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Behaviour and some impacts of a large wildfire in the Gnangara maritime pine (*Pinus pinaster*) plantation, Western Australia

NEIL BURROWS, BRUCE WARD AND ALEX ROBINSON

CALMScience Division, Department of Conservation and Land Management, Locked Bag 104, Bentley Delivery Centre, WA 6983

ABSTRACT

One of the largest and most intense softwood plantation wildfires in Western Australia burnt 850 ha of the Gnangara maritime pine (*Pinus pinaster)* plantation and 365 ha of banksia woodland in less than 12 hours. The fire started on private property adjacent to the plantation and appeared to have been lit by children. It threatened nearby homes and properties, cost in excess of $300 000 to suppress and resulted in a major operation to salvage more than 100 000 m^3 of logs. Burning under hot, dry weather conditions in December 1994, the wildfire spread 2–3 times faster than predicted. Over-prediction of fuel moisture content and under-prediction of wind speeds in the plantation contributed to the under-prediction of headfire rates of spread, which exceeded 2000 m h^{-1}. The quantity of fuel burnt directly affected fire intensity and flame height but appeared to have little affect on rate of spread. All *P. pinaster* trees that were defoliated or fully scorched by the fire died, but trees with more than 2 m of green crown tip survived. In stands that carried heavy needlebed fuel loads, low intensity backfires killed large mature trees by girdling the stems near ground level. Conditions of weather, fuel and fire behaviour experienced during the wildfire are presented and discussed and some fire management recommendations are made.

INTRODUCTION

Softwood plantations in the south-west of Western Australia (WA) provide an important timber resource, supplementing timber production from native hardwood forests. The total area of State-owned softwood plantations is about 72 000 ha of which about 45 000 ha is *Pinus radiata* and about 27 000 ha is *P. pinaster* (De Braganca 1987; and Moore *et al.* 1987). Currently, most of the State's *P. pinaster* plantations are grown on the poor sandy soils of the coastal plain from Harvey in the south to Wanneroo in the north and are managed by the Western Australian Department of Conservation and Land Management (CALM). Each year about 190 000 m^3 of sawlogs, veneer logs and other timber products are harvested from these plantations (CALM 1998). The 23 000 ha Gnangara maritime pine plantation (*P. pinaster*), about 10 km east and north of the city of Wanneroo, was first established in the 1930s, but most planting was undertaken between 1951 and 1975 following the clearing of banksia woodlands and heathlands. The region experiences a strongly Mediterranean-type climate with an average annual rainfall of 750 mm, of which about 90 per cent falls during the cooler months from April to October. While the winter months are cool and moist, the summer months are warm to hot and dry. Early morning and evening easterly land breezes and strong afternoon south-westerly sea breezes are common over the summer/autumn months. The 'fire season', or the period of the year when fuels within the plantations are dry enough to sustain fire, can extend from September to May, with peak fire weather conditions (hot, dry and windy weather) usually experienced over the period December to March.

An increase in the frequency of wildfires in the plantation over the last 20 years has been associated with increased urbanization, which has encroached on the plantation. Today, almost all wildfires are human-caused and most of these can be attributed to arson. Over the last five years, CALM has attended 222 wildfires in the plantation of which156 were suspected arson. The plantation's wildfire protection is based on rapid detection and dispatch of suppression crews and strategic fuel reduction burning. This strategy has been highly successful, with 98 per cent of wildfires being quickly suppressed and the median wildfire size restricted to 0.1 ha. Occasionally, when fuel and weather conditions are such that fires develop rapidly, early suppression may fail, resulting in wildfires that can be costly to suppress, can cause significant timber losses and disruption to supply and can threaten lives and nearby property. Such a wildfire occurred in the Gnangara plantation on 30 December 1994. The fire burnt about 850 ha of *P. pinaster* plantation and about 365 ha of banksia woodland in 12 hours before it was finally contained, making it one of the largest wildfires in the history of the Gnangara maritime pine plantation and one of the largest in softwood plantations in WA.

This paper reports on the cause of the fire, observed fire behaviour, fuel and weather conditions, and the impact of the fire on *P. pinaster* trees. Some fire management implications of these observations are also discussed.

IGNITION CAUSE AND DETECTION

The wildfire (No. P58) was first detected and reported at 1407 hours (Western Standard Time) on 30 December 1994 by an observer on CALM's Pinjar fire lookout tower located about 6.5 km north-east of the ignition point. The fire originated on private property (location number 1882) on the south-western corner of the plantation and about 8 km east of Wanneroo. Initially, the fire was thought to have been caused either by a faulty transformer or an electric stock fence near the fire origin. However, subsequent investigation and reconstruction of the fire revealed that it was most likely caused by children playing in a horse paddock on private property adjacent to the plantation. The following evidence led to this conclusion.

(1) The pole-mounted transformer near the ignition point was functioning normally when inspected a day after the fire and there was no evidence of previous shorting or malfunction. The overhead high voltage power lines showed no evidence of flashover, and power problems were not reported or experienced by nearby residents. The ground around the transformer was clear of any flammable material for a distance of about 5 m.

