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Fire behaviour during the Pickering Brook wildfire, January 2005 (Perth Hills Fires 71 – 80)

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ABSTRACT

Wildfire burnt 27 700 ha of jarrah (*Eucalyptus marginata*) forest in the Pickering Brook area of the Perth hills during January 2005. Fuels in the area ranged from 1 year-old to 22 year-old in a broad mosaic. A detailed reconstruction of the spread over two days allowed the testing of fire-spread prediction models and the examination of the effects of prescribed burning on fire behaviour.

The Forest Fire Behaviour Tables for Western Australia grossly under-predicted fire spread when a wind ratio of 5:1 was used to convert open wind speed to in-forest wind speed. Using a wind ratio of 3:1, the tables predicted reasonably well at low to moderate wind speeds but over-predicted at high wind speeds.

The fire spread equations based on Project Vesta experiments predicted fire spread reasonably well over the full range of fuel loads and wind speeds. However, the data suggested the need for better models to predict fuel moisture content, particularly after a day of low humidity

Comparison of predicted and observed rates of spread indicated that reducing fuel load by prescribed burning reduced the rate of spread below the rate predicted in 20 year-old fuel loads for at least 8 years. Fire in 3 year-old fuel spread six times slower and was 20 times less intense than fire in 20 year-old fuel

In the absence of a prescribed burning program and assuming the area had not been burnt for 20 years it was estimated the fire would have burnt into the outer suburbs of Perth with the potential for extensive property damage. The final burnt area could have exceeded 100 000ha, or more than three times the area actually burnt.

Keywords: bushfire, jarrah, fuel reduction, Project Vesta

INTRODUCTION

The Pickering Brook fire burnt on lands managed by the Department of Environment and Conservation[1 1] (DEC) east of Karragullen during a ten day period from 15–25 January 2005. The fire resulted from a number of deliberate ignitions, and subsequent spot fires identified as Perth Hills Fires numbers 71–80.

The fire was influenced by strong easterly winds which persisted during the night on several days. A period of strong north-easterly winds preceded the passage of a trough line across the fire area on 17 January. These winds carried the fire across the Brookton Highway, but the forward spread of the fire was immediately stopped in 1 year-old fuels resulting from recent prescribed burning.

On 18 January a new fire, possibly a lightning ignition associated with the passage of the cold front, started to the east of the previous fires. South-westerly winds after the change pushed the main fire east and north though the Beraking pine plantation. On 19 January south-easterly winds pushed the lightning fire into the main fire and drove the fire towards Mundaring weir. The fire took a further 6 days to bring under control and eventually burnt 27 700 ha.

The easterly spread of the fires directly threatening Karragullen was checked after two days, but the fire had the potential to penetrate the proposed Pickering Brook National Park and posed a major threat to the township of Roleystone in the event of an extreme fire danger with strong north-east to north-westerly wind.

This report reconstructs the spread of the fires during the initial period of easterly spread from 15–17 January. The fire burnt over gently undulating terrain east of the Darling Escarpment and was stopped before it reached the steeper terrain west of the escarpment. Where the fire ran into one or two year-old fuel resulting from recent fuel reduction burns its spread was either stopped completely or checked to such a degree that suppression was easy. However, a detailed reconstruction was required to assess the impact of prescribed burning on fire spread and suppression difficulty in older fuels and to check the applicability of new fire spread equations developed during Project Vesta (Gould *et al.* 2007a).

Project Vesta was a seven-year fire behaviour study of fire behaviour in dry eucalypt forest (jarrah) fuels of different ages. More than 100 experimental fires were conducted in the jarrah forest over three fire seasons to

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[1 1] Prior to 1 July 2006 fire management on State forests and conservation reserves was the responsibility of the former Department of Conservation and Land Management.

determine the relationship between fire behaviour and wind speed, fuel moisture content, and fuel characteristics.

The fire event illustrates the potential threat of fire to the peri-urban areas of the Perth Hills and has implications for the management of the proposed Pickering Brook National Park and other parks on the Perth Hills close to suburban development. In particular, this event highlights the need to manage fuels by prescribed burning to reduce rates of spread and make fire suppression easier.

Sources of Data

Details of fire spread were drawn from information in fire diaries maintained by departmental staff, planning documents prepared by incident management teams, satellite imagery taken both during and after the fire, photographs taken by departmental staff and through personal interviews in the field with some of the key firefighting personnel.

Fuel conditions in the fire area were determined by visiting nearby areas of similar fuel ages and assessing the fuel hazard according to the system used in Project Vesta. This system is being recommended to fire agencies, both to quantify the fuel characteristics used in equations to predict fire spread and to better assess the fire threat and suppression difficulty of different fuel types. Fuel load was determined using the load/age relationship in the Forest Fire Behaviour Tables (FFBT, Sneeuwjagt and Peet 1985).

Weather data were obtained from Perth Airport (30km north-west of the fire area) and automatic weather stations located at Bickley (13km north) and Wandering (50km south-east). Although the anemometer at Bickley was mostly less than 13km from the areas of measured fire spread, the wind direction indicated by the anemometer was not necessarily consistent with the direction of spread of the fire as indicated by the field observations and the scorch pattern apparent in the Landsat imagery.

The wind speed recorded at Bickley was used to compare the observed rate of spread and the predicted the rate of spread from the Project Vesta equations and FFBT. It is possible that wind speeds experienced over the fire area varied considerably from those recorded at Bickley.

Fuel moisture content during the period of the fire was estimated using the initial moisture content calculated at the DEC office at Mundaring Weir and interpolated using a process-based fuel moisture transport model (Matthews 2006) and the equations to determine absorption moisture content developed by Alan McArthur (McArthur 1962; 1967).

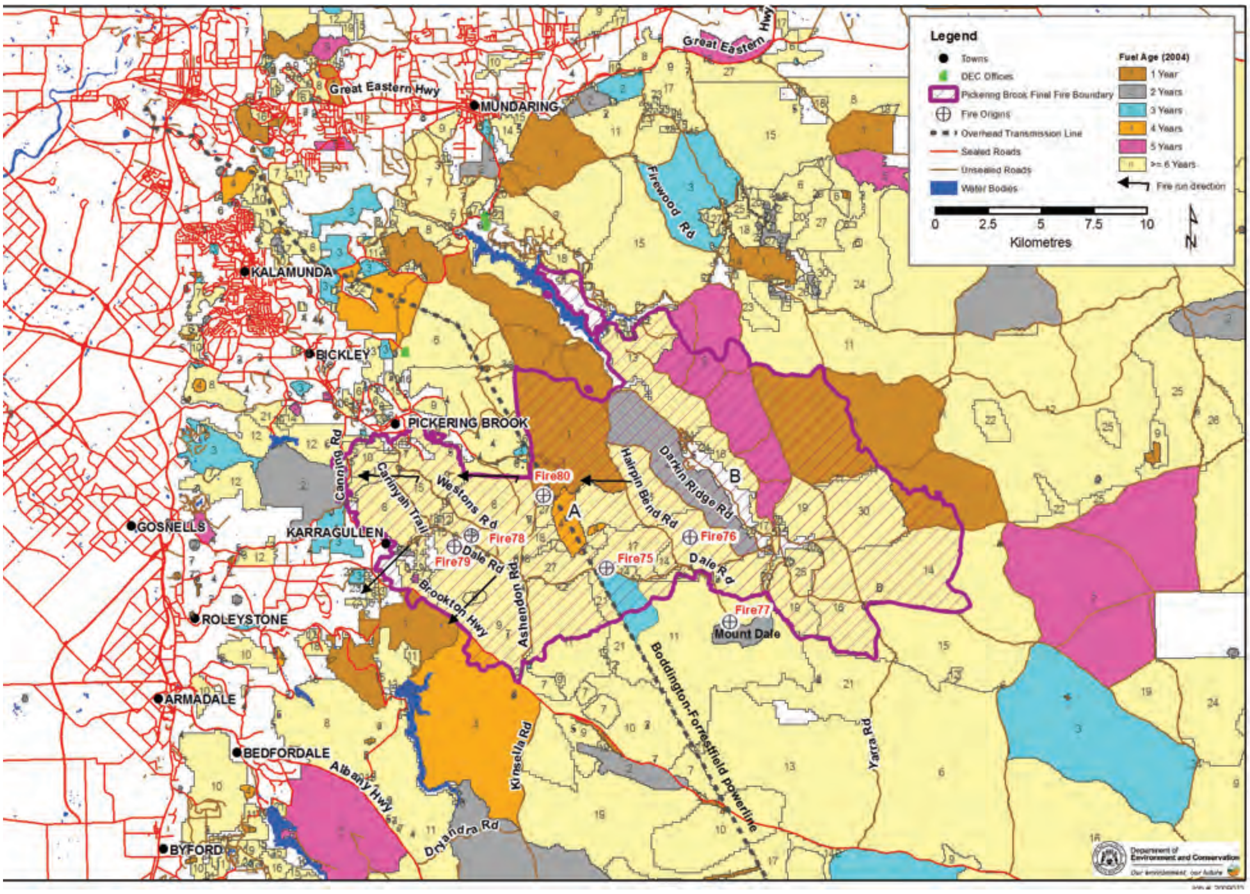

Figure 1. Overview map of the Pickering Brook fire showing the final fire boundary major place names and features mentioned in the text, and fuel age as at January 2005.

