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Soil temperatures during autumn prescribed burning: implications for the germination of fire responsive species?

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Abstract

Prescribed fire is a widely applied management tool in native forests. There have been concerns raised about the ecological impacts of prescribed fire on native flora. One aspect of the debate is the extent to which prescribed fire heats the soil to levels reported to trigger germination in the soil seed banks. We used Thermochrons to test soil temperatures at 2 and 5 cm in prescribed burns in dry sclerophyll forests. Soil temperatures during the burns were generally low ($<40^{\circ}\text{C}$) with less than 5% of sites being exposed to temperatures necessary for the germination of fire-dependent shrub species. High temperatures were associated with high fuel consumption and large woody debris. This information suggests that prescribed fires, carried out according to standard practices, in these forests are unlikely to trigger germination in the majority of the soil-stored seed banks. If ecological burns in these forests are aimed at promoting populations of senescing obligate seeder species, they need to be hotter than standard practice if they are to achieve their objectives, although we acknowledge that there are inherent risks associated with hotter burns.

Keywords

fire, responsive, species, implications, burning, prescribed, autumn, during, temperatures, germination, soil

Disciplines

Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

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Soil temperatures during autumn prescribed burning: implications for the germination of fire responsive species?

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Abstract. Prescribed fire is a widely applied management tool in native forests. There have been concerns raised about the ecological impacts of prescribed fire on native flora. One aspect of the debate is the extent to which prescribed fire heats the soil to levels reported to trigger germination in the soil seed banks. We used Thermochrons to test soil temperatures at 2 and 5 cm in prescribed burns in dry sclerophyll forests. Soil temperatures during the burns were generally low (<40°C) with less than 5% of sites being exposed to temperatures necessary for the germination of fire-dependent shrub species. High temperatures were associated with high fuel consumption and large woody debris. This information suggests that prescribed fires, carried out according to standard practices, in these forests are unlikely to trigger germination in the majority of the soil-stored seed banks. If ecological burns in these forests are aimed at promoting populations of senescing obligate seeder species, they need to be hotter than standard practice if they are to achieve their objectives, although we acknowledge that there are inherent risks associated with hotter burns.

Additional keywords: dry sclerophyll, forest, management, seed dormancy.

Introduction

Prescribed burning is a common management tool used in native forests worldwide (Turner *et al.* 1994). Often, these burns are used to reduce fuels in an attempt to reduce future fire risk in order to protect assets and property. Prescribed burning also encompasses ecological burns (i.e. burns that are beneficial for some ecological communities or single species), although these are far less commonly implemented. Generally, prescribed burns are low-intensity fires that are hot enough to spread throughout the burn area and consume a significant proportion of the leaf litter, small woody debris and standing fuel without causing significant damage to the canopy (McArthur 1966; Cheney *et al.* 1992). In order to achieve this, prescribed burning is generally conducted in the cooler months when weather conditions are more conducive for fire control.

There has been considerable debate regarding the impacts of prescribed burning on native vegetation. The 'ecological consequences of high-frequency fires' has been listed under the NSW Threatened Species Conservation Act 1995 as a key threatening process for native flora and fauna (DEC 2004). There is less information on the effects of fire exclusion and the available information suggests the effects vary between systems (e.g. Lunt and Morgan 1999; Woinarski *et al.* 2004; Gent and Morgan 2007). Short fire intervals (as experienced in frequent fires) are thought to result in the decline or disappearance of some species, most commonly obligate seeding shrubs, and the increase in other species with short maturation times, e.g. grass species (Gill 1981; Bradstock *et al.* 1996; Keith 1996). If the fire interval is shorter than the time to maturation, species will not add seed to

the soil seed bank and over time, soil seed bank stores will be depleted and those species will be lost from the sites.

One aspect of the debate surrounding the impacts of frequent burning is the extent to which species recruit following a prescribed burn. Many species require heat and/or smoke cues from fires to trigger germination (Keeley 1987; Auld and O'Connell 1991; Keeley 1991; Bell *et al.* 1999). If certain temperatures are not reached, germination will not be triggered in these species and post-fire recruitment will be low or non-existent. However, the seeds of many species will usually remain in the seed bank for a period of time, even if the species disappears from the visible plant community. If a prescribed burn is classified as an ecological burn, one of the objectives might be to restore or promote populations of obligate seeders that are senescing. In this case, temperatures should be sufficient to trigger germination in a significant proportion of the seed bank or the burn will fail to achieve its objectives.

