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A review of prescription burning in rehabilitated bauxite mines in Western Australia

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SUMMARY

Alcoa of Australia has been rehabilitating after bauxite mining in the jarrah forest for 30 years. In the last 20 years these mined areas have been seeded with understorey legumes to prevent erosion. These legume species grow rapidly and assist in returning the nutrient status through nitrogen-fixation. They are, however, short-lived and senescence has led to large accumulations of fuel in 10- to 20-year-old sites (16-62 t ha^{-1}). These fuel loads can be reduced through burning.

This paper summarizes research conducted on prescription burning in these rehabilitated areas. The vegetation structure and fuel loadings of rehabilitated areas are different from those of the native jarrah forest. Fuel loads are higher in rehabilitated areas and have a relatively high proportion (45 per cent) of trash fuel which assists in carrying fire into the crown regardless of fuel moisture conditions. Reaccumulation of fuel following burning in rehabilitated areas is rapid. Vegetation structure appears to be more important than fuel loadings in determining when rehabilitation sites should be burnt. A low proportion of live to dead plant material below 2 m in height would indicate the potential for prescription burning of a rehabilitation site.

Prescription burning of rehabilitated areas has been carried out successfully in both autumn and spring. Spring burns of moderate intensity appear to be the best prescription to maximize native plant establishment and minimize deleterious effects of burning such as the establishment of high densities of non-native eucalypts. Damage to the overstorey in rehabilitated areas was lower after spring than autumn burns.

Seeding of post-burn sites with jarrah and an understorey mix will lead to increased species richness and the potential for establishing jarrah as the overstorey dominant.

Further research is required on the burning of younger rehabilitation sites and the effect of prescription burning on the fauna and soils of these areas. Prescription burning of rehabilitation sites has the potential to reduce fuel loads as well as increasing the establishment of native species in these areas.

INTRODUCTION

Alcoa of Australia Limited has been rehabilitating mined sites in the jarrah forest since 1966, following the commencement of bauxite mining in 1963. Early rehabilitation sites were planted with pines (e.g. *Pinus pinaster*) or non-native eucalypt species with no understorey seeding. The fuel loads in these areas are generally low and are composed of two layers (litter layer and overstorey). Prescription burns have been carried out in these areas (Appendix 1) but these are not within the scope of this review.

Sites rehabilitated since 1976 have generally been seeded with an understorey mix containing a high proportion of native legume species. As many of these species are short-lived (10 to 15 years) older rehabilitation sites of this style have accumulated substantial fuel loads which are a potential fire hazard. These areas tend to have a fuel structure with three distinct layers: the litter, standing dead and live vegetation, and overstorey. This contrasts with much of the native jarrah (*Eucalyptus marginata*) forest which generally has only two distinct layers of available fuel (litter and overstorey). Sites rehabilitated since 1988 contain exclusively native overstorey species (e.g. *E. marginata* and *E. calophylla*). However, the majority of sites rehabilitated prior to 1988 contain either a mixture of native and non-native overstorey species or contain exclusively non-native species as the overstorey dominants (e.g. *E. resinifera*, *E. maculata* and *E. saligna*). Eastern Australian eucalypts were used owing to the known susceptibility of jarrah to dieback (*Phytophthora cinnamomi*) in the native forest. Subsequent research showed that jarrah stands established in rehabilitated bauxite mines would not be severely impacted by the dieback fungus (Colquhoun 1992).

This review concentrates on fire management of those sites rehabilitated between 1976 and 1988 that contain a legume understorey and a non-native *Eucalyptus*-dominated overstorey. Fire management of post-1988 rehabilitation is currently not necessary as these sites have not accumulated substantial fuel loads of senesced *Acacia* species, although burning in these areas will need to be investigated in the future. It is likely that many of the principles and procedures that apply to the burning of 1976 to 1988 rehabilitation areas will also apply to post-1988 rehabilitation areas.

The current policy of the Department of Conservation and Land Management (CALM) is to exclude fire from rehabilitation areas and burn the surrounding forest areas which act as fuel-reduced buffer zones. Recent research has involved investigating the possibility of burning rehabilitation sites to reduce fuel loads so that these areas are similar in structure and composition to the surrounding forest. The objective of this review is to provide a summary of the accumulated knowledge on prescription burning in rehabilitated areas. The majority of the material presented in this paper has not been previously published. The information has been collected from 14 recorded burns in rehabilitated areas (Appendix 1). This paper examines fuel characteristics of old rehabilitation and then discusses fire behaviour and important factors that may affect fire behaviour in these areas. The response of the rehabilitated vegetation to burning is then investigated, followed by a discussion of site manipulations which may accompany prescription burns. The response of fauna to burning and the effect of fires on soils in rehabilitated areas are also briefly discussed.

Associated with this review is a practitioners guide to burning rehabilitation that outlines the information that should be collected before, during and after burns in rehabilitation (Appendix 2). This guide was formulated based on the findings reported in this paper to ensure that information collected on burning rehabilitation is standardized and can therefore be directly compared. This will increase the information base about fire response in rehabilitated areas.

All fuel loads described in this review exclude the tree overstorey.

FUEL CHARACTERISTICS

Vegetation Structure

Vegetation structure and associated fuel loadings of rehabilitated areas differ from those of the native jarrah forest. While the rehabilitation has three distinct fuel layers (litter, standing vegetation, and overstorey), the native upland forest generally has only two (litter and overstorey). Vegetation structure in the rehabilitated areas and in the native forest was estimated using the point-contact method (Levy and Madden 1933). A pole was divided into 30 cm intervals and the number of contacts of live and dead vegetation up to 3.9 m were recorded in each interval at 28 points in five replicate plots for each burn in rehabilitation and ten replicate plots in the native forest (each plot 20 x 20 m).

While the native forest is dominated by live plant material, 11- to 13-year-old rehabilitation is dominated by dead plant material (Fig. 1a, 1b). The proportion of live to dead plant material is low in the rehabilitation below 1.2 m in height, whereas in the native forest this proportion tends to be high. Dead plant material carries less water than live plant material and therefore tends to be more flammable (Sneeuwjagt and Peet 1985). Another feature of the rehabilitated vegetation structure is the development of a prominent mid-storey layer composed of senescing *Acacia* material. This has important implications in terms of fire management as this dead material assists in carrying fire into the crown under mild burning conditions. The lack of live plant material in the understorey of some of the rehabilitated areas indicates that these systems are in need of a further disturbance, such as a fire, to stimulate regeneration.

The vegetation structure and available fuel loads of rehabilitated areas do not fit any of the standard scrub structural types currently recognized by CALM (Sneeuwjagt and Peet 1985). Instead they represent a unique vegetation structure and therefore require a different fire management strategy. A comprehensive study on the fuel characteristics of 4- to 20-year-old rehabilitation has been carried out by Collins (1996). The results of this study will assist in determining at what age rehabilitated areas can be safely burnt for the first time. Examination of the rehabilitation structure one year after burning (Fig. 1c) showed that burning was successful in decreasing the amount of dead material in these areas as well as stimulating the germination of native species that have the potential to re-establish live vegetation cover.

All burns carried out to date have been in rehabilitated pits that are 8 to 17 years old (Appendix 1). Vegetation structure, the proportion of live to dead plant material and the strategic importance for fire control in rehabilitated areas were the most important factors determining whether a site should be burnt.

Fuel Loads

Fuel loads in rehabilitated areas (excluding the tree overstorey) have been estimated by collecting all fuel (litter, standing dead <25 mm, and live vegetation <4 mm) present in a 1 x 1 m quadrat. Estimates indicate that in 10- to 15-year-old rehabilitation that has been seeded with an understorey, fuel loads are extremely high (range 16 to 62 t ha^{-1}, see Appendix 1). These fuel loads are two to eight times greater than the level recommended for burning under normal prescribed conditions in the jarrah forest (Burrows 1994). Fuel loads in rehabilitated areas either need to be reduced through prescription burning and/or the surrounding forest needs to be burnt regularly to buffer these areas in case of a wildfire.