Origin and development of the Fires

1800 hours Saturday 15 – 1200 hours Sunday 16 January 2005

The fires were the result of deliberate ignition (arson) during the evening of Saturday 15 January 2005. The first fire, Fire 75, was lit near the junction of a forest track and Dale Road about 500 m east of the Boddington-Forrestfield powerline (Fig. 1)[2 2]. The fire was detected at 1815 hours after routine aerial detection had been completed for the day. It is possible that the fire was lit some 15 to 20 minutes earlier than when detected. For the purpose of determining average fire spread, it was assumed that the fires originated 15 minutes before they were detected.

The second fire, Fire 76, was detected off a forest track between Hairpin Bend Road and Darkin Ridge Road at around 1825 hours. This fire may have been lit at around 1810 hours. It was not attacked early because it was headed towards an area of low fuel near the Boddington-Forrestfield powerline and resources were directed to other fires.

Fire 77 was detected at 2030 hours burning in light fuel on Mount Dale and was quickly suppressed.

Fire 75 was initially burning in 16 year-old fuel and was held at the Boddington-Forrestfield powerline for several hours by crews from DEC and the Roleystone Bush Fire Brigade. A spot fire was detected east of the powerline and burning towards Permit Road. No time was recorded for this ignition, but I have assumed that it was around 2200 hours when the fire approached the powerline break. East of the powerline, the fire was burning in 26 year-old fuel and reported to be spotting up to 1km ahead of the main flame front. Attempts were made to control fire on tracks 500 m east of Ashendon Road at around 0300 hours but these were unsuccessful due to short distance spotting and equipment breakdown. From ignition, the wind direction was steady from the east-south-east.

A further fire (Fire 78) was detected 2km west of Ashendon Road near Dale Road at 0130 to 0140 hours on Sunday morning. This fire was thought to be another deliberate ignition, although it was only a little over 2km directly downwind from a fire spreading vigorously in 26 year-old fuel (Fire 75) and may well have been a spot fire originating from Fire 75. Another fire, Fire 79 was located near Carinyah Trail at about the same time and was also thought to be a deliberate ignition. The location of this fire was a little south of the projected centre line of Fire 75 but was still within the 12 degree arc where spot fires are most likely to occur downwind (Cheney & Bary 1969). Both fires were contained to a small area and did not contribute to the spread of the larger fires.

By 0800 hours on Sunday morning Fire 75 had crossed Ashendon Road into eight year-old fuel, and by 1100 hours the western end of the fire had been contained by heavy equipment after burning about 300 m west of Ashendon Road.

Fire 76 burnt unchecked in 16 year-old fuel in a west-north-westerly direction. It soon crossed Hairpin Bend Road and continued to burn strongly until it ran into an area of sparse fuel. This area was rated as a three year-old fuel but it was an area that had been logged and regenerated and was carrying little or no surface litter fuel. A new fire, Fire 80, was detected in 1 year-old fuel between the Boddington-Forrestfield powerline and Ashendon Road at 0200 hours. This fire was also downwind of Fire 76 and, in my opinion, was probably a spot fire originating from a fire burning in heavy 16 year-old fuel. No suppression action was taken on this fire and it was allowed to spread slowly in light fuel.

There was only limited information on the initial spread of Fire 76, but between 0400 and 0500 hours an

Figure 2. Southern flank of Fire 76 at 0411 hours, 16 January 2005. (Photograph courtesy of Sam Hurd, CALM)

[2 2] Spread maps in this article are reproduced at too small a size to legibly show all place and road names included in the text. Readers are referred to 1:50 000 Operational graphics (COG) map sheets 2134 III Mundaring, 2134 II Chidlow, 2133 IV Kelmscott and 2133 I Beraking.

officer mapped the head of the fire and photographed the flank of the fire (Fig. 2). The measurement at the head of the fire indicates that it had entered the light fuel and was almost at the extent of its run for that period and was reported to have dropped in intensity considerably compared to the flank fire, which was photographed at 0411.

These observations suggest that between 1810 and 0410 hours the fire burnt 6km at an average speed of 600 m h^{-1}. However, it is likely that it took some time for the fire to build to its potential rate of spread for the prevailing conditions, and at times may have been spreading at twice this rate in 16 year-old fuel. The fire burnt under steady easterly winds and was unconfined by suppression action on the flanks, and at 0400 hours had a length-to-breadth ratio of 6:1. This ratio indicates very slow flank fire rate of spread and was used in the reconstruction of other fires.

By 1100 hours the northern flank of Fire 75 had moved north towards the southern flank of Fire 76 and the crews had edged the eastern side of Ashendon Road between the Fire 75 and the spot fire (Fire 80) in the 1 year-old fuel. As conditions became more severe during the morning, crews were experiencing increasing difficulty with hop-overs from the edging in the 16 to 17 year-old fuel which would have had a bark hazard rating of between 3 and 4 (Gould *et al.* 2007b). The southern edge of the fire between the Boddington-Forrestfield powerline and Ashendon Road was contained by direct attack along the flank.

1200 – 2400 hours Sunday 16 January

Shortly after 1200 hours the fire broke away at a number of locations along 2km of Ashendon Road at the north-western end of Fire 75 and at Fire 80, and suppression efforts were abandoned at 1215 hours (Fig. 1). Wind speed at Bickley was 27 km h^{-1} from a direction of 100° at 1200 hours and then backed to due east (90°) at 1400 hours. The wind speed then decreased slowly to 16.5 km h^{-1} after 1700 hrs.

The fire started spreading from a number of locations in separate narrow heads, which made field observations and interpretation of the scorch pattern from satellite imagery difficult (Fig. 3). There was an observation of a narrow head fire crossing Westons Road at around 1500 hours, and an observation of strong fire activity in the gully north of Westons Road suggests that the main head fire was further advanced to the west at this time.

An air-observer plotted the position of the fire at 1547 hours, at which time it appears that the individual fire fronts had coalesced into a single front. Between 1215 and 1547 hours the fire travelled 5.25km at an average rate of spread of 1475 m h^{-1}

The air observer estimated that the rate of spread of the fire at 1710 hours was 1200 m h^{-1}. This estimation was made by selecting GPS way-points over a period of 5 minutes. Spot fires were thrown 2–3km ahead, starting to the west of Canning Road and Springvale Road.

At 1737 hours the wind changed to the north-east and the fire behaviour and rate of spread reduced dramatically. The fire had also burnt over a low ridge south of the Munday Brook Walk which further slowed the rate of spread as it backed downhill against a fire-induced eddy wind. Fire fighters commenced burning-out from a private property boundary near Karragullen at around 1800 hours.

Over this period the fire burnt mostly through 8 year-old fuel. There was a block of 18 year-old fuel between Westons Road and Carinyah Road which would have dramatically increased the intensity of the fire in the period from 1500 to 1530 hours. Fire in this heavy fuel may well have been the source of firebrands that caused spot fires east of Canning Road some 5km downwind.

The fire crossed Canning Road at 2200 hours and a spot fire was reported west of Springvale Road. Two and three year old fuel west of Canning Road enabled fire crews to contain the breakaway and the spot fires to a relatively small area.

Fire suppression along the eastern flank proceeded from Ashendon Road west across Dale Road and Carinyah Trail to private property in line with Illawarra Road.

2400 – 1200 hours Monday 17 January

Most of DEC's resources were attending to the protection of private property in conjunction with Fire and Emergency Service Authority staff and bushfire brigades, with the result that the southern flank of the fire was largely unattended. At 0400 hours the wind at Bickley was 90° and rose to 28 km h^{-1} and maintained this speed until shortly before 1000 hours. After 0600 hours the wind direction at Bickley started shifting towards the north and was 60° at 1000 hours and 30° at 1100 hours. There were no observations of wind direction in the fire area in the early morning hours, but it appears from interviews with staff and examination of the scorch pattern from Landsat imagery that the wind at the fire area went to the north-east earlier than at Bickley, and tended to blow more consistently from a direction of 45°.

