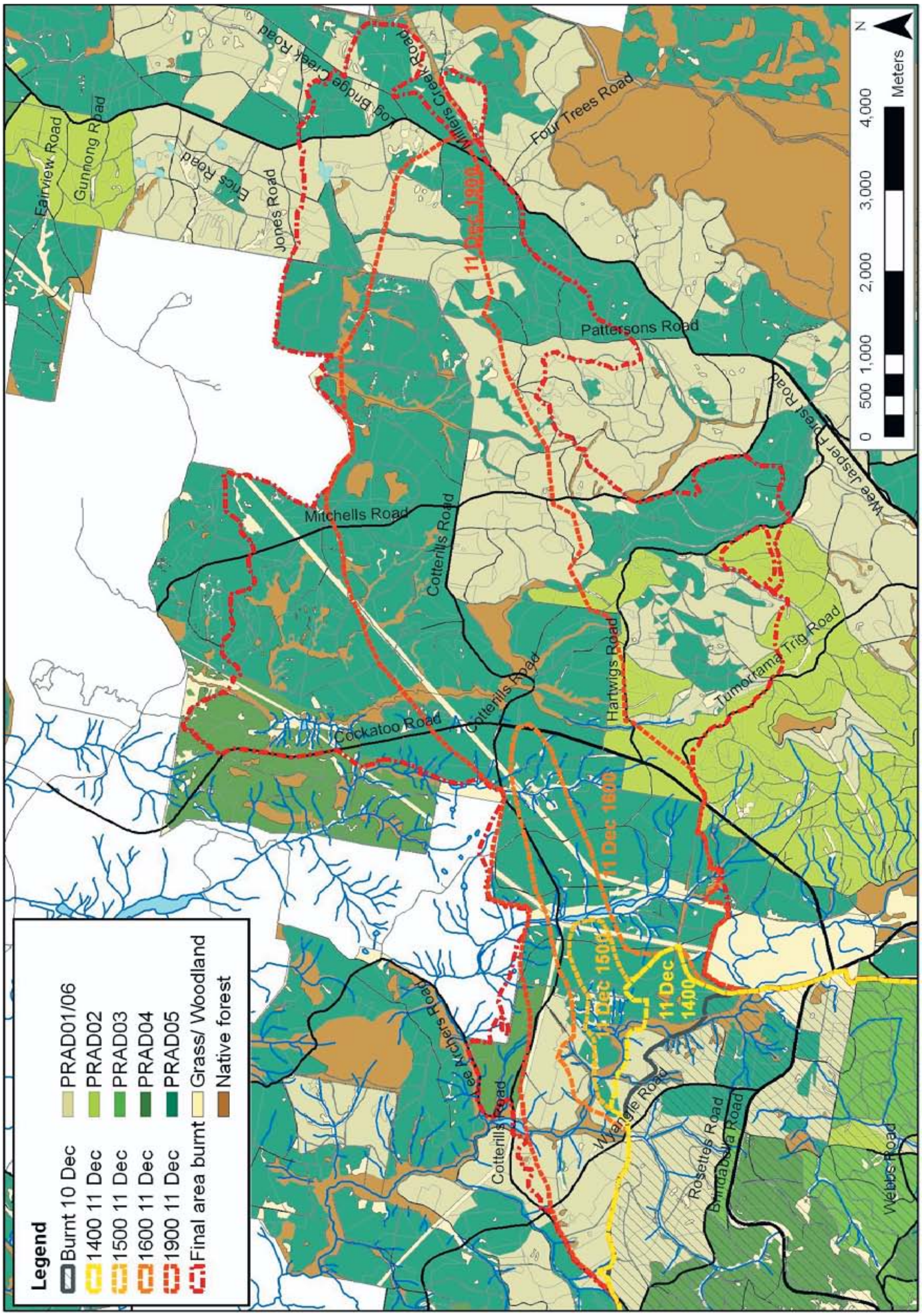

Figure 24. Map of fuel complexes and progression of the fire perimeter of the main run of the Billo Road Fire up between 14:00 and 19:00 on 11 December 2006.

Figure 25. Fire spreading accross recently planted radiata pine compartments (PRAD01) at 15:42 on 10 December 2006. The burning of the logging slash rows is noticeable. (Photo Steve Cathcart).

Figure 26. Fire crowning in 15-year old radiata plantation (PRAD04) at 15:59 on 10 December 2006. Stand height is approximately 18 m. (Photo Steve Cathcart).

Figure 27. South flank of the fire burning PRAD03 fuels along Brindabella Road at 18:42 on 10 December 2006. At 19:30 this flank turned into the main active flame front. (Photo Steve Cathcart).

Figure 28. Fire crowning and spotting across 200 m wide fuel break at 14:58. This was the start of the northeastern run of the Billo Road Fire on the 11 of December 2006. (Photo Steve Cathcart).

Figure 29. Spot fires in radiata pine logging slash (PRAD06 fuels) at 18:54 on 11 December 2006. (Photo Steve Cathcart).

Figure 30. Extent of flaming combustion in radiata pine logging slash (PRAD06 fuels) at 18:50 on 11 December 2006 (Photo Steve Cathcart).

7. FIRE BEHAVIOUR ANALYSIS

In this section we aim at analyse the factors that lead to high intensity runs and large rates of area and perimeter increase associated with the Billo Road Fire. Personnel involved in the suppression of the fire commented on the level of fire behaviour observed in the first and second day runs was not expected given the actual calculated fire danger indices. Through an understanding of the behaviour of the main fire runs we want to assess in a general sense the adequacy of existing fire danger models in anticipating the level of fire behaviour that occurred and the value of fire behaviour models in describing it. The location of the flame front at different times (Figs. 22 to 24) was the basis to individualise the fire propagation or burning periods (Table 6). For each fire propagation period we determined the fuel types involved in the propagation of the main flame front, type of fire activity, and perimeter and area statistics (Table 6). For selected periods where the most significant fire behaviour occurred, we determined the representative fire weather conditions, and computed the associated rate of fire spread and intensity (Table 7 and 8). A map of canopy damage was produced from an analysis of Landsat images. In the standing forest (radiata pine fuel stages PRAD02 to PRAD05 and native forest), three classes of damage were considered: green canopy (i.e., little or no canopy damage), canopy scorched and canopy consumed or flame defoliated. Based on this classification we divided the burn area in the standing forest into three levels of fire severity: low intensity surface fire (green canopy), moderate to high intensity surface fire (canopy scorched), and crown fire (canopy consumed) (Fig. 31). Total surface fuel consumption was assumed in the remaining fuel complexes -- i.e., grassland and PRAD01/06 fuel types (Figs. 40 and 41). This analysis framework allowed us to discriminate the type of fire activity per burning period per fuel complex (Figs. 31, 32 and 33). Detailed analyse of the fire behaviour in the selected burning periods follows.

Burning period 2: 11:00 – 12:15, 10 December 2006

At the start of this period the alignment of wind speed and slope, with an expected acceleration of wind on exposed slopes lead to a gradual increase in fire behaviour. The level of fire activity went from a high intensity surface fire, to the occasional torching of individual trees, followed by sustained crown fire propagation characterized by narrow crown fire runs. The crowning and the increase in spotting activity made direct attack unsafe and ineffective, and lead to the fire breakaway. Although the actual calculated FFDI at Bondo WS was only 14, the increase in wind within the windward exposed slope would have resulted in a locally higher value. At the time, the fire was spreading in an unthinned mature (PRAD05) pine stand that could be classified as PRAD04 due to the large amount of ladder fuels connecting the surface and crown fuel layers. Following the onset of crowning, the dynamics lead to an extreme escalation in fire behaviour with down slope crown fire runs and feedback winds which in turn lead to groups of trees being snapped off and blown down. For this burning period, the average rate of fire spread was 19 m/min (1.1 km/h) driven by a wind speed of 17 km/h and a estimated fine dead fuel moisture content of 7%. Within PRAD04 fuel complex the fire spread mostly as a crown fire whereas in PRAD05 fuel complex, crowning accounted for 37% of the area burned with moderate to high intensity surface fire accounting for 55% of the area burned (Fig. 32.a)

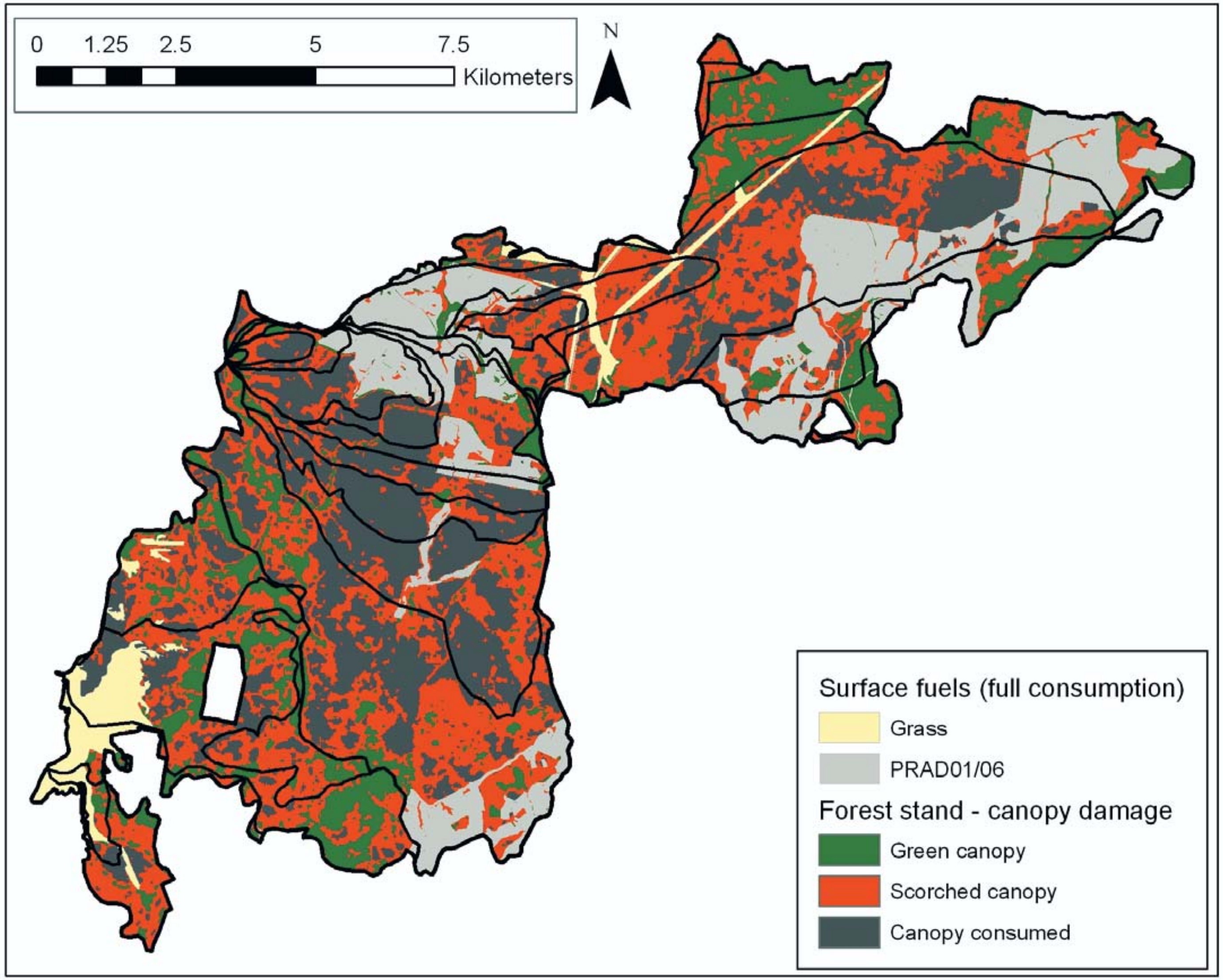

Figure 31. Fire severity (normalized burn ratio) map for the Billo Road Fire. See appendix 2 for details of derivation.

Table 6. The time interval and duration the burning period, fuel complexes, type of fire activity and fire size and growth characteristics associated with selected burning periods of the Billo Road Fire.

Burning period	Time	Duration (hh:mm)	Fuels	Fire activity	Perimeter (km)	Perimeter growth rate (km/h)	Area burned (ha)	Area growth rate (ha/h)
10/12/2006								
BP1	24:00-11:00	11:00	PRAD05, PRAD03	Low to moderate intensity surface fire	0.9	0.1	5.7	0.5
BP2	11:00-12:15	1:15	PRAD05, PRAD04	Crowning and spotting	3.6	2.1	65	47.1
BP3	12:15-13:15	1:00	PRAD05, PRAD04	Crowning and spotting	5.4	1.7	134	69.8
BP4	13:15-15:50	2:35	PRAD06, PRAD04	Crowning and spotting	9.7	1.7	439	118.0
BP5	15:50-16:20	0:30	PRAD04, PRAD03	Crowning and spotting	10.2	0.9	565	253.2
BP6	16:20-18:00	1:40	PRAD06, PRAD01, PRAD04, PRAD05	High intensity surface fire and crown	15.2	3.0	1001	260.9
BP7	18:00-19:00	1:00	PRAD01, PRAD02, PRAD03	Surface and intermittent crown fire	15.9	0.7	1331	330.2
BP8	19:00-21:10	2:10	PRAD02, PRAD03	Crown fire	17.7	0.8	1629	137.4
BP9	21:10-23:40	2:30	PRAD02, PRAD03	Crown fire	21.8	1.6	2447	327.1
11/12/2006								
BP10	23:40-14:00	14:20	All	Surface fire	34.3	0.9	4476	141.5
BP11	14:00-15:00	1:00	PRAD05	Surface and occasional crown fire	35.9	1.6	4581	105.0
BP12	15:00-16:00	1:00	PRAD05	Surface and intermittent crown fire	40.5	4.6	4819	237.9
BP13	16:00-19:00	3:00	PRAD01, PRAD05, PRAD06	Surface and crown fire	56.7	5.4	7110	763.9
12/12/2006								
BP14	19:00-11:00	18:00	All	Surface and occasional crown fire	82.4	1.4	9370	125.5
BP15	11:00-19:00	8:00	All	Surface and occasional crown fire	87.9	0.7	10935	195.6
13/12/2006								
BP16	19:00-15:00	20:00	All	Surface and occasional crown fire	93.9	0.3	11156	11.1
BP17	15:00-16:15	1:15	PRAD04	Surface and crown fire	97.4	2.7	11232	60.6
15/12/2006								
BP18	15:00-11:00	18:45	PRAD02, PRAD03, PRAD04	Surface fire	104.6	0.4	11513	15.0

Table 7. The time interval, fuels complexes, weather conditions (from Bondo weather station, FNSW), and the estimated rate of fire spread and fireline intensity associated with selected burning periods of the Billo Road Fire.

Burning period Fuel complex	Air temp. (C)	RH (%)	Wind speed (km/h)	Wind direction (°)	Observed rate of spread (m/min)	Peak fireline intensity (kW/m)
10/12/2006						
BP2 (11:00-12:15) PRAD05, PRAD04	32	40	17	250	19 (1.1 km/h)	10 200 – 13 000
BP3 (12:15-13:15) PRAD05, PRAD04	33	38	19	223	8 (0.5 km/h)	5 000 – 6 200
BP4 (13:15 - 15:50) PRAD06, PRAD04	31	39	17	254	10 (0.6 km/h)	6 300 – 15 700
BP5 (15:50 - 16:20) PRAD04, PRAD03	32	35	18	262	37 (2.2 km/h)	20 100 – 23 200
BP8 (19:00 - 21:10) PRAD02, PRAD03	27	39	6	174	6 (0.4 km/h)	3 300 – 4 100
BP9 (21:10 - 23:40) PRAD02, PRAD03	23	46	2	53	21 (1.3 km/h)	11 500 – 14 200
11/12/2006						
BP12 (15:00 - 16:00) PRAD05	26	48	44	235	41 (2.5 km/h)	64 800
BP13 (16:00 - 19:00) PRAD05, PRAD06	23	53	39	236	39 (2.3 km/h)	31 300- 61 500

Fireline intensity (I_B) calculated as per Byram (1959): $I_B = ROS \cdot w_a \cdot h_c$; with *ROS* being the rate of fire spread (m/sec), w_a the fuel available for flaming combustion (kg/m^2) and h_c the average heat content of fuel particles (18 000 kJ/kg).

Burning period 3: 12:15 – 13:15, 10 December 2006

At the beginning of this period, the fire had an estimated perimeter of 1.7 km and had burned 134 ha. The leading flame front had a width of 0.5 km and was burning in two distinct fuel types, PRAD04 and PRAD01. Within this time period the fire burned simultaneously in the PRAD04 thinned and unthinned stands as either a high intensity surface fire or as a crown fire (Fig. 32.b). The burn pattern identified in the post-fire survey and through analysis of aerial photography indicated passive crown fire spread. Analysis of the crown damage did not identify differences in fire behaviour between the two treatments. In the PRAD01 compartment, fire was spreading essentially by short range spotting with relatively high rates of spread (10 m/min or 0.6 km/h). Flame heights were moderate (Fig. 25), but the large amount of fuels burning in the windrows limited any direct suppression action. In this period, wind speeds averaged 19 km/h and fine dead fuel moisture content was estimated at 6%, for an FFDI of 16. Rate of spread in the PRAD04 stand averaged 8 m/min (0.5 km/h).

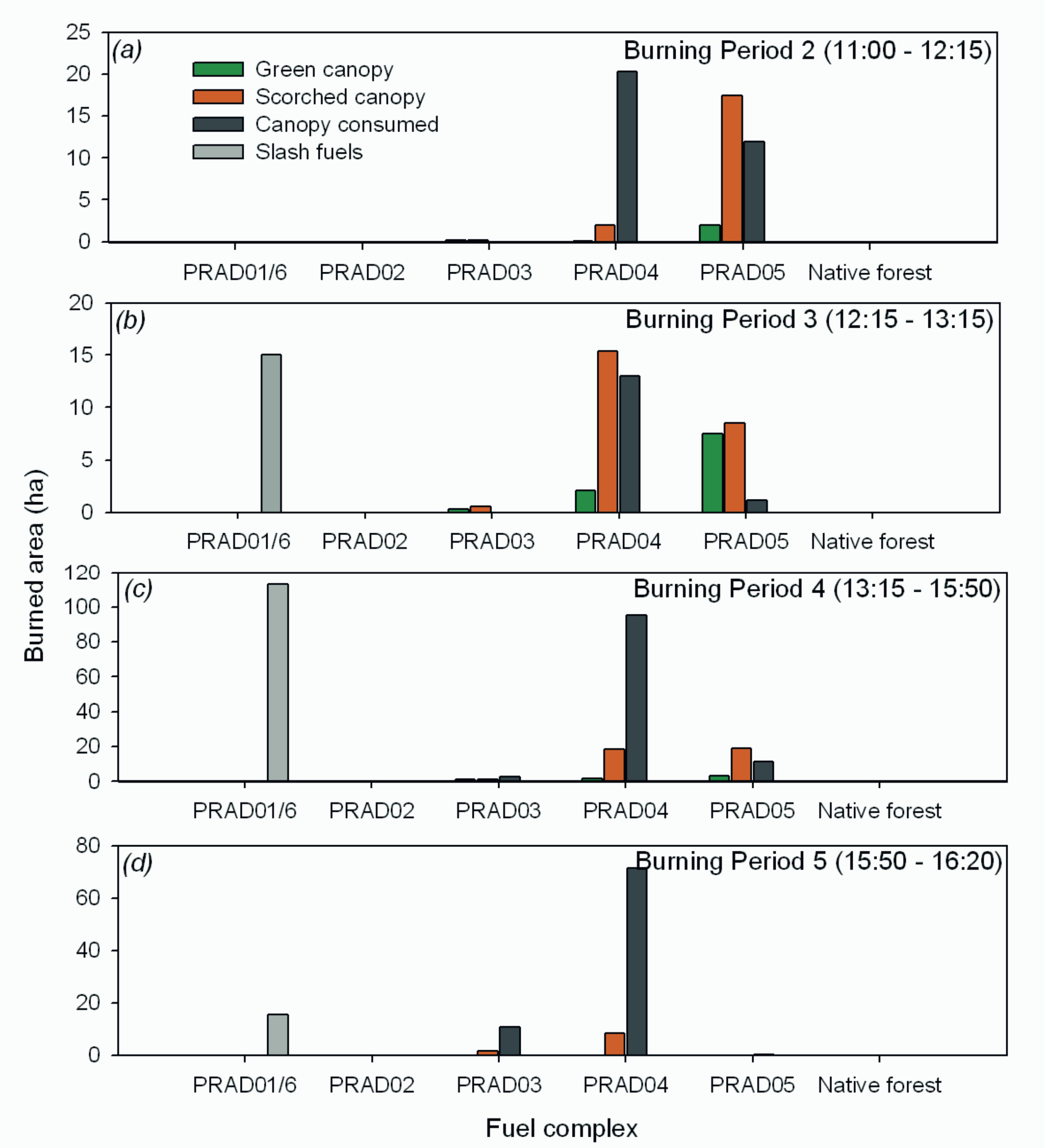

Figure 32. Area burned per type of fuel complex and canopy fire severity class for selected burning period of the Billo Road Fire on 10 December 2006.

