

Relationships between soil temperatures and properties of fire in feathertop spinifex (*Triodia schinzii* (Henrard) Lazarides) sandridge desert in central Australia

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Abstract. Soil temperatures during wildfires are known to influence seed bank and plant resprouting dynamics in arid Australian grasslands. Nevertheless, relationships between soil temperatures and factors such as fuel load, fuel type, season of burn, time-of-day and soil moisture are poorly understood. This study used small-scale experimental burns to determine the effects of these five variables on soil temperature profiles (0–4 cm) during fire in spinifex sandridge country in the Haasts Bluff Aboriginal Reserve, west of Alice Springs. Fuel load and type were found to strongly influence soil temperatures, with soils directly beneath *Triodia* hummocks experiencing more heating than hummock edges or between-hummock gaps, and soils beneath *Triodia* hummocks experiencing more heating than either mulga (*Acacia aneura* F.Muell. ex. Benth.) litter or *Aristida holathera* Domin. tussocks. Season and time-of-day also had strong effects on below-ground heating, with soil temperatures remaining elevated for longer periods during summer compared to winter burns, and day-time burns producing higher temperature maxima and longer durations of elevated soil temperatures than night burns. Soil moisture also had a strong impact on temperature profiles during fire, with high levels of soil moisture strongly reducing the soil heating during fire. These results indicate that the examined factors will strongly influence soil temperature regimes during spinifex wildfires. Hence, they are likely to affect the composition of plant assemblages in post-fire environments through their impacts on vegetative regeneration and on seed bank processes.

Additional keywords: *Aristida holathera*, fire intensity, mulga, seed banks, temperature.

Introduction

Spinifex sandridge deserts occupy ~22% of the Australian landmass and are distributed primarily across arid and semi-arid inland regions (Griffin 1990). Large-scale wildfires periodically burn across these deserts, and mainly occur when fuel volume and continuity increase following extreme rainfall events (Griffin *et al.* 1983). These fires are often very large and intense, occasionally burning areas as great as 10 000 km² and reaching intensities of up to 14 000 kW m⁻¹ (Burrows *et al.* 1991; Allan and Southgate 2001). Fire intervals may also be short, and there are cases where extended periods of high rainfall have resulted in large areas burning twice within time intervals of 2–3 years (P. K. Latz, pers. comm. 2003).

Despite the extent, intensity and occasional high frequencies of spinifex wildfires, few studies have examined the effects of fire on soil heating in these ecosystems. This represents an important knowledge gap, given that the recruitment of many plants within spinifex habitats rely on soil heating during fire to release seeds from dormancy (Maconochie 1982; Hodgkinson 1991; Letnic *et al.* 2000; Nano 2005). Furthermore, soil heating during a fire is a strong driver of demographic processes for standing plants in spinifex systems. This is because the majority of woody species are able to regenerate following fire by resprouting from

underground stems, and are, hence, affected by soil heating during fire (Hodgkinson and Griffin 1982). Recent investigations examining the effects of fire regime on resprouting support this view, with the survival of four arid *Acacia* shrub species (*Acacia aneura* F.Muell. ex. Benth., *Acacia kempeana* F.Muell., *Acacia maitlandii* F.Muell., *Acacia melleodora* Pedley) being strongly influenced by factors such as pre-fire fuel load and season of burn (Wright and Clarke 2007a).

Soil temperatures during fire are affected by three main factors: (1) the total amount and rate at which heat is transferred to the soil by fire; (2) the rate that this heat is dissipated from the soil; and (3) soil physical properties (Steward *et al.* 1990). The amount and rate of heat transferred to soil by a fire is related to Byram's fire intensity index (Byram 1959), which is defined as the rate of energy released per unit time per unit length of fire front. The numerical value of this index [I (kW/m)] is predicted using the following equation:

$$I = H \times w \times r, \quad (1)$$

where H (kJ/kg) is the heat released for a given mass of fuel, w (kg/m²) is the weight of combusted fuel, and r (m/s) is the rate of spread of the fire front. The rate of flux of heat through the soil is then largely determined by the magnitudes of the temperature

gradients between: (a) the soil surface and the atmosphere, and (b) the soil surface and lower soil levels. Larger gradients between these boundaries produce higher rates of heat transmission and, therefore, faster rates of heat penetration and heat loss (Baver 1940). For this reason, there is likely to be seasonal and diurnal variability in the rate at which heat dissipates after fire, owing to changing baseline soil and air temperatures between different seasons and between day and night (Geiger 1957). Furthermore, seasonal and diurnal variation in soil heating is likely to be magnified by cyclic changes in fuel moisture and weather conditions such as air temperature, relative humidity and wind speed; although these factors have never been tested experimentally. Finally, soil temperatures during fire are affected by soil physical properties and soil moisture, as these factors influence the rate of heat conduction through soils (thermal conductivity) (Steward *et al.* 1990).

