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Measurement and effects of fire heterogeneity in south-west Australian wheatbelt vegetation

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ABSTRACT

Shrub vegetation in the Western Australian wheatbelt is very spatially heterogeneous, with variation in structure, floristics and litter cover. Using Thermocolor pyrometers and thermocouples, we show that this vegetation heterogeneity translates into heterogeneity in fire-fuel configurations which result in marked variability of fire treatment within individual fires. Vegetation heterogeneity combines with variations in windspeed to produce variation in fire severity at broad and fine scales. Temperatures can vary greatly in the shrub canopy and at and under the soil surface over very short distances and between species. Variation in litter cover also affects temperatures reached, and we show that this is related to variation in the post-fire establishment of seedlings. Fire heterogeneity may be an important factor contributing to the coexistence of shrub species in species-rich heath communities. We argue that some measure of fire heterogeneity needs to be incorporated into fire studies.

INTRODUCTION

Most natural vegetation exhibits a degree of spatial heterogeneity in composition and structure. The scale and degree of heterogeneity varies between vegetation types, with some types exhibiting little heterogeneity (e.g. shrublands with monospecific dominance) and others considerably more (e.g. species-rich heathlands, which exhibit marked structural and floristic variation, or open woodlands which exhibit considerable structural variation).

We contend that this spatial heterogeneity in vegetation results in heterogeneity in the spatial configuration of standing fuel and litter which in turn affects the spatial pattern of fire severity. Our previous studies of the spatial variability of fires in south-west Western Australian vegetation supports this idea, with marked differences in temperatures reached both between vegetation types with different fuel configurations, and between different vegetation components within particular vegetation types (Hobbs and Atkins 1988). This variation in fire treatment may then have important effects on the post-fire vegetation response since fire-induced seed mortality and/or germination stimulation will also vary spatially.

In this paper, we discuss the measurement and effects of fire heterogeneity with particular reference to management fires in heath and shrubland vegetation in the Western Australian wheatbelt.

METHODS

Study Sites

In this paper we discuss two management fires conducted in Durokoppin Nature Reserve, north of Kellerberrin in the central wheatbelt (117° 42' E, 31° 24' S). The vegetation of the reserve is a mosaic of heathland, shrubland and woodland type (Hobbs *et al.* 1989). A 40 ha area in the extreme north-west corner of the reserve was burned on 6 April 1988. Most of the burned area consisted of dense shrubland dominated by *Allocasuarina campestris, Melaleuca uncinata, Calothamnus gilesii* and *Acacia* spp. Shrub heights ranged between 1 and 2.5 m, often with an understorey of smaller shrubs and sedges, especially *Ecdeiocolea monostachya*. Some patches of taller shrubs (3-4 m), woodland dominated by *Acacia stereophylla* (4-5 m), and open heath (0.5-1.5 m) were also present.

The second fire area was 80 ha in the eastern section of the reserve, consisting mainly of open low heath with a high diversity of shrub species varying in height between 0.5 and 2.5 m, with occasional emergents of *Grevillea eriostachya* and *Eucalyptus burracoppinensis*, and areas dominated by *Xylomelum angustifolium, Allocasuarina huegeliana* and *Leptospermum erubescens*. This area was burned on 15 March 1989.

Prefire vegetation sampling was carried out in both fire areas during the spring prior to the fire. Quadrats of 10 m x 10 m were set up throughout the fire areas (18 in the 1988 fire and 20 in the 1989 fire area) and analysed floristically (species complement and percentage cover), and structure was analysed by counting the number of hits by vegetation on 10 levee rods randomly placed in each quadrat. In addition four 5 x 5 m quadrats within the 1989 fire area were harvested for above-ground biomass estimates. Samples were divided into the following fuel components: live stems <6 mm diameter, live stems >6 mm diameter, litter <1 cm diameter, litter >1 cm diameter, and standing dead. Each component was oven dried and weighed.

Fire Temperature Measurements

Two methods of assessing fire temperatures were used. Firstly, thermocolor pyrometers were used, as described by Hobbs *et al.* (1984) and Hobbs and Atkins (1988). These consisted of strips of mica sheet 50 x 37.5 x 0.08 mm, on which stripes of heat sensitive Thermocolor paints were painted. Ten paints were used, each of which changed colour irreversibly at a different temperature over the range 65-770°C. These were painted in an array on two mica strips, which were then joined with paper clips with the paints on the inside surfaces. These pyrometers provide a relatively inexpensive way of obtaining comparative temperature estimates from a wide range of locations within a fire area. In the experimental fires discussed here, pyrometers were distributed over numerous locations, including within the canopies of particular shrub species, on the ground surface, and at 2 cm depth in the soil. Generally 10 pyrometers were placed within each location type.

Following the fire, the pyrometers were retrieved and changes in paint colour recorded. For each location type, a frequency distribution of temperatures experienced was produced. In such diagrams, a uniform, intense fire will produce a straight line, while a heterogeneous fire will yield a more ragged curve (Fig. 1).

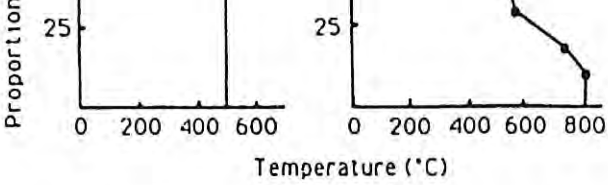

Figure 1. Method of presenting pyrometer results, showing the shape of a graph for hypothetical fires with the same mean temperature (500 °C) which are (a) uniform and (b) heterogeneous (from Hobbs and Atkins 1988).