(2) Reconstruction of the fire revealed that it actually back-burned (burned into the wind) towards, rather than away from, the transformer. This was ascertained from the low (10–20 cm) defoliation height to vegetation within 20 m of the down-wind side of the transformer. From the freeze direction of the vegetation, the fire burnt under the influence of a south-west wind, which is consistent with weather observations. Freeze is a term used to describe the live (green), fine vegetation which has been killed but not consumed by the fire and which becomes supple owing to heat and bends under the influence of the prevailing wind. When the vegetation cools after the passage of the flames, it stiffens and remains fixed (frozen) in the wind-bent orientation. This indicates the direction of the wind, hence the direction of headfire spread at the time of the passage of flames. The height of scorch, char and defoliation provide additional clues as to the intensity of the fire and whether a particular location experienced a headfire, flankfire or a backfire.

(3) The fire had back-burned towards, rather than away from, the electric stock fence, thus eliminating this as a possible ignition cause.

(4) The north-west corner of the horse paddock was burned. If the fire started at the transformer or the stock fence, it is highly unlikely that it would have been able to back-burn through the very short sparse grass covering the paddock and cross a 3 m mineral earth break surrounding the paddock. The most likely scenario is that the fire started in grass in the horse paddock and the headfire, under the influence of a south-west sea breeze, was driven across the sparse grass and the mineral earth break. Such a scenario is consistent with the field evidence described above.

(5) Two fresh sets of small (children's) footprints (track shoes) were observed in sand near the estimated ignition source in the horse paddock.

INITIAL SUPPRESSION RESPONSE

Two heavy-duty fire fighting units and two officers were immediately dispatched from CALM's Wanneroo office, arriving at the fire at about 1420 hours. The fire was burning in light (3–4t ha^{-1}) dry grass and needlebed fuels beneath open, mature *P. pinaster* plantation on flat sandy soil. When the crews arrived they estimated the fire to be about 2 ha with a headfire rate of spread of about 500 m h^{-1} and headfire flame heights averaging 1.5–2 m. An initial attempt at direct suppression almost succeeded, but the mobility of the suppression vehicles heavily laden with water was hampered by the very dry and therefore boggy sand. By the time additional suppression forces had arrived at the fire (about 1430 hours), the headfire was too intense and moving too fast to attempt a direct headfire attack (see Tables 1 and 4). The wind was forecast to shift to the south-east later in the day, blowing the fire towards homes and farms. Consequently, the suppression strategy was to concentrate resources along the western flank of the fire, to bring this flank under control, then attack the eastern flank, pinching the headfire off. Eventually this tactic was successful and running fire was stopped at 0200 hours the following day (31 December 1994). Mop-up was completed by 1500 hours the same day. Resources committed to the fire during the peak of suppression activity included about 120 firefighters, 32 pumpers (fire fighting units), 6 earth moving machines and spotter (reconnaissance) aircraft. Agencies involved included CALM, Bush Fires Board, State Emergency Services, volunteer bush fire brigades, Royal Australian Air Force, and local government officers. The total area burnt was 1215 ha (850 ha *P. pinaster* plantation, 365 ha banksia woodland). Other damage caused by the fire included the loss of two light duty fire fighting units (burnt) and 105 000 m^3 of sawlog that needed to be salvaged.

WEATHER

The months leading up to the time of the fire were very dry with only 0.8 mm and 4.6 mm of rain being recorded at CALM's Wanneroo office (Wanneroo) on 25 and 27 November respectively. This is well below the average for November, which is about 16 mm. The average rainfall for December is about 10 mm, but no rain was recorded for December 1994. The mean maximum daily temperatures for November and December 1994 were 25.6 °C and 31.2 °C respectively which is about average for this time of year (Fig. 1). As a result of well below average spring rainfall, the Soil Dryness Index (SDI) (Mount 1972; Burrows 1987), a measure of drought and of the general moisture status of heavy fuels and vegetation, climbed rapidly and was 1753 on 30 December, the day of the wildfire (Fig. 1). The SDI ranges from 0, when the upper soil profile and heavy forest fuels are saturated, to 2000, when the upper soil profile and surface fuels are dry. Ambient temperature and relative humidity (measured at the Perth office of the Bureau of Meteorology some 25 km south of the fire) before and during the wildfire are shown in Figure 2. Continuous open (tower) wind speed and direction (recorded at the Perth office of the Bureau of Meteorology) for the day of the fire are shown in Figure 3. Tower wind speed observations were also made at 2 hourly intervals at the CALM Wanneroo office (Wanneroo) and are shown in Table 1.

