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**VARIABILITY IN JARRAH (*EUCALYPTUS MARGINATA*)  
DENSITY ON REHABILITATED BAUXITE MINES RELATES  
TO FACTORS AFFECTING EMERGENCE RATHER THAN  
SURVIVAL**

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## SUMMARY

The establishment of eucalypts on rehabilitated bauxite mine pits is highly variable, ranging from 300 to 5,000 stems per hectare. Management, such as re-seeding or herbicide spraying, occurs one year post-rehabilitation to achieve a density consistent with the standard specified in Alcoa's rehabilitation completion criteria. Intervention could be reduced by understanding and targeting the causal factors of the variation. We investigated five factors and determined whether they had an effect on jarrah emergence or survival. The factors were: temperature, presence of *Phytophthora* spp. in the soil, topsoil handling techniques, soil particle size and seed theft. Desktop studies and/or field experiments were conducted by obtaining tree densities from Alcoa's routine nine month botanical monitoring or establishing 25 plots in newly rehabilitated sites at Huntly mine. Field emergence of jarrah was highly variable, ranging from 2% to 38%. Once seedlings had emerged, survival was high (96%), indicating that it is during emergence that factor(s) are causing the observed variability. Temperature was the only factor that was significantly correlated with jarrah emergence ( $P= 0.006$ ). The highest emergence occurred on sites that experienced warmer weekly maximums and cooler weekly minimums. Sites displaying high emergence had both extremes. In previous studies, cool temperatures were found to reduce jarrah emergence so it is probably the warmer maxima that were responsible for high emergence. Despite large variations in soil substrate and overburden depth between sites, there was no correlation with jarrah emergence and survival. *Phytophthora* spp. were not isolated from any of the sites and seed theft was minimal.

## INTRODUCTION

The establishment of jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*) trees on rehabilitated bauxite mined areas is highly variable, ranging from 300 to 5,000 stems per hectare (Mattiske, 2001; Mattiske, 2002). The target density for tree establishment is 1,300 stems per hectare with a minimum of 600 stems per hectare. In 2005, a new

rehabilitation completion criterion was introduced that specifies an upper density limit of 2,500 stems per hectare. Greater densities are undesirable because competition between trees results in slow growth rates and high water use (Croton and Reed, 2007). Re-seeding of areas below the minimum density and herbicide spraying of areas that exceed the maximum density occurs the year following rehabilitation to meet mine site completion criteria requirements. An understanding of the factors responsible for the variability could be used to manage establishment densities and reduce the need for intervention.

Alcoa aims to establish a jarrah:marri ratio of 80:20 in rehabilitated sites, based on the ratio recorded in the northern jarrah forest. Due to the dominance of jarrah, the variability in tree establishment is hereon referred to as the variability in jarrah establishment. Biotic or abiotic factors responsible for the variability may have an effect during first emergence (between germination and protrusion of cotyledons from the soil, hereon referred to as emergence) or survival to nine-months of age (after the seedling has developed the first true leaves). Despite improvements in rehabilitation techniques, such as seeding directly after soil scarification (Ward *et al.*, 1996), the cause of the variable establishment is unknown. Seed quality (viability) has been excluded as a possible factor because most pits receive the same seed mix which contains 5-20 different jarrah seedlots. Fertiliser application rate and timing (summer, winter or spring) have also been excluded by previous studies (Stoneman *et al.*, 1994; Norman and Koch, 2005a).

Numerous factors have been investigated in the past, however no single factor has accounted for the observed variability. Jarrah emergence was reduced on lowland areas (3%) compared with upland areas (9%), probably due to the greater number of days at 5°C or less in low topographic positions (Gartrell, 1993). It was suggested that ‘cold air drainage’ resulted in lower jarrah emergence. However, the experimental sites were chosen towards the extreme ends of upland and lowland sites, which only account for a small proportion of the total rehabilitation undertaken each year. In addition, it is unknown whether it was within-pit or landscape-scale temperature differences that affect jarrah emergence.

