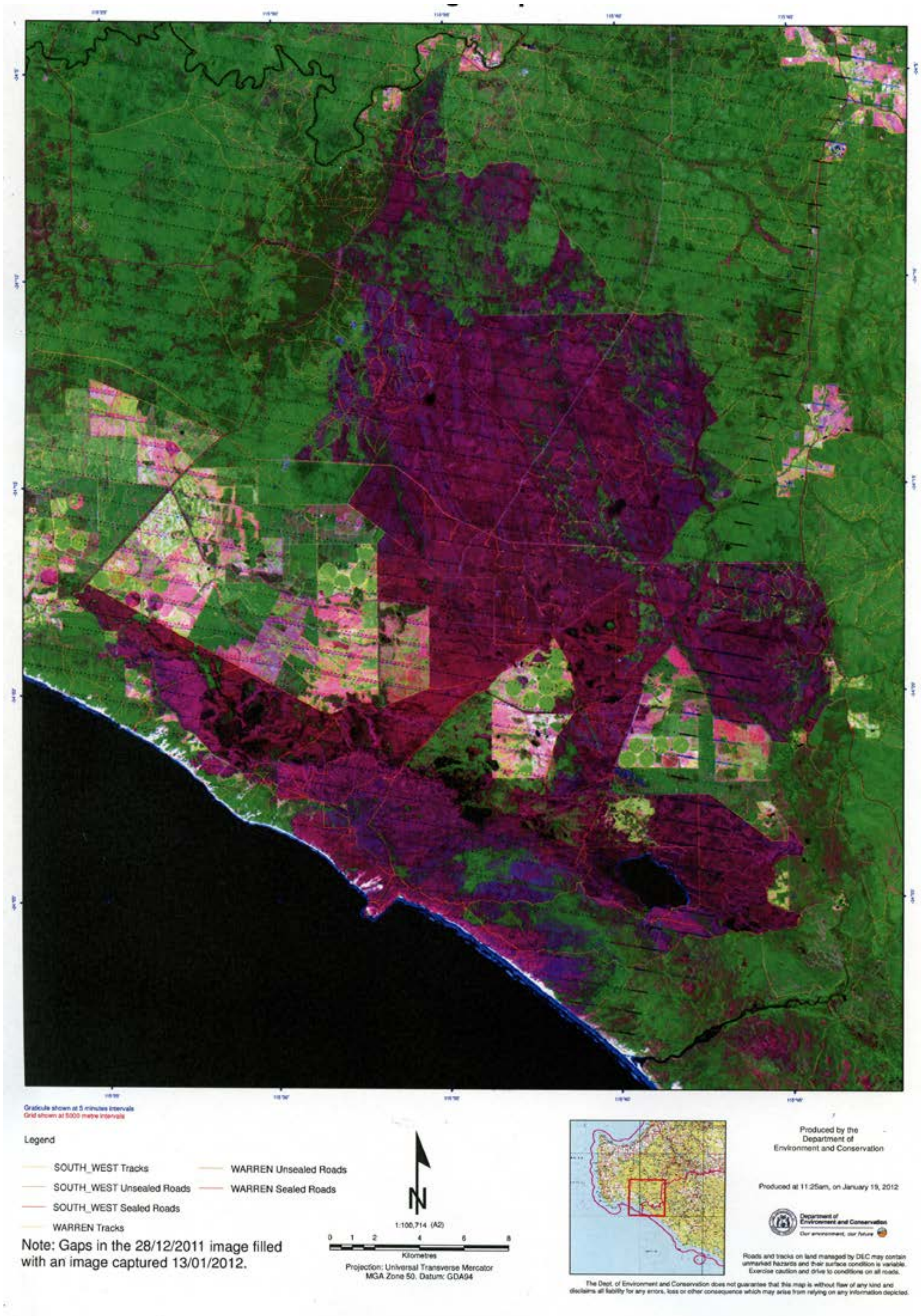
Milyeannup Bushfire

Causal factors and fire behaviour

N.D. Burrows
Science Division
Department of Environment and Conservation

April 2012



1. Introduction

The Milyeannup fire burnt a total of 51,594 ha, making it the largest bushfire in the south-west region of WA since 1961. As well as its size, this fire is notable because it was started by an escape from a prescribed burn carried out by the Department of Environment and Conservation (DEC). Although there was no loss of life or significant property damage, the fire indirectly caused a vehicle accident and injury to a person on private property, caused disruption and concern to local land managers, land holders and the broader community, it had the potential to threaten the communities of Augusta East and Molloy Island, it was difficult, dangerous and costly to suppress and it undermined community confidence in DEC's ability to safely carry out prescribed burning.

It is important that such notable fires are formerly analysed and documented, not only for the record, but to identify causal factors and lessons to be learnt in order to reduce the risk of a reoccurrence. This report focuses on aspects of weather, fuels and fire behaviour associated with the Milyeannup bushfire and identifies causal factors for its start, spread and difficulty of suppression. Other than making brief occasional comment, it is not the purpose of this report to analyse fire suppression strategies, tactics and resources employed on the fire. These aspects are dealt with elsewhere.

Structure of this report

First, a context for prescribed burning is presented, followed by a brief description of the vegetation, fuels and climate of the area involved in the Milyeannup bushfire. This is followed by a chronology of key fire behaviour events and an associated narrative, commencing with the Milyeannup Sollya prescribed burn (BB125). The bushfire, which was started by escapes from the prescribed burn, is reconstructed and analysed in three phases, being times of most active fire behaviour and when there was sufficient information for reconstruction:

Phase 1: 1200 hrs 23 November to 1040 hrs on 24 November (initial escape from BB125)
Phase 2: 1040 hrs 24 November to 0800 hrs on 25th November (run south)
Phase 3: 0800 hrs 30 November to 0800 2 December 2011 (Quitjup / run west)

Reconstructing the fire

By south-west Australian standards, the Milyeannup bushfire was a large and relatively complex one. It was active at the same time as the Margaret River fire and other fires, so suppression activities were poorly resourced and poorly structured in the early phases (Phases 1 & 2). Most resources were directed to the Margaret River fire where life and property were under threat. There were also few reliable on-ground or aerial observations of the location of the fire perimeter in the early phases, which made the task of reconstructing the path of the fire with time, difficult. Satellite imagery showing fire severity (scorch and defoliation patterns) was important for interpreting fire location and behaviour in space and time. Aerial photography of the fire ground was not completed and available until early April, more than 4 months after the event. By this time, important evidence of fire severity had begun to perish – scorched leaves had fallen and vegetation had begun to re-sprout. The fire isochrones mapped in Figures 10 and 11 are inferred from the available evidence described above and from known behaviour (headfire rates of spread) of the fire at various times.

For each phase of analysis, details about weather, fuels and fire behaviour are tabulated and discussed, and the fire perimeter at various times (isochrones) is reconstructed using evidence from a variety of sources including:

- Chronologies of events from dairies of DEC staff involved in the suppression effort and follow-up interviews and meetings.
- Fire behaviour observations from on-ground and aerial observers.
- Fire ground forensic evidence (defoliation, scorch, char, freeze, fuel consumption).

- Actual and forecast weather, Soil Dryness Index (SDI) and synoptic charts and reports from the Bureau of Meteorology (BoM) and Department of Agriculture and Food (DAFWA) weather stations.
- Burn prescription, SDI, Fire Danger Indices (FDI), fire spread and fuel moisture content predictions, office daily log book from DEC's Kirup office.
- Fuel age plans from DEC Fire Management Services.
- Fire maps from the Incident Management Team.
- Satellite imagery and aerial photography of the fire ground.
- Participation in the Incident Management team (IMT) for a short period (1-2 December 2011).

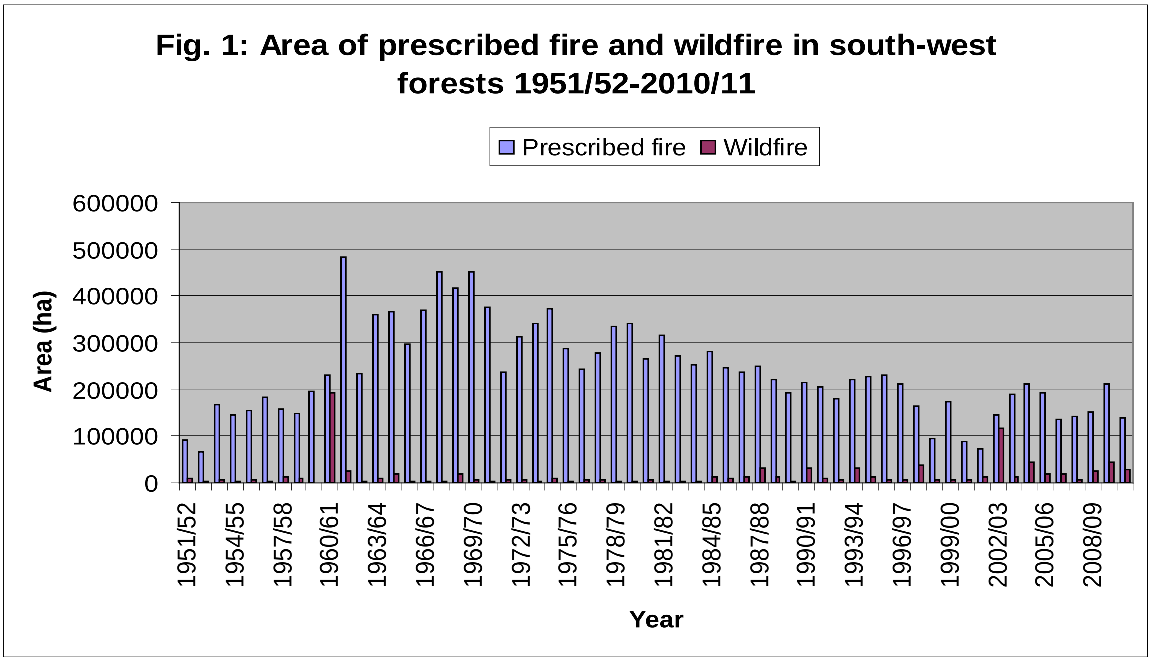
2. Context

In fire-prone south-west Western Australia, prescribed burning of native vegetation is an important management strategy for achieving conservation and land management objectives. This includes the protection of communities from damaging wildfires, protecting and conserving the environment and biodiversity, and for other reasons such as silviculture and scientific research. Wildfires develop speed, energy and killing power from the amount of live and dead vegetation that burns and this accumulates over time. Prescribed burning done at the appropriate spatial and temporal scales reduces the overall flammability and quantity of fuel across the region, thereby reducing the intensity, killing power and speed of wildfires, making them easier to suppress and less damaging.

Broad area fuel reduction burning as an asset protection strategy has been implemented in south-west WA since the mid-1950s, almost 60 years ago. Since that time, an estimated 8,500 prescribed burns have been carried out, burning a total area of about 15 million ha (Figure 1). Over this time, an inverse relationship between the area burnt by prescribed fire and the area burnt by wildfire has been well established (Boer *et al.* 2009 and 2011), i.e., prescribed burning significantly reduces the impact of bushfires by reducing fire area and intensity.

However, from Figure 1 it can be seen that the annual area of prescribed burning is trending downwards since the 1980s, and the annual area burnt by wildfires is trending upwards over the same period. Reflecting this trend, the proportion of the south-west forest region that is carrying fuels older than 7 years was ~60% (prior to the 2011/12 fire season) and in many situations, these old fuels form contiguous tracts (see Figure 5. If at least 8% (~200,000 ha) of the total area of the south-west forest region is burnt each year, then based on historical data, the mean annual area burnt by wildfire can be expected to be <~1.5% (<~36,000 ha).

Although prescribed burning has a firm scientific basis, and the Department of Environment and Conservation (DEC) has considerable experience and expertise with prescribed burning, there remains a level of uncertainty surrounding an ability to accurately forecast weather (especially wind) and to predict fuel moisture and fire behaviour, so prescribed burning is not without risk. Since the 1950s, the various departments responsible for prescribed burning in south-west forests have an outstanding record in carrying out the burns safely and effectively. Over the last few decades, only about 2% of prescribed fires have escaped, but in almost all cases, the escaped fires have been quickly contained with little damage done. However, this fire season (2011/12) has seen several prescribed burns escape with one (the Margaret River fire) causing significant property damage and the other (the Milyeannup bushfire) being the largest wildfire in the south-west region since the 1960s.



Incidents such as the Milyeannup bushfire can be considered as accidents and analysed accordingly. A useful framework for analysis of such events is one proposed by Reason (2004) which considers accident causation as a series of events, or failures, that must occur in a specific sequence and manner for an accident to occur. Reason classifies these factors as ‘latent’ and ‘active’. Latent factors are pre-existing problems or circumstances, and active ones are the acute failures that lead to, or triggered an accident. An anaysis of the weather, fuel and fire behaviour conditions of the Milyeannup bushfire will help to better understand latent and acute events, or primary causal factors of the fire. With this understanding, action can be taken to reduce the risk of reoccurrence of such accidents.

3. A description of the fire ground

The location, scale and fragmented nature of the Milyeannup fire can best be seen from the map (Figure 2) and satellite image below (Figure 3). Covering an area of some 52,000 ha and with a perimeter of about 205km, the wildfire impacted a variety of vegetation types from tall southern jarrah forest to coastal heath, and a variety of land tenures and land uses. However most of the land impacted was land managed by the Department of Environment and Conservation as state forest, national park or nature reserve. The regional topography is subdued, gently undulating or flat, with elevation ranging from about 10m near the coast to 120m in the hinterland forests. During the calculation of fire rates of spread, slope was ignored because of the subdued landscape and because the pattern of upslope and downslope terrain would have negated slope effects over the scale of this fire.

While the fire was active over the period 23/11 to 5/12, the final fire area and shape was predominantly determined by weather and fuel conditions during the main uncontrolled fire runs on 23, 24 and 30 of November and on 1 December. Outside these periods, the shape was further influenced by suppression actions including containment line construction, edging and backburning. Either because of difficulty of ground access or the severity of fire behaviour, this fire was mostly fought using indirect rather than direct suppression tactics including constructing containment lines away from the fire perimeter and burning out intervening fuels (edging or backburning). Because ground access was often difficulty, an assortment of aircraft was used to drop water and retardant on the fire, especially on hop overs and spot fires. Aerial suppression rarely extinguishes a bushfire, but in some circumstances it can significantly slow its progress, buying time for other strategies to be put in place.