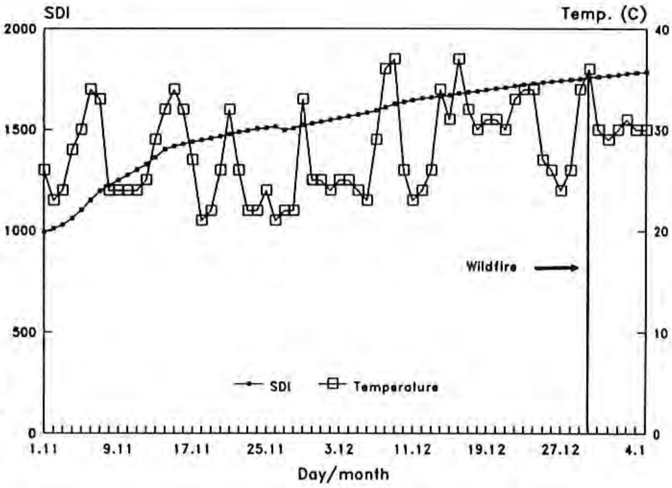

Figure 1. Daily maximum temperatures and Soil Dryness Index (Mount 1972) for Wanneroo near the Gnangara pine plantation leading up to and during the wildfire period.

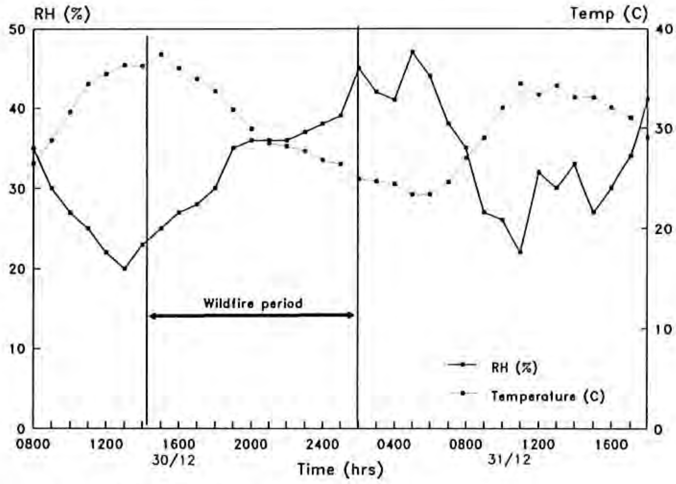

Figure 2. Hourly relative humidity and temperature observations made at Wanneroo near the Gnangara pine plantation wildfire.

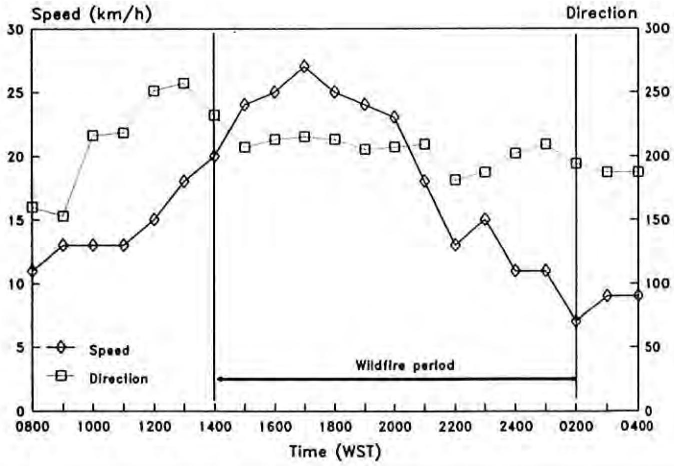

Figure 3. Wind speed and direction recorded at Perth, some 25 km south of the Gnangara pine plantation wildfire locality.

FUELS

The Gnangara plantation was established over the period 1951 to 1975 and in each planting year, up to 20 cells each about 20 ha were planted in a block. Generally, the plantation was established from south to north. Seven fuel types were recognized within the plantation affected by the wildfire. Native vegetation (banksia woodland) comprised an eighth type (Table 2). Each plantation fuel type was associated with plantation cells and blocks of cells with similar histories of silvicultural treatment (including year planted) and fire. The fuels were measured and described several days after the wildfire by matching, as far as possible, burnt cells with unburnt cells across the fire boundary, then sampling the adjacent unburnt cells. Detailed plantation maps showing each cell and the year of planting were used to match burnt and unburnt cells. The plantation fuel types were either needlebed, needlebed and short grass or needlebed and thinning slash (red tops) resulting from silvicultural operations 3–6 months prior to the fire (see Table 2). The banksia woodland fuel consisted of a shallow surface litter and low woody shrubs (Burrows and McCaw 1990).

In each fuel type except the red tops, the quantity of needlebed and fine litter fuel (< 6 mm diameter) was estimated by collecting all material in 20 randomly located quadrats each 0.125 m^2. The material was oven dried and the fuel weight expressed in t ha^{-1}. Mean fuel weights for each type are shown in Table 2. Stand characteristics such as stocking, basal area, height to crown base and mean top height were measured in the vicinity of the fuel samples. These data are summarized in Table 2 and fuel types are mapped in relation to the area burned in Figure 4.

FUEL MOISTURE CONTENT

The moisture content of the various fuel types involved in the wildfire was not measured during the wildfire (30 December 1994) but was measured the following day (31 December 94) (Table 3). No rain fell over the period and diurnal temperature and relative humidity trends were

TABLE 1. Weather forecast issued at 1000 hours and observed weather conditions (CALM Wanneroo office) from 1100 hours – 1700 hours on the 30 December 1994. Tower wind speed observations are 10 minute averages taken on the hour. Overnight winds were forecast to be SE at 8 km h^{-1}.