The objective of this study was to determine the effects of five factors on soil temperatures during spinifex burns: fuel load, fuel type, season, time-of-day and soil moisture. Such information should be useful for managers of vegetation in spinifex and other vegetation types, as soil temperatures during pyric disturbance can drive both resprouting dynamics and seedling regeneration processes. We predicted that:

- (1) higher fuel loads would produce higher soil heating during fire than lower fuel loads,
- (2) denser fuel types would produce higher soil heating during fire than less dense fuel types,
- (3) burns conducted during summer would result in higher soil heating than burns conducted during winter,
- (4) burns conducted during daylight hours would produce higher soil heating than burns conducted at night, and
- (5) burns conducted under dry soil conditions would produce higher soil heating than burns conducted under moist soil conditions.

Materials and methods

Study site

The study site was located in spinifex sandridge country in the Haasts Bluff Aboriginal Reserve, ~250 km west of Alice Springs, Northern Territory. The climate of the region is characterised by high seasonal and diurnal fluctuations in temperature and solar radiation, with the mean maximum daily temperature in summer (January) being 35.9°C, and the mean minimum being 20.9°C (Australian Bureau of Meteorology 2008). During winter (July), the mean maximum daytime temperature is 19.5°C, and the mean minimum is 3.7°C (Australian Bureau of Meteorology 2008). The 100-year mean annual rainfall for Alice Springs is 279 mm, with the majority of this falling during summer months due to the influence of tropical monsoon systems from the north (Griffin *et al.* 1983).

Vegetation at the site was a spinifex-mallee association interspersed with scattered patches of mulga (*Acacia aneura*) vegetation. The over-storey of the spinifex-mallee association was dominated by *Brachychiton gregorii* F.Muell., *Eucalyptus gamophylla* F.Muell. and *E. oxymitra* Blakely, and the over-storey of the mulga vegetation was completely dominated by mature *A. aneura*. Plants common among the shrub layer of these associations included various species of *Acacia*, *Senna* and

Eremophila. The spinifex-mallee association was patchily burned during 2002, which resulted in the ground layer consisting of a mosaic of mature *Triodia schinzii* (Henrard) Lazarides (feathertop spinifex) in unburned areas, and regenerating *T. schinzii* seedlings and the post-fire colonizing grass *Aristida holathera* Domin. in burned areas. The mulga vegetation had not been burned during the 2002 fire and the ground layer of these areas consisted almost entirely of a dense and homogeneously packed 2 cm deep apron of unburned mulga phyllode litter. The soils of the spinifex-mallee association were composed primarily of deep, red siliceous sands that were nutrient poor, had little horizonation or development of organic layers, and were relatively free-draining (Prescott 1952). Soils of the mulga vegetation were composed of a heavier, red earth soil type (Bowman *et al.* 1995).

Experimental burn categories

Thirty-nine experimental burns were conducted between July 2004 and January 2005, with five replicate burns taking place within each of seven experimental burn categories and four burns being conducted in the 'gap' burn category (see Table 1). It was not possible to collect data for one of the gap burns owing to a malfunction in some electronic equipment in the field. The scale of the burns was small, with each burn taking place within a square of ~100 m² surrounded by firebreaks. Fires were lit in three fuel types of differing densities: mature *Triodia* hummocks, mulga litter, and *Aristida holathera* tussocks. Estimates of dry mass for each fuel type were obtained by weighing 10 × 1 m² samples of material in the field, followed by oven-drying 5 × 100 g subsamples and using mean moisture content to convert fresh weight to dry weight on sampled quadrats. *Triodia* hummocks were found to have a mean dry weight of 1.55 kg/m² (s.e. (standard error) 0.05 kg/m²), mulga litter had a mean dry weight of 0.9 kg/m² (s.e. 0.02 kg/m²), and *Aristida holathera* tussocks had a mean dry weight of 0.5 kg/m² (s.e. 0.04 kg/m²).

In conducting the burns, the upwind sides of the blocks were lit at several points, allowing the fires to burn in a continuous line until firebreaks were reached on the downwind side. All burns were lit under low and relatively constant wind conditions, as high wind conditions would have increased the rate of fuel combustion, and this would have affected both the magnitude and the duration of temperatures reached during the burns. Burning under low wind conditions also reduced the danger of small-scale experimental burns getting out of control and becoming large-scale wildfires. It was not expected that temperature conditions

Table 1. Categories of experimental burns conducted between July 2004 and January 2005 in Haasts Bluff Aboriginal Reserve

Fuel type	Fuel load (kg m ⁻²)	Time of day	Month	Soil moisture
<i>Triodia</i> hummock	1.55	Day	Winter	Dry
<i>Triodia</i> hummock	1.55	Night	Winter	Dry
<i>Triodia</i> hummock	1.55	Day	Summer	Dry
<i>Triodia</i> hummock	1.55	Day	Summer	Moist
<i>Triodia</i> edge	0.3	Day	Winter	Dry
<i>Triodia</i> gap	0	Day	Winter	Dry
Mulga litter	0.9	Day	Summer	Dry
<i>Aristida holathera</i>	0.5	Day	Summer	Dry

during these experiments would simulate actual wildfires, which would be far more intense with significantly higher rates of spread (Byram 1959). Rather, it was hoped the experiments would explore the potential for temperature variation that may occur during larger scale fires under a range of climatic conditions and fuel types.