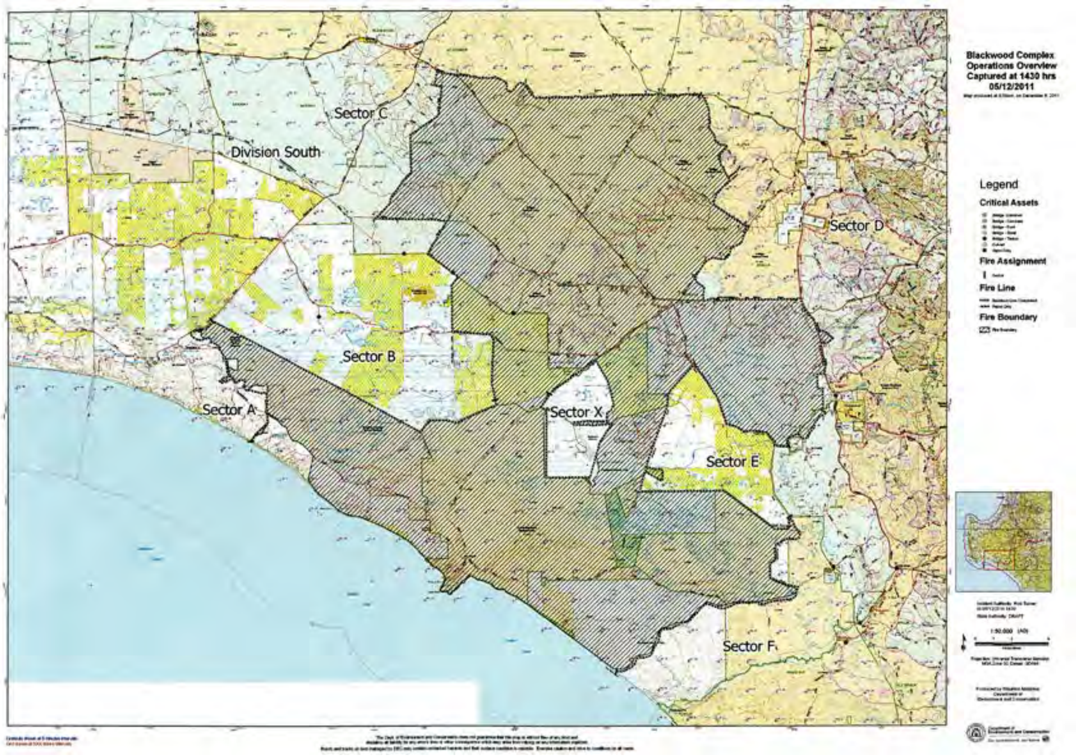


Figure 2: Final footprint of the 52,000 ha, 205 km perimeter Milyeannup bushfire

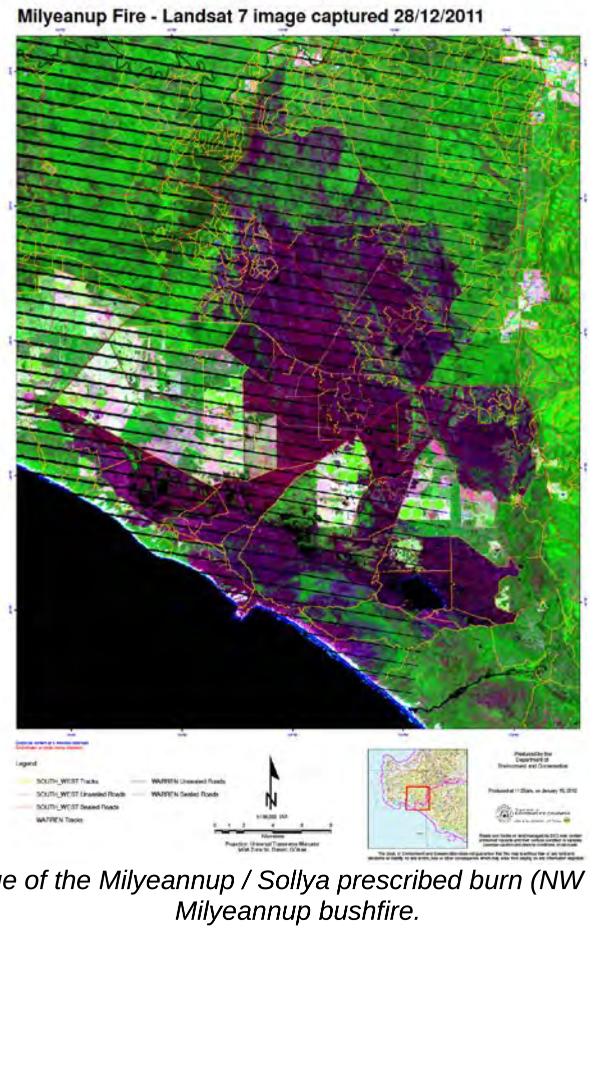


Figure 3: Satellite image of the Milyeannup / Sollya prescribed burn (NW patchy section) and the Milyeannup bushfire.

Climate, vegetation and fuel types
The climate of the region is typically a Mediterranean-type climate with cool wet winters and warm to hot dry summers. There is evidence of the climate of the region becoming warmer and drier, consistent with climate change models. Long term annual average rainfall varies from about 1000 mm near Nannup to as high as 1300 mm on the south coast. Vegetation, which also becomes fuel, comprises a diverse, relatively fine scale mosaic of forests, woodlands, healthlands and sedgelands (seasonally inundated flats). These vegetation complexes reflect landform, climate and soil characteristics and have been mapped at a scale of 1: 250,000 by Mattiske and Havel (1998). These complexes form the basis of broad characterizing the fuels involved in the Milyeannup bushfire. Once the fire exceeded about 500 ha, it was usually burning in more than one vegetation complex. Similarly, once headfire width exceeded about 1 km, then it was usually burning in multiple vegetation complexes.

Four broad fuel types have been identified, based on an amalgamation of the finer scale vegetation assemblages. The fuel types are primarily based on vegetation structure, which ranges from open jarrah forest (and embedded ecosystems) in the north of the fire ground to peppermint woodlands and coastal heath to the south (Figure 4; Table 1). There exists variation within these broad types, but the within fuel type variation is considerably is less than variation between the types and larger moderate intensity fires (>500 ha) tend to integrate this finer scale within fuel type variation. As can be seen from the fuel ages classes mapped at Figure 5, the fire burnt mostly in long unburnt vegetation (>7 years since last fire).

Current fire behaviour prediction models (the Red Book and the Vesta models) exist for the jarrah forest vegetation / fuel type, but there are no specific models for the other vegetation types involved in this fire. Although not designed for these vegetation types, the mallee-heath model (DEC 2010, McCaw *et al.* 1993) was used to predict fire rates of spread in non-forest fuels.

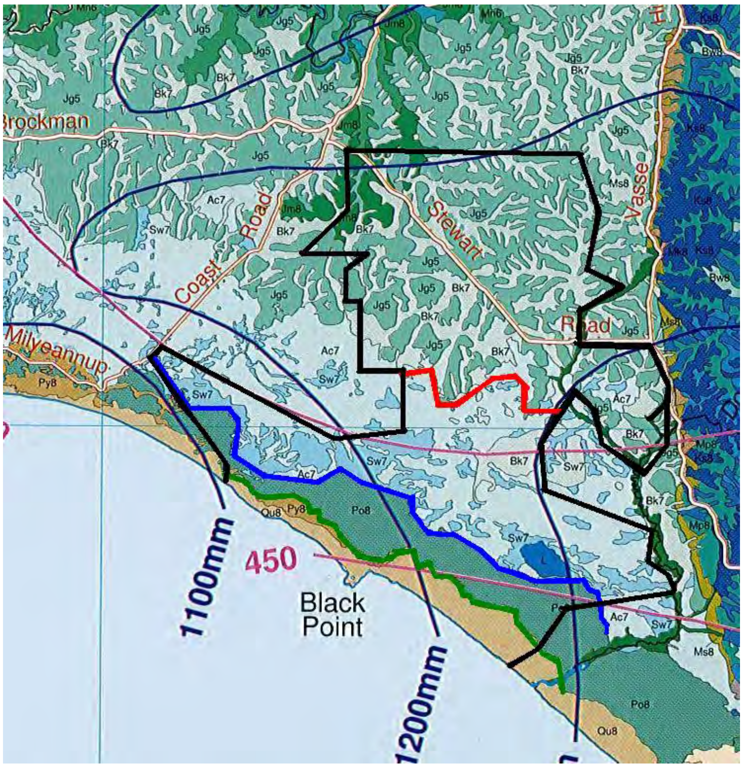


Figure 4: Four broad fuel types based on vegetation assemblages. Jarrah forest mosaic is above the red line, jarrah woodland mosaic is between the red and blue lines, peppermint woodland mosaic is

between the blue and green lines and coastal heath mosaic is below the green line. Black line is approximate perimeter of Milyeannup fire. See Table 1 for descriptions of fuel types.




Major fuel types (see Table 1): from top left; open jarrah forest; jarrah woodland; peppermint woodland; coastal heath

Table 1: Description of the four broad fuel types involved in the Milyeannup fire (see Figure 4).

Broad Fuel type	Mattiske & Havel vegetation assemblages	General Description
Open jarrah forest	Jg5, Bk7, Ms8	Open jarrah forest mosaic: Mostly low (15-20 m) open forest of jarrah and marri with a moderately dense shrubby understory, occasional patches of tall forest (to 25 m), thickets of sheoak and patches of 'stunted' jarrah to 10 m. On broad valley floors, very low open forest or woodland of jarrah, marri and sheoak often with dense shrubby understorey. Embedded heathlands and wetland patches.
Jarrah woodland	Ac7, Sw7	Low open jarrah woodland mosaic: Sandy and sandy loam plains with low open woodlands of jarrah, marri, banksias, sheoak, peppermint and paperbark with low, moderately dense shrubby understory. Embedded heathlands and wetland patches.
Peppermint woodland	Po8	Peppermint woodland mosaic: Stabilised dunes. Low peppermint forests with low moderately dense shrubby understorey. Embedded wetlands.
Coastal heath	Py8, Qu8	Coastal heath mosaic: Coastal swales and dunes. Low open peppermint woodlands with low shrubby understorey and low, dense coastal shrublands. Embedded wetlands.

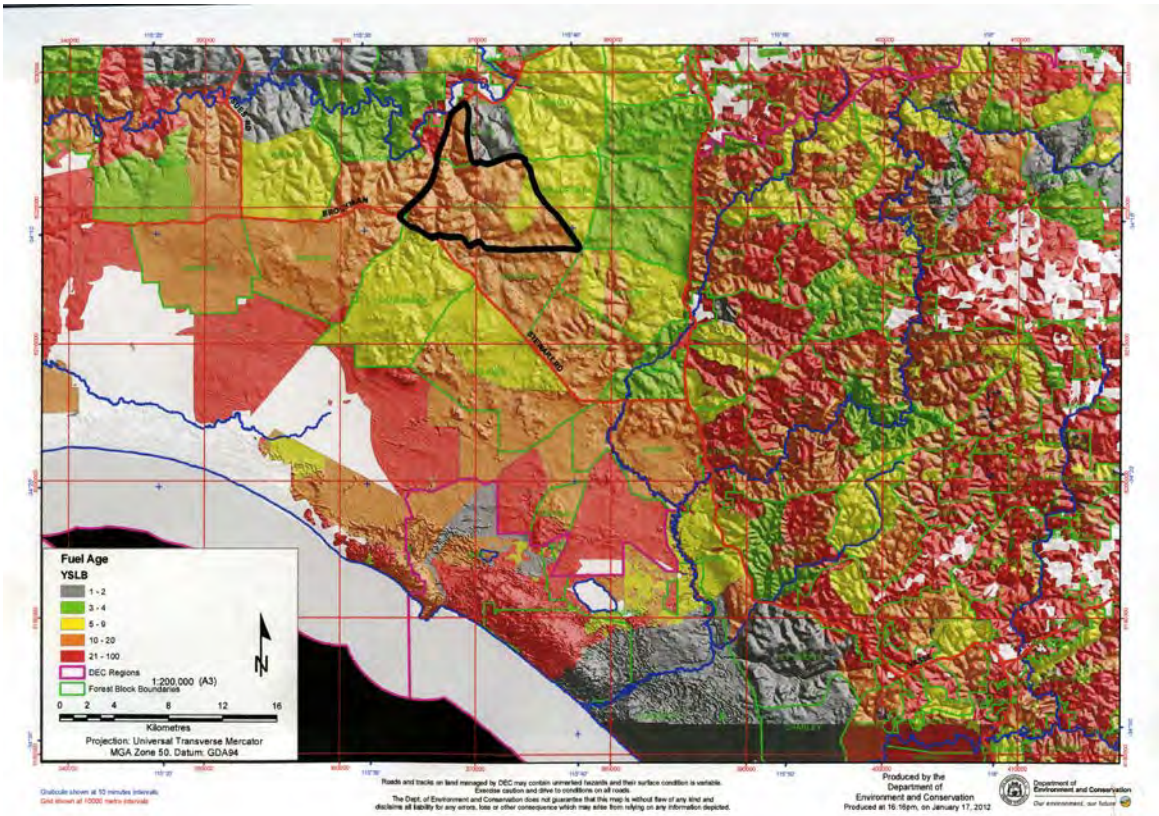


Figure 5: Regional fuel age plan showing extensive, contiguous hazardous fuels; yellow= 5-9 years old, orange= 10-20 years old and red=20+ years old. Black outline is Milyeannup prescribed burn boundary (BB125).

4. The Milyeannup Sollya prescribed burn (BB125)

The Milyeannup Sollya forest prescribed burn was within the Milyeannup National Park and Sollya State forest some 20 km SW of Nannup. The burn (BB125), encompassing an area of ~8,000 ha (reduced to ~6,555 ha the when NE section was burnt in May 2011) and a total perimeter of ~45 km, is bounded by the Brockman Highway to the west and north, Milyeannup Rd to the south, Sollya Rd to the north-east, Darradup Rd to the east, and Blackwood Rd to the north (Figure 6).

Milyeannup forest block lies within the 1200 mm -1300 mm average annual rainfall isohyets and is part of the Blackwood Plateau Jarrah Forest Ecosystem. As discussed, the topography is generally subdued, with slopes mostly < 4^o and elevation varies from 80 m - 120 m above sea level. Milyeannup is within the Blackwood Plateau Landscape Conservation Unit (Havel and Mattiske 1998), comprising a variety of vegetation complexes (Havel and Mattiske 2000). Gravelly yellow-brown soils on upland slopes support an overstorey of *Eucalyptus marginata* (jarrah) and *Corymbia calophylla* (marri) to 25 m with an often dense and diverse understorey to 2 m. Understorey often includes dense and extensive patches of highly flammable *Taxandria parviceps (tea tree)* and *Allocauarina fraseriana (sheoak)*. Yellow-brown sands and grey sands overlaying laterite often support low open jarrah forest (to 15 m) with a low open understorey. Another less common vegetation assemblage occurs on alluvial flats with brown sandy loams supporting an overstorey of jarrah, marri and occasionally *E. patens* (blackbutt). Creeklines support dense, tall (to 3m) and flammable vegetation such as *T. linearis* and *Hakea lasianthoides.* Overstorey canopy cover is variable, depending on site productivity (edaphic and topographic characteristics) and forest health. *Phytophthora*-caused jarrah dieback is widespread along roadsides with patches of severe impact resulting in overstorey collapse.

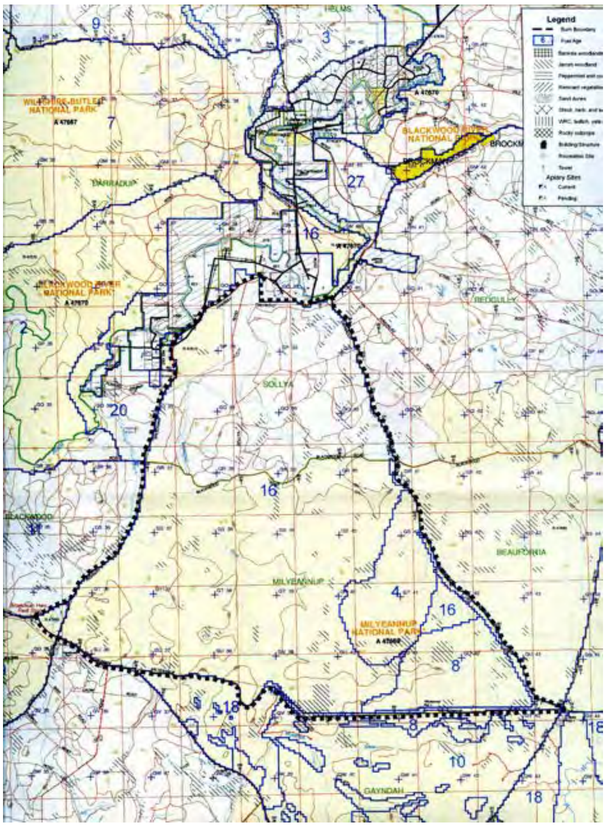


Figure 6: BB125 - Milyeannup prescribed burn (boundary marked) south of Jalbaragup and ~20 km SW of Nannup. The NE section (between Sollya Rd and Darradup Rd) was burnt in May 2011.

