The path and behaviour of the Kin Kin fire (Donnelly Fire 31)

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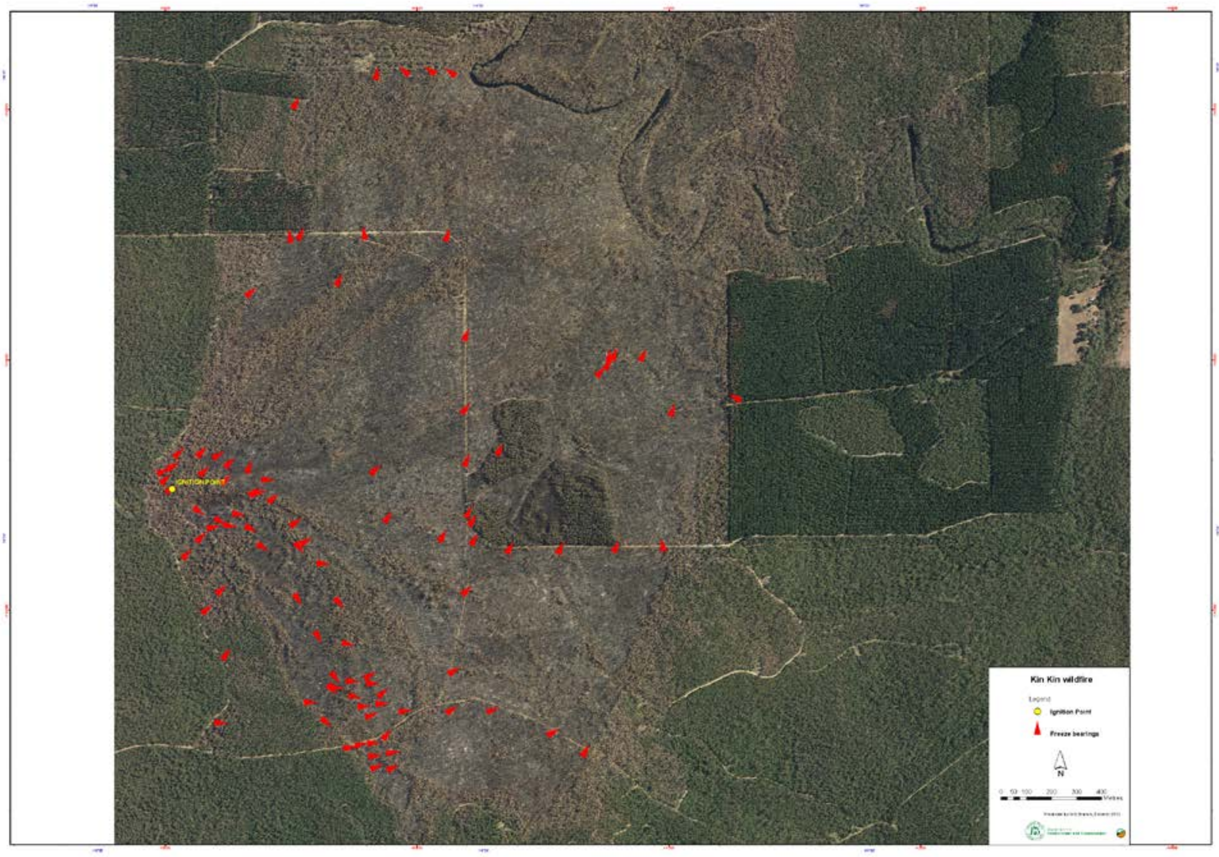

Aerial photograph of the Kin Kin fire ground. Red arrows indicate vegetation freeze, or approximate wind and headfire direction when the fire was at that location.

1. Introduction

The Kin Kin fire (DEC Donnelly Fire 31) started in Kin Kin State forest about 25 km south-east of Manjimup from a lightning strike around noon on Wednesday 13 February 2013. A total of 1,232 ha was burnt comprising State forest (850 ha), private property (328 ha) and other public lands (54 ha). The fire is significant because it may have caused the death of a local resident whose dwelling on private property location 3573 was destroyed by the fire. The fire is also significant because of its severe behaviour in the first 4-5 hours of its run.

The purpose of this report is to reconstruct the path and behaviour of the fire from its origin in Kin Kin forest at about 1215 h to when it crossed the Warren River some four hours later at about 1630 h. It was during this run that a dwelling and other buildings on private property (pp) location 3573 were destroyed and when the fire displayed its most severe behaviour. After this time, the fire behaviour moderated significantly, commensurate with a moderation in surface burning conditions. This report does not deal with the incident management structure, suppression strategies and tactics.

Reconstruction and analyzing the behaviour of bushfires also provides an opportunity to evaluate the performance of fire behaviour prediction models. Two such models are used for jarrah forest fuels; the Forest Fire Behaviour Tables for Western Australia, or the Red Book (Sneeuwjagt and Peet 1998), and the Vesta Fire Behaviour Model (Cheney *et al*. 2012). The Red Book was developed from relatively small (< 1 ha), low to moderate intensity experimental fires mostly lit in 5-7 year old (yo) jarrah forest fuels (Burrows 1999) so is most suited to planning and implementing prescribed fires. The Vesta model was developed from larger (4 ha), moderate to high intensity summer fires in a range of fuel ages, so is most suited to predicting the behaviour of summer bushfires. Fuel quantity is the single fuel input for Red Book predictions whereas the Vesta model uses measures of fuel structure (Gould *et al*. 2007).

From a point ignition, a forest fire will develop slowly through an initial build-up phase before reaching a *quasi* steady state, or its potential rate of spread for the prevailing fuel and weather conditions. The rate of build-up, or acceleration of a bushfire starting from a point ignition, will depend on fuel and weather conditions, especially wind speed and moisture content, and fires may take 30-40 minutes to reach their potential rate of spread. This underlines the importance of early detection and a rapid and aggressive initial suppression response while fires are in the build-up phase and fire behaviour is relatively benign.

Reconstructing the path and behaviour of a bushfire after the event is a complex process involving a level of uncertainty and the necessity to make some assumptions in the absence of reliable information. I have used evidence gathered primarily from the following sources to determine the fire's cause and origin, and to reconstruct its path and behaviour:

- Fire dairies and eyewitness accounts of Department of Environment and Conservation (DEC) personnel involved in the suppression effort including ground and air crews.
- A fire ground survey to gather information about the extent of defoliation, scorch and charring to the vegetation as an indicator of flame height, fire architecture (shape) and fire intensity; the nature and extent of fuel removal as an indicator of fire intensity and fuel moisture condition; vegetation 'freeze' as an indicator of wind and headfire direction at various locations (see Plates 1-4). Field work was carried out on 18-20 February 2013. In all, more than 100 points were surveyed, focusing on the fire's likely path from its origin to when it reached the Warren River. Each survey point was geocoded using a GPS. Direction of vegetation freeze was determined using a compass.

- Observed and forecast weather and atmospheric soundings were obtained from the Bureau of Meteorology (BoM). Observed weather was sourced from BoM's automatic weather station (AWS) at Manjimup.
- Post-fire high resolution aerial photography of the fire ground undertaken by DEC on 20 February 2013, seven days after the fire.
- Opportunistic photographs and videos taken by DEC fire fighters on or near the fire ground.

Plate 1(Top left): Vegetation freeze indicating wind and headfire direction.
Plate 2 (Top right): Low scorch, defoliation to 0.5 m indicating low fire intensity.
Plate 3 (Bottom left): Full scorch, defoliation to 3 m indicating moderate fire intensity.
Plate 4 (Bottom right): Full defoliation to 30 m indicating very high fire intensity and a crowning fire.

