predictions disguises some significant assumptions that were necessary in making the predictions. For example, the Grassland curing factor (as used in Mark 3 meter) is not applicable to heathlands, where a large portion of the fuels consist of live yet highly flammable vegetation; and fuel loads (t/ha, as used in Mark 5 meter) in grasslands may be only one tenth of those in heathlands. The "Condon" Modified Grassland Meter (Condon 1979), which is used in the mallee shrublands of western New South Wales, appears to be a poor alternative. The Grassland Mark 3 meter, consistent with the experience of Billing (1987) and with the assumption of a 100% curing factor, may serve a useful role in predicting the upper limits of rate of spread that can be expected in heathland fuels, especially where the wind speeds are 15-20 km/h or higher and the FDI's are Low to Moderate.

Conclusions

Infra-red line scanning, coupled with representative observations of the prevailing fuel and weather conditions, can provide rates of spread with an accuracy of ±0.2 km/h over distances of 1.0 km and time periods of one hour. Increased use of this technology during periods of significant wildfire spread is needed, to provide further data for improving spread predictions. In fuel types where the existing meters and models are known to be poor predictors, the use of this technology can provide Fire Control Teams with better information on how fast fires have and can be expected to spread.

The Heywood data show that rate of spread depends significantly on fuel type. Fires are known to spread faster in heathland than in open forest with heath or wiregrass understorey, than in open forest with bracken/grass understorey. The absence of tree canopy (in heathland) and the presence of elevated, flammable fuels, increases rate of spread substantially and is clearly shown in this case.

In evaluating the use of the existing meters for predicting rates of spread in heath or elevated fuels, it should be remembered that non of these were designed for use in these fuel types. The Forest meter can greatly under-predict rate of spread in open forest with an elevated fuel understorey. The Condon Modified Grassland meter can over-predict rate of spread in heathland by a factor of 10. The Mark 3 Grassland meter appears to be a useful means of predicting the upper limits of rate of spread in heathland, especially where the wind speeds are 15-20 km/h or higher and the FDI's are low to moderate.

These findings only emphasise the need for a fire spread meter specifically designed for heath and elevated fuels. Further documented examples of rates of fire spread in these fuel types are needed so that these meters can be developed.

Acknowledgments

The assistance of Andrew Matthews (Monash University, Earth Sciences Dept. and CNR Fire Management Branch) and Des Cooper (CNR Fire Management Branch) with the scan processing and mapping; Andrew Treloar and Peter Gigliotti (Severe Weather Section, Bureau of Meteorology, Melbourne) with meteorological data; Greg

Esnouf, Peter Ellis and staff from CNR Portland Region for assistance with fire details; Peter Billing for critical comments and Andrew Wilson for discussion, and guidance is gratefully acknowledged.

The *Bibliography of Fire Ecology in Australia* (Gill and Noble 1989) was used in the research for this report.

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34. Monitoring vegetation for fire effects, MA Wouters 1992.
35. Elevated Fuel Guide, AAG Wilson 1993.