Temperature readings were made in soils along the downwind edges of the burn areas. For *Triodia* hummock burns, thermocouples were placed beneath the centre of the hummocks, where fuel height was 0.5–0.6 m. All hummocks were of roughly uniform size and density of fuel packing, and were selected from vegetation that had not been burned by the 2002 wildfire. The hummocks were hemispherical in shape (1–1.2 m in diameter) and had not developed an annulus in the centre, as is typical of some species of *Triodia* as they age and senesce. For hummock edge burns, thermocouples were placed beneath the hummocks at points 10 cm from the outer edges of the hummocks. Fuel loads for these edge burns were estimated at one fifth of the entire hummock, with only a light layer of *Triodia* (2–3 cm depth) covering the ground at these points. For *Triodia* gap burns, readings were taken at points mid-way between two hummocks which were spaced precisely 60 cm apart, along the firebreak of the downwind side of the plot. These gaps were devoid of vegetation and soil temperature profiles at these points responded purely to the heat emitted by the two hummocks burning either side of the monitoring point. *Aristida holathera* burns were conducted in areas that had been burned by the 2002 wildfire, with temperature readings being made from beneath the bases of *Aristida* tussocks. For mulga burns, thermocouples were placed under the litter apron towards the outer edge of mulga shrub canopies. For these burns, the fires were carried entirely by the mulga phyllode litter.

In order to test the effect of seasonality on soil temperatures during fire, temperature profiles of daytime hummock burns in winter (conducted in July 2004) were compared against temperature profiles of daytime hummock burns conducted in summer (conducted in January 2005). To test the effect of time of day on soil temperatures during fire, temperature profiles of night hummock burns (0330–0430 hours) in winter were compared against daytime hummock burns (1000–1600 hours) in winter. To examine the effect of soil moisture on soil temperatures during summer fire, the soil beneath five *Triodia* hummocks was moistened by pouring 5 L of water on a cleared space beneath each hummock. These hummocks were then left for 15 min before burning to allow the water to pass through the upper soil horizon.

Temperature measurement

Soil temperatures during fire were measured using four insulated chrome-alumel thermocouples (K-type). Before positioning the thermocouples in the soil, any fuel was carefully removed and placed aside. One thermocouple was then placed on the soil surface and the remaining three were inserted into the vertical face of a previously excavated pit at 1, 2 and 4 cm below the soil surface. By placing the thermocouples in an undisturbed soil profile in this manner, the structure of the soil was maintained and heat conduction through the soil emulated natural conditions (Norton and McGarity 1965). Once the thermocouples were positioned, the protruding wires were carefully buried and the

previously removed plant material was restored to its original position. Temperature data from the thermocouples were read by a remotely placed data logger (Datataker 50, Data Electronics, Rowville, Vic., Australia) and subsequently downloaded to a portable laptop computer and saved on a removable USB data storage device. The cables connecting the data logger to the thermocouples were buried in a 20 cm deep trench in order to avoid heat damage. Temperature readings were made every 30 s and monitoring for each experimental fire continued until all sensors read less than 60°C. This temperature was chosen because it represents a biological threshold, above which rapid and lethal damage can occur to plant tissues (Rundel 1981). Monitoring soil temperatures until all sensors read below 60°C also permitted observation of soil temperatures in ranges that were capable of breaking dormancies of seeds for certain *Acacia* and *Senna* species in the study area (Nano 2005).

Data analyses

Temperature maxima and duration of temperatures greater than 60 and 80°C at all soil depths were compared between burn categories using one-factor ANOVAs. In analysing temperature maxima data from the seasonal and time-of-day datasets, only the absolute maxima were compared between datasets (rather than comparing relative changes between pre-fire soil temperatures and post-fire maxima). This analytical approach was adopted because absolute temperature maxima and the duration of high temperatures are the ultimate drivers of biological responses to fire. Prior to analysis, all temperature data were transformed using a log $10(x + 1)$ transformation. Homogeneity of variances was checked for all data using Cochran's test with the significance for these tests being determined at $P < 0.05$ (Quinn and Keough 2002). Scheffe's post-tests were used to determine statistical differences between treatment means.

Temperature time curves were also constructed for the five burn factors, which involved plotting mean temperatures at 30-s time intervals for each series of burns. These curves were terminated when temperatures were below 60°C at all depths. The peak temperatures and durations >60°C for these curves do not necessarily correspond to the maximum temperature values and mean durations >60°C given in the tables. This is because the values in the tables were mean values calculated from the temperature data for each individual burn, while the graphs report the mean values of the various burns at 30-s time intervals (from 1 minute before burns, to the moment when mean temperatures dipped below 60°C).