Fuel loads in rehabilitated areas are heterogenous in their distribution (Table 1). Within a single pit (~10 ha), fuel loads may range from almost zero to over 60 t ha^{-1} in

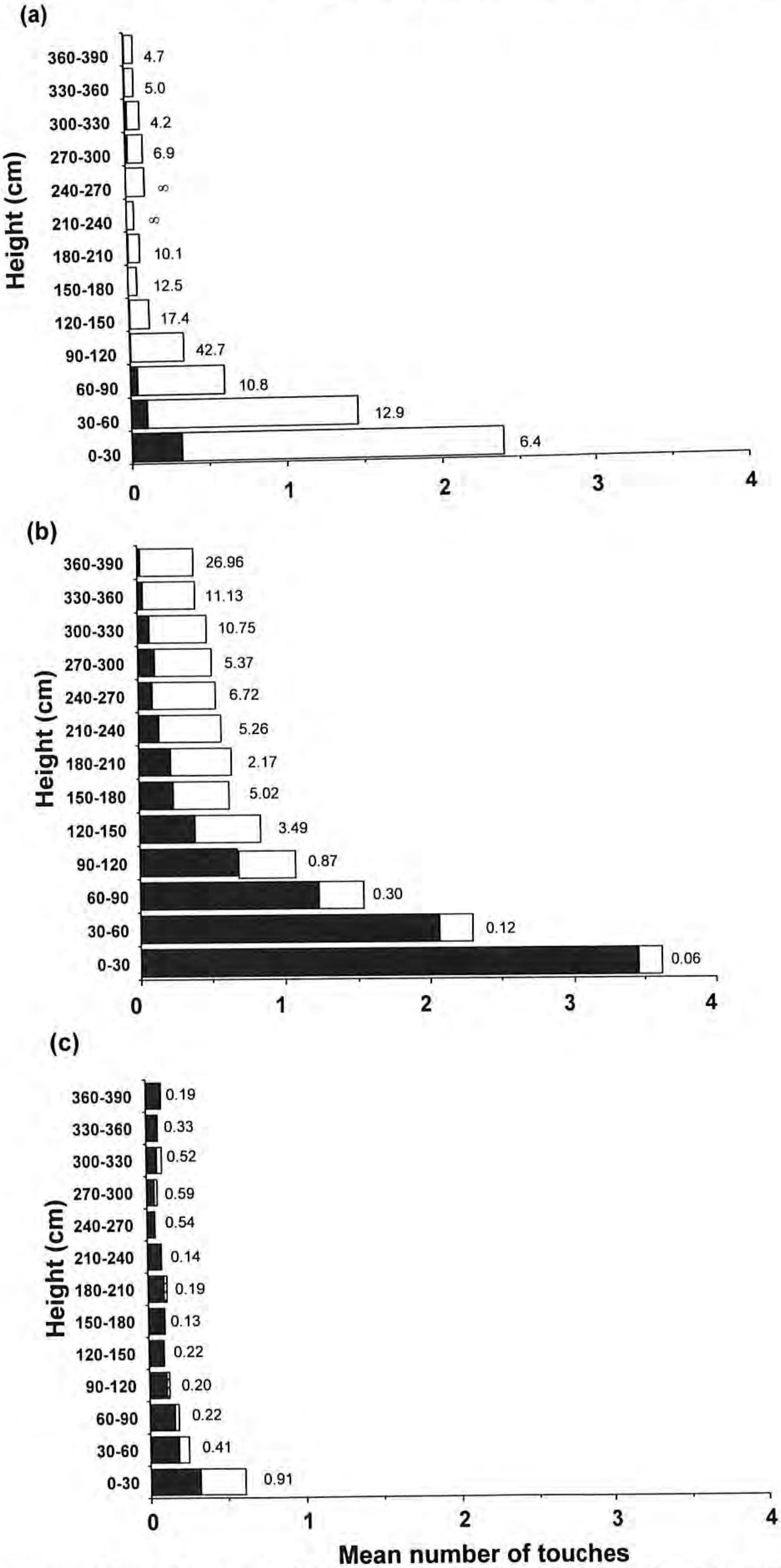

Figure 1. Vegetation structure estimated using the levy pole method for (a) the native jarrah forest, (b) 11 to 13 year-old unburnt rehabilitation sites and (c) rehabilitation sites one year after a prescribed burn. Solid bars represent dead plant material and open hatched bars represent alive plant material. Numbers on bars are proportions of live to dead plant material.

TABLE 1

Selected variables for six prescription burns carried out in 1994/95.

YEAR OF REHABILITATION	1981	1982	1981	1982	1983	1981
SEASON	AUTUMN	AUTUMN	SPRING	SPRING	SPRING	SPRING
DATE OF BURN	18/05/94	17/05/94	19/09/94	10/11/94	7/10/94	6/11/95
SITE	Jarrahdale	Jarrahdale	Jarrahdale	Jarrahdale	Jarrahdale	Huntly
PRE-BURN FUEL LOAD (t ha^{-1}) : Range	23.5-49.3	15.4-36.8	6.3-46.1	18.2-35.4	19.6-32.5	12.2-39.5
: Mean	34.7	28.5	23.4	26.1	25.1	27.35
POST-BURN FUEL LOAD 1 YEAR (t ha^{-1})	6.4	9.5	7.9	7.5	8.0	NA
LITTER DEPTH (cm)	3.21	2.65	2.17	2.07	2.61	3.94
SOIL MOISTURE (%): 0-5 cm	NA	NA	13.3	6.2	17.3	10.4
: 5-10 cm	NA	NA	10.6	5.6	12.8	11.2
LITTER MOISTURE (%): 0-5 cm	NA	NA	16.28	15.63	18.03	8.66
: Whole	NA	NA	19.17	15.95	70.58	22.5
LITTER REMAINING (%)	12.9	9.9	46.5	24.7	53.2	NA
FLAME HEIGHT (m)	2.0-20.0	10.0-20.0	NA	NA	NA	0.5-10
FIRE INTENSITY (kW m^{-1})[a] : Range	3050-20300	270-14700	720-2080	1044-1566	188-1255	320-3950
: Mean	8070	5734	1312	1248	376	1820
WIND SPEED (km h^{-1})	0.0-30.0	0.0-5.0	20.0-38.0	0.0-6.0	8.0-30.0	2.0-10.0
SOIL DRYNESS INDEX	1962	1960	442	1119	506	
TEMPERATURE AT LIGHTING (°C)	21	18	16	17	16	24
RELATIVE HUMIDITY AT LIGHTING (%)	45	53	35	58	38	
TIME OF LIGHTING	4 pm	4 pm	2 pm	8 am	2 pm	4 pm
RATE OF SPREAD (m h^{-1})	200-900	35-800	60-200	80-120	15-100	24-200

[a] Fire intensity is based on fuel load, rate of spread and energy release from the burning of material (Byram 1959).
NA = Not Available.

a very small area. Collins (1996) also found fuel loads in rehabilitated bauxite mines were large and highly variable. In one 15-year-old pit, for example, the fuels ranged from 20 to 120 t ha^{-1}. Ground litter fuel is not always continuous in these areas as fuel tends to accumulate in the bottoms of riplines. This results in some areas not being burnt. These unburnt areas are valuable in terms of recruitment of flora and fauna.

In areas where an understorey has been seeded, a large proportion of the available fuel load is present as standing trash. In fact, this layer constitutes on average 45 per cent of the total fuel load (n = 50, range 0 - 90.5 per cent). By contrast, the majority of the native jarrah forest fuel load is leaf and twig material lying on the ground (Burrows1994). The prominent trash layer in rehabilitated sites has the potential to carry a fire into the crown regardless of the moisture conditions present in the litter layer.

Collecting entire fuel loads over areas of 1 m^2 in order to establish relationships between litter weight (t ha^{-1}) and depth (mm) is extremely time consuming. Such relationships have been established in other forest systems (Sneeuwjagt and Peet 1985). This was first attempted for rehabilitated areas by Smith (1990) in an area that had not been seeded with a legume understorey and contained non-native overstorey species such as *E. globulus* and *E. microcorys* (Fig. 2).