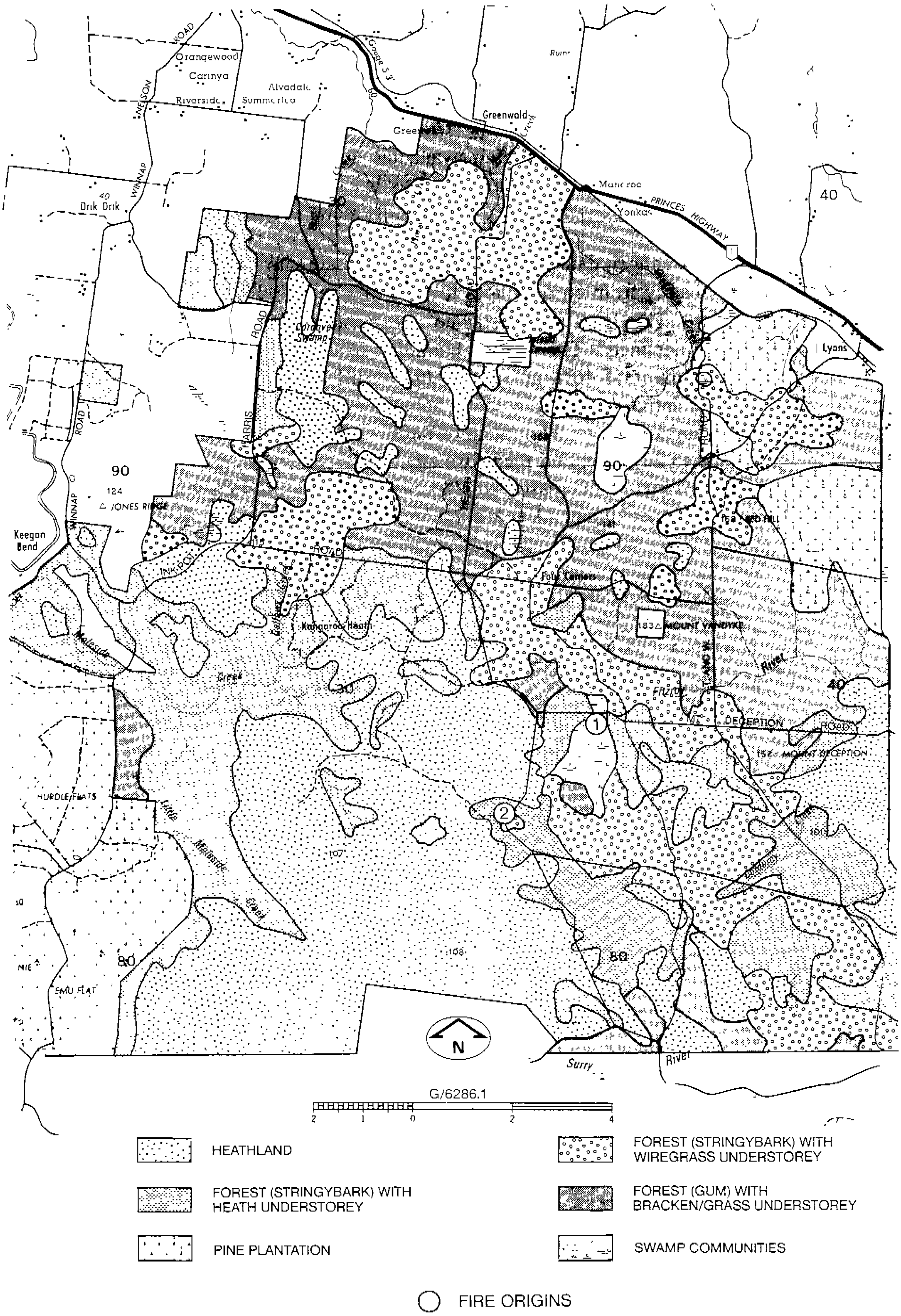
Figure 3: Heathland

Figure 4: Open Forest with Heathy Understorey

Figure 5: Open Forest with Wiregrass Understorey

Figure 6: Open Forest with Bracken Understorey

Figure 7: Vegetation and Fuel Types



Source Adapted from Land Conservation Council (1981)

Weather and Fire Danger

The weather conditions for the fire location during the fire period were well represented by the conditions that prevailed at Mt Gambier, 45 km to the north west. The hourly measurements of temperature, relative humidity, wind speed and wind direction at Mt Gambier are shown in Figures 8-9. From these data the fire danger indices were calculated using the formulae of Noble *et al* (1980) and Sirakoff (1985), and are shown in Figure 10. For the Grassland meters calculations, 100% fuel curing and a fuel load of 4.5 t/ha (the maximum available) were assumed; similarly a fuel depth of 1.2 m was assumed for the "Condon" meter calculations. A drought factor of 10 and a fuel load of 12.5 t/ha were used for the Forest meter calculations.

The weather and fire danger data for Day 2 of the fire are shown in Table 1. The temperature rose steadily from an overnight low of 13°C at 0400 and 0700 hours, to 20°C at 1200 hours. This level was sustained until around 1700 hours, after which temperatures slowly declined. The relative humidity decreased steadily from 82% at 0700 hour to a minimum of 46% at 1200 hours. This remained stable until 1500 hours, after which relative humidity rose to 56% at 1800 hours. The wind began steadily from the south-east, at 19 km/h[1] until 0800 hours. Between 0900 and 1500 hours this increased to 28 km/h, and then rose again between 1600 and 1700 hours to 37 km/h. At 1800 hours it decreased to 28 km/h. The forest FDI during Day 2 remained relatively low peaking at 11 at around 1500 hours and achieving an overnight low of 1.

Table 1: Hourly Measurements of Weather at Mt Gambier[2] on 26 Feb. 1991.