DEC staff observed a break-away burning in a swamp south of Dale Road at 0445 hours between Permit Road and Ashendon Road. The fire was 500 m long and described as burning quietly close to the road which indicates that the fire had broken away from the southern flank some time earlier and burnt under an east-north-easterly wind. The time that the wind direction shifted to the north-east is uncertain, but the pattern of the fire spread indicates that it did not travel much further west than the location at 0445 hours and I have assumed that it started travelling in a south-westerly direction at 0500 hours.

Air observation plotted the head of this breakaway across Ashendon Road at 0630 and at 0951 hours Landsat imagery mapped the headfire at Brookton Highway with significant spotting south of the highway. There is significant thermal flare in the Landsat imagery which exaggerates the extent of the fire perimeter, but from examination of the imagery and the scorch pattern in the vegetation I have concluded that the fire had just reached the Brookton Highway at 0951 hours. I have assumed that the fire travelled 4.5km between 0445 and 0951 hours at an average rate of spread of 900 m h^{-1}.

Figure 3. Scorch pattern resulting from fire spread on 16 January looking north-east along Dale Road from the junction with Westons Road. The green band on the left side indicates slow spread where the fire was checked overnight before breaking away at 0430 hours on 17 January (Photo: Tim Foley).

The Landsat image at 0951 hours showed that a wind change associated with a cold front had just reached the fire area and was blowing from the west, although the wind at Bickley did not shift to 260? until 1500 hours. In any event, the scorch pattern shows that there was little spread towards the south-west after 1000 hours. As the cold front passed over there was very unstable cold air above the area which resulted in a spectacular convection cloud over the fire, but as the wind speed was low there was only slow spread on the northern and eastern sectors of the fire.

Fuel characteristics

Fuel age maps maintained by DEC were used to identify adjacent unburned areas where fuels were of similar ages to those in the burnt areas. Fuels were inspected in October 2005 with Dr Lachie McCaw[3][3]. The areas inspected had only a small addition of leaf fall over the winter months since the fire, and were therefore considered to be of a similar hazard for equivalent forest types in the burnt area. Fuel hazard ratings for selected fuel types are given in Table 1 using the fuel hazard and fuel scoring procedure adopted for Project Vesta (Gould *et al* 2007b).

There was a distinct difference in the fuel hazard between the eastern and the western sections of the fire.

In the area near the origin of the fire, 3 year-old and 20 year-old fuels were rated for near-surface fuel hazard at 1.5 and 3 respectively. These hazard ratings were very close to the hazard ratings for the northern jarrah fuel type (Sneeuwjagt and Peet 1985) observed at Dee Vee block during Project Vesta (Fig. 4).

Fuel hazards in forests on the western side of the fire close to the Darling escarpment were rated for near-surface fuel hazard in two, three, and 26 year-old fuels. Hazard ratings were 2–2.5 for the two and three year-old fuels, and 4 for the 26 year-old fuel.

These hazard ratings were a full hazard class higher than the average rating for the northern jarrah fuel type at Dee Vee and slightly higher than the average fuel hazard rating for the southern jarrah fuel type at McCorkhill forest block near Nannup. This difference in fuel characteristics most likely reflects the greater productivity of the forests close to the escarpment which have an annual average rainfall of 1200mm, compared to further east within the fire area where annual rainfall is 900mm or less. Fuels closer to the escarpment had a much denser low shrub layer including a high proportion of the grass tree *Xanthorrhoea gracilis*, which supports the bark and litter in the near-surface layer to a height of 30 cm.

At the one location beside Canning Road, a forest with 10 year-old fuels had a distinct grassy-like understorey characterised by *Loxocaria sp.* The fuel load was not sampled and visually it appeared to be lighter than the average fuel load for a 10 year-old southern jarrah fuel type. However, because of fine grassy structure of the *Loxocaria sp.* fires in this fuel type would spread faster than in the litter and low shrub fuels characteristic of the northern jarrah fuel type.

In my opinion the average near-surface fuel hazards score for the jarrah forest at the Dee Vee site would be appropriate for predicting fire spread for the initial runs of the fire up to Canning Road. However, for extrapolation of fire spread west of Canning Road, fuels would need to be rated a full hazard rating class higher than the average rating based on the Dee Vee site.

The average height of the near-surface fuel for the Dee Vee and McCorkhill sites is given in Fig. 5. The fuel sampling suggested that the near-surface fuel heights of 8 cm and 12 cm observed for 3 and 20 year-old fuels respectively in the western area of the fire were lower than the standard average curves for Dee Vee which were 14 cm and 20 cm. However, there was wide variation of near-surface height in the northern jarrah fuels at Dee Vee depending on local plant associations (Fig. 5). Without a comparable fuel type over the bulk of the fire run on 15–17 January, the average near-surface fuel height for Dee Vee was assigned to fuel ages east of Canning Road.

West of Canning Road, the near-surface fuels long-unburned areas were considerably higher than the average for Dee Vee fuels with a dense layer of low shrubs supporting leaf twig and bark litter. These fuels were

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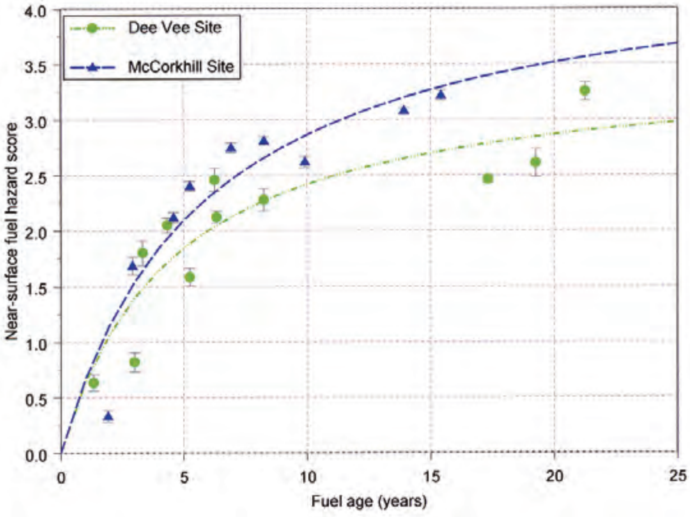

Figure 4. Change in hazard score of the near-surface fuel layer on blocks of different age after burning at Dee Vee and McCorkhill sites (bars indicate one standard error of the mean) from Project Vesta (Gould et al *2007a).*

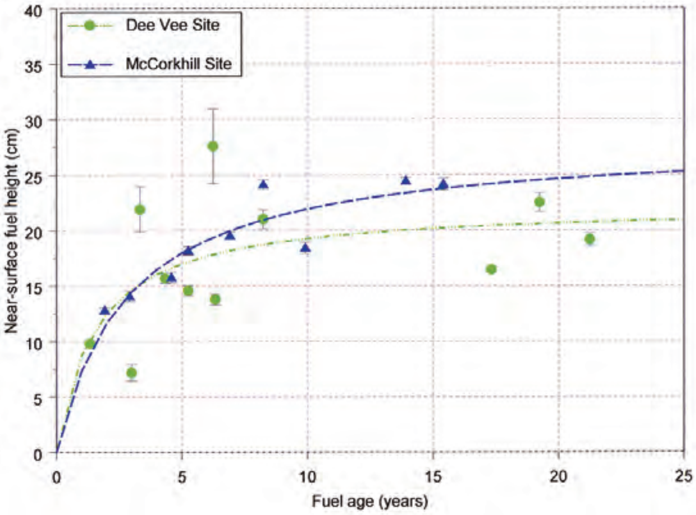

Figure 5. Accumulation of height of the near-surface layer on blocks of different age after burning at Dee Vee and McCorkhill sites (bars indicate one standard error of the mean).

