

Resprouting responses of *Acacia* shrubs in the Western Desert of Australia – fire severity, interval and season influence survival

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Abstract. The hummock grasslands of arid Australia are fire-prone ecosystems in which the perennial woody plants mostly resprout after fire. The resprouting ability among these species is poorly understood in relation to environmental variation; consequently, little is known about the impacts that contemporary fire regimes are having on vegetation within these systems. We examined the resprouting ability of adults and juveniles of four widespread *Acacia* species (*A. aneura*, *A. kempeana*, *A. maitlandii*, *A. melleodora*) by experimentally testing the effects of fire severity, interval and season. We found that fire severity and season strongly affected survival, but the magnitude of the effects was variable among the species. Unexpectedly, a short fire interval of 2 years did not have a strong negative effect on resprouting of any species. Fire severity had variable effects among the four species, with those species with more deeply buried buds being more resilient to high-severity soil heating than those with shallow buds. Season of fire also strongly affected survival of some species, and we propose that seasonal variation in soil heating and soil moisture mediated these effects. The species by environment interactions we observed within one functional group (resprouters with a soil-stored seed bank) and in one genus suggest that modelling landscape response to fire regimes will be complex in these arid ecosystems. We predict, however, that the dominant resprouting acacias in hummock grasslands of central Australia are highly resilient to a range of fire regimes.

Introduction

Resprouting from underground organs is a common means of plant regeneration in ecosystems that are prone to periodic disturbances such as fire, drought or frost (Bellingham 2000; Bond and Midgley 2001; Bond and Midgley 2003). In frequently burnt environments, resprouting allows plants an efficient means by which to rapidly regain above-ground biomass. This confers on resprouters a competitive advantage over plants that are fire-killed and that re-establish from seed. Hence, the numbers of resprouting species are often higher than fire-killed species in frequently burnt landscapes (Bellingham 2000; Clarke and Knox 2002; Clarke *et al.* 2005b). The ability of species to resprout is not only determined by their genotype but also the disturbance regime, resource availability, abiotic conditions and age or size of individuals. Consistent with this, there is an expectation for variability in resprouting ability in relation to these factors.

Short fire intervals are known to reduce the abundance, growth and reproductive output of resprouting plants in fire-prone sclerophyllous habitats (Nieuwenhuis 1987; Morrison *et al.* 1995), but these effects are poorly known in semi-arid environments. The direct effects of fire frequency are further complicated by the severity and season of fire events and the stress imposed by aridity (Noble 1989; Allan and Southgate 2001).

Fire severity, which is a quantitative measure related to fire impact and biomass consumption, is known to strongly affect post-fire resprouting through its influence on below-ground

temperatures (Scotter 1970; Bradstock *et al.* 1992; Schimmel and Granstrom 1996; Morgan 2001). Such temperature effects are largely driven by the volume and density of surface fuels together with soil and atmospheric conditions during fire. Consequently, post-fire vegetation patterning is often influenced by the pre-fire distribution of fuels in relation to plants (Flinn and Wein 1977; Rice 1993; Odion and Davis 2000). Vegetation patterning is also determined by the sensitivity of individual species to soil heating, with some species being afforded greater insulation from soil heating than others owing to deeper burial of buds (Flinn and Wein 1977; Canadell *et al.* 1991; Odion and Davis 2000). Neither of these hypotheses has been tested in hummock grasslands, but experiments in the semi-arid rangelands of New South Wales have reported that resprouting after fire is correlated with plant size, stem number, and the severity of soil heating in relation to bud burial depth (Hodgkinson 1998; Veski *et al.* 2004).