2. Fire location and site description

During its main run on 13 February, the fire burnt in Kin Kin State forest, the Kin Kin pine plantation and bushland on private property some 25 km south-east of Manjimup. The location of the fire ground, the fire's final perimeter (19.6 km) and the control sectors are shown in Figure 1. From its origin in Kin Kin forest, the fire ran south-east under the influence of a NW wind, then spread to the north-east following a wind shift to the SSW (Figure 2). It initially burnt about 1.3 km south-east prior to the wind shift, then about 2.1 km north-east to the Warren River. Greatly assisted by a 4 yo prescribed burn in Topanup State forest, the fire was eventually contained and controlled south of Cormint Road, some 5 km north of Kin Kin Road.

2.1 Climate and fire weather

The region experiences a Mediterranean-type climate with cool wet winters and warm dry summers so is prone to bushfires. The long term average annual rainfall is ~1000 mm, with an average of about 110 wet days per year. Features of summer fire weather include the predominance of easterly and south-easterly winds, the onset of afternoon, southerly sea breezes, the development and movement of low pressure troughs and associated hot, dry and unstable weather (thunderstorms and lightning) east of the trough line and hot, dry northerly winds associated with troughs and blocking high pressure systems centred in the Bight. Relatively abrupt wind changes on the fire ground from the north to the south associated with trough movement or on-shore winds are a common feature during the bushfire season, often with dangerous consequences for fire fighters.

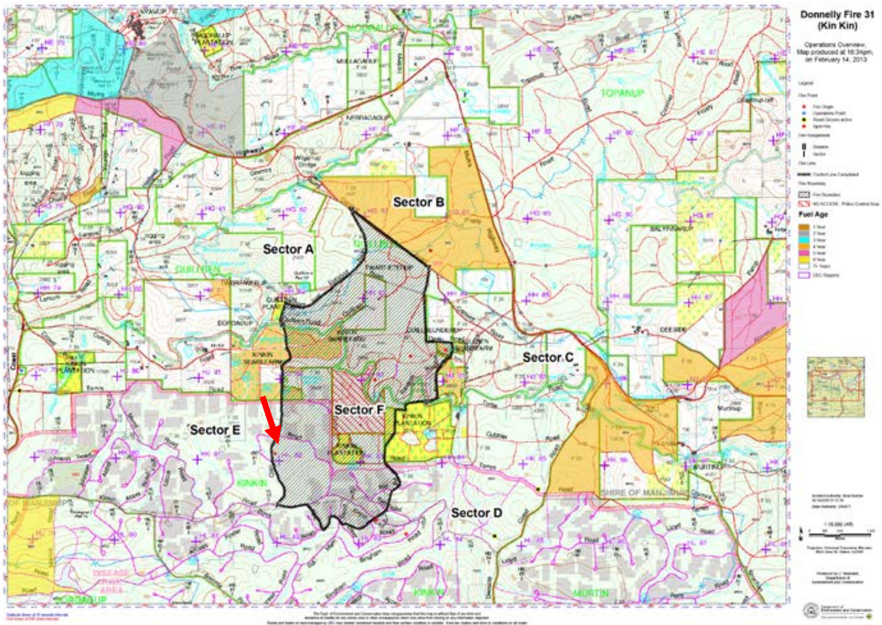

Figure 1: Location and final boundary of the Kin Kin fire ~25 km south-east of Manjimup. Arrow points to origin.

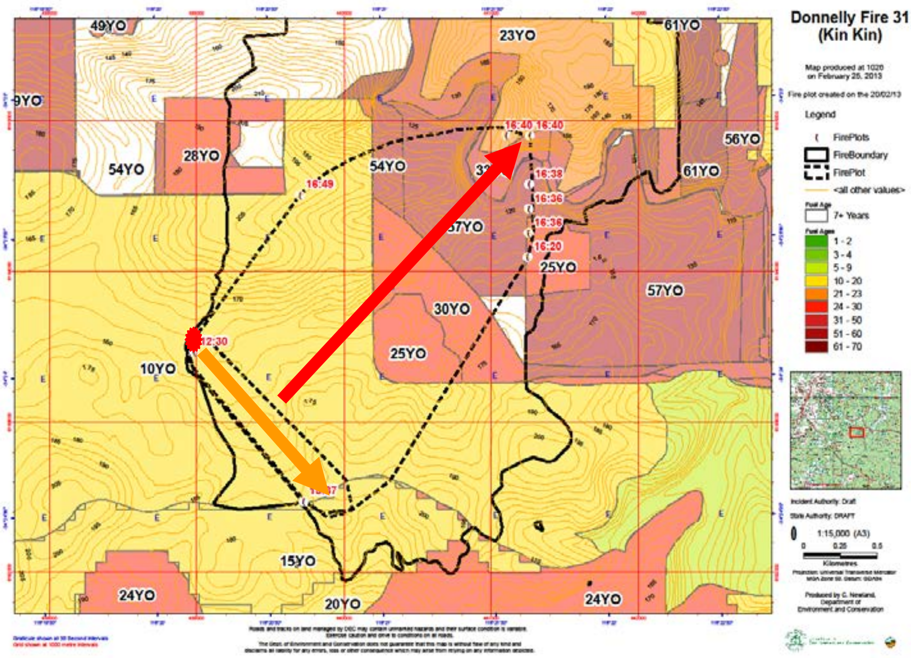

Figure 2: Topography and fuel ages involved in the Kin Kin fire. Red dot is origin, yellow arrow is phase 1 run, red arrow is phase 2 run.

2.2 Vegetation and fuel characteristics

Vegetation involved in the fire mostly comprised a mosaic of high quality jarrah forest (overstorey top height ~30 m) (Plate 5), open low jarrah with shrubby understorey, tall dense scrub in low lying swamps and drainage lines (Plate 6), and mature *Pinus radiata* plantations (Plate 7). The upland jarrah forest occurs predominantly on moderately fertile gravelly yellow-brown duplex soils with an overstorey of jarrah (*Eucalytpus marginata*) and marri (*Corymbia calophylla*), a mid-storey of jarrah and marri saplings, *Banksia grandis and Persoonia longifolia*, and an understorey to 1.5 m of a diversity of species including *Podocarpus drouyianus*, *Xanthorrhoea spp*., *Macrozamia riedlei*, *Leucopogon* spp., *Bossiaea* spp., *Hovea* spp. and Hakea spp. Low lying swampy areas comprised an overstorey of scattered *Melaleuca* spp. and often dense thickets of *Taxandria* spp. and *Hakea* spp. to 2m. The dominant fuel in the pine plantations was a deep needle bed and in some stands, red tops from thinning operations.

As a result of cycles of timber harvesting in state forest over many decades, the jarrah forest is a mix of stand structures and tree size / age classes, but much of the basal area comprises saplings and poles creating a secondary canopy beneath large, older trees. Stand basal area of upland forest was in the range 30-40 m^2 ha^{-1} with a canopy cover of 40-60%. The top height of the mature pine plantations was ~30 m, with crown break about 10 m above ground. Apart from scattered small wildings and a few shrubs, there was little or no understorey in the plantations.