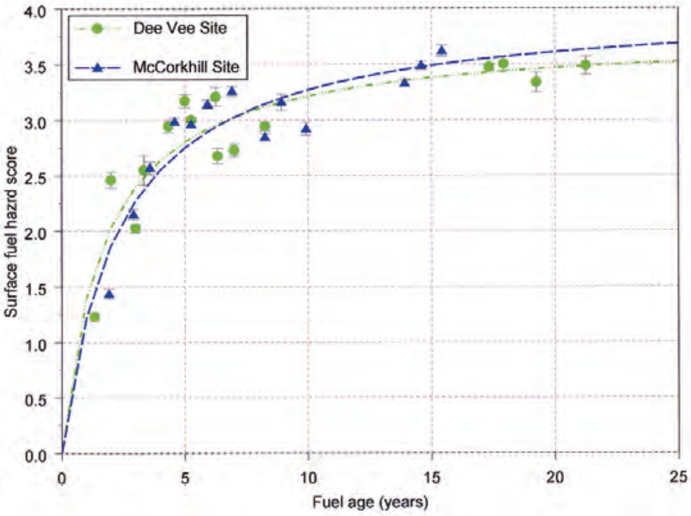

Figure 6. Change in hazard score of the surface fuel layer on blocks of different age after burning at Dee Vee and McCorkhill sites (bars indicate one standard error of the mean).

assigned a fuel height of 35 cm based on depth measurements in layers visually assessed as the mean layer when subjectively stratified into low, medium and high categories. These fuels did not burn because the fire was controlled in light fuels but the figures were used later for extrapolation of fire spread in the absence of prescribed burning.

Surface fuel characteristics varied according to time since fire, but a difference between western and eastern parts of the fire was less evident. This is consistent with the surface fuel hazard score for the Dee Vee and McCorkhill sites. Surface fuel hazard ratings were therefore estimated directly from the accumulation curve for Dee Vee developed using Project Vesta data (Fig. 6)

COMPARISON OF RATE OF SPREAD WITH FIRE PREDICTION TABLES

The emergency nature of fire suppression means that it is difficult to obtain sufficient data to accurately validate experimentally-determined fire spread equations. Fire crews have limited opportunities to make a detailed record of fire perimeter locations. Even when officers are specifically designated to record fire spread, access and visibility are limited, and it can take considerable time (sometimes hours) to negotiate forest roads and move from one location to another. Aerial observations for fire control are often more concerned about whether the fire has crossed a particular road or not, rather than the exact position or shape of the fire. Suppression action may hold up the spread of the fire, and when crews are having difficulty holding a fire the exact time of a breakaway may not be recorded.

A reconstruction of the fire spread is presented in Fig. 7. In this reconstruction, I have made the following assumptions:

- wind speed and direction recorded at the automatic weather station at Bickley could be applied at the fire area;
- fire starting at a point and spreading under a steady wind direction, would have a length to breadth ratio of 6:1;
- fire spread into the prevailing wind direction (backing spread) was constant at 30 m h^{-1}
- narrow strips of unscorched canopy, roughly parallel to the prevailing wind direction, were the result of a backing fire of low intensity resulting from a local wind shift causing the wind to blow the flames along the flank towards the burnt area. The rate of spread within these narrow strips was similar to the backing rate of spread of 30 to 50 m h^{-1};
- narrow strips of unscorched canopy designated the shape of the perimeter of the fire in that area;
- intermediate rates of spread between confirmed observations of the head fire location were adjusted proportionately for variation in wind speed, fuel moisture and fuel load using the Vesta fire spread equations (Gould *et al.* 2007a).

This reconstruction was necessary to place point observations of fire location in context with the overall fire perimeter and to allow more a detailed evaluation of the performance of the fire spread equations.

Observed average rates of spread were determined for three periods:

- Fire 76 from origin at 1810 hours on 15 January to location at 0410 hours on the 16 January of 6km in 10 hours (600 m h^{-1});
- combined fire spread from Ashendon Road at 1215 hours to the headfire location plotted by the air observer at 1547 hours on 16 January. Average spread was 1475 m h^{-1}. A 5-minute estimate of rate of spread at 1600 hours was 1200 m h^{-1};
- spread of the major head of the breakaway along the southern flank on 17 January between 0400 and 0500 hours. The fire broke away near the Boddington-Forrestfield powerline, crossed Dale Road at 0630 hours and the Brookton Highway at 0951 hours, as recorded on Landsat imagery.

The predicted maximum rate of spread using the FFBT is given in Table 2. The wind ratio generally used by DEC for fire danger rating is 5:1 and this ratio was used for spread prediction calculations at the Mundaring office.

This ratio gives very low rates of spread across the range of wind speeds commonly encountered during the fire and, in my opinion, grossly under-predicts fire spread. The exposure of the anemometer at Bickley is about 8 m above the top height of the canopy and a 3:1 ratio is considered to be more appropriate for this exposure. Also, a ratio of 3:1 was found to be common for several tower sites (Neil Burrows[4] [4] pers. comm.) and I consider this should be used universally in dry forests for wildfire spread prediction during summer. Although a ratio of 3:1 is used for wildfire prediction by some fire behaviour officers (Lachie McCaw pers. comm.[5]), it is apparent from the documentation this was not the case for the determination of initial spread made at the Mundaring office.

The Project Vesta equation to predict fire spread from wind speed, fuel moisture and fuel characteristics is:

$$R_{ss} = [30 + 3.102(U_{10} - 5)^{0.904} \exp(0.279 S_{fhs} + 0.611 NS_{fhs} + 0.013 NS_h)] \cdot [(M_f^{-1.495})/0.0545] \cdot [exp^{0.069\,\Phi}]$$

where:

R_{ss} = the potential quasi-steady rate of spread (m h^{-1})
U_{10} = wind speed at 10 m in the open (km h^{-1})
S_{fhs} = surface fuel hazard score
NS_{fhs} = Near-surface fuel hazard score
NS_h = Near-surface fuel height (cm)
M_{f}= fine dead fuel moisture content (%)
? = slope of the ground surface

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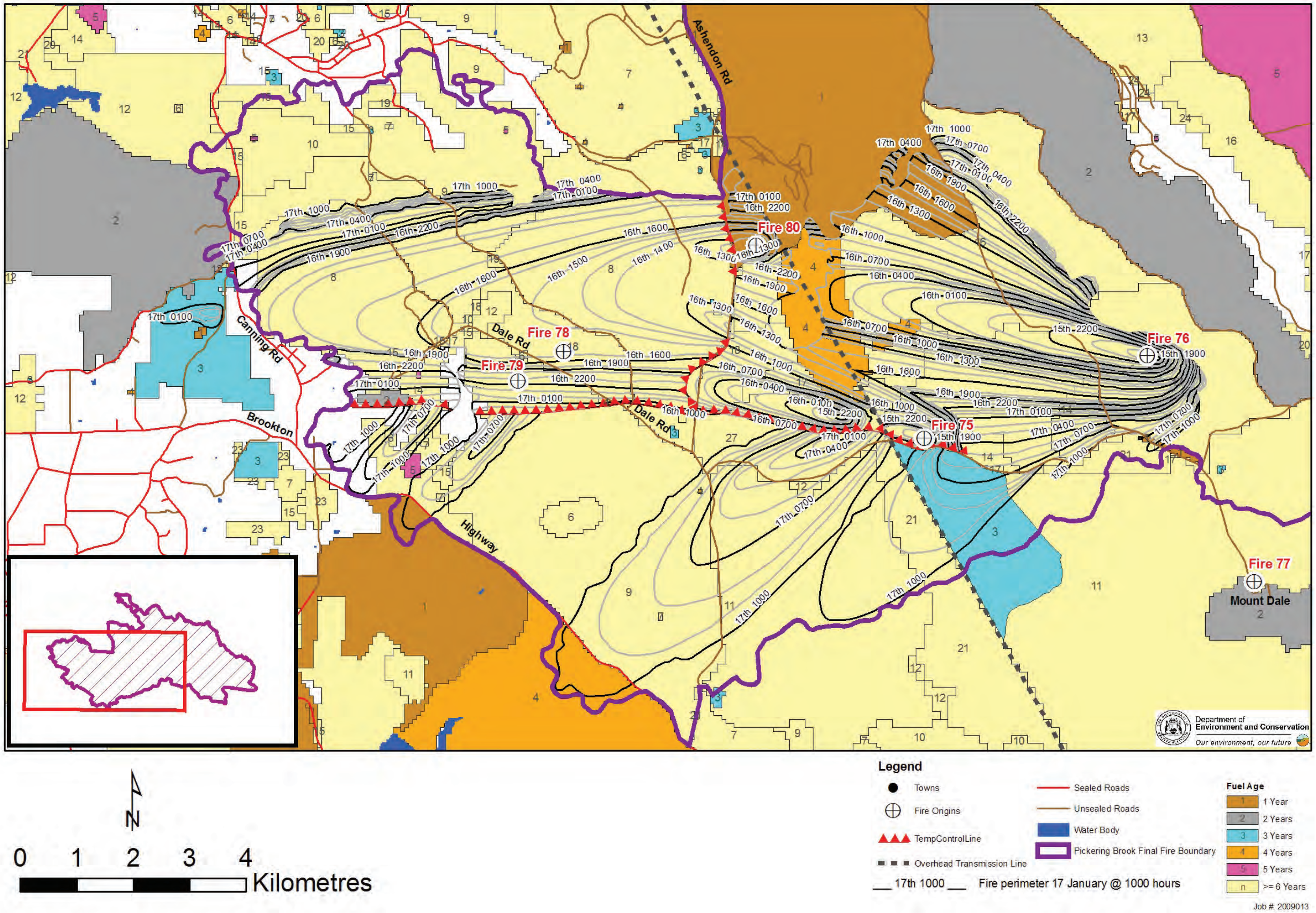

Figure 7. Reconstruction of the pattern of fire spread of the Pickering Brook fire, between 1800 15 January and 1000 17 January 2005. Isochrones show the perimeter of the fire at hourly intervals with additional isochrones at 1430 and 1545 hours 16 January.