For rehabilitation that has been seeded with a dense legume understorey and has a mixed canopy species composition, a relationship has been established between litter depth and litter weight:

Litter weight (t ha^{-1}) = 4.143 + 0.399 (litter depth mm)
(r^2=0.27, F=8.7, p=0.01)

The litter fuels in these areas consist of eucalypt leaf and twig material as well as *Acacia* leaf, twig and fruit material. Comparison of litter depth to weight relationships in karri, jarrah and wandoo fuel areas (Fig. 2) show that the fuel composition of these rehabilitated areas has led to a different relationship between litter depth and weight. Rehabilitated areas tend to have higher fuel loads at shallow litter depths but fuel loads comparable to karri or jarrah in areas with a deeper litter profile.

Collins (1996) found strong relationships between easily measured fuel characteristics and total fuel weights (Fig. 3). This is important because it allows fuel loads to be measured quickly and easily without the need for intensive sampling, drying and weighing procedures. In rehabilitation that was 13 years old or more the total fuel load was best predicted by the equation:

Total fuel (t ha^{-1}) = 1.07 (litter depth) + 8.83
r^2 = 0.81

where litter depth is measured in millimetres.
Where the areas were less than 13 years old the best predictor was;

Total fuel (t ha^{-1}) = 2.09 (age) + 0.56 (litter depth) - 0.60
r^2 = 0.92

where age is years since rehabilitation and litter depth is measured in millimetres.

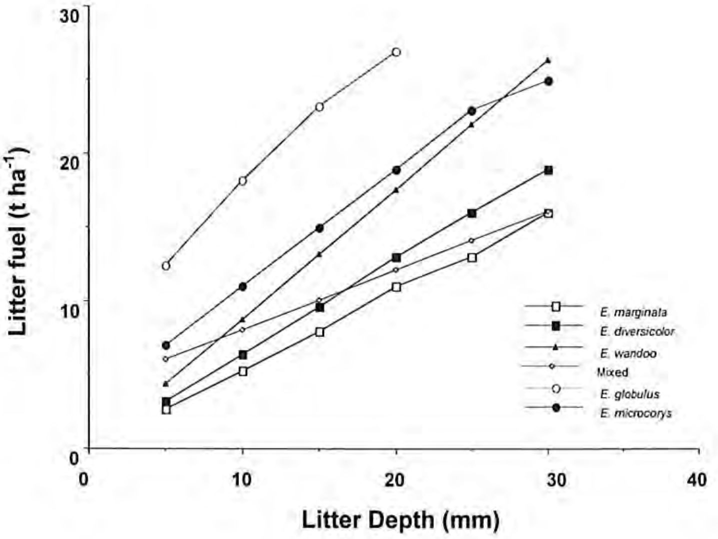

Figure 2. Litter fuel loads associated with litter fuel depths across a range of overstorey components.

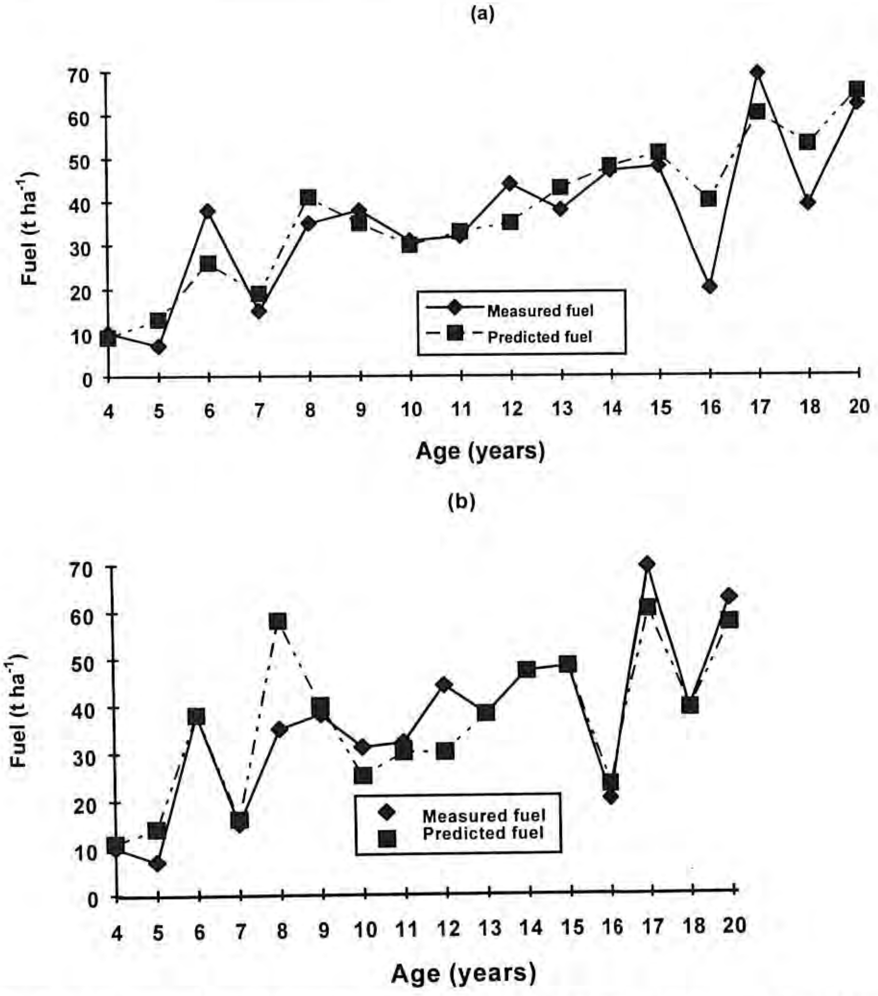

Figure 3. Predicted and actual total fuel loads. (a) Best model for rehabilitation younger than 13 years. Total fuel (t ha^{-1}) = 2.09 age (years) +0.56 litter depth (mm) - 0.60 $r^2 = 0.92$ (b) Best model for rehabilitation 13 years or older. Total fuel (t ha^{-1}) = 1.07 litter depth (mm) + 8.83 $r^2 = 0.81$. From Collins (1996).

Reaccumulation patterns of fuel loads are currently being studied following burning in rehabilitated areas. Fuel levels of between 5 and 10 t ha^{-1} are being obtained one year after prescription burning (Table 1). As these levels are already approaching those recommended as maxima for fire management for the native jarrah forest (8 t ha^{-1}) it appears that proportions of live to dead plant material and vegetation structure will be the major determinants of successive fires rather than fuel loads *per se*. However, continuing research into this area will provide more insight as the vegetation develops following burning.

FIRE BEHAVIOUR AND INFLUENCING FACTORS

Season

Burning in different seasons can have important effects on fire behaviour and vegetation response. Burning in summer is not practical owing to the extreme fire danger that occurs at this time of the year and imposed legislative constraints. Burning in winter is usually not possible because the fuel is too wet. A comparison of season of burning therefore involves autumn versus spring burning. Autumn burns tend to be of higher intensity owing to the drier nature of the fuel after summer where more fuel is likely to be consumed in the flaming zone. By contrast, spring burns tend to be of lower intensity owing to the high moisture contents of fuels after winter rains.

Five prescription burns encompassing a range of intensities and seasons were carried out in 1994 (Appendix 1, Table 1). The two autumn burns undertaken with dry soil conditions were moderate to very high intensity burns while the burns carried out at different times in spring tended to be low to moderate intensity burns. The Soil Dryness Index (SDI - Burrows 1987) in the spring burns ranged from 442 to 1119 while in the autumn burns the values were approximately 1960. Dry conditions in autumn increase the available fuel load and therefore lead to burns of higher intensity. The lighting technique was similar in four of the five burns with lines of fires being run through the pit at 50 to 100 m spacing with junction zones occurring on a falling hazard. An autumn burn in the 1981 rehabilitation area was established in the center of the pit and the perimeter was then lit. The centre fire drew the perimeter fire towards the middle of the pit leading to extreme fire behaviour when the two lines of fire met.