Burning period 4: 13:15 – 15:50, 10 December 2006

The fire developed two separate main fronts, one spreading in a young plantation (PRAD01) and another burning in PRAD04 fuels. Fire weather conditions (average wind speed of 17 km/h; fine dead fuel moisture content of 5%; and FFDI of 14) and the associated fire behaviour in PRAD01 (average rate of spread of 12 m/min or 0.7 km/h) were similar to the previous burning period. The flame front entered several PRAD04 unthinned stands and spread as an active crown fire (Fig. 26) with full crown fuel involvement. Simultaneously, south of the ignition point, a series of upslope crown fire runs caused a substantial increase in the fire perimeter burning with high intensity. Within this period 80%, of the fire spreading in standing plantation was classified as crown fire (Fig. 32c). The fire perimeter increased at a rate of 0.9 km/h, with the fire tripling its size. At 15:50 the estimated burned area was 439 ha.

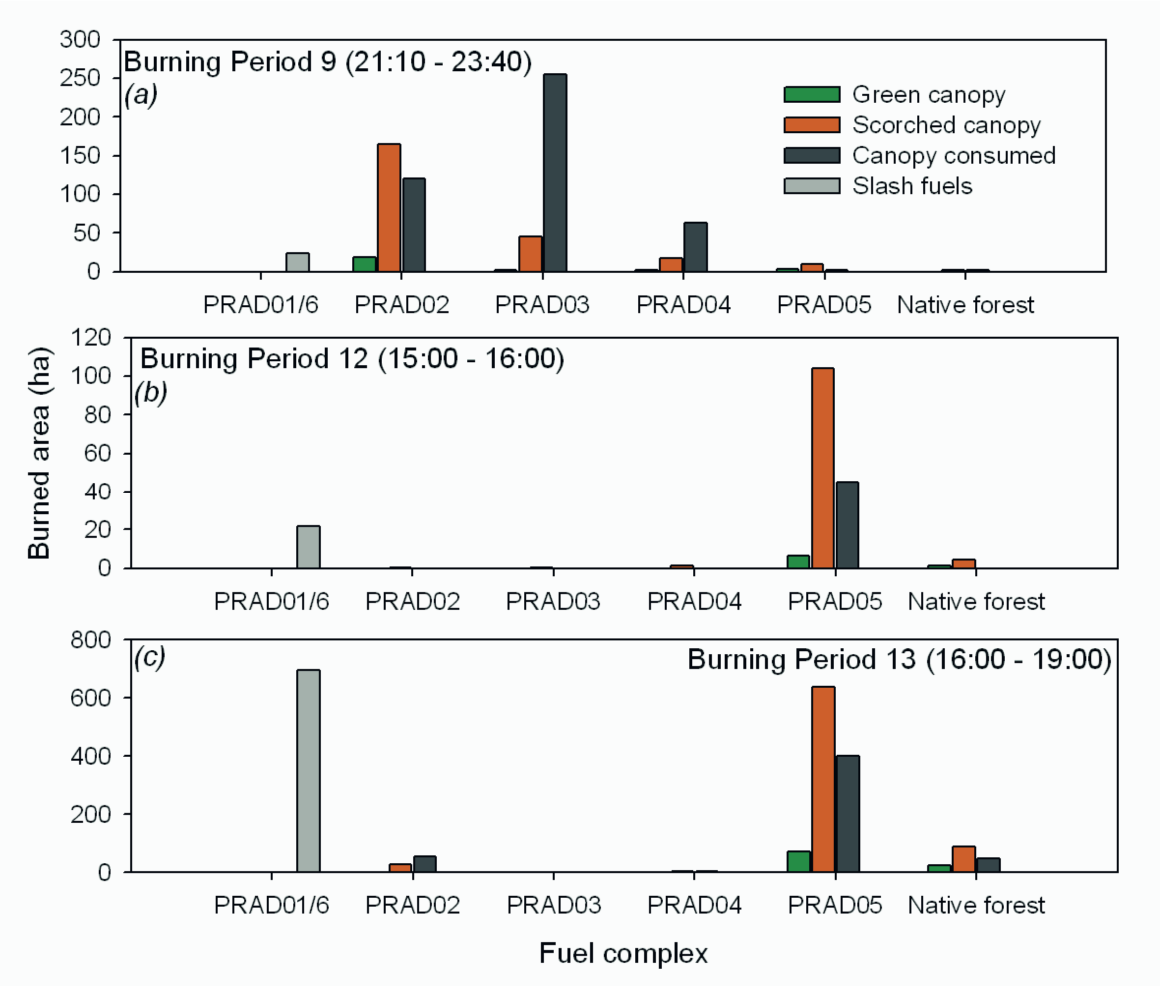

Figure 33. Area burned per type of fuel complex and canopy fire severity class for selected burning period of the Billo Road Fire on 10-11 December 2006.

Burning period 5: 15:50 – 16:20, 10 December 2006

Within this period the wind direction shifted slightly to the west-northwest. The fire made an intense upslope crown fire run in a 13-year old unthinned stand (PRAD03/PRAD04 fuels) with an average rate of spread of 37 m/min (2.2 km/h), the wind speeds averaged 18 km/h and the fine dead fuel moisture content was estimated to be 5%. This run followed the previous time period of crowning activity (Fig. 32d). Fire behaviour subsided in the PRAD01 fuels in the north-easterly portion of the fire.

Figure 34. Post-fire view of canopy fire severity mosaic in the Billo Road Fire. Ignition occurred in the area within the top left corner of the photograph. The crown fire patterns shown in the background occurred as a result of fire spread on 10 December 2006.

Figure 35. Post-fire view of PRAD05 understorey with combination of green and scorched overstorey canopies.

Figure 36. Post-fire view of an open PRAD05 fuel complex exhibiting a fully scorched overstorey canopy.

Figure 37. Post-fire view of PRAD05 stand that sustained passive crown fire spread. The lower canopy portion of the canopy was consumed while the upper portion of the canopy was only partially consumed.

Figure 38. Post-fire view of surface fuel consumption in an unthinned 18-year old radiata pine (PRAD04) stand.

Figure 39. Post-fire view of full canopy fuel consumption in a PRAD05 stand.

Figure 40. Post-fire view of surface fuel consumption and crown “freezing” in a PRAD01 stand.

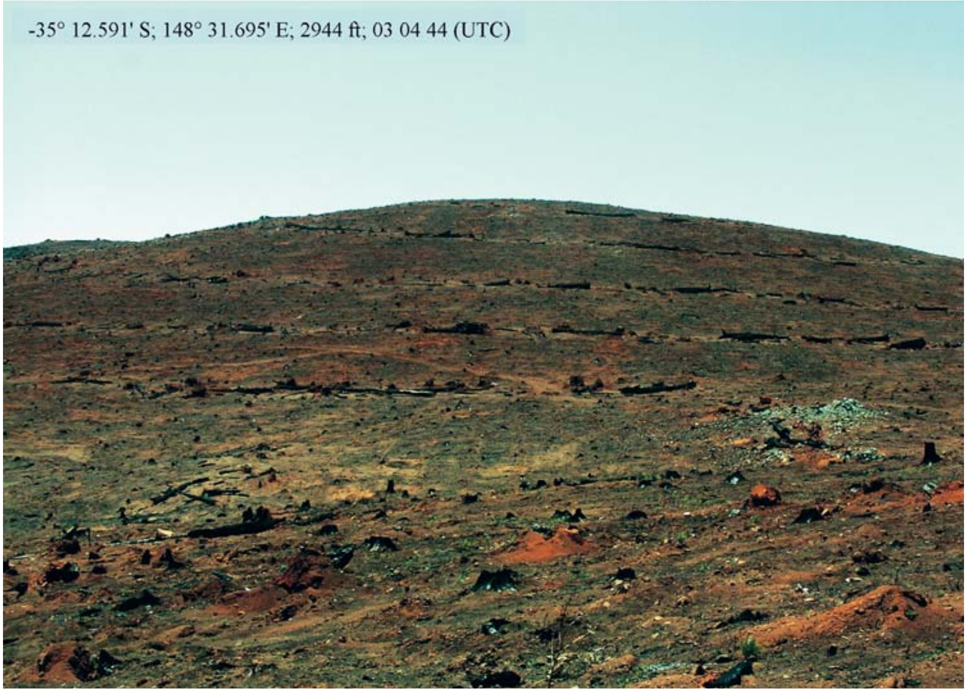

Figure 41. Post-fire view of surface fuel consumption in a PRAD06 stand.

Burning period 9: 21:10 – 23:40, 10 December 2006

After a peak FFDI of 26 at 16:40 there was a continuous abatement of fire potential (Fig. 20). Nonetheless, the fire made an unexpected crown fire run towards the south under a light northerly wind. This run was driven by a combination of low fuel moisture contents (9%) and the high flammability characteristic of fuel complex PRAD02 and PRAD03. Within this period, the wind speeds measured at Bondo weather station were quite low (~2 km/h with maximum winds averaging 11 km/h[2]. Under an estimated FFDI of 6, the observed rate of fire spread averaged 21 m/min (1.3 km/h). It is not known if spotting activity increased the rate of spread, but the post-fire crown fuel consumption pattern suggests the fire spread as an active crown fire in PRAD03 fuels and more as a passive crown fire in PRAD02 fuels (Fig. 33a). The evidence from post-fire impacts to the overstorey canopy suggests that higher wind speeds than that reported at the Bondo weather station would have been required in order to match the presumed fire behaviour. Average wind speeds measured at the Wagga Wagga weather station during this time period varied between 9 and 11 km/h. This translates into an estimated FFDI of 7 for this period period.

Burning period 12: 15:00 – 16:00, 11 December 2006

After a period of high intensity surface fire and intermittent crowning in PRAD05 fuels, the fire spotted over a fuelbreak and made a 2.5 km east-northeast run in the fuel type. Wind speed during this period averaged 44 km/h and the estimated dead fine fuel moisture content was 7%. The FFDI varied between 13 and 22 with an average of 16. Post-fire evidence indicates that the fire spread in the PRAD05 fuel complex was a combination of high intensity surface fire (66% of the area) and crown fire (30%) runs (Fig. 33b). Most of the crowning within this burning period occurred after the fire gained momentum in native forest patches. The existence of a powerline corridor oriented northwest-southeast might also have contributed to the high rate of spread during this period due to the presence of dry flashy fuels (e.g., cured grass) and the channelling of winds along the corridor.

Burning period 13: 16:00 - 19:00, 11 December 2006

The fire continued to spread under the influence of strong west-southwest winds with an average rate of spread of 39 m/min (2.3 km/h). The main fuel contributing to the high rate of spread was logging slash (PRAD06), recent plantations (PRAD01), and mature plantations (PRAD05), including some unthinned areas. Fire spread in PRAD01 and PRAD06 fuel complexes was driven by spotting activity (Fig. 29). The fine dead fuel moisture content estimated by McArthur's (1967) guide was 8%, but in the slash fuels directly exposed to solar radiation it would have likely been lower. Post-fire observation indicated that under the prevailing weather conditions the mature fully stocked radiata pine plantations sustained crowning whereas in the thinned mature plantations the fire spread as either a high intensity surface fire with occasional torching of groups of trees or as a passive crown fire.

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[2] Although we corrected the wind speeds measure at Bondo WS to describe wind measured at a height of 10-m in the open, it is believed that this correction might not be representative of the low wind speed range, and that wind speed during this burning period might have averaged 10 km/h.

Table 8. Fire chronology of the main spread events, the associated fuel complexes and burning conditions (Bondo WS) for the Billo Road Fire.

Time (duration)	Description	Fuel complex	EFMC / Wind speed / FFDI
10/12/2006			
Overnight	Ignition by burning car during the evening of 09 to 10 December. Fire crept throughout night with low intensity.	PRAD05 PRAD03	<10% / 2 km/h / 2 (1-7)
09:20 – 11:00 (1:40)	Initial attack commences. Fire was estimated to be 6 ha. Flame heights at head fire reported to be 6 m.	PRAD05 PRAD03	7% / 9 km/h / 10 (7-12)
11:00 - 12:15 (1:15)	Fire behaviour activity increases with crowning and spotting activity in PRAD05 frustrating initial attack. Fire perimeter rate increase reaches 2 km/h; Initial crown fire run spreads at 19 m/min.	PRAD05 PRAD04	5% / 17 km/h / 14 (12-16)
12:15 - 13:15 (1:00)	Fire spotting intensely in logging slash and high intensity surface fire with intermittent crowning in thinned PRAD04. Rate of spread average 10 m/min in PRAD01 and 8 m/min in thinned PRAD04.	PRAD04 PRAD01	5% / 19 km/h / 16 (14-18)
13:15 – 15:50 (2:35)	Fire front was moving east with a rate of spread of 12 m/min in logging slash. In this fuel complex fire propagation was dominated by spotting phenomena. Fire crowning upslope in PRAD04.	PRAD01 PRAD04	5% / 17 km/h / 14 (10-19)
15:50 – 16:20 (0:30)	Crown fire develops in 13-year old unthinned stand (PRAD03/PRAD04). Rate of fire spread was 37 m/min.	PRAD04 PRAD03	5% / 18 km/h / 17 (13-19)
21:10 – 23:40 (2:30)	Nighttime crown fire run in immature plantation. Rate of spread was 21 m/min.	PRAD02 PRAD03	7% / 2 km/h / 6 (5-6)
11/12/2006			
14:00 – 15:00 (1:00)	Shortly after breaking containment lines due to spotting the fire makes a series of narrow intermittent crown fire runs in mature pine stands.	PRAD05	6% / 36 km/h / 18 (15-24)
15:00 – 16:00 (1:00)	Fire spots over 200 m wide fuel break and spreads as an high intensity surface fire with sporadic crowning activity to a full fledge crown fire. Fire rate of spread averaged 41 m/min.	PRAD05 Native forest	7% / 44 km/h / 18 (13-22)
16:00 – 19:00 (3:00)	Fire makes a long east-northeast run spreading through spotting in recently planted compartments and crowning in mature stands. Rate of spread averaged 39 m/min.	PRAD01 PRAD06 PRAD05	8% / 39 km/h / 11 (8-16)
13/12/2006			
~15:30 - ~16:30 (uncertain)	Spot fire activity north of Argalong Road was followed by a vigorous upslope 1-km long crown fire run in 18-year old pine stand.	PRAD04	7% / 9 km/h / 9 (8-13)

[1] Estimated fine dead fuel moisture content (EFMC) according to the McArthur (1967) guide.

8. ANALYSIS OF FIRE DANGER INDICES AND FIRE BEHAVIOUR PREDICTIONS

Analysis of McArthur (1967) Forest Fire Danger Index (FFDI) and the predicted rate of spread by the McArthur (1967) Forest Fire Danger Meter (FFDM) suggest that the indices and the meter failed to identify the potential for high intensity fire propagation that was observed. There are several possible reasons for this apparent underestimation of fire potential: (1) the uncertainty of the RH sensor at the Bondo WS biasing both the FFDI and FFDM to lower spread potential; (2) location of the Bondo WS anemometer; (3) the possible inadequacy of the FFDI and FFDM to describe fire dynamics (e.g., effect of fuel moisture and wind) in a fuel type distinctly different from the dry sclerophyll eucalyptus forest they are designed to represent; and (4) when considering solely the FFDM rate of spread predictions, it has been found that this model under predicts the rate of spread of high intensity wildfires by a factor of 3 or more (McCaw et al., under review).

The comparative analysis of RH readings at Bondo WS with a CSIRO weather station located at similar altitude near Laurel Hill (near Batlow in Fig. 2) revealed readings normally 10 RH percentage points lower than at Bondo. If such error existed, the FFDI was being underpredicted by 6 to 12 points at Bondo and fine dead fuel moisture content overpredicted by 1.3 percentage points. Nonetheless, the application of such a correction to the FFDI and FFDM calculations at the fire area would still not explain the extreme fire behaviour observed during the Billo Road Fire.

The main fire runs of the Billo Road Fire occurred in fuel complexes with quite distinct characteristics, from young pine plantations with a large quantity of flash fuels exposed to solar radiation and wind (Fig. 5) to fully stocked, unthinned middle age pine plantations exhibiting vertical continuity between the surface fuel layer and a dense canopy layer (Fig. 7). The FFDI and FFDM are based on fire observations in dry sclerophyll eucalyptus forests where the fuel consists essentially of “leaf, twig and bark litter with a smaller percentage of grass and low shrubs” (Cheney 1968). It is perhaps an opportune time to question the capacity of the FFDI and FFDM to assess fire potential in fuel complexes with decidedly different fuel arrangement and fire spread dynamics than associated with a dry sclerophyll eucalypt forest. Under severe burning conditions the fire dynamics in eucalyptus forest is known to be dominated by profuse, short range spotting (McArthur 1967). Fire behaviour in pine plantations have altogether different dynamics (Van Wagner 1968). In these fuel complexes, stand structure, namely the dense canopy layer, reduces wind flow in the understorey or trunk space and limits drying of surface fuels due to solar radiation. Fire spread is a function of the heat transfer from the leading edge of the flaming front to unburned fuels, a process essentially dependent on the mechanical effect of wind in bending the flame front and increasing the efficiency of radiative and convective heat transfer.

To analyse the hypothesis that the FFDI and FFDM might not be adequately describing fire behaviour potential in pine plantations we calculated similar indices and rate of spread using the models found in the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) and the Canadian Forest Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992). The Canadian FWI System components are deemed applicable to mature pine stands found in Canada. Two of the 16 fuel types in the Canadian FBP System, C-6 (conifer plantation) and S-1 (jack or lodgepole pine logging slash), describe site specific fire behaviour in fuel complexes that are structurally similar to the radiata pine stands (PRAD03 thinned to PRAD05) and logging slash found in the Buccleuch State Forest. We also calculated the rate of fire spread using the Forest Fire Behaviour Tables (FFBT) for WA (Sneeuwjagt and Peet 1985) relying on its radiata pine calibration. For this model we assume surface fuel loads of 8, 11 and 17 T/ha for PRAD03, PRAD04 and PRAD05, respectively. For these fuel complex stages the wind adjustment factors were 4, 5 and 5 (Beck 1995), respectively.

A comparative analysis of the Initial Spread Index (ISI)[3] trace with the FFDI on the 10 and 11 of December 2006 (Bondo WS data) shows that the ISI identified peaks in fire spread potential that was not captured by the FFDI (Fig. 42). This was most noticeable on the 11 December afternoon run. Reflecting on the low sensitivity to the FFDI throughout these periods, the FFDM rate of spread prediction (assuming a fuel load of 15 T/ha) never exceeded 8 m/min (0.48 km/h).

When the ISI is converted into a rate of spread prediction for PRAD03, using FBP System fuel type C-6 with a crown base height (CBH) of 1.5 m, the calculated ISI values are indicative of high rates of spread (Fig. 43). The average observed rate of spread for the main fire runs on the 10 and 11 of December and the predicted value by FFDM are also included in Fig. 43. During all the main burning periods, the FFDM (fuel load of 15 T/ha) considerably underpredicted the observed rate of spread in the pine plantation fuel complexes. The simulation for the PRAD03 fuel complex with the low CBH indicated the potential for crown fire activity and high rates of spread by midmorning on the 10 of December and possibility for extreme fire behaviour throughout the day and on the afternoon of 11 December. The rate of spread predicted for FBP System C-6 fuel type shown in Fig. 43, is indicative of the capacity of this model to identify the potential for high rates of fire spread in the pine plantations (i.e., > 30 m/min, 1.8 km/h). Fig. 44 provides a better breakdown of the predicted rate of spread using the FBP System for the main pine fuel complexes associated with the Billo Road Fire. In this simulation we considered three distinct fuel strata gaps (1.5, 10 and 16 m for PRAD03, PRAD04 and PRAD05, respectively) to describe the evolution of the vertical arrangement of the fuel complexes along the pine plantation rotation (Table 2). The S-1 fuel type in the FBP System best describes pine plantation logging slash. The system predicts a significant range of fire spread for the fuel complexes being considered. The model identified that the increase in the fuel complex vertical discontinuity with age limited the occurrence of crowning phenomena and the associated higher rates of spread in the PRAD04 and PRAD05 fuel complexes. For these two fuel stages, crowning was predicted to occur occasionally on 10 December and throughout the peak burning period on the 11 of December. For 10 December, the model identified correctly the occurrence of crown fire behaviour in the PRAD04 fuel complex during the early stages of the fire (between 11:00 and 15:00) and the potential for very high rates of spread in PRAD03 and PRAD04 fuels in the afternoon. The simulation identifies PRAD06 and PRAD03 as the fuel complexes yielding the highest potential rates of fire spread.