The second temperature measurement system used consisted of chromel-alumel thermocouples connected via insulated leads to mechanical data loggers. Two loggers, each with 8 thermocouples, were used in each fire. The Grant Instruments ROK8/1r recorders have a 30 s recording interval, and were positioned in fire-resistent vacuum containers, buried in the ground. Thermocouples were placed in a variety of locations, as for the Thermocolor pyrometers, although replication was limited due to the low number of thermocouples available. The thermocouples provided data on the time course of temperature changes during the fire.

Effects of Litter Cover

A feature of the shrub communities studied is the patchy distribution of litter on the ground. Litter accumulates in soil depressions, under shrubs and in other places where lateral movement is restricted. Other areas have predominantly bare mineral soil. We investigated the effects of this heterogeneity in litter cover on fire temperatures and post-fire vegetation regeneration. Prior to the 1989 fire, an area of open heath (approximately 50 x 50 m) was categorized into areas with and without a pronounced litter cover. Ten 50 x 50 cm quadrats were marked in areas with litter, and adjacent to each of these an equivalent quadrat was marked in an area without litter cover. Close to each quadrat, all the litter within an equivalent 50 x 50 cm area was collected, oven dried and weighed. A Thermocolor pyrometer was placed within each marked quadrat at the soil surface (i.e. under the litter where present). In the year following the fire, seedling establishment was followed in each quadrat.

In order to explore further the influence of litter cover on fire temperatures and subsequent vegetation development, we experimentally added litter to plots within the area to be burned. Within the same general area as the 50 x 50 cm quadrats were marked, six 5 x 5 m plots were marked prior to the fire. In three of these, dry foliage and stem material of *Allocasuarina campestris* harvested from nearby was placed on the ground so that bare soil areas were covered in this simulated 'litter' at a rate of approximately 500 g^{-2} (5 t ha^{-1}). Adjacent plots were left with no added litter. Thermocolor pyrometers were placed at 1 m above ground, the soil surface and 2 cm soil depth within each of these sets of plots. In May 1990, 14 months after the fire, counts of seedlings were taken in ten 50 x 50 cm quadrats randomly placed within the litter added plots and an equivalent set in the plots without litter.

RESULTS AND DISCUSSION

Vegetation and Fire Heterogeneity

The vegetation in both areas was very heterogeneous, with marked spatial variation in composition and structure (Figs 2, 3). This variability was apparent both at a broad scale (e.g. between quadrats in different locations separated by hundreds of metres in the burn areas) (Fig. 2a and b), and at a narrower scale, such as within individual 10 x 10 m quadrats (Fig. 2c) or between quadrats located 5-10 m from each other (Fig. 3). Our studies have also indicated that considerable floristic differences can occur between closely located quadrats (R.J. Hobbs and L. Atkins, unpublished data).

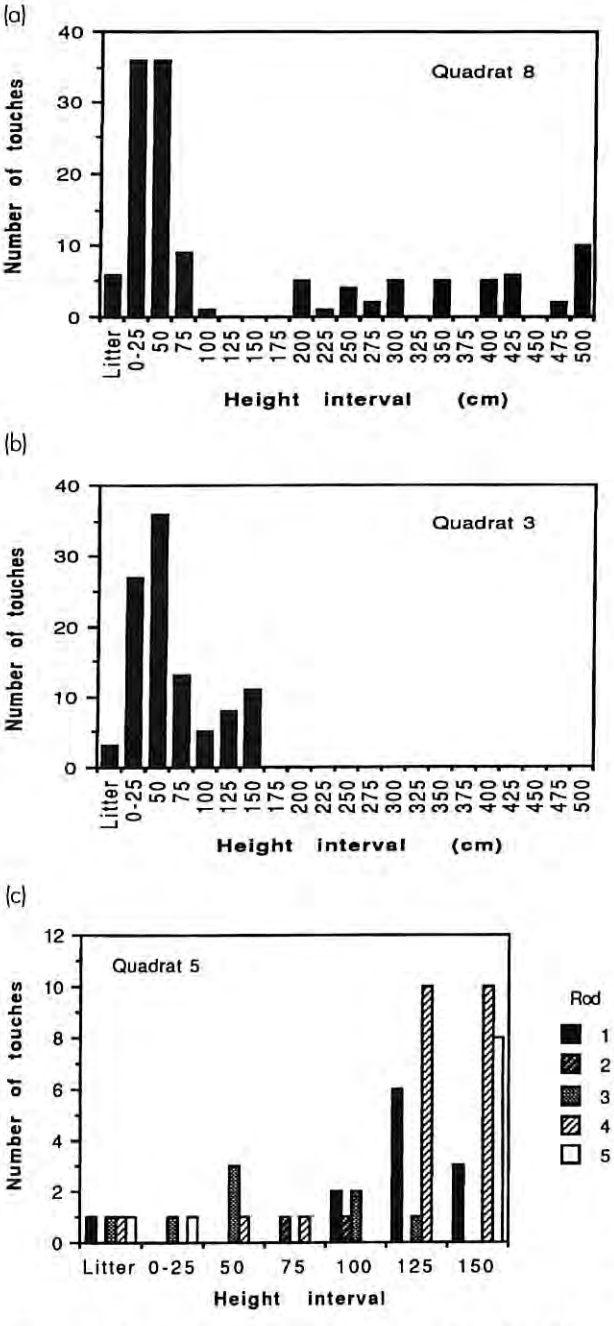

Figure 2. Results from levee rod sampling within 10 x 10 m quadrats in shrub vegetation in western Durokoppin Nature Reserve prior to burning. Graphs indicate the total number of touches by vegetation at height intervals from ground level to 5 m on 10 rods in each quadrat (Quadrats 8 and 3), and the number of touches on five individual rods within one quadrat (Quadrat 5).