Results

Fuel load and fuel type

Pre-fire fuel load was found to strongly affect temperature maxima reached during fire, with maximum soil surface temperatures higher under burning *Triodia* hummocks than in gaps, but not significantly different from hummock edges (Fig. 1; Table 2). Maximum surface temperatures under hummocks and edges ranged from 250 to 700°C, averaging 366.8°C for hummocks and 324.3°C for hummock edges. The depth and duration of soil heating increased according to the load of fuel being burned, with greater penetration and duration of heating experienced under burned hummocks compared to edges and

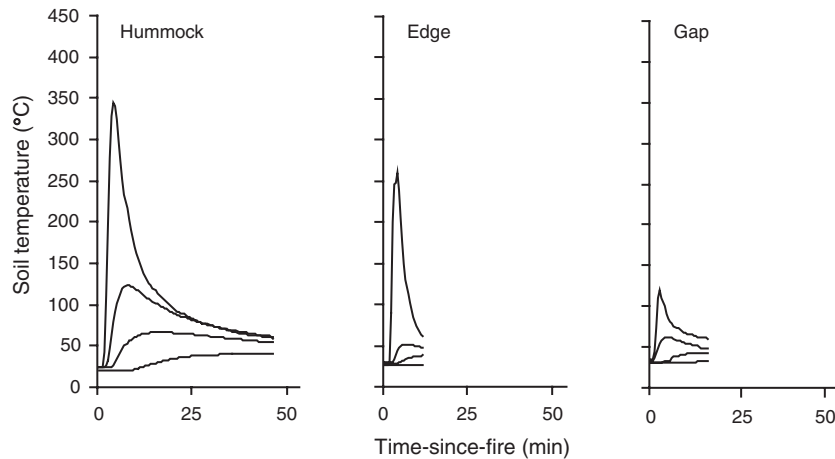


Fig. 1. Mean soil temperatures at surface, 1, 2 and 4 cm depth, from daytime burns conducted in winter under *Triodia* hummocks, edges and gaps. Thermocouple depths, in order from uppermost to lowest temperature curves, are: surface, 1, 2 and 4 cm.

Table 2. Mean soil temperatures during daytime winter burns at surface, 1, 2 and 4 cm depth under *Triodia* hummocks, *Triodia* hummock edges and gaps

Within rows, means followed by different letters indicate significantly different temperatures and duration times under Scheffe's post-hoc tests. n.s., not significant at $P < 0.05$

	Hummock	Fuel load Edge	Gap	F-value	P-value
Initial surface temp. (°C)	23.4	27.6	32.3	1.1	n.s.
	<i>Maximum (°C)</i>				
Surface	366.8a	324.3ab	131.1b	6.5	0.0136
1 cm	125.4a	52.4b	63.1b	13.7	0.001
2 cm	66.9a	38.7b	38.9b	20.7	0.0002
4 cm	40.3a	29.7b	32.5ab	4.4	0.0391
	<i>Duration >60°C (min)</i>				
Surface	47a	9b	8.4b	12.8	0.0013
1 cm	45.1a	1.8b	4.5b	16.3	0.0005
2 cm	20.9a	0b	0b	5.2	0.026
4 cm	0	0	0	—	—
	<i>Duration >80°C (min)</i>				
Surface	24.3a	5.8b	4.1b	15.9	0.0006
1 cm	21.1a	0b	0b	127.4	<0.0001
2 cm	1.4	0	0	0.9	n.s.
4 cm	0	0	0	—	—

gaps (Fig. 1 and Table 2). Mean soil temperatures higher than 60°C were observed to 2 cm depth under burned hummocks, but were observed only at the soil surface at hummock edges and to 1 cm depth in the gaps. The mean duration of temperatures higher than 60°C under hummocks was 47 min at the soil surface, and 45 and 21 min at 1 cm and 2 cm, respectively. A similar duration pattern occurred for temperatures above 80°C. Under all fuel loads the level of heating was found to decline exponentially as depth of soil increased, with very little temperature change to soils occurring at 4 cm depth (Table 2).

Fuel type also affected soil temperature dynamics during fire. Although ANOVA indicated that temperature maxima were not significantly different among the three fuel types, a short-lived spike in soil temperature >400°C was evident soon after mulga litter was ignited (Fig. 2). The duration of soil temperatures above 60°C was significantly higher at the surface and 1 cm under burned hummocks than under mulga litter and *Aristida* tussocks (Fig. 2; Table 3). The duration of soil temperatures above 80°C was also less under both mulga litter and *Aristida* tussocks compared to *Triodia* hummocks, but only at the soil surface.