The prescribed burn area and the surrounding forests are / were mostly long unburnt (Figure 5). Most of the burn area carried 17 year old (yo) fuels although there were some patches of 9 yo and 5 yo fuel south of Blackwood Rd. Fuel age in the surrounding vegetation varied from 7 yo and 11 yo to the south, 8 yo to the east and 21 yo north of Blackwood Rd. Fuel on private property to the north and west is unknown but is characterized as "extremely old".

In summary, BB125 carried long unburnt, heavy, flammable fuel and is within a landscape of similar long unburnt and flammable fuels (Figure 5). Prior to the fire, the Vesta Fuel Hazard Rating (VFHR) for all fuel layers is estimated to have been 3-3.5 (High to Very High) across most of the burn area and surrounding vegetation, with extensive patches of VFHR = 4 (Extreme) in the oldest (15+ yo) fuels. Mean leaf litter (surface) fuel load is estimated at 8.5-20 t/ha depending on fuel age, canopy cover and site productivity, with patches up to 40 t/ha beneath sheoak thickets. Measured available fuel quantity as reported in the Burn Implementation Plan (DEC 2011) ranges from 6.3 t/ha to 21.5 t/ha.

Prescribe burn BB125; chronology and narrative

A detailed, comprehensive and somewhat onerous planning, checklists and endorsement process is undertaken before executing any prescribed burns, and such was the case for the Milyannup Sollya burn. From these documents, the prescribed burn had the dual purpose of a) "strategic protection" and b) "biodiversity management", described as being:

"To minimise the potential size and intensity of bushfires and the risk from bushfire damage to Darradup and Jalbarragup communities and associated infrastructure, adjacent private property, the Milyeannup and Blackwood River National Parks, Sollya Forest Block and surrounding jarrah regeneration by the application of fire under prescribed conditions to reduce the quantity of combustible material".

"*To protect, maintain and enhance biodiversity values and ecological processes within Solya Forest Block, Blackwood River National Park and Milyeannup National Park by applying fire under prescribed conditions to achieve a mosaic of fire intensities and burnt and unburnt areas both at a landscape and a local scale*".

It is worth noting that is difficult to achieve a mosaic of burnt and unburnt patches in long unburnt vegetation (older than about 5-6 yrs) because of its high flammability rating across the landscape.

Burn prescriptions are documented in the departmental records (Burn Implementation Plan versions 12/03/2011 & 29/08/2011), and can be summarized as:

Autumn 2011 edging:
Standard: Obtain a minimum of 100 m of complete burnt edge with no unburnt pockets.
Desirable season: Autumn
FDI: 18-26.
SDI: To fall by 500.
Wind: Any suitable <16 kph.

Spring 2011 edging:
Standard: Obtain a minimum of 100 m of complete burnt edge with no unburnt pockets.
Desirable season: Spring
FDI: 18-26.
SDI: Any suitable SDI.
Winds: Any suitable <16 kph

Core ignition Spring 2011:
Preferred FDI : 18-26
Wind: <16 kph
Preferred ROS: 26-30 (in forests)
Maximum Scorch ht: 11 m

The prescription does not specify preferred conditions of Soil Dryness Index (for core ignition), ambient temperature, relative humidity or surface (or profile where appropriate) fuel moisture content (SMC) for the day of the burn and for the following 3-5 days. Including this information in the prescription would a) improve the likelihood of meeting the desired range in fire behaviour and b) reduce the risk of fire escape on the burn day or later.

The Milyeannup Sollya burn was a 'Red Flag Burn' or a potentially risky and difficult burn. It was recognized by planners that if the fire escaped it would be difficulty to suppress, largely because of the long unburnt vegetation surrounding the burn, and the potential existed for damage / loss of community and conservation values. It is not clear from the documentation whether any additional precautionary measures were taken because of the RED Flag status of this burn.

29 April-10 May 2011: Edging:
In preparation for core ignition of BB125 the following spring, edging was carried out on several days over the period 29 April – 10 May 2011, when much of the eastern and south-eastern boundaries were edged (Darradup Rd, Sollya Rd and eastern end of Milyeannup Rd). Some edging was also completed along the western boundary south of Blackwood Rd.

Fuels on the western part of the southern boundary (Milyeannup Rd) and the southern part of the western boundary (Brockman Hwy) were too wet to edge. Further efforts to edge were made into early May but fuels were too wet to complete effective edging of the entire boundary. On 10 May, 1400 ha in the NE sector was successfully burnt by aerial ignition. The autumn edging was carried out within the recommended range of fuel, weather and Soil Dryness Index (SDI) conditions (Burrows 1987). The SDI is an index of ecosystem dryness or drought; it reflects the dryness of the soil profile, deep forest fuels and of coarse woody debris, and ranges from 0 (saturated) to 2000 ('bone' dry). The SDI at Bridgetown had fallen by more than the minimum recommended 400 units, from a summer high of ~1750 to ~1100 by early May, and 26.6 mm of rain was recorded at Nannup in the 7 days prior to the commencement of edging. The range of weather conditions recorded at Bridgetown (the nearest AWS) on the days of autumn edging is shown in Table 2 below. Conditions for burning were marginal because of high fuel moisture content, so there were no reported control issues during the autumn edging.

Table 2: Summary of mild weather conditions during autumn 2011 edging of BB125. The SDI had fallen by ~650 units from its summer maximum.

Max. Temp (^{o}C)	Min. RH (%)	Wind	Cloud
20.5-25.1	39-50	Mostly SE@7- 15 km/h	7/8

While the prescription specified "*a minimum of 100 m of complete burnt edge with no unburnt pockets*" it is not clear from the documentation what the standard of edging was like in terms of a) extent of fuel removal, b) depth or distance of burnt fuel from roads/tracks and c) the actual perimeter extent of edging achieved. However, given the marginal burning conditions (wet fuel) around much of the burn boundary, it is highly likely that the quality of edging was patchy both in terms of depth of fuel removal and distance in from the edge. It also appears that only about 26 km of the total of about 44 km was able to be edged in autumn 2011.

While the edging was carried out diligently and within recommended SDI guidelines, the outcome of the edging activities does not appear to have been formerly assessed and documented. However it was likely incomplete and the standard of edging (distance /depth and extent of fuel removal) probably variable. Factors contributing to this include:

- Mild weather and moist fuels.
- Long unburnt forest, so patches of relatively deep and wet litter fuel profiles and fuel complexes along sections of the perimeter.
- Dense riparian vegetation was probably damp and non-flammable.
- Limited window of opportunity (conditions of fuel and weather) and a long perimeter to edge (~45 km) with limited resources.

19 November 2011: Edging and core ignition

Prior to core ignition, further edging was carried out on the NW boundary (Brockman Hwy) on account of the SE winds and potential containment pressure on the NW perimeter following core ignition. Edging commenced along Brockman Hwy at 1230 hours (h) and aerial core ignition commenced at 1400h. Ignition spacing was 150 m x 75 m with flight lines running N-S, working from W to E into a SE wind. The first two lines were parallel to the edging along Brockman Hwy.

Soon after 1400h, an on-ground observer reported flame heights 0.5 m-0.7 m in open areas with a "crackle grass" understorey and 0.3 m – 0.5 m in areas with no "crackle grass" (Note: I'm not familiar with the term "crackle grass" but it is possibly *Anarthria prolifera*?). The fire being observed was backburning into a moderate SE wind with rates of spread (ROS) ~20-25 m/h.

At 1430h, when 10 flight lines had been completed, the aircraft observer reported fire behaviour as:

- Open jarrah: Flame height 1-2 m up to 5-6m. ROS ~100 m/h

At 1505h, when 20 flight lines had been completed, the aircraft observer reported fire behaviour as:

- Open jarrah: 60% take (ignition of incendiaries), flame heights 1-2 m, ROS 150-200 m/h, fires burning in oval shape.
- Southern jarrah: 20% take, 0.3-0.5 m flame heights, ROS 20-30 m/h, fire shape round (mild fire behaviour).

At 1730h, the aircraft had completed core ignition and provided the following final fire behaviour observations:

- Open jarrah: 80% take, flame heights 2-3 m, up to 10 m, ROS 100-500 m/h, fire shape elongated.
- Closed jarrah (southern jarrah?): 40-50% take, flame height 0.5 m, ROS 30-40 m/h, fire shape round to oval.

During the day, several small hop-overs were extinguished.

On 18/11, the day before edging, 4.4 mm of rain was recorded at Nannup. Consequently, an field measurement of the surface litter moisture content (SMC) taken on the 19/11 was 18%, which is high and close to the moisture content of extinction (~21%). It was noted that the duff, or humus layer beneath the surface fuel was "moist" (Martin). The SDI calculated for Kirup for 19/11 was 259 (equivalent to 25.9 on the graph at Figure 7), which is the lowest recorded for this time of year over the last five years, and ~500 (50 -Figure 7) units lower than the average value for the last 5 years (Figure 7). The unseasonally low SDI was a result of average winter rainfall and generally above average, late spring rainfall across the south-west. The recommended upper spring SDI limit for prescribed burning in southern jarrah forest is 700 (or 70 – Figure 7), which is normally reached by about late October. In Kirup in 2011, this was not reached until early in December. Weather conditions for 19-22/11 at Bridgetown, the nearest BoM weather station (AWS) to BB125, are summarized in Table 3.

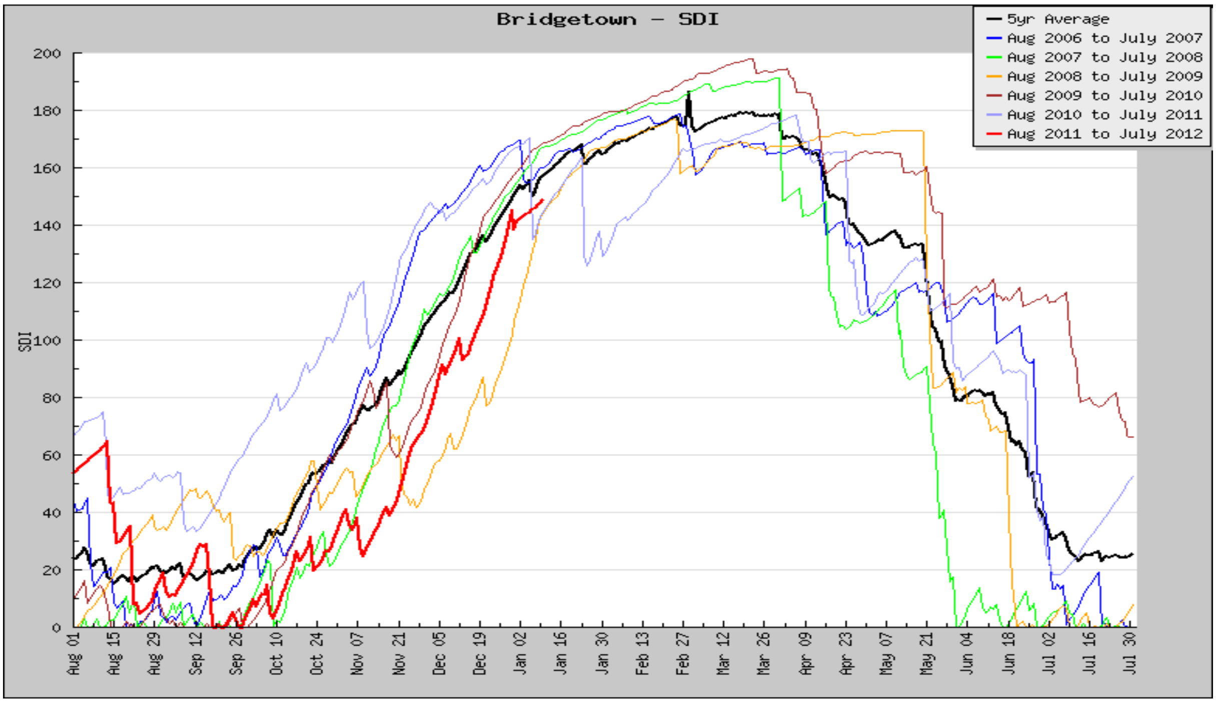


Figure 7: The last five years of Soil Dryness Index (SDI) for Bridgetown (note: multiply SDI values by 10 to align with DEC SDI units).

20 November 2011: Edging and core ignition

Under the influence of a light SE wind (10-15 km/h), edging continued during the morning on the SW boundary of BB125 along Stewart Hwy between Brockman Hwy and Milyeannup Rd. and along Milyeannup Rd east to Milyeannup Brook. Fire behaviour was mild, ranging from 10-15 m/h along Stewart Hwy, to 30-40 m/h along Milyeannup Rd. with flame heights to 0.5 m.

At 1200h, the aircraft was authorised to light some larger unburnt pockets in the vicinity of Milyeannup Brook N of Milyeannup Rd. At 1245h the aircraft reported fire behaviour as;

- 60-70% take, flame heights 0.3-0.5 m, ROS 20-40 m/h, fire shape round (indicating mild fire behaviour).

By 1400h, edging along the southern boundary (Milyeannup Rd.) was completed. While the edging had travelled N of Milyeannup Rd some 50-100 m, much of the fuels along the southern boundary were described in fire diaries as “duffy” (particularly near Milyeannup Brook and west to Stewart Rd) (Mitchell). Vegetation along the western end of Milyeannup Rd is productive, tall jarrah forest which, prior to the prescribed burn, carried 17 yo fuels. Near surface fuels (litter) would have been quite deep and “duffy” with a well developed duff or humus (partially decomposed) layer beneath a fresh surface litter layer. Because of the low SDI and moist fuel conditions, it appears that the earlier autumn edging had removed some of the drier, fresh surface litter but little of the wetter, lower duff layer, as suggested above.

Some of the residual duff fuel was able to be burnt during the spring edging, but it was reported to be patchy, with fires “trickling” around, indicating that the duff material in deeper fuels was probably damp and did not burn to mineral earth. This is not surprising given a) the old fuel age, and hence depth of duff, b) the sheltered micro-climate beneath these tall forests with good (~50%) canopy cover and c) the low SDI. Some additional burning was done along Sollya Rd. Weather conditions for 19-22/11 are summarized in Table 3. Forecasts were issued by the BoM at 0750h WST for Bridgetown.

The synoptic situation over the period of spring edging and core ignition of BB125 is shown in Figure 8. As usual for this time of year, weather is dominated by a high pressure system ridging in from the Indian Ocean and establishing in the Bight, generating SE to E winds. With the approaching cold front, a trough of low pressure forms down the west coast, with a NE airflow on the east side of the trough and SE airflow on the west side.