Time	Temperature (°C)	Relative Humidity (%)	Wind Speed (km/h)	Wind Direction (°)	Forest Mk 5 FDI	Grass Mk 3 FDI	Grass Mk 5 FDI	Condon FDI
0600	14	77	19	135	2	4	5	16
0700	13	82	19	135	2	3	4	15
0800	14	77	19	135	2	4	5	16
0900	16	68	28	135	4	8	11	34
1000	17	63	28	135	5	9	12	39
1100	18	56	28	135	7	10	14	46
1200	20	46	28	135	10	13	18	58
1300	20	46	28	158	10	13	18	58
1400	19	49	28	158	9	12	17	54
1500	20	46	28	158	10	13	18	58
1600	20	49	37	158	11	20	25	85
1700	19	52	37	158	10	19	23	85
1800	18	56	28	135	7	10	14	50

Fire Development

The development of the fire is shown in Figure 11. This report specifically examines the fire behaviour of Day 2, when the fire burnt through heath and shrub fuel types. At

[1] Wind speed at 10m in the open (standard meteorological conditions).

[2] Weather data recorded by the Bureau of Meteorology's automatic weather station at Mt Gambier.

Figure 8: Temperature and Rel. Humidity at Mt Gambier on 25-27 Feb. 1991.

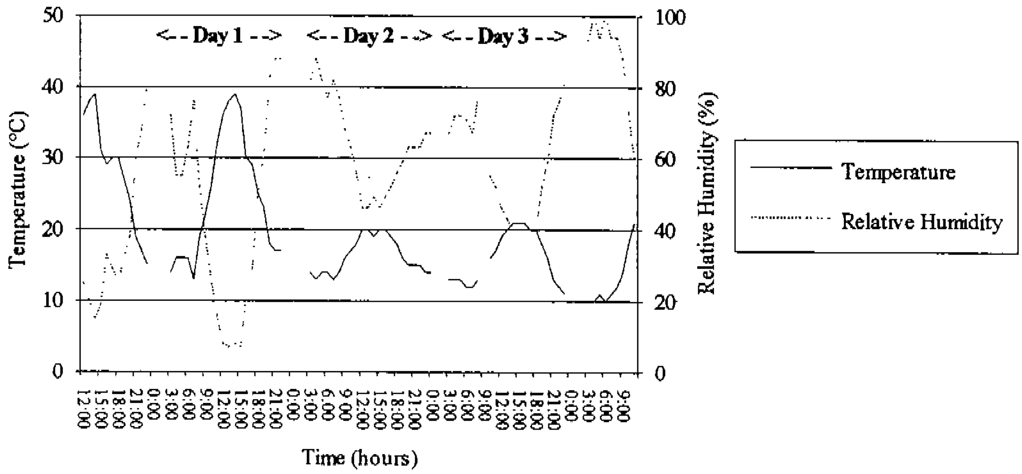


Figure 9: Wind Speed and Direction at Mt Gambier on 25-27 Feb 1991.

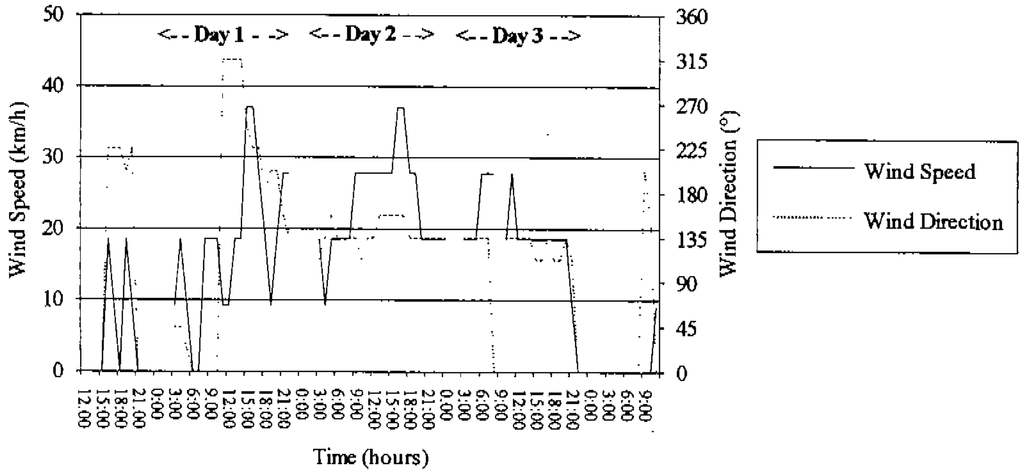


Figure 10: Fire Danger Indices at Mt Gambier on 25-27 Feb 1991.