The predicted rate of spread using the FFBT radiata pine model for the time periods discussed above is presented in Fig. 45. This system predicted higher rates of spread than the FFDM, and identified the potential for peaks in fire spread during the morning of the 10 of December and the potential for extreme fire behaviour that occurred during the afternoon of 11 of December, although the magnitude of the observed rate of spread was overpredicted.

None of the models identified the potential for high rates of spread during the night run on the 10 of December. Although the predicted fuel moisture contents were relatively low (9% according to the McArthur (1967) guide), the light winds recorded (averaging 2 km/h) resulted in low predicted rates of spread for all models. We believe that the location of the wind sensor at the Bondo WS (Fig. 2) with a row of trees located north of the sensor, obstructed wind flow in a way that our calibration was not able to capture, thereby producing an unrealistic low wind speed. The average wind speed measured during the same time period at the Wagga Wagga weather station (situated at 200 m ASL and 90km to the west-northwest of the fire) was 11 km/h. As this was the calmest period of the night, it is reasonable to assume that similar conditions might have occurred in the fire area. The predictions of rate of spread for the various models for this time period assuming a wind speed of 11 km/h was: FFDM - 2.2 m/min (0.13 km/h); FFBT for PRAD03 - 1.4 m/min (0.1 km/h); and FBP System fuel type C-6 with a CBH = 1.5 m - 14.8 m/min

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[3] ISI is a numerical rating of the expected rate of fire spread. It combines the effects of wind and Fine Fuel Moisture Code (FFMC), a surrogate for fine dead fuel moisture content, on rate of spread alone without the influence of variable quantities of fuel (Van Wagner 1987).

(0.9 km/h). The FFDM and FFBT greatly underpredicted the observed rate of spread of 21 m/min (1.3 km/h). The Canadian C-6 model underpredicted the rate of spread by 30%.

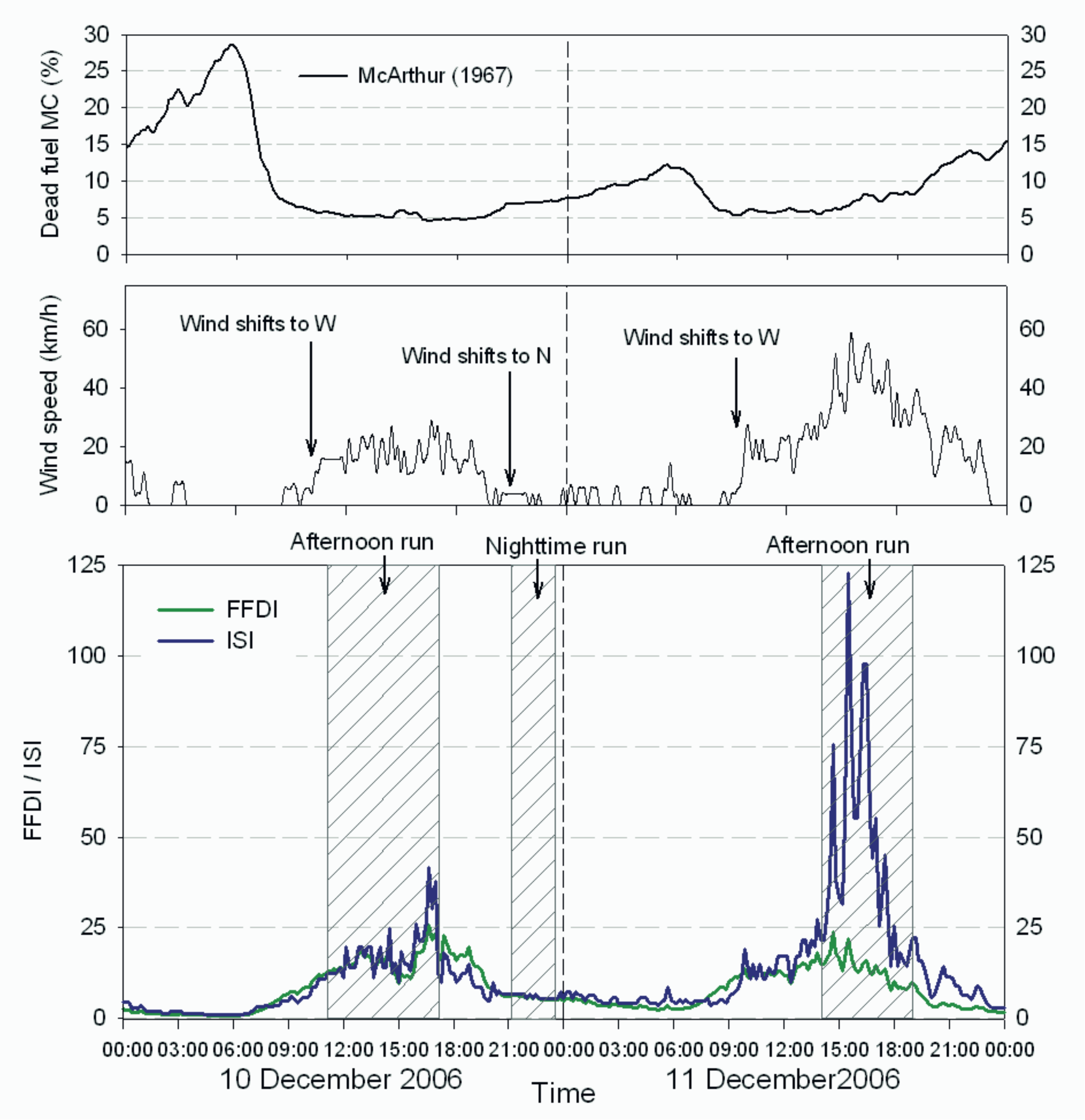

Figure 42. Diurnal trends in estimated fine dead fuel moisture content (MC), wind strength and fire potential according to the McArthur (1967) Forest Fire Danger Index (FFDI) and the Initial Spread Index (ISI) component of the Canadian Forest Fire Weather Index System for the 10 and 11 of December 2006 based on weather observations from Bondo weather station (FNSW).

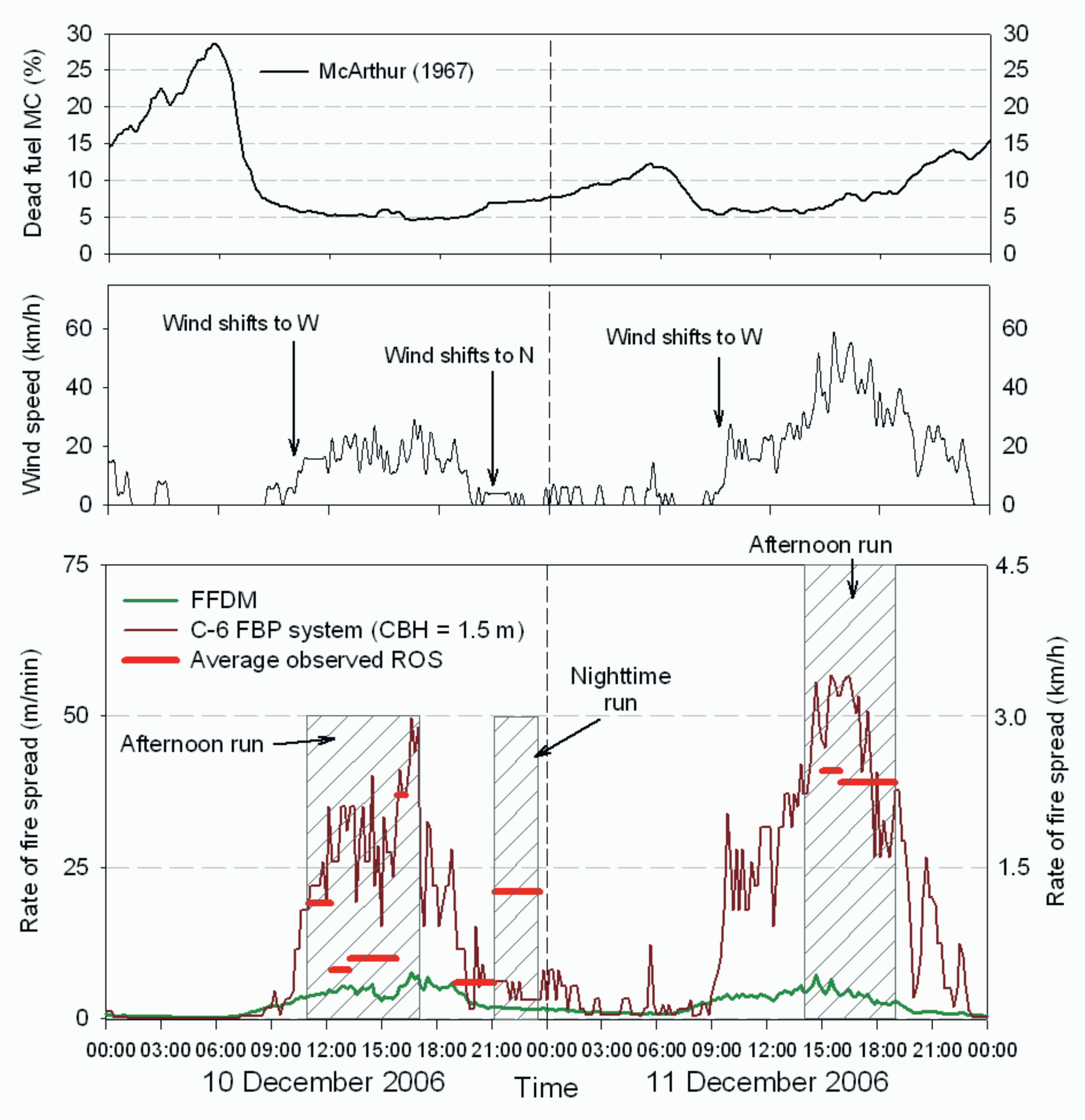

Figure 43. Diurnal trends in estimated fine dead fuel moisture content (MC), wind strength and predicted rate of spread based on the McArthur (1967) Forest Fire Danger Meter (FFDM) and the C-6 (conifer plantation) fuel type in the Canadian Forest Fire Behavior Prediction (FBP) System (assuming a crown base height of 1.5 m) in relation to the average observed rates of spread during the Billo Road Fire for the 10 and 11 of December 2006 based on weather observations from Bondo weather station (FNSW).

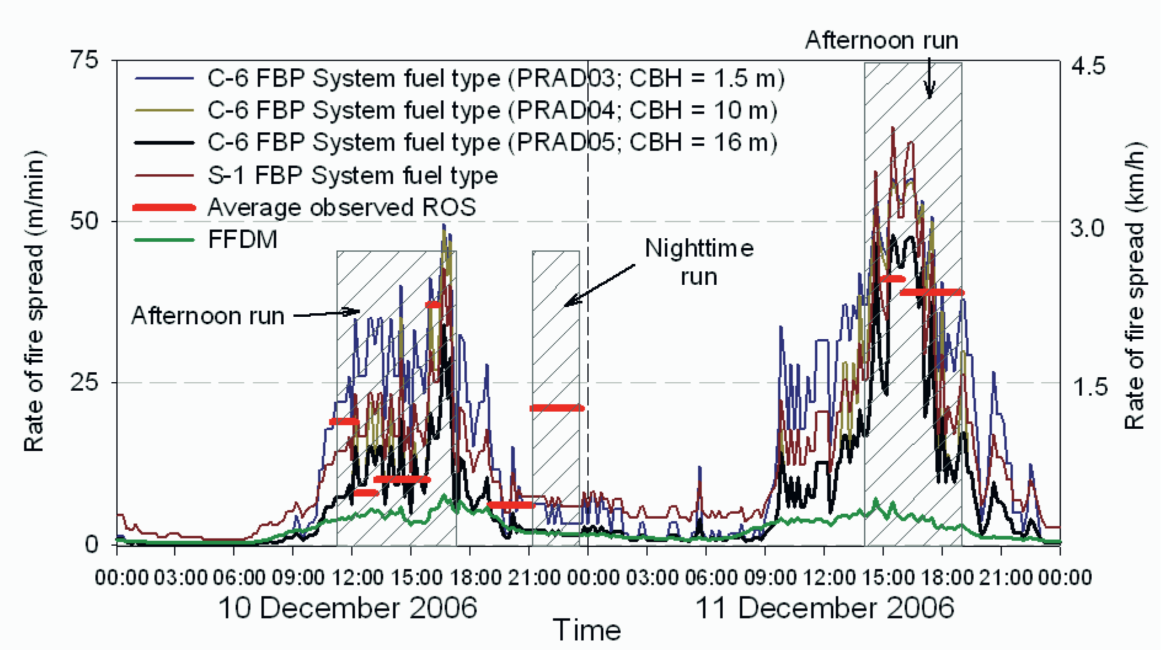

Figure 44. Diurnal trends in predicted rate of spread based on the McArthur (1967) Forest Fire Danger Meter (FFDM) and C-6 (conifer plantation) and S-1 (jack and lodgepole pine slash) fuel types in the Canadian Forest Fire Behavior Prediction (FBP) System assuming variable canopy base heights (CBH) representing different radiata pine plantation fuel complexes (i.e., PRAD03, PRAD04) in relation to the average observed rates of spread during the Billo Road Fire for the 10 and 11 of December 2006 based on weather observations from Bondo weather station (FNSW).

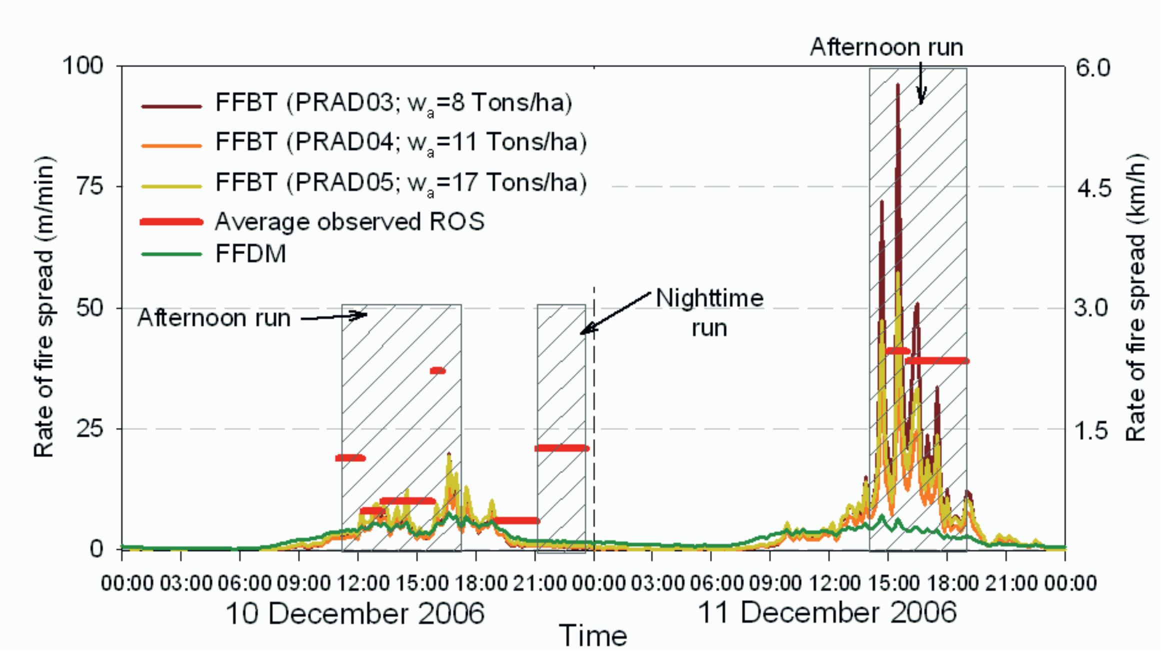

Figure 45. Diurnal trends in predicted rate of spread for the McArthur (1967) Forest Fire Danger Meter (FFDM) and the radiata pine fuel type in the Forest Fire Behaviour Tables (FFBT) for Western Australia assuming variable fuel loads representing different radiata pine plantation fuel complexes (i.e., PRAD03, PRAD04) in relation to the average observed rates of spread during the Billo Road Fire for the 10 and 11 of December 2006 based on weather observations from Bondo weather station (FNSW).

The above analysis indicate that models such as the Canadian FBP System and the FFBT give a much better indication of fire behaviour potential in pine plantations than the FFDM. The outputs from the C-6 FBP System fuel type model, considering the distinct radiata pine fuel structure stages, identified much of the increase in observed fire behaviour for the three main burning periods of the Billo Road Fire (Fig. 44). An important question to consider is this: could the FBP System have provided insight into the potential for crown fire activity and high rates of spread observed during the Billo Road Fire? This is especially important as the onset of crowning lead to a rapid step-wise increase in fire rate of spread that is not captured by the FFDM, where the increase in rate of spread is inherently gradual. We calculated the rates of fire spread for the various fire spread models from the afternoon of the 10 of December until the evening of the 11 of December based on the Special Fire Weather Forecast issued by the Bureau of Meteorology at 13:32 on the 10 of December and 06:06 on the 11 of December for the Billo Road Fire incident. These Special Fire Weather Forecasts gave predictions of temperature, relative humidity, wind speed and direction at 3 hour intervals from 14:00 on the 10 December to 20:00 of the 11 December. Fig. 46 shows the forecasted and observed weather plus the associated rate of spread predictions. The weather forecast predicted slightly higher temperatures than the ones measured at the Bondo WS. The measured RH was also higher than the predicted values, although a rigorous comparison is limited by the aforementioned problem associated with the RH sensor. Nonetheless, this possible source of error should only account for a part of the difference between the observed and predicted values. Relative to the wind speed, the forecast gave a good indication of the winds driving the first main fire run on the afternoon of 10 December and lead to an overprediction throughout the night, although the magnitude of this overprediction is questionable given the apparent inadequacy of the Bondo wind sensor to measure open winds. For the second day of the fire, 11 of December, the weather forecast correctly predicted the magnitude of the winds until 14:00 and partially underpredicted the winds driving the main fire run during the afternoon.

Both the FFDM and FFBT models underpredicted the rate of spread of the faster spreading fire runs, but adequately predicted the slower rates that occurred during burning periods 4 and 8. Burning period 5 was associated with relatively fast spreading crown fires in PRAD03 and PRAD04 fuel complexes. Based on the weather forecast, the C-6 FBP System fuel type model overpredicted the observed rate of spread (37 m/min or 2.2 km/h) for these fuel complexes by 21%. It is important to point out that the simulations presented in Fig. 46 aim to provide a general picture of the potential rate of fire spread assuming flat topography. The main fire run during burning period 5 was driven partially by slope and a site specific simulation for this case would result in a larger overprediction by the C-6 FBP System fuel type model. During the 10 December night run (i.e., burning period 9) the fire was carried mainly in PRAD02 and PRAD03 fuels. The simulation with C-6 FBP System fuel type model for PRAD03 based on the forecasted weather conditions resulted in an overprediction in relation to the observed rate of spread of 21 m/min (1.3 km/h) with predictions of 39.3 and 31.4 m/min (2.4 and 1.9 km/h) for 20:00 and 23:00, respectively (Fig. 46). The Special Fire Weather Forecast identified an increase in wind speed (40 km/h with gusts to 60 km/h) at 14:00 on the 11 December. The FFDM failed to identify this increase in wind speed as a driver for fast fire spread rates and the potential for crown fire activity. For the conditions forecasted for 14:00 and 17:00, the S-1 FBP System fuel type model predicted rates of spread of 59.7 and 31.3 m/min (3.8 and 1.9 km/h), respectively. For these conditions the simulation for the PRAD05 fuels using C-6 FBP System fuel type model in turn predicted rates of fire spread of 47.1 and 21.1 m/min (2.8 and 1.3 km/h), respectively.

The purpose of this analysis was not to evaluate the adequacy of any of the models for the situation being discussed, but rather to highlight the fact that with the Special Fire Weather Forecast and adequate models for predicting fire potential in pine plantation fuel complexes, the potential for extreme fire behaviour could have been identified hours in advance. Such knowledge could have resulted in requests for further firefighting resources and support decision making relative to selecting the best strategies to limit fire propagation during the 10 December night crown fire run and the afternoon run on 11 December. We believe that a more accurate forecast of the potential fire behaviour in pine plantations such as occurred on the Billo Road Fire would have been possible had the Canadian FBP system been applied and in turn might have lead to better firefighting strategies.