Weather

Weather conditions, such as wind speed, ambient temperature, relative humidity and moisture conditions present at the time of burning can drastically affect fire behaviour. Burrows (1994) identified the two most important factors influencing the rate of spread of fires in the jarrah forest as wind speed and fuel moisture content. Recording soil and litter moistures before three spring burns undertaken in rehabilitation in 1994 (Table 1) showed that soil moisture did not have a direct relationship to fire intensity. However, soil moisture influenced fire behaviour in the litter layer with percentage soil moisture being positively correlated with percentage remaining litter (r^2=0.57, F=17.3, p=0.001). The different vegetation structure of the rehabilitation with a prominent mid-storey layer affected fire behaviour in a more profound way than the normally important influencing factors of soil and litter moisture. Burning under high soil moisture conditions will not guarantee a low intensity fire in rehabilitated areas.

Ward *et al.* (1991) attributed a difference in fire behaviour between rehabilitation areas burnt at Jarrahdale and Huntly to a difference in wind speed recorded during the fires. The Huntly fire intensity was estimated at between 600 and 1200 kW m^{-1} with a wind speed of 9 to 16 km h^{-1}, while fire intensity at the Jarrahdale site ranged from 30 to 283 kW m^{-1} with no wind. This difference in intensity occurred even though the Jarrahdale site had higher fuel loads and lower surface moisture contents (SMC) than the Huntly burn. Smith (1990) indicated that burning in rehabilitated areas with their associated heavy fuel loadings could be successfully undertaken if burning occurred under specific atmospheric conditions. These were calm winds, clear sky and a falling fire hazard (rising humidity and falling temperature). SMC needs to be low enough to sustain fire without being wind driven and fire spots need to be spaced far enough apart so that junction zones of the fires occur late in the day when there is a drop in temperature and rise in humidity.

EFFECTS OF BURNING ON SOILS

The influence of fires on forest nutrition, in particular the effects on forest soils in Australia, has been the subject of a number of reviews (O'Connell *et al.* 1979; Humphreys and Craig 1981). The intensity, frequency and season of burning, as well as soil and vegetation characteristics, influence the nature and extent of changes in soil chemical properties (Grove *et al.* 1986). Only one major study examining the effect of burning on forest nutrient status has been carried out in rehabilitation areas. Ward *et al.* (1991) examined the effect of two prescribed burns on the nitrogen and phosphorus pools in the soil, litter and understorey at two different sites rehabilitated in the late 1970s. In total, 206 kg ha^{-1} of nitrogen (or 46 per cent of the total before the fire) was lost from the understorey, litter and topsoil (0-5 cm) at the Huntly site following a moderate intensity prescribed burn. At the Jarrahdale site, which contained higher fuel loads and a greater proportion of live plant material, 242 kg ha^{-1} of nitrogen was lost but this represented only 23 per cent of the total nitrogen in the understorey, litter and topsoil at this site. There was no evidence of any loss of phosphorus from either site. The loss of 20 to 50 per cent of the nitrogen from a rehabilitated area could have a significant effect on the growth of trees as nitrogen is the nutrient primarily limiting growth of trees in the jarrah forest (Abbott and Loneragan 1986).

While some nitrogen was lost from the sites, the fire did have some beneficial effects on the cycling and availability of plant nutrients. Available nitrogen, in the form of ammonium ions, increased in the topsoil after the fire and the phosphorus increased in the top 0-2 cm of the soil layer. The concentrations of nitrogen and phosphorus in the litter at both sites were significantly greater after the fire. This should result in a more rapid mineralization of the litter and hence an increased availability of nutrients for uptake by plant roots. In addition, some of the nutrients contained within the standing dead understorey, which are not readily available to be cycled through the system, were redistributed to the soil and litter during the fire, thus becoming more available for cycling and plant uptake (Ward *et al.* 1991). Burning rehabilitation sites stimulated the establishment of nitrogen-fixing legumes (Fig. 4), particularly following autumn fires. These species are capable of re-establishing the pre-fire nitrogen levels. The critical issue therefore appears to be the time interval between burning and the restoration of pre-fire nitrogen levels by legumes. Further research into this aspect of soil nutrition following prescription burning in rehabilitated areas is required.

VEGETATION RESPONSE

Trees

Rehabilitation sites seeded with an understorey were also planted with a range of native and non-native eucalypt species in variable proportions. The canopy composition is more variable than in the native jarrah forest with 14 overstorey species recorded in three rehabilitation pits (rehabilitated between 1981 and 1983). Different overstorey species can vary in their tolerance to fire and their seedling recruitment levels following burning. Pre-burn assessment of tree species in five prescription burns carried out in 1994 entailed measurement of bark thickness, diameter at breast height over bark (d.b.h.o.b.) and health of all tree species encountered in five 20 x 20 m plots situated randomly within a pit.

A number of authors have recognized the importance of bark thickness in tree survival following burning (McArthur 1968; Vines 1968; Gill 1980; McCaw *et al.* 1994). A bark thickness of 12.5 mm at breast height is often quoted as the minimum thickness of bark required to survive a moderate intensity burn (Vines 1968). Of 734 trees measured in 11- to 13-year-old rehabilitation, only 13.5 per cent of the trees had a bark thickness of <12.5 mm. The mean d.b.h.o.b. of the tree species in the rehabilitated areas was 16.8 ± 0.3 cm with an average bark thickness of 22.0 ± 0.2 mm and a height of 10.2 ± 0.2 m.

Examination of the effect of five prescription burns of variable season and intensity on 578 trees (14 species) showed that only 3 per cent of the trees were killed across these burns. A further 15 per cent that resprouted basally (below 2 m in height) may be regarded as a partial loss of tree growth. Trees that resprouted from the base or were killed by the burns tended to have thinner bark, smaller diameter and lower height than aerially resprouting trees (Grant *et al.* 1997). Considering that fire intensity in the majority of these burns was high to very high, the overstorey species have shown a remarkable resilience to fire. The extremely low tree mortality recorded can be partly explained by the lack of large fuel components (e.g. fallen logs) in rehabilitation areas that can burn for long periods and lead to tree mortality or fire scar formation. Tree mortality in rehabilitation burns of even high intensity should therefore be relatively low.

Smooth-barked eucalypt species are usually more fire sensitive than rough-barked species owing to differences in the structure and thickness of the bark layer (McArthur 1968). In rehabilitated areas, smooth-barked species showed a 60 per cent greater mortality and number of

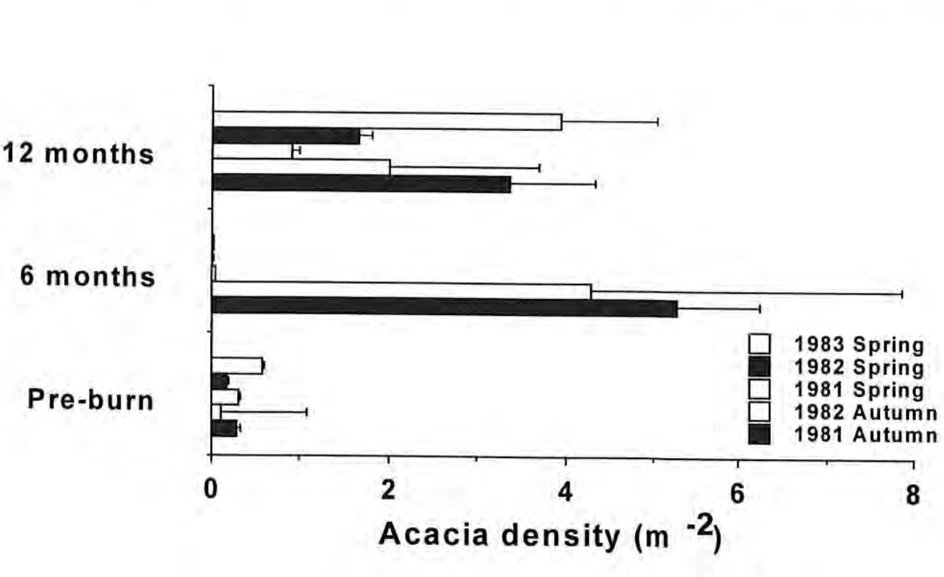

Figure 4. Acacia density (m^{-2}) pre-burn, six months and one year after five prescription burns carried out in 1994 with variable intensities and seasons of burn.

basal resprouts than rough-barked species (Grant *et al.* 1997). Fire management of rehabilitated areas must involve consideration of bark type of the dominant overstorey: lower fire intensities should be used in areas dominated by smooth-barked species. Trees burnt in the higher intensity autumn burns had 40 per cent higher levels of mortality and exhibited 80 per cent higher levels of basal resprouting than those in spring burn areas. In terms of the effect of fire on the tree species in rehabilitated areas, spring burns appear to be preferable, leading to lower tree mortality and a more rapid and vigorous resprouting response (Grant *et al.* 1997).