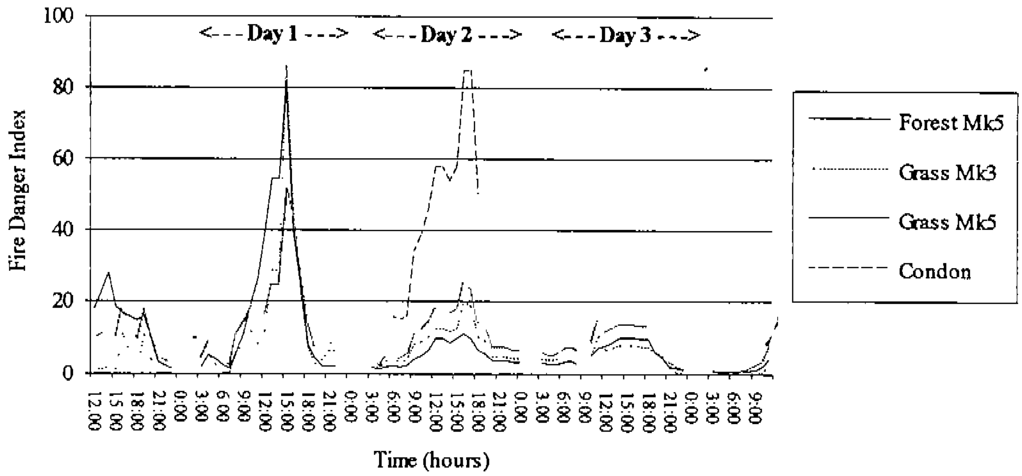
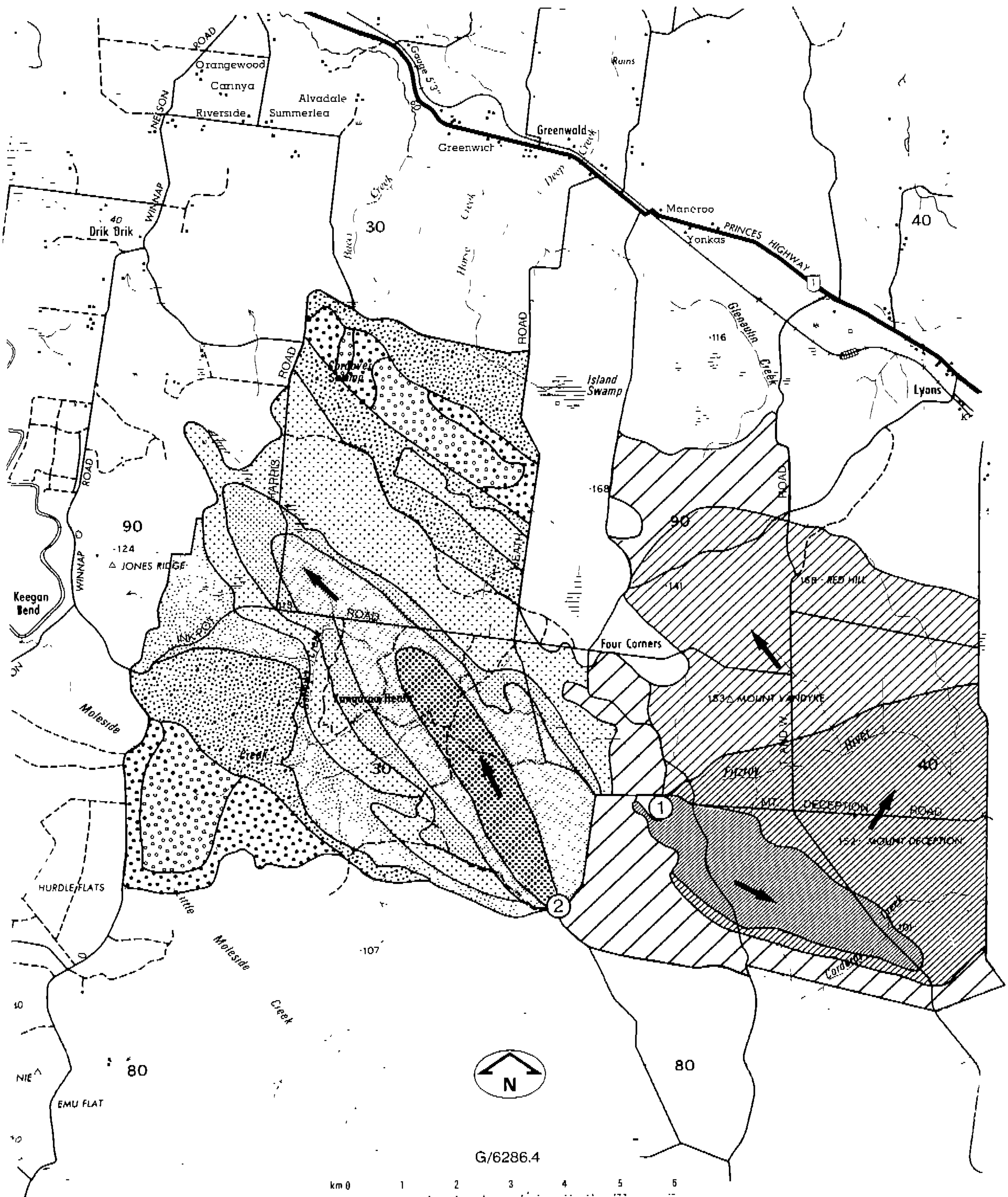