Season of fire is also regarded as a strong determinant of resprouting success (e.g. Malanson and Traub 1988; Olson and Platt 1995; Lamont *et al.* 2000; Drewa *et al.* 2002; Bowen and Pate 2004), although relatively few studies have focussed on seasonal effects in relation to aridity in Australia (Allan and Southgate 2001). Two models explain the effects of season on resprouting ability: the ambient temperature hypothesis and the plant physiology hypothesis. The ambient temperature hypothesis states that seasonal variation in resprouting occurs because summer fires generate more intense soil heating than winter

fires, owing to higher post-fire solar radiation and flammability of fuels in summer (Grant *et al.* 1997; Williams *et al.* 2004; B. R. Wright, unpubl. data). The plant physiology hypothesis explains seasonal fire effects by relating variation in post-fire resprouting to the physiological status of species (Matlack *et al.* 1993). This hypothesis predicts that resprouting ability is driven by seasonal variation in physiological traits such as plant water status and storage levels of non-structural carbohydrates (Bowen and Pate 1993; Cruz *et al.* 2003; Lloret *et al.* 2004). One of the few arid Australian studies on fire season, in the *Triodia*/mallee lands of southern New South Wales, found that fire season and interval can influence resprouting dynamics (Noble 1989). Higher mortality rates for shrubs were recorded for those burnt at short between-fire intervals, as well as higher mortality rates for shrubs burnt at the end of the growing season.

Resprouting from underground organs is a common adaptive trait among woody plants from the hummock grasslands of central Australia. Little is known, however, about the components of fire regime that affect resprouting in these systems (Hodgkinson 1982; Allan and Southgate 2001). We examined the effect of fire regime on resprouting vegetation in hummock grasslands by manipulating the effects of fire interval, severity and fire season on survival of four *Acacia* species that commonly occur in these grasslands. Three of these *Acacias* are considered resprouters (*A. kempeana*, *A. maitlandii*, *A. melleodora*), whereas one is considered an obligate seeder (*A. aneura*). Specifically, we tested whether: (1) survival was reduced by short fire intervals, high severity fires, and summer fires; (2) adults had higher survival than juveniles; and (3) survival was related to allometric factors and the position of resprouting buds.

Methods

Study site

Our experiments were conducted in the Haasts Bluff Aboriginal Reserve, on a vegetated sandplain ~250 km west of Alice Springs in central Australia. The soils of the site are composed of silicious sand that formed during the Holocene amelioration; they are nutrient-poor, show little soil development, and have poor water-holding capacity. The overstorey vegetation of the site is composed of shrub species in the genera *Acacia*, *Grevillea*, and *Hakea* with scattered trees in the genera *Eucalyptus* and *Brachychiton*. The ground stratum is dominated by the hummock grass *Triodia schinzii*, as well as a variety of short- and long-lived forb and grass species, the composition of which is dependent on previous rain and time-since-fire (Burbidge 1943; Allan and Southgate 2001). Long-term return fire intervals in these grasslands are generally in the order of 15–20 years, with fires

normally occurring after high rainfall years that cause large volumes of fuel to accumulate. Shorter fire intervals can also occur (<3 years), when good rains occur following initial fires and lead to further accumulations of fuel (Allan and Southgate 2001).

Rainfall

The mean annual rainfall for the study area is 270 mm, and during the study period good rain fell during May 2004, but following this, there was a long dry spell that lasted until June 2005 (Table 1). Throughout the study period, the moisture levels at the soil surface remained relatively constant and ranged from 0.3 to 0.5%. Soil moisture levels at 1 m, however, fluctuated considerably during the study period, and were in synchrony with the rainfall. Following the good rains in May 2004, soil moisture at 1 m was 2.8% when it was recorded in June, but in January 2005, after 6 months of minimal rain, it had declined to only 1.5% (Table 1).

Experimental design

The effects of fire severity, interval and season on resprouting were examined via a factorial combination of treatments for each species. The effects of fire interval on resprouting were examined by comparing the post-fire response of plants burnt after two interval treatments. The first treatment was a 'long interval' treatment where 20 plants selected for burning were chosen from each species in unburned patches. These plants were randomly selected from a pool that had remained unburned for at least 20 years, with the last recorded fire occurring in the early 1980s. The second treatment was a 'short interval' treatment where 20 plants were selected that had already resprouted recently following a wildfire that took place 20–26 months before the study. As this fire had been patchy, the 'short' and 'long' interval plants were interspersed amongst each other.