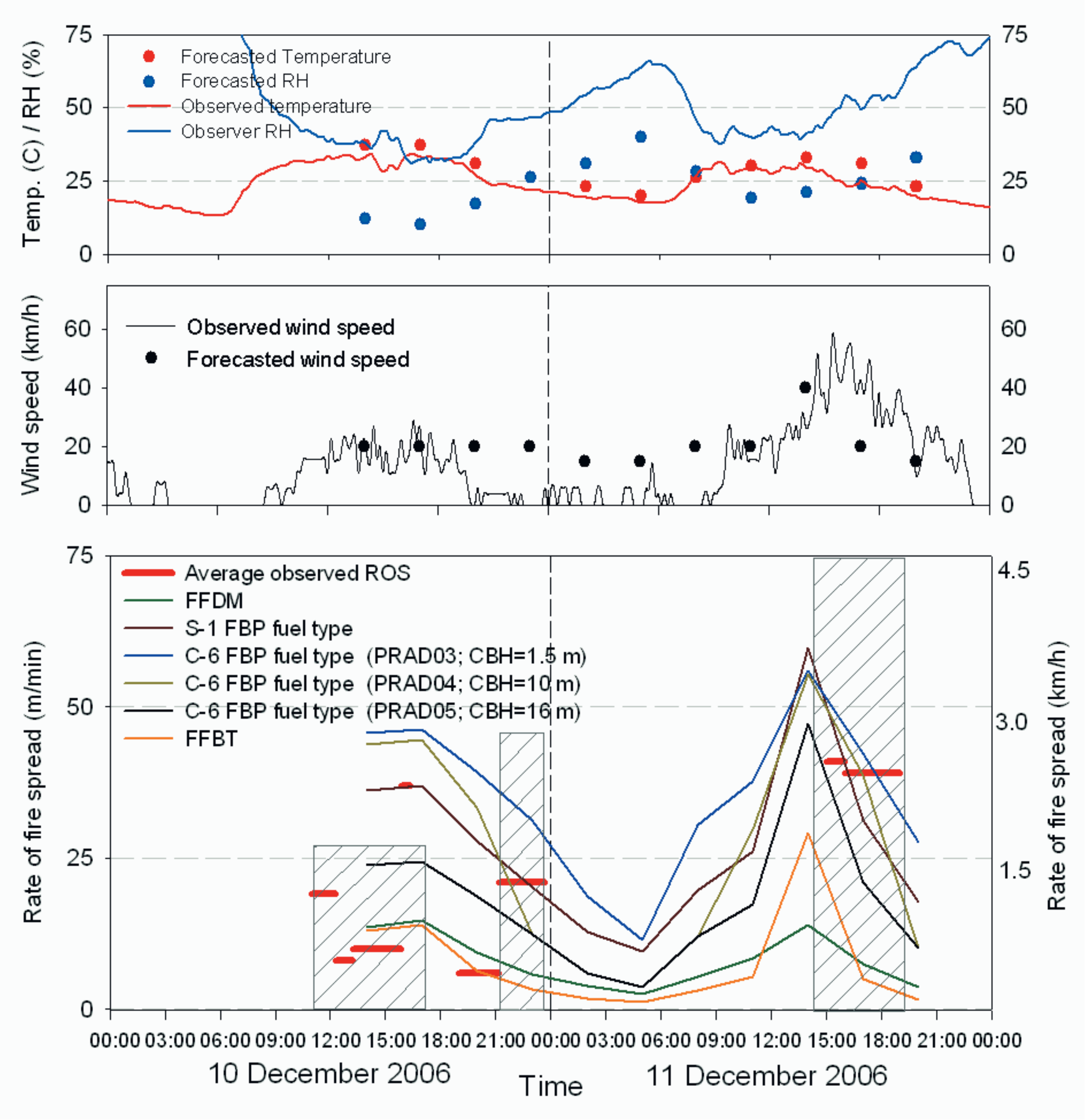

Figure 46. The observed weather at the Bondo weather station (FNSW) versus the forecasted values (Bureau of Meteorology) and the predicted fire spread rates according to the McArthur Forest Fire Danger Meter (FFDM), Forest Fire Behaviour Tables (FFBT) for Western Australia and the S-1 and C-6 (for variable crown base heights (CBH)) in the Canadian Forest Fire Behavior Prediction (FBP) System in relation to the average observed rates of spread on the Billo Road Fire for the 10 and 11 of December 2006.

9. FIRE SUPPRESSION

9.1. DETECTION

The Billo Road Fire was approximately 6 ha in size when first detected. This is a relatively large area for a fire to go unnoticed, and was much larger than the average fire size at first attack for State Forests in NSW. The large fire size at first detection can be attributed to the source and timing of the ignition. Recent research has found that the fire size at initial attack is the most important factor for determining the success of initial attack resources (Plucinski et al 2007).

The majority of wildfire ignitions that occur in the Tumut area are the result of lightning strikes. Lighting forecasts and detection systems are in place to facilitate early discovery of fires, with reconnaissance aircraft often being used to confirm fire starts. The timing and location of ignitions resulting from arson cannot be predicted with any certainty, although there are peaks in the instances of arson on Friday and Saturday nights in some areas (Australian Institute of Criminology 2007).

Most of the time new fires are only able to be detected once they begin to develop during the times of the day when the fire danger rises. For this reason, fire towers are manned during the peak burning conditions for the day. The Tumorrama fire tower, which overlooks much of the Buccleuch State Forest is normally manned from 10:00 till 19:00 during the fire season (actual hours may vary with FFDI and drought conditions). This approach has been successful. There have been no fires burning greater than 20 hectares of pine plantation in the area since records have been kept starting in 1979 (Forest Fire Management Group 2007).

The Billo Road Fire was ignited sometime during the evening of Saturday 9 December or during the early hours of Sunday 10 December. The drought conditions at the time meant that night fuel moisture conditions were lower than normal and the fire was able to spread in the litter of a 10-year old pine stand. The fire was first detected by a local resident travelling along Billopoola Road at 08:57. Had it been a weekday it probably would have been detected by a forest worker earlier in the day when the fire would have been smaller in size and weather conditions were more favourable for direct and aggressive initial attack.

9.2. INITIAL ATTACK

The timing of the ignition also affected the initial response. If the fire had started on a week day many of the local FNSW workforce and contractors would have been available to assist in the initial attack response more quickly as they would have been working in the forest nearby.

The first people to attend to the fire were two FNSW staff who live nearby and were able to report the situation back to the duty officer and suggest resources that they thought would be required to suppress the fire. There was a tanker crew and contract helicopter rostered for standby duty starting at 10:00. These were able to be assembled early to respond to the fire. Heavy equipment operators were harder to find and only one D3 dozer was on site by 10:15. A larger dozer was required to work around the front of the fire in the 16-year old plantation but did not arrive until the fire intensity built to levels that this resource could not be safely deployed to construct fireline.

Direct attack was only possible before 11:00 when the majority of the fire was burning in 10-year old pine. The large infestation of blackberries (*Rubus fruticosus* agg.) in this compartment limited crew access to the fire. An attempt was made to cut off the northern side of the head fire using a tanker and D3 dozer at 10:47 but had to be abandoned soon after when the fire's intensity increased beyond a safe working level.

At this time a group of trees were torching and short range spotting was occurring and the head fire was well within a compartment of mature pines. At that time a decision was made to pull crews away from the fire to a safe area. The intensifying fire behaviour was the result of increasing winds and an increase in slope steepness. From this point the fire made a 0.7 km upslope run. The only fuel breaks in advance of the developing fire were 2 narrow compartment tracks which were deemed to be unsuitable for establishing containment lines in the prevailing conditions.

The only fall back line thought to be wide enough to halt the easterly spread of the fire was Cotterills Road. Unfortunately, there was not enough time to backburn from Cotterills Road before the fire reached it. Crews concentrated on extinguishing spot fires that developed across Cotterills Road, but were eventually overcome by their density and had to retreat to a safe location. The next sizable break was Brindabella Road, 1.7 km away. However, once again, the fire was too intense to be controlled.

9.3. RESOURCING

The first attack resources included a tanker, some strikers[4], a light helicopter with 600 l bucket, a D3 dozer and a bulk water carrier. Additional resources continued to arrive during the day, with the first NSW Rural Fire Service (RFS) tankers arriving soon after 10:00. Resources arriving on the first day of the fire were mainly from the local area, consisting of tankers from nearby RFS Brigades and strikers and tankers from the FNSW Hume Region. A light helicopter under contract to FNSW and based in Tumut started dropping water on the fire at 09:51. However, by this time it was realised that additional aircraft would be required. A medium helicopter started working at 12:30. Two fixed-wing aircraft that were on standby at Wagga Wagga started bombing at 11:30.

The fire was declared a Section 44 emergency under the 1997 NSW Rural Fires Act at 15:30 on the 10th of December and remained in place until 20:00 on the 21st of December. This allowed for greater assistance from other parts of NSW including the supply and coordination of firefighters and vehicles as well other forms of assistance from external agencies such as police, ambulance, health service providers, power companies, and the local council. Prior to the Section 44 emergency declaration, some arrangements for further FNSW firefighting resources were in place to assist the local crews into the night and next morning. More containment line could have been constructed during the first evening had there been additional resources. The actual amount of resources working on the fire would have been adequate for the expected fire behaviour and growth based on the McArthur (1967) FFDM during this time. Most resources were assigned to backburning operations along the eastern and northern boundaries of the fire at this time, which were the priority areas for limiting fire spread into the higher value forest areas.

Fig. 47 shows the number of ground suppression resources assigned to the Billo Road Fire. These figures show the rapid buildup in the firefighting effort as local resources arrived at the fire on the afternoon of 10 December followed by resources from other areas. The peak in the amount of resources and personnel (Fig. 48) working on the fire occurred during the afternoon of 14 December and the following morning. This was when many of the local firefighters who had been working since 10 December returned to work following a day of rest after they had been replaced by out of area crews. During this peak 16 FNSW and 35 NSW and ACT RFS tankers were working on the fire along with 40 FNSW strikers. The number of resources and personnel declined once non local resources were released following containment. The number of resources remained steady after the evening of 16 of December when a second fire (the Common Trail Fire) that was also covered by the same Section 44 emergency declaration started near Tumut. A number of

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[4] A light firefighting vehicle, usually a 4 wheel drive utility, with a 400 litre tank and pump, sometimes referred to as a slip-on or category 9 tanker.

other resources were sent to the Billo Road Fire that are not listed in Fig. 47 that also had important support roles. These include bulk water carriers, command vehicles, communications vehicles, fuel trucks, and a retardant mixing facility.

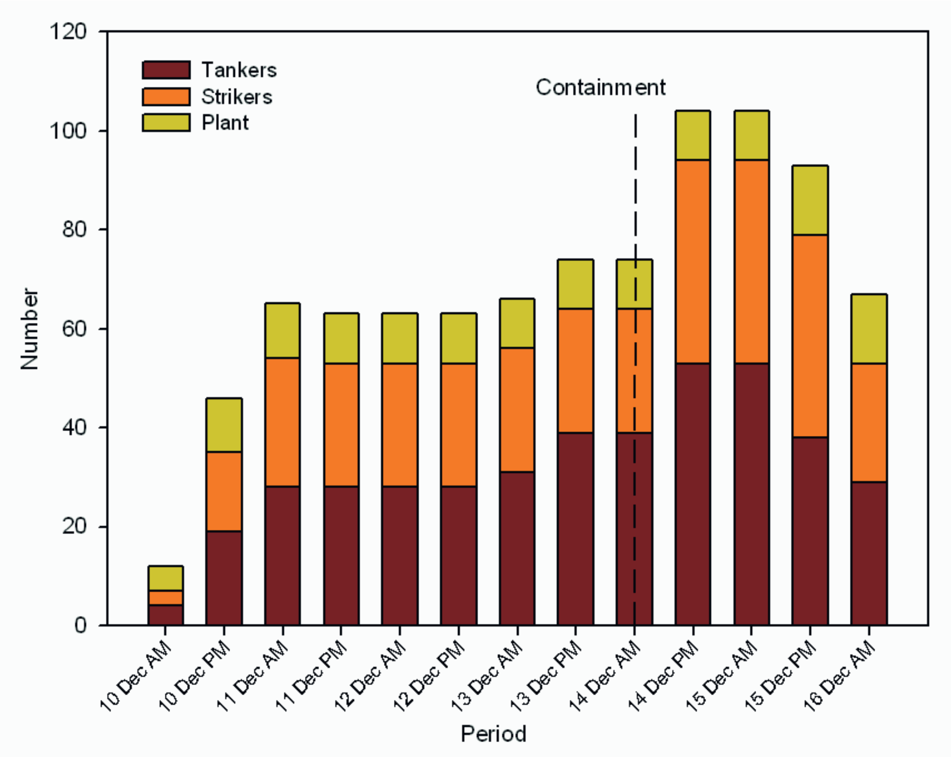

Figure 47. Number of ground suppression resources (data source ICON[5] situation reports). Plant refers to dozers and graders.

The incident management team (IMT) consisted of 11 people for the first three days of the fire and peaked at 38 on 14 December. The IMT took the structure of the Australian Interagency Incident Management System, and consisted mainly of personnel from FNSW, RFS and the NSW National Parks and Wildlife Service (NPWS). The operations and planning officers in the IMT and divisional commanders in the field mainly consisted of local FNSW staff who were familiar with the Billapoola State Forest and each other. The local knowledge of the area and timber assets held by these personnel played an important role in facilitating quick decision making for important issues such as prioritising containment strategies. The IMT coordinated requests for resources through the State Operations section of the NSW RFS. Firefighting resources that would generally be available for campaign fires in southern NSW were limited during this busy fire season, with concurrent large fires burning in the Blue Mountains and north eastern Victoria which resulted in a significant demand on firefighting resources from the wider region.

Fig. 49 shows the number of firefighting aircraft assigned to the Billo Road Fire increased rapidly. Aircraft travelled from Wagga Wagga, Canberra and Cowra to start work on the first afternoon of the fire. Additional helicopters from Sydney arrived early on the second morning. A medium helicopter that was working on the fire the first day was redeployed to another fire on the second day. One medium helicopter

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[5] ICON is the "Incident Control Online" system used by all bushfire fighting agencies in NSW. It is an automated system for the online sharing and storage of incident control documents including maps, incident action plans and situation reports.

that arrived on the morning of 11 December was grounded after only working for a few hours and did not fly again until 13 December.

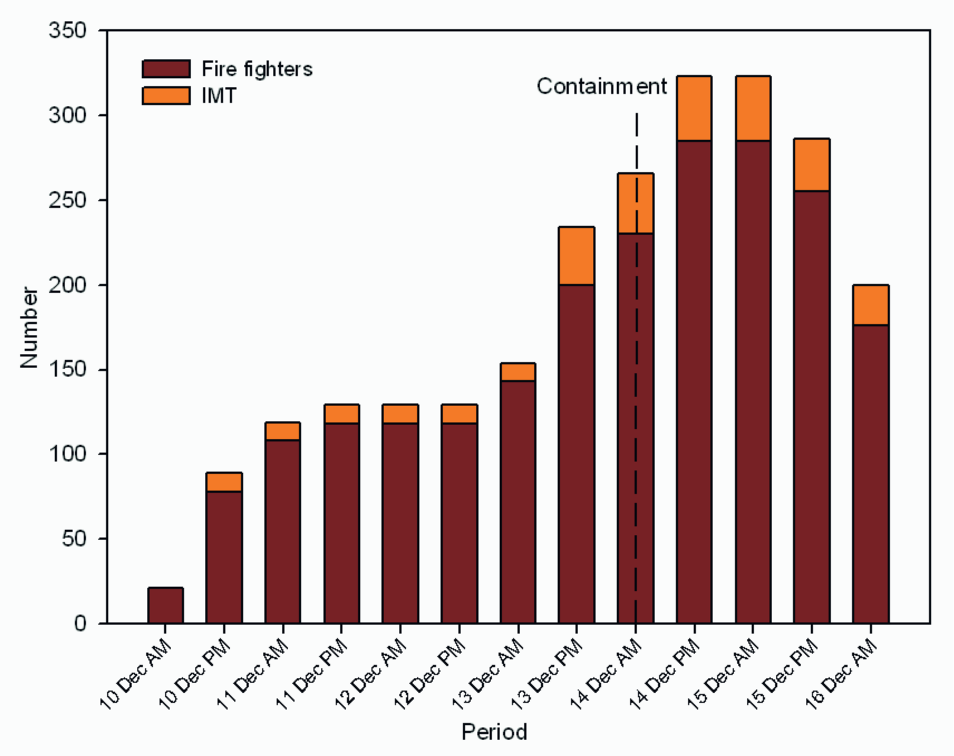

Figure 48. Number of firefighting and incident management team (IMT) personnel assigned to the Billo Road Fire (data source ICON situation reports).

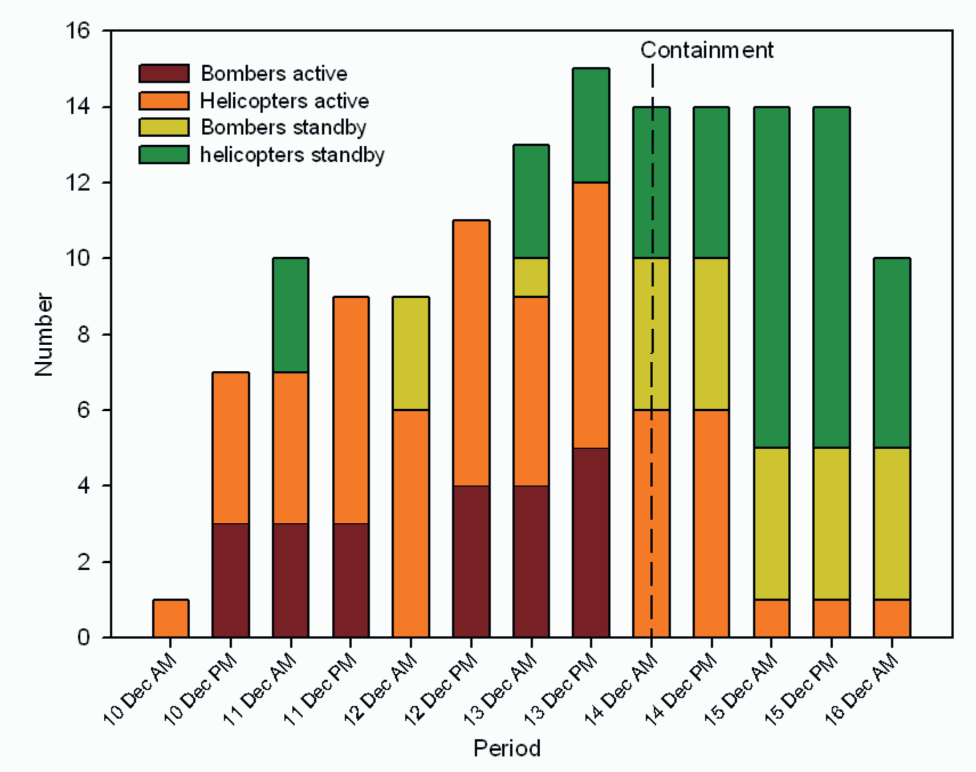

Figure 49. Number of firefighting aircraft assigned to the Billo Road Fire (data source aircraft activity lists, aircraft operations).

The number of aircraft working on the fire at any one time varied depending on the fire activity and demand as well as decisions made to conserve pilot flying hours. Many aircraft were often kept on the ground in the mornings so that pilots would have enough daily flying hours to work through the afternoon if required. The number of aircraft working on the fire peaked on the afternoon of 13 December, when a high-volume heavy helicopter and its air attack platform (light helicopter) arrived at a time when the fire was making its last run before containment. Some aircraft were released from the fire once containment had been achieved, while others were kept at the Tumut Airport in case the fire escaped containment. After 17 December most of the remaining helicopters were tasked to the Common Trail Fire.

9.4. OBJECTIVES AND STRATEGIES

Following detection the main objective for suppression was to contain the fire and stop any further damage to the plantation, other assets, and the environment. Once the fire conditions became too dangerous for direct attack, plans were made for containment using fuel breaks. The objectives listed in the incident action plans (IAP's) identified locations for establishing containment lines. These had to consider the predicted fire behaviour and spread as there were periods when many fuel breaks, such as roads, could not be used to hold the fire. Control strategies for achieving the objectives are also listed in the IAP's, as were fallback strategies. The IAP's considered the relative priorities of the different objectives and in turn the IMT assigned resources to them. The most common objective in the IAP's was to establish and consolidate containment lines by undertaking and patrolling backburns.

The most critical containment line during the Billo Road Fire was along Masons Road and Webbs Paddock. These were the only breaks suitable for defending on the first day of the fire and were used to halt the eastward spread of the fire. FNSW pine plantations extend for 12 km to the east of Masons Road. The fire reached these breaks around 18:00, 10 December (Fig. 23) after the fire intensity had started to ease as a result of a decrease in wind speed.