The prevalence of long unburnt forest fuels is a feature of the fire ground and surrounds (Figure 2). It is reasonable to speculate that if weather conditions, especially wind speed, had not abated, the fire would have been considerably larger and more damaging. Jarrah forest fuels involved in the fire ranged from 10 yo in the south-west section of the fire ground to 57 yo on private property (location 3753). Fuels in jarrah forest in the northern section, north of the Warren River, were 23-27 yo (see Figure 2). Four yo fuels north of Cormint Road greatly assisted suppression, providing an anchor point from which to carry out edging and back-burning.

Plate 5: Upland jarrah forest typical of forest involved in the Kin Kin bushfire. This forest was last burnt by prescribed fire in spring 2002.

Plate 6: Thick, flammable myrtaceous scrub in drainage lines and swamps formed part of the vegetation / fuel mosaic on the Kin Kin fire ground. Foreground is a containment line on the south-west corner of the fire ground.

Plate 7: Mature Pinus radiata (pine) plantations with deep needle bed and in some stands, red tops following thinning operations, formed part of the fuel mosaic on the Kin Kin fire ground.

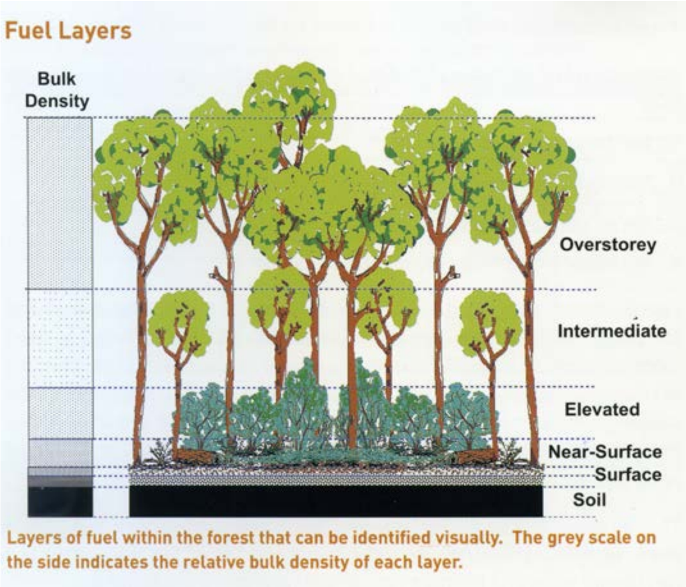

Figure 3: The Vesta dry eucalypt forest fire model fuel layers (Source: Gould et al. 2007)

Table 1: The Vesta fuel model hazard rating of fuel layers in 10 yo and 57 yo jarrah forest fuels. For 10 yo fuels, measurements were made in adjacent unburnt forest. For 57 yo fuels, estimates are based on fuel age as all of this forest was burnt by the wildfire. Pine fuel loads were estimated from an adjacent unburnt plantation.

Fuel layer	Hazard rating	Hazard score	Available fuel (t/ha)
Surface			
10 yo	High	3	Established litter layer 15-20 mm deep, available fuel load ~11.5 t/ha; Complete consumption
57 yo	Extreme	4	Estimated total available fuel load ~17 t/ha; Complete consumption
Near–surface			
10 yo	Moderate	2.5	Scattered suspended leaves etc. (~3 t/ha); Complete consumption
57 yo	Extreme	4	Complete consumption (~4.0 t/ha)
Elevated			
10 yo	High	3	Moderately dense scrub to 1.5 m (~3 t/ha); Complete consumption
57 yo	Extreme	4	Dense scrub to 1.5m; Complete consumption (~4.0 t/ha)
Bark			
10 yo	High	3	Lower parts charred, upper parts partially charred (~3.0 t/ha)
57 yo	Extreme	4	Virtually complete consumption of loose bark (~6 t/ha)
Pine plantation	N/A	N/A	Needle bed 40-50 mm deep (~18 t/ha); Red tops (~4 t/ha)

2.3 Topography

Topography, especially its shape, slope and aspect can significantly influence fire behavior. Fire rate of spread approximately doubles for every 10° increase in positive (up) slope but the influence of negative (down) slope on fire behaviour is less clear. The shape of the topography, such as the position and scale of valleys and ridges, can have a strong local influence on wind speed and direction. On the fire ground, topography varied from flat to gently sloping terrain to moderately steep slopes, to very steep slopes associated with the Warren River valley and other drainages. From the ignition point south-east to Kin Kin Rd, the first phase of the fire run before the southerly wind shift, the terrain is essentially flat or gently sloping up-hill (+1° slope) with respect to the headfire run. When the headfire spread northwards on the wind shift, the fire was burning on a wide front across complex terrain, or approximately along the contours on a south-east facing slope. Slopes ranged from 5°-11°, on mostly south-easterly aspects not aligned with the north-east headfire run.

On its north-east run, the headfire roughly followed a drainage line, or tributary of the Warren River that is orientated roughly south-west, north-east (see Figures 1 & 2). The alignment of the wind, the flat terrain and the valley further north, together with the position of pine plantations, may have caused some funneling of the wind, increasing its speed and influence on the headfire. The flanks of the fire would have been influenced by the relatively steep up-hill slopes either side of the valley, causing the flankfires to display more significant fire behaviour than would otherwise be expected. Other significant topographical features include often steep slopes associated with the Warren River, which runs more-or-less east-west and perpendicular to the direction of the headfire run on this part of the fire ground (Figure 1).

3. Weather and fire danger

3.1 Rainfall and drought

Rainfall recorded at Pemberton (~19 km west-south-west of Kin Kin forest) for 2013 to 13 February was 12.5 mm, which is about half of what could normally be expected by this time of year. Prior to this, no significant falls (> 5 mm) were recorded since 18 December 2012 (5.4 mm). Light rain (< 5mm) was recorded throughout January, with the last rain (0.6 mm) falling on 30 January. At this time of year, the influence of light falls on fuel moisture is ephemeral. The relatively warm and dry summer months ensured that the surface and near surface fuels were dry and were responding to diurnal changes in temperature and relative humidity.

On 13 February 2013, the Soil Dryness Index (SDI), a continuous numerical measure of the regional dryness of the top soil, deep forest litter, logs and of the vegetation generally (Mount 1972; Burrows 1987) was about 1700 (~170 in Figure 4) at Pemberton, which is slightly above average for this time of year. The SDI at Pemberton rarely exceeds 1700, so by 13 February, top soil, vegetation and heavy fuels in the region were almost at peak dryness.

There was a high level of combustion of dead and downed woody material, with many large logs reduced to ash, indicating a high drought index. The fuel age, the fuel ladder created by the structure of the vegetation, moderate wind speeds and dryness of the vegetation profile were factors conducive to strong vertical convection development and crowning fire, which totally defoliated much of the forest.