Of the 20 individuals allocated to each interval treatment, 10 were burned under a 'high severity' treatment and 10 were burned under a 'low severity' treatment. Plants receiving the 'long interval' with the 'high severity' burn treatment were burned by placing a hummock of spinifex (*Triodia schinzii*), of diameter 1–1.2 m and height 0.5 m, around their base. The flames from this fuel were generally 1–2-m high and were sufficient to scorch the above-ground vegetative parts, although on some larger shrubs, the upper part of the plant had to be further scorched using a propane torch. This 'high severity' burn treatment was intended to simulate a natural fire in which the plant received scorching of its above-ground parts, as well as heating to the soil around its base.

Table 1. Summary of soil moisture and rainfall data for burning experiments involving four *Acacia* species in central Australia

	Winter 12 June 2004	Spring 14 October 2004	Summer 6 January 2005
Soil moisture (surface) (%)	0.5	0.3	0.3
Soil moisture (1 m) (%)	2.8	2.3	1.5
Previous 3 months' rainfall (mm)	147.6	15.7	30.3
Previous 6 months' rainfall (mm)	261.8	162.4	46.1

Pilot burns using thermocouples and a datalogger (Datataker 50, Data Electronics, Rowville, Victoria, Australia) were used to estimate the soil temperature profiles that could be expected under different seasons for these ‘high severity’ burns. We found that the mean maximum surface temperatures were not significantly different between summer and winter burns, being 302 and 367°C respectively. However, it was found that soil temperatures during summer burns were significantly more ‘severe’, with longer durations of heating above 60°C both at the surface (147 min as opposed to 47 min during winter) and at 2-cm depth (50 min as opposed to 21 min during winter). Temperatures greater than 60°C are damaging to plant tissues (Schimmel and Granstrom 1996), so it was predicted that plants with below-ground bud banks of less than 2-cm depth would be susceptible to heat damage from the intense burns, given that the below-ground bark thickness is less than 2 mm for all species. Plants burned with the longer fire interval at ‘low severity’ had the above-ground portion of the plant scorched using a propane torch until all leaves had browned. No heat was applied to the basal area of these plants during the burns, so this treatment simply tested for ‘top kill’ effects and stem resprouting. A thin layer of soil was also piled around the bases of these plants to further ensure that no ground heating occurred while the above-ground part was being scorched.

Plants that received the ‘short interval’ treatment with a ‘high severity’ fire were burned by placing tussocks of wire grass (*Aristida holathera*) around the base of the resprouting plant. This grass was used because ‘natural’ short interval fires that occur in spinifex grasslands are always fuelled primarily by wire-grasses (*Aristida* spp.) rather than spinifex (*Triodia* spp.). This is because wire grasses are fast-growing and are normally the only fuel available to carry fire at short times-since-fire (spinifex normally takes at least 7–10 years before it has grown enough to carry fire again). Pilot studies showed that fires from *Aristida* fuels can heat the soil surface to similar maximum temperatures to *Triodia* spp. (241°C during summer), although the ‘severity’ of the *Aristida* burns were much less, with soil temperatures at 2 cm only remaining above 60°C for periods of up to 7 min, depending on season. Those plants receiving the ‘short fire interval’ treatment but ‘low severity’ fire were burned using a propane torch and no heat was applied to the basal area.

Twenty juveniles from each species were also selected to test the effects of variation in fire severity on juvenile resprouting ability. Juveniles were selected on the basis that they were less than 20 cm in height and were likely to have recruited after the 2002 fire (*Acacia* spp. seeds are normally heat cued and seedlings are generally only abundant after fire). Juvenile plants burned

with the ‘high severity’ treatment were burned using wiregrass fuels (*Aristida holathera*) placed around the plant. Using this fuel mimics nature, as recently recruited juveniles will generally only ever be burned in the event of ‘short interval’ follow-up fires, which are fuelled predominantly by *A. holathera*. Juvenile plants burnt with the ‘low severity’ treatment were burned using a propane torch until all leaves were scorched.