Part of the head fire was successfully attacked when it reached Webb's paddock near the intersection of Brindabella and Cockatoo Roads as a result of a combination of ground and air attack. The heavily grazed and open nature of this paddock reduced the fire's intensity to levels that could be directly suppressed by tankers and provided the first real opportunity for tanker crews to safely access the main fire edge and spot fires. This area became a crucial anchor point for halting the easterly spread of the fire.

Webbs Paddock was linked to Masons Road via part of Brindabella Road and the Bondo Airstrip. The fire was able to be held on these, and a backburn was lit along the western edge of Masons Road from north to south in 6-7 year old plantation. This was the main focus of the firefighting operation during the evening of 10 December and early morning of 11 December, with around 4 km of backburn lit during the night hours. Masons Road is a major gravel road with open verges. Dozers were used to widen the fuel breaks on either sides of the road ahead of the backburning. The Masons Road backburn was patrolled for the duration of the fire as it was seen as critical for stopping the fire spreading into the plantation area to the east. Many spot fires breached Masons Road on 11 December, particularly in 5 year old compartments around the intersection with Boyds Road. Quick action using helicopters, dozers, and tankers saw that all of these were contained to small sizes. Had any of these spots not been contained, they could have potentially made a sustained run like the northeastern run that took place on the afternoon of 11 December (Fig. 24). The breaches in containment responsible for this run occurred when embers ignited spot fires in slash fuels and gully lines that crews were not able to safely access once they took hold.

Many other containment lines were attempted and established using backburns around the fire perimeter. The extensive road network within the FNSW estate provided many options for containment lines, though the major roads with the widest verges tended to be used most often. Backburns were mainly ignited during the evenings and early mornings to minimise the intensity and in turn the risk of escape and were typically consolidated by tanker crews blacking out the edges before fire weather conditions increased with dozers and graders widening the mineral earth fire breaks. Unburned patches within the fire perimeter were burnt out in the first few days after containment to eliminate them as a potential source of embers. The extremely dry state of the heavy dead fuels meant that more water was required to completely extinguish them during the mop-up stage of the fire. The backburn conducted during the evening of 13 December containing the section of perimeter south of Argalong Road was supported by a number of large dozers that cleared breaks over 30 m in width. This backburn was important for keeping the fire out of areas with difficult terrain to the south.

The IAP's also identified alternate objectives and strategies, which identified fallback containment lines if the primary containment lines failed to hold the fire. These were usually roads that paralleled primary fallback lines. Plant machinery was sent to some of these roads to make sure that they were in a suitable condition for access by firefighting traffic and to increase their width.

Aside from objectives and strategies to contain the fire, another major objective was to protect structures and grazing areas on private property around and within the fire area and the FNSW depot at Bondo. Many resources were tasked to implement this strategy. In particular an 83 ha grazing property in the south western area of the fire known as "Ballards", which is entirely surrounded by the pine plantation, was completely enclosed by the fire and threatened from all sides from early on 12 December until the surrounding forest was blacked out a few days later. The protection of this property required a large number of firefighting resources which could have been used to fight other parts of the fire. The protection of other properties also occupied significant resources at the same time.

9.5. TACTICS

The firefighting tactics were determined by the objectives and strategies listed in the IAP's as well as the current and anticipated fire behaviour and weather conditions, fuels, access to the fire and available resources. Direct firefighting tactics were restricted due to the limited safe access to the fire edge. The higher stocking in medium age (5 - 15-years) plantation areas limited accessibility to most dozers. Most firefighting occurred from roads and other hard containment lines as access into compartments was often unsafe and sometimes blocked by blackberry thickets in the standing pine compartments or in logging slash in recently felled compartments. Blackberries were particularly prevalent along road verges and in pre canopy closed second rotation plantations. Most of the area burnt during the first day and night was in second rotation compartments.

Figure 50. Fixed-wing bomber attacking a long distance spot fire 17:50 on 11 December 2006 in PRAD01 (Photo Steve Cathcart).

Direct attack was limited to the first two hours of suppression, in spot fire containment and on open paddocks. Aircraft were often the first resource to work on spot fires, as they had fewer access and safety restrictions than ground resources. Once attacked by aircraft, most spot fires were extinguished using tankers followed by mineral earth containment with dozers. One noticeable exception to this tactic that occurred during the Billo Road Fire was a spot fire near the Mt Tumorrama fire tower at 17:46 on 10 December. This spot fire was ignited 3 km ahead of the main fire front in 2 year old plantation fuels. It was immediately attacked by two bucketing helicopters, which extinguished the flames and continued bucketing water onto it afterwards. This spot fire was not able to be followed up by ground crews that afternoon and could not be located on the following days. Sometimes there were too many spot fires to practically manage, while at other times heavy fuels and windy conditions limited suppression effectiveness, such as the spot fires that lead to the major run on the afternoon of 11 December.

Aircraft were more effective at directly attacking spots in open fuels such as grasslands, newly planted areas and logging slash. While heavy fuels would have limited their suppressing capability, there were instances where rapid aerial attack was able to hold initiating spots fires until dozers and tankers reached them. A good example of this occurred on 11 December at 17:50 when fixed-wing aircraft were able to hold a 1 ha spot fire (Fig. 50), burning 4 km ahead of the main fire, until dozers and tankers could access it. This spot could have resulted in a considerable expansion of the fire area.

The open paddocks were better suited to direct ground attack than the forested areas due to the lighter fuel loads which were much easier to extinguish and increased visibility and accessibility allowed for a safer approach. Despite the light fuel loads the paddocks were still able to carry fire, and were at risk of ignition from embers originating from the adjacent forest. Ember attack from adjoining forests would have threatened containment lines and caused concern for the protection of property in these areas.

Aircraft were occasionally tasked to direct attack without support of ground crews. This was done to slow the fire’s progress when it could not be safely accessed on the ground. A good example of this tactic occurred on the final run of the Billo Road Fire at around 17:00 on 13 December when the fire had crossed Argalong Road. At this time five fixed-wing aircraft, two medium helicopters and a high-volume heavy helicopter were used to narrow the width of head fire with a sustained succession of drops on the western flank.

The changing number of aircraft used for tactical and support roles is shown in Fig. 51. These numbers reflect the demand for aircraft at different stages of the fire.

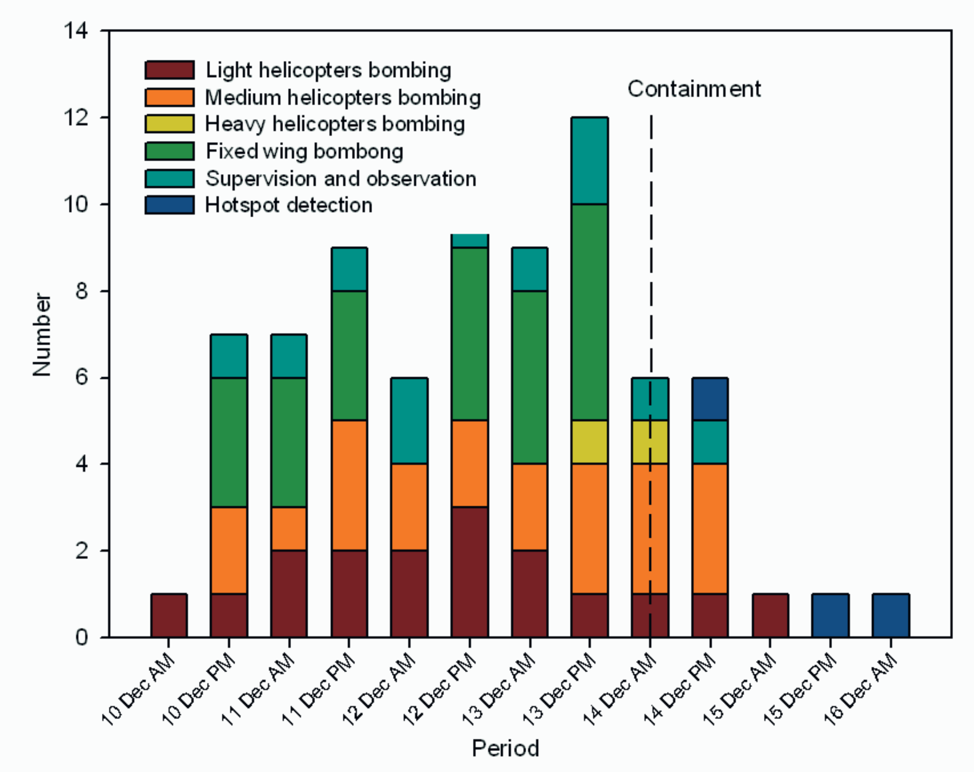

Figure 51. Roles of firefighting aircraft assigned to the Billo Road Fire (data source aircraft activity lists, aircraft operations)

Aircraft were also used to support backburning and the consolidation of containment lines, mainly by cooling down sections of fire that were generating embers. A helicopter was used for aerial ignition at 10:00 on 11 December where it ignited the top of a hill ahead of the fire to limit the intensity of the up-hill run of the fire and thereby the ember generation.

Fixed-wing bombers were also used for indirect attack when dropping fire retardant. A retardant line was laid when the first bombers arrived at the fire at 11:30 on 10 December. At this time part of the northern flank had crossed Rosettes Road on the western side of Cotterills Road. This retardant line managed to stop the northward spread of the flank in mature pine with the assistance of tanker crews and a large dozer. A retardant mixing facility was set up at Tumut Airport to support this. The retardant mixing capability was boosted when the state contracted retardant suppliers mixing truck and staff arrived at the airport later on in the fire.

Other aircraft roles were filled by light helicopters, including supervision, observation and hotspot detection. An Air Attack Supervisor was used most of the time that bombing aircraft were working. This role is primarily used to manage aerial firefighting tactics, though they also assist with observation duties, reporting on spot fires and containment breaches. At times a helicopter was dedicated to an observational role, particularly once the fire area was large and potential locations for fire escape was high. After the fire was contained, a light helicopter fitted with an infrared camera was used to detect and map hotspots that had potential to breach containment. A non-tactical line scanning aircraft was used to map the fire, showing the extent of the burnt area and areas of active burning. This aircraft was used six times, though only two missions were undertaken before the fire was contained.

Mopping-up continued for weeks after containment of the fire. Maintaining the established containment lines was particularly important on the first day of containment (14 December) as the weather conditions on this day were very similar to 10 December. Small fires started in the scorched needles that fell to the ground in the weeks following containment, presumably ignited by hot spots such as smouldering stumps. This problem was probably minimised by regular aerial infrared patrols during the early stages of containment. The fire was listed at patrol status on 19 December but not declared out until 24 January 2007.

10. CONCLUDING REMARKS AND RECOMENDATIONS

Affecting close to 10 000 ha of radiata pine plantation, the Billo Road Fire was the single largest fire in this fuel type in NSW and demonstrated the vulnerability of exotic pine plantation estates to wildfire under Australian drought conditions. Burning under a wide range of weather dependent fire danger conditions and over the full array of fuel complexes characteristic of the pine plantation rotation, this fire constituted a unique event from which to advance our understanding of fire dynamics in this fuel type and improve our capacity to implement sound fire management strategies and diminish the likelihood of similar large scale fire events occurring in the future.

The main fire runs occurred over relatively short periods, 2 to 5 hours in length, on 10 and 11 December, were characterized by extreme fire behaviour resulting from a combination of an extended period of low fuel moisture content, a landscape made up of highly flammable fuel complexes and the occurrence of relatively strong wind speed events.

Conditions contributing to the rapid rates of perimeter and area growth that occurred in the first afternoon (FFDI between 14 - 17) were the low fuel moisture contents and the spatial continuity of flammable fuel complexes, namely logging slash, recently planted areas with logging slash and unthinned immature plantations, at the landscape level. The flammability so characteristic of immature pine plantations was verified by a significant night crown fire run under relatively mild burning conditions. This constituted the second major run of the Billo Road Fire, and lead to a significant increase in the fire perimeter and area burned.

During the afternoon of the second day of the fire and under Moderate to Very High fire danger levels the fire exhibited crown fire activity in mature pine plantations (FFDI = 18; rate of spread = 41.3 m/min or 2.5 km/h) and other characteristics of extreme fire behaviour (e.g., mass spotting and high rates of spread) in logging slash (FFDI = 11; rate of spread = 39.2 m/min or 2.3 km/h).

The nature of the landscape burned by the Billo Road Fire with its covering of pine compartments representing the various radiata pine rotation fuel complex stages, presented a unique opportunity to study differences in fire behaviour in relation to different fire danger levels and fuel complex structures. The data collected in the present study allows us to link fire danger indexes with levels of fire behaviour for distinct plantation fuel complexes. The study also assisted in quantifying the fire potential associated with the most flammable stages in the pine plantation rotation.

The information gathered on fuels, weather and fire behaviour in the preparation of this report also provided a unique opportunity to investigate the adequacy of current fire danger and fire behaviour models used in Australia to assess fire potential in pine plantations. The McArthur (1967) FFDI and FFDM did not identify the potential for extreme fire behaviour observed in some of the pine plantation fuel complexes. The FFBT radiata pine model developed in Western Australia identified the potential for extreme fire behaviour that occurred on the afternoon of 11 December but failed to identify the high rates of fire spread associated with main runs in the immature plantations on the 10 of December. The level of detail of the Canadian FBP System fuel type C-6 model affords in separating surface from crown fire spread and explicitly considering the onset of crowning, allowed us (admittedly in hindsight) to adequately discriminating fire spread potential by fuel complex stages throughout these two main burning days of the Billo Road Fire.

It is becoming increasingly well known now that the McArthur (1967) FFDM has a definite under-prediction bias when applied to dry sclerophyll eucalyptus forest types under wildfire conditions (McCaw et al, in review). Nonetheless, it is not known if the under-prediction bias observed in the present study arises from that feature or from the inadequacy of the FFDM to adequately assess the fire dynamics in exotic pine plantations. Differences in the structural characteristics of the native eucalypt (e.g., open forest, low canopy bulk density, understorey vegetation) versus pine plantation forest fuel complexes (e.g., aerated surface fuel bed, vertical discontinuity and high canopy bulk density) and the specific mechanisms driving fire propagation processes (e.g., profuse spotting in eucalypt forest vs. flame front radiative and convective heat transfer in pine fuel beds), suggests that empirical fire spread models based on one fuel type are not applicable to the other.

Large fires in exotic pine plantations, such as the Billo Road Fire, are relatively uncommon in Australia. Under normal conditions, the extensive road network that characterizes these plantations allow for a rapid and effective initial attack leading to successful fire suppression while the fire is still fire small in size. Nonetheless, in the last few years, several wildfires in Australian pine plantations have illustrated the potential that exists for widespread losses. As the present case study has shown, weather conditions do not need to be particularly severe for large, damaging wildfires to occur. The occurrence such incidents can have a devastating impact on the medium and long-term sustainable yield on a State's softwood plantation estate. This disruption on the quality and quantity of timber products to local forest industries has strong repercussions on the economical and social sustainability of the local communities linked to the forest industry. This situation and current climatic trends, with the increase in the duration and severity of fire seasons, warrants the development and implementation of proactive fuel and fire management practices that limit the occurrence of large fires in exotic pine plantations. The analysis of the events associated with the Billo Road Fire coupled with other previous large plantation fires, has highlighted several shortcomings in our current understanding of fire behaviour and fire management practices in pine plantation fuel types. **A series of recommendation arise from this analysis:**

10.1. FUEL MANAGEMENT AND FIRE BEHAVIOUR ASSESSMENT

10.1.a. *Assessing fire behaviour potential in exotic pine plantations*

There is a general lack of understanding of high intensity fire behaviour in pine plantations. Fuel dynamics in radiata pine plantations are characterized by relatively fast changes in the structure of the fuel complex, resulting in fuel stages with quite distinct fire behaviour characteristics. A fire behaviour model aiming to describe this variability needs to consider the phenomena driving surface and crown fire spread. There are models available that are more suited for describing fire behaviour in pine plantations than the McArthur (1967) FFDM. **Such models along with appropriate technology transfer for the understanding of fire dynamics in pine plantations should be adopted by fire management agencies in general, and in particular agencies responsible for managing large pine plantations.**

10.1.b. *Assessing fire danger in pine plantation estates*

Fire danger information, integrating both constant and variable factors that affect the start, spread and difficulty of control of a fire, has a variety of applications, from public awareness to the communication of fire intensity and spread potential to personnel involved in fire suppression activities. Although the current FFDI is adequate for a number of fire management activities, it is not satisfactory to convey site-specific fire potential in pine plantations as might be required for presuppression activities such as fire detection planning and crew readiness, and initial attack dispatching.

Given the specificity in pine plantation fire behaviour, a danger index of fire spread and intensity potential in this fuel type is considered necessary. This could be based on the Canadian FWI System or other system (e.g., Sneeuwjagt and Peet 1985; Cruz el al. 2007). **Linkages between fire behaviour and**

fire danger indices are essential, namely the assessment of fire danger based on expected fire behaviour. Based on a fire danger classification scheme put forward by Alexander (1994), Palheiro et al. (2006) determined the ISI thresholds for fire intensity classes in pine plantations. By reflecting the expected fire behaviour such fire danger levels are readily linked to suppression difficulty, providing unambiguous information regarding initial attack resourcing and are useful to support decision making into suppression methods and strategies.

10.1.c. *Fuel management - stand level*

It is apparent that no active fuel management activities were carried out in the pine stands of the Buccleuch State Forest. The current silvicultural practices, with the first thinning occurring after age 15, lead to a rotation characterized by high flammability until the stand is about 20 years old.

What would be the necessary fuel modifications to limit fire behaviour to acceptable levels under the burning conditions experienced during the Billo Road Fire? How could a silvicultural system be modified to create a "fire resilient" stand that at the same time would meet timber yield objectives? **These questions highlight the need to develop integrated silviculture and fuel management prescriptions that meet economical, ecological and fire management objectives** (Johnson and Peterson 2005). The implementation of a landscape level fuel management program (see 10.1.d. below) requires the definition of fuel complex structures that limit fire behaviour to acceptable levels. Information collected as part of wildfire case studies like the Billo Road Fire and others (e.g., Alexander 1998; Burrows et al. 2000) combined with a modelling approach (Cruz et al. 2007) will presumably allow for the definition of such structures. Integrating this information with stand dynamics will **determine the characteristics of sustainable and economically viable "fire resilient" silvicultural systems**.

10.1.d. *Fuel management - landscape level*

At the landscape level, the Buccleuch State Forest formed a continuum of flammable fuel complexes capable of sustaining high intensity fire behaviour through long time periods. Would the strategic location of "fire resilient" stands such as conceptualised above create a less flammable landscape and preclude the development of large fires such as the Billo Road Fire? Analysis of the propagation mechanisms associated with large fires have shown the viability of this approach to reduce the size and severity of fires burning under severe burning conditions (Finney et al. 2005). **Research into the impact of fuel management on the economics, yield and sustainability of pine plantation forestry is required to assess the viability of implementing landscape level fuel management into forest management plans**.

10.1.e. *Using weather data as a decision support tool*

The local offices of Forests NSW, National Parks and Wildlife Service and Rural Fire Service have implemented a network of automatic weather stations that allow real time monitoring of weather conditions and associated fire potential. This information is then used to support decision making relative to the most adequate suppression strategies for a given fire. Nonetheless, **it was verified that these weather stations do not follow common standards for measuring weather elements, thereby producing biased information in observed fire danger, hence resulting in misleading information for planning and suppression activities, and potentially jeopardizing the safety of firefighting personnel**. In the case of the two weather stations (Bondo and Tumut) that the authors of this report inspected, the wind sensors were located close to the ground and near obstructions (e.g., buildings and row of dense trees). Wind measurements, both strength and direction, were not representative of the wind driving the fire, consequently suggesting a much more benign situation that what was really occurring. We are not sure the weather information was used in planing suppression strategies in the Billo Road Fire.

Installation of weather sensors should follow published standards (e.g., WMO 1983). The collected weather data will then more accurately reflect the weather influencing the fire propagation process.

10.1.f. *Use of fire behaviour prediction models in support of fire suppression decision-making*

The use of relevant fire behaviour models coupled with forecasted weather conditions correctly identified the observed periods of extreme fire behaviour and the associated expansion in the burned area during the Billo Road Fire. **The availability of Fire Behaviour Analysts on the Incident Management Teams trained in the prediction of fire behaviour at the landscape level are a necessity in order to define safe and effective fire suppression strategies that take into account the likely fire behaviour and growth** (Alexander and Thomas 2004).