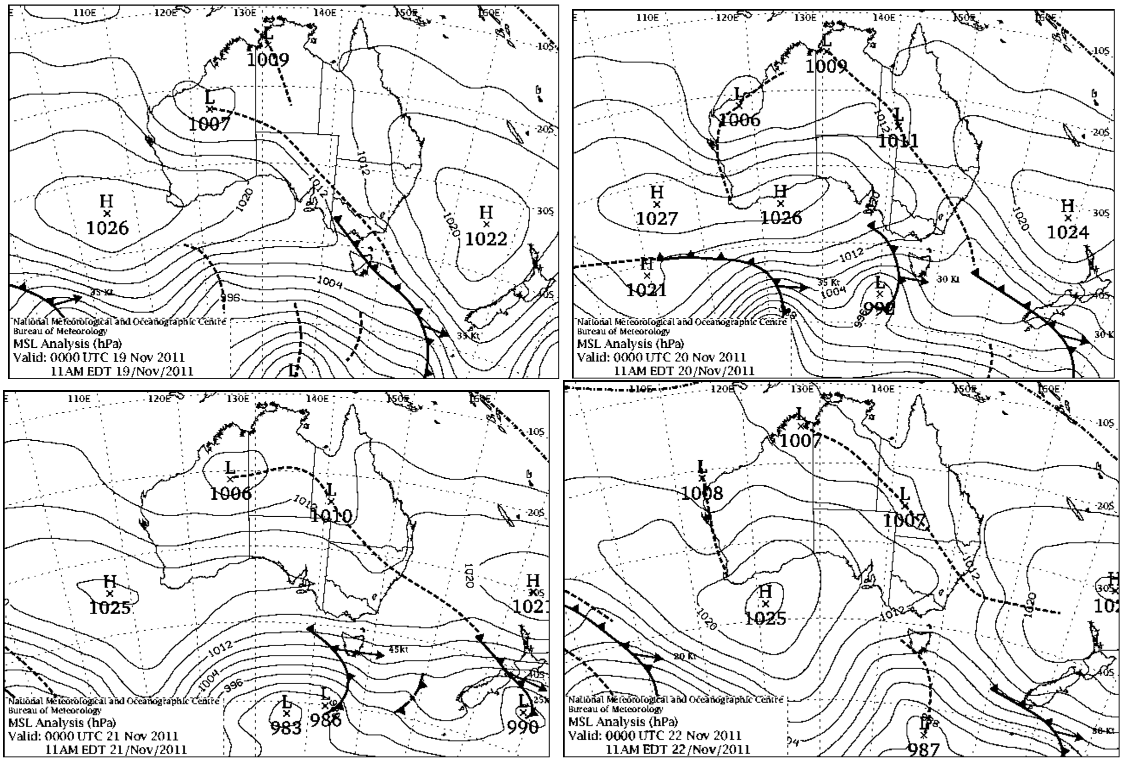


Figure 8a,b,c,d: Sample weather charts for the period during edging and core ignition of prescribed burn BB125.

Table 3: Weather conditions for 19-22 November 2011 for Bridgetown. Some on-site wind and SMC readings also shown. N/R = not recorded. Forecast (F/cast) and actual (Act.)

Max. Temp (^{o}C)		Min. RH (%)		Winds (km/h)		Min. SMC (%)	
F/cast	Act.	F/cast	Act.@ 1500	Forecast	Actual	Pred.	Act.
19/11							
22	21.8	31	42	1100: SE @15 1300: SSE @10 1500: S @15 1700: SSE @12	0900: SSE@15 1500: NW@2 On-site: SE@10-25		N/A
20/11							
24	24.7	36	38	1100: ESE @10 1300: SSE @5 1500: S @20 1700: S@17	0900: ENE@9 1500: WNW@6 On-site: SE@10-15		18%
21/11							
25	24.3	34	47	1100: ESE @14 1300: SSE @10 1500: SE @13 1700: S@18	0900: SE@7 1500: SSE@13 On-site: N/R		N/A
22/11							
29	28.1	27	30	1100: ENE @12 1300: ENE @9 1500: ENE @8 1700: ENE@7	0900: NE@11 1560: WSW@2 On-site: N/R		N/A

21 November 2011: Edge consolidation
Crews continued working to strengthening edging along Darradup Rd (eastern boundary), Milyeannup Rd near Milyeannup Brook (south-west boundary) and the southern boundary generally (Milyeannup Rd, Stewart Rd), and on mopping up. Towards the end of the day, it was reported that edging on most boundaries was "good", although it was noted that "*edging was poor on the eastern side of the creek*" (Mitchell) (presumably the creek referred to is Milyeannup Brook).

22 November 2011: Mop-up
Crews were dispatched to mop up around BB125 perimeter, take down road signage, etc. There is a noticeable change in weather conditions as a high pressure system establishes in the Bight with associated ENE winds bringing warmer, drier air over the south-west (see Figure 8d and Table 3).

5. Summary observations: Milyeannup prescribed burn

Strategic issues:

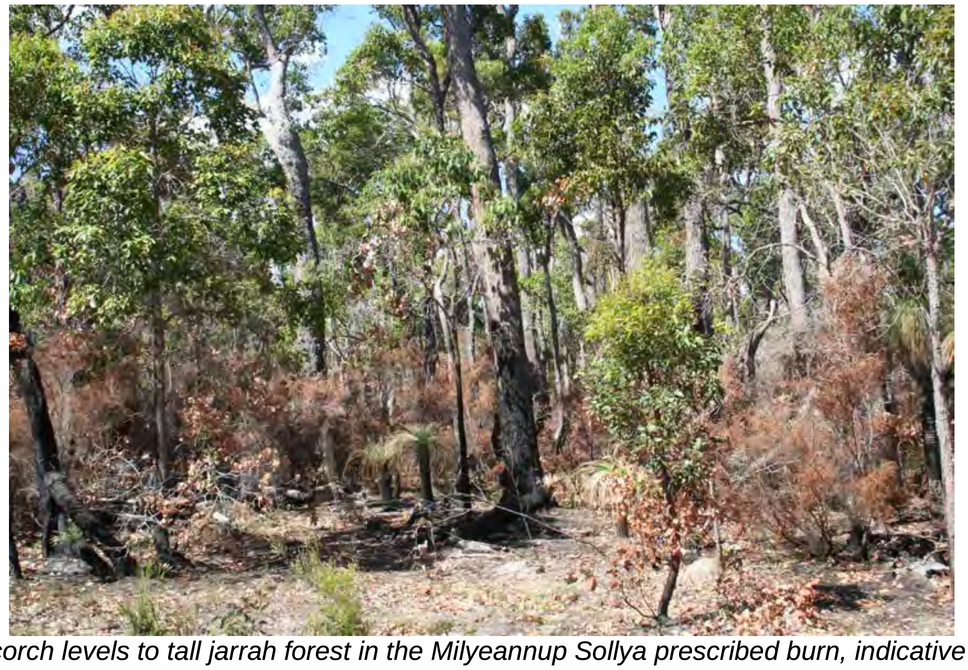
- Prescribed burning is not without risk of fire escape, but the risk escalates with increasing fuel age. This prescribed burn comprised long unburnt fuels and was surrounded by long unburnt fuels.
- Large burns with long perimeters require adequate resourcing, especially Red Flag burns.
- On Red Flag burns, core ignition should not proceed until edging meets prescribed standards.
- Planning, implementation and resourcing of prescribed burns should also consider the extended (4 day) weather forecast.

Tactical issues:

- Implementation of edging and core ignition was within prescribed fuel and weather conditions and recommended burning guidelines.
- There was a long perimeter to burn and to consolidate, even though some edging was achieved in autumn.
- Considerable effort was put into edge consolidation before, during and after core ignition but there does not appear to have been a formal assessment of the standard of the edging prior to core ignition.
- Edging did not meet the prescribed standards (clean for 100 m). While much of the edging was deemed "good" in that it achieved a good depth of burn (50-100 m), there were patches, especially along the western end of the southern boundary (Milyeannup Rd, Stewart Rd), where the fuels were "duffy", probably moist, and edging was patchy and 'weak'.
- In some places, the edging was not deep enough and fuel was not removed to mineral earth; there was a residual "duff" fuel layer on the soil surface. The autumn edging along Stuart Rd to Milyeannup Rd was characterised as "*not strong*" by an overseer (Blythe).
- The moist "duffy" residual fuels were probably a consequence of a) relatively deep, long unburnt litterbed, mild burning conditions and b) unseasonally low SDI due to intermittent late spring rain (see above).
- A strong fuel moisture content differential existed in the landscape because of a) seasonal conditions (low SDI, late spring rain), b) long-unburnt fuels and c) variability in vegetation / fuel structure and exposure.
- The ignition of incendiaries (take) was reported as varying between 20% in tall closed forest to 80% in low open forest, further evidence of fuel moisture content variability resulting in burn patchiness and incomplete combustion of some fuel arrays.
- As with the edging, it is likely that there were patches of residual fuel that did not completely burn during core ignition. Deep litter with a moist profile, insulated fuel complexes and thick creekline vegetation are unlikely to have burnt, or may have partially

burnt, under conditions of low SDI and mild weather because of a relatively higher moisture content (i.e., fuel availability factor <1.0).

- Fire behaviour (ROS and flame heights) following core ignition was highly variable, with some very active and intense behaviour reported. This reflects the variability of vegetation structures / fuel complexes, ranging from tall forests to low open forests, Banksia and Allocasuraina woodlands and heaths / flats. Each of these complexes has different fuel characteristics and different exposures to wind and sunshine (insolation), effecting both fuel moisture content and fire behaviour.
- Fire behaviour in tall closed forest was mild and within the range of predictions and expectations. Fire behaviour in low, open and exposed forests, woodlands and heaths / flats was considerably more active and exceeded predictions and expectations, probably due to drier fuels, greater exposure to wind and insolation and the High fuel hazard (17 yo fuels).
- On such a low SDI, there was probably relatively little mop-up required on the day of the burn.
- At this late time of year (late November), weather patterns can quickly change from spring weather (cool, moist) to typical summer weather (warm, dry). With a long period of daily insolation (~14 hrs of sunshine), surface and near surface residue fuels can dry rapidly, changing from low flammability (~18%) to highly flammable (8-10%) within 24 hrs (see Burrows 2011), even though the SDI may be low. North winds in particular are notoriously warm and drying.
- Prescribed burning of BB125 was within limits set by burning guides and within the burn prescription. However, burning guides and prescriptions are based on more typical fuel and weather situations. That is, they are designed for 5-7 yo fuels and for ‘normal’ patterns of seasonal drying (SDI trend). The situation at BB125 was unusual in that a) fuels were long unburnt (17 yo) and b) the SDI was very low for this time of year on account of late spring rain.
- DEC officers are experienced with burning under more ‘normal’ conditions of fuel and weather. However, under this almost unprecedented combination of fuel age and unusual seasonal weather pattern, the burning guides and prescriptions failed to account for a) extent of residual fuels following prescribed burning and b) rapid surface and near surface fuel drying and escalation of FDI at this time of year. This combination can result in re-ignition and blow-up fires.



Low scorch levels to tall jarrah forest in the Milyeannup Sollya prescribed burn, indicative of low intensity prescribed fire

6. The Milyeannup fire (BWD011)

Phase 1: *1200h 23 November to 1040h 24 November: Escape from BB125*

Weather

The weather was dominated by a fairly intense high pressure system centered in the Bight, directing a warm, dry northerly airflow across the south-west. A cold front and associated low pressure system was moving in from the Southern Ocean south of the continent (Figure 9). Forecast (issued for Bridgetown @0750 hrs) and actual weather conditions (Bridgetown), and some casual observations made on the fire ground for 23/11 & 24/11 2011 are shown in Table 4.

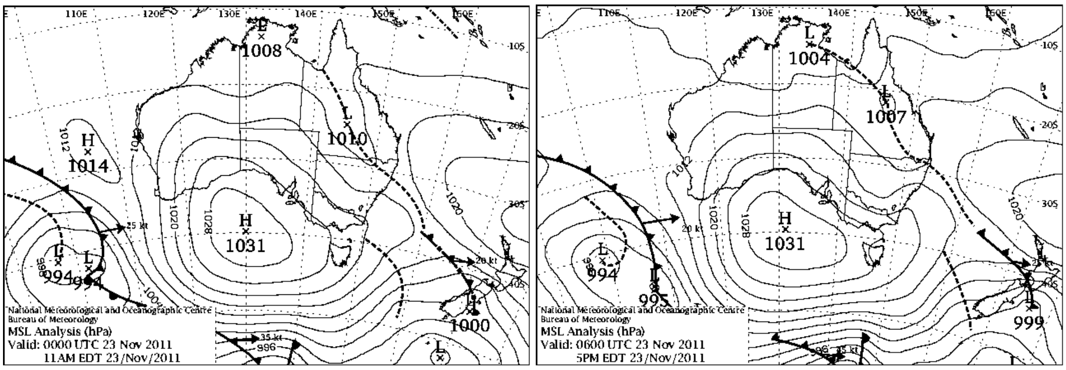


Figure 9a,b: Sample weather charts for 23 November 2011 – initial fire escape from BB125

Table 4: Actual and forecast weather for Bridgeton 23 & 24 November 2011.

Max. Temp (^oC)		Min. RH (%)		Winds (km/h)	
F/cast	Act.	F/cast	Act.@ 1500	Forecast	Actual
23/11					
33	33.3	17	18	1100: NNE @21 1300: N @18 1500: N @13 1700: N @7 0300: NE @14	0900: NNE@15 1500: N@15 Fire ground: estimated NW @ 25-30 (Blythe).
24/11					
33	32.5	16	19	Spot f/cast: 0700: NE @28 1000: N@36 1300: N @38 1600: NNW @34 1900: NW@18 0300: WNW@10	0900: NNE@17 1500: NNW@17 Fire ground: estimated NE @20-30 in the AM (Blythe).

23 November 2011

Crews (2 heavy duty fire trucks and a light unit) were deployed on patrol and mop-up of BB125, concentrating on Darradup and Milyeannup Rds because of the moderate-strong NW wind estimated by ground crews to be 25-30 km/hr (Blythe). There were a number of hot spots along Milyeannup Rd as a result of attempts to strengthen edging during and after core ignition the previous days. The Overseer noted that "*this edge was not strong*".

At 1152h the Blackwood spotter reported fire activity ~50 m north of Stewart Rd (within Milyeannup burn) at GU3620 (Kirup office log). At 1209h, the spotter reported a hop-over at GV3618 – just south of Stewart Rd and ~150m west of Kookaburra Rd. Headfire rate of spread was estimated at 100 m/hr with 1.0-1.5 m flames with fire size ~ 1 ha. The hop-over probably occurred at ~1200h (Figure 11).

At around 1220h, the Overseer noticed the hop-over just west of the Stuart Rd – Kookaburra Rd intersection (at ref. GV3629). On further investigation, he reported that the north wind had "*pushed the fire out through previously burnt ground, up a large red gum and from there, it had thrown over to the south-side of Stewart Rd*".

At this time (~1220h), the hop-over was about 100 m x 200 m (2 ha) (Blythe) and was developing quickly. The Overseer attempted to deal with it using his light unit, but fire behaviour was too active, so he radioed for the two trucks working further east on Milyeannup Rd. On arriving at the hop-over, the crews assessed that it was too intense to safely attack with hoses. By around 1300h, the headfire was reported to have reached near the intersection of Kookaburra and Crow Rds (Blythe) and crossed both roads near this point (see Figures 10 and 11). This was confirmed by field inspection, which revealed high levels of defoliation at this location consistent with the passage of an intense headfire. The average headfire rate of spread from initiation to this point was ~650 m/h.