Season

Season of burn did not affect maximum temperatures experienced during *Triodia* fire in the upper soil layers, although maximum temperatures at 4 cm were significantly higher under summer than winter burns (Fig. 3; Table 4). Mean pre-fire surface soil temperatures were also significantly higher during summer than winter, being 23.4°C in winter and 39.8°C in summer. Season of burn also affected the duration of heating and the depth of heat penetration after fire. Following summer fires, the average duration of temperatures greater than 60°C was 147 min at the soil surface, and 139 and 50 min at 1 cm and 2 cm, respectively. Surface temperatures above 80°C lasted for 41 min on average. These durations were all significantly higher than those experienced at the corresponding soil depths under winter burn conditions. For both summer and winter burns, soil heating was minimal at 4 cm, with temperatures never rising higher than the 60°C threshold at this depth (Table 4).

Time of day

Burns of *Triodia* hummocks conducted during the night produced considerably less soil heating than those conducted during the day (Fig. 4; Table 5). For night burns, the mean absolute temperature maxima at all depths were significantly lower than the corresponding daytime maxima. Pre-fire soil surface temperatures were also significantly lower during night burns. There was also lower heat duration and less penetration during

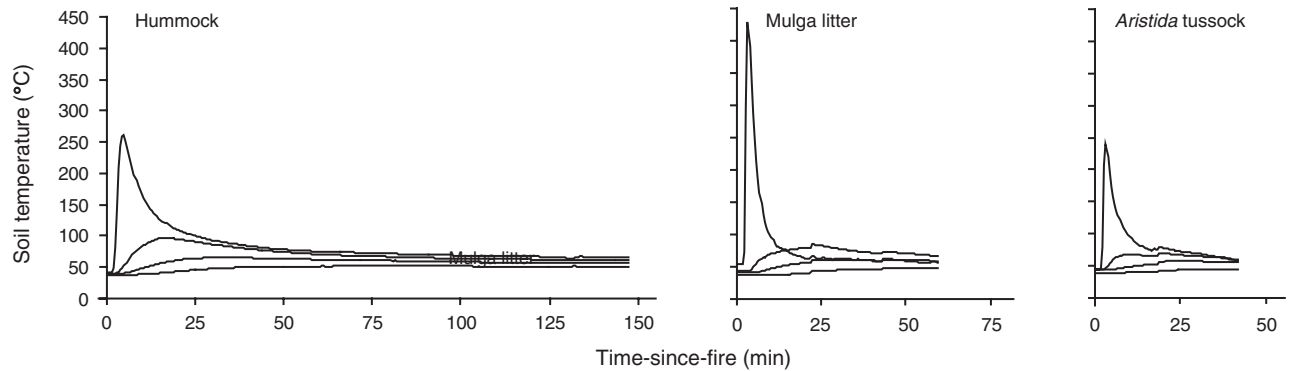


Fig. 2. Mean soil temperatures at surface, 1, 2 and 4 cm depth, from burns conducted in summer under *Triodia* hummocks, under mulga leaf litter and under *Aristida* tussocks. Thermocouple depths, in order from uppermost to lowest temperature curves, are: surface, 1, 2 and 4 cm.

Table 3. Mean soil temperatures during daytime summer burns at surface, 1, 2 and 4 cm depth under *Triodia* hummocks, mulga litter and *Aristida* tussocks

Within rows, means followed by different letters indicate significantly different temperatures and duration times under Scheffe's post-hoc tests. n.s., not significant at $P < 0.05$

	Fuel type			F-value	P-value
	<i>Triodia</i> hummock	Mulga litter	<i>A. holathera</i> tussock		
Initial surface temp. (°C)	39.8	43	44.1	0.5	n.s.
	<i>Maximum (°C)</i>				
Surface	301.8	440.3	241.3	2.3	n.s.
1 cm	99.1	82.2	67.8	3.3	n.s.
2 cm	65.7	57.5	54.1	2.3	n.s.
4 cm	52.7	43.8	45.1	2.6	n.s.
	<i>Duration >60°C (min)</i>				
Surface	147.2a	33.9b	40.6b	8	0.0062
1 cm	139.2a	58.9b	20.4b	4.2	0.0427
2 cm	49.5	19.7	7.3	1.6	n.s.
4 cm	0	0	0	–	–
	<i>Duration >80°C (min)</i>				
Surface	40.9a	13.5b	8.6b	17.1	0.0003
1 cm	21.6	9.1	1.4	1.4	n.s.
2 cm	1.3	0	0	–	–
4 cm	0	0	0	–	–

night burns, with temperatures above 60°C only lasting for an average of 17 and 11 min at the surface and 1 cm, compared with 47 and 45 min at the corresponding depths for daytime burns.