Figure 11: Development of the 1991 Heywood Wildfire.



① DAY 1 FIRE ORIGIN 24:00 24/2/91
AREA BURNT TO 14:20 25/2/91
AREA BURNT TO 16:30 25/2/91
AREA BURNT TO 21:00 25/2/91
AREA BURNT TO 09:00 26/2/91

② DAY 2 FIRE ORIGIN 08:22 26/2/91
AREA BURNT TO 13:00 26/2/91
AREA BURNT TO 15:59 26/2/91
AREA BURNT TO 17:53 26/2/91
AREA BURNT TO 05:00 27/2/91

DAY 3
AREA BURNT TO 09:19 27/2/91
AREA BURNT TO 13:00 27/2/91
AREA BURNT TO 04:00 28/2/91
AREA BURNT TO 17:00 28/2/91

about 0820 hours the fire spotted[3] over Heath Rd into the area that is known as the Kentbruck Heath. For the next 4 hours and 40 minutes the fire spread to the north-west through some 4.5 km of heathland (much of which had been previously burnt in 1986) and about 1 km of forest with heathy understorey (most of which had also been burnt six years previously). During the next three and a half hours the fire spread through some 2 km of forest with a wiregrass understorey and about 0.8 km of forest with a bracken and grass understorey. The location of the fire front was determined by a trained aerial observer at 1300 hours (with an estimated maximum error of ±250 m) and by infra-red line scan at 1559, 1651 and 1750 hours.

Infra-red line scan mapping techniques

The IR scans were obtained from a flying height of about 10 000 feet (approx. 3 000 m) above ground level, in two infra-red bands, 8-14 μm and 3-5 μm. Output from the scanner was produced in two forms, a "quick look" print that was produced in "real time" during the flight (an example is illustrated in Figure 12) and digital image that was recorded on high density digital tape for subsequent processing by computer.

The process of mapping the headfire perimeter from these digital images[4] involved identifying the line of maximum IR saturation contrast[5]. In order to adjust the image for the errors caused by aircraft movement during the scanning, up to eight control points were used to transfer the image onto a digitised topographic map. The resulting map, which is shown in Figure 13, shows the location of the headfire at three times during Day 2. This process has an estimated error of no more than ±100 m[6], probably closer to ±50 m in this example. Rates of spread were then calculated for each time period, with a confidence of approximately ±0.05 km/h (A. Matthews and D. Cooper pers. comm.[7]).

[3] The fire spotted across Heath Rd during back-burning operations. More than one spot fire probably started from this spotting and these smaller fires quickly joined to form the fire front which spread into the Kentbruck Heath.

[4] Andrew Matthews of the Earth Sciences Department Monash University, in co-operation with CNR's Fire Management Branch, is developing computer software to further automate and improve IR scanning techniques as a part of his post-graduate studies. This software uses IMAGE version 1.41 on an Apple MacIntosh II computer.

[5] i.e. the points of greatest IR emission by the fire front. The same level of saturation was used in all scans to ensure consistency between measurements.