Understorey

An important difference between burns in spring and autumn is the delay between the burn and the winter rains which allow seed germination. Germination is often almost immediate after an autumn burn with the onset of winter rains while seeds in spring burn areas often have to wait until the following winter (~6 months) before they receive adequate water for germination. If plants germinate following spring burns, they may not be sufficiently mature to survive the long summer drought and, therefore, valuable seed resources may be wasted. Burning in autumn tends to favour seeding species (i.e. those species that are killed by fire and rely on seed reserves to invade the post-fire habitat) while burning in spring tends to favour resprouting species (i.e. those species that are not killed by fire and have dormant buds that resprout following burning) as summer is their normal growing season.

Assessment of the understorey response to burning in rehabilitation areas was undertaken following five prescription burns carried out in 1994. These burns encompassed a range of fire intensities and seasons of burning (Table 1). The vegetation response was assessed periodically following the burns. Burning rehabilitation areas caused an increase in plant density one year after the fires (Fig. 5). Pre-burn densities of 2 to 6 plants per square metre increased to 15 to 53 plants per square metre one year after burning.

Seedling establishment was greater following autumn than spring burns. In areas burnt in spring, there is a six-month delay before sufficient water becomes available for germination while germination is almost immediate following autumn burns. Very few plants were recorded in the spring burn areas six months after the fire (Fig. 5) as germination had not commenced. Loss of viability, seed predation and fungal attack of seeds can occur over summer following spring burns. This is the most probable explanation for lower plant establishment following spring compared with autumn burns.

Even though plant densities following spring burns are lower than those following autumn burns they are still three to four times higher than pre-burn densities. Furthermore, a significant proportion of the increased plant establishment following autumn burning is owing to a large increase in the density of eastern Australian eucalypt seedlings (i.e. *E. maculata* and *E. resinifera* - Fig. 6). The high levels of crown scorch and consumption observed in the autumn burns led to a large seed fall from the bradysporous fruits of the eastern Australian eucalypts. Current research is examining reasons for the low level of recruitment of eastern states eucalypt seedlings following spring burns and it appears that predation by ants is the major factor leading to seed loss.

All five burns were successful in stimulating the establishment of at least one *Acacia* per square metre (Fig. 4), which is an establishment criterion for new rehabilitation areas. Legume species are important nitrogen-fixers in the post-fire environment and assist in returning the nutrient status of burnt rehabilitation areas to pre-burn levels. The higher initial densities of *Acacia* spp. following autumn than those following spring burning may be owing to greater penetration of heat during autumn burns leading to greater stimulation of hard-seeded species such as *Acacia*.

One year after burning, weed densities were similar across all burns (Fig. 7) indicating that fire intensity and season had little effect on the flush of weed species often seen in recently-burnt areas. The majority of weed species in rehabilitated areas are wind-dispersed daisies (Asteraceae) including *Conyza* spp., *Senecio* spp., *Sonchus* spp. and *Hypochaeris glabra* (flatweed). Although weed densities were higher in burnt areas than in areas that were not burnt, it is expected that weed densities will decrease with time in burnt areas as the vegetation matures and begins to out-compete annual weed species.

Unlike the native jarrah forest, unburnt rehabilitated areas are dominated by seeding species rather than resprouting species (Fig. 8). This has a large impact on the recovery of the system following a disturbance such as fire. In the native forest which is dominated by resprouting species, very few individuals are killed by fire thus resulting in relatively little change in species composition. In rehabilitation, on the other hand, seeding species are killed by fire and this opens up a gap for reinvasion. Species composition of rehabilitation following a burn may be very different from that before a burn depending on which species invade and successfully establish at a site. For example, burning rehabilitation in autumn at high intensity has led to the proliferation of eastern Australian eucalypt species which are dominating in some areas and out-competing most other species. This is also associated with a shift in fire response strategy in the post-fire environment compared with that of the pre-fire area (Fig. 8). The large increase in resprouters seen in areas burnt in autumn is owing to the proliferation of non-native eucalypt seedlings.

At this stage, it would appear that burning in spring is preferable to burning in autumn in terms of the understorey response as the spring burns did not lead to a proliferation of eastern states eucalypts (Fig. 6) but still showed the positive aspects of burning such as increased plant establishment (Fig. 5). It is often not practical to prescribe a large number of burns in autumn as the available 'window' for burning is often small (i.e. one to two weeks), whereas in spring there are usually two to three months where prescription burning is possible.

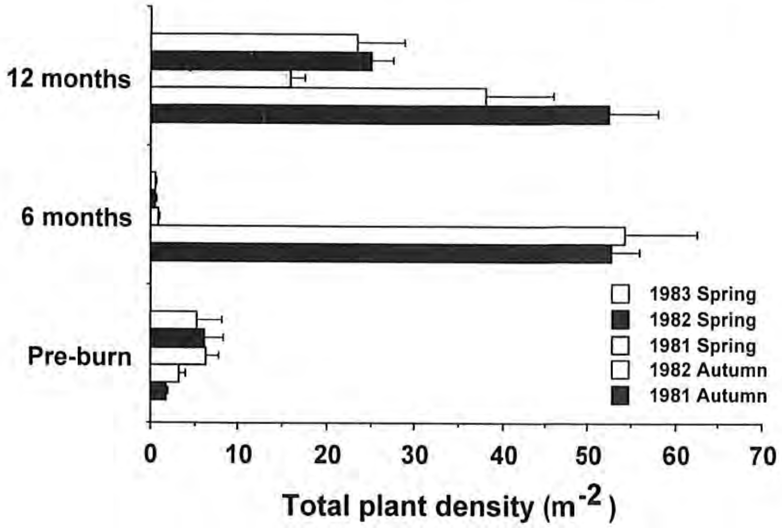

Figure 5. Total plant density (m⁻²) pre-burn, six months and one year after five prescription burns carried out in 1994 with variable intensities and seasons of burn.

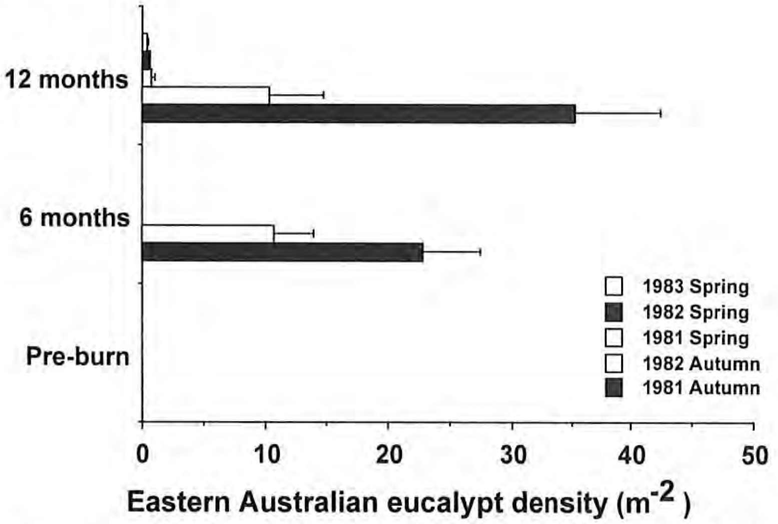

Figure 6. Eastern states eucalypt density (m⁻²) pre-burn, six months and one year after five prescription burns carried out in 1994 with variable intensities and seasons of burn.