There has been limited work examining the temperatures of the soil during prescribed burns. In *Eucalyptus pauciflora* woodland, Raison *et al.* (1986) found mean temperatures of 54°C and 42°C at 2- and 5-cm depth respectively. Bradstock and Auld (1995) recorded slightly lower temperatures in low open woodland on Sydney sandstone with mean temperatures of 50 and 30°C at 2- and 5-cm depth respectively. In dry sclerophyll forests, Penman *et al.* (2006) only recorded temperatures of up to 28°C at 5 cm, although the sample size was very small. In the present paper, we tested if prescribed burns in dry sclerophyll forests were able to achieve temperatures reported to trigger germination in seeds at 2 and 5 cm below the soil surface.

Fig. 1. Location of the three burn sites used in the study.

Methods

The study examined prescribed burns that were conducted at three discrete sites within Yambulla and Timbillica State Forests in south-eastern New South Wales, Australia (Fig. 1) in April 2007. These forests are classified as south-east dry sclerophyll forests, which are dominated by *Eucalyptus sieberi*, *E. agglomerata*, *E. globoidea* and *Angophora floribunda* (Keith 2005). The understorey of these forests consists of a variety of

sclerophyllous shrubs and sparse grasses and sedges. A large number of these species, such as *Acacia longifolia*, *Euchiton gymnocephalus*, *Microleana stipoides*, *Daviesea buxifolia* and *Aotus ericoides*, are known to respond to fire-related germination cues (e.g. Auld and O'Connell 1991; Read *et al.* 2000; Hill and French 2003). Burns at Sites 1 and 2 were broad-area burns conducted for fire management practices and reflect the normal operational situation. These burns were considered to be

Table 1. Fire details for each of the three study sites

Note these values are based on coarse estimates across broad areas

	Site 1	Site 2	Site 3
Planned burn area (ha)	1100	1400	184
Fuel loads (t ha^{-1})	10–25	10–25	8–15
Burn coverage (%)	41	82	20
Fuel moisture (%)	23	15	18.5
Average flame height (m)	1	1	0.5
Average rate of spread (m min^{-1})	4	12.5	2.5
Estimated intensity (kW m^{-1})	430–1100	1300–3500	200–400

of a medium to high intensity for prescribed burns in this area (R. Clark, Fire Officer, Forests NSW, pers. comm. 2007). Site 3 is a study site established to examine the long-term impacts of frequent burning on ecological attributes of the site (operational details of the burns are presented in Table 1). Burns in this site are conducted in a standard operational manner for the purposes of the long-term research and were classed as low to medium intensity for this area (R. Clark, pers. comm. 2007). For all fires, ground crews used drip torches to ignite spot and line fires along boundary roads and internal lines where appropriate and safe.

Soil temperature was measured at 2 and 5 cm below the mineral soil surface using DS1922 L i-buttons (Maxim Integrated Products, www.maxim-ic.com, accessed March 2007). These data loggers are a cylinder measuring 17 mm in diameter and 6 mm high. Temperature is recorded every 60–90 s (depending on set-up requirements) accurate to 0.0625°C . A single i-button is able to record temperatures up to 85°C and fails at $\sim 100^{\circ}\text{C}$. Data loggers were installed by digging a small trench and inserting the i-buttons horizontally into the soil profile and returning the soil to the trench and the fuels above the trench. The depths chosen were based on several studies that have found the majority of seeds lie in the upper 5 cm of the soil (Holmes 2002; Pickup *et al.* 2003; Auld and Denham 2006). Two centimetres was chosen to represent seeds buried in the upper layers of the soil and 5 cm was chosen to represent the lower limits of the main soil seed bank. Burial at depths less than 2 cm would have caused significant disturbance to the soil profile, which could have influenced our results.

Soil temperature measurements were taken at four plots on 150-m transects running parallel to the line of ignition. Sites 1 and 2 were large broad-area burns (1100 and 1400 ha), which allowed for several transects within the fire to be established (two and three respectively), resulting in eight plots in Site 1 and 12 plots in Site 2. Within these fires, each transect was established to ensure it was affected by a fire front from separate ignitions, either by spatial separation (>200 m) or placing either side of a fire barrier such as a large creek. Site 3 comprised six discrete areas (average size 30 ha) being burnt with a single soil temperature transect established in each, resulting in 24 plots in Site 3. All burn transects at Site 3 were monitored for 4 days before the burn to measure natural daily fluctuations in soil temperatures, which were considered in the analysis as six control transects. Similarly, a seventh control transect with a further four plots was established adjacent to the burn area at Site 2 and monitored on the day of the burn.