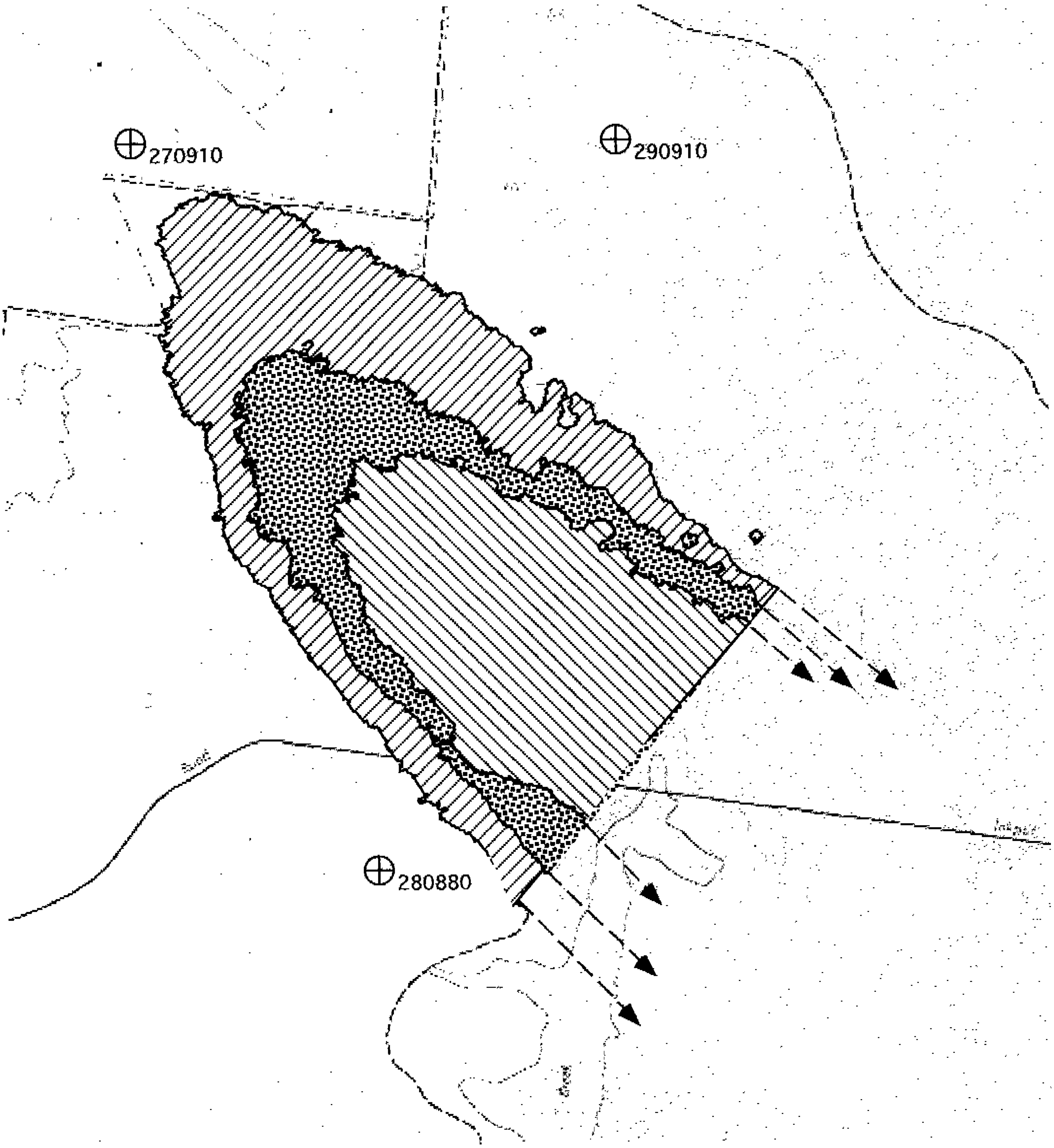
[6] Error estimates (calculated by Andrew Matthews):

Source	Amount	Notes
pixel size	±5 m	
fire front determination	±10-20 m	(cancels in successive scans)
warping	±10-20 m	(close to control point)
	±50-100 m	(away from control point)
assumed fire shape	±20 m	(cancels in successive scans)
sum of errors	±25-105 m	(averaged).

[7] Des Cooper, Infra-red Scanner Operator and Technician, Fire Management Branch, Dept. Conservation and Natural Resources, Melbourne.

Figure 12: An Infra-Red "Quick-Look" Print of the 1991 Heywood Wildfire at 1753 hours on 26 February.

Figure 13: Development of the Headfire on Day 2 of the 1991 Heywood Wildfire, as Determined by Computer Adjustment of Infra-Red Scans.