10.2. FIRE SUPPRESSION

10.2.a. *Detection readiness level during periods of extreme drought and fire danger*

Fire detection and crew readiness levels should be stepped up during periods of extreme drought and fire danger. **The fire towers should be manned for longer hours during periods of elevated and prolonged drought** and **extreme fire danger**, particularly when these are combined with dry air masses that prevent night recovery of fine dead fuel moisture contents. This is more critical on weekends and public holidays when the forest workforce is not present.

10.2.b. *Rapid arrival of reinforcement crews*

Reinforcement crews from out of the region should be requested as soon as it is apparent that a fire is going to exceed the capacity of local suppression forces. If conditions allow, reinforcement crews should start work as soon as possible. Out of region crews need to be familiarised with the fireground and should work closely with local crews or field officers.

10.2.c. *Use of field officers with local knowledge*

It is apparent that one of the leading reasons for the success of suppression strategies during both the Billo Road and Mount David (Appendix 1) fires was the use of field officers who were intimately familiar with the plantation fuels, geography and values. FNSW field officers in command roles were able to quickly prioritise and implement suppression strategies that minimised the impact of the fire on plantation assets. **FNSW should continue to maintain a critical number of field staff with a high level of fire knowledge and firefighting competency to fill important command roles.**

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APPENDIX 1: MOUNT DAVID FIRE

On 19 December 2006, under Very High fire danger conditions the Mount David Fire burned 857 ha, 721 being radiata pine plantation. Seventy percent of the plantation area burned (497 ha) was within the Mount David State Forest (6800 ha). This fire was the largest plantation fire to occur in the Macquarie region since 1986. The close temporal proximity to the Billo Road Fire, and the extreme fire behaviour observed on two relatively short lived crown fire runs made it a case study of special interest.

The Mount David State Forest (149°35'E, 33°53'S), located in the Central Tablelands 53 km south of Bathurst, NSW, lies on an elevated plateau with grazing properties, native forest and other private pine plantations estates (Fig A1.1.). The area has an undulating topography, with elevations varying between 1000m and 1150m (Fig A1.2). Slope did not have an important role in the spread of the fire. Climatologically, the area experiences a temperate climate, averaging 840 mm annual rainfall spread evenly throughout the year.

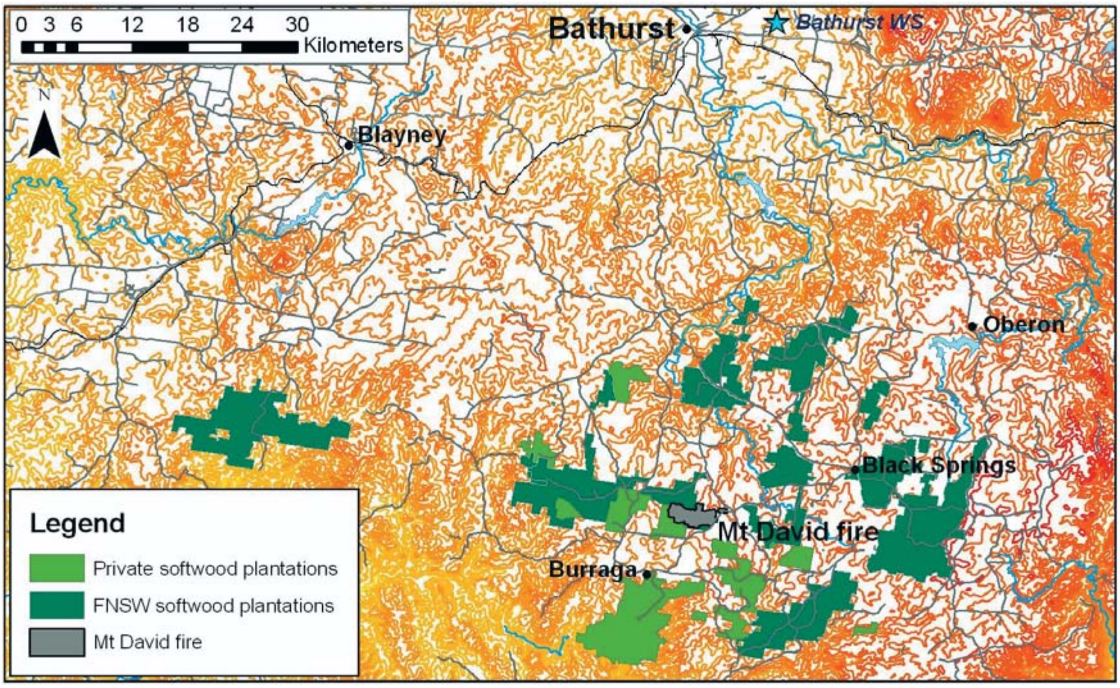

Figure A1.1. Location of the Mount David Fire and weather stations (Bathurst Airport and Oberon) used in the analysis.

Fuels

Radiata pine plantation comprised 84% of the area burned by the Mount David Fire (Table A1.1, Fig. A1.3). The main fire carrying fuel complexes were PRAD03 (11 and 8 years old; 49% of burned area), PRAD04 (18 year old; 9%) and PRAD05 (26%) - see Table 2. Age and silvicultural history for the privately owned mature plantation was not available.

The grassland areas in the neighbouring paddocks were heavily grazed and fully cured at the time of the fire. Grass areas within the forest areas were generally associated with frost hollows, waterlines, and road verges. Many of the road verges had been recently slashed to reduce biddy bush (*Cassinia arcuata* F. Muell. ex Sonder), an endemic woody weed species.

Small areas of remnant native forest were scattered throughout the FNSW plantation area and the adjacent grazing land. These were variable in their composition and structure, but include some species with loose ribbon bark, that could easily generate embers ahead of the fire.

Table A1.1. Burned area in the Mount David Fire by fuel type

Fuel type	Burned area (ha)	% of total burned area
Dry sclerophyll eucalypt forest	29	3%
Grassland	108	13%
Radiata pine forest (age classes)		
PRAD03 (3 – 8 years)	422	49%
PRAD04 (8 – 13 years)	75	9%
PRAD05 (> 20 years)	224	26%

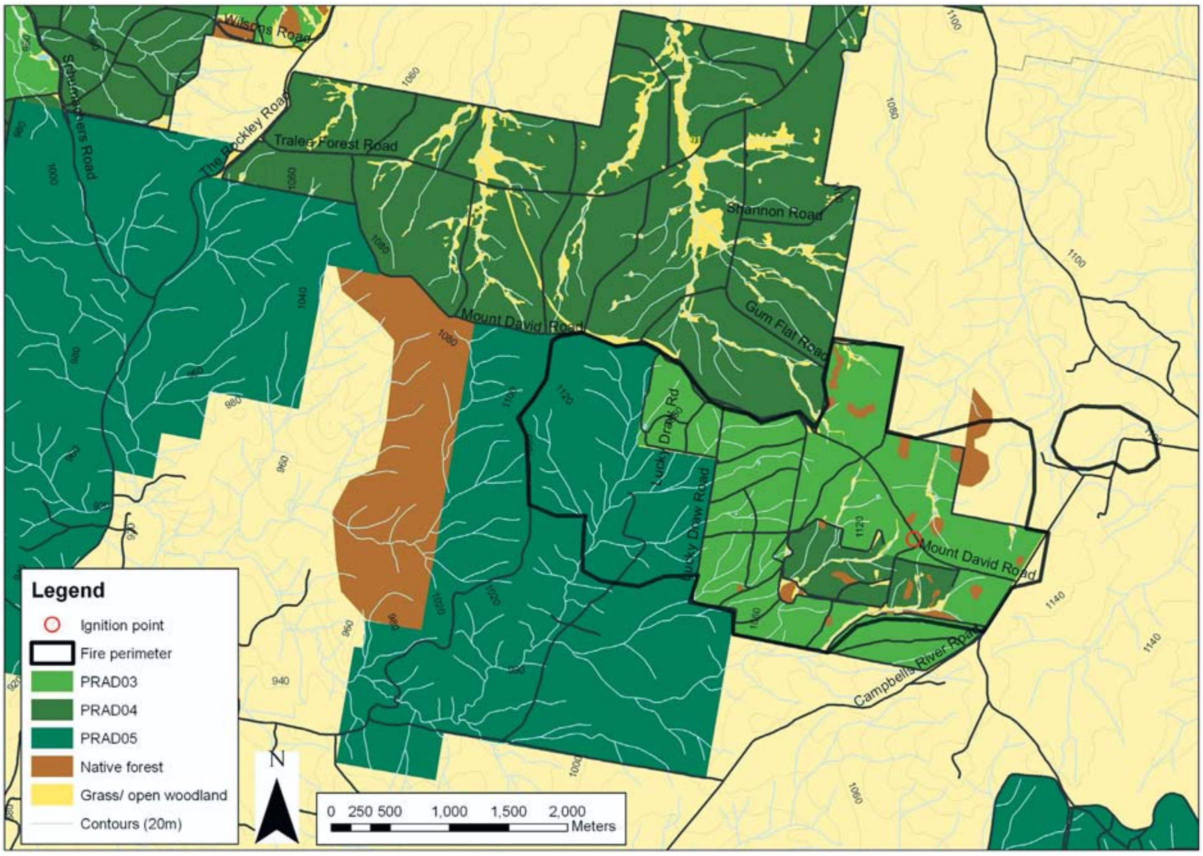

Figure A1.2. Spatial distribution of fuel complexes within the Mount David fire.

Climate and fire weather

Late 2006 was unusually dry in the Bathurst with the region experiencing an early fire season with a number of large bushfires occurring in October and November[6]. The KBDI for Bathurst (53 km to the North and 745m ASL, Fig. A1.1) on the 19 December 2006 was 128.

The synoptic situation on the 18 and 19 December was a typical summertime pattern for south-eastern Australia. On the 18th a high pressure system east of NSW directed dry continental air over the fire ground, resulting in low RH and light wind speeds. These conditions result in very dry fuels and elevated fire danger. On the 19th the high moved into the Tasman Sea and dissipated. A front passed south of NSW, while the fireground was situated in the convergence zone at the southern end of a trough of low pressure extending SE from the Northern Territory. The location of the trough resulted in light SW winds and unstable conditions. During the afternoon the trough retreated somewhat (Fig. A1.3), and a ridge of high pressure extending from a high west of Tasmania directed an easterly synoptic flow over the fireground. This synoptic pattern combined with a sea breeze to produce strong easterly winds in the afternoon and evening.

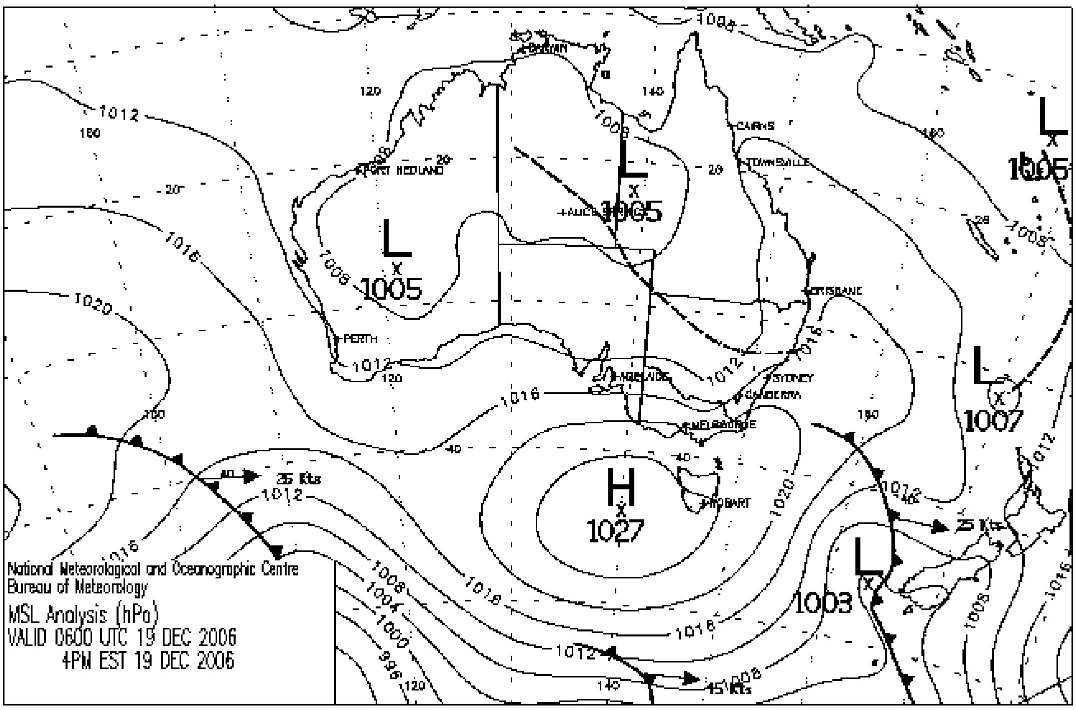

Figure A1.3. Mean surface level (MSL) analysis for Australia for 16:00 EST on 19/12/2006. Source: Bureau of Meteorology.

The Mount David Fire occurred under very high fire danger conditions (FFDI 35 – 49; weather measurements at Bathurst weather station, BoM). The day of the fire was preceded by a night in which the maximum RH was only 60% leading to minimal overnight recovery in fuel moisture. Predicted dead fuel moisture content by the McArthur (1967) guide for the early hours of the day of the fire varied between 10 and 13%. RH drop significantly on the day of the fire reaching 12% at 11:00 and remaining below 10% until the arrival of the sea breeze occurred around 17:00. The estimated fine dead fuel moisture content dropped below 5% at

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[6] These included: Mt Horrible 15000ha, Billy's fire 1797ha, Barkers Creek 8720ha, Blue Mountains fire14440ha.

10:00 and varied between 3 and 4% through most of the afternoon. Average 10-m open wind speeds throughout the day were light to moderate, varying between 15 and 25 km/h prior to the arrival of the sea breeze. The sea breeze brought higher average wind speeds, between 20 and 30 km/h and lead to a change in wind direction, from W-SW to ESE and then E. The FFDI associated with these weather conditions varied between 35 at 14:00 and 49 at 15:30. The sea breeze, bringing moister air lead to a decrease in calculated FFDI, with values dropping to the 10 – 20 level (Fig. A1.4). Throughout the active burning period of the Mount David Fire the ISI varied between 15 and 33. Fig. A1.4 shows the distinct dynamics between the FFDI and ISI. Although both picked up the potential for extreme fire behaviour during the peak burning period, with the sea breeze arrival the combination of high RH and moderately strong wind speeds (between 25 - 35 km/h) lead to different responses in the indices. The FFDI dropped considerably from Moderate to Low fire danger levels, whereas the ISI, being more sensitive to wind speed and less sensitive to RH, maintained higher values throughput the later hours of the 19 of December 2006.

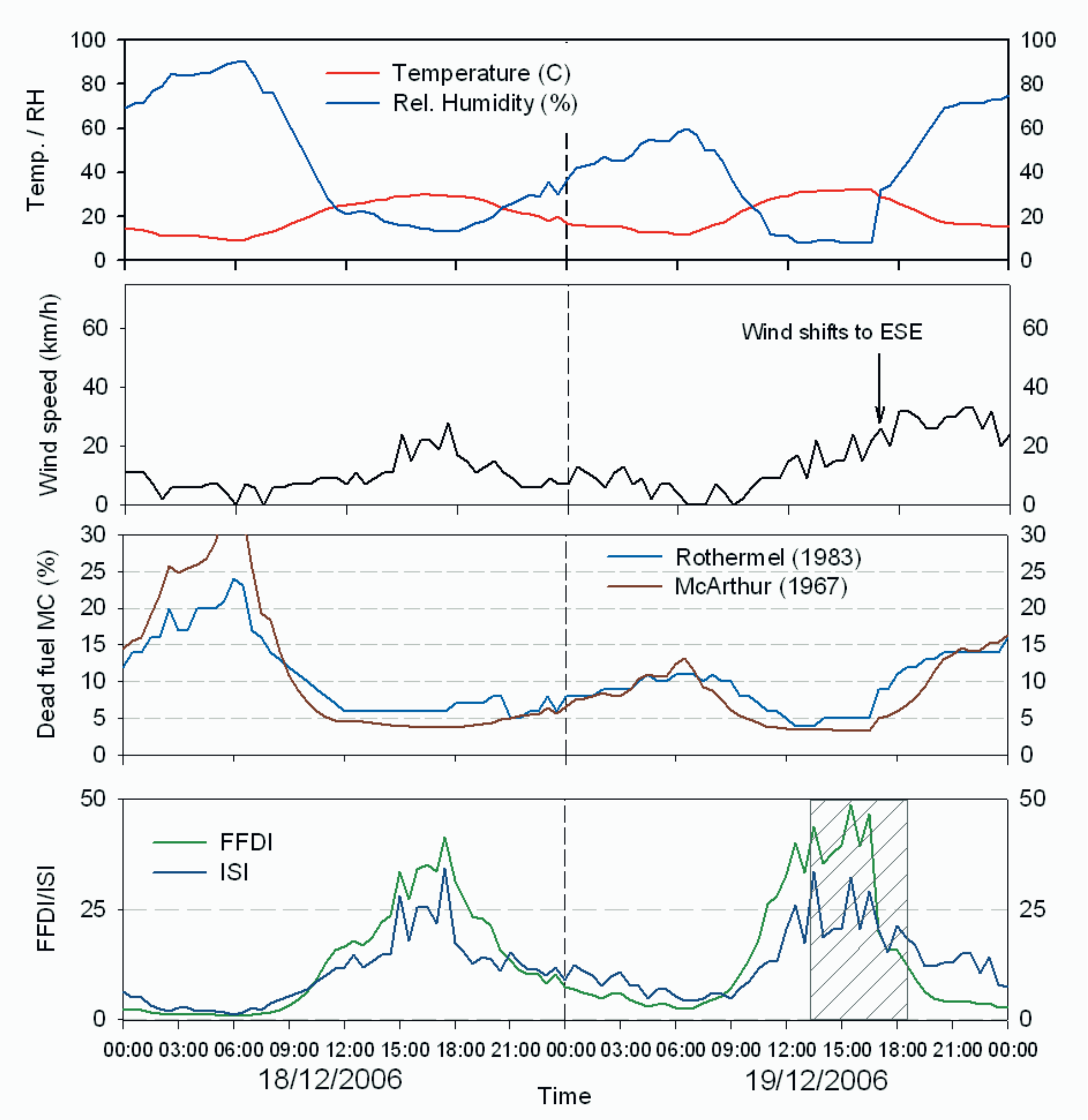

Figure A1.4. Diurnal pattern in fire weather observations, estimated fine dead fuel moisture content (MC), McArthur (1967) Forest Fire Danger Index (FFDI) and the Initial Spread Index (ISI) component of the Canadian Forest Fire Weather Index System at the Bathurst Airport weather station (BOM) from 18-19 December 2006. The shaded areas in the FFDI/ISI graph identify period of active fire propagation.

Fire chronology

Unlike the Billo Road Fire, the reconstruction of the Mount David Fire is limited due to the scarcity of information on fire propagation and behaviour. The radio log has very few references to flame front locations and behaviour. Most of the information has been gathered through onsite interviews with field officers and on-site investigation. This field survey was conducted over a month after the fire occurred and many of the post-fire indicators had deteriorated during this time.

The fire was ignited at around 13:30 on the 19 of December 2006 by a member of a pruning crew working 20 m from the Mount David Road. Attempts by the pruning crew to extinguish the burning litter with knapsacks failed, and the fire quickly developed vertically into the standing trees (unpruned PRAD03) thereby limiting any suppression action. The loft of burning embers propagated the fire to the north side of Mount David Road. In this fuel complex the spot fires coalesced and formed a vigorous surface fire that crowned within a few metres of the road. This newly developed active crown fire in turn propagated in a narrow front in an eastward direction (Fig. A1.5).