The presence of pathogenic *Phytophthora* species in the soil may also affect the establishment of jarrah in rehabilitated sites. ‘Dieback-soil’ is soil from an area known to be infested with *P. cinnamomi*, while ‘dieback-free-soil’ is from non infested areas. The two main species of *Phytophthora* that cause seedling deaths in rehabilitated bauxite mines are

*Phytophthora cinnamomi* and *P. multivora*<sup>1</sup> (Scott *et al.* 2009). Failed plant establishment (damping-off) due to *Phytophthora* species can be pre-emergent, where seeds and germinants are affected before they emerge from the soil, or post-emergent, which causes constriction and necrosis of the seedling hypocotyls (Woodman 1993). In one-year-old rehabilitated bauxite mined areas *P. cinnamomi* is responsible for approximately 1% of jarrah deaths (I. Colquhoun, pers. comm.). Lockley and Koch (1996) suggested the observed difference in jarrah establishment between Alcoa's three different mines may be related to soil dieback status. The average density of eucalypt seedlings was 7,800 stems ha<sup>-1</sup> at Huntly mine, 4,700 at Jarrahdale mine and 1,000 at Willowdale mine. The topsoil at Willowdale was 'dieback-soil' while at the other mines it was 'dieback-free'. In contrast to *P. cinnamomi*, the pathogen *P. multivora* is widespread in the soils of southwest Western Australia, yet it is difficult to map its presence because its presence in the soil may not be associated with any symptoms in the vegetation. *Phytophthora multivora* caused lower emergence of jarrah in inoculated soil in rehabilitated bauxite mines (Woodman, 1993), and has been frequently isolated from dying two-to three-year-old jarrah seedlings in rehabilitated areas (Bunny, 1996). In 2004 rehabilitated sites, one-third of all post-emergent deaths in one-year-old plants were due to *P. multivora* (N. Kerp, pers. comm.).

The observed variation in jarrah density may relate to differences in topsoil handling techniques such as soil age (freshly returned or stockpiled), date of soil return and date of ripping. Lockley and Koch (1996) suggested the lower number of eucalypt stems ha<sup>-1</sup> at Jarrahdale (4,700) compared with Huntly (7,800) may be caused by Jarrahdale areas receiving stockpiled soil and Huntly receiving fresh soil. The timing of soil return may affect jarrah establishment because soils returned earlier have a longer period of time to accumulate seed from the unmined forest boundary. Tillage of the soil (in this case deep ripping with a bulldozer) late in the season (April) reduces the density of species establishing from the topsoil compared with ripping in December or February (Ward *et al.*, 1996). We believe this reduction is caused by germination

<sup>1</sup> Previously believed to be *P. citricola* but now a new species using molecular diagnostics.

commencing with the break-of-season rains, commonly mid-April in the south-west of Western Australia, followed by ripping which kills the germinating plants.

Jarrah emergence on fine sand tends to be lower than on coarser sand and gravel ( $P = 0.07$ ) (J. Koch, unpublished data). Monitoring only occurred for five months to the spring following seeding, whereas to gain an accurate indication, survival needs to be monitored after the summer drought when plant available water would be at a minimum. Overburden depth may also affect the survival of jarrah, because trees that are able to access the underlying clay layer will have higher water availability during the summer drought.

The effect of seed theft on jarrah establishment has not been quantified. Majer (1978) found that seed theft by ants and birds was not a factor responsible for the low germination of the broadcast seed mix. Only five species of ants (one seed collecting species) were found in newly rehabilitated sites compared with 50 species in adjacent undisturbed forest (Majer, 1978). Birds were not observed in a seeded pit over a period of seven days, while mammals were not investigated.

The aims of this study were to investigate several factors (temperature, soil dieback status, topsoil handling techniques, soil properties and seed theft) that may be responsible for the variability observed in jarrah establishment.

## **MATERIALS AND METHODS**

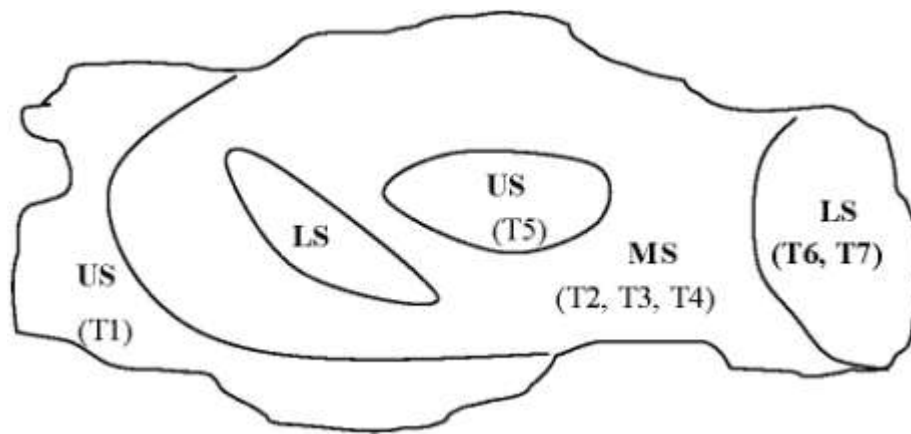
### *Temperature*

To assess eucalypt establishment in relation to within-pit slope, 2002 and 2003 rehabilitated pits at Huntly and Willowdale mines were divided into upland, middle and lowland areas during Alcoa's routine nine-month botanical monitoring (Figure 1). The routine monitoring assesses the