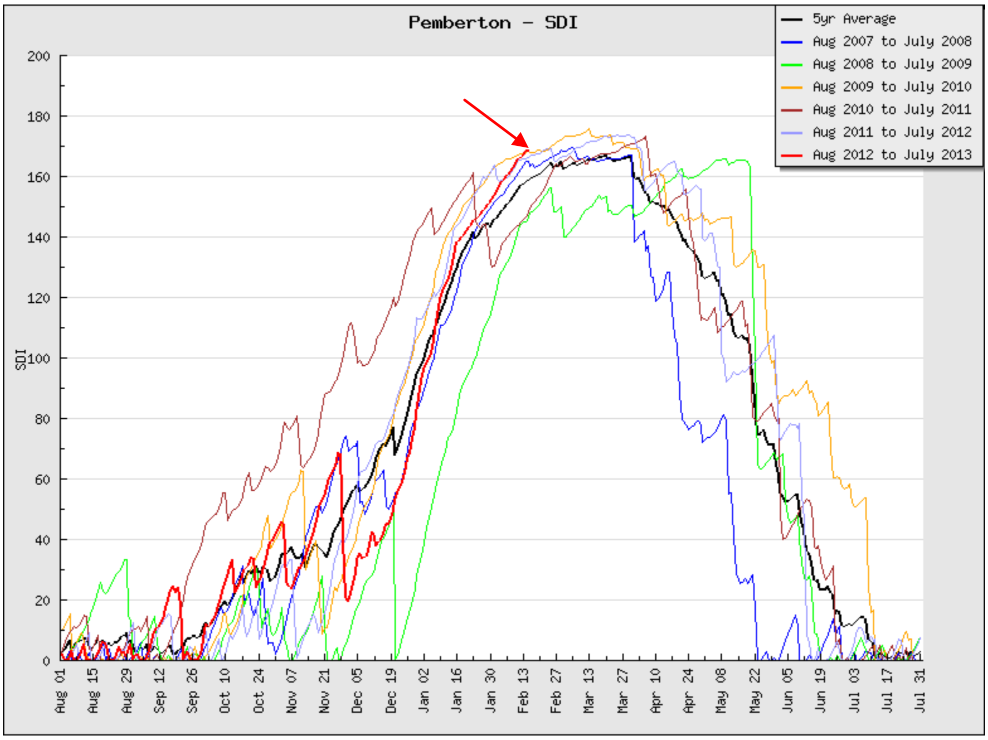

Figure 4: Soil Dryness Index (SDI) for Pemberton for various years including 2013 (red) and the five year average (black). Arrow shows SDI on 13 February 2013.

3.2 Mean Sea Level (MSL) Synoptic situation and atmospheric conditions

The surface weather map (Figure 5) for 0800 hrs (WST) on 13 February 2013 is a typical summer pattern and shows a high pressure system centered in the Great Australian Bight and a low pressure trough near the west coast, directing a warm, dry northerly air flow into the south-west region. The relatively wide spacing of the isobars in the south-west suggests light to moderate wind speeds. A trough associated with a front has formed down the west coast with accompanying unstable air and thunderstorm activity east of the trough line. On Tuesday 12 and Wednesday 13 February, DEC crews attended 8 lightning-caused fires in the Donnelly District; 7 were suppressed while small (< 1 ha) and in the build-up phase. There was no rain associated with the thunderstorms and lightning strikes.

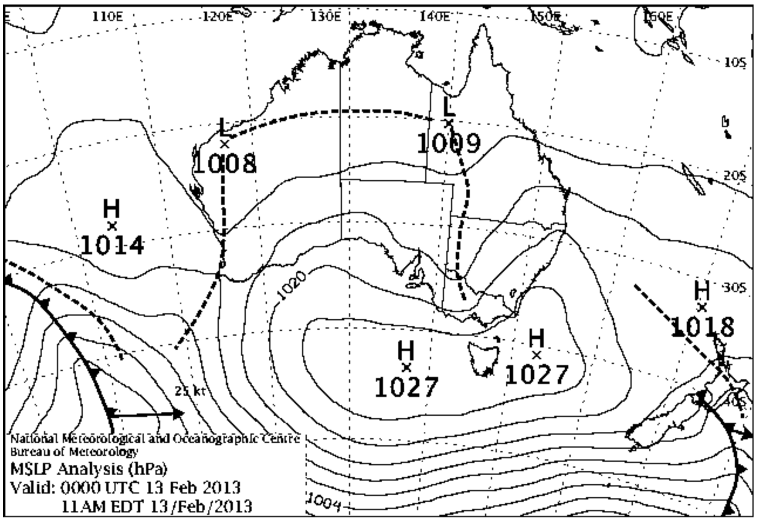

Figure 5: Surface weather chart at 0800 hrs WST for 13 February 2013.

Upper atmosphere soundings (to 700 hPa) made by BoM from Albany are shown on the aerological diagram in Figure 6. Albany is some 150 km from the fire ground, so these soundings serve to highlight the warm dry air aloft (~800 m or 925 hPa), which is probably fairly constant across the southern region. The large difference between temperature and dew point at ~ 800 m indicates very dry air, which could mix to the surface, affecting fuel moisture and burning conditions. The Haines Index (HI), or continuous Haines Index (c-HI) reflects the potential for rapid fire growth of plume driven fires. The index is derived from the temperature difference between different altitudes (at pressures of 850 hPa and 700 hPa) and moisture content (dew point depression) at 850 hPa altitude. Fire behaviour has not been strongly linked to the index, i.e., it has not been used to predict fire behaviour, but there have been observed associations between the index and the potential for fires to develop rapidly such that: H = 2 – 3; very low potential; HI = 4; low potential; HI = 5; moderate potential; HI = 6+; high potential for rapid fire development. The c-Haines Index calculated for the fire ground, based on the Albany soundings, was 11.8, suggesting high potential for strong convection development and rapid fire growth.

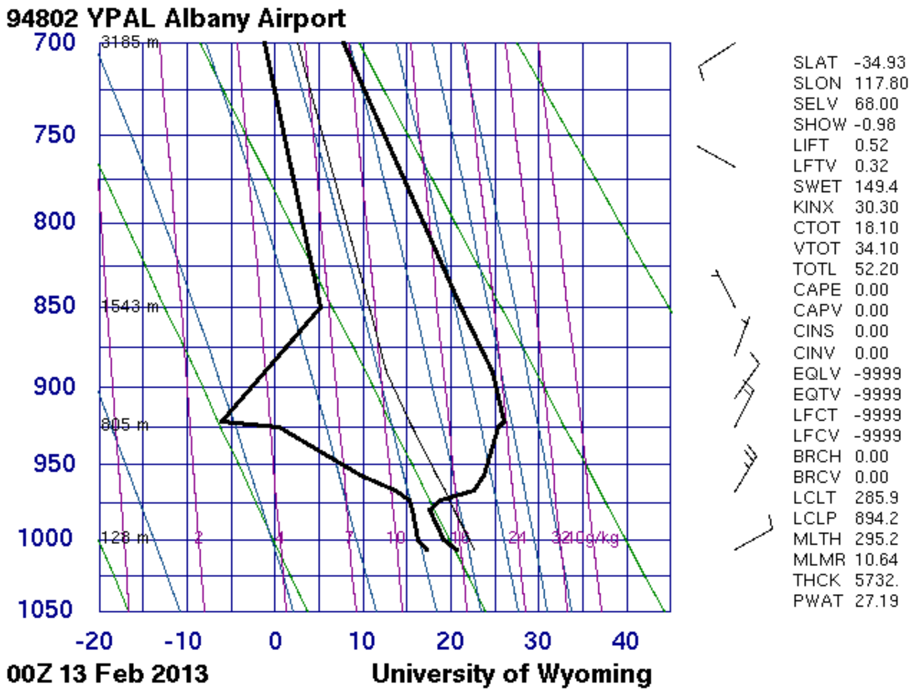

Figure 6: Upper air soundings of dew point (L) and air temperature (R) by BoM Albany on 13 February 2013. Below about 800 m (925 hPa) the air temperature increases with altitude, suggesting an unstable atmosphere to about 1500 m. Beyond this, the environmental lapse rate is similar to the dry adiabatic lapse rate. The large difference between dew point and air temperature at ~800 m indicates very dry air at this level and a high Haines Index.