WEATHER VARIABLE	FORECAST	OBSERVED
Max. Temp (°C)	37	37
Min. RH (%)	19	20
Tower wind speed (km h^{-1}) & direction Time (hours)		
1100	ENE12	SW12
1300	SW18	SW12
1500	SW25	SSW24
1700	SW15	SSW24
1900	Overnight–SE8	SSW24
2100		SSW16
2300		SW16

similar (Fig. 2) so it is reasonable to assume that fuel moisture contents on the day of the wildfire were similar to those measured the following day. Actual fuel moisture contents for each fuel type shown in Table 2 were determined by oven drying 7–10 samples (about 60 g each). Fuel moisture content predictions were made using the Forest Fire Behaviour Tables for Western Australia (Sneeuwjagt and Peet 1985) and are shown in Table 3.

FIRE BEHAVIOUR

The fire perimeter was mapped at regular intervals during the fire either from the air during daylight hours or from the ground. These maps were checked against observations made by fire control officers who submitted regular fire situation reports via radio to the control point at CALM's Wanneroo office. These reports described the position of the fire in relation to features such as roads and plantation cells and provided fire behaviour information including an estimate of headfire rate of spread and flame height. A composite map of the fire perimeter at various time intervals was constructed from these sources (Fig. 4) and used to calculate headfire rate of spread, fire perimeter and area (see Table 4).

Aided by moderate to fresh winds and dry fine fuels, the fire accelerated quickly through the open 43-year-old cells (planted 1951) and through relatively light fuels (4–6 t ha^{-1}). The quantity of needlebed and grass fuel was low in these cells as a consequence of prescribed burning which had been carried out some two years earlier. Tracks and mineral earth firebreaks throughout the plantation, some up to 30 m wide, were ineffective at stopping or significantly slowing the fire. Numerous spot fires developed 50–100 m downwind of the main fire front with a few developing 200–400 m downwind. These were usually over-run by the headfire before they developed to any significant size. While largely confined to the surface fuels, there were bursts of sustained crown fire spread (50–100 m) particularly in well stocked stands (about 600 stems ha^{-1}) with moderate to heavy surface fuel loads (> 8 t ha^{-1}). Headfire rates of spread and flame heights at various intervals during the wildfire run are shown in Table 4. There was no obvious or significant variation in headfire rate of spread associated with the different fuel types under these dry and windy conditions. However, flame height, therefore fire intensity, varied significantly with the taller flames being associated with the heavier fuels (Table 4). Headfire intensity varied from about 1500 kW m^{-1} to about 18 000 kW m^{-1}. The unusually long and narrow shape of the fire (Fig. 4) was largely owing to suppression action, which concentrated on the flanks of the fire, distorting the fire's shape and restricting the area burnt. A more-or-less constant wind direction during the fire run also contributed to the elongated shape. Fanned by moderate wind speeds, headfire behaviour was quite active, even during the relative cool of evening (Table 4), and was finally suppressed in the banksia woodlands in the cool early hours (0200) of 31 December 1994 when the wind speed fell to below about 10 km h^{-1}.

Observed rates of spread were generally higher than expected and higher than predicted by the Forest Fire Behaviour Tables for Western Australia (FFBT) (Sneeuwjagt and Peet 1985). Below is a worked example of predicting rate of spread during the period from about 1400–1500 hours when the fire was burning in cells containing the fuel code 2 (see Table 2).

Inputs for predicting rate of spread using FFBT:

Litter depth = 10 mm
Total litter quantity = 4.9 t ha^{-1}
Surface (fuel) moisture content (SMC) = 7%
Profile (fuel) moisture content (PMC) = 7%
Available fuel factor = 1.0
Tower wind speed = 25 km h^{-1}; 4:1 ratio
Slope = 0°

Calculating predicted rate of spread:

Available litter quantity = 4.9 x 1.0 = 4.9 t ha^{-1}
Rate of Spread Index = 160
Fuel correction factor = 2.7
Slope correction factor = 1.0
Predicted rate of spread = 160 x 2.7 x 1.0 = 432 m h^{-1}

The predicted rate of spread for this stage of the wildfire was 432 m h^{-1} compared with the actual rate of spread of 790–945 m h^{-1}. One of the factors contributing to the under prediction is that actual surface fuel moisture content (SMC) in these open cells was lower than that predicted by about 2 per cent. If the actual SMC is used in the calculations (4.9 per cent), then the predicted rate of spread is about 650 m h^{-1}. It is also possible that the wind ratio of 4:1 (tower wind speed: wind speed at 1.5 m) used in the prediction is too high for these open stands (about 175 stems ha^{-1}). Burrows *et al.* (1988) reported a wind

TABLE 2. Major fuel types and associated stand characteristics for *P. pinaster* plantation and banksia woodland burnt by wildfire. Approximate distribution of each fuel type is shown in Figure 4.