density of eucalypts and understorey plants in March, about nine months following the completion of rehabilitation operations. Live and dead jarrah and marri trees are recorded in two metre wide transects throughout the pit. The transects follow the rip line contours, and are spaced approximately 20 rip lines apart to provide adequate coverage (3-5%) of the pit. Slope divisions were performed by standing at the pit edge and drawing rough slope boundaries on the pit map. Usually, the whole pit could not be viewed from the one standing point, therefore divisions into the three areas continued to be updated as the monitoring was undertaken. Transect lines followed the contours in each slope division. When moving from one slope position into another, total tree numbers were recorded and a new transect started. Slope areas had varying transect line lengths, depending on their size in relation to the whole pit. Analysis was undertaken on jarrah tree numbers rather than all eucalypts.

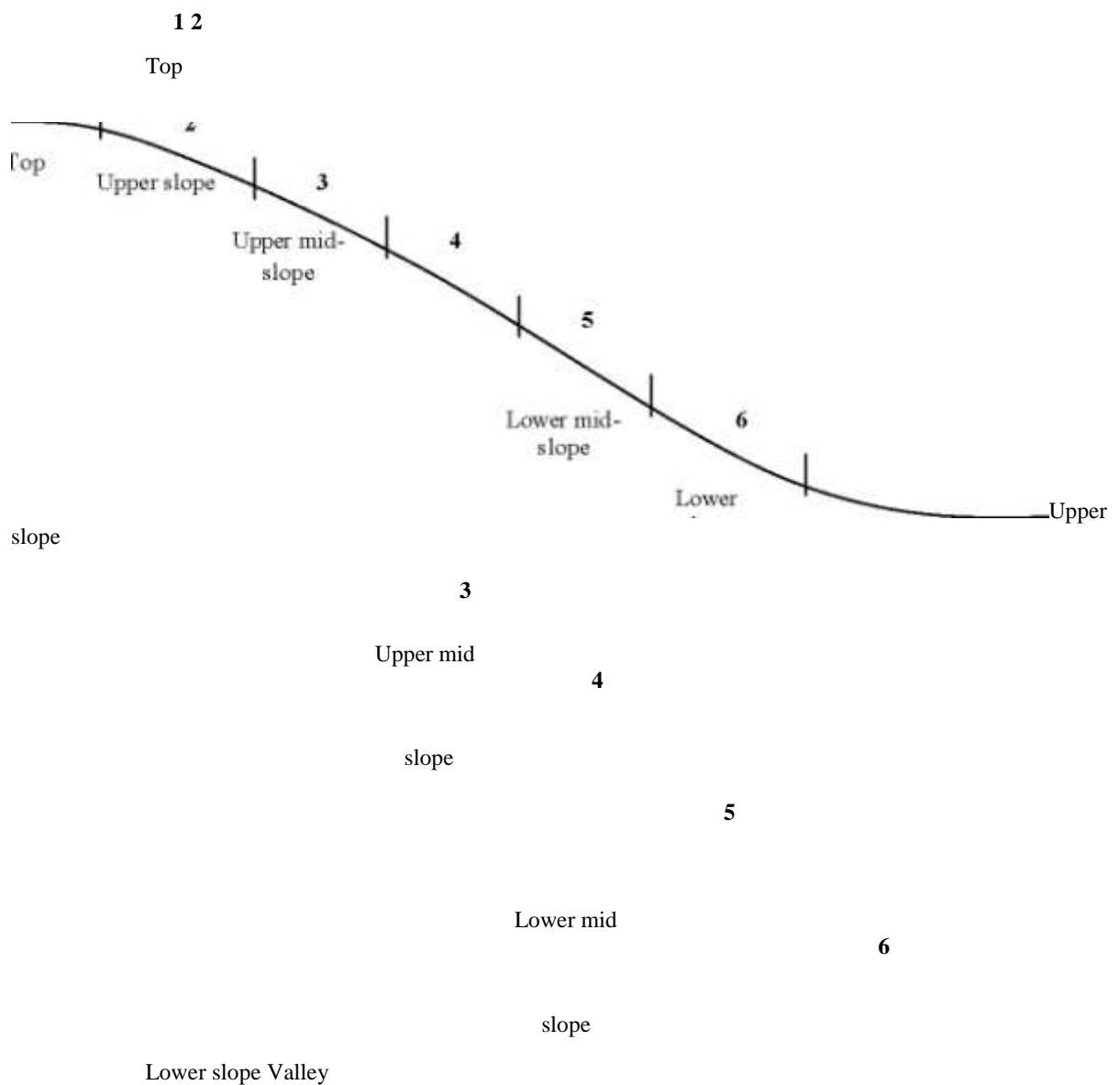
**Figure 1:** Hypothetical pit map showing location of slope areas (US = upper slope, MS = middle slope, LS = lower slope) and tree monitoring transects (T).