For both the adult and the juvenile experiments, burn treatments were applied in three seasons: (1) winter conditions between July and August 2004; (2) spring conditions between September and October 2004; and (3) summer conditions between December 2004 and January 2005. It is acknowledged that this seasonal comparison lacked replication of season; hence, the results from the analyses have been interpreted cautiously.

Prior to the application of the treatments, the height, stem number, basal diameter and canopy diameter were recorded for each plant. A soil-moisture reading was also made in each season of burn using gravimetric methods on soils taken from the study site. Mortality, number of resprouting stems, and the depth of resprouts were recorded 6 months following the burn treatments. A final check of the plants was also made in December 2005 to examine plants that had resprouted and died, or that were recorded as dead but had been in a dormant state.

Statistical analyses

The effects of fire severity, season and interval on adult plant mortality were analysed using three-factor general linear models (GLM) using a binomial error structure and a log link function with orthogonal combinations of treatments. The significance of these models was tested using Pearson’s correlation coefficients. We also used the continuous variables of plant height, girth and stem numbers as factors in logistic regressions for each species. The effects of fire severity and season on juvenile mortality were analysed using GLM using a binomial error structure with a log link function with orthogonal combinations of treatments. The depths of resprouts were compared between species, seasons and intervals using GLM with a normal error structure and an identity link function. Plots of residuals for all analyses were examined initially to detect any non-linear trends. All statistical procedures follow those recommended by Quinn and Keough (2002).

Results

Fire severity, season and interval

The ‘high severity’ burn treatment resulted in cambial death in basal stems in all instances, causing plants to resprout from

Table 2. Configuration of treatments for burn treatments of four *Acacia* species. Number of replicates for each species (in bold) and proportion of plants (in brackets) that resprouted from above-ground buds v. total number of surviving plants

Fire severity	High						Low					
	Long			Short			Long			Short		
Fire interval	Winter	Spring	Summer	Winter	Spring	Summer	Winter	Spring	Summer	Winter	Spring	Summer
<i>A. aneura</i>	10 (0/1)	10 (0/0)	10 (0/3)	10 (0/2)	10 (0/4)	10 (0/3)	10 (0/0)	10 (2/5)	10 (7/7)	10 (0/6)	10 (0/7)	10 (0/9)
<i>A. kempeana</i>	10 (0/5)	10 (0/3)	10 (0/6)	10 (0/1)	10 (0/2)	10 (0/4)	10 (1/4)	10 (2/5)	10 (7/10)	10 (0/8)	10 (0/5)	10 (0/6)
<i>A. maitlandii</i>	10 (0/9)	10 (0/1)	10 (0/5)	10 (0/9)	10 (0/3)	10 (0/1)	10 (4/10)	10 (1/1)	10 (0/7)	10 (0/10)	10 (0/10)	10 (0/9)
<i>A. melleodora</i>	10 (0/0)	10 (0/0)	10 (0/0)	10 (0/4)	10 (0/0)	10 (0/0)	10 (7/7)	10 (2/6)	10 (0/2)	10 (0/5)	10 (0/0)	10 (0/7)

Table 3. Summary of results of the proportion of adult species surviving from three factor generalised linear models (GLM)

Species (Sp)	Sequential GLM						Season % survival			Interval % survival		Severity % survival		
	Season (S)	Interval (I)	Severity (Sv)	S × I	S × Sv	I × Sv	Winter	Spring	Summer	Long	Short	High	Low	
<i>A. aneura</i>	*	**	*	ns	ns	ns	22	40	55	27	52	22	57	
<i>A. kempeana</i>	*	ns	**	ns	ns	ns	45	37	65	–	–	35	63	
<i>A. maitlandii</i>	***	ns	***	*	ns	*	95	37	55	–	–	47	78	
							Long	95	10	60	–	–	50	60
							Short	95	65	50	–	–	43	97
<i>A. melleodora</i>	**	ns	***	***	*	**	40	15	22.5	–	–	7	45	
							High	20	0	0	–	–	–	
							Low	60	30	45	–	–	–	
							Long	35	30	10	–	–	0	50
							Short	45	0	35	–	–	13	40

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns: not significant.

underground organs in order to survive (Table 2). Overall, the 'high severity' treatment had a consistently negative influence on survival across all species and it had some significant first order interactions with 'season' and 'interval' for *A. maitlandii* and *A. melleodora* (Table 3). Under the 'long interval' by 'high severity' treatment, *A. melleodora* showed the weakest ability to resprout basally (100% mortality), whereas *A. kempeana* and *A. maitlandii* both demonstrated relatively strong resprouting ability, with 47 and 50% survival from basal resprouts respectively (Table 2).