FUEL CODE	YEAR PLANTED	STOCKING (STEMS (per ha^{-1})	BASAL AREA (m^{2}ha^{-1})	HEIGHT TO CANOPY BASE (m)	TOP HEIGHT (m)	DOMINANT FUEL TYPE	MEAN FUEL LOAD (t ha^{-1})
1	1951	175	35.4	12.6	22.3 long unburnt	Needlebed	37.4
2	1951	175	34.8	12.8	22.9	Needlebed and grass recently prescribed burnt	3.8
3	1953	600	25.0	10.6	17.3	Needlebed long unburnt	22.8
4	1953	200	25.3	10.8	18.7	Red tops and needlebed	40
5	1957	350	28.1	10.2	18.9	Needlebed	15.6
6	1961	600	27.1	7.9	16.8	Needlebed	11.4
7	1965	400	26.4	8.6	16.3	Needlebed	8.6
8	Banksia woodland					Shallow litter and live shrubs 20 years since last fire	7

TABLE 3. Predicted and actual mean fuel moisture contents. Predictions were made using the Forest Fire Behaviour Tables for Western Australia (Sneeuwjagt and Peet 1985) for the day of the wildfire (30 December 94). Actual moisture contents were determined from samples taken the day after the wildfire (31 December 94). SMC = needlebed surface moisture content, PMC = needlebed profile moisture content and red tops = aerated red needles in debris resulting from thinning operations. Standard error in parentheses.

TIME (hours)	PREDICTED SMC 30/12/94 (%)	ACTUAL SMC 31/12/94 THINNED STAND (%)	ACTUAL SMC 31/12/94 UNTHINNED STAND	ACTUAL PMC 31/12/94 UNTHINNED STAND (%)	ACTUAL RED TOPS 31/12/94 (%)	ACTUAL LIVE NEEDLES 31/12/94 (%)
1500	7	4.9 (0.84)	6.5 (0.61)	7.4 (0.82)	6.8 (0.52)	162.3 (8.9)
1800	9	6.3 (0.66)	7.2 (0.63)	8.0 (0.72)	7.9 (0.55)	not sampled

speed ratio of about 6:1 for a heavily stocked (2000 stems ha^{-1}), unpruned stand of 17-year-old *P. pinaster*. Fire behaviour is highly sensitive to wind speed, particularly under hot, dry conditions and uncertainty about the most appropriate wind speed ratio to choose when predicting rate of spread is one of the major limitations of the FFBT system.

TREE MORTALITY AND DAMAGE

P. pinaster, like other introduced conifers, is not as well adapted to fire as native tree species such as jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*). While mature *P. pinaster* has thick protective bark which enables it to withstand low intensity fire (Fig. 5), it does not have the capacity to re-sprout following fires that kill