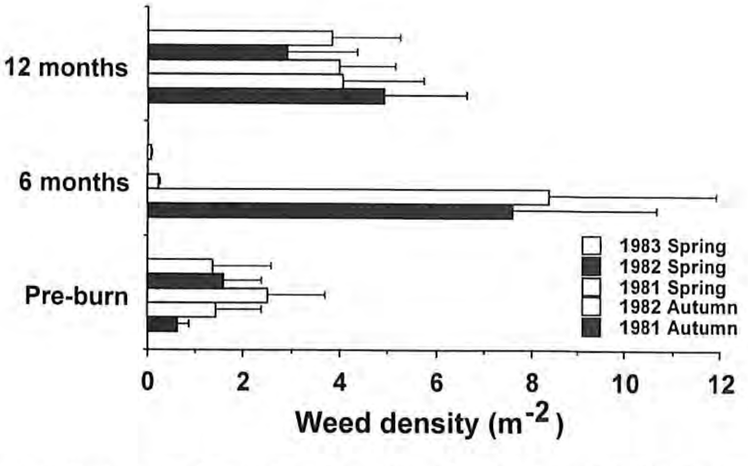

Figure 7. Weed density (m⁻²) pre-burn, six months and one year after five prescription burns carried out in 1994 with variable intensities and seasons of burn.

FAUNA RESPONSE

The response of the fauna to prescription burning in rehabilitated areas has not yet been investigated and is in need of research. During the experimental burns, a number of mammals such as kangaroos, bandicoots and wild pigs were seen escaping. Birds and flying insects can escape through flight while burrowing animals such as lizards, snakes and ants are insulated from the heat of the fire by soil. Of greatest concern are the soil and litter-borne invertebrates and fungi that are so important in nutrient cycling. Although no work has been attempted on these groups in rehabilitation, studies in the native jarrah forest indicate that generally fire has either a small or short-term effect on them. For example, Abbott (1984) found that earthworms, spiders, slaters, termites, earwigs, crickets, beetles, millipedes, flies and ants occurred at significantly greater densities in burnt plots in the jarrah forest while centipedes, silverfish and cockroaches occurred at significantly lower densities in the burnt plots. It was concluded that all but three taxa recovered in density within three years of a moderate intensity fire in the jarrah forest and the relative abundance and/or activity of three other taxa remained depressed on the burnt plot during the same period. By contrast, Springett (1976) concluded that mild fires reduce the density and diversity of soil fauna. In a study on the effect of wildfire on vesicular-arbuscular mycorrhizal fungi Bellgard *et al.* (1994) concluded that although infection was reduced immediately after a burn, infection levels in burnt areas were comparable to pre-burn areas within six months of a wildfire. A comprehensive review of the effect of fire on invertebrates in Australia was recently carried out (Friend 1995) and findings from this study have application to rehabilitated systems.

Burning in rehabilitated sites is always going to occur in relatively small areas (5-15 ha) until these sites can successfully be included in a general fuel reduction program, and therefore the edge effect tends to be relatively large thus allowing mobile animals to escape. A lighting technique that allows an escape passage for animals should be used where possible rather than surrounding them by fire.

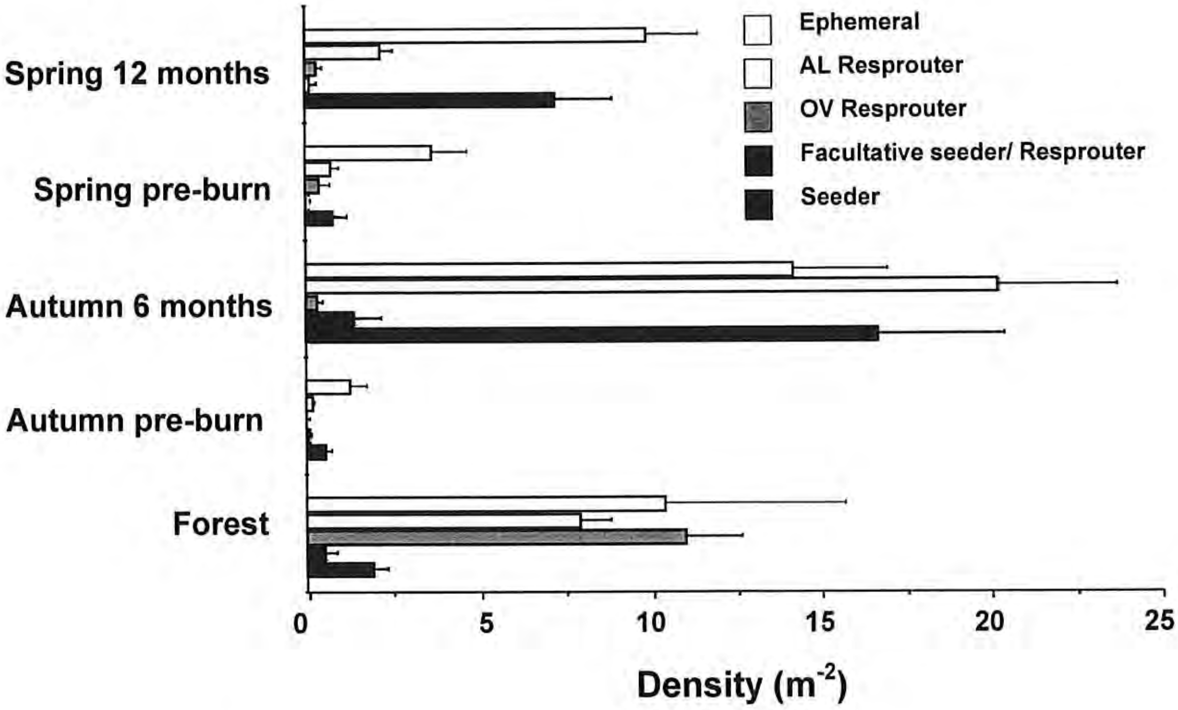

Figure 8. Densities (m^{-2}) of various fire response categories in the native jarrah forest, rehabilitation sites pre-burn and rehabilitation sites one year after being burnt in autumn and spring. Fire response categories are taken from Bell et al. *1984. OV resprouters are obligate vegetatively-reproducing resprouters that exhibit very little or no seedling recruitment after fire and AL resprouters are autoregenerating long-lived resprouters that exhibit relatively high levels of seedling recruitment following fire.*

SITE MANIPULATIONS

It would be desirable to establish jarrah as the overstorey dominant in rehabilitated areas that were originally planted with non-native eucalypt species. Burning in autumn has led to proliferation of eastern Australian eucalypt species (Fig. 6) which makes the task of establishing jarrah as the overstorey dominant more difficult. It is possible to reduce fuel loads and establish jarrah as the overstorey dominant in a single manipulation. A current experiment is investigating the possibility of killing the eastern Australian eucalypt overstorey (through ring-barking or tree notching) leading to seed fall, followed by burning of the area to reduce fuel loads and kill the seed of the eastern Australian eucalypts. Following the burn, these sites will be seeded with jarrah and an understorey mix to increase species richness. Seeding of understorey species has been shown to significantly increase understorey species richness (Fig. 9).

Jarrah establishment rates have been good under an existing canopy although it is unlikely that these seedlings will develop into saplings until competition for water from the existing canopy is removed (Stoneman *et al.* 1994). A number of studies have reported improved seedling establishment following soil scarification (Olsen and Vickery 1989; Koch 1992). In a recent study involving combinations of burning or not burning and soil scarification or not, scarification did not increase jarrah density in burnt or unburnt areas but there was a significant increase in jarrah density following autumn but not spring burning (Fig. 10).

The decreased plant establishment in spring burn areas appears to be related to the seeds remaining dormant in the soil for six months following burning. It appears that burning rehabilitated areas followed by seeding is the most effective treatment to increase understorey richness and establish jarrah as the potential overstorey dominant.