3.3 Surface weather and fuel moisture

Weather conditions at the fire ground during 13 February 2013 are best represented by conditions observed at BoM's AWS at Manjimup, about 25 km north-west of the fire ground. Hourly measurements of key fire weather elements are shown in Table 2 and 10-minutely wind speed and direction are shown in Figures 7a and 7b.

Aside from the high maximum temperature (39^{o}C) and a short period of low humidity (17%), other weather elements experienced on 13 February are unsurprising. Dew point is relatively high and RH is moderately low – from the soundings shown in Figure 6, it appears that the very dry air aloft did not mix to the surface. The other feature of the weather is the low to moderate wind speeds and the shift in wind direction, backing from the N through NW, then to SSW. At Manjimup, the wind started to shift at about 1600 h and was established in the SSW by about 1620 h (Figure 7a). The 15-20 minute time lapse for such wind shifts to occur is fairly typical, but the shift is often subtle on the fire ground. Based on reports from the fire ground, the wind started to shift from the NW to the SSW at about 1530 h and was established in the SSW by about 1545 h. By about 1900 h, the wind at Manjimup had shifted more southerly and the wind speed abated (Figure 7a). This, together with decreasing temperature and increasing RH as evening approached significantly modified surface burning conditions and fire behaviour on the fire ground (Table 2).

As mentioned the SDI for the region had almost peaked for the season, so the top soil, logs and deep forest fuels were very dry. The moisture content of surface (litter) and near surface fuels was responding to diurnal fluctuations in temperature and relative humidity. Using weather data from Manjimup and Vesta Tables M1 and M2, the predicted minimum SMC for 13 February was ~5% during the peak of the day (~1200 h – 1500 h) (Figure 8), rising to ~13% by 2200 h as conditions cooled and RH increased.

Table 2: Hourly surface weather conditions recorded at the BoM AWS at Manjimup for 13th February 2013. The fire was first detected when very small at 1226 h, but probably started at started ~1215 h.

Time	Temp C	RH %	Dew pt. C	Wind drn (degrees)	Wind spd (km/h)	Wind gust (km/h)
0900	28.9	40	13.9	10	22	31
1000	31.9	34	14.1	10	15	26
1100	34.4	28	13.3	360	13	21
1200	39.9	23	11.5	330	21	30
1300	37.3	22	12	320	13	24
1400	38.4	19	10.7	350	15	26
1500	37.8	17	8.6	320	18	35
1600	35.7	21	10	310	18	24
1700	31.2	38	15.2	210	20	26
1800	28.2	48	16.1	200	22	28
1900	26.2	57	17	190	13	21
2000	24.5	62	16.7	190	13	21
2100	23.5	64	16.3	210	11	15
2200	23.3	64	16.1	190	11	13
2300	21.9	69	16	0	0	0

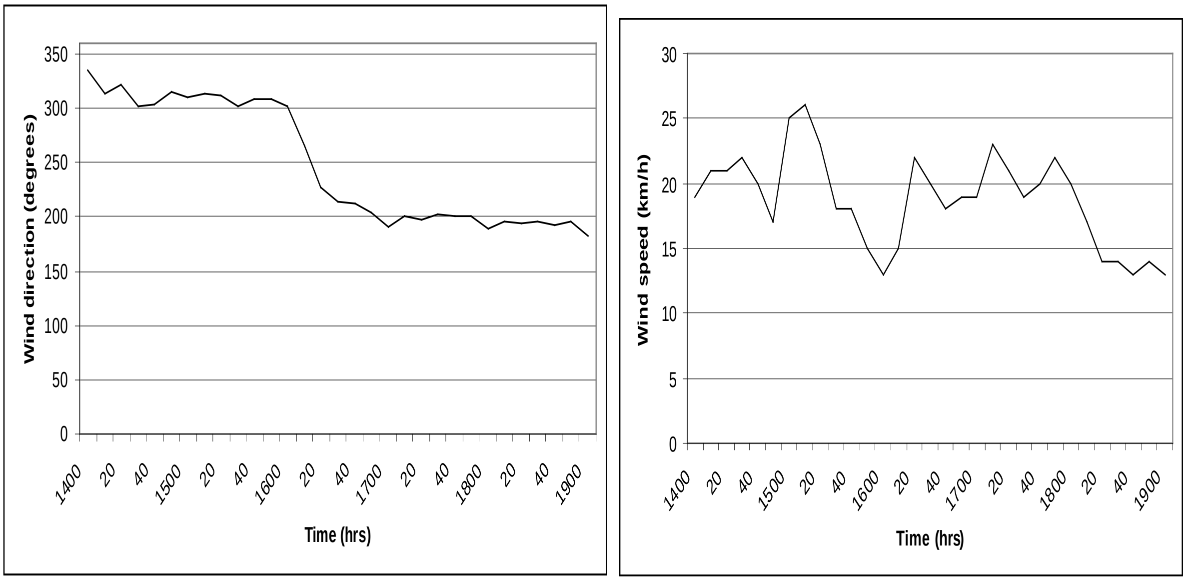

Figure 7a (L): Ten-minutely wind direction (L) and Figure 7b (R): wind speed measured at the BoM's AWS at Manjimup for 13 February 2013. Note the wind shift from NW to SW and SSW commencing at ~1600 h.

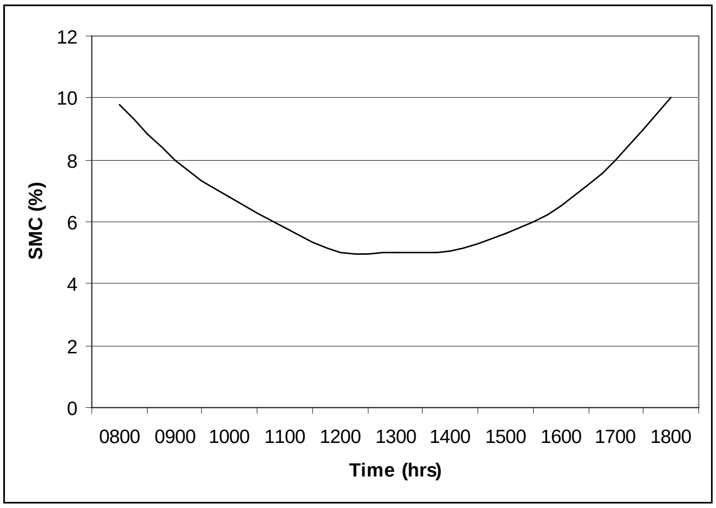

Figure 8: Surface fuel moisture content (SMC) predicted from temperature and RH (Project Vesta Tables M1 and M2) for 13 February 2013.

3.4 Forecast weather vs observed weather

Spot weather forecasts and actual weather observed are shown in Table 3. Generally, the forecasting was good, especially for temperature, RH and dew point during the peak fire weather period of the day (from 0900 h to 1700 h). The wind was forecast to be WSW by 1500 h, but at Manjimup, it did not begin to shift to SSW until about 1600 h (Figure 8). However, on the fire ground, it was observed to start to shift to the SSW at about 1530 h, close to the forecast time. It should be noted that because forecasts are given in time intervals ranging from 3-6 hours, the actual time of the wind shift is not forecast, unless it is provided in commentary associated with the time block forecast. Forecast wind speeds are close to those observed at Manjimup. Overall, the weather forecasts could be characterised as reasonably accurate with no observed surprises that could create difficulties for fire fighters or for predicting fire behaviour.

Based on the vegetation freeze and the initial run of the fire, the wind direction at the fire ground was ~NW from time of ignition (~1215 h) until about 1530 hrs when it began to back to the SSW. Assuming it took a similar time to shift on the fire ground as it did at Manjimup, then it took about 15-20 minutes to shift from NW to SSW, so it was probably established in the SSW by about 1545 h.