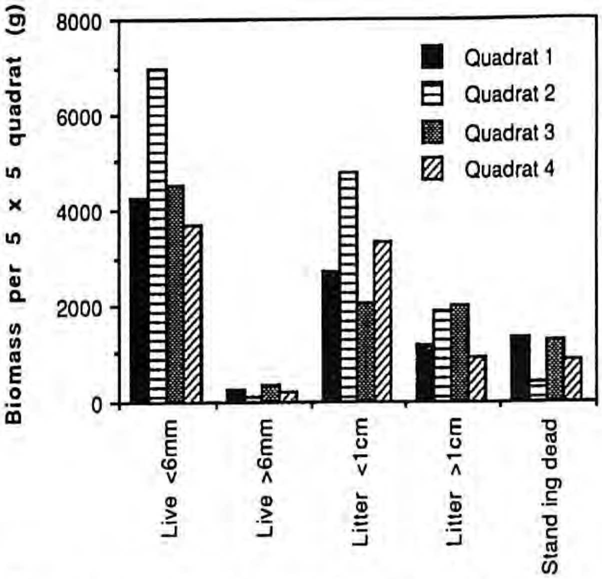

Figure 3. Above ground biomass (oven dry-weight) of various components harvested from four 5 x 5 m quadrats taken in close proximity in sandplain heath prior to fire in east Durokoppin Nature Reserve.

The 1988 fire resulted in a very patchy burn (Fig. 4), with a range of fire severities over the burn area. Two factors appear to have contributed to the patchiness of the fire, i.e. vegetation patchiness and variations in windspeed. Windspeeds varied considerably during the fire ranging from 0-15 km h^{-1}. The fire report prepared by K.J. Atkins (CALM) reads:

> 'The fire moved rapidly into the surrounding bush until the windspeed dropped, then the fire suddenly slackened. If there was no ground fuel, such as a *Borya* herbfield, then the fire would tend to be dampened right off with occasional flareups in areas of denser vegetation. An increase in windspeed may cause an increase in fire behaviour, but often the fire had dropped to such an extent that there was no such response. .... In areas where there was a ground fuel present the fire would display more intense behaviour and with a drop in windspeed would still burn as a ground fire. Increases in windspeed would result in a rekindling of fire behaviour.'

Thus, variation in fire severity was caused by two interacting factors. Dense vegetation and ground cover led to a more intense and/or continuous burn, especially at higher windspeeds. Less dense vegetation still ignited, but generally only at higher windspeeds. The interaction of vegetation heterogeneity and variation in windspeed is thus likely to produce a very variable fire treatment. A further variable which we did not include in this study was canopy moisture content, which might also vary spatially and between species.

The 1989 fire was conducted with more uniform and stronger winds (10-20 km h^{-1}) and resulted in a considerably more complete burn. Even so, unburned and partially burned patches remained, presumably as a result of the same interplay between fuel distributions and windspeeds.