At each of the plots, coarse measurements were taken of the fuels within a 0.5-m quadrat. Within this quadrat, an assessment was made of the cover of leaf litter, small woody debris (SWD) (i.e. <10 -cm diameter), large woody debris (LWD) (i.e. >10 -cm diameter), rocks and bare ground. In addition, an average depth of leaf litter in the quadrat was calculated. These measurements were repeated after the fire to provide an estimate of fire intensity, i.e. the proportion of fuels that had been consumed. In addition, a visual estimate was made of the proportion of the surrounding area that was burnt within a 10-m radius ($\sim 315 \text{ m}^2$).

To determine if soil temperatures were sufficient to achieve germination, we identified four trigger points from the scientific literature. We used the levels presented by Auld and O'Connell (1991) for Fabaceae, i.e. 40 , 60 , 80 and 100°C . These levels have been supported for several other Australian species (40°C – Hill and French 2003; 60°C – Portlock *et al.* 1990; Thomas *et al.* 2003; 80°C – Kenny 2000; Morris 2000; Read *et al.* 2000; Hill and French 2003; 100°C – Brown *et al.* 2003). Counts were made of the number of buttons that achieved these levels at each soil depth. We acknowledge that many species are not solely dependent on heat, but also the interaction of heat and smoke compounds (e.g. Bell 1999; Baker *et al.* 2005). In the present study, we assumed that in prescribed fires, there is sufficient smoke to trigger the smoke response as there are no data to the contrary.

We used a multimodel inference approach to determine the factors affecting the maximum temperature reached. To examine the relationships, we used generalised linear models with a gamma distribution. The response variable was simply the maximum temperature reached for each button. The factors considered in the modelling process were the depth of the button, the consumption of fuels (measured by before and after visual assessments), the proportion of the surrounding area burnt (10-m radius) and the site of the burn (i.e. 1, 2 or 3). We used Akaike's Information Criterion (AIC) to determine the best model(s) from all possible subsets of the above factors (Akaike 1973; Burnham and Anderson 2002). We also applied the principle of Occam's Razor and excluded all models that were more complex than the best model (Ellison 2004), i.e. those with more factors. All analyses were run in the R-package (R Development Core Team 2006).

Results

A total of 40 of the 44 plots expected to be burnt were directly exposed to fire, all of which were affected by head-fires. Across all fires, a mean (± 1 s.d.) of $90 \pm 29\%$ of vegetation, $77 \pm 62\%$ of leaf litter, $80 \pm 36\%$ of SWD and $100 \pm 0\%$ of LWD was consumed. Further details for each of the three areas are presented in Table 2. Maximum temperature at 2 cm ranged from 19.7°C through to in excess of 100°C with a median of 36.4°C and a mean (± 1 s.d.) of $40.3 \pm 19.1^{\circ}\text{C}$ ($n = 40$). At 5 cm, the maximum temperature ranged from 17.0°C through to 77.0°C with a median of 22.8°C and a mean of $25.0 \pm 11.7^{\circ}\text{C}$ ($n = 40$). In the seven control transects, the sensors at 2 cm had a mean daily maximum temperature of $20.0 \pm 2.6^{\circ}\text{C}$ ($n = 96$) and those at 5 cm had a mean of $18.9 \pm 2.3^{\circ}\text{C}$ ($n = 96$) (Fig. 2). The highest temperatures were achieved at sites with LWD. As a result, heating at these sites was often slower than other sites, but the soil

Table 2. Average percentage of fuels consumed during the prescribed burns

For each category, *n* represents the number of sites that had the fuel type before the burn. SWD, small woody debris; LWD, large woody debris

	Site 1	Site 2	Site 3	Total
Vegetation				
<i>n</i>	6	12	20	38
Mean	75	99.5	90	90.625
s.d.	41.833	1.8	30.779	28.092
Leaf litter				
<i>n</i>	6	12	22	40
Mean	9.167	100	83.225	77.149
s.d.	133.057	0	35.319	61.919
SWD				
<i>n</i>	5	8	22	35
Mean	75.667	80	79.545	79.095
s.d.	31.658	25.1	39.818	35.052
LWD				
<i>n</i>	0	2	4	6
Mean	NA	100	100	100
s.d.	NA	0	0	0

Fig. 2. Ranges of values for the maximum temperature reached at the burn sites and the control transects at depths of 2 and 5 cm. N.B. Plots that did not experience fire in a 10-m radius from the plot centre were excluded from the burnt sites category.

reached and remained at higher temperatures for longer periods (e.g. Fig. 3).