Soil moisture

Soil moisture had a strong effect on soil temperature during *Triodia* hummock fires, with high levels of soil moisture reducing the magnitude, penetration and duration of soil heating (Fig. 5; Table 6). Mean maximum temperatures were significantly lower under moist burn conditions at all depths, with the mean maximum at the soil surface reaching only 173°C. This compared to the mean maximum for dry soil which reached 302°C at the surface. The duration of soil heating was also significantly lower under moist compared to dry burn conditions, with temperatures

under moist conditions remaining above 60°C for only 6, 3 and 1 min at the surface, 1 cm and 2 cm, respectively. In contrast, temperatures above 60°C lasted for more than 2 h at the surface and 1 cm depth of dry soil. Temperatures exceeded 80°C at the surface of moist soils for only 4 min, and did not exceed this temperature at all at 1, 2 and 4 cm depth (Table 6). The corresponding durations for temperatures >80°C were 41 and 32 min at the surface and 1 cm depth of dry soil.

Discussion

Relationships between soil temperatures and properties of fire

This study showed that higher fuel loads and denser fuel types produced higher temperature maxima and more prolonged soil heating. These findings are consistent with those of previous studies on soil temperatures during fire, in both forested and grassland ecosystems (Scotter 1970; Bradstock *et al.* 1992; Schimmel and Granstrom 1996; Morgan 1999; Molina and Llinares 2001). In comparison with other grassland studies, however, soil temperatures during fire in the Haasts Bluff Reserve had higher severity (potential to impact on vegetation); soil temperature maxima were similar to other grassland fire studies, but durations of temperatures above 60°C were much longer (Cook 1939; Norton and McGarity 1965; Tothill and Shaw 1968; Scotter 1970; Morgan 1999). This result probably reflects the higher bulk densities of the hummock type fuels in *Triodia* grasslands (compared with the low bulk densities of most grassland fuels), but may also reflect longer flame residence times that occur under *Triodia* fuel-types.

Although our study indicated that absolute soil temperature maxima are unlikely to vary in different seasons of burn, the penetration and duration of soil heating were significantly less during winter compared to summer burns (Table 4). We suggest that the accelerated rate of soil heat loss under winter burns is due to the steeper temperature gradients that exist between soil–air and soil–subsoil layers in winter. These steeper gradients are the result of lower levels of incoming solar radiation during this season, which cause lower conductive heat penetration into soils, resulting in lower base-line soil temperatures. Lower levels of winter-time solar radiation would also cause decreased levels of convection and radiation to the atmosphere, resulting in lower

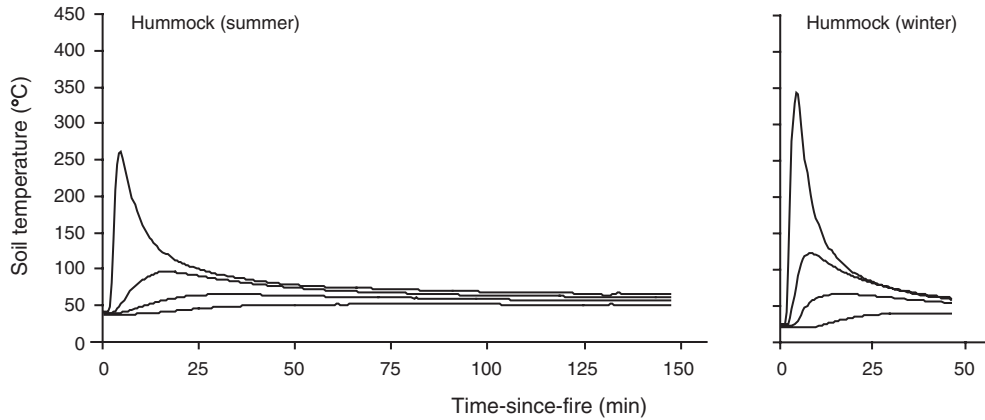


Fig. 3. Mean soil temperatures at surface, 1, 2 and 4 cm depth, from burns conducted under *Triodia* hummocks in summer and winter. Thermocouple depths, in order from uppermost to lowest temperature curves, are: surface, 1, 2 and 4 cm.

Table 4. Mean soil temperatures at surface, 1, 2 and 4 cm depth under *Triodia* hummocks during daytime summer and winter burns
n.s., not significant at $P < 0.05$

	Summer	Winter	F-value	P-value
Initial surface temp. (°C)	39.8	23.4	13	0.0069
	<i>Maximum (°C)</i>			
Surface	301.8	366.8	4.19	n.s.
1 cm	99.1	125.4	2.72	n.s.
2 cm	65.7	66.9	0.02	n.s.
4 cm	52.7	40.3	12.91	0.007
	<i>Duration >60°C (min)</i>			
Surface	147.2	47	43.8	0.0002
1 cm	139.2	45.1	41.8	0.0002
2 cm	49.5	20.9	0.75	n.s.
4 cm	0	0	–	–
	<i>Duration >80°C (min)</i>			
Surface	40.9	24.3	7.6	0.0248
1 cm	21.6	21.1	0.91	n.s.
2 cm	0.0	1.4	–	–
4 cm	0	0	–	–

base-line air temperatures (Baver 1940). Thus, any soil-heating occurring during a winter fire is likely to be lost much more rapidly to the cooler air and soil layers.