FURTHER RESEARCH

In the jarrah forest, determining whether a site should be burnt or not is dependent primarily on fuel loads. In all but very young rehabilitation, fuel loads tend to be well above those recommended for the native jarrah forest owing to the high density of legume species at these sites. Further research needs to be carried out to determine the accumulation pattern of fuels in areas rehabilitated after 1988. The response of fauna to burning rehabilitated mine sites and the effect of prescribed burns on soil nutrient levels are areas in need of further research. Current research is concentrating on formulating a one-step manipulation of old rehabilitation sites that will reduce fuel loads and establish jarrah as the overstorey dominant and increase understorey diversity.

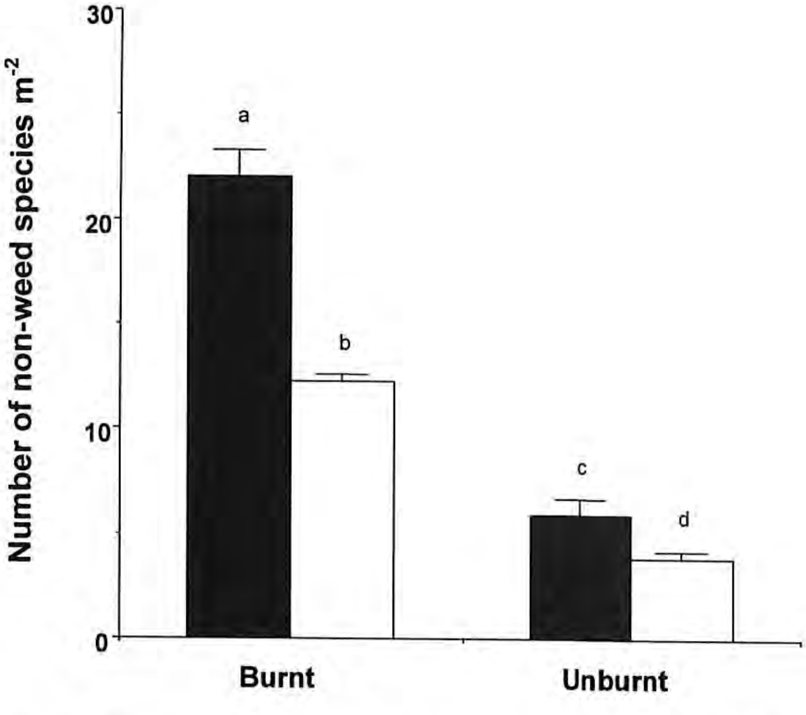

Figure 9. Number of non-weed species recorded in 2 m x 2 m plots over four treatments (burnt/seeded, burnt/unseeded, unburnt/seeded and unburnt/unseeded) one year after an autumn burn. Solid bars represent seeded treatments and open hatched bars are unseeded treatments. Different letters represent a significant difference (p<0.05) using ANOVA. Bars are means ± SE.

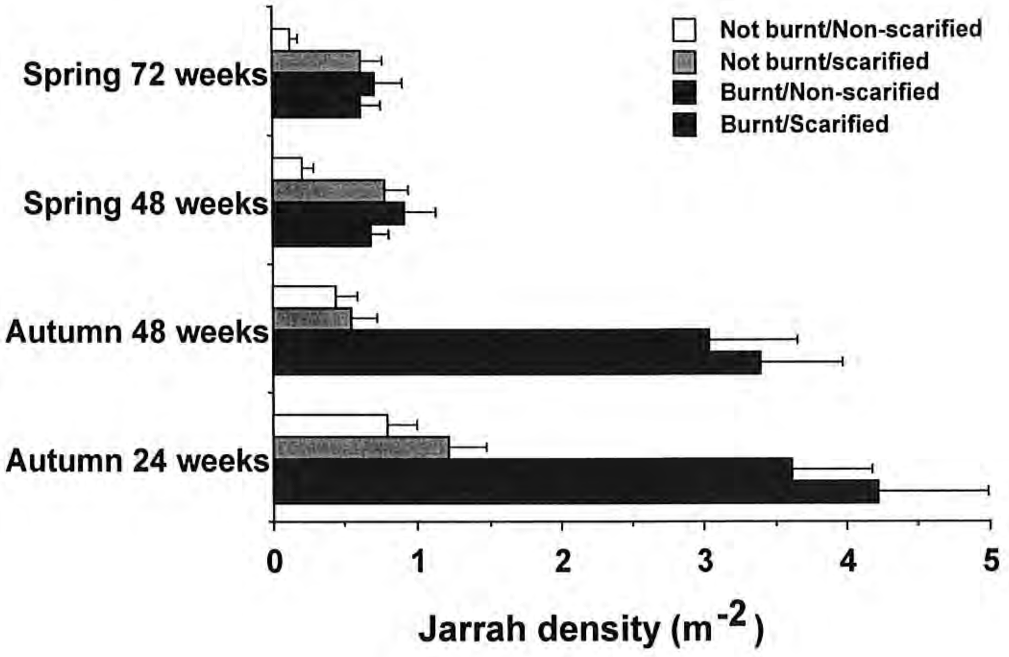

Figure 10. Jarrah density (m^{-2}) 24 and 48 weeks after autumn burning and 48 and 72 weeks after spring burning across four treatments. This represents the best ecological comparison of jarrah density across the two seasons of burning. Bars are means ± SE.

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APPENDIX 1

Selected features of the 14 recorded burns carried out in rehabilitated areas.

REHAB. YEAR	DOMINANT OVERSTOREY	YEAR OF BURN	FUEL LOAD ($t\ ha^{-1}$)	FIRE INTENSITY ($kW\ m^{-1}$)	AGE AT BURN	MINESITE	SEASON	SIZE (ha)
1971	E. microcorys	1986	13.57	50-100	15	Jarrahdale	Spring	1
1979	E. resinifera, E. maculata E. saligna	1989	61.75	30-283	10	Jarrahdale	Spring	
1971/1979	E. agglomerata, E. calophylla, E. wandoo, E. laeliae	1988			11,17	Jarrahdale	Spring	8
1977	E. laeliae	1987	42.95	600-1200	10	Huntly	Spring	
1982	E. wandoo	1994	16	1000-1600	12	Jarrahdale	Spring	9
1982	E. maculata, E. resinifera, E. saligna	1994			12	Jarrahdale	Summer	1
1981	E. maculata, E. resinifera, E. wandoo	1994	34.7	3050-20300	13	Jarrahdale	Autumn	10
1982	E. maculata, E. resinifera, E. wandoo	1994	28.5	270-14700	12	Jarrahdale	Autumn	10
1981	E. maculata, E. resinifera, E. wandoo	1994	23.4	720-2080	13	Jarrahdale	Spring	10
1982	E. maculata, E. resinifera, E. wandoo	1994	26.1	1044-1566	12	Jarrahdale	Spring	15
1983	E. maculata, E. resinifera, E. wandoo	1994	25.1	188-1255	11	Jarrahdale	Spring	15
1981	E. maculata, E. resinifera, E. wandoo	1995	27.35	320 -3240	13	Huntly	Spring	6
1981	E. maculata, E. resinifera, E. wandoo	1996	35.73	390-2106	13	Huntly	Autumn	8
1977	E. laeliae, E. wandoo	1985			8	Jarrahdale	Autumn	6

APPENDIX 2
Practitioners Guide to Rehabilitation Burns.

Objectives and Planning

Prior to any burning taking place in rehabilitated areas, it is essential that the risks be assessed and compared with the potential gains. The risks that should be considered include: the potential threat the rehabilitation poses to the strategic fire buffer system, the values at risk both to the rehabilitation directly from the burning and the rehabilitation ecosystem and the forest values adjacent to or near the rehabilitation. If the potential gains do not outweigh the environmental costs then burning should not be undertaken.