Fuel characteristics for predicting fire spread in different fuel ages are given in Table 1.

A comparison of the rate of spread predicted by the Project Vesta equations and the FFBT using a 3:1 wind ratio with the average observed rate of spread is given in Table 3.

Both the Project Vesta equation and the FFBT for northern jarrah using a wind ratio of 3:1 predicted reasonably well for mean rate of spread on the 15 and 16 January. There were insufficient observations to directly validate rate of spread predictions for individual fuel ages. However, DEC officers observing the fire noted the increased fire behaviour in older fuel loads, and it is reasonable to accept that the relative fire spread in different fuels of different age described by the Project Vesta equation is more accurate than that predicted by the FFBT.

DISCUSSION

The function in the FFBT that describes the increase in rate of spread (R) with increasing wind speed (U) is of the form (Peet 1965):

$$R = 1/(a-bU)$$

where a and b are constants determined experimentally.

This type of function results in a very rapid increase in rate of spread at high windspeeds so that the speed of the fire eventually exceeds the wind speed, which is clearly impossible. There is now good evidence that the relationship describing the spread of a large continuously heading fire is linear (Cheney *et al.* 1998, Linn and Cunningham 2005). The curvilinear relationships described by Peet (1965), McArthur (1962; 1967) Rothermel (1972) and Burrows (1999) are inappropriate for extrapolation to strong winds beyond the range of the original data because they describe the spread of small developing fires where there is a change in spread mechanism from a backing to a heading fire. It is now accepted that two equations are needed to describe spread above and below the threshold wind speed, above which the fire changes from a predominantly backing fire to a continuously spreading headfire.

The statistical model used to form the Project Vesta equation describes rate of spread as a power function of wind speed within an exponent of 0.904, which is almost linear above a threshold wind speed of 5 km h^{-1} at 10m in the open. For this reason, and because the Project Vesta equation used fuel structural characteristics to determine rate of spread, a further comparison of the performance of the Project Vesta equation was made for key periods of fire spread.

1800 hours 15 January – 1200 hours 16 January

Fire 76 burnt under a steady wind direction of 110°, which was confirmed by the bearing from the origin of the fire to the location of the head fire at 0500 hours. The fire burnt for 6km through 16 year-old fuel until it ran into three year-old fuels, which effectively stopped the forward spread of the fire. If no allowance is made for the initial build-up of the fire, then the Project Vesta equation over-predicts distance travelled in six hours by 18%. However, under such a steady wind direction and under stable atmosphere at night, the time for a forest fire to develop a head fire wide enough to reflect its potential rate of spread could be as long as three hours. I have assumed a constant build-up over three hours between 1800 and 2100 hours before the fire reached its predicted potential rate of spread of 826 m h^{-1} and it then spread at the rate predicted for the prevailing conditions over the next seven hours. On this assumption, the difference between the predicted and actual distance travelled is -3%.

Fire 75 started at around 1800 hours and spread considerably slower that the predicted rate of spread. However, it was held up by suppression forces at the Boddington-Forrestfield powerline for several hours until it spotted across the powerline break. The exact time and location of the spot fire is not known but it is assumed it originated 500 m west of the powerline along the projection of the central axis of fire at 2200 hours. After allowing three hours for the spot fire to build up to the potential rate of spread, the predicted rate of spread appeared to reasonably describe the progress of the fire until it was held up by suppression crews taking action east of Ashendon Road at around 0300 hrs. This fire crossed Ashendon Road but was contained in eight year-old fuels west of Ashendon Road.

1200 – 2400 hours 16 January

The exact time and number of breakaways across Ashendon Road after 1200 hours is uncertain. Field inspection identified two major breakaway fires. One was opposite Fire 80 in the two year-old fuel and the second breakaway fire 1.5km south. Crews tried to track the flanks of these fires before attempts at suppression were abandoned. Fires originating from these locations are consistent with later observations of fire spread and the shape of the fire as indicated by the scorch pattern interpreted from Landsat imagery.

I have assumed that these fires would individually take time to develop before they coalesced into a wide head and assumed that they spread west some 750–1000 m by 1300 hours, which is reasonably close to the rate of spread predicted by the Project Vesta equations of 769 m h^{-1}. These fires coalesced more rapidly over the next 90 minutes to form a single continuous head by 1430 hours. However, if this assumption is correct, the average rate of spread between 1430 and 1600 hours was around 2000 m h^{-1}, or twice the predicted rate of spread in 18 year-old fuels under the prevailing conditions.

Models to predict the fuel moisture content use different assumptions. The latest process model by Matthews (2006), used for these calculations, predicts the moisture content from an initial moisture value and tracks the progressive changes in moisture with changing atmospheric conditions. The empirical model used by McArthur (1967) in his forest fire danger meter assumes there is some time-lag after a change in relative humidity before the fuel reaches the equilibrium moisture content and his tables predict an average value from temperature and relative humidity when the fuel is absorbing water. This model predicts lower fuel moisture contents during the afternoon and, if used as an input to the Project Vesta fire spread equation, results in a higher predicted rate spread (see Table 4).

Between 1430 and 1700 hours the McArthur model predicts fuel moisture content of 4%. When used in the Vesta equations this would give a predicted rate of spread of 1743 $m\ h^{-1}$, which is closer to the rate of spread deduced from field observations.

There are other factors that may have contributed to a higher rate of spread observed during this run:

- the front created by multiple breakaways from Ashendon Road was more than 1km wide and is significantly higher than that of the experimental fires which were mostly around 100 m wide. The potential rate of spread of very wide fronts may be higher than that determined by the experimental fires;
- tall grass trees in the area may have carried substantial fuel in unburned skirts. The elevated fuel supported by the grass trees' skirts may result in a higher rate of spread than that determined using the characteristics of the surface and near surface fuel alone;
- wind speed in the fire area may have been significantly higher than that measured by the anemometer at Bickley;
- errors in observation of time and location.

Measurements during the Project Vesta experiments and observations during the Canberra bushfires in 2003 show that the spatial variation of wind in the landscape is substantial and often poorly represented by a measurement at a single location. This creates considerable uncertainty in the reconstruction of any wildfire or, for that matter, the prediction of forward spread during wildfire events. It also means that precise verification of experimental results describing the effect of fuels on rate of spread using wildfire data is very difficult, if not impossible.

In my opinion, the adjustment of rate of spread according to the ratios determined by the Project Vesta fire spread equations for fuels of different age provided a reasonable description of the fire behaviour as manifested by the spread pattern illustrated in Fig. 7, the pattern of fire behaviour illustrated by the differential burning patterns, the spot observations of fire spread, and the observational reports of changes in fire behaviour made by experienced fire officers.

0000 – 1000 hours 17 January

Analysis of the spread pattern suggests that the first breakaway on the southern flank occurred in the vicinity of Occidental plot number one between midnight and 0100 hours when the wind first shifted to an east-north-easterly direction. This breakaway was described as a long, narrow fire and was observed across Dale Road at around 1545 hours.

The rate of spread predicted from the Project Vesta equations was about 40% less than the average spread deduced from fire spread observations (Table 4). The relative humidity overnight reached a maximum value of only 52% at 0400 hours. As a result the difference in moisture content predicted by Matthews' process moisture content model and the McArthur absorption moisture content model was up to 4%.