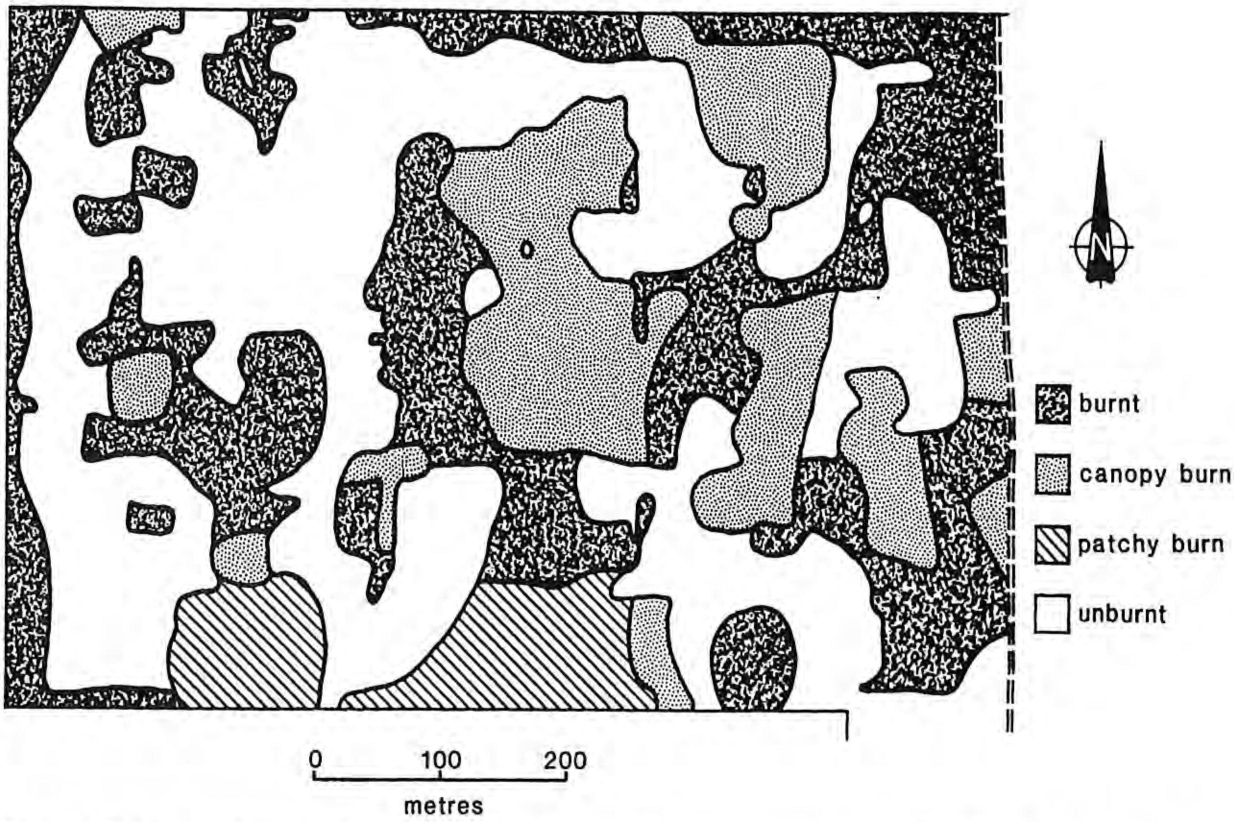

Figure 4. North-western portion of Durokoppin Nature Reserve following management fire in April 1988, indicating variation in severity of fire. Burnt = complete burn of understorey and ground layer, without complete removal of canopy layer; Canopy burn = complete removal of canopy and understorey; Patchy burn = partial burn with some unburnt areas; Unburnt = no fire treatment.

Temperature recordings during the two fires indicate that the scales of variation found in the vegetation are replicated in the range of temperatures experienced. Thus, within marked 10 x 10 m quadrats, considerable variation occurred in temperatures experienced in the canopy and at and below the soil surface (Fig. 5). Thermocouples placed in and under different plant species situated within metres of each other indicate that quite different fire treatments can be experienced by plants within close proximity, even in what was considered a reasonably intense fire (Fig. 6). As well as this fine scale variation in temperatures, larger scale differences can also be observed. Data from three 10 x 10 m areas situated about 10-20 m apart (Fig. 7) indicate that areas with approximately similar vegetation (i.e. mixed heath) can have markedly different fire treatments, with no soil heating in one case and soil heating to 500°C in another. Variation is also caused by the presence of particular species, such as the emergent *Eucalyptus burracoppinensis*. In this case, a considerably more uniform fire treatment was experienced, with soil temperatures reaching 770°C, presumably as a result of an increased litter cover.

Addition of litter to mixed heath quadrats altered the fire treatment markedly, with higher, more uniform temperatures experienced in the canopy and at and below the soil surface following litter addition (Fig. 8). This is reflected in data from marked areas with and without litter before the fire, and temperatures reached at the soil surface were significantly higher where litter was present (Table 1). Bradstock *et al.* (1992) have also discussed the influence of litter type and depth on soil temperatures in mallee shrublands.

Litter and Post-fire Vegetation Response

Data from marked quadrats with and without litter prior to the fire indicate significant differences in seedling establishment between the two microhabitats. Several species had significantly more seedlings in the litter areas, while others had more in the areas with no litter (Table 1). There was no apparent relationship between seedling numbers and species of adult shrub present before fire. One might expect greater seedling establishment in areas with litter since seeds are liable to collect in these areas and there may be some response to post-fire nutrient release in ash. Ash deposits were, however, dispersed by wind in the days following the fire. The fact that some species were more abundant in areas without litter indicates that these factors alone do not account for the post-fire distributions of seedlings. Data from quadrats where litter was experimentally added support this contention (Table 2). Here, the same species which were abundant in the areas with litter occurring naturally (Table 1) were also abundant