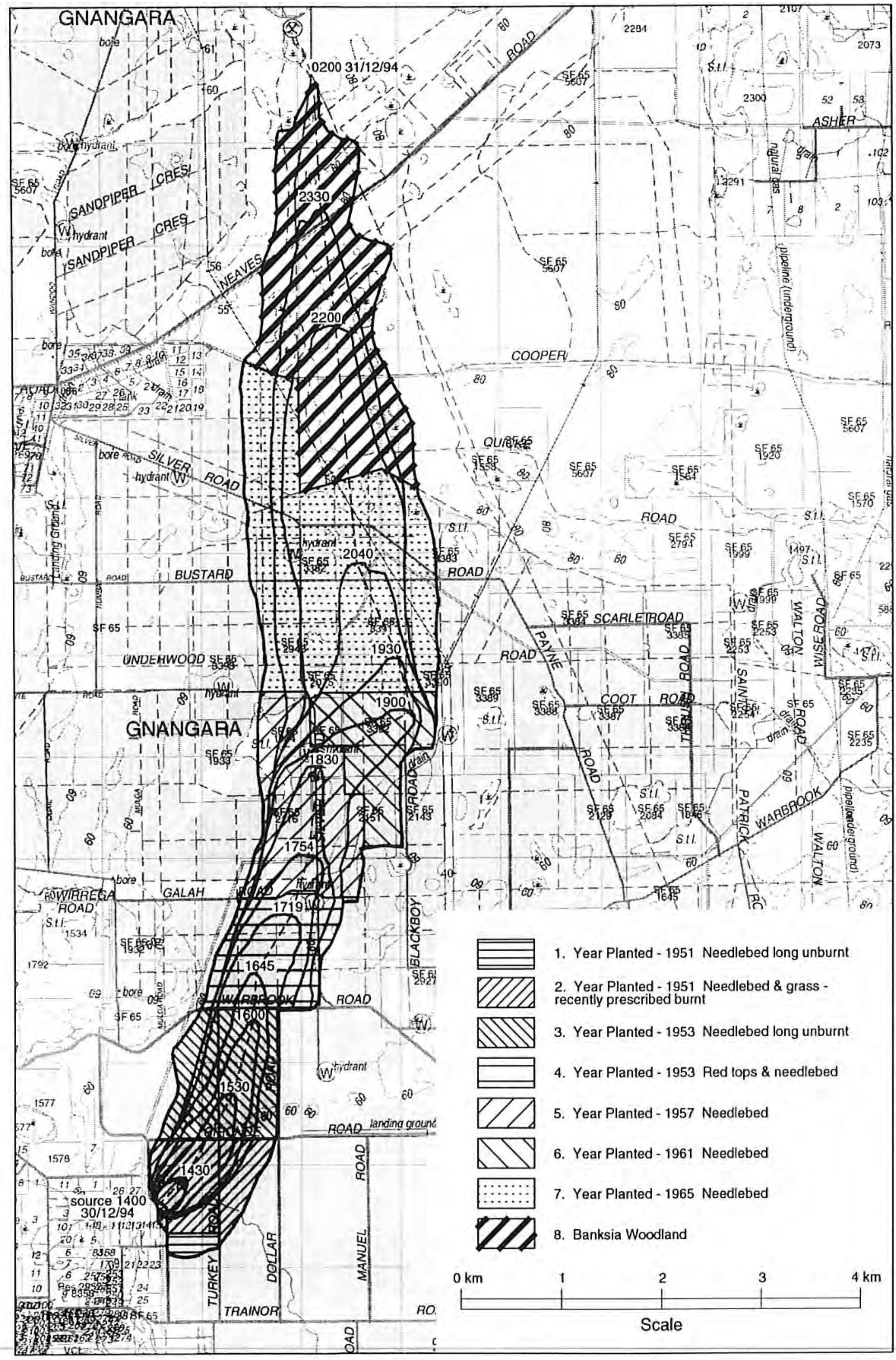

Figure 4. Wildfire perimeter with time.

TABLE 4. The behaviour and size of the Gnangara pine plantation wildfire at various time periods. The estimated ignition time was 1400 hours on December 30th 1994. See Table 2 for fuel code descriptions.

TIME (hours)	FUEL CODE BURNING	HEADFIRE RATE OF SPREAD ($m h^{-1}$)	HEADFIRE FLAME HEIGHT (m)	FIRE AREA (ha)	FIREPERIMETER (m)
1400–1430	2	790	1–2	7	1 007
1430–1530	2&3	945	3–4	42	3 037
1530–1600	3	1 480	3–5	86	4 642
1600–1645	3&4	620	2–4	130	5 620
1645–1719	4	913	6–8	254	7 858
1719–1754	5&6	1 044	4–6	307	9 190
1754–1830	5&6	1 463	4–6	367	10 996
1830–1900	5&6	2 144	8–10	462	13 067
1900–1930	7	1 078	3–5	557	14 167
1930–2040	7	869	3–5	650	16 148
2040–2200	7&8	1 746	6–8	924	20 808
2200–2330	8	753	4–6	1077	22 897
2330–0200	8	490	1–2	1444	26 055

the crown or the bole. Thus, the extent of fire-caused damage to the plantation is of concern to plantation managers. It has ramifications for post-fire salvage operations and for the short and long term economics of the plantation. There is no information available for *P. pinaster* to allow the extent of fire-caused damage and mortality to be forecast or predicted. If managers could predict the fate of trees and cells after a wildfire, then they would be able to plan which trees or cells to salvage log and what the salvaging priority should be. That is, which trees are dead or will die and therefore should be salvaged immediately before they are affected by wood-degrading insects and fungi, and which trees, although damaged, are alive or likely to live and can either be salvaged later or left to grow.

To estimate the extent of canopy scorch and tree mortality, and to develop a relationship between crown damage (extent of scorch and defoliation) and mortality, a series of sample lines were placed across the width of the burned area. Seven lines were used to sample the most common age classes burned (Table 5). Four days after the wildfire, 30–34 trees were selected along each transect by selecting the tree nearest the line at 20–30 m intervals. Another ten trees per line were selected in adjacent unburnt cells as controls. Each tree was numbered and measured for d.b.h.o.b. (diameter at breast height over bark), bark thickness, total height, height to the base of the canopy, scorch height and stem char height (windward side). The site was re-visited some 3 months after the wildfire to assess whether the marked trees were alive or dead. This was ascertained by both visual assessment and by taking four cambial core samples from the stem at about 20 cm above ground. Live cambium is white in colour, whereas dead cambium is a brown-yellow colour. Without exception, trees that were deemed to be dead by visual inspection showed no signs of live cambium.

Trees were killed either by crown damage (crown scorch or defoliation) or by stem girdling, with the former being the most common cause of death. A summary of the mortality rate and of the extent of crown scorch among the sample trees is shown in Table 5 for each of major tree/cell ages affected by the wildfire. The highly stocked 1953 plantings suffered the highest mortality rate with 91 per cent of sampled trees being killed by the fire. This was probably owing to the combination of intense fire behaviour, moderate to heavy fuel loads (needlebed and red tops, see Table 2 above), and the relatively small height and d.b.h.o.b. of the trees. The mortality rate in other cells was between 50 and 60 per cent.