The 'low severity' burns did not cause cambial death in all cases, and shrubs frequently resprouted from above-ground stems (Table 2). Under the 'low severity' by 'long interval' treatment, *A. kempeana*, *A. maitlandii* and *A. melleodora* all showed relatively strong ability to resprout from above-ground stems, with 76, 60 and 50% above-ground resprouting respectively (Table 2). Under the 'low severity' by 'short interval' treatment, *A. maitlandii* showed the strongest resprouting ability (97%) whereas *A. melleodora* showed the lowest (40%).

Fire season had a variable effect on adult survival rates among the different species, and there were some significant first order interactions with 'severity' and 'interval' (Table 3). In two species (*A. melleodora*, *A. maitlandii*), survival was lower after summer and spring burns, although for *A. melleodora* there was a strong interaction with severity, with almost no survival under any season for 'high severity' burns, but with higher survival under spring and summer burns for the 'low severity' burns. Post-fire survival was highest under summer burns for *A. aneura* and *A. kempeana*, and there were no significant interactions between season and the other fire treatments for either of these species (Table 3).

Unexpectedly, a short fire interval did not decrease the survival of any species (Tables 2 and 3). This could occur because individuals chosen for the short interval treatment had already resprouted following the 2002 fire and consequently had been selected for fire resistance. Whether plants were stronger resprouters because they had previously been burnt was difficult to test. One species (*A. aneura*) appeared to have higher survival under the 'short interval' treatment. The logistic regressions revealed that plant height, stem number and basal area did not significantly influence the post-fire survival of any *Acacia* species.

Table 4. Summary of results of the proportion of juveniles surviving in four species of *Acacia* for three factor generalised linear models (GLM)

Probability significances under sequential GLM are as follows: Season (S), $P < 0.001$; Severity (Sv), $P < 0.001$; S × Sp, $P < 0.001$; Sv × Sp, $P < 0.05$; Sv × S, $P < 0.001$

	Season % survival			Severity % survival	
	Winter	Spring	Summer	High	Low
<i>A. aneura</i>	16	27	4	4	27
<i>A. kempeana</i>	5	35	0	0	27
<i>A. maitlandii</i>	5	25	0	0	20
<i>A. maitlandii</i>	5	0	0	0	3
<i>A. melleodora</i>	50	50	15	17	60

Juvenile survival was lower than adult survival and overall resilience to fire varied among species. However, resilience did not correspond with adult survival, but rather they were inversely correlated (Pearson's $r = -0.93$). Across all treatments, the mean survival of juveniles ranged from 38% (*A. melleodora*) to 2% (*A. maitlandii*) and there were strong interactive effects of season and severity on survival patterns (Table 4). All juvenile species had no or lower survival after the summer burn (Table 4). Higher fire severity reduced survival to zero in all species except *A. melleodora*, which only showed reduced survival.

Resprouting buds

Across all species, there was a significant positive relationship between survival and depth of resprouting buds in plants burnt under the 'long interval' treatment (adjusted $R^2 = 0.87$, $P < 0.1$), but this relationship was less strong for the full adult dataset (adjusted $R^2 = 0.37$, $P > 0.1$). *A. maitlandii* displayed the deepest resprouting response, with resprouts arising from a mean depth of 4.25 cm. Buds of this species are located on a single, robust taproot and are arranged in a collar ~4–5 cm below the soil surface. Two species (*A. aneura* and *A. kempeana*) also had relatively deep resprouting buds, with emergence depths of 3.25 and 3.41 cm respectively (Fig. 1). The buds of these two species occur on laterally branching roots, as well as around the central trunk. The depth to resprouting buds varied among species and fire intervals in a complex way as there was a significant first order interaction among the species and fire interval