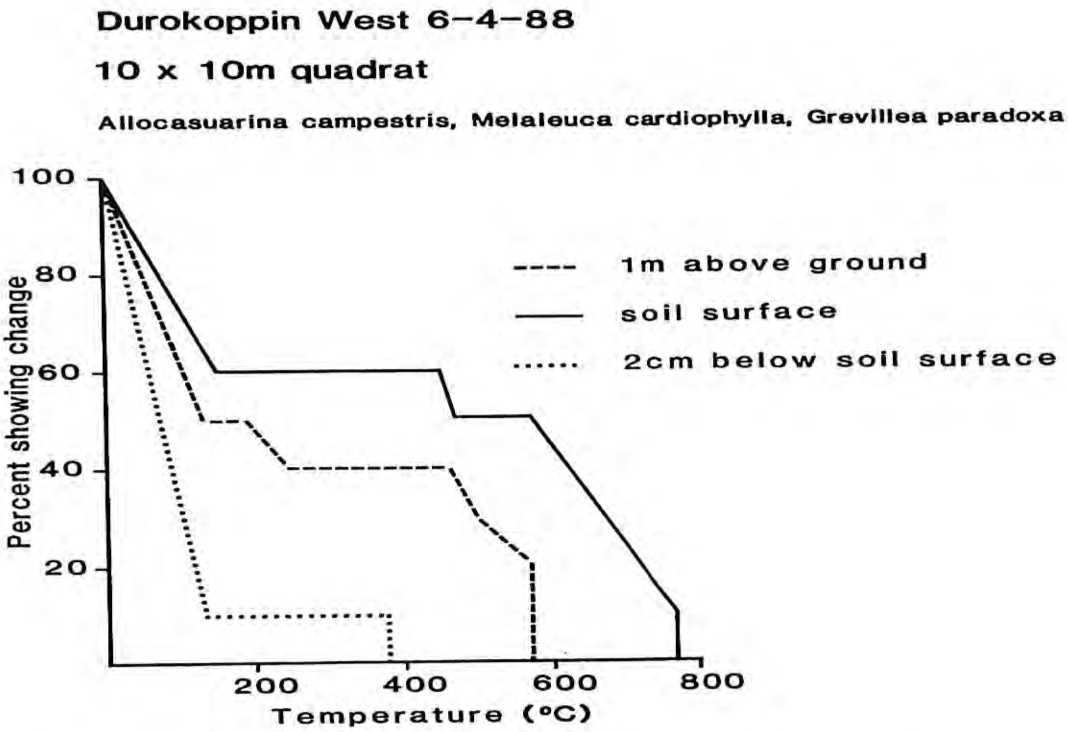

Figure 5. Thermocolor pyrometer results from within one 10 x 10 m quadrat during the fire in western Durokoppin in April 1988. Results from ten pyrometers in each location.

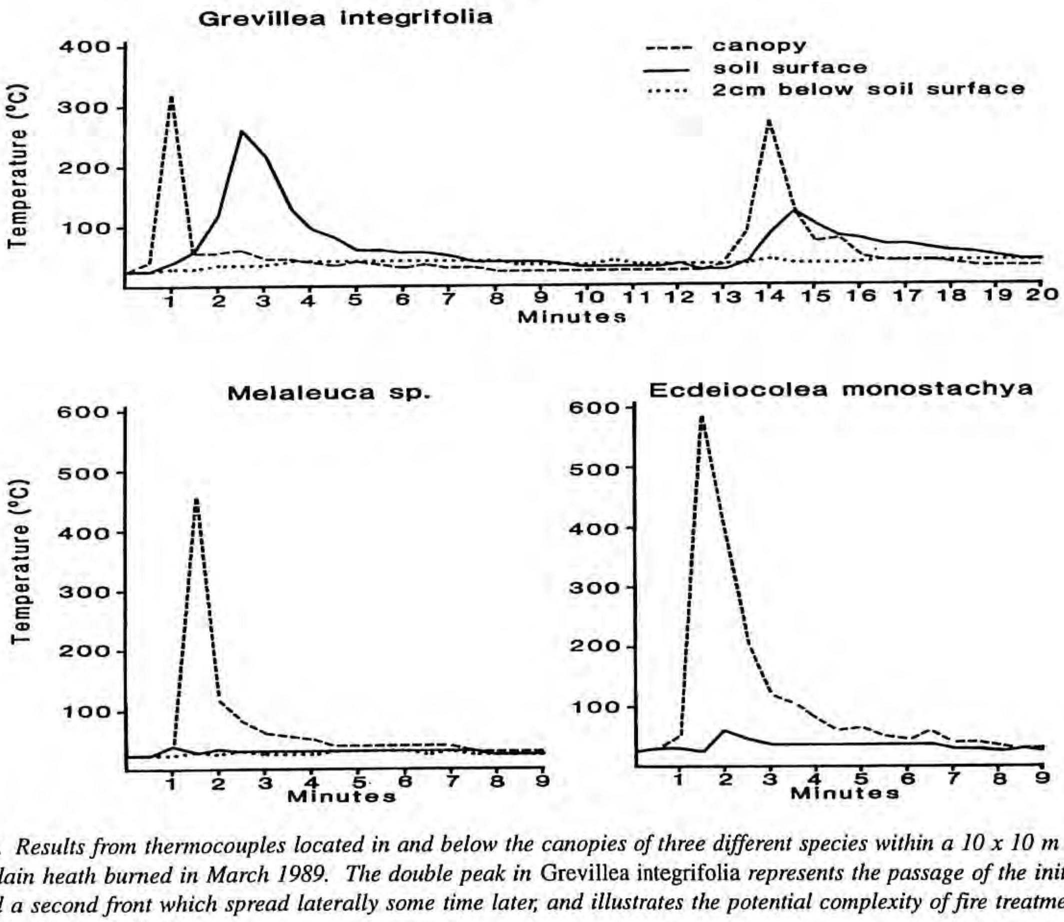

Figure 6. Results from thermocouples located in and below the canopies of three different species within a 10 x 10 m quadrat in sandplain heath burned in March 1989. The double peak in Grevillea integrifolia *represents the passage of the initial fire front and a second front which spread laterally some time later, and illustrates the potential complexity of fire treatment within heterogeneous fuels.*