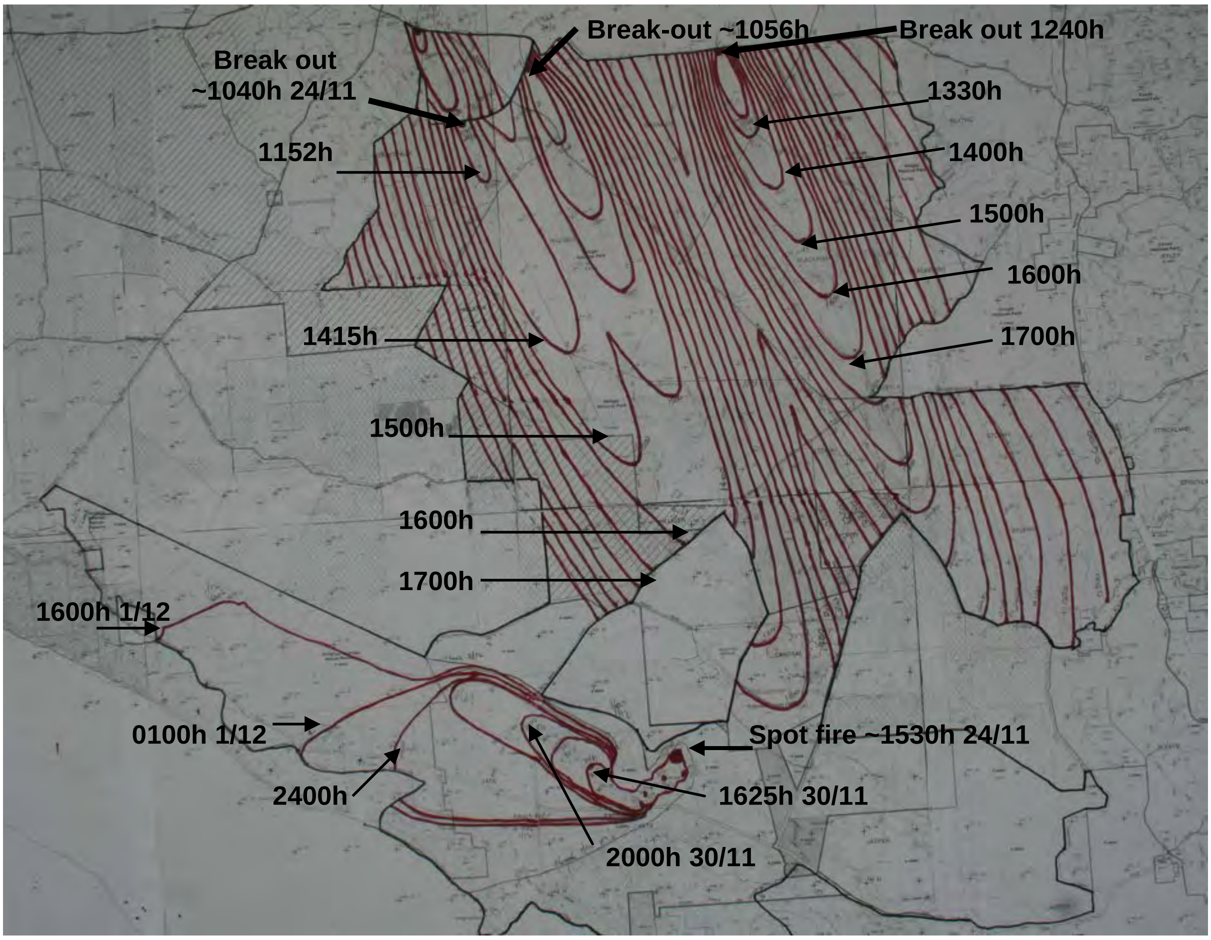


Figure 10: Reconstruction of the path of the Milyeannup bushfire during main fire runs. There were at least 3 break outs and a long distance spot fire on 24/11/2011. See also Figures 11 and 14.

Additional resources including 2 more trucks and a dozer arrived at about 1430h (Blythe). At 1530h the dozer commenced tracking the fire from the NW corner working S-SE off Stewart Rd along the west flank of the fire (Meehan). A contract dozer arrived at 1600h and opened up tracks in front of the fire (Meehan).

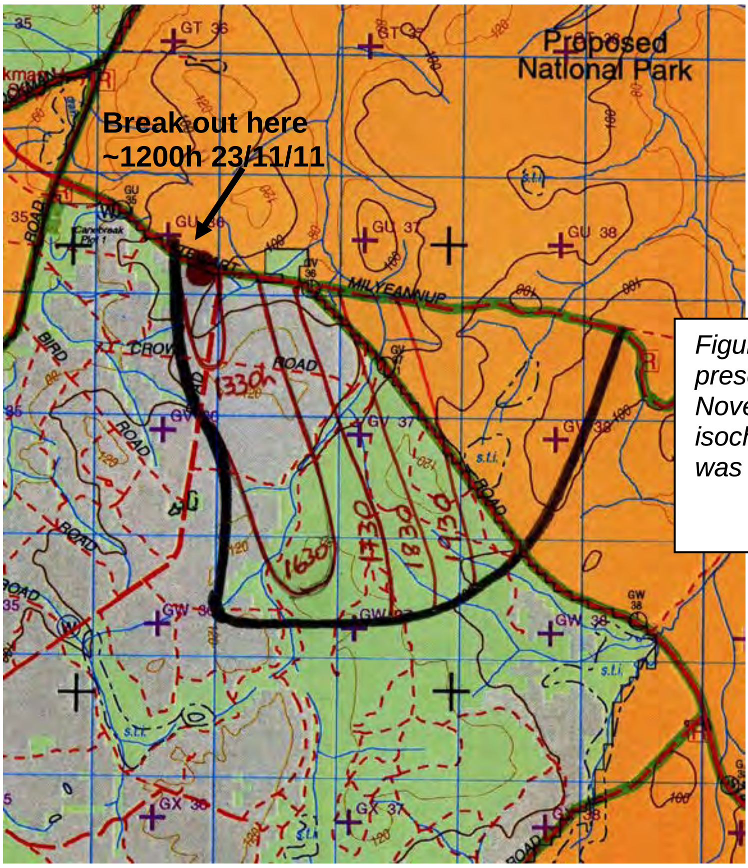


Figure 11: Phase 1; break out from prescribed burn BB125 at ~1200h 23 November 2011 and reconstructed fire isochrones until 1930h. This break out was contained by ~0530h 24 November.

The next reported fire positions were given at 1605h when the spotter reported the headfire at GX3688 (Kirup office log), and at 1630 hrs, when it reported the headfire at GX3683 (Meehan). Note: These locations are not consistent with the final fire perimeter, being south of the dozed containment line by about 1.6km, so it is possible that the headfire location was in the grid cell to the north, at GW3683 (Figure 10).

Mean rate of spread from initiation to 1630h was ~600 m/h. At 1915h the flank fire crossed Stewart Rd near Milyeannup Rd (Meehan) and was reported as being on both sides of Stewart Rd level with a parking bay on Stewart Rd (Meehan). This information was used to reconstruct the fire perimeter as shown in Figure 10. (Note: Figure 10 - fire perimeter reconstruction to be mapped in a GIS environment – hand mapping is included in this draft as an interim measure).

By 0535h on 24/11, the fire was tracked to Milyeannup Rd (see Figure 10) and edging and mop up had commenced (Meehan). Much of the low lying heath / flats systems were wet and boggy, so the dozer could not work close to the fire edge, but had to operate on firm ground sometimes away from the fire edge (Meehan).

Fuels and fire behaviour

To this point the escaped fire had burnt in 7 year old jarrah forest mosaic fuels, including forests and treeless flats / heathlands. A summary of fuels and fire behaviour during phase 1 is provided in Table 5 below. While the calculated mean headfire rate of spread was ~600 m/h over the duration of phase 1, from field observations and defoliation levels, headfire flame height varied from 1.5-6 m with localised torching and defoliation of the overstorey suggesting variable fire behaviour in response to changing vegetation and fuel structures. While the jarrah SMC was low (predicted 6%), fuel moisture content was probably variable. Deeper fuel profiles and fuels / vegetation in low-lying parts of the landscape were probably moist given the low SDI.

Fire behaviour was not unusual and was in the range of model predictions. Based on assumptions and the inputs to the various models, the Red Book under-predicted fire ROS while the Vesta model over estimated ROS.

Table 5: Predicted and actual fire rates of spread for Phase 1:1200h – 1630h 23 November 2011 (assumes 4:1 wind ratio and no net slope effect).

Fuel Type/age	RedBook Av. fuel (t/ha)		Vesta fuel haz. score			Min. SMC (pred.) (%)	Open Wind (km/h)	Mean ROS (m/h)	Mean headfire intensity (kW/m)	Predicted ROS (m/h)	
	Litter	Scrub	NS-ht	NS	S					RedBook	Vesta
1 (Jarrah south) 7 y.o.	11.4	4	20	3	3	6	22	600	4,620	360	830

Phase 2: *1040h on 24 November to 0800h on 25 November 2011 (run south)*

Weather

A high in the Bight continued to influence weather on 24/11 with warm, dry moderate strength northerly winds holding throughout the day, evening and into the early morning of the 25/11 (Figure 12). A low pressure system and associated front moved in from the Southern Ocean and by early morning of 25/11, winds were backing from the north to the west, holding a westerly influence throughout the morning of the 25 and backing further to the south-west by late afternoon. The passage of the cold front was accompanied by cool, moist air, cloud and isolated drizzle in the morning of the 25/11.

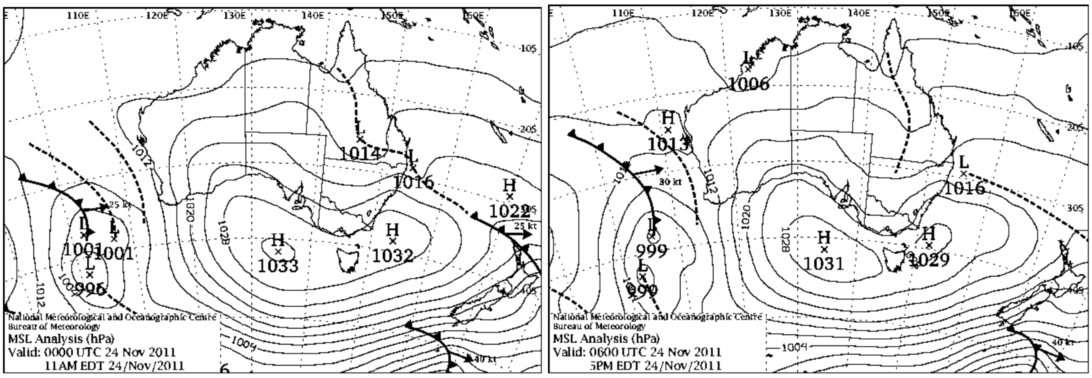


Figure 12: Sample weather charts for Phase 2 – rapid fire expansion south.

Forecast and some actual weather conditions for Bridgetown, ~40 km NE of the fire ground, are summarized in Table 6. There are no weather stations close to the fire ground, with the nearest automatic weather station (AWS) being on Channybearup Rd ~35 km SE, and at Witchcliffe ~55 km W. As Withcliffe is near the west coast, conditions record by the Channybearup AWS are show here in Figure 13. This AWS is on an exposed location and the anemometer is 2 m above ground. Because of the geographic separation and local topography differences, weather, particularly wind speed and direction, at the AWS will not necessarily match those experienced on the fire ground, but the trends in speed and direction recorded at the AWS are probably indicative of trends experienced at the fire ground, particularly while the wind was from the northern quarter.

On 24/11, a maximum temperature of ~33^{o}C and minimum RH of ~20% was reached at ~1200h. Overnight (to midnight), RH increased to ~70% and the temperature remained above 20^{o}C throughout most of the night. Into the early hours of 25/11, RH increased to ~95% suggesting cloud cover and possibly drizzle as wind backed to the west. No rainfall was recorded at the AWS.

Wind speed on 24/11increased from the NNW at about 0700h to a moderate strength and stayed in this range until ~1800h when it decreased in strength. Winds backed to the west at around 0100h.

Table 6: Actual and forecast weather for Bridgeton 24 & 25 November 2011.

Max. Temp (^{o}C)		Min. RH (%)		Winds (km/h)	
F/cast	Act.	F/cast	Act.@ 1500	Forecast	Actual
<u>24/11</u>					
33	32.5	16	19	Spot f/cast: 0700: NE @28 1000: N@36 1300: N @38 1600: NNW @34 1900: NW@18 0300: WNW@10	0900: NNE@15 1500: N@15 Fire ground: ~1220: NW @ 25-30 (Blythe). ~1700: NW@18 (Martin)
25/11					
26	23.6	32	70	1100: WNW@10 1300: W@14 1500: WSW@18 1700: SSW@18 0300: S@8 (morning drizzle) Spot f/cast: 0300: W@15 0600: WNW@13 0900: WSW@20 (morning drizzle)	0900: W@9 1500: SSW@20

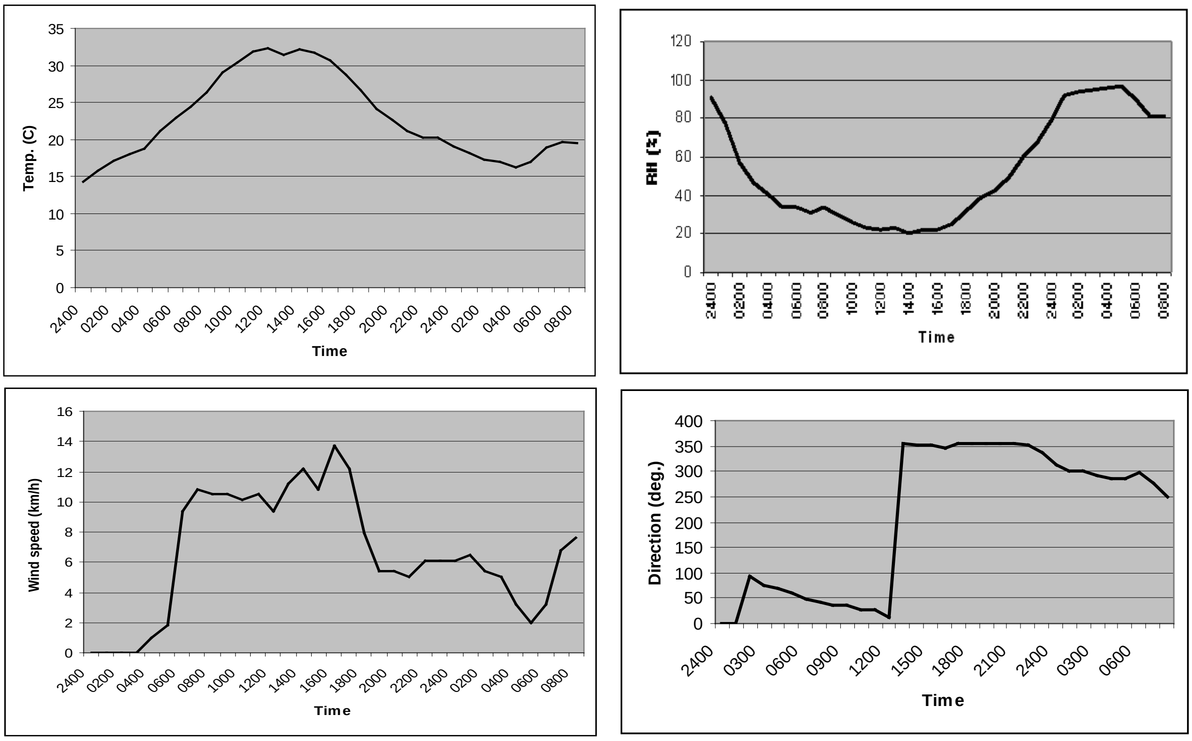


Figure 13: Weather conditions recorded at a AWS on Channybearuop Rd some 35 km SE of the fire ground. The AWS is in an exposed location and the anemometer is ~2 m above ground.