Night burns produced lower soil temperature maxima than day burns at all depths (Table 5). This probably reflected the higher humidity and fuel moisture at night, which would have resulted in slower rates of heat release from fuels than daytime conditions. Day fires produced significantly deeper levels of heat penetration and longer durations of heating than night fires. This could be explained partly by the increased levels of absorption of solar radiation during day fires, following the blackening of the soil surface by fire (Geiger 1957). Additionally, it may reflect the steeper temperature gradients that exist between the soil–air and soil–subsoil interfaces during night burns, which would result in faster rates of heat loss from the soil (Baver 1940). This hypothesis is certainly plausible, as the day/night treatments were conducted in winter when ambient air temperatures at night were

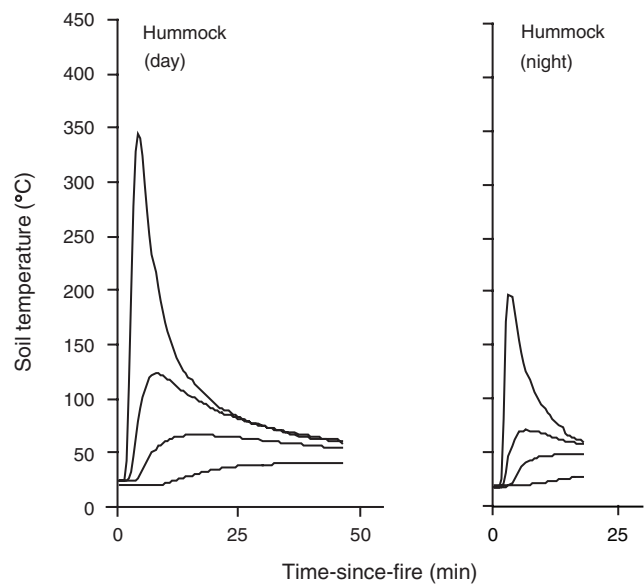


Fig. 4. Mean soil temperatures at surface, 1, 2 and 4 cm depth, from winter burns conducted under *Triodia* hummocks during day and during night. Thermocouple depths, in order from uppermost to lowest temperature curves, are: surface, 1, 2 and 4 cm.

only a few degrees above 0°C, while day temperatures were ~20°C.

The results from our soil moisture treatment were expected, as previous studies have demonstrated that soil moisture limits the penetration of heat in soils by influencing thermal conductivity and thermal diffusivity (Aston and Gill 1976; Campbell *et al.* 1995). This finding has important implications for vegetation managers who conduct burns under moist soil conditions or at times of the year when seasonal rains are likely.

Biological implications of soil heating during spinifex fire

Our study demonstrated that soil temperatures sufficient to cause damage to plant tissues (60°C or more) rarely occur at depths greater than 4 cm, regardless of whether fires are fuelled by

Table 5. Mean soil temperatures at surface, 1, 2 and 4 cm depth under *Triodia* hummocks during daytime and night winter burns
n.s., not significant at $P < 0.05$

	Day	Night	F-value	P-value
Initial surface temp. (°C)	23.4	16.2	5.64	0.045
<i>Maximum (°C)</i>				
Surface	366.8	204.8	21.4	0.0017
1 cm	125.4	72.2	20.32	0.002
2 cm	66.9	49	9.9	0.0138
4 cm	40.3	31.4	6.58	0.0334
<i>Duration >60°C (min)</i>				
Surface	47	16.8	13.81	0.0059
1 cm	45.1	10.8	23.5	0.0013
2 cm	20.9	0.8	4	n.s.
4 cm	0	0	–	–
<i>Duration >80°C (min)</i>				
Surface	24.3	9.4	18.58	0.0026
1 cm	21.1	0.1	30.1	0.0006
2 cm	1.4	0	1	n.s.
4 cm	0	0	–	–

Triodia hummocks, mulga litter or *Aristida* tussocks. Plants in spinifex ecosystems are, therefore, unlikely to experience lethal heating during fires if their regenerative organs are buried at depths greater than 4 cm. This finding may help to explain the high levels of post-fire survival of lignotuberous mallee *Eucalyptus* species, which are known to have deeply buried resprouting buds (Noble *et al.* 1980). It should be pointed out, however, that a range of other factors are also likely to be important in determining the likelihood of survival of a burned plant after fire. These factors include the interval at which plants are burned (Zedler *et al.* 1983; Vlok and Yeaton 2000), the size and age of individual plants (Hodgkinson 1998), and the level of intrinsic resilience to heating of a plant's regenerative tissue (Rundel 1981; Hartford and Fradson 1992). Factors that determine the physiological health of plants at the time of fire, such as disease, insect predation and pre-fire rainfall, are also likely to be important (Rundel 1981; Riba 1997).