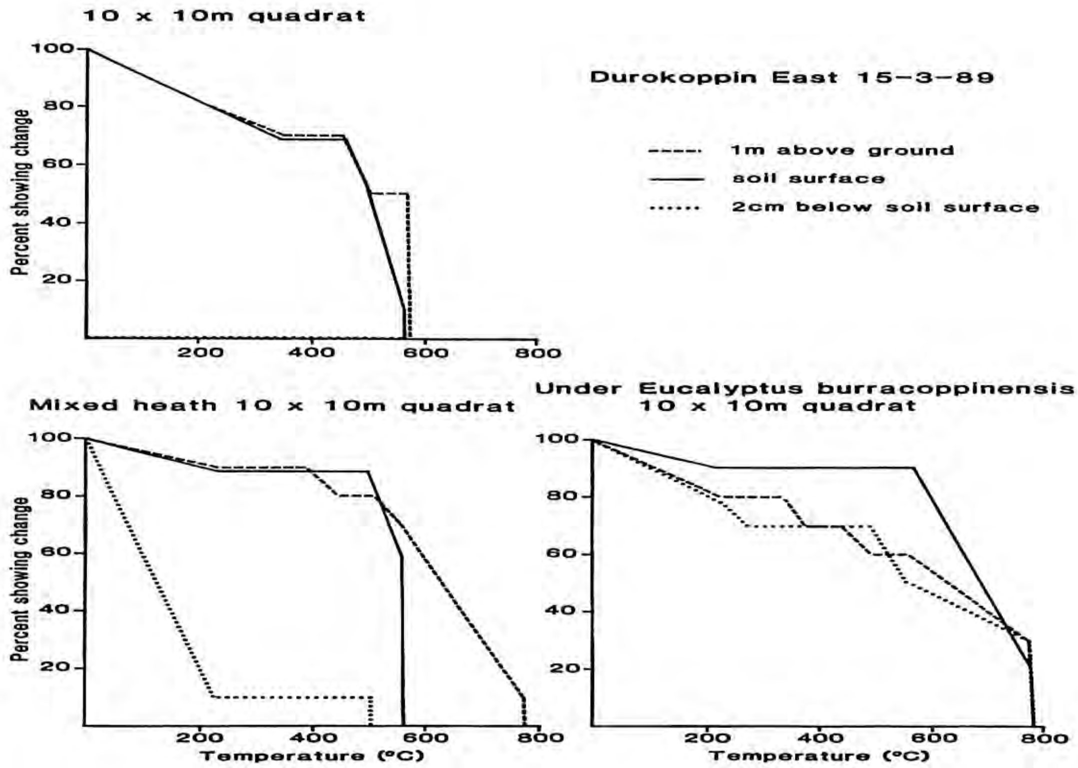

Figure 7. Thermocolor pyrometer results from within three different closely located 10 x 10 m quadrats in sandplain heath burned in March 1989. Two quadrats were in mixed heath and the third was located within an individual of Eucalyptus burracoppinensis. *Results from ten pyrometers in each location.*

TABLE 1

Dry weight of litter present before fire, maximum temperature recorded at the soil surface during fire, and numbers of seedlings of most common plant species present 14 months after the fire in marked areas with and without litter cover in kwongan in east Durokoppin Nature Reserve, 1989. Data from ten 50 cm x 50 cm quadrats in each microhabitat type (mean ± 1. S.E.), with significant differences between microhabitats indicated, as determined by t test for litter weight and temperature, and Mann-Whitney U test for seedling numbers. Litter was collected from 50 x 50 cm quadrats located near to marked areas immediately prior to the fire in March 1989.

	LITTER		BARE SOIL
Litter dry weight (g m^{-2})	212 ± 24	p< 0.001	8 ± 3
Maximum temperature, soil surface	665 ± 36	p< 0.01	560 ± 0
NUMBERS OF SEEDLINGS			
Allocasuarina acutivalvis	3.1 ± 0.8	p<0.05	0.5 ± 0.2
Allocasuarina campestris	1.9 ± 0.9	p<0.05	0.2 ± 0.2
Baeckea floribunda	2.4 ± 1.6	-	0.3 ± 0.3
Grevillea integrifolia	0.6 ± 0.4	-	0.3 ± 0.1
Grevillea pritzelii	1.3 ± 0.5	p<0.05	0.3 ± 0.2
Leucopogon hamulosus	1.0 ± 0.5	p<0.05	20.1 ± 10.7
Verticordia chrysantha	0.4 ± 0.2	p<0.05	1.3 ± 0.3

TABLE 2

Numbers of seedlings of common species present in May 1990 within 5 x 5 m plots which received additional litter (approximately 500 g m^{-2}) prior to fire in March 1989 and adjacent areas with no added litter, within kwongan vegetation in east Durokoppin Nature Reserve. Data are from ten 50 cm x 50 cm quadrats taken randomly within 3 litter-added plots and 10 taken in immediately adjacent 5 x 5 m areas (Mean ± 1 S.E., with significance of difference indicated, as determined by Mann-Whitney U test).

	LITTER ADDED		ADJACENT
Acacia nigripilosa	3.5 ± 1.2	$p < 0.05$	0
Allocasuarina campestris	3.9 ± 1.4	$p < 0.05$	0.6 ± 0.6
Grevillea integrifolia	2.2 ± 1.5	-	5.4 ± 2.0
Grevillea pritzelii	5.7 ± 2.2	$p < 0.05$	0.8 ± 0.4
Leucopogon hamulosus	1.8 ± 1.1	$p < 0.05$	17.0 ± 5.0
Verticordia chrysantha	0.2 ± 0.2	$p < 0.05$	2.2 ± 0.6

in areas with litter added. Similarly, species most abundant in areas with no litter were also more abundant in the plots with no addition of litter. If seedling distributions were related only to the pre-fire distribution of litter and its effect in trapping seed, addition of litter shortly before the fire should have had no impact on seedling distributions. All the species recorded here store seed in the soil, except the two *Allocasuarina* species, which maintain canopy seed stores. However, the fact that seedling numbers of *Allocasuarina* spp. were higher in the quadrats with litter and in quadrats with litter added indicates either that these species may also have a soil seed store with heat-stimulated germination, or that seed dispersed from the canopy germinates preferentially (or seedlings survive better) in areas with a pre-fire litter cover. Clearly, more detailed study is required to investigate these possibilities.