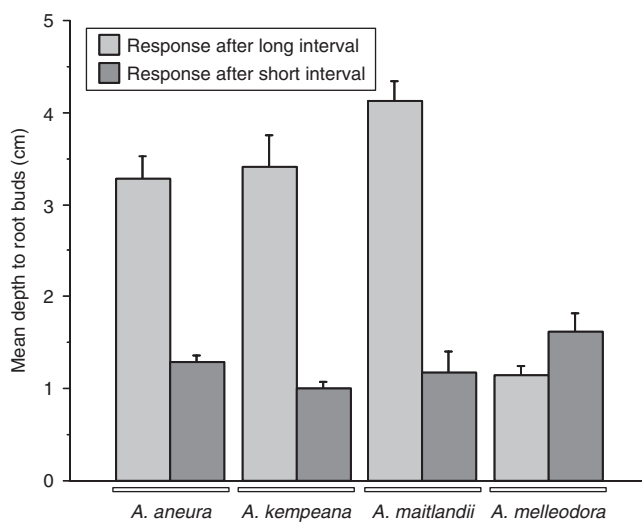


Fig. 1. Mean (s.e.) depth to root buds produced after fire for each species of *Acacia* after a 'long interval' fire and after a 'short interval' fire. The shallower resprouting response after repeated fire arose because secondary buds were developed from the primary resprouts.

($F = 28.6$, $P < 0.0001$). Under the 'long interval' treatment, *A. aneura*, *A. kempeana* and *A. melleodora* shrubs produced buds from deeper depths than shrubs burnt under a 'short interval' (Fig. 1).

Discussion

We found that the severity of fire strongly influenced post-fire survival of shrubs commonly found in fire-prone hummock grasslands of central Australia. This finding is consistent with other post-fire studies in Mediterranean ecosystems, which found that the depth of resprouting buds in relation to heat penetration in soil was a crucial factor in determining post-fire recovery of plants (Canadell *et al.* 1991; Moreno and Oechel 1991; Odion and Davis 2000). We observed a similar relationship in spinifex grassland shrubs, where species with relatively deep resprouts had higher survival than species with more shallowly buried buds. Given that pre-fire fuel loads strongly influence heat penetration into soils, our findings indicate that the landscape responses of certain *Acacia* species to fire are contingent on the pre-fire distribution of fuels in relation to plants. Basal area and stem number are, however, not good predictors of adult survival, unlike a broader analysis of growth forms in other parts of semi-arid Australia (Vesk *et al.* 2004).

Juveniles of all species had high mortality after more severe fires reflecting their shallow and less well developed root buds and possibly lack of carbohydrate storage products. Unexpectedly, total juvenile survival was inversely correlated with adult survival among the four species. This might reflect an evolutionary trade-off in recruitment and persistence if there were greater numbers of seeds and seedlings produced by adults that are more susceptible to mortality.

Mortality of adults and juveniles at landscape scales not only relates to the amount and continuity of fuel but to season of fire because soil heating is elevated after summer fires and the

physiological status of species changes. Previous studies have demonstrated that carbohydrate reserves of shrubs can diminish considerably during growing seasons (Malanson and Trabaud 1988; Drewa *et al.* 2002; Cruz *et al.* 2003). It is therefore possible that species that have buds deep enough to 'escape' the heating effect of summer fires (*A. maitlandii*) are still susceptible because plants have not retained sufficient carbohydrate reserves during summer to recover after fire. It is also possible that the higher spring and summer mortality observed for *A. maitlandii* and *A. melleodora* was driven by the exceptionally low rainfall that preceded the spring and summer burns. This lack of soil moisture would cause significant additional stress to the spring- and summer-burned plants, and previous studies have demonstrated that plants with lower water status have lower resprouting capability (Lloret *et al.* 2004). Variation in other environmental factors such as nutrient availability is also known to influence resprouting ability (Rice 1993; Cruz *et al.* 2002; Knox and Clarke 2005) and this may explain the highly variable seasonal effect on mortality across species.