For plants that possess shallow resprouting tissues, it appears that post-fire survival will be strongly driven by the pre-fire proximity of plant stems to fuels. For these species, our study suggests that plants growing in inter-hummock spaces of feathertop spinifex will be unlikely to experience lethal temperatures to belowground organs, as little heating occurs even at the soil surface under these types of burn. The actual temperature profile beneath a plant growing in an inter-hummock space will differ somewhat from the profile of the 'gap' burns conducted in our study, owing to the likelihood that the plants themselves are likely to catch fire and influence the soil temperature scenario. However, if mortality rates of plants growing in inter-hummock gaps were compared with plants growing in close proximity to large fuel loads or dense fuel types, we predict that higher levels of mortality will occur under higher loads and denser fuels.

Regardless of fuel type or fuel load, burns occurring in summer, during the day, or under dry soil conditions are far more likely to produce 'severe' soil temperatures. This finding helps to account for anecdotal reports of increased plant mortality following summer fires in central Australia (D. Nolan, Papunya Community Council; P. K. Latz, pers. comm. 2002), and for observed increases in mortality of *Acacia* shrubs following experimental summer burns in the Haasts Bluff Reserve (Wright and Clarke 2007a).

Our study also indicated that seeds insulated by less than 1 cm of soil may experience temperatures sufficient to break dormancy or cause death under most burn conditions (depending on germination and mortality thresholds for the given species). Seeds buried deeper than 2 cm, however, such as those located in underground ant or rodent seed caches, are unlikely to be affected by fire under most burn conditions. In terms of the horizontal distribution of seed in relation to fuel load and fuel type, those seeds that are distributed under higher fuel loads and denser fuel types will experience more intense heating during fire than seed under lighter or less dense fuels (for a given depth of burial). Consequently, the post-fire recruitment response of spinifex communities should be driven largely by the pre-fire proximity of seed reserves to fuels. We have shown that fires in summer, during the day, and under dry soil conditions will promote greater

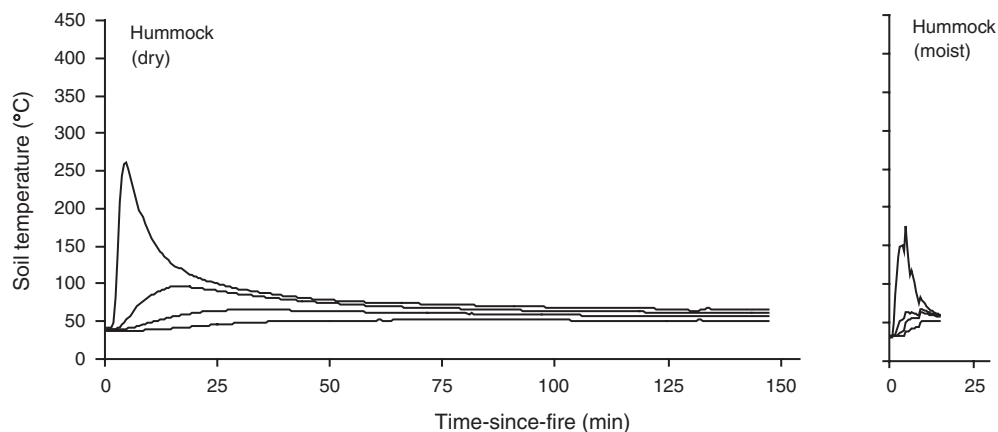


Fig. 5. Mean soil temperatures at surface, 1, 2 and 4 cm depth, from burns conducted in summer under *Triodia* hummocks in dry and moist soil. Thermocouple depths, in order from uppermost to lowest temperature curves, are: surface, 1, 2 and 4 cm.

Table 6. Mean soil temperatures at surface, 1, 2 and 4 cm depth under *Triodia* hummocks with dry and moist soil during daytime summer burns
n.s., not significant at $P < 0.05$

	Dry soil	Moist soil	F-value	P-value
Initial surface temp. (°C)	39.8	32	2.4	n.s.
	<i>Maximum (°C)</i>			
Surface	301.8	173.3	5.9	0.041
1 cm	99.1	57.6	9.6	0.0147
2 cm	65.7	46.5	8.8	0.0181
4 cm	52.7	38.2	9.1	0.0165
	<i>Duration >60°C (min)</i>			
Surface	147.2	6.3	169	<0.0001
1 cm	139.2	2.5	134	<0.0001
2 cm	49.5	1.4	6.8	0.0312
4 cm	0	0	–	–
	<i>Duration >80°C (min)</i>			
Surface	40.9	3.6	37.4	0.0003
1 cm	21.6	0	4.3	n.s.
2 cm	0	0	–	–
4 cm	0	0	–	–

penetration of heat than fires in winter, at night or under moist soil conditions. As a result, recruitment of species with seeds that require heat for dormancy release should be maximised when burns take place under these conditions that promote more heat penetration. This finding may help to explain why post-fire densities of seedling cohorts are so spatially variable in spinifex sandridge deserts (Wright and Clarke 2007b).

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