Fire situation: 24 November 2011

Fire was reported to have escaped containment lines (see Phase 1) via a hop-over at ~1040h (Meehan). However, there is evidence from ground and aerial observations and from the banding patterns on aerial photography and satellite imagery and defoliation patterns on the ground, that there were multiple hop-overs and escapes. This is supported by the observation that, "*Had several hop-overs on SW side of Stewart Rd, which we contained, then more over the break between Stewart Rd and Mily Rds and more further around to the SW towards Kookaburra Rd. Doc Meehan directed all crews to pull back and let it go*" (Blythe).

Because of the dangerous fuel, weather and fire behaviour conditions, all crews were withdrawn to safer ground (Meehan). There was some uncertainty as to exactly where the break outs had occurred, probably because there were many hop-overs, crews withdrew from the fire ground for safety reasons and smoke made aerial observation difficult. While there are several clearly recognizable large fire runs on the satellite imagery, there was probably several other hop-overs that coalesced into one of the three or so major fire runs that occurred during this phase.

Mass hop-overs leading to multiple fire outbreaks along the containment line was, under these fuel and weather conditions, a dangerous situation for firefighters who were at risk of being trapped while attempting to contain hop-overs. It was a wise, and possibly life-saving decision to order all crews away from the escaping fire(s) and to safety rather than attempt to contain the hop-overs.

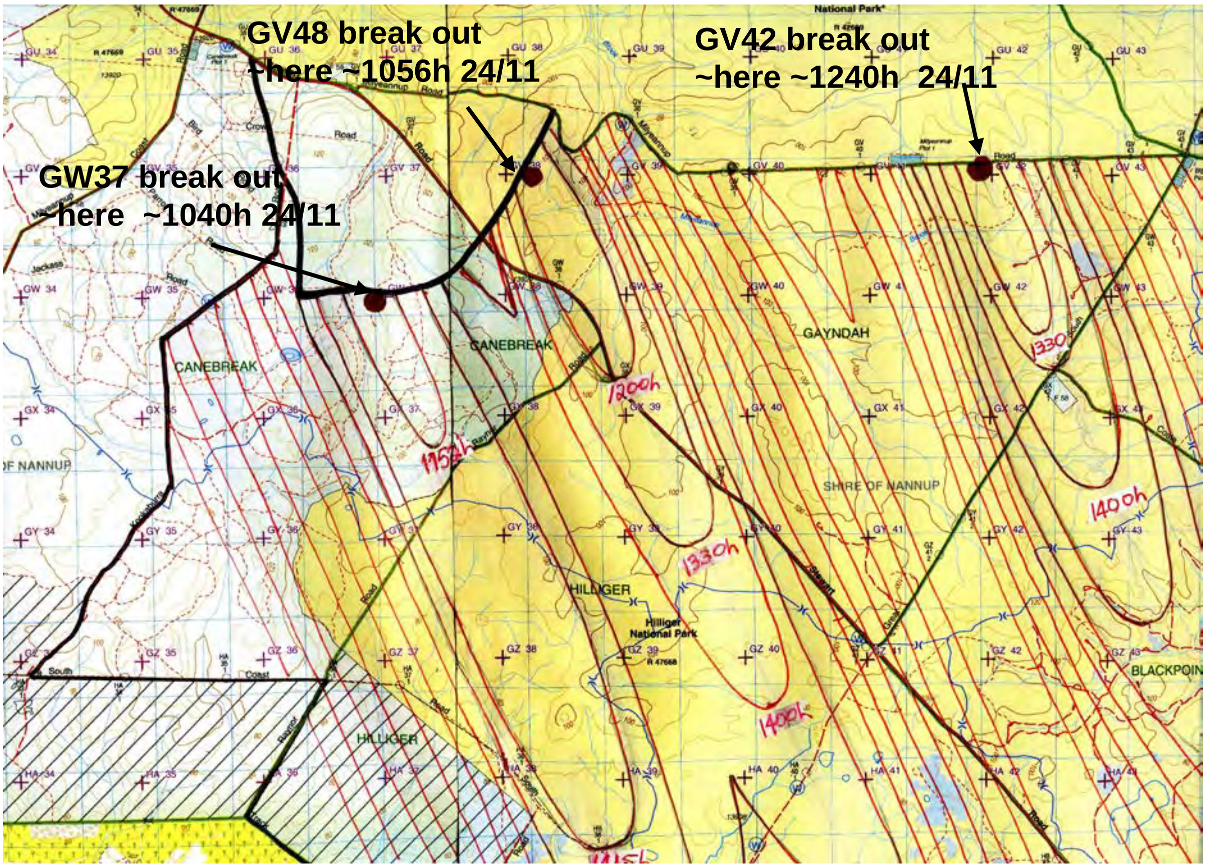


Figure 14: Reconstructed isochrones showing and locations of the origin and initial spread of three Phase 2 break outs on 24 November 2011 (see also Figures 10 and 15).

The spotter first reported a hop-over at 1056h at GV3820 (see Figure 14) and noted that it was under the influence of a NW wind (Kirup office log). The spotter also reported active fire behaviour north of Milyeannup Rd. (at this time, inside the prescribed burn at GV4177, GV3897) and again at 1040h and 1056h (Kirup office log).

At 1152h, the headfire of one of the break-outs, probably the escape from near GW27, was reported at GY3748. At 1240h the spotter reported that active fire within the Milyeannup burn – BB125 (at GV4177) was at risk of jumping Milyeannup Rd (Kirup office log).

At 1330, the spotter reported running headfire at GX4226 (south of Milyeannup Rd.) and noted that it was a hop-over from GV4177 (Figure 14).

The spotter reports and the fire severity banding evident on the satellite imagery and the aerial photography, confirmed by ground inspection, suggests that by 1330h, there were at least three and possibly more breakouts from containment lines, resulting in at least three separate fires running parallel under the influence of a moderate strength NNW wind (~160^{o}). There was one fire south-west of Stewart Rd. originating near GW37 and at least two fires north-east of Stewart Rd. originating near GV38 & GV42 (Figure 14). These fires are dealt with separately in the following chronology and associated narrative.

Fire GV42

This most easterly fire started from a hop-over from running fire north of Milyeannup Rd. in BB125. At 1025h the spotter reported running fire at GV4177 (in BB125). At this time the fire was about 3 ha. At 1240h, the spotter reported a risk of a hop-over from this fire. The next spotter report was at 1330h, when a 100 ha fire, a hop-over from the above GV4177, was reported at GX4226, some 2.2 km south of Milyeannup Rd. It is uncertain whether the reported location for this fire is the location of the headfire or the centre of the fire. It is also uncertain whether this was a spot fire that started some distance south of Milyeannup Rd, or a hop-over that started off Milyannup Rd. For reconstruction purposes, I have assumed that a) it was a hop-over that started near GV42 (off Milyeannup Rd.) and b) that the reported location at 1330h was the headfire of this hop-over. Given this, and based on the spotter reports, the hop-over probably occurred at ~1240h some 2.8 km west of Great South Rd (near GV42). From this point to its location at 1330h (GX4226), its calculated mean rate of spread was ~2,650 m/h (Figure 10; Table 7).

Over the next 11 hours or so this fire made a ~20 km run to the SE to Storry block. Based on its calculated rate of spread from its source (GV42) to GX4226, the fire crossed Great South Rd near Coate Rd. intersection at around 1345h (see Figure 10). Full defoliation of the forest canopy near this location is evidence of intense headfire and bursts of crown fire development. It appears crews were unaware of this fire, which, given its speed and high intensity, would have been extremely dangerous for crews working on or standing by on Great South Rd. south of Milyeannup Rd.

At ~1830h, this fire crossed Black Point Rd into Bidella block near HB45 (Martin). From the last spotter location of the headfire (GX4226) to this point is a distance of ~8.85 km, so over this run the average rate of spread was ~1,770 m/h. However, this was most likely the east section of the headfire or an active flank fire near the head because satellite imagery and field evidence suggest that the centre of the headfire crossed Black Point Rd slightly north of the Stewart Rd. intersection (near ref. Tree HC44-2). Assuming a mean headfire rate of spread of 2,500 m/h, the headfire would have crossed near this point at about 1745 hrs.

The east section of the headfire stopped at about 1800 h when it encountered three year old fuel in Bidella block, demonstrating the benefit of prescribed burning and of young fuels. (note, the fire spread simulation (Figure 15) does not show the fire stopping at Bidellla block because the incorrect fuel age was applied to this cell). However, the west section of headfire crossed into Storry block near reference tree HC44-4 and continued burning in 12 yo fuels with significant fire behaviour until it ran into green paddocks (see Figure 10). There are no further reliable reports of the location of the fire until the early hours of 25/11 when it reached Vasse Hwy. The reconstructed fire isochrones (Figures 10) are based on the assumption that, under the influence of moderate strength NW wind, the fire maintained its earlier rate of spread and is projected to have crossed Jangardup Rd. at about 1830h and reached Pneumonia Rd. and farmland to the south (Loc. 12899) at about 2000h. As wind speed at the Channybearup Rd AWS abated after ~1800 hrs, projections after this time may have the fire further advanced than what it was.

Green paddocks on farmland stopped the headfire and western flank at this point. The reconstruction (Figure 10) suggests that the active eastern flank just off the headfire continued to burn in Storry block. The fire did not spread into farmland because of the green paddocks. Field observations estimate that the active flanks maintained rates of spread of 500-1,500 m/h throughout the night (Martin), becoming headfires when the wind started to back to the west at around 0100 hrs.

By about 0300 h, the wind was W @ ~15 km/h, and the eastern flank was running as a headfire which spread east at an estimated ~800-1,000 m/h. However, with the temperature falling, relative humidity rising and wind speed reducing, fire behaviour abated. By the time the fire reached Vasse Hwy at about 0430 h, its behaviour was relatively mild, with flame heights <1.5 m (based on defoliation heights). The exception was very active fire behaviour experienced in a small pine plot on the edge of Vasse Highway (near HE49-1), which resulted in a hop-over to the east of the highway. There was concern that if the fire crossed Vasse Hwy it would be difficult to contain in 20-27 year old fuels in Strickland block.

However, the hop-over burnt mildly because of the mild weather conditions and because it was burning downslope. Also, by this time the fire had burnt into a different broad fuel / forest complex (see Figure 4) – being more typically tall southern jarrah forest, often with a damp, karri-like understorey. The hop-over (~4 ha) was readily tracked and suppressed.

Summary of fuels and fire behaviour

For the first 2.9 km of its run (from ~1240h to ~1345h), fire GV42 burnt in 11 year old jarrah forest fuels (see Table 1) in Gayndah block. At about 1345h, it crossed into 18 yo jarrah forest fuels in Blackpoint block. At about 1800h the western section of the headfire fire crossed into 12 yo predominantly jarrah forest fuels in Storry block and the eastern section of the headfire burnt into 3 yo jarrah forest fuels in Bidella block and stopped. Predicted and observed / reconstructed fire behaviour during the most active run of GV42 are shown in Table 7. Temperature and RH over this period are graphed in Figure 13.

The high rates of spread and fire intensities shown Table 7 are due to the combined influences of very dry surface fuels (as a result of warm, dry air), moderate wind speed, generally a vegetation mosaic low open forest and heath, and long unburnt, heavy, flammable fuel. The reduced rate of spread over the period 1340h-1800h, even though the fire was burning in older fuels, is probably a reflection of cooler, moister atmospheric conditions (Figure 13) giving rise to a slightly higher fuel moisture content. There was no recorded observations of spotting, but no doubt this occurred given the conditions. The Vesta spotting distance model suggests spotting up to 2 km under these conditions.

The Vesta fire spread prediction model gave a reasonably accurate prediction of fire spread from 1340h-1800h, but under-predicted the earlier run. This may be because of the uncertainty surrounding the actual time and location of the ignition point of the earlier run, as described above, or normal variability in rates of spread. The Red Book predictions are highly sensitive to selection of wind speed ratio. Rate of spread predictions made using a 4:1 ratio, the most likely ratio to apply in this fuel / forest type, were significantly lower than the observed rates of spread by up to a factor of three. However, predictions made using a 3:1 wind ratio, while still below the observed rates of spread, were much closer. Selecting the most appropriate wind speed reduction ratio in this vegetation is not straightforward because it comprises a mosaic of different vegetation structures. Also, once intense fire has defoliated the vegetation, the wind speed reduction through the forest profile would be considerably less than for an unburnt forest.

Table 7: Predicted and actual fire rates of spread for Phase 2 fire GV42 during its most active period from 1240h – 1800h on 24 November 2011. There were no on-site fuel moisture or wind speed measurements taken, so these are inferred from predictions (SMC) and casual on-site observations and forecast conditions (wind speed). Red Book predictions are made for both 4:1 and 3:1 wind ratios.

Fuel Type/age	RedBook Av. fuel (t/ha)		Vesta fuel haz. score			Min. SMC (pred.) (%)	Open Wind (km/h)	Actual mean ROS (m/h)	Mean headfire intensity (kW/m)	Predicted ROS (m/h)	
	Litter	Scrub FL	NS-ht	NS	S					RedBook	Vesta
1240-1340 hrs: Jarrah 11 yo	16.3	10	25	3	3	6	28	2650	26,897	4:1wind=840 3:1wind=2040	2140
1340-1800 hrs: Jarrah 18 yo	21.3	15	30	3.5	3.5	7	28	2020	24,543	4:1=660 3:1=1590	1920

Fire GV38
At 1056h the spotter reported a hop-over at GV3820, south of the containment line and north of Stewart Rd (see Figure 10). There are no further reports of the location of this fire, so its spread has been reconstructed and inferred by assuming that it behaved similarly to GV42 (above) as it was burning under similar fuel and weather conditions. By reconstruction, the fire progressed rapidly under the influence of a NNW wind and the headfire flanked, then crossed Stewart Hwy. near the Raynor Rd. intersection at about 1200h (see Figure 10). The initial path of the fire shown in the reconstruction in Figure 10 and the simulation in Figure 15 is supported by a wide band of defoliated forest along Stewart Rd. for about 2 km either side of the Raynor Rd intersection, indicating intense headfire behaviour. By reconstruction, this fire crossed the Great South Rd. at around 1430h near HA40-1. Its calculated mean rate of spread from initiation at around 1056h to the Beenup Powerline was ~2,500 m/h. It is estimated to have coalesced with fire GW37 (see below) at about this time and location.

Fire GW37
This fire was reported to have escaped Phase 1 containment lines at 1040h on 24/11, but no precise location of the escape is given (Meehan). The next location report was provided by the spotter at 1152h, when the headfire was reported at GY3748 (Meehan), some 2 km S of the Phase 1 containment line (see Figure 14). Based on the spotter report and the wind direction, this fire probably escaped near reference grid GW37 (Figure 12). Air observers estimated spread rates of 1,000-1,500 m/h with flame heights of 30-40 m (Meehan). The calculated mean rate of spread from 1040h – 1152h based on the above headfire positions is 1,708 m/h.

The next report of fire GW37 was at 1415h when it was reported to have crossed Beenup powerline at HB38-1 (Meehan), having travelled 5.85 km since the last report at 1152h. This equates to a mean rate of spread of ~2450 m/h, which is similar to fire GV42 (described above) burning at about the same time and in similar fuels.

Based on the fire reconstruction shown in Figure 10, and the simulation in Figure 15, fires GW37 and GV38 coalesced at about 1430h west of the Great South Rd. in Hilliger National Park. Coalescence would have at least doubled the width of the headfire, increasing it from ~1.5 km to ~3 km, with subsequent escalation in fire behaviour (rate of spread and fire intensity). Coalescence substantially increased the column's kinetic energy, thereby creating the potential for long distance spotting. It is likely that the spot fire reported east of Quitjup at 1700h was launched at around this time. Because of the light to moderate wind speed, the density of short range spotting (out to 300 m) was probably moderate or light.