The majority of sensors failed to reach the lowest trigger point of 40°C (38 out of 40 at 5 cm and 23 out of 40 at 2 cm). At 5 cm, two sensors reached the 60°C trigger point, but no other buttons registered at any other trigger point. At 2 cm, nine buttons reached the 40°C trigger point, a further six buttons

Fig. 3. Examples of fast heating rates from leaf litter and vegetation surface fuels and slow heating rates for sites with woody debris. **Fig. 4.** Number of sensors with a maximum temperature exceeding the trigger points: 40, 60, 80 and 100°C. Note that counts for trigger points are not additive, i.e. sensors reaching the 60°C trigger point are not included in the counts of the 40°C trigger point.

reached the 60°C, one button reached the 80°C and one button reached the 100°C (Fig. 4). Note that counts for trigger points are not additive, i.e. sensors reaching the 60°C trigger point are not included in the counts of the 40°C trigger point.

The best model in the generalised linear models (GLM) approach indicated that the maximum temperature reached was a function of depth of the sensor, the proportion of fuels consumed

Table 3. Final model for the generalised linear model (GLM) analysis of the maximum soil temperature reached
Model used a gamma response with an identity link

Estimate	Estimate	s.e.	t-value	<i>P</i>
(Intercept)	19.8724	3.56392	5.576	0.0000
5 v. 2 cm	-2.43363	4.70717	-0.517	0.6067
Percentage plot burnt	0.24459	0.04894	4.998	0.0000
Percentage plot burnt $\times$ depth (5 v. 2 cm)	-0.15398	0.06144	-2.506	0.0143

Table 4. Comparison of competing models using Akaike information criterion (AIC)

Model description example, $T \sim \text{Depth}$ represents a model where T (maximum temperature) is a function of the depth of the sensor; Site, location of the burn; and % Plot, percentage of the plot burnt. Complexity, number of factors. Shaded models indicate those within four AIC points of the best model

Model description	Complexity	AIC	ΔAIC
$T \sim \text{Depth} + \% \text{ Plot} + \text{Depth} \times \% \text{ Plot}$	3	608.84	0
$T \sim \text{Depth} + \% \text{ Plot} + \text{Depth} \times \% \text{ Plot} + \% \text{ 10-m radius}$	4	610.77	1.93
$T \sim \text{Depth} + \% \text{ Plot} + \text{Depth} \times \% \text{ Plot} + \text{Site}$	4	611.00	2.15
$T \sim \text{Depth} + \% \text{ Plot}$	2	615.01	6.17
$T \sim \text{Depth} + \% \text{ Plot} + \% \text{ 10-m radius}$	3	616.78	7.93
$T \sim \text{Depth} + \% \text{ Plot} + \text{Site}$	3	617.59	8.75
$T \sim \text{Depth} + \% \text{ Plot} + \% \text{ 10-m radius} + \text{Site}$	4	619.05	10.20
$T \sim \text{Depth} + \text{Site}$	2	626.03	17.19
$T \sim \text{Depth} + \% \text{ 10-m radius} + \text{Site}$	3	628.03	19.19
$T \sim \text{Depth}$	1	629.44	20.60
$T \sim \text{Depth} + \% \text{ 10-m radius}$	2	631.32	22.48
$T \sim \% \text{ Plot}$	1	636.22	27.38
$T \sim \% \text{ Plot} + \% \text{ 10-m radius}$	2	637.79	28.95
$T \sim \text{Site} + \% \text{ 10-m radius}$	2	639.12	30.28
$T \sim \% \text{ Plot} + \% \text{ 10-m radius} + \text{Site}$	3	640.88	32.04
$T \sim \text{Site}$	1	650.08	41.23
$T \sim \% \text{ 10-m radius} + \text{Site}$	2	652.00	43.15
$T \sim \% \text{ 10-m radius}$	1	654.34	45.49