Fire at 15:59 26/2/91

Fire at 16:51 26/2/91

Fire at 17:53 26/2/91

Map Produced by:
Andrew Matthews
Earth Sciences
Monash University

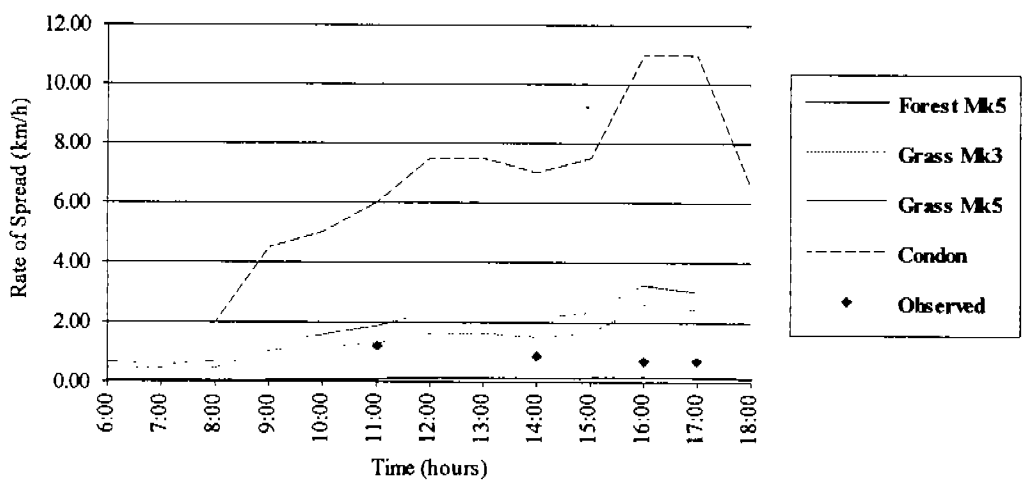
Rates of Spread

The predicted and observed rates of spread for the four periods of the fire run on Day 2 are shown in Figure 14 and Table 2. In heathland, the observed rate of spread of 1.2 km/h was greater by a factor of 10 than that predicted by the Forest Mk 5 meter, similar to that predicted by the Grassland Mark 3 meter and less than those predicted by the Grassland Mark 5 and Condon meters by factors of 1.5 and 4 respectively. In the open forest fuels, the observed rates of spread of 0.9 km/h (heath and wiregrass understorey) and 0.7 km/h in bracken/grass understorey were greater than those predicted by the Forest meter by factors of 3.5 to 5. The estimated maximum error for each of these observed rates of spread was ± 0.2 km/h.

The observed rate of spread of 1.2 km/h in heathland is within the range of those observed in the same fuel type by Rawson (1979) in 1976 in the area immediately to the south of the present fire (0.5-2.4 km/h at 1500 hours with a steady wind of 20 km/h, temperature and RH of 33°C and 18%), and is consistent with those of Billing (1986b and pers. comm.[8]) in the same area in 1986 (up to 0.5 km/h with a steady wind of 40 km/h, a much lower drought index of 21, and fire danger index rising to 8). Even when surface fuel moisture conditions are high (in the case of Billing 1986b, the ground was covered with water), high wind speeds (greater than about 20 km/h) can readily lead to high rates of spread in heathland fuels.

In heath and wiregrass understoreys under a forest canopy, the observed rate of spread of 0.9 km/h is similar to the rate of spread observed at a subsequent wildfire in 1992[9] in open forest with heath understorey vegetation some 2 km to the west of the present fire area (about 0.5 km/h with a wind of 34 km/h from the north, temperature 33°C, RH 31%, drought factor 10, and Forest FDI 29 - unpublished data). In wiregrass fuels under a forest canopy, the observed rate is consistent with the wildfire observations of Buckley (1992) in a wiregrass understorey in forest in East Gippsland, Victoria. He

Figure 14: Predicted & Observed Rates of Fire Spread for Day 2.



[8] Peter Billing, Fire Operations Officer, Dept Conservation & Natural Resources, Melbourne, Victoria (formerly Fire Research Officer at Stawell).

[9] Portland Fire No. 16 (1991/92).

Table 2: Predicted and Observed Rates of Spread for Day 2.

Time[10]	Predicted ROS				Observed ROS	Time Period	Fuel Type[11]
	Forest Mk 5	Grass Mk 3	Grass Mk 5	"Condon"			
(hrs)	(km/h)	(km/h)	(km/h)	(km/h)	(km/h)	(hrs)	
1100	0.1	1.3	1.9	6.0	1.2 ±0.2	0822-1300	A
1400	0.2	1.6	2.3	7.5	0.9 ±0.2	1300-1559	B,C,D[12]
1600	0.2	2.6	3.3	11.0	0.7 ±0.2	1559-1651	D
1700	0.1	2.4	3.0	11.0	0.7 ±0.2	1651-1753	D

observed rates of spread of 2-4 km/h when weather conditions were wind 75-95 km/h, RH 26-45%, temperature 24-30°C, drought index 29 and profile fuel moisture content greater than 20%. In comparison with litter fuels, the presence of these heath and wiregrass understorey types of elevated fuel can cause rates of spread to be substantially higher.