At ~1530h, the coalesced fire was reported to have crossed Black Point Rd. near HE4162 (Gardiner), travelling ~6.65 km from the Beenup powerline in 1.25 hrs, or spreading at a staggering 5,200 m/h over this section. The average rate of spread from its position at 1152h to its position at 1530h (when it reached Black Point Rd) was ~3,471 m/h, with mean rate of spread from initial escape being ~ 3,050 m/h.

All three fire break outs reached speeds and intensities that exceeded the threshold for successful direct attack. Direct attack is likely to fail when fire intensity exceeds ~2,500 kW/m – the headfire intensity of these fires was >20,000 kW/m.

At 1700h, the spotter reported a spot fire at HK4057, ~1 km NE of Lake Quitjup. The spot fire was reported to have been 50-100 ha in size, so had probably been burning for about 1.5 hrs. It is likely that coalescence and escalation of fire behaviour of the main fire to the north resulted in strong convection development and the long distance launching of numerous embers. At around 1530h, about the time the spot fire is estimated to have started, the main headfire was ~ 6.5 km away. Over the following days, numerous attempts to suppress the spot fire by aerial suppression failed, and this spot fire eventually develop into Phase 3 of the Milyeannup fire.

By the early hours of 25/11, weather conditions and fire behaviour had abated, as described above. Suppression activity focused on the construction of containment lines, edging / burning out unburnt pockets, mopping up and suppressing the numerous, mainly small, hop-overs. With the exception of the active spot fire east of Lake Quitjup, the remainder of the fire was contained and controlled over the next 4 days. Because of the difficulty of accessing the Quitjup spot fire, aerial suppression was deployed. Numerous retardant and water drops were made on the fire over the next 5 days, and while the spread of the fire was slowed and its perimeter fragmented, it was not extinguished. Due to mild weather conditions and the aerial suppression effort, the spot fire behaviour was mild, the fire developed slowly.

Summary of fuels and fire behaviour – GV38 & GW37
Apart from an initial spotter report of a hop-over and escape, there are no further reports of the location of the fire that started near GV38. For the purpose of reconstructing this fire, it was assumed to have behaved similarly to fire GW37. Therefore, fire GV38 will not be discussed further in this summary of fuels and fire behaviour, which will focus on the fire that started near GW37 and the fire resulting from the coalescence of fires GW37 and GV38.

Following its reported escape at ~1040h to ~1200h, fire GW37 burnt in 7 yo jarrah forest mosaic fuels in Canebreak block. At about 1200h, it crossed into 11 yo jarrah forest fuels in Hilliger National Park. It also burnt through ~250 ha of 17 yo fuels NE of Jack Track. Fires GV38 and GW37 coalesced in the middle of Hilliger National Park and north of the Beenup powerline (near GZ39) at around 1430h. The large coalesced headfire burnt rapidly through Hilliger National Park, displaying extreme fire behaviour, including intermittent and sustained crown fire, and reached Black Point Rd. and green paddocks on private property at ~1530h (Gardiner). The flank fires continued burning in bushland to the west and east. At around 2200h the east flank joined the west flank of fire GV42.

Predicted and observed / reconstructed fire behaviour during the most active run of GV38/GW37 are shown in Table 8. Temperature and RH over this period are graphed in Figure 13.

As with GV42, the very high rates of spread and fire intensities shown in Table 8 are due to the combined influences of very dry surface fuels (as a result of warm, dry air), moderate and consistent wind speed and direction, generally a vegetation / fuel mosaic of low open forest and heath, and long unburnt, flammable fuel. The increased and severe rate of spread from about 1415h to 1530h is attributed to the coalescence of two fire fronts and the increasing proportion of open woodlands and flats/ heathlands in the landscape. While there is no record of spotting, given the size, speed and energy of this fire, there would have been prolific long distance spotting. Many of the spots probably landed in green paddocks, although some started fires in patches of remnant bushland on private property.

The precise start time of the Lake Quitjup spot fire is unknown. Recreating the fire behaviour suggests it started around 1530h, just as the main headfire reached Black Point Rd. and private property. Interestingly, this spot fire is some 25^{o} W of the main axis of the headfire run (~160^{o}) suggesting the possibility of more northerly winds aloft or that the spot fire originated from an active flank fire. If the spot fire started around 1530 hrs, then it travelled ~6.5 km from the main fire. The Vesta spotting distance model suggests spotting up to 5.2 km under these conditions.

The Vesta fire spread prediction model gave reasonably accurate predictions of fire spread from 1040h-1415h. However, the model seriously under-predicted rate of spread over the period 1415h-1530h. The UWA simulator (see Figure 15), using the Vesta spread algorithms, predicts the arrival of the main front at Black Point Rd. at about 1740h – some 2 hours later than reported by ground observers. Based on reported locations of the headfire by ground observers, the rate of spread over this period was in excess of 5,000 m/h, which is about double that predicted and double the rate of spread in the preceding hours. Given that there was no apparent or observed change in the conditions of fuel and weather (including wind speed) during this period, there can only be two explanations for this. Either the ground observations of headfire position at various times is erroneous, or if they are correct, then the extraordinary rate of spread over this period can only be attributed to the coalescence of the two fires. This may have resulted in a rapid escalation in rate of spread, but more likely given the long unburnt fuels, it resulted the development of intermittent and periods of sustained crown fire, mass spotting and an increase in spot fire development ahead of the main fire front. It is possible that the fire recorded by ground observers at Black Point Rd. at 1530h was actually spot fires ahead of the main fire. At about 1500h, the coalesced fire burnt through a patch (~200 ha) of 17 yo fuels, which generated severe fire behaviour, including intermittent crown fire and extensive spotting. Otherwise, it is difficult to explain such an escalation (doubling) in rate of spread, *ceteris paribus*.

As discussed above, the Red Book predictions are highly sensitive to selection of wind speed ratio. Rate of spread predictions made using a 4:1 ratio were significantly lower than the observed rates of spread by up to a factor of three. However, predictions made using a 3:1 wind ratio, while still well below the observed rates of spread, were much closer.

Table 8: Predicted and actual fire rates of spread for Phase 3 fires GV38/GW37 during the most active period from 1040h – 1530h on 24 November 2011. There were no on-site fuel moisture or wind speeds taken, so these are inferred from predictions (SMC) and casual on-site observations and forecast conditions (wind speed). Red Book predictions are made for both 4:1 and 3:1 wind ratios. Fires GV38 and GW37 coalesced at about 1430h.

Fuel Type/age	RedBook Av. Fuel (t/ha)		Vesta fuel haz. Score			Min. SMC (pred.) (%)	Open Wind (km/h)	Actual mean ROS (m/h)	Mean headfire intensity (kW/m)	Predicted ROS (m/h)	
	Litter	Scrub FL	NS-ht	NS	S					RedBook	Vesta
1040-1200 hrs: Jarrah forest mosaic 8 yo	12.4	10	25		3	6	28	2,290	18,778	4:1wind=840 3:1wind=2,040	2,140
1200-1415 hrs: Jarrah forest mosaic 11 yo	16.3	12	30		3.5	6	28	2,226	22,593	4:1=840 3:1=2,040	2,300
1415-1530 hrs Jarrah forest mosaic 11 yo	16.3	12	30			6	28	5,500	56,840	4:1=840 3:1=2,040	2,300

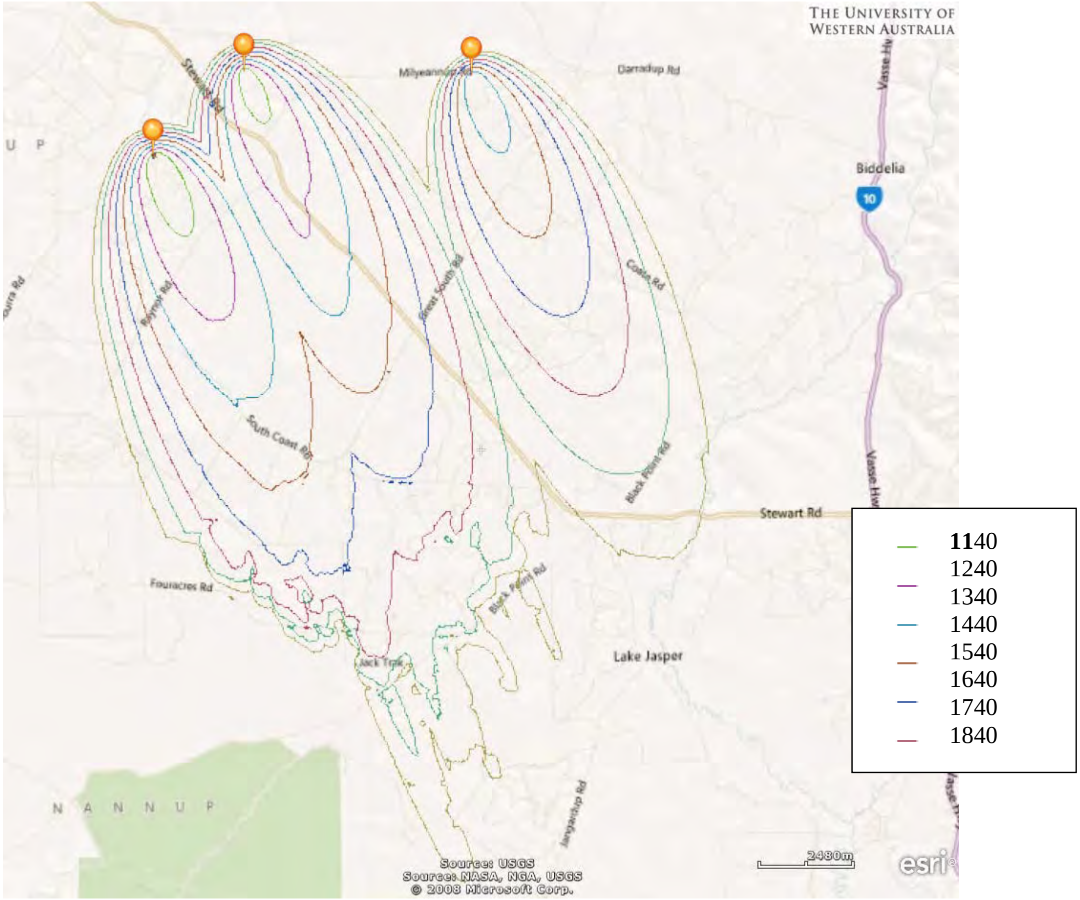


Figure 15: University of WA simulation of the milyeannup bushfire – Phase 2. Note – This is a preliminary simulation – it needs to be adjusted to reflect 3 yo fuels in Bidella block which stopped the fire. The simulation assumed 11 yo fuels. Otherwise, the simulation is a relaible estimate of fire ishochrones.

Scorched low open jarrah forest beginning to resprout after the Milyeannup fire

Complete defoliation of low open jarrah forest following a high intensity crown fire run in long unburnt fuels during the Milyeannup fire

Phase 3: The Quitjup spot fire: 1625h 30th November – 0100h 1 December 2011 (run west)

Weather
A ridge of high pressure off the south-west corner of WA directed a light to moderate ENE airflow over much of the south-west and continued to influence weather on 30/11 through to the 2/12 as the high established in the Bight. Under a coastal influence, the fire ground experienced a relatively cool, moist air flow on 30/11, predominantly from the SE, but temperatures steadily increased as the high moved eastward, a trough of low pressure formed along the north west coast and winds tended more NE, moderating the influence of the SE sea breeze.

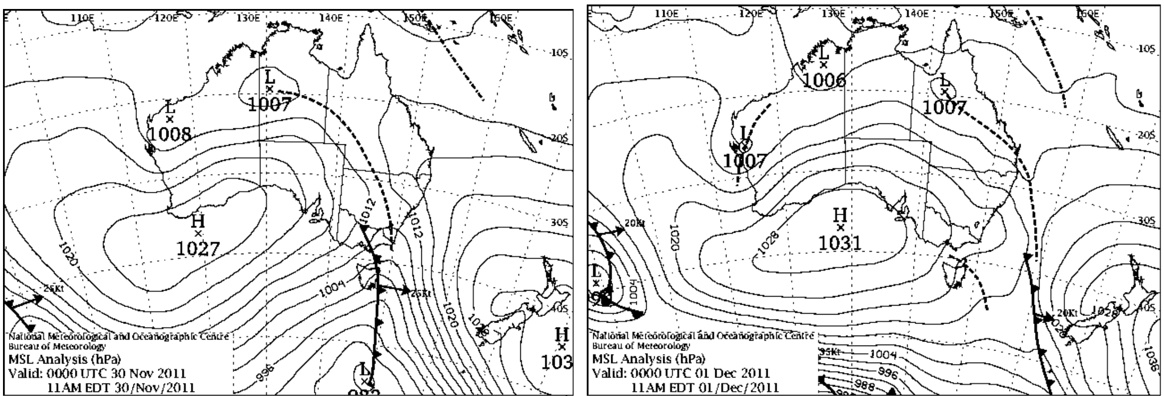


Figure 16: Weather charts for 30th November and 1st December 2011.

Forecast and actual weather conditions for Pemberton, ~37 km E of the fire ground, are summarized in Table 9. A temporary automatic weather station (AWS) was installed at the intersection of Four Acres Rd and Milyeannup Coast Rd (near Grid ref. HA31) ~19km NW of Quitjup on 30/11 at ~2100h. As can be seen from Figure 17 below, there are some gaps in the data from this station, so data from the AWS on Channybearup Rd (~27 km E of Quitjup) are also included.

The AWS at HA31 recorded relatively warm, dry conditions late in the evening of 30/11, with the temperature remaining above ~19 ^{o}C and the RH falling to ~25% overnight (Figure 17). This AWS was commissioned at ~2100h on 30/11 but there is no data from 2300h to ~1000h on 1/12. From 2100h to 2300h on the 30/11 the temperature ranged from 19.8 ^{o}C- 22.8^{o}C and minimum RH from 54%-24%. During this period, the moderate strength wind (10-12km/h @2m) backed from SE to E with the diminishment of the sea breeze at around 2300h, which probably accounts for the warm, dry conditions. Interestingly, the AWS at Channybearup Rd recorded the wind direction change but, unlike the AWS near the fire ground, recorded cool and moist overnight conditions (see Figure 17). This suggests the possibility of a localized warm, dry air mass descending, or mixing down over the fire ground late in the evening of 30 /11.

Moderate strength E-SE winds were experienced during most of the day and into the evening on 30/11 (Figure 18), with the Channybearup AWS recording wind speeds consistently above 10 km/h @2m above ground. During 1/12, wind speeds were light to moderate, in the range 5-10 km/h, and from the E or the SE with the onset of a sea breeze. This pattern continued into the 2/12, although there was an increase in wind speed from about 1400h with the arrival of a stronger sea breeze. The pattern of the arrival of the SE sea breeze is clear from Figure 18b. The sea breeze generally persisted for 4-8 hours each day, generating wind gusts up to 20 km/h near the fire ground (Figure 18c). This wind pattern of easterly winds during the morning and a SE sea breeze in the afternoon dominated fire behaviour over this period.

Table 9: Actual and forecast weather for Pemberton 30 November 2011 to 1 December.