The GIS package ARCVIEW (ESRI 1996) is used by Alcoa to record each stage of the rehabilitation process, for instance the status of soil return (direct returned or stockpiled) and the dieback status of areas.



ARCVIEW was used to obtain pit elevation (metres above sea level) based on 5 m contour lines for 2000 to 2002 rehabilitated mine pits at Huntly and Willowdale. Pits occurring over a range of contour lines (steep slopes) were omitted from the assessment, because a single 5 m elevation category could not be assigned. Pit elevation was correlated with tree data obtained during Alcoa's routine nine-month botanical monitoring. Analysis was undertaken on jarrah tree numbers rather than all eucalypts.

ARCVIEW was also used to assign pits a number from 1 to 6 based on position in the landscape for 2000 to 2002 rehabilitated mine pits at Huntly and Willowdale. Hilltops were assigned the lowest value (1), which progressed to lower slopes (6) near valley floors (Figure 2). Valleys were not assigned a number due to the absence of pits in this location. Landscape position was correlated with tree data obtained during Alcoa's routine nine-month botanical monitoring. Analysis was undertaken on jarrah tree numbers rather than all eucalypts.



**Figure 2:** Pit position within the landscape from hilltop to lower slope (1-6).

Twenty-five plots were established at Huntly mine over 14 pits in mid-June 2003 to monitor the effect of local temperature variation on jarrah emergence. Sites were selected at random and at varying distances from the pit edge. The plots were in 2003 rehabilitation and had received the normal seed mix, which contains  $0.55 \text{ kg ha}^{-1}$  of jarrah seed (approximately 22 seeds per plot). Each plot was  $8 \text{ m} \times 4 \text{ m}$ , consisting of two  $4 \text{ m} \times 4 \text{ m}$  subplots (control and treatment). The plots were scarified

with a rake to remove the surface soil crust. The treatment plot received 200 surface sown jarrah seeds. The seeds were from the Huntly collection zone and had an average incubator germination of 83%. An electronic max-min thermometer was located at each site and monitored weekly from July to October 2003. The weekly maximum and minimum temperatures recorded at each site were range standardised (RS) using the following equation:

$$RS = ((x - \text{min}) / (\text{max} - \text{min})) * 100$$
 where x is the individual temperature value, min is minimum temperature recorded for the week and max is the maximum temperature recorded for the week. The daily rainfall for Huntly mine in winter 2003 was obtained from the Huntly weather station.

Jarrah emergence was monitored on the 30<sup>th</sup> October 2003, approximately four months post-sowing.

#### *Dieback*

The dieback status (dieback or dieback free) of 2000 and 2001 rehabilitated pits at Huntly and Willowdale was obtained from ARCVIEW and correlated with tree data obtained during Alcoa's routine nine-month botanical monitoring. Analysis was undertaken on all eucalypts.

The 25 plots established for the temperature experiment were also used to monitor damping-off of jarrah seedling due to *Phytophthora* spp. Plots were re-monitored for jarrah survival following the summer drought on the 15<sup>th</sup> March, 2004. Any dead seedlings and 1 kg of surrounding soil were collected and sent to the Department of Environment and Conservation (DEC) for testing. *Phytophthora* spp. were identified by methods employed by the Vegetation Health Service of the DEC.

In May 2004, 12 of the 25 original plots were chosen to investigate the effect of pre-emergent damping-off on jarrah. There were four plots in each of three groups based on the emergence results; high (30% – 38%), mid (10% to 18%) and low (2% to 4%). A total of 24 permeable nylon bags containing 50 jarrah seeds were placed at random along the length of a rip line at each plot. Sachets were pegged at the corners to hold them in the soil and buried at a depth of 2 cm. Sachets were exhumed weekly for a period of six weeks. The first sachet was removed on 11<sup>th</sup> May 2004, one week post sowing, and the final sachet was removed on 15<sup>th</sup> June 2004. Following sachet removal, the number of live