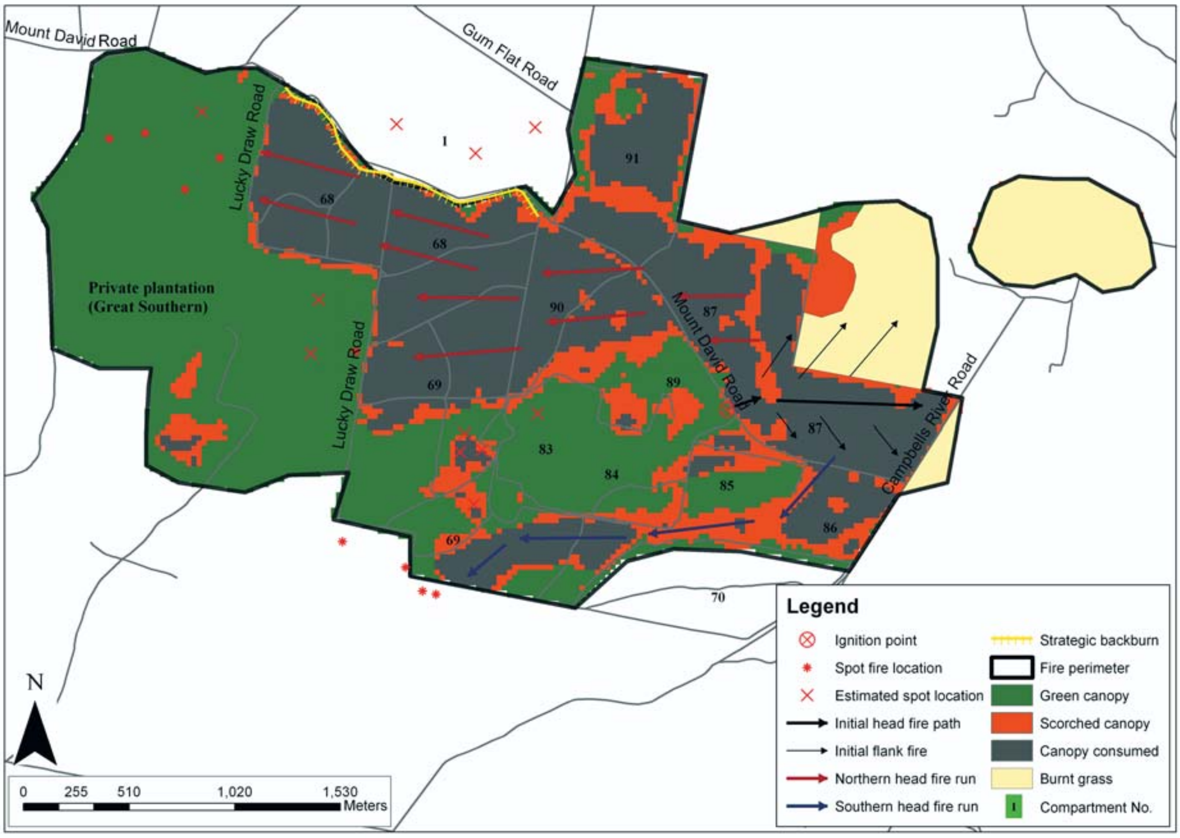

Figure A1.5. Canopy damage, head fire spread directions, and spot fire locations during the Mount David Fire. Green canopy is associated with low intensity surface fire; scorched canopy reflects moderate to high intensity surface fire; and areas of canopy consumption (i.e., flame defoliation) are indicative of crown fire activity. The canopy fire severity map was generated from Landsat image. See Appendix 2 for details on images dates and remote sensing methods used.

The fire was reported soon after ignition, with the first two slip-on fire suppression units arriving about 12 minutes later, followed closely by two tankers (all FNSW). At this stage the fire would have been less than one hectare in size, but the head of the fire was estimated to be around 150 metres in from the Mount David Road and burning as a crown fire. A small dozer (D3) and grader arrived on scene soon after. The dozer had trouble pushing over trees. Crews commenced backburning off the north side of the Mount David Road as direct attack was not feasible. Resources continued to arrive at the fire during this time. The number of resources assigned to the fire is given in Fig. A1.6.

By 14:20 the fire had spread into the nearby grazing paddock (Fig. A1.5) with a front about 200-250 m wide. Shortly after reaching the plantation boundary a spot fire was detected in grass fuels to the northeast of the fire. This spot fire crossed Campbell's River Road and burned nearly 20 ha.

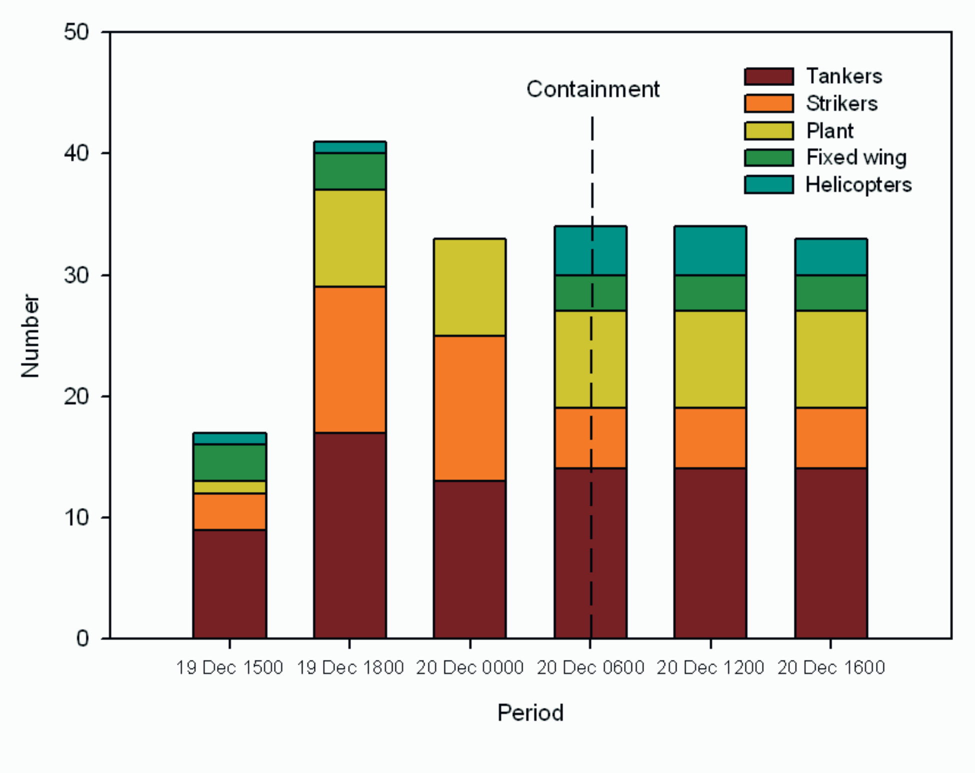

Figure A1.6: Suppression resources assigned to the Mount David Fire during the first two days (data sourced from Rural Fire Service's Incident Control Online Situation Reports).

A significant wind change associated with the arrival of the sea breeze reached the fire area soon after 15:00. There were no records of the timing of this event reported in the radio logs. The field officers interviewed estimated that the change arrived at the fire ground at 15:10. The weather log from nearby Burraga tower (5 km SSE of the fire area) places the change between 15:00 (SW 15-60 km/h) and 16:00 (SE 20-40 km/h), but with the direction swinging to the east by 17:00. The change occurred between Lithgow and Oberon at 15:00[7]. It reached Bathurst Airport WS between 16:30 (wind SW 22-33km/h; RH 8%) and 17:00 (ESE 26-39 km/h; RH 32%). The wind remained predominantly from ENE for the remainder of the fire and brought about a steady recovery in RH.

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[7] These stations only record readings at 09:00 and 15:00 daily.

The wind change redirected the fire on two fronts back into Mount David State Forest (Fig. A1.5). The most significant of these came from what was originally the northwestern flank of the fire. This front spread in WNW direction as a crown fire for a distance of 2.5 km in PRAD03 fuels. The other front came from the southern flank of the fire and burned in a southwesterly direction through a mix of fuel ages, slowing down and narrowing when burning through PRAD05 fuels (20-year old plantation).

The FNSW field officers decided that the northern front posed the greatest threat to the forest estate. Suppression priority was to keep the fire from burning the stand of 20-year old thinned pine on the northern side of Mount David Road (compartment 1 in Fig. A1.2). A strategic backburn was started along the Mount David Road immediately south of this compartment, from east to west (Fig. A1.5). At this time the main fire was burning to the south in compartment 68. The field officers report that they used the in-draft of the main fire to assist with the backburn, and they had to ignite the backburn while jogging in order to keep up with it. A number of crews in tankers followed-up on the backburn, cooling it down, and extinguishing the edge. A few spot fires were quickly detected and extinguished in compartment 1. This stand had been thinned and high pruned, which facilitated visibility and firefighter access.

The northern fire front continued burning through the heavily stocked 13-year old pine plantation up to Lucky Draw Road, probably slowing with time due to the moderating weather conditions. A few spot fires had started in the privately-owned mature pine plantation more than 750 metres ahead of this front, before the weather conditions had fully eased. The main fire burned as a low intensity surface fire into parts of the mature pine, due to the milder weather conditions and decrease abundance of ladder fuels. The IMT decided to fall back to a road along a ridge in the privately-owned pine plantation area as they did not know extent of spot fires within this area. Backburns were conducted along the ridge road and remainder of the Mount David Road during the evening, but they did not carry very far due to the low fire potential at this time.

The southern front was burning into the 20-year old fuels in compartment 85 by 16:00. Firefighters working in this area were able to hold the flank fire along a creek line to the north of compartment 70. This front burned mainly as a surface fire while in the 20-year old pines, but the fire picked up in speed and intensity when it reached the 13-year old plantation fuels in compartment 69. A run of crown fire burned to the southern boundary of compartment 69, starting a number of spot fires in the adjoining grass paddock. Crews in this area continued backburning along this boundary, and along the boundary with the Great Southern pine plantation. Some spot fires were started in the private plantation, but were easily extinguished in the moderating weather conditions. Dozers were used to establish mineral earth breaks around all the spot fires to the southwest of the fire, and worked on the access roads in the Great Southern plantation. The remaining perimeter in this area was eventually backburned, while fires between the two fronts and within the containment lines were allowed to burn freely. The fire was listed as contained at 06:50 on the 20 December. Following reconnaissance flights the IMT decided to conduct fill-in burning from the helicopter in the unburned patches in the Great Southern plantation area. Suppression crews were used to mop-up and patrol the perimeter of the fire. Aircraft were used to put water on hot spots.

Along with the direction of the main fire runs, Fig. A1.5 provides insight on the level of fire behaviour associated with them. The main runs were supported by unthinned PRAD03 fuels and were characterized as crown fires. While the PRAD03 supported active crown fire propagation, the PRAD04 island (compartment 83, 84 and 85, Fig. A1.5) sustained only intermittent crowning. In the PRAD03 fuels flanks, fires spread with canopy fuel involvement (e.g. compartment 91). Within the private plantation with PRAD05 fuels to the west, the fire spread as a downslope low intensity surface fire on the evening of 19 December, after the sea breeze arrival, hence burning under milder weather conditions than the other fuels. The areas shown as having the crown scorched or consumed in the southwestern section of this compartment (Fig. A1.5) correspond to grassland fuels in a frost hollow.

APPENDIX 2: REMOTE SENSING METHODS

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Burn severity mapping

Burn severity maps show the degree of physical damage to vegetation that can be observed after a fire has passed (Hammill and Bradstock, 2006). This contrasts with fire intensity, which is the rate of energy released per unit length of fire line (Bryam, 1959).

Two types of image data were acquired for this analysis: Landsat Thematic Mapper imagery and a colour infra-red aerial photograph of the Billo burn area, which was supplied by Forests New South Wales staff. This report described the use and processing of each of these datasets in this project.

Landsat Thematic Mapper image data

The Thematic Mapper (TM) sensor aboard the Landsat 5 and 7 satellites record the brightness of sunlight reflected from the Earth's surface in spectral bands ranging from visible and infra red to thermal wavelengths (Table A2.1). Landsat continuously acquires images and transmits them to receiving stations for archiving. Landsat passes over the same part of the globe every 16 days, and Landsat satellites have been collecting images since 1972.

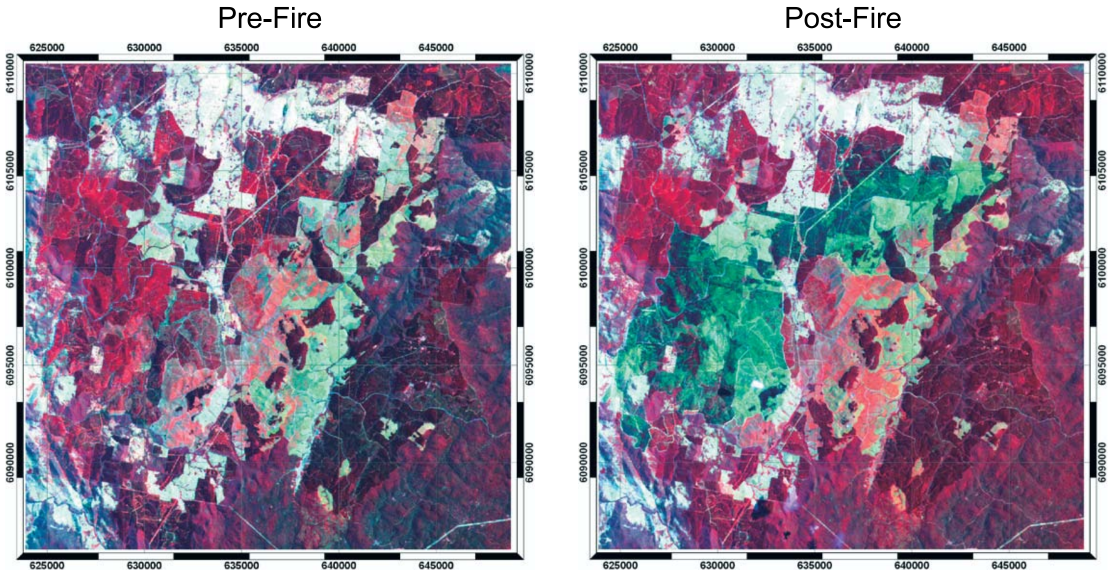
Table A2.1. Spectral and spatial characteristics of Landsat 5 and 7 TM images

Band	Band Number	Wavelengths (nm)	Pixel size (m)	Image width
Blue	1	450 - 515	25	185 km
Green	2	525 - 605	25	
Red	3	630 - 690	25	
Near Infrared (NIR)	4	750 - 900	25	
Middle Infrared (MIR)	5	1550 - 1750	25	
Thermal Infrared (TIR)	6	10400 - 12500	120m(L5) 60m (L7)	
Middle Infrared (MIR)	7	2080 - 2350	25	

Landsat's unique combination of moderate spatial and spectral resolution, the longest historical archive of satellite data and relatively low cost make it ideal for time-series analysis of dynamic and variable ecosystems at the landscape scale. The Thermal Infra-red band (Band 6) is usually removed for most applications leaving 6 bands of data spanning visible and infra-red wavelengths. Band 6 has been removed from the images used in this report.

All Landsat images were converted to exoatmospheric reflectance using the ENVI (Environment for Visualizing Images software) Landsat TM calibration tool, which accounts for gains and offsets in sensor calibration and illumination conditions. Further atmospheric correction was not considered necessary due to the high atmospheric clarity in this elevated region.

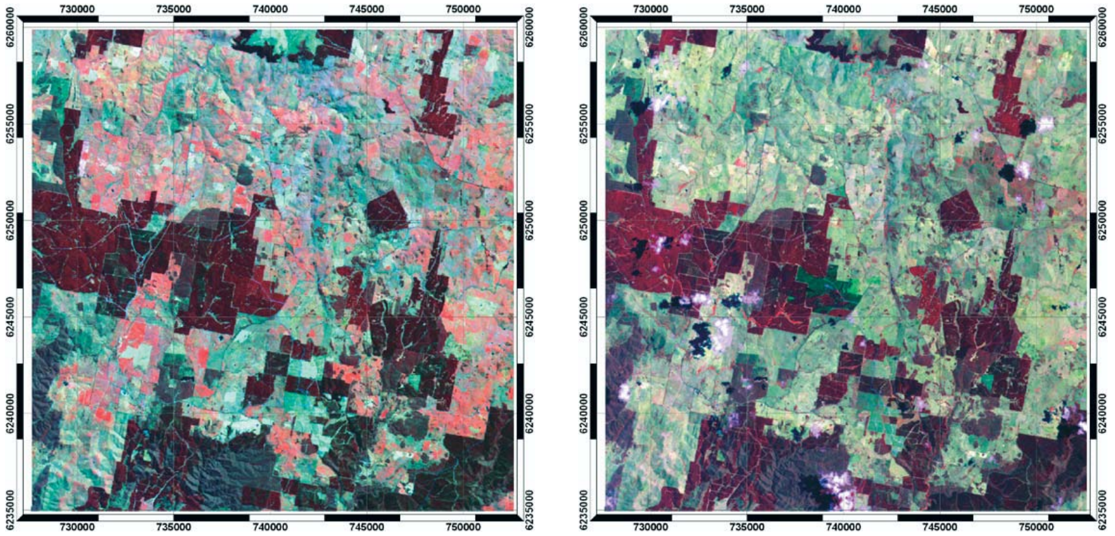
Four Landsat TM images were purchased for this project including pre and post-fire images for both the Billo and Mt David fires (Fig. A2.1). Vigorously growing vegetation appears red and burned areas appear emerald green in the post-fire images.


Pre-Fire

Post-Fire

Billo 16 November 2006

Billo 19 January 2007



Mount David 22 September 2006

Mount David 27 December 2006

Figure A2.1. Landsat Thematic Mapper images used in the project (TM bands 1,7,4 as BGR).

Colour infra-red digital image

Airborne digital colour infra-red image data were captured by Forests New South Wales over the area burned in the Billo fire on 28 December 2006 (Fig. A2.2). This image shows the burned are at 2m pixel spacing in 4 spectral bands: Blue, Green Red and NIR. Compared to Landsat, this image contains less spectral information but increased spatial detail.

A burn severity classification of this imagery conducted by FNSW staff (Russell Turner, Pers. Comm.) and was made available for this project. Due to the absence of pre and post fire CIR images, and the lack of CIR imagery over the Mount David Fire, the CIR data was not used for quantitative burn severity assessment in this project. This image was invaluable, however, as a visual guide to the distribution of burn severity throughout the Billo plantation.

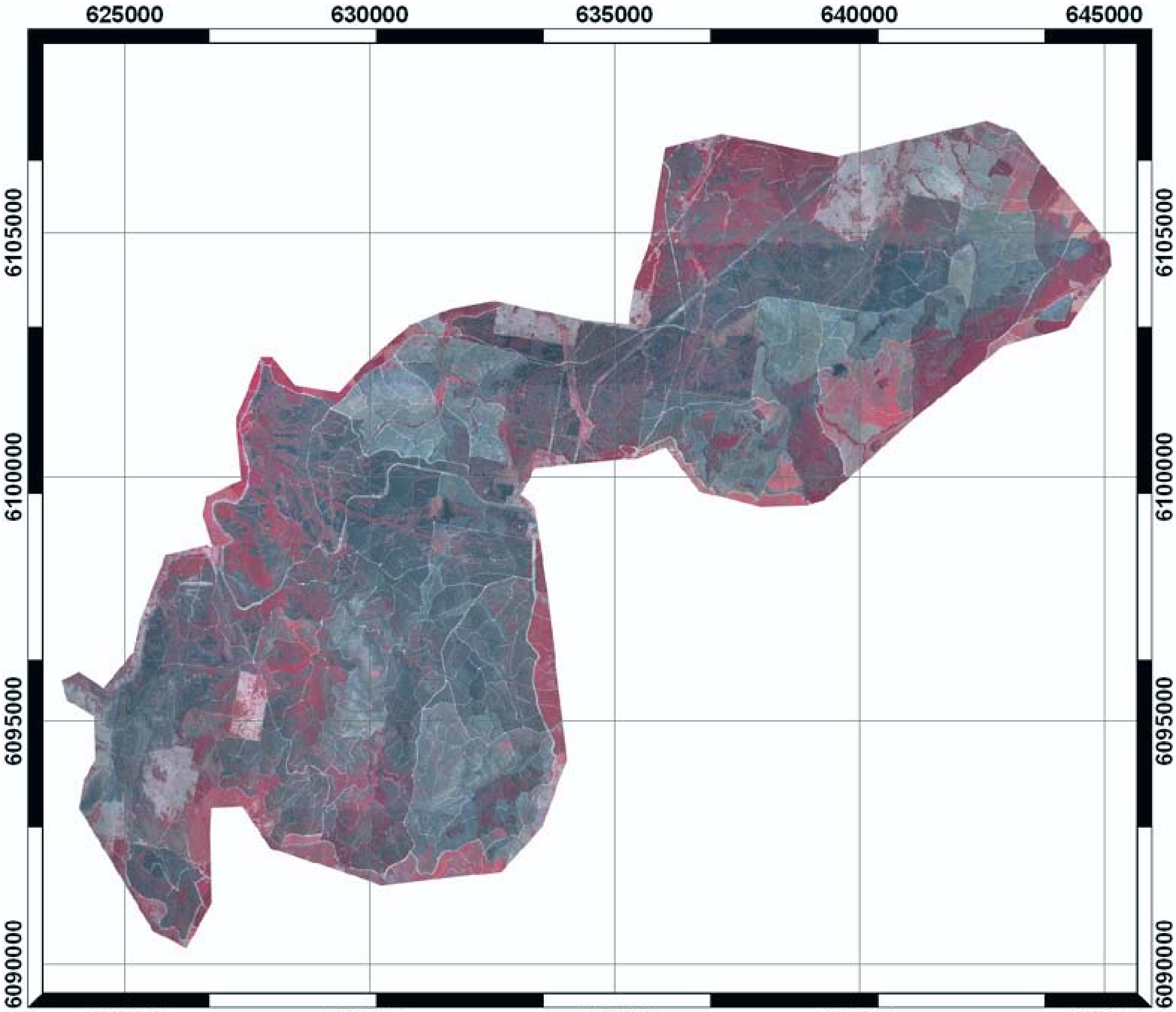


Figure A2.2. Post-fire colour infra-red digital airborne imagery over the Billo fire area, captured in January 2007.