Max. Temp (^{o}C)		Min. RH (%)		Winds (km/h)	
F/cast	Act.	F/cast	Act.@ 1500	Forecast	Actual
30/11					
24	23.4	31	28	1100: E@16 1300: E@15 1500: E@15 1700: E@16 0300: E@13	0900: ENE@19 1500: E@17
1/12					
28	27.9	22	26	1100: E@25 1300: E@20 1500: E@20 1700: E@20 0300: E@18 Spot f/cast: 1400: ESE@20 1700: SE@32 2000: SEW@32 2300: E@25 0200: E@25	0900: NE@13 1500: ESE@9

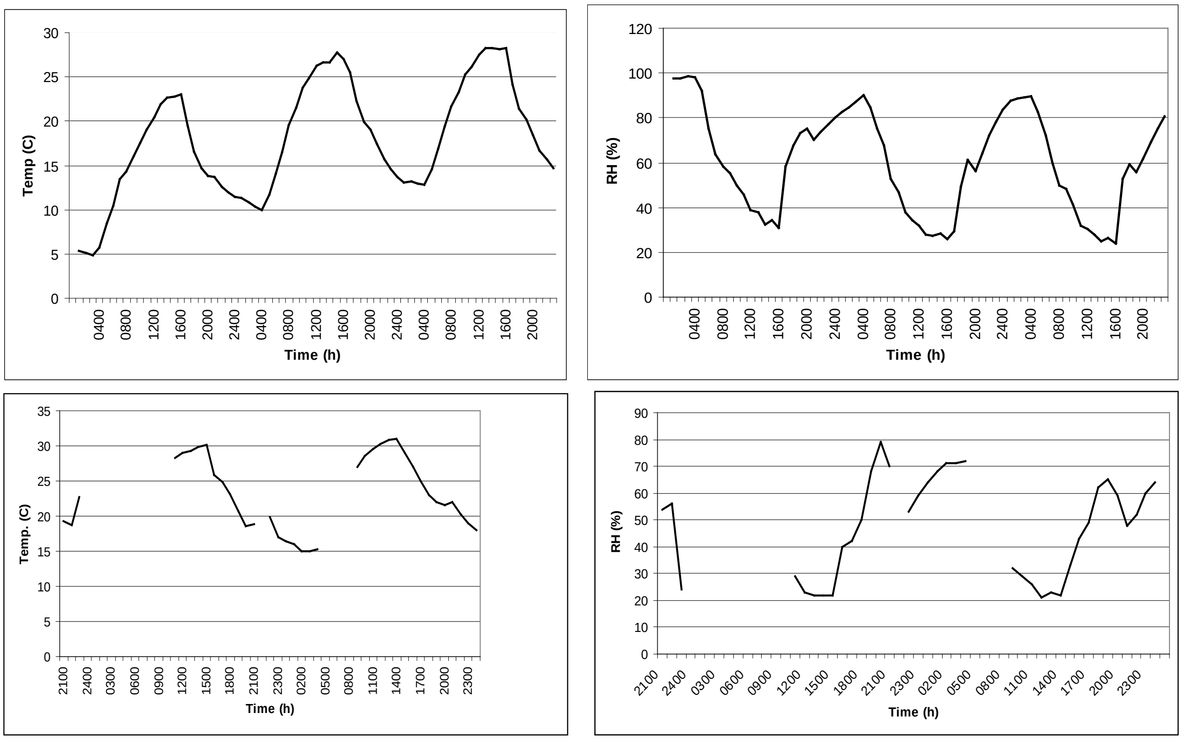


Figure 17a and b (top): Temperature and relative humidity recorded at an AWS on Channybearup Rd ~ 27 km E of Quitjup Lake from 0100 h 30/11 to 2400 h 2/12 2011. Figure 17c and d (bottom); conditions at an AWS at the intersection of Four Acres Rd and Milyeannup Coast Rd ~18 km WNW of Quitjup from 2100h 30/11 to 2400h 2/12.

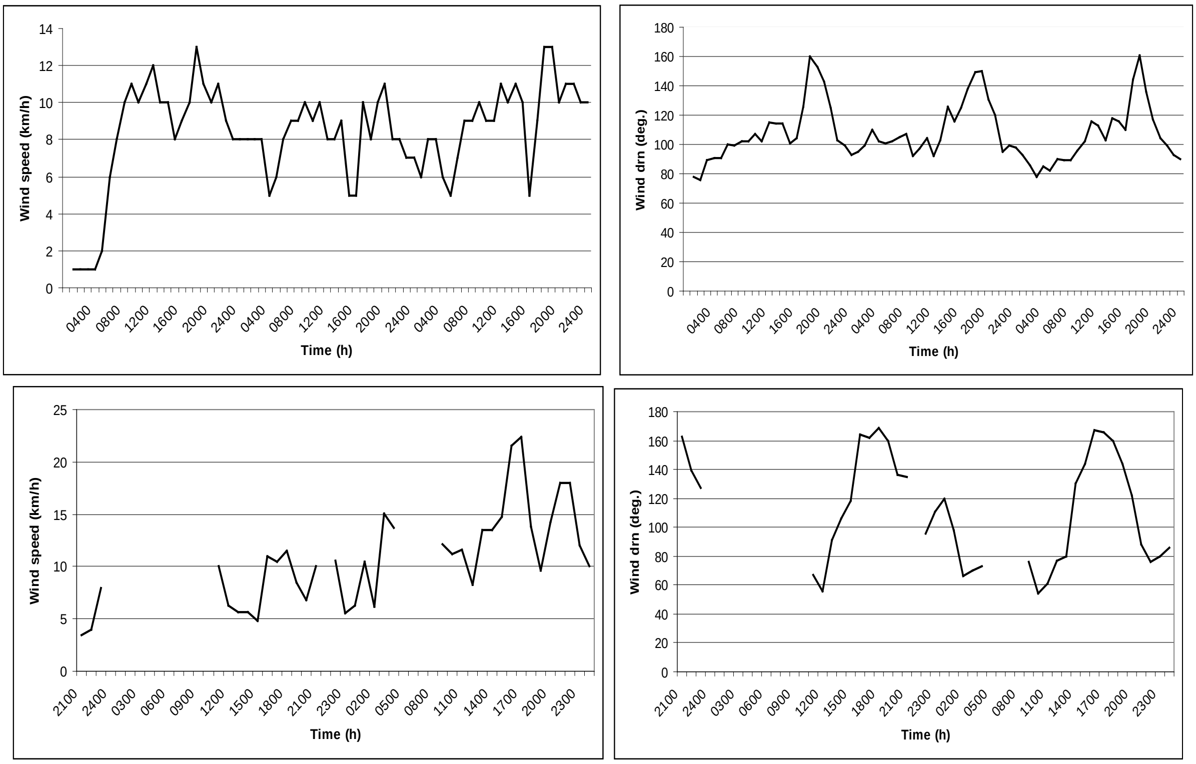


Figure 18a and b (top): Wind speed and direction @ 2m above ground recorded at an AWS on Channybearup Rd ~27 km E of Quitjup. Figure 18c and d (bottom); wind speed and direction @2m above ground at an AWS at the intersection of Four Acres Rd and Milyeannup Coast Rd ~19 km WNW of Quitjup . An Open wind speed @ 10 m is estimated to be double the wind speed shown.

Fire situation Phase 3; 1530h 30 November – 1800h 1 December 2011
As described above, long distance spotting resulted in a spot fire east of Quitjup Lake, first reported by the spotter aircraft at 1700h on 24/11 (see Figure 10). Because of difficulty of ground access (wet, boggy conditions), a significant aerial suppression effort was attempted over the ensuing 5-6 days, but failed to suppress the spot fire. From 24-30/11 the fire, in predominantly wetland heath vegetation, burnt sporadically as a result of suppression action and fuel and weather conditions, generally displaying mild to moderate fire behaviour covering an area of ~150 ha. Its western flank was held up by Quitjup Lake. Aerial observers reported that the fire was often burning vegetation across the top of the water in seasonally inundated swamps and wetlands.

At about 1350h on 30/11, under the influence of a moderate SE sea breeze, the fire progressed around the south-western end of Quitjup and then spread in a NW direction. From ~1625h to 2230h, the fire travelled ~4.8km, averaging ~800 m/h. By 2230h, the fire had burnt about 700 ha with a length-to-width ratio (L:W) ratio of about 3.7, suggesting light to moderate wind strengths. With the diminishing sea breeze at around 2230h the fire came under the influence of a backing moderate E-ENE wind, which turned the western flank of some 4.8km long into a headfire that travelled in a WSW direction. Between 2230h on 30 to 0100h on 1/12, the headfire travelled ~5.5km with an average rate of spread of ~2,500m/h.

The next known position of the fire perimeter was obtained from an aerial observer plot at 1640h on 1/12, which placed the headfire at an unnamed track north of Woodarburrup Rd near grid refs HF31 and HF 32 and the southern flank on Woodarburrup Rd. (Figure 10). Due to a lack of reliable locations of the fire perimeter between these time periods, it is not possible to calculate rate of spread. Throughout the remainder of the 1/12, and influenced by suppression actions including aerial suppression and edge and back burning, the fire tracked steadily NW to be held at Milyeannup Coast Rd and Woodarburrup Rd. (Figure 10).

Forecast weather conditions for 2/12 were for moderate to strong easterly quarter winds, which, coupled with warm, dry air, had the potential to generate moderate to severe fire behaviour in the coastal heath vegetation. Based on these forecast conditions, and using the mallee-heath fire spread model, the fire had the potential to spread rapidly (~2,500 m/h) along the coast and threaten communities at Molloy Island and Augusta East, should it have broken containment lines. Fortunately, the weather conditions, wind speed in particular, were not as severe as initially forecast and as a result of hard work by fire fighters, the fire was held at Milyeannup Coast Rd.

Summary of fuels and fire behaviour –Quitjup spotfire
Over the period 30/11 to 1/12, the Quitjup spot fire burnt in a mosaic of 10 yo peppermint woodland, wetland/heathland and coastal heath (Table 1), at times displaying very active headfire behaviour. After 0100h on 1/12, there are no reliable locations of the fire perimeter, so Table 10 below summarise fire behaviour from 1625h on 30/11 to 0100h on 1/12. As no fire spread models exists specifically for these fuel types, the mallee-heath model was used for predicting rates of spread. Similarly, there are no models of fuel accumulation and fuel load for these fuel types, so fire intensity could not be reliably calculated. Because of data gaps in the AWS nearest the fire ground, weather data used in predictions (Table 10) were supplemented from the Channybearup Rd AWS. This station is some 27km from the fire ground so may not accurately reflect weather at the fire ground.

Table 10: Predicted and actual fire rates of spread for Phase 4 fire (Quitjup spot fire) during the most active period from 1625h on 30 November to 0100h on 1 December 2011. Fire behaviour predictions are made using the mallee-heath model as no models exist specifically for mosaics of coastal heath, peppermint woodlands and associated wetland heath.

Fuel type	RH (%). (C)	Temp (C)	Predicted fuel moisture content (%)	Wind speed @ 2m (km/h)	Observed ROS (m/h)	Predicted ROS (m/h)
Peppermint woodland / wetland mosaic 10 yo						
1625h-1900h	58	20	10	8	500	830
1900h-2230h	53	20	9	8	1057	925
2230h – 0100h	24	22	6	8	2100	1285

Fire behaviour over the period 2230h-0100h (Table 10) is surprisingly active, with relatively high rates of spread given the time of day the fire was burning. During the first two time periods (1625h-2230h –Table 10) the fire was under the influence of a relatively cool, moist SE sea breeze and exhibited moderate spread rates. However, fire behaviour increased from about 2230h, probably due to the relatively warm, dry air and to the moderate wind speeds as the sea breeze dissipated and the fire came under the influence of a light to moderate ENE wind. While the mean wind speed (@ 2m) was ~8km/h over this period, the AWS nearest the fire ground recorded gusts up to 25 km/h and consistently recorded gusts > 10km/h over the period 2200h-2300h, after which there is a gap in the data from the station.

Rate of spread predictions made using the mallee-heath model were in the 'ball park' of observed rates of spread, but given this model was developed for a different fuel complex, which may have some similarities to fuels involved in this fire, it cannot be expected to perform with a high degree of reliability. As mentioned above, there is also the issue of lack of continuity of reliable weather data from near the fire ground, particularly over the most interesting period being from 2230h to 0100h.

During the evening of 1/12 and the morning of 2/12, the fire burnt steadily NW to Milyeannup Coast Rd. where it was contained with a combination of edging, backburning and aerial suppression. Over the coming days, effort was put into strengthening containment lines, burning out unburnt pockets and mopping up.

Over the next three days, to 5/12, the fire extended some 13 km east of Lake Quitjup to Lake Jasper under the influence of westerly winds and was contained along Lake Jasper Rd and Pneumonia Rd. While there were periods of active fire behaviour in the coastal woodland/heath vegetation, there is little or no fire behaviour information and no reliable or adequate fire perimeter locations or maps for this phase of the fire that I have been able to source, so a reconstruction and commentary on its behaviour have not been included here. Also, there was no unusual fire behaviour reported or other notable incidents during this phase to warrant reconstruction and analysis.

Coastal woodlands and heath resprouting after the Milyeannup fire.

7. Concluding remarks

The Milyeannup bushfire, caused by an escape from a DEC prescribed burn, was the largest fire in south-west WA since 1961. Fortunately, there was no loss of life, serious injury or significant property damage. Nonetheless, it was a large and expensive fire to suppress and had the potential to threaten a number of communities.

The single most important factor that caused the fire escape and its subsequent severity and large size was tracts of long unburnt, hazardous fuels in the prescribe burn area and the surrounding landscape. It is notable that the 3 yo fuels in Bidella forest block, the only young fuels to be encountered by the fire, actually stopped that part of the headfire run. Weather conditions were relatively mild and the Fire Danger Rating was mostly HIGH, or occasionally, VERY HIGH during the major fire runs, but contiguous tracts of long unburnt vegetation resulted in significant fire behaviour – very high rates of spread, high fire intensities, intermittent and sustained crown fires and long distance spotting. This, coupled with poor ground access, made suppression very difficult and dangerous.

Other factors contributing to the cause of this fire include insufficient resources to carry out the initial prescribed burn resulting in an adequate standard of edging, patrol and mop-up given the fuel and weather context. The burn was carried out late in the year when weather conditions can turn to a summer pattern of warm, dry conditions, which, coupled with long unburnt flammable fuels, can and did result in severe fire behaviour.

Resourcing and suppression structures in the early phases of the fire were inadequate, largely because many resources were committed to the Margaret River fire, and other fires in the south-west, where life and property were under threat. Given the severe fire behaviour exhibited during major runs, and access difficulties, it is possible that more resources would not have altered the outcome in terms of the final fire size and shape. It is a testament to the skill, training and experience of firefighters on the fire ground in a very dangerous environment that there were no fatalities or serious injuries to firefighters and no significant equipment loss or damage during this long, exhausting suppression campaign.

The fire behaviour exhibited by this fire, in all of the broad fuel types, was not unusual or surprising given the fuel and weather conditions. The Vesta forest fire spread model performed adequately when the fire was burning in forest fuels, the exception being for a short period on 24/11 when extreme fire behaviour was exhibited following the coalescence of two large fires. It is uncertain whether actual headfire rates of spread increased two-fold after coalescence, or spotting actually promulgated the rapid spread of the fire.

The University of WA's bushfire simulator performed well and is a tool that should be used, or at least further evaluated, to assist with forecasting and mapping fire spread as part of the Incident Management Team Planning activities during bushfires.

In the absence of a fuel-specific fire spread model, the mallee-heath spread model was used to predict fire spread in coastal heath. Not surprisingly, the model did not perform particularly well in these fuel types, which are structurally and compositionally different to mallee-heath. Further research is needed to better understand fuel dynamics and fire behaviour in coastal heaths, especially those vegetation types in the vicinity of towns and settlements.

Acknowledgements
This report would not have been possible without input by way of diary notes, maps, logs and personal observations of numerous DEC personnel who worked on this fire. I also thank George Milne and Drew Mellor at UWA for preparing the fire simulation Figure 15.

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