When the absorption fuel moisture content predicted by the McArthur model was used in the Vesta equations, the predicted rated spread is much closer to the observed rate of spread (Table 4).

It would appear from these observations that during the afternoon of 16th under windy conditions at night on the 17th January the absorption fuel moisture content model used by McArthur provides a better prediction of rate of spread than when moisture contents are derived from process fuel moisture model. However, this model too is really not appropriate because desorption conditions with rapidly falling relative humidity existed after 0400 hours. High rates of spread during the night were also observed at the January 2003 Mount Cooke fire in Perth Hills District (L. McCaw pers. comm.[6]). There appears to be a real need to develop better models to predict fuel moisture content, particularly when low humidity persists overnight.

East of the Boddington-Forrestfield powerline, the uncontained flank of Fire 76 spread southward towards Dale Road. Some edging had been carried out for about 2km east of the powerline along Dale Road. There is no record of the time that this flank crossed Dale Road, but it appears it had not crossed by 0400 hours. Landsat imagery and the shape of the final perimeter indicate that this breakaway made a south-westerly run and had crossed Permit Road by 1000 hrs. This run of the fire spread first though 3 year-old fuel east of the powerline and then through 20 year-old fuel west of the powerline. The spread rates predicted by the Vesta equations for the prevailing fuel and weather conditions using the calculated absorbtion moisture content are illustrated in Fig. 7 and indicate that the fire broke across Dale Road shortly after 0400 hours.

The rate of spread in the 20 year-old fuel was six times faster than the three year-old fuels and the intensity of the fire in the 20 year-old fuel was more than 20 times the intensity in the three year-old fuel (Table 5). The difference in fire intensity and the resulting impact on vegetation either side of the Boddington-Forrestfield powerline was very obvious in the fire severity map developed by Dr Li Shu[5] [7] from Landsat imagery taken after the fire (Fig. 8). Nine months after the fire some of the mature trees had been killed outright and epicormic sprouting on trees in the 20 year-old fuel was sparse in the crowns indicating that lethal heat had penetrated to the cambium on quite large branches, and sprouting was mainly confined to the

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[5] [7] Dr Li Shu Fire Management Services, Department of Conservation and Environment Perth WA.

[6] Principal Research Scientist, Science Division, Department of Environment and Conservation, Manjimup.

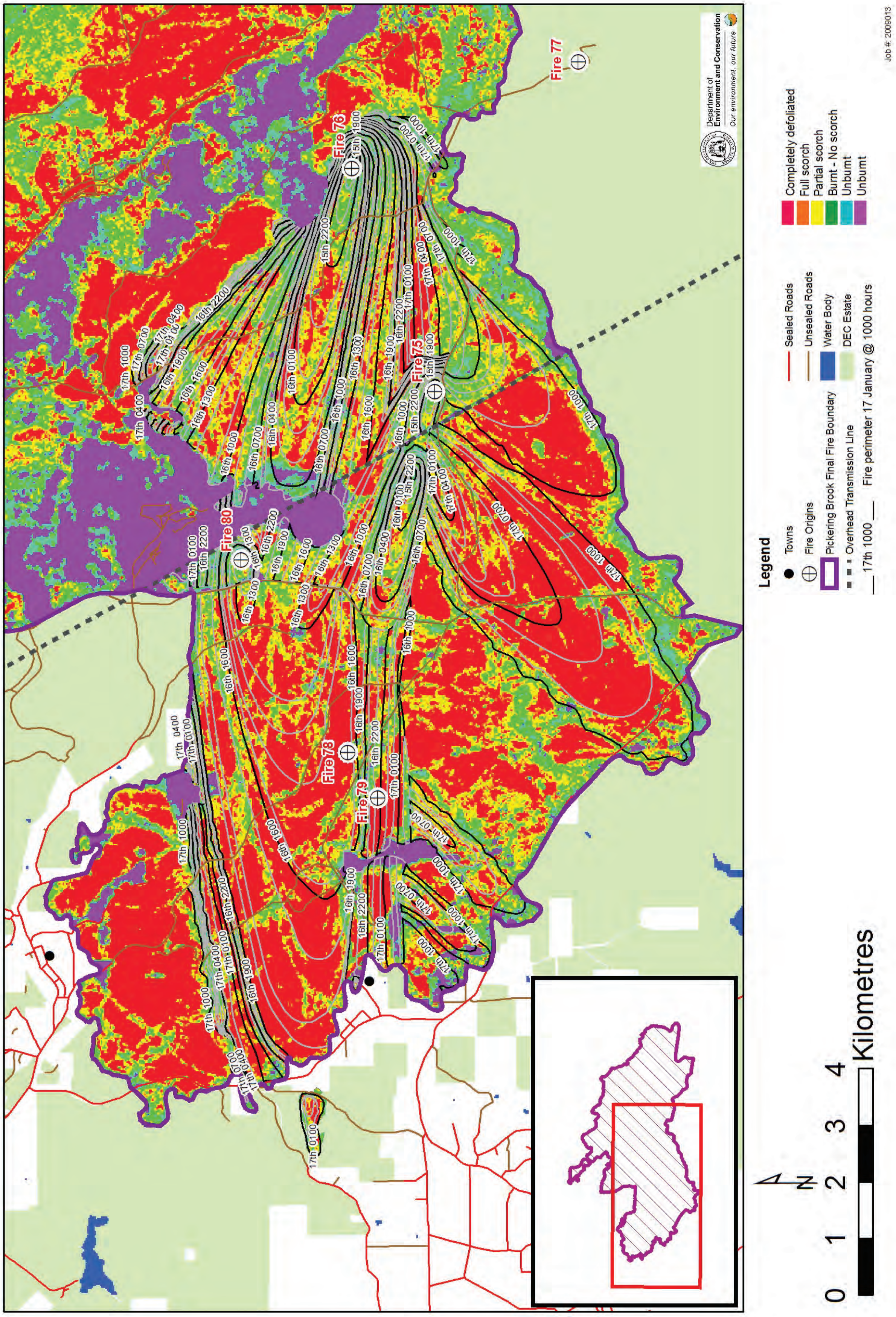

Figure 8. Enhanced satellite image showing relative change in above ground biomass following the fire. Isochrones show the perimeter of the fire at hourly intervals with additional isochrones at 1430 and 1545 hours 16 January.

Figure 9. Comparison of damage by fire in 3 year-old fuel (left) and 20 year-old fuel (right) on either side of the Boddington-Forrestfield powerline. Photographs taken nine months after the fire (Photos: Phil Cheney).

lower trunk where the bark was thickest (Fig. 9). Although the burning conditions increased in severity from the start of the spread in the 3 year-old fuels until the finish of spread in the 20 year-old fuels, the conditions at the time of crossing the powerline would be the same allowing a valid direct comparison at this location.

Projected fire threat in the absence of fuel reduction

The extent of burning in rural Western Australia, and particularly within forest areas is probably the lowest it has ever been in recent history (Ward & Sneeuwjagt 1999). However, the fuel reduction program carried out by DEC provided a mosaic of areas of low fuel load that were significant in reducing the area burnt by the Perth Hills fires, both by restricting the rate of spread and by reducing the intensity thereby making fire suppression more efficient.

If we assume that there had been no fuel reduction burning and there had been no recent wildfires in the area for at least 20 years we can construct a realistic scenario using the expected rate of spread in 20 year-old fuels (fires in fuel older than 20 years will behave in much the same way) and observations of the difficulty of suppression experienced during these fires.

15 January 1800 – 2400 hours

On the first night we can assume that with similar resources initial attack would control Fire 77 on Mount Dale and that Fire 75 and Fire 76 would burn at much the same rate and present the same suppression difficulty; i.e. Fire 75 would be checked at the Boddington-Forrestfield powerline until it spotted across the powerline around midnight, and that Fire 76 would burn unchecked for six hours.

16 January 0000 – 0900 hours

After midnight the influence of continuous heavy fuel would become apparent. Although it is likely that there would be more spot fires, we can assume that Fires 78 and 79 that occurred near Carinyah trail around 0130 hours would also be controlled but Fire 80, which started to at 0215 hours down-wind of Fire 76, would develop rapidly and cross Ashendon Road. Fire 76 would not be held up by three year-old fuels and would also cross Ashendon Road by 0800 hours.

Whereas fire fighters were able to hold the head fire of Fire 75 in the eight year-old fuel west of Ashendon Road, they were unable to contain spot fires from burning-out operations in 16 to 17 year-old fuels east of Ashendon Road once the fire danger increased around 1200 hours. In our scenario where the fuel is 20 years old, it is highly unlikely that they would be able to check the spread of both fires, and if they did they would not have been able to hold them after 0900 hours when fuel moisture content dropped below 10%. At this level of fuel moisture content, ignition by small fire brands becomes increasingly common.