and an interaction of these two. Higher temperatures were reached in sensors at 2 cm when compared with 5 cm. The maximum temperature reached increased as the proportion of fuels consumed increased and this effect was more pronounced at 2 cm than at 5 cm (Table 3). All other competing models, i.e. those within four AIC points, were more complex and by the principle of Occam's Razor were excluded (Table 4). In these models, there were no significant differences between the three study sites (minimum P value = 0.32) and the maximum temperature reached was not affected by the percentage of the area within a 10-m radius that was affected by fire (minimum P value = 0.83).

Discussion

In the present study, we examined soil temperatures during prescribed burns in south-east dry sclerophyll forests. Sensors buried at 2 and 5 cm below the soil surface rarely recorded

temperatures reported to trigger germination in several fire-dependent plant species (i.e. $>60^\circ\text{C}$). Higher fuel consumption resulted in higher temperatures with the effects being reduced at greater depths as a result of the insulating properties of soils.

Soil temperatures during a fire are a function of the quantity and type of fuels consumed on the soil surface and residency time of the fire at a point in the landscape and not necessarily fire intensity (Aston and Gill 1976; Bradstock and Auld 1995). Although we used a relatively coarse measurement of fuel consumption, i.e. a pre- and post-fire visual assessment, the relationship still held in the current study. Fuels at our sites were generally leaf litter to a depth of 3 cm, with small (less than 10%) cover of vegetation and SWD and less than 5% coverage of LWD. These fuels would have resulted in a relatively short residency time of the fire. The highest temperatures for both the 2- and 5-cm sensors were achieved at sites where LWD was within the plot before the fire or fell into the plot during the fire. Residency time in these sites would have been significantly longer than sites with only a cover of leaf litter, with many logs still alight the day after the fire. Higher temperatures would be expected to be reached where greater fuel loads have accumulated, although we acknowledge that this may be associated with a higher risk of unplanned fire.

Temperatures between 80° and 100°C are considered necessary to trigger germination in many Australian plant species (Auld and O'Connell 1991; Kenny 2000; Morris 2000; Read *et al.* 2000; Hill and French 2003). In our study, only two plots at 2 cm (5%) achieved these temperatures. Although higher temperatures are almost certainly achieved more frequently at shallower depths, these are only likely to be confined to the top 0–0.5 cm (after Bradstock and Auld 1995). Tozer (1998) and Auld and Denham (2006) both report low germination rates in the upper 1 cm, which is argued to be due to either seed death during the fire or death of seedlings through desiccation. Therefore, although temperatures required for germination may be restricted to these layers, this may be offset by high mortality. Overall, the results suggest that rates of germination of such species from soil-stored seed banks and survival of seedlings in these forests is likely to be low following autumn prescribed burns.

Low-intensity fires may result in population decline for obligate seeder species that have soil-stored seed that requires heat to stimulate germination. An immediate population reduction will occur if the fire-induced mortality of standing plants is not adequately compensated by the rate of recruitment. In the longer term, repeated low-intensity burning may cause depletion of soil seed banks through attrition of dormant seed without adequate replenishment from adult plants, eventually leading to long-term population decline of such species. Species with relatively short-lived seed banks are most at risk, as those with more persistent seed banks are able to respond to infrequent higher-intensity fires (Keith 1996).

Population decline of susceptible species is based on the assumption that the burns affect the entire burn area equally. Prescribed burning in these forests is heterogeneous with average burn coverage of 40% expected (Penman *et al.* 2007). Within all of the burns in the present study, there were a range of temperatures recorded and obligate seeders with heat-dependent germination cues may persist in small patches of higher intensity. Conducting prescribed burns across broad areas would

ensure some germination of fire-responsive species. Greater consideration must be given to how this may affect population structure and competitive interactions.

The challenge for biodiversity managers is to develop a range of fire management strategies that enable sufficient germination of fire-dependent species to maintain floral diversity while ensuring the prescribed burns achieve the wildfire management objectives (Gill 2001). In developing such strategies, consideration should be given to the methods of ignition employed, seasonality of the burn and time since the last fire. Through varying these aspects, higher soil temperatures may be reached, thereby increasing the ecological value of the burning program.

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