Table 3: Spot weather forecast (For) issued by BoM at 1522 hrs on 12 February 2013 and observed (Obs) weather at Manjimup.

Time	**Temperature C**		**Dew pt C**		**RH%**		**Wind km/hr**	
	For	**Obs**	**For**	**Obs**	**For**	**Obs**	**For**	**Obs**
Spot forecast issued at 1532 hrs on Tue. 12 Feb. for Wed 13 Feb.								
0900	30	29	12	14	33	40	NNE 20 gust 30	NNE 22 gust 31
1500	39	38	8	9	18	17	WSW 15 gusts 20	NW 18 Gusts 35
Spot forecast issued at 1520 hrs on Wed. 13 Feb. for Wed. 13 Feb								
1600	38	36	9	10	17	21	WSW 25 gust 35	NW 15 gust 24
1900	29	26	13	17	37	57	SW 10 gust 20	SSW 13 gust 21
2200	23	23	18	16.1	73	64	WSW 5 gust 10	WSW 11 gust 13

4. Fire path and behaviour

4.1 Origin and cause

The fire was caused by lightning, which struck a large marri tree in Kin Kin State forest at about 34.3983 S latitude and 116.3366 E longitude about 1215 h on 13 February 2013 (Plate 8). This fire was one of eight lightning-caused fires attended by crews in the Donnelly District associated with thunderstorm activity on 12 and 13 February. Seven of the fires were suppressed when < 1ha in area.

Plate 8: A large marri (Corymbia calophylla) tree struck by lightning that caused the Kin Kin fire at about 1215 h on 13 February 2013.

A fire spotter pilot first sighted the smoke while on circuit and overhead Kingston forest ~30 km north. He flew towards the smoke and lodged an initial report with the DEC Pemberton office at 1229 h and a full report once overhead the fire at 1236 h. At this time the fire was approximately 500 m^2, roughly circular (~26 m diameter), and displaying very mild fire behaviour (flames <0.5m). Given the mild fire behaviour and the size of the fire at 1236 h, the lightning ignition probably occurred at ~1215 h.

As mentioned above, this fire behaviour reconstruction and analysis covers that period of the fire from its origin to soon after it crossed the Warren River sometime around 1630 h. This is the period of most intense fire behaviour and it was during this run that a dwelling and other buildings were destroyed and a person may have been killed. Human remains were found in the burnt rubble of the dwelling, but at the time of preparing this report, it is uncertain whether the person died before the fire or was killed by the fire. The fire reached the dwelling on pp location 3573, where the remains were found, at about 1620 h (Figure 9).

The reconstructed path of the fire, shown in Figure 9, is discussed in two phases;

Phase 1: From its origin south-east to Kin Kin Road, a distance of ~1,350 m. During this phase, which included the build-up phase from a point ignition, the fire was under the influence of a NW wind and reached Kin Kin Road at ~1530 h. Vegetation freeze (Figure 9) indicates that the wind may have begun to shift from NW to SW and SSW about 200 m before the fire reached Kin Kin Road. However, fire fighters observed that the wind was NW when the fire crossed the road, so the freeze at this location may be due to the SW wind arriving while the unburnt vegetation was still hot and supple.

Phase 2: From Kin Kin Road north-east to the Warren River (~2,100 m) following the wind shift to SSW. It took 15-20 minutes for the wind to shift from NW to SW and SSW at Manjimup, so the wind on the fire ground probably started backing from the NW at ~1530 h and was probably established in the SSW by ~1545 h. During that time, the fire pushed eastwards briefly before running north-east under the influence of the SSW wind.

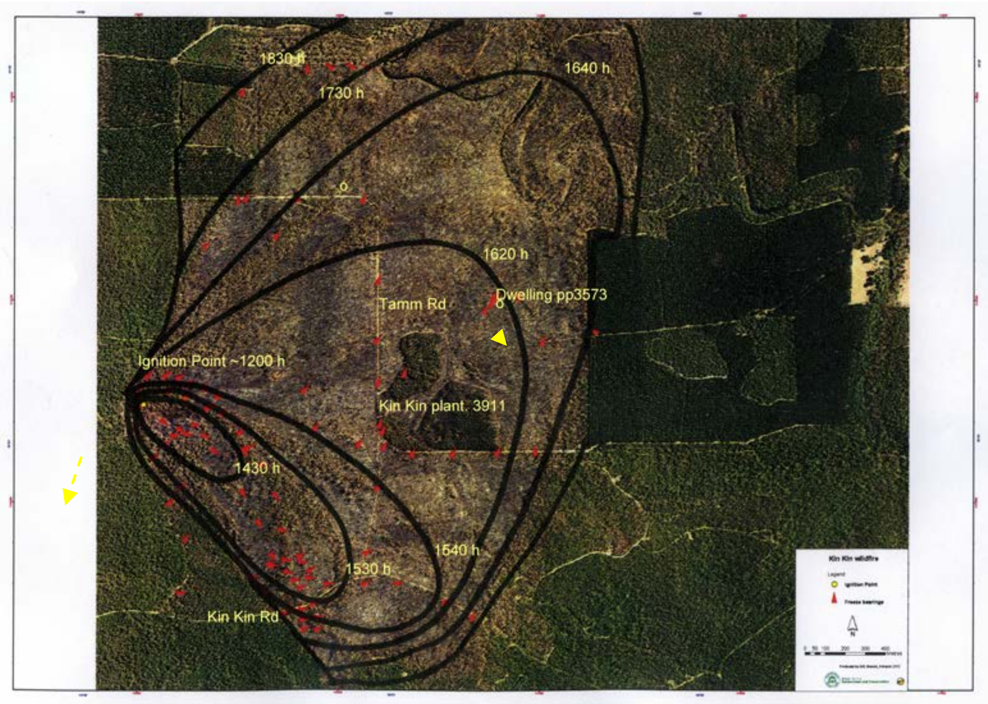

Figure 9: Reconstructed approximate position of the Kin Kin fire at various times on 13 February 2013. Red arrows show vegetation freeze (wind and headfire direction).

4.2 Phase 1: Origin to Kin Kin Road

When the fire was first reported at 1236 h, it was roughly circular with ~26 m diameter. At this stage, it was burning in 10 year old mid-slope jarrah forest fuels and still in the build-up phase with a rate of spread probably about 30-40 m/hr. Based on the defoliation levels, flame heights ranged from 0.5-1.5 m. Although fire intensity was low, surface (litter) fuels were completely burnt to mineral earth, indicating a dry fuel profile.

After travelling about 65 m in a south-east direction from its origin, the fire crossed a creek and from this point it was burning on a 60-80 m wide front in a dense tea tree (*Taxandria spp*.) shrubland ~2m tall on virtually flat terrain. From here, fire behaviour escalated, defoliating the shrubland with occasional defoliation of overstorey trees to 20 m. The fire continued south-east, burning in a mosaic of shrubland and forest. In the headfire zone, the forest was mostly fully defoliated to 20 m. At ~1431 h, the fire was reported (by spotter aircraft) to be ~500 m long and ~200 wide. From its origin at ~1215 h, the fire's average rate of spread was ~200 m/h and from its position at 1431 hrs to when it reached Kin Kin Road, its average rate of spread was ~765 m/h with headfire flame heights from 10-20 m. When the fire reached Kin Kin Road it was ~320 m wide with a length-to-width ratio of about 4.2, consistent with a moderate wind speed. The acceleration of the fire is apparent from the chronology of its rate of spread; from its origin to Kin Kin Road, the fire averaged ~430 m/h, starting at about 30-40 m/h soon after ignition and averaging ~765 m/hr in its final run to Kin Kin Road.