In my opinion, the net result would be that at 0900 hours the head fire would be at least 2km west of Ashendon Road and less than 4km of the southern perimeter would be controlled along Dale Road.

16 January 0900 – 2400 hours

After 0900 hours the fires would start to spread rapidly with erratic fire behaviour. At an average rate of spread of

900 m h^{-1}, the head fires would join up and burn across Westons Road and the Carinyah Trail by 1200 hours. After 1200 hours, the average rate of spread is calculated to be around 1800 m h^{-1} over the next four hours, so that by 1600 hours the fire would have crossed the Canning Road and Springvale Road north of the Brookton Highway. If the fuel west of the Canning Road had the characteristics of 20 year-old northern jarrah fuel that has been used to estimate rate of spread up to this point, the fire would have continued to burn over the escarpment, and by 2000 hours is estimated to be west of the Kwinana Northern Terminal powerline and within 2km of the Albany Highway at Gosnells.

If however, the fuel west of Canning Road had characteristics similar to those measured at Stinton Cascades Nature Reserve where the near-surface fuel was rated a full hazard class higher than the 20 year-old fuels and elsewhere and had a near-surface depth of 35 cm, the rate of spread between 1600 and 1700 hours is estimated to be 4300 m h^{-1}. The projected fire would then burn across the Albany Highway at 1700 hours and burn into Roleystone and Gosnells by evening.

17 January 0000 – 1000 hours

The rapid spread of fire into the peri-urban built-up area would mean that all suppression forces would be direct to property protection so that by midnight of 16 January none of the southern flank would have been controlled apart, perhaps, for a stretch of 4km of flank along Dale Road west of Ashendon Road.

In continuous 20 year-old fuels it is calculated the fire would travel around 10km between midnight and 1000 hours. This means that the fire would burn through the area of Roleystone across the northern end of the Canning Dam and through the Darling Range Regional Park and reach the Albany Highway in the vicinity of Bedfordale. Again, if the fuels were given the higher rating applicable to escarpment fuel, the fire would have continued in a south-westerly direction to the vicinity of Byford.

Although a small fire would be influenced to by the negative slopes as it burnt over the Darling escarpment, when fires are large and are burning under dangerous strong-wind conditions, spotting carries the fire across negative slopes and the overall spread appears similar to that on level ground. It is also interesting to note that the wind at Perth airport during the night was stronger than that measured at Bickley whilst the north-easterly winds were blowing, indicating that there may have been a strong katabatic effect as the north-easterly blew down the Darling Range.

The confusion associated with a high-intensity fire burning into a built-up area at night cannot be understated. It is likely that there would be a breakdown of normal communications and the suppression effort would be chaotic, leaving most individuals threatened to fend for themselves. A similar situation occurred in Victoria during Ash Wednesday 1983 when the Trentham fire burnt into the townships of Macedon and Mount Macedon after dark, causing widespread destruction of houses and other buildings.

In the absence of organised fuel reduction it is possible that high fuel loads would build up on individual properties and home gardens, as was the case in Canberra in 2003. As a result, fire would be likely to penetrate a significant distance into the continuously built-up area and cause widespread damage.

17 January 1000 – 2400 hours

After 1000 hours the wind changed to the southwest and a massive convection column developed above the fire (Fig. 10), reflecting very unstable atmospheric conditions associated with the change (Mills and McCaw 2010). At the time this photograph was taken around 1500 hours, more than 50% of the perimeter of the fire had been

Figure 10. Massive convection column development associated with unstable air, circa 1500 hours 17 January 2005 (photo from Perth airport by A Felton).

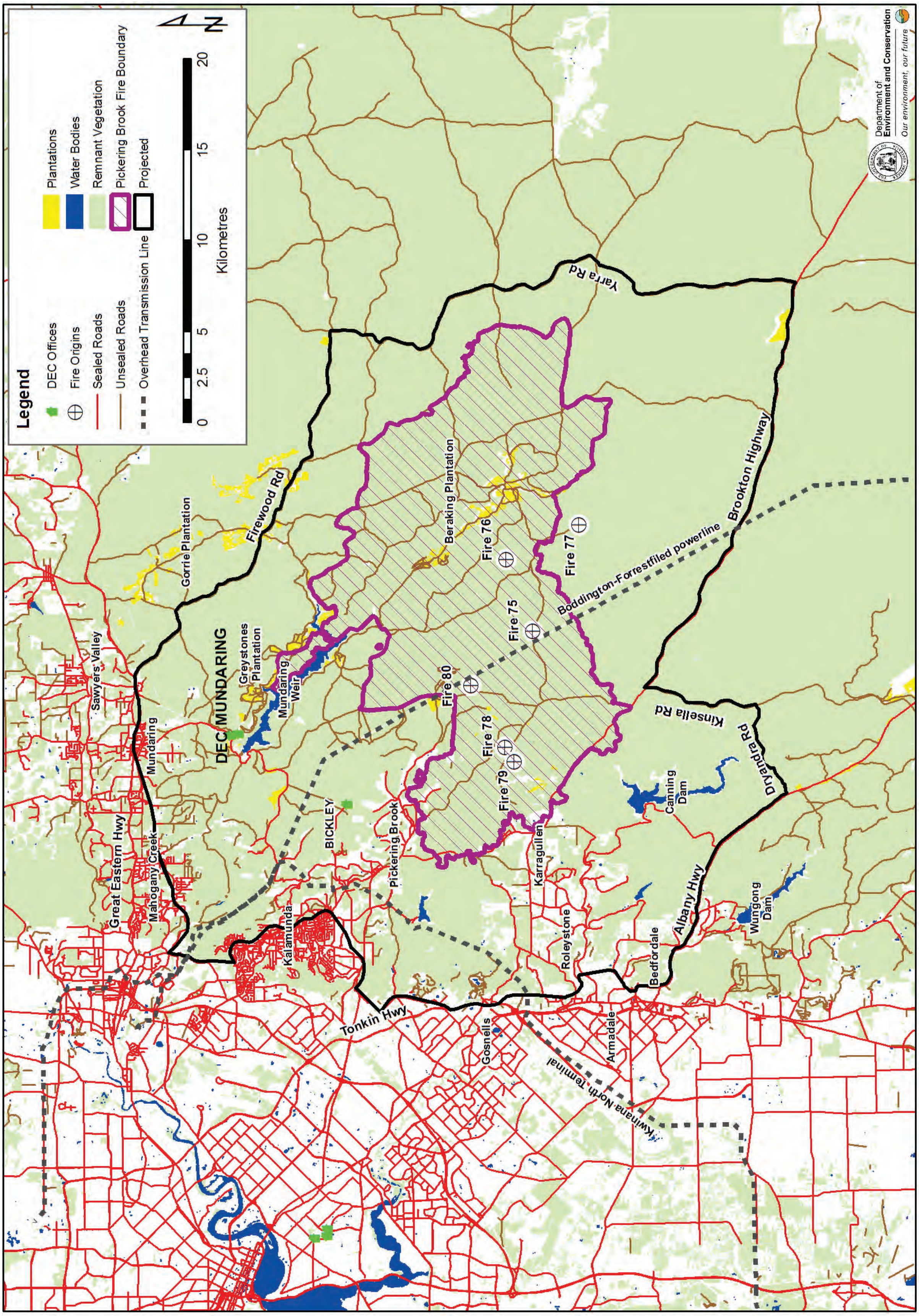

Figure 11. Comparison of the actual area burnt and the projected area that could have been burnt assuming uniform fuel age of 20 years in the absence of prescribed burning.

controlled in light fuel leaving only 30km of burning perimeter, mostly on the eastern side of the fire.

As discussed earlier, in a scenario where fuels are uniformly heavy, little of the perimeter would have been controlled at this time except where the fire had reached the western edge of continuously built-up area at Gosnells and Armadale. Under the south-westerly wind, pockets of unburnt fuel in the Roleystone area would burn rapidly upslope; the additional heat release from the heavier fuels, including that of burning houses and the total perimeter, could have created powerful convective winds due to the unstable air and resulted in a mass conflagration and widespread property damage along the Darling escarpment.

Projected fire spread after 17 January

I have not examined the spread or the development of the fire on days after 17 January in any detail. It was obvious that two year-old fuels either side of the Mundaring weir were critical in preventing rapid spread of the fire towards the north-west.