The apparent inconsistency on Day 2 between the increasing severity of the weather conditions (Forest FDI rising from 7 to 10) and the decreasing rate of spread of the fire (from 1.2 km/h to 0.7 km/h) can be attributed to the changes in the fuel type. The flammability of the fuel types progressively decreased, and the absence or presence of a tree canopy changed[13] and its interaction with wind effects. For the fuel types and under the weather conditions that were experienced on Day 2, the rate of spread of fire is higher in a heathland than it is in a forest with an understorey of heath or wiregrass, than it is in a forest with an understorey of bracken and grass.

The significant under-predictions of rate of spread by the Forest meter in the elevated fuels under a forest canopy can be attributed to the presence those of elevated fuels. Presumably the fire was less affected by the relatively high fuel moisture contents, and more responsive to the wind speed, than this meter predicted. This is consistent with the experience in Western Australia, where Sneeuwjagt and Peet (1985) suggest that elevated "scrub" fuels which are highly flammable may, in comparison with an equivalent weight of surface fuels, have up to five times the effect on rate of spread. The observed rate of spread from the 1992 wildfire mentioned earlier was 1.3 times greater than that predicted by the McArthur Forest meter (0.4 km/h). The Forest meter was not designed for use in elevated fuels under an open forest canopy. Under mild conditions, it can greatly under-predict rates of spread and should not be used for these fuel types.

In the heathland, the predictions from the Grassland Mark 3 meter appear similar to the rates of spread that were observed. This similarity may reflect the elevated arrangement and exposure to wind of both of these fuel types. However, the Grassland meters were not designed for heath fuel types and the similarities in

[10] The meteorological readings closest to the mid-point between scans was used to calculate FDI and Predicted ROS.

[11] Fuel types: A = heathland, B = open forest with heath understorey, C = open forest with wiregrass understorey, D = open forest with bracken/grass understorey.

[12] During this period the fire burnt through the following fuel types: 0.5 km B, 1.8 km C and 0.7 km D.

[13] Observations by Sneeuwjagt and Peet (1085) and P. Billing (pers. comm.) indicate that wind speed at 1.5 m above ground level can be expected to be about twice as high in grassland or heathland then it would be under the canopy of an open eucalypt forest. Increased wind speed at flame level will increase rate of spread.

predictions disguises some significant assumptions that were necessary in making the predictions. For example, the Grassland curing factor (as used in Mark 3 meter) is not applicable to heathlands, where a large portion of the fuels consist of live yet highly flammable vegetation; and fuel loads (t/ha, as used in Mark 5 meter) in grasslands may be only one tenth of those in heathlands. The "Condon" Modified Grassland Meter (Condon 1979), which is used in the mallee shrublands of western New South Wales, appears to be a poor alternative. The Grassland Mark 3 meter, consistent with the experience of Billing (1987) and with the assumption of a 100% curing factor, may serve a useful role in predicting the upper limits of rate of spread that can be expected in heathland fuels, especially where the wind speeds are 15-20 km/h or higher and the FDI's are Low to Moderate.

Conclusions

Infra-red line scanning, coupled with representative observations of the prevailing fuel and weather conditions, can provide rates of spread with an accuracy of ± 0.2 km/h over distances of 1.0 km and time periods of one hour. Increased use of this technology during periods of significant wildfire spread is needed, to provide further data for improving spread predictions. In fuel types where the existing meters and models are known to be poor predictors, the use of this technology can provide Fire Control Teams with better information on how fast fires have and can be expected to spread.

The Heywood data show that rate of spread depends significantly on fuel type. Fires are known to spread faster in heathland than in open forest with heath or wiregrass understorey, than in open forest with bracken/grass understorey. The absence of tree canopy (in heathland) and the presence of elevated, flammable fuels, increases rate of spread substantially and is clearly shown in this case.

In evaluating the use of the existing meters for predicting rates of spread in heath or elevated fuels, it should be remembered that non of these were designed for use in these fuel types. The Forest meter can greatly under-predict rate of spread in open forest with an elevated fuel understorey. The Condon Modified Grassland meter can over-predict rate of spread in heathland by a factor of 10. The Mark 3 Grassland meter appears to be a useful means of predicting the upper limits of rate of spread in heathland, especially where the wind speeds are 15-20 km/h or higher and the FDI's are low to moderate.

These findings only emphasise the need for a fire spread meter specifically designed for heath and elevated fuels. Further documented examples of rates of fire spread in these fuel types are needed so that these meters can be developed.

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