All trees whose crowns were either fully scorched or defoliated, died and, with the exception of those trees which were killed by stem girdling, 90 per cent of trees which retained more than 2 m of green crown, survived (Fig. 5). As expected, none of the trees in the unburnt cells had died when assessed three months after the wildfire.

Low intensity backfire (about 350 kW m^{-1}) burning in heavy needlebed fuels (fuel code 1, Table 2) killed about 50 per cent of large trees (planted in 1951), even though the scorch and stem char heights were relatively low (see Table 5). Inspection of these trees, whose crowns were mostly undamaged, or slightly damaged, revealed that the trees had been killed by stem girdling. These cells, which had not been burnt before the wildfire, carried deep and heavy needlebed fuel (fuel code 1, Table 2) which, under the very dry conditions, burnt completely. Consequently, the bark on the trees was burned down to the cambium,

TABLE 5. Damage to *P. pinaster* trees burnt during the Gnangara pine plantation wildfire. A total of 238 trees were sampled (30–34 trees per line). Standard errors are shown in parentheses.

LINE NUMBER & YEAR PLANTED	TOP HEIGHT (m)	HEIGHT TO CANOPY BASE (m)	d.b.h.o.b. (cm)	SCORCH HEIGHT (m)	STEM CHAR HEIGHT (m)	MORTALITY RATE – CROWN SCORCH (%)	MORTALITY RATE – STEM GIRDLING (%)
L1 1951	23.3 (0.32)	11.6 (0.25)	49.1 (0.96)	21.0 (0.55)	5.22 (0.59)	53	0
L2 1953	17.2 (0.47)	10.6 (0.26)	22.5 (1.31)	16.9 (0.50)	6.9 (0.61)	91	0
L3 1957	18.9 (0.54)	10.2 (0.43)	32.0 (1.26)	16.6 (0.66)	3.2 (0.16)	56	0
L4 1965	16.8 (0.34)	8.6 (0.34)	26.1 (1.30)	14.8 (0.44)	3.0 (0.56)	54	0
L5 1965	17.5 (0.27)	8.9 (0.33)	33.6 (1.21)	14.5 (0.44)	5.2 (0.55)	30	0
L6 1965	16.2 (0.34)	8.5 (0.47)	28.1 (1.67)	14.2 (0.65)	5.9 (0.73)	47	0
L7 1951	22.6 (0.34)	13.8 (0.31)	51.3 (1.24)	14.3 (0.65)	3.8 (0.31)	7	46

TABLE 6. A comparison of bark thickness on burned and unburned *Pinus pinaster* trees in the Gnangara pine plantation. Standard errors in parentheses.

	BURNT TREES (N = 153)	UNBURNT TREES (N = 70)
Mean bark thickness (mm)	19.5 (0.53)	29.7 (0.79)
Mean d.b.h.o.b. (cm)	30.4 (0.81)	30.3 (1.31)

Note: d.b.h.o.b. = stem diameter at breast height over bark.

from ground level to the height of the needlebed (40–80 mm), effectively girdling the trees. These trees could have been saved had the low intensity backfire been suppressed.

The wildfire significantly reduced bark thickness by about 30 per cent on all burned trees measured at breast height (1.5 m). The moisture content of the outer 5 mm of bark measured one day after the wildfire was about 10 per cent, so it is not surprising that during the wildfire a significant proportion of bark was burned (Table 6). The relationship between bark thickness measured at breast height and d.b.h.o.b. for unburned *P. pinaster* and *P. radiata* is shown in Figure 6. The *P. radiata* data are from Blackwood Valley plantations near Nannup and Kirup (Burrows 1985) and are included to show that *P. pinaster* develops thicker bark, which probably helps to explain its observed greater fire resistance.

CONCLUDING DISCUSSION AND MANAGEMENT IMPLICATIONS

The increasing level of arson in the Gnangara pine plantation and surrounds is a serious land management issue, not only for the plantations but also for other land uses in the region. Early detection and a rapid suppression response have been highly successful in limiting the size and impact of most wildfires, but situations will arise when this will not be the case, and large and damaging wildfires will result.

In the absence of management intervention, the fuels beneath *P. pinaster* plantations accumulate to very high levels. Wildfires in these heavy fuels can be difficult, dangerous and expensive to suppress. Heavy surface fuels are also conducive to the development of crown fires (Burrows *et al.* 1988). Reducing fuel loads by prescribed burning reduces the potential fire intensity, therefore the suppression difficulty and damage potential of wildfires. However, the introduction of prescribed fire into mature open stands encourages the growth of ephemeral grasses and other weeds, which support a fast spreading wildfire under dry, windy conditions. This is not an issue in stands