About 200 m north-west of Kin Kin Road and through to Kin Kin Road, vegetation freeze varies from 60° – 90° suggesting that the wind was backing from NW to the SW and pushing the headfire in a more easterly direction before swinging north-east (although, as mentioned above, observers noted that the wind was NW when the fire reached Kin Kin Road). The headfire spread east-south-east with considerable intensity, completely defoliating the forest to 30 m suggesting flames to 40 m. During this phase, at least two spot fires were reported by spotter aircraft some 1-1.5 km downwind of the headfire (see Figure 10).

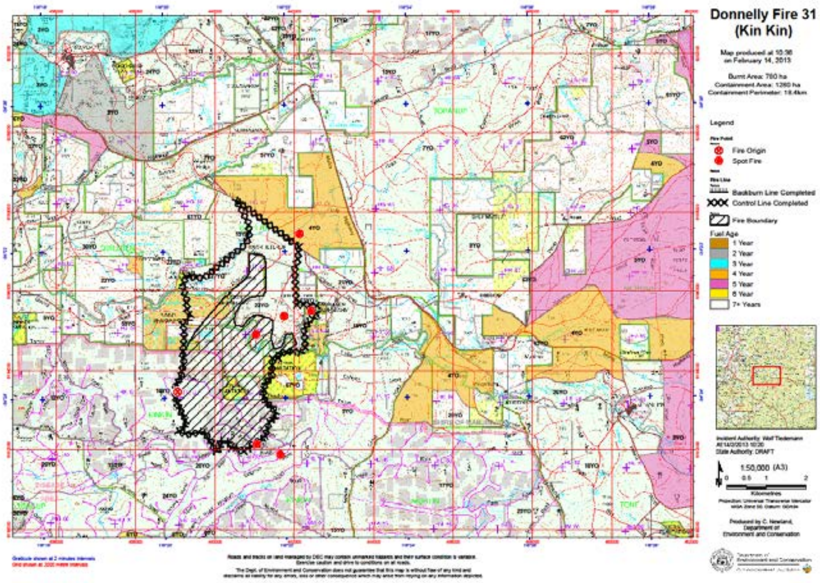

Figure 10: Spot fires (red dots) ~1-1.5 km down wind of the main fire on the south-east run (phase 1) and ~1.5-2.2 km down wind of the main fire on the north-east run (phase 2).

Fire behaviour (reconstructed and predicted), fuel and weather conditions during phase 1 are summarized in Table 4. In using the Forest Fire behaviour Tables for WA (Red Book - RB) (Sneeuwjagt and Peet 1998) to predict headfire rate of spread, the following assumptions and calculations were made:

- Used Jarrah Forest for rate of spread calculations.
- The litter fuel (surface fuel) depth and quantity was measured in adjacent unburnt 10 yo jarrah forest.
- The litter fuel profile was dry so fuel availability factor = 1.0 (RB Table 5.4).
- Assumes a surface fuel moisture content (SMC) of 5% (Figure 9).
- Wind ratio = 3:1 (RB Table 6.5). Note: areas of open forest / heath.
- Jarrah rate of Spread Index = 240 (RB Table 6.7).
- Total available fuel = litter + trash + scrub (RB Table 7.4).
- Fuel quantity correction factor = 2.7(based on total available fuel) (RB Table 6.8).
- Slope correction = 0 (flat terrain).

As described above, the fire was slow to develop following its ignition at ~1215 h. This was due to the relatively low wind speed in tall forest. However, after the fire crossed a creek some 65 m from the ignition point, its behaviour quickly escalated when the vegetation changed to exposed tea-tree scrub beneath scattered trees before reverting to closed forest. From Table 4, the Red Book accurately predicted the overall mean rate of spread of the fire, including the slow build-up period, but significantly under predicted the potential (*quasi* steady state) rate of spread. The Vesta model over predicted the potential rate of spread of the fire.

Table 5: Reconstructed (Observed) and predicted rates of spread (ROS) for phase 1 of the fire: Two spread rates are included: A. - the mean ROS from origin to Kin Kin Rd and B. - the quasi steady state mean ROS (post build-up). Predictions use the Forest Fire Behaviour Tables for WA (Red Book) and the National Fire Spread Model for Dry Eucalypt Forest (Vesta). Fire intensity calculated using reconstructed ROS and fuel quantities in Table 1.

Fuel Type/age	Red Book fuel (t/ha)		Vesta fuel hazard score			Min. SMC % (Fig. 8)	Open Wind (km/hr)	Observed ROS (m/hr)	Mean headfire intensity (kW/m) and mean flame height (m)	Predicted ROS (m/hr)	
	Total Litter	Total fuel (litter+ trash+ scrub)	NS ht (cm)	NS Hazard Score	SF Hazard Score					Red Book	Vesta
Jarrah forest 10 yo fuel	11.5	17.5	20	2.5	3	5	17	A. 430 B. 765	A. 4,985 B. 8,867 Flame hts 1.5-20 m Mean~ 8 m	648	1041

Plate 9: Fire behaviour escalated when the fire crossed a creek about 65 m from the origin and entered more open, scrubby vegetation

Plate 10: Contrasting fire behaviour during phase 1 of the fire while it was under the influence of a NW wind: L – low fire intensity (~450 kW/m) near the ignition point as the fire was developing. High fire intensity (~9,000 kW/m) as the developed headfire approached Kin Kin Rd from the north-west.

4.3 Phase 2: From Kin Kin Road to Warren River.

The wind gradually shifted from NW to SSW over a 15-20 minute period based on the Manjimup AWS weather observations. As the wind shifted, it pushed the headfire to the east and then to the north-east (Figure 9). By about 1545 h, the wind was established in the SSW and the long flank fire of some 1,700 m became a rapidly spreading, intense head fire.

During this phase, the headfire burnt in 10 yo jarrah forest fuels in Kin Kin forest, 57 yo jarrah forest fuels on private property location 3573, and a small block of the Kin Kin pine plantation. From ~1540 h to ~1630 h when the headfire crossed the Warren River, the fire travelled ~2,100 m at an average rate of spread of 2,521 m/h. The forest is mostly defoliated, indicating crowning headfire with flame heights to 35 m. Other indicators of very high fire intensity include complete combustion of all fuel strata, deep charring (up to 10 mm) of bark on standing live trees, combustion of live shrub stems at ground level to 5 mm in diameter, and melting and carbonizing of resin in live grass tree stems up to 1.5 m above ground. During this phase, at least two spot fires started some 1.5-2.2 km ahead of the main fire (Figure 10).

The local topography most likely contributed to the fire's speed and intensity. Wind and headfire direction aligned with a drainage system, a tributary of the Warren River with a narrow (~200 m wide) valley floor flanked by steep hills with 10-12^{o} slopes (Figure 4). It is likely that the shape of the topography acted to funnel the wind, increasing its speed and influence on fire behaviour. The steep slopes flanking the valley floor increased the rate of spread and intensity of the flank fires, resulting in ~80% total defoliation of the jarrah forest with occasional bands of fully scorched forest.