The results suggest that the effect of litter on fire treatment may be an important factor in determining post-fire seedling distributions. The mechanism for this is likely to be differential responses by the seeds of different species to fire treatment. It is likely that seeds of some species require a high temperature treatment to stimulate germination (Cushwa *et al.* 1968; Martin *et al.* 1975; Portlock *et al.* 1990; Auld and O'Connell 1991; Bell *et al.* 1993), while seeds of other species will be intolerant of high temperatures. Differential heating

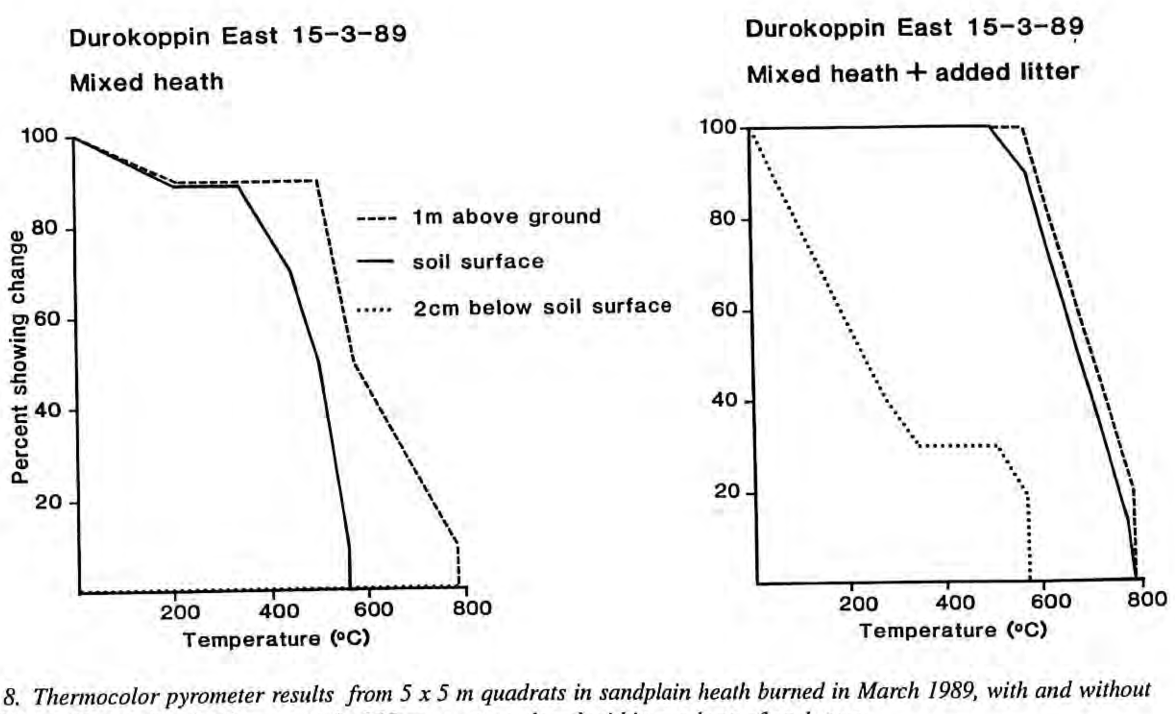

Figure 8. Thermocolor pyrometer results from 5 x 5 m quadrats in sandplain heath burned in March 1989, with and without the addition of litter. Results from a total of 10 pyrometers placed within quadrats of each type.

of seeds stored either in the canopy or in the soil will then result in a heterogeneous response to fire. We do not have data on the effects of elevated temperatures on germination of the species found in our study quadrats, but data on understorey species from *Eucalyptus salmonophloia* woodland, another major vegetation type in the region, indicate that species' responses can vary markedly (Fig. 9). Some species were inhibited and others stimulated by high temperatures, and subtle differences in temperature response are evident. Species coexistence may thus be facilitated by their differential responses to a heterogeneous fire treatment.

In this respect, fire heterogeneity may be an important mechanism promoting the maintenance of species diversity in shrublands and other vegetation types, in addition to other mechanisms proposed (Hnatiuk and Hopkins 1980; Hopkins and Griffin 1984). Other studies have indicated the importance of heterogeneity in post-fire litter distribution in determining species' establishment success (Enright and Lamont 1989; Lamont *et al.* 1993), but the present results indicate that pre-fire distributions can also be important.

CONCLUSIONS

In this paper we have indicated that heterogeneity in fire severity is an important aspect of fires in shrub communities. This heterogeneity can be attributed to variability in ground and canopy fuel configurations, possibly in conjunction with variation in wind strength during the course of a fire. The fires studied were both controlled management fires, and it is possible that such heterogeneity would be less evident in a wildfire situation. Nevertheless, even under such conditions it appears likely that variations in windspeed and in the distribution of canopy and, especially, litter fuels would induce some spatial variation in fire treatment. This spatial variation in fire severity in turn influences the patterns of post-fire regeneration.