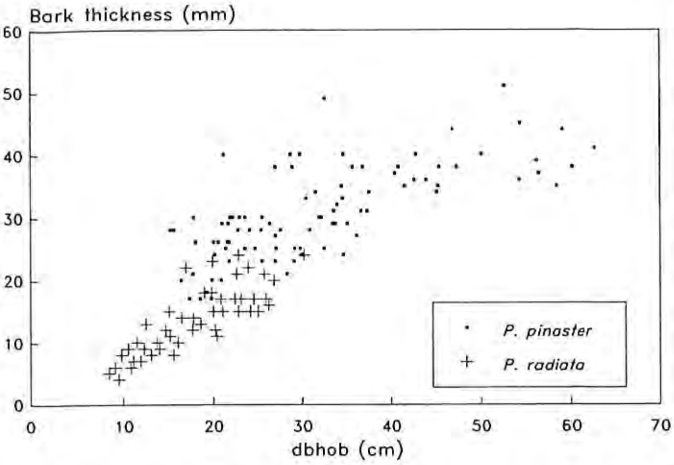

Figure 5. Relationship between bark thickness and stem diameter at breast height over bark (d.b.h.o.b.) for unburned Pinus pinaster *and* P. radiata *trees (Burrows 1985).*

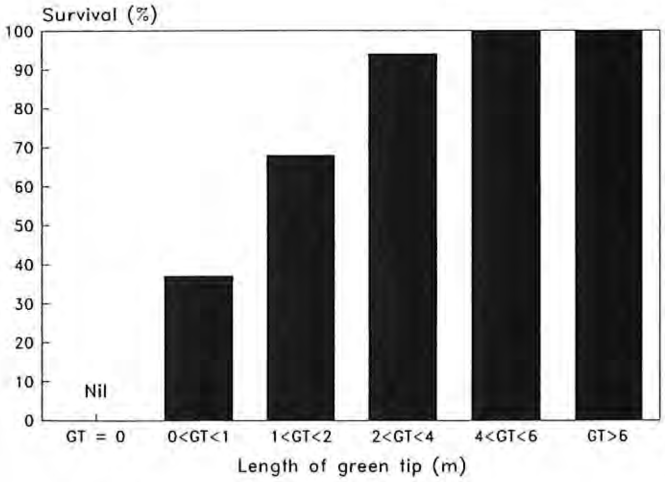

Figure 6. Probability of survival and length of green tip (unscorched crown) for Pinus pinaster *following the Gnangara pine plantation wildfire. This relationship applies to trees whose stems were not girdled by fire.*

with closed or near-closed canopies. The rate of spread of the wildfire described in this paper appeared to be unaffected by fuel load but affected by wind speed. However, fire intensity, flame dimensions, suppression difficulty and tree damage levels were significantly greater in those cells carrying heavier fuel loads. Trees that were defoliated or fully scorched by the wildfire, died, whereas more than 90 per cent of trees that retained more than 2 m of green tip, survived. The headfire spread significantly faster than predicted by the Forest Fire Behaviour Tables for Western Australia (Sneeuwjagt and Peet 1985) largely because the Tables over-predicted the moisture content of the fuel (i.e. fuels were drier than predicted) and wind speed through the stand was probably under estimated.

This wildfire provided an opportunity to evaluate, and where necessary, refine the existing fire management prescriptions. Many of the following management recommendations arising from this investigation are, to varying degrees, already incorporated in existing fire management plans. This case study serves to reinforce management practices.

(1) Further studies are needed to improve prediction of wind speeds in various plantation structures. Maps showing wind speed ratios that should apply when predicting fire behaviour in various parts of the plantation would be of assistance in forecasting fire danger and rate of spread. In the interim, predictions could be improved by using a wind ratio of 3:1 for mature (15–20 m) open stands (<250 stems ha^{-1}), a ratio of 4:1 for mature, moderately stocked stands (250–750 stems ha^{-1}) and 5:1 for mature, heavily stocked stands (750–1250 stems ha^{-1}).

(2) Regular (weekly) field checks of surface fuel moisture content should be made during the fire season to correct predictions.

(3) Detailed and up-to-date records and maps of all silviculture and fire management activities (including fuel maps) within plantations should be maintained to improve fire behaviour predictions. Ideally, these records should be maintained in a geographic information system (GIS).

(4) Weather equipment in Stevenson's screens should be maintained and calibrated regularly. Both the humidity and temperature sensors on thermohydrographs should be operational and accurate.

(5) The Soil Dryness Index (SDI) should be maintained and the current year SDI should be graphed with that of previous years and displayed in a prominent place so that fire managers can be appraised of the severity of the impending fire season.

(6) Rather than prescribe burning cells on a mosaic throughout the plantation, a series of wide, long fuel reduced buffers should be installed and maintained. If practical, the buffers should run east-west across the width of the plantation (perpendicular to prevailing winds), they should be 500–1000 m deep, be placed at about 3 km intervals and be burnt every 2–3 years to maintain fuel loads below about 6 t ha^{-1}. The purpose of these buffers is to reduce the potential for large intense wildfires to develop. In open areas within the buffers, grasses and other weeds should be managed to reduce the potential for fast spreading headfires to develop.

(7) During post-wildfire salvage operations, cells in which the trees have been defoliated or fully scorched should be removed first as these trees have been killed and the wood quality will deteriorate quickly. Trees with more than 2 m of green crown are expected to survive and need not be salvaged, or can be salvaged later if necessary.

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