During the planning phase, it is essential to determine the objective of the burn. Once the objective is defined, it is possible to analyse the benefits and costs associated with the burn. Other issues in need of consideration include the level of fuel reduction required, the target fuel strata (i.e. litter, standing fuel and/or overstorey), understorey and overstorey management and the impact burning will have on the overstorey seed in the topsoil or in the crown. These issues will determine the composition of the forest remaining after burning and prediction of this outcome prior to burning will assist in longer-term management. These assessments should occur before the development of a prescription because it may identify alternative objectives or strategies. Once it is determined that the burn will proceed, it is necessary to:

(1) develop a prescription using the standard CALM format that relates directly to the burn objectives and ensures all standard operating procedures are met. This prescription must identify the acceptable level of fuel reduction (>75 per cent) and the required proportion of the area that should be burnt (>75 per cent).

(2) incorporate the rehabilitation objectives into the development of a prescription. Burning of rehabilitated areas can lead to a change in vegetation structure from a three-tiered profile (i.e. litter, trash and overstorey) to a two-tiered profile (litter/small scrub and overstorey). Burning rehabilitated systems will also change the nutrient cycle of the system and it is essential that the impact be considered prior to ignition. Season of burning will be an important decision inthis process as this has enormous effects on the post-burn vegetation.

Pre-burn Assessment

During the fuel sampling phase, the following information should be collected.

(1) In burn areas of less than 10 ha, three fuel sampling transects should be randomly allocated. In burn areas of 10 to 30 ha one transect should be allocated randomly to each 3 ha of burn area. Where the burn area is larger than 30 ha, ten transects should be allocated randomly to the burn area.

(2) At 10 m intervals along the 100 m transect measure litter depth, estimate scrub height, density and percentage dead foliage. This information should be recorded on CALM Fuel Assessment Record sheets.

(3) Using the mean litter depth, calculate the total fuel loads for each transect using the following equations (from Collins 1996).

In rehabilitation that is 13 years old or more

$$\text{Total fuel } (t\ ha^{-1}) = 1.07 \text{ litter depth (mm)} + 8.83$$

In rehabilitation that is less than 13 years old

$$\text{Total fuel } (t\ ha^{-1}) = 2.09 \text{ age (years)} + 0.56 \text{ litter depth (mm)} - 0.60$$

Fuel loads can also be calculated using the Forest Fire Behaviour Tables for Western Australia (Sneeuwjagt and Peet 1985) which is commonly called 'the red book'. The relationship between total available fuel loads calculated from litter depth using the red book and the Collins equations is very strong (Fig. 11).

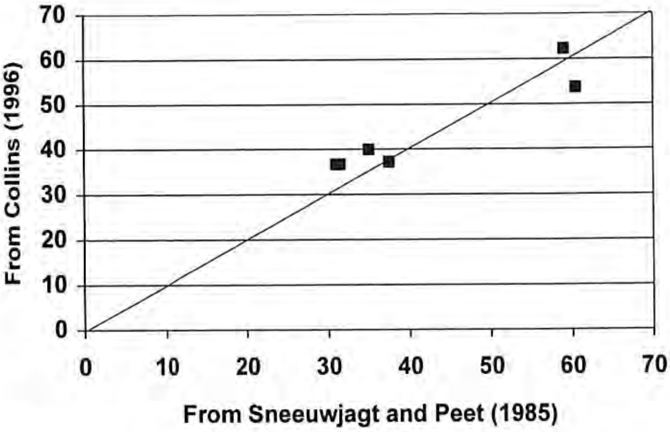

Figure 11. Relationship between total available fuel ($t\ ha^{-1}$) calculated using Forest fire behaviour tables for Western Australia (Sneeuwjagt and Peet 1985) and the Collins equations in rehabilitated bauxite mines (Collins 1996).

When using the red book to calculate fuel loads in rehabilitated areas the following procedure should be used (underlined phrases are those used in the red book):

From the average litter depth per transect, determine the total litter weight from table 7.2.1. Assume the forest type is karri dominant.

From the average scrub height per transect, determine the scrub fuel weight from table 7.4.1. Assume scrub structural type 2 and Total foliage (consumed in moderate wildfires). Dense rehabilitation understorey is classed as Medium and sparse rehabilitation understorey is classed as Sparse in table 7.4.1.

Add together total litter weight and scrub fuel weight from 1 and 2 above to give total fuel weight.

Multiply total litter weight by the available fuel factor to give the available litter weight. In most cases the available fuel factor is 1.0. In very moist conditions the available fuel factor is 0.7. Available trash is not calculated because this fuel fraction is accounted for in the scrub fuel weight calculation.

Multiply total scrub fuel weight by the scrub flammability factor from table 7.4.2 to give available scrub fuel weight. Dense rehabilitation has a scrub flammability of HIGH while sparse rehabilitation understorey has a scrub flammability of LOW. The average percent dead foliage should also be used in this table to choose the scrub flammability factor.

Available fuel weight = available litter weight + available scrub weight.

(4) Calculate the maximum rates of spread of fire given the available fuel loads that will keep fire intensity below 1500 kW m^{-1}.

(5) Record the location of sampling transects on the burning plan.

(6) Measure the height, bark thickness and diameter at breast height of 10 dominant trees along the fuel sampling transects. Trees less than 10 cm dbh and with a bark thickness of <15 mm are likely to suffer bole damage at fire intensities greater than 1500 kWm^{-1}. If greater than 20 per cent of the dominant trees measured fall into this category then the burn should not occur. Measuring tree height will assist in determining the flame and scorch heights that will be acceptable to meet the objectives.

(7) Identify roads and tracks that will be safe exit locations.

(8) Locate water resources for fire fighting.

(9) Determine the best season for burning to occur. The majority of burns will occur in spring (unless there are specific objectives for the rehabilitation) although a variable fire regime in rehabilitated areas should be encouraged. The smaller 'window of opportunity' for burning in autumn will restrict broad-scale rehabilitation burns at this time of year.

During the Prescription Burn

The following should be carried out just prior to and during the burn.

(1) Ensure that all of the standard operating procedures have been met prior to ignition.

(2) Determine a spot and strip width that will achieve the objective of the burn. Owing to the limited information available on burning in rehabilitated areas, it is essential to be conservative. Junction zones of spot fires should meet on a falling hazard when the humidity is rising and ambient air temperature is falling. An absence of cloud will assist in achieving a falling hazard and subsequent reduced fire intensities.

(3) Record the surface moisture content (SMC) and the pre-burn wind speed and direction. SMC should be above 7 per cent and wind speed below 20 km h^{-1} for spring burns. Soil Dryness Index (SDI) should be in the range 400 - 800 for spring burns, although recording fuel moistures in the rehabilitation is more important than the SDI. Burning under these conditions may still lead to 100 per cent crown scorch in some areas but should avoid complete consumption of the canopy.

(4) Record the rate of spread (ROS) of the head and tail fire at the fuel sampling locations.

(5) Record the flame length for the head, flank and tail fire.

(6) Record the temperature, relative humidity and cloud cover and type.

Below is a summary of the ideal pre-burn conditions for burning rehabilitated areas:

PARAMETERS	SPRING BURN	AUTUMN BURN
SMC (%)	7 - 15	5 - 10
SDI	400 - 800	1000 - 1500
Wind Speed (km h^{-1})	0 - 20	0 - 10
Lighting Time	12 - 4 pm	2 - 6 pm
Humidity (%)	40 - 60	30 - 50
Temperature (°C)	18 - 24	20 - 25
ROS	20 - 120	50 - 150
Flame Height (m)	1 - 4	1 - 10
Fire Intensity (kW m^{-1})	500 - 1500	1500 - 2500

Post-burn Assessment

Following the burn:

(1) Remeasure litter depths in the fuel sampling transects and estimate the remaining scrub fuel.

(2) Calculate the quantity of scrub and litter fuel consumed.

(3) Determine fire intensity (I) using the equation:

$$I\ (\text{kW m}^{-1}) = \text{ROS}\ (\text{m h}^{-1}) \times \text{fuel consumed}\ (\text{t ha}^{-1}) \times 0.516$$

Burrows (1994)

(4) Calculate fire intensity based on flame length (L) using the equation:

$$I\ (\text{kW m}^{-1}) = 293.871(L)^{1.118}$$

Burrows (1994)

and compare to fire intensity calculated using ROS.

(5) Record all of the data and retain with the prescription for the burn.