Is this spatial variability in fire severity important? Certainly, in order to derive an understanding of the processes influencing vegetation response to fire, it is important to recognize that such variability exists (see also Gill 1981). Fire studies frequently rely on simple descriptors which summarize the fire treatment, using mean fuel loadings and single parameter intensity measures. While this is probably appropriate for broad management considerations, for more focussed analysis of fire effects more consideration of fire heterogeneity is needed. The biota exhibits a varied response to fire, and heterogeneity in fire severity clearly has important ramifications for the long-term persistence of that biota. For management, the implication seems to be that heterogeneity of fire treatment should be aimed at; uniform low or high temperatures will not provide the range of treatments and hence cues for the range of species present.

The measurement of fire heterogeneity is an intensive process, requiring adequate replication and spatial coverage. The pyrometers more efficiently captured the range of spatial variation in temperature than did the thermocouples, since these were restricted in number. Unfortunately, Thermocolor paints are no longer available, and tests of alternatives have shown them to be less satisfactory. However, since variation in fire severity can be linked directly to fuel configuration and is also probably mediated by windspeed variations, it should be possible to derive estimates of fire heterogeneity from these two variables. This then involves building variation into standard methods of estimating fire intensity.

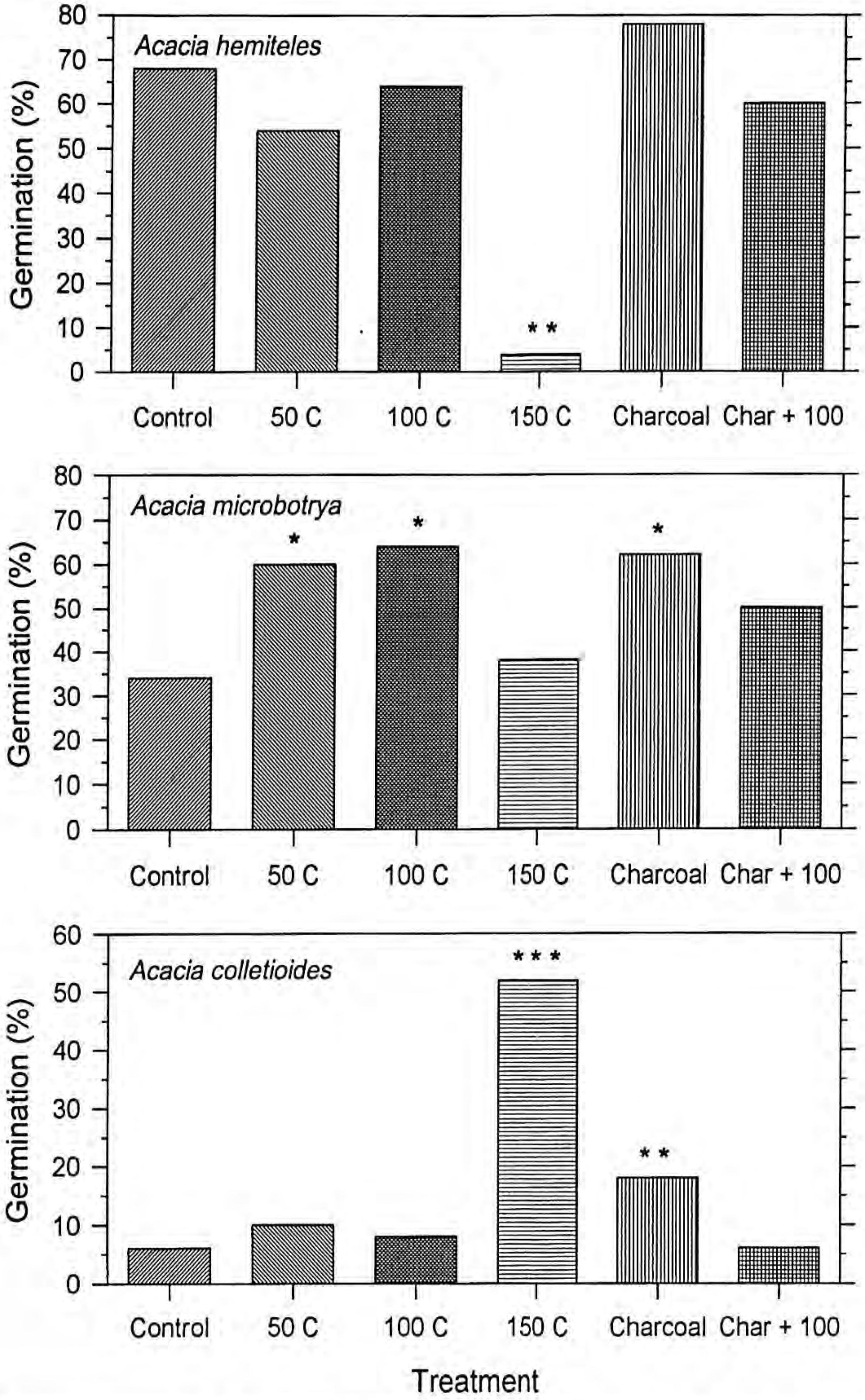

Figure 9. Germination (percentage) of three Acacia *species which are common components of the understorey in* Eucalyptus salmonophloia *woodland in the central wheatbelt, following various treatments. Seeds were scarified and subjected to different temperatures in an oven for 10 minutes, placed on filter paper in petri dishes and watered regularly for 38 days. In addition, charcoal fragments were added to some dishes. Controls received no heat or charcoal. Five dishes were assigned to each treatment, with ten seeds per dish. Asterisks indicate significant differences from control, as determined by t test on square root transformed data: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.*

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