Interestingly, fire behaviour abated when the headfire burnt through the isolated Kin Kin 3911 mature pine plantation (~24 ha). The fire crowned through the jarrah forest, with 25-35 m flames, but largely became a surface fire in the plantation, with 4-5 m flames. Only about ~25% of the plantation was defoliated with the remainder being fully scorched. Fully scorched pine trees will die; to survive fire, pine trees require at least 3-4 m of green crown tip provided they have not been heat girdled near ground level.

The fire behaviour abated in the plantation because of the simple fuel structure, with essentially only needlebed (surface) fuels to sustain fire spread. Crowning occurred in the plantation adjacent to a creek system and associated dense tea-tree thicket, which facilitated a localised crown fire in the plantation.

It was during this phase, the moist intense part of the fire, that a dwelling, other buildings and property on location 3573, which was in the path of the headfire, were destroyed. Human remains were found in the rubble. The buildings were set amongst highly flammable forest fuels that had not been burnt for 57 years with little setback or evidence of any significant fuel modification around the buildings. The highly flammable forest was just 5-10 m from of the buildings. The forest around the buildings was totally defoliated, indicating that a very intense fire with 25-35 m flames impacted the buildings.

Fire behaviour (reconstructed and predicted), fuel and weather conditions during this phase are summarized in Table 5. In using the Forest Fire behaviour Tables for WA (Red Book - RB) (Sneeuwjagt and Peet 1998) to predict headfire rate of spread, the following assumptions and calculations were made:

- Used Jarrah Forest for rate of spread calculations.
- Total available fuel (litter, trash, scrub) estimated from the Red Book for 57 yo fuels.
- The litter fuel profile was dry so fuel availability factor = 1.0 (RB Table 5.4).
- Assumes a surface fuel moisture content (SMC) of 5% (1540-1620 h) and 6% 1620-1640 h) (Figure 8).
- Assumes a wind ratio = 3:1 (RB Table 6.5).
- Jarrah rate of Spread Index = 240 for 10 yo fuel @5% and 200 for 50+ yo fuel @6% (RB Table 6.7).

- Fuel quantity correction factor = 2.7 for 10 yo fuel (see above) and 3.0 for 57 yo fuel (RB Table 6.8)
- Slope correction = 0 (flat terrain)

Table 4: Reconstructed (Observed) and predicted rates of spread (ROS) for phase 2. Predictions use the Forest Fire Behaviour Tables for WA (Red Book) and the National Fire Spread Model for Dry Eucalypt Forest (Vesta). Fire intensity calculated using reconstructed ROS and fuel quantities in Table 1.

Fuel Type/age	Red Book fuel (t/ha)		Vesta fuel hazard score			Min. SMC % (Fig. 14)	Open Wind (km/hr)	Observed ROS (m/hr)	Mean headfire intensity (kW/m) and mean flame height (m)	Predicted ROS (m/hr)	
	Total Litter	Total avail. Fuel (litter +trash +scrub)	NS ht (cm)	NS Hazard Score	SF Hazard Score					Red Book	Vesta
Jarrah forest 10 yo fuel (~1540-1620 h)	11.5	17.5	20	2.5	3	5	18	1,174	13,609 10-20m flames flaring to 30 m	648	1,186
Jarrah 50+ yo fuel (~1620 h – 1640 h)	17	25	30	4	4	6	18	2,808	39,312 20-30m flames flaring to 40m	600	2,171

The Vesta fire spread model accurately predicted rate of spread when the fire was burning in 10 yo forest fuels and on largely flat terrain. However, it under predicted rate of spread in the 57 yo fuels when the fire was burning along a valley flanked by relatively steep terrain. As discussed above, the shape of the topography may have funneled the wind, increasing its speed, resulting in increased fire behaviour.

The Red Book significantly under-predicted rate of spread, with the error increasing in the 57 yo fuels. This highlights the major shortcomings of the Red Book model – it was developed for small fires, not large ones, and it does not account for changing flammability with changing fuel age and structure, but relies on fuel quantity to drive the model. The Vesta studies have demonstrated the importance of fuel structure rather than fuel quantity *per se*, on fire rate of spread.

Plate 11: Top L: Most (~80%) of the forest was defoliated by high intensity crowning fire during the period of peak activity.
Top R: Contrasting fire behaviour between jarrah forest (crowning fire) and pine plantation (surface fire).
Bottom L: Dwelling on pp 3573 destroyed by very high intensity crowning fire in long unburnt vegetation with flame height estimated to be 25-35 m. Note close proximity of the forest to buildings.
Bottom R: Well developed convection column during phase 2 of the fire run.

Plate 12: L– Destruction of organic substrates and associated root systems. R- Resin 'boiled' and carbonized from grass trees – indicative of very high fire intensity

5. Conclusion

After its initial development, and for the next four hours or so during its period of peak activity, the Kin Kin fire displayed high rates of spread and bursts of very high energy release (intensity) with most of the jarrah forest being totally defoliated. The main drivers of this severe fire behaviour where:

- long unburnt, flammable fuels, and,
- low fuel moisture content associated with a high SDI, high temperatures and low relative humidities during the peak of the day.

Wind speeds during the event, both before and after the wind shift from NW to SSW, were moderate. The high energy release rates associated with dry, plentiful fuels, together with a moderate strength wind field, resulted in strong convection development, with high kinetic energy (vertical motion), which likely increased fire winds at the site. It is also possible that the surface winds were influenced by the shape of the topography on the fire ground, which was conducive to funneling the wind following the wind shift to the SSW. Surface burning conditions abated into the evening, with a commensurate reduction in fire behaviour and by about 1800 h, fire behaviour had moderated considerably. The significant reduction in fire behaviour when the fire entered the pine plantations was apparent.

Because of the wind shift, the severe behaviour exhibited at its peak and the extensive area of old flammable fuels, this fire had the potential to be very large and very dangerous. The short period of low to moderate wind speed, the abatement of surface burning conditions into the late afternoon and evening, and a 4 yo prescribed burn north of Cormint Road provided fire fighters with the opportunity to safely contain this fire. The usual wind shift from the northerly quarter to the southerly quarter, a common fire weather phenomenon in the south-west during the bushfire season, was potentially dangerous to firefighters, however, they were clearly aware of this and on the wind shift, no fire fighters were in the 'deadman zone', so avoiding possible death and injury.

The buildings (and possible life) lost on private property location 3537 were not defendable against this fire given the close proximity of extremely hazardous forest vegetation / fuel, the fire weather and fire behaviour conditions on the day and the narrow, hazardous access tracks into the property. These buildings were directly in the path of the fast moving, high intensity headfire, so were readily destroyed.

The Vesta fire behaviour model provided reasonably accurate predictions of rate of spread when the fire was burning in 10 yo fuels during its north-east run. The model under-predicted rate of spread when the fire was burning in 57 yo fuels and over-predicted rate of spread when the fire was in the build-up phase. It is possible that the local topography funneled the SSW wind, increasing its speed and influence on the fire, hence accounting for the under-prediction. The Vesta model also predicted spotting distance with encouraging accuracy. The Red Book performed reasonably well in the initial stages of the fire's development, but seriously under-predicted rate of spread once the fire had fully developed and reached its potential speed.

This fire, as with other notable fires in south-west forests in the past decade, emphasizes:

- The significant influence that long unburnt forest vegetation has on bushfire rate of spread, flame dimensions, spotting potential, fire intensity, suppression difficulty, and physical and environmental damage to forest and associated ecosystems.
- The rapid and dangerous escalation in fire behaviour following the inevitable wind shift when a long, well established flankfire becomes a headfire.
- The importance of having low fuel zones from which to anchor suppression operations such as edging or back burning.

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