In the absence of prescribed burning to reduce fuel and in the event of the large fire, the suppression strategies available to fire control are very much reduced and are usually confined to burning-out from established roads and tracks as favourable wind directions blow the fire away from the control lines. As the fire gets larger and control becomes more urgent there is less time to open up minor tracks. The final area of the fire could well have been bounded by the Albany Highway, Dryandra Road, Kinsella Road and the Brookton Highway in the south; Yarra Road in the east and the Firewood Road connecting Yarra Road with the Great Eastern Highway in the north-east (Fig. 11). It is quite possible that under the weather conditions that prevailed over the next five days, the north-westerly run of the fire would have burnt through Greystones plantation and threatened the towns of Mundaring, Sawyers Valley, Mahogany Creek and most of the peri-urban development on the Darling escarpment between the Great Eastern Highway and Roleystone. The estimated area burnt under this scenario is 106 000 ha.

CONCLUSION

Fuel reduction by prescribed burning was a very significant factor in reducing the area burnt and the damage done to State forest, conservation reserve and private property during the Pickering Brook fire. Prescribed burning reduced both the spread and intensity of this wildfire by changing the structure of the fuel and reducing the load of fine fuel. This reduction persisted for at least eight years. Fires that ran into areas one year after being prescribed burnt were stopped and required no further suppression action. Fires will spread slowly in two and three year-old fuels in jarrah forest, but these fires are relatively easy to suppress. Wherever possible, spot fires in light fuel should not be left to slowly develop but should be suppressed as soon as possible. They are capable of throwing firebrands across control lines under severe burning conditions and until they are mopped-up are potential sources of outbreak.

Compared to the behaviour in 20 year-old fuels, fires in 8 year-old fuels spread significantly slower and were easier to control, confirming observations made during Project Vesta experiments.

The fuel structure in higher rainfall forests along the Darling escarpment is considerably more hazardous than in fuels of the same age further east that are representative of most of the northern jarrah. Under similar weather conditions, rates of spread in these fuels will be 2–3 times faster than in the same-aged fuel elsewhere. Particular attention should be paid to changing the structure of the fuel by prescribed burning in forests and reserves along the Darling escarpment where they are close to private property and suburban development. Because of the increased hazard of these fuels, they should be burned at a shorter rotation than is normally applied in the northern jarrah and this rotation should not exceed five or six years.

Project Vesta equations satisfactorily describe the change in fire behaviour with change in fuel structure. Predictions of rate of spread using fuel moisture values predicted by a process moisture content model appeared to under-predict rate of spread compared to the observed spread rates. This was particularly evident when low humidity and low fuel moisture persisted at night. Rates of forward spread predicted by the Project Vesta equation were much closer to observed rates over a range of fuel ages and structure when fuel moistures from the McArthur (1967) absorption moisture content model were used. There is a need to better predict fuel moisture when the relative humidity is low and dry windy conditions persist overnight and examine the relationship between rate of spread and fuel moisture under these conditions.

The FFBT equations provided a reasonable estimate of the initial rate of spread using a wind ratio of 3:1 at wind speeds less than 25 km h^{-1}. The shape of the relationship describing the effect of wind on the rate of spread is such that these equations will overestimate rate of spread at high wind speeds, thus making it difficult to verify the relationship between fuel load and the rate of spread.

If the fuel reduction burning program by the Department of Environment and Conservation had not been carried out, very little effective suppression would have been possible for several days until the weather moderated and indirect suppression could be carried out from established roads. The Pickering Brook fire would have burnt over the Darling escarpment and into the areas of Roleystone and Gosnells in less than 24 hours after ignition. In my opinion this fire would have resulted in extensive damage to homes and the loss of life in the Perth Hills suburbs.

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Table 1

Fuel characteristics assigned to fuels of different ages to predict rate of spread using the FFBT and the Project Vesta equation.

Fuel age (years)	Fuel load [1] (t/ha)	Surface fuel Hazard score	Near-surface Hazard score	Near-surface fuel height (cm)
26 (west)	25	3.5	4	35
20	22.5	3.5	2.9	20
18	21	3.5	2.8	20
16	20	3.4	2.7	20
11	15	3.3	2.5	19
9	13	3.2	2.4	18
8	13	3.1	2.2	17.5
3 (west)	5.5	2.5	1.5	15
3 (east)	5.5	2.5	1.5	15
2 (east)	4	2	1.5	10

[1] Fuel load taken from Table 6.8 FFBT (Sneeuwjagt and Peet 1985)

Table 2

Predicted rate of fire spread (ROS) using FFBT for wind ratios of 3:1, 4:1 and 5:1

Spread Period	Wind Speed[1] (km h^{-1})	Estimated FMC[2] (%)	Fuel Age (years)	Fuel Corr. Factor	Wind 3:1[3] ROS (m h^{-1})	Wind 4:1 ROS (m h^{-1})	Wind 5:1[4] ROS (m h^{-1})
January 15 – 16 1800 – 0400							
1800 – 2100	20	6	16	2.7	756	391	297
2100 – 2400	32	8	16	2.7	2052	837	351
2400 – 0400	31	12	16	2.7	715	324	183
January 16 1200 – 2000							
1200 – 1430	27	6	8	1.6	1088	448	232
1430 – 1600	21	5	18	2.7	972	499	351
1600 – 1700	21	5	8	1.6	576	296	208
1700 – 2000	16.5	7	8	1.6	192	144	105
January 17 0400 – 1000							
0500 – 0630	28	13	11	2.1	378	174	101
0630 – 0830	28	11	9	1.8	432	189	108
0830 – 1000	28	7	9	1.8	954	396	216

[1] From Bickley anemometer 8 m above top height of the canopy.
[2] Estimated by model of Matthews (2006).
[3] Recommended wind ratio for Bickley anemometer.
[4] Wind ratio used for fire spread prediction by DEC Mundaring.

Table 3

Comparison of Rate of Spread (ROS) predicted by the Project Vesta equations and the FFBT with mean observed rate of spread

Spread Period	Wind Speed[1] (km h^{-1})	Temp. (°C)	RH (%)	FMC[2] (%)	Fuel Age (years)	ROS Vesta (m h^{-1})	ROS FFBT[3] (m h^{-1})	ROS Mean (m h^{-1})
January 15 –16 1810 – 0410								
1800 – 2100	20	24	23	6	16	826	756	600
2100 – 2400	32	19.6	38	8	16	897	2052	
2400 – 0400	31	13.6	63	12	16	473	715	
January 16 1200 – 2000								
1200 – 1430	27	29.4	24	6	8	769	1088	1110
1430 – 1600	21	30.3	20	5.5	18	1083	972	2000
1600 – 1700	21	30.3	20	5.5	8	1011	576	1050[4]
1700 – 2000	16.5	24.9	26	7	8	353	192	855[5]
January 17 0445 – 0951								
0445 – 0630	28	16.6	52	13	11	322	378	860
0630 – 0830	28	20.0	40	11	9	375	432	750
0830 – 0951	28	27	25	7	9	737	954	1133

[1] From automatic weather station Bickley.
[2] Extrapolation from model of Matthews (2006).
[3] Northern jarrah; wind ratio 3:1.
[4] 5-minute spread of 1200 m h^{-1} observed at 1548 hours.
[5] Spread measured from 1700 to 1900. Spread after 1900 may include back burning.

Table 4

Comparison of predicted rates of spread (ROS) using different moisture models with the observed rate of spread deduced from field observations.

Time (hrs)	Process FMC (%) (Matthews)	Predicted ROS (m h^{-1})	Absorption FMC (%) (McArthur)	Predicted ROS (m h^{-1})	Observed ROS (m h^{-1})
16 January					
1200 – 1430	6	769	5	1009	1110
1430 – 1600	5.5	1083	4	1743	2000
1600 – 1700	5.5	667	4	1074	1050
1700 – 2000	7	353	4.5	683	855 [1]
17 January					
0400 – 0630	13	352	9	558	860
0630 – 0830	11	382	8	603	750
0830 – 1000	7	749	5	1218	1133

[1] 1700 – 1900 hours but may include back burning after 1900 hours.

Table 5

Comparison of the head fire rate of spread and intensity in three year-old and 20 year-old fuel

Fuel age (years)	Rate of spread (m h^{-1})	Fuel load (t ha^{-1})	Head fire intensity [1] (kW m^{-1})
3	300	5.5	825
20	1854	22.5	20 645

[1] Calculated using a heat yield of 18 000 kJ kg^{-1}