Burn severity maps

A method for mapping burn severity was developed by Key and Benson (2002). This involves creating a burn severity index from pre-fire and post-fire images, calculated using the normalised burn ratio (TM4 – TM7)/(TM4+TM7). TM Band 4 (NIR) is sensitive to changes in vegetation vigour and biomass, and Band 7 (SWIR) is sensitive to the visibility and character of soils (Cocke et al., 2005; Key and Benson, 2002). A normalised burn ratio (NBR) difference image is then calculated (NBRdiff = NBRprefire – NBRpostfire) which shows change in NBR due to fire.

In addition to the NBR difference images, a number of other image processing methods were tested, including:

1. Unsupervised classification of the post-fire images using a range of classification algorithms
2. Supervised classification of the post fire images based on burn severity regions identified from field data using a range of classification algorithms

Each image was classified into 10 classes which were grouped to represent 3 burn severity levels: (1) green canopy (unburned), (2) crown scorched and (3) crown consumed (all needles removed).

Map accuracy assessment

Initial analysis of the burn severity maps identified three versions as being most suitable for further analysis:

1. A supervised classification of the post-fire Landsat image captured on 19 January 2007
2. An unsupervised classification of the NBR difference image

The accuracy of classified burn severity maps was assessed in two ways. First, an Error matrix was calculated between regions of burn severity identified during fieldwork. An error matrix indicates the classification accuracy of individual classes and the map overall. Second, a 250m by 250m grid identifying burn severity at each of approximately 1800 intersection points was created from expert knowledge of the Billo Fire. The accuracy of classified maps was compared using correlation analysis.

Two statistics from confusion matrix analysis were used to describe the classification accuracy of the map as a whole: (1) the Overall Accuracy (OA) score and; (2) Khat statistics from Kappa analysis. The OA score shows the proportion of pixels that have been correctly classified according to the field data. This is calculated from the sum of the correctly classified pixels (the main diagonal in the matrix) divided by the total number of pixels. OA scores tend to Khat statistics account for chance agreement in the classification by incorporating the row and column totals, (which indicate the probability of getting a correct classification by random chance) into the accuracy assessment (Congalton and Green, 1999). OA values tend to overestimate the accuracy of classified images (Ma and Redmond, 1995) and Kappa analysis tends to underestimate map accuracy (Foody, 1992), with true map accuracy between the 2 values.

Overall Accuracy and Khat statistics from confusion matrix assessment are shown in Table A2.2. This assessment indicates the classification of post fire Landsat provides the most accurate indication of the distribution of burn severity classes. Due to some concern over the true character of regions used to spectrally define classes in the supervised classification, however, a second accuracy assessment was conducted which compared the classes produced by image classification with a 250m by 250m grid identifying burn severity at each of approximately 1800 intersection points across the Billo fire extent.

Results from the grid correlation analysis (Table A2.3) indicate that classification of the Normalised Burn Ratio image provides the highest map accuracy in relation to the 250m grid (r = -0.49). This correlation is highly significant, but explains only 24% of the variation in burn severity levels indicated in the grid). On this basis a decision was made to use the Normalised Burn ratio image to create the burn severity map (Fig 31).

Burn severity in the Mout David fires was mapped using using an unsupervised K means classification of the Mount David NBR difference image to identify 6 image classes, which were grouped to show 3 burn severity levels. This is the same method used to create the Billo burn severity map. This image indicates widespread crown consumption in the large areas of PRAD03 fuels (Fig. A1.5 and Table A2.4).

Table A2.2. Overall accuracy and Khat statistics from confusion matrix accuracy assessment.

Image	Overall Accuracy (%)	Kappa (%)
19 January 2007	85	75
NBRdiff	75	57

Table A2.3. Overall accuracy and Khat statistics from grid based accuracy assessment

Image	*r*	R^2	*P*
19 January 2007	-0.36	0.13	<0.01
NBRdiff	-0.49	0.24	<0.01

Table A2.4. Area of each burn severity class for Mount David as mapped from the burn severity image

Post-fire canopy condition	Class area (ha)
Canopy consumed	304
Canopy scorched	191
Green canopy	323

APPENDIX 3: APPLICABILITY OF THE PROJECT VESTA RATE OF FIRE SPREAD MODEL TO PINE PLANTATION FUEL COMPLEXES

One of the results from the recent Project Vesta effort is a new model for predicting fire behaviour in dry eucalypt forest (Gould *et al*. 2007). This model was designed for use in dry eucalypt forest with a litter and understorey shrub fuels. The model has not been tested for open forests with a predominantly grassy understorey nor in pine plantations of different ages, stand structures and silviculture treatments. Gould *et al*. (2007) concluded that rate of spread of surface fires in dry eucalypt forest is directly related to characteristics of the surface fuel bed and understorey shrub layers.

A robust and practical fuel hazard scoring system was develop that numerically characterises the identifiable fuel strata in a eucalypt forest fuel complex comprised of surface fuel of leaves, twigs and bark; near-surface fuel of grasses, low shrubs and suspended dead fine fuel; elevated fuel contributed by tall shrubs; and bark on intermediate and overstorey fuels. These hazard scores have provided an effective way to quantify changes in fuel structures as fuel develops with time after disturbance. The visual assessment is considered very robust for assessing the different eucalypt forest fuel strata but more investigation and validation is required for a visual fuel hazard to be applied to pine plantations. The current visual assessment appears to describe the surface fuels and some components of the near-surface layers in pine plantation reasonably well but does not adequately describe the canopy fuel structure for hazard assessments purposes.

For practical use of the new eucalypt forest fire behaviour model, like all fire behaviour models, requires good input data. Fuel assessment that includes stratification into the critical fuel layers and estimates of hazard scores and the height of the near-surface fuel and elevated fuel is relatively straight forward and more reliable than estimating fuel loads in eucalypt forest. Even though we can get good visual estimates of the surface and near-surface fuels in the unburnt plantation near the Billo Road Fire, we were unable to account for the fuel hazard of the ladder and canopy fuels (see Figs. 6-8). Thus, the fuel score estimates of surface and near-surface fuels could possibly be used to predict surface fires in pine plantation using the new fire spread model. But this model does not describe and or take into account the canopy fuels in predicting crown fire behaviour. Therefore we conclude that the new fire behaviour model developed as part of Project Vesta would be applied outside its application bounds. Future research into visual fuel assessment and fire behaviour in pine plantations is therefore recommended.

APPENDIX 4: HOURLY WEATHER DATA

Table A3.1. Hourly weather data and calculated Forest Fire Danger Index (FFDI), Fine Fuel Moisture Code (FFMC) and Initial Spread Index (ISI) for the Bondo weather station (FNSW). FFMC calculated from hourly data.

Time	Air temp (C)	RH (%)	Wind speed (km/h)	Wind direction	FFDI	FFMC	ISI
10/12/2006							
0:00	18.7	75	14.5	332	2	85.3	4.6
1:00	17.9	81	11.3	239	2	84.4	3.4
2:00	16.8	83	0.0	176	1	84.4	1.9
3:00	16.3	89	7.4	162	1	81.8	2.0
4:00	15.5	88	0.0	159	1	81.8	1.4
5:00	13.9	92	0.0	159	1	79.4	1.1
6:00	13.2	93	0.0	159	1	79.4	1.1
7:00	17.8	83	0.0	159	1	84.4	1.9
8:00	26	59	0.0	159	4	88.0	3.2
9:00	29.5	50	5.8	10	7	89.0	4.9
10:00	31.8	46	5.8	28	9	89.9	5.7
11:00	31.5	42	15.8	241	12	90.8	10.7
12:00	33.5	38	11.3	252	13	92.8	11.2
13:00	33.7	37	22.6	248	18	92.8	19.9
14:00	33.1	38	22.6	266	17	92.8	19.9
15:00	28.3	42	11.3	266	10	91.8	9.8
16:00	32.1	36	22.6	263	18	94.8	26.2
17:00	33.2	33	27.1	247	23	95.8	37.8
18:00	32.6	32	15.8	256	18	91.8	12.3
19:00	31	33	15.8	245	16	90.8	10.7
20:00	27.1	39	0.0	321	8	90.8	4.8
21:00	23.6	46	3.9	97	6	91.8	6.7
22:00	23.2	46	0.0	53	6	91.8	5.5
23:00	22	47	0.0	37	5	91.8	5.5
11/12/2006							
0:00	21	49	0.0	42	5	91.8	5.5
1:00	20.6	50	5.8	33	5	90.8	6.5
2:00	19.5	54	0.0	12	4	90.8	4.8
3:00	19.6	57	0.0	3	3	89.9	4.2
4:00	19	60	0.0	3	3	89.9	4.2
5:00	17.6	64	0.0	3	2	89.9	4.2
6:00	17.5	65	3.9	47	3	89.0	4.5
7:00	20.3	59	0.0	47	3	89.9	4.2
8:00	26.9	46	0.0	138	6	89.0	3.7

9:00	30.7	39	3.9	62	10	90.8	5.9
10:00	27.4	44	22.6	255	12	90.8	15.1
11:00	29.5	40	15.8	248	12	90.8	10.7
12:00	27.5	43	22.6	246	12	91.8	17.3
13:00	29.3	41	27.1	274	15	91.8	21.7
14:00	29.2	42	27.1	232	15	91.8	21.7
15:00	27.9	45	38.4	218	17	90.8	33.5
16:00	24.5	52	42.9	220	13	92.8	55.4
17:00	25.5	49	42.9	253	15	92.8	55.4
18:00	22.5	54	38.4	243	10	89.0	25.6
19:00	22.5	55	38.4	249	10	88.0	22.4
20:00	19.8	64	11.3	257	3	88.0	5.7
21:00	18.9	70	22.6	237	4	89.0	11.5
22:00	17.9	73	15.8	232	3	87.1	6.3
23:00	16.8	68	4.5	293	2	89.0	4.6
12/12/2006							
0:00	16	74	0.0	293	2	87.1	2.8
1:00	15.3	83	13.7	50	2	84.4	3.9
2:00	13.4	97	13.7	88	1	77.7	1.8
3:00	12.7	100	19.5	95	1	77.7	2.5
4:00	12	100	23.4	71	1	77.7	3.0
5:00	10.7	100	27.3	104	1	77.7	3.7
6:00	10.1	100	19.5	110	1	77.7	2.5
7:00	10.9	100	27.3	97	1	77.7	3.7
8:00	13.4	90	23.4	81	1	84.4	6.3
9:00	14.9	84	23.4	80	2	85.3	7.2
10:00	15.7	81	27.3	53	2	86.2	9.9
11:00	17.4	75	44.4	174	5	87.1	26.5
12:00	17.8	73	27.1	254	3	89.0	14.5
13:00	20.3	65	27.3	64	5	89.0	14.6
14:00	20.9	64	19.5	42	4	89.9	11.3
15:00	19.6	68	44.4	137	7	89.0	34.6
16:00	20.3	64	13.7	57	4	91.8	11.0
17:00	17.8	69	37.0	163	5	90.8	31.2
18:00	15	76	19.5	84	2	86.2	6.7
19:00	13.3	80	23.4	85	2	85.3	7.2
20:00	11.7	85	27.3	84	2	84.4	7.7
21:00	10.4	89	33.1	101	2	81.8	7.4
22:00	8.9	94	37.0	92	2	78.5	6.4
23:00	8.1	96	33.1	82	1	77.7	4.9
13/12/2006							
0:00	7.8	100	33.1	96	1	77.7	4.9

1:00	7.8	100	27.3	95	1	77.7	3.7
2:00	7.7	100	25.9	122	1	77.7	3.4
3:00	8	100	25.9	172	1	77.7	3.4
4:00	8.1	100	15.8	216	1	77.7	2.0
5:00	8.3	100	5.8	350	1	77.7	1.2
6:00	8.9	100	3.9	75	1	77.7	1.1
7:00	11.3	95	13.7	42	1	77.7	1.8
8:00	14.7	85	18.5	166	2	84.4	5.0
9:00	18.1	75	9.8	118	2	86.2	4.1
10:00	20.3	70	9.8	86	3	88.0	5.3
11:00	25.6	57	3.9	37	5	89.0	4.5
12:00	27.8	51	5.8	330	6	90.8	6.5
13:00	27.5	46	3.9	40	7	90.8	5.9
14:00	29.2	39	18.5	139	13	92.8	16.2
15:00	29.8	40	14.5	328	12	91.8	11.5
16:00	28.3	41	11.3	290	10	93.8	12.9
17:00	26.3	45	11.3	291	8	92.8	11.2
18:00	24	49	15.8	271	8	89.0	8.2
19:00	24.9	46	5.8	323	7	89.0	4.9
20:00	21	53	0.0	328	4	89.0	3.7
21:00	16.7	65	0.0	328	2	89.0	3.7
22:00	16.4	66	5.8	328	2	89.0	4.9
23:00	15.1	70	0.0	328	2	87.1	2.8

Table A3.2. Hourly weather data and calculated Forest Fire Danger Index (FFDI), Fine Fuel Moisture Code (FFMC) and Initial Spread Index (ISI) for the Wagga Wagga weather station (BoM). FFMC calculated from hourly data.

Time	Air temp (C)	RH (%)	Wind speed (km/h)	Wind direction	FFDI	FFMC	ISI
10/12/2006							
0:00	26.6	23	15	100	20	96.8	23.5
1:00	26	26	11	60	16	95.8	16.8
2:00	25.3	38	17	70	12	93.8	17.2
3:00	24.5	44	15	70	9	92.8	13.5
4:00	23.9	48	17	60	8	91.8	13.1
5:00	23.6	46	13	50	8	91.8	10.7
6:00	25.5	40	13	70	10	92.8	12.2
7:00	28.6	30	13	40	16	94.8	16.1
8:00	29.9	27	21	360	22	91.8	16.0
9:00	31.6	23	13	350	22	92.8	12.2
10:00	34.1	18	17	310	31	94.8	19.7
11:00	36.5	14	18	340	40	94.8	20.8
12:00	36.7	12	26	290	52	95.8	35.7
13:00	38.5	11	13	320	42	95.8	18.5
14:00	38.2	10	21	320	52	95.8	27.7
15:00	39	7	24	310	64	96.8	37.1
16:00	38.3	7	18	330	54	98.9	36.1
17:00	37.9	8	22	310	57	98.9	44.2
18:00	37	10	15	340	43	93.8	15.5
19:00	34.2	13	11	350	32	93.8	12.7
20:00	33.8	12	15	330	36	97.8	27.0
21:00	29.9	20	9	10	21	96.8	17.4
22:00	29.7	19	11	360	23	96.8	19.2
23:00	28	22	11	20	19	96.8	19.2
11/12/2006							
0:00	25.4	24	9	280	16	96.8	17.4
1:00	33.2	12	18	320	38	97.8	31.5
2:00	30.1	20	18	260	26	96.8	27.4
3:00	27.9	26	13	20	18	95.8	18.5
4:00	27.7	26	8	40	16	95.8	14.4
5:00	28.7	21	17	10	24	96.8	26.0
6:00	27.3	25	13	260	18	95.8	18.5
7:00	27.8	28	1	0	12	95.8	9.6
8:00	32.1	16	18	270	32	93.8	18.1
9:00	33.4	16	31	190	46	93.8	34.8
10:00	33.7	15	26	230	42	94.8	31.1

11:00	34.6	14	33	250	53	94.8	44.2
12:00	32.1	17	35	240	46	95.8	56.2
13:00	31.2	21	37	230	41	94.8	54.1
14:00	31.3	24	37	240	37	94.8	54.1
15:00	27.2	40	30	250	16	91.8	25.1
16:00	29.2	28	26	240	23	95.8	35.7
17:00	28.4	28	28	240	24	95.8	39.5
18:00	26.9	29	31	240	23	91.8	26.4
19:00	25.3	22	28	240	26	92.8	26.1
20:00	23.7	23	21	240	20	96.8	31.9
21:00	22.6	24	15	240	16	96.8	23.5
22:00	21.1	21	31	220	25	96.8	52.7
23:00	18.8	26	24	230	17	94.8	28.1
12/12/2006							
0:00	16.4	32	26	220	13	94.8	31.1
1:00	13.7	42	9	310	6	92.8	10.0
2:00	12.4	42	13	240	6	92.8	12.2
3:00	11.5	49	5	260	4	91.8	7.1
4:00	10.5	50	9	270	4	90.8	7.6
5:00	9.5	54	9	30	3	89.9	6.6
6:00	10.8	48	9	350	4	91.8	8.7
7:00	13	42	8	300	5	92.8	9.5
8:00	16	37	4	20	7	89.9	5.2
9:00	19	38	5	330	7	89.9	5.4
10:00	23	34	9	320	10	91.8	8.7
11:00	24.7	29	13	70	14	92.8	12.2
12:00	26.2	27	17	60	18	93.8	17.2
13:00	26.7	24	18	50	20	94.8	20.8
14:00	27.5	24	21	60	22	94.8	24.2
15:00	27.8	22	9	360	18	94.8	13.2
16:00	27.9	23	18	80	22	96.8	27.4
17:00	27.9	21	18	100	23	96.8	27.4
18:00	26.9	23	17	70	21	92.8	15.0
19:00	24.1	31	21	40	16	90.8	13.9
20:00	21.7	35	21	40	13	93.8	21.0
21:00	19.7	40	13	40	8	92.8	12.2
22:00	17.8	46	13	50	6	91.8	10.7
23:00	16.3	51	24	60	6	90.8	16.2
13/12/2006							
0:00	15.6	51	31	80	7	90.8	23.1
1:00	15.4	53	37	80	8	90.8	31.2
2:00	15	58	24	70	5	89.9	14.1

3:00	15	58	22	90	5	89.9	12.8
4:00	14.9	60	21	80	4	89.9	12.2
5:00	14.8	61	30	80	5	89.9	19.1
6:00	16.1	57	28	70	6	89.9	17.3
7:00	17.7	53	31	70	7	90.8	23.1
8:00	19.7	48	24	80	8	89.0	12.4
9:00	21.9	43	17	60	9	89.9	9.9
10:00	24.1	37	18	20	12	91.8	13.7
11:00	27.1	31	15	30	15	91.8	11.8
12:00	27.6	23	24	10	25	94.8	28.1
13:00	29.6	18	18	30	28	95.8	23.8
14:00	29.8	18	9	20	22	95.8	15.2
15:00	30.7	18	15	320	27	95.8	20.5
16:00	30.9	19	18	360	28	97.8	31.5
17:00	30.6	17	11	310	25	97.8	22.1
18:00	29.8	20	15	330	24	92.8	13.5
19:00	28	25	8	240	16	91.8	8.3
20:00	23.9	36	9	190	10	93.8	11.5
21:00	22.4	34	9	200	10	94.8	13.2
22:00	23	34	2	140	9	94.8	9.3
23:00	22.2	35	0	0	8	93.8	7.3

LIST OF ABBREVIATIONS

ACT	Australian Capital Territory
BoM	Bureau of Meteorology
BP	Burning Period
CBH	Crown Base Height
CFFBPS	Canadian Forest Fire Behaviour Prediction System
CFFDRS	Canadian Forest Fire Danger Rating System
CIR	Colour Infra-red imagery
CRC	Cooperative Research Centre
ENVI	Environment for Visualising Images (software package)
FFBT	Forest Fire Behaviour Tables
FFDI	Forest Fire Danger Index
FFDM	Forest Fire Danger Meter
FNSW	Forests New South Wales
FSG	Fuel Strata Gap
GIS	Geographic Information System
ICON	Incident Control Online (NSW RFS reporting system)
IMT	Incident Management Team
ISI	Initial Spread Index
KBDI	Keetch-Byram Drought Index
LAPS	Limited Area Prediction System
MC	Moisture content
MSL	Mean Surface Level
NBR	Normalised burn ratio
NIR	Near Infrared
NPWS	National Parks and Wildlife Service (NSW Department of Environment and Climate Change)
NSW	New South Wales
OA	Overall accuracy
RFS	Rural Fire Service
RH	Relative humidity
SA	South Australia
TM	Thematic Mapper
VIC	Victoria
WA	Western Australia
WS	Weather Station