Two species (*A. kempeana* and *A. aneura*) were not as strongly affected by season of fire, possibly because their bud banks are relatively deep and perhaps experience sufficient insulation, even against the more penetrating heat imposed by summer fires. Both species are also relatively large and long-lived, with much more extensive root systems that would allow greater access to soil moisture during the summer burns, thereby reducing the stress to plants at the time of burn. Given the more extensive root systems of these two species, it is also likely that they would possess larger stores of below-ground carbohydrates from which to recover. We find it difficult to explain how survival of *A. aneura* shrubs could actually increase under summer burns, although the low replication of the seasonal component of the present study warrants caution in interpreting these results.

Paradoxically, the most widely recognised 'fire sensitive' species (mulga, *A. aneura*) showed some resprouting ability of adult plants (total survival 39%) and also had high survival after a short fire interval. Despite this high survival, our analyses of plant traits failed to link survival in this species with any morphological characteristics. Consequently the factors that drive the sporadic basal resprouting of mulga after 'natural' fires remain unknown. It is possible basal resprouting in mulga is the result of genetic variation among plants, with most individuals simply not possessing the required below-ground anatomical structures necessary to resprout. Such infraspecific variation in fire response has been shown in populations of *Erica* (Verdaguer and Ojeda 2005), but why such resprouting genotypes of mulga are unable to become numerically dominant in these fire-prone landscapes remains unresolved.

We suggest that the three resprouting species (*A. kempeana*, *A. maitlandii*, and *A. melleodora*) possess substantial quantities of stored buds and carbohydrate reserves that allow them to repeatedly resprout. In part, their repeated resprouting response is related to the lack of high severity (*Triodia*) fuel accumulation after short fire intervals (<3 years); hence, repeat fires (fuelled by *Aristida*) are likely to produce less soil heating. If this holds, then it is likely that populations of these dominant acacias in hummock grasslands are largely resistant to a range of fire regimes provided juveniles have sufficient time to become fire resistant. This is consistent with our field observations after

the 2000–2002 fire events, where we found 95% of all woody resprouting plants survived short interval fires.

We also observed complex synergistic effects of fire severity, fire interval and species morphology for resprouting species. In three of the shrub species that had been burned under a ‘short interval’, depth of resprout production was lower compared with plants burned under a ‘long interval’ (Fig. 1). These shallower root buds are a product of lateral shoots, induced by the previous fire, giving rise to secondary bud growth. Whether these buds are susceptible to further repeated fires remains to be tested. Generally, however, we rejected the idea that short fire intervals in hummock grasslands are likely to cause major declines in dominant acacias.

Overall, our study indicated that fires in spinifex grasslands are unlikely to cause rapid, landscape-level shifts in composition of the examined *Acacia* species. However, some combinations of interval, season and severity could result in landscape declines of certain species, especially where invasive grasses are present (see Clarke *et al.* 2005a). These circumstances would arise in periods of extreme weather fluctuations where monsoon rains, which promote intense repeated summer fires, are followed by prolonged drought. Persistence in these landscapes will, therefore, be highly dependent on the nature of seed bank dynamics, about which little is known. Finally, the strong interaction between species and environment we have observed within one functional group (resprouters with a soil-stored seed bank), and in one lineage, suggests that modelling landscape responses to fire regimes will be complex in these arid ecosystems.

Acknowledgements

The present study was funded by an Australian Postgraduate Award scholarship to BRW. We thank Grant Allan, Kirsten Knox, Catherine Nano and Fernando Ojeda for their comments on the draft manuscript. Appreciation is extended to Scott and Kathy McConnell and the Haasts Bluff community for their support, and to the traditional owners of the lands where we did our experiments. The Northern Territory Central Lands Council is also thanked for their assistance in conducting research on Aboriginal Freehold Land.

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Manuscript received 14 July 2006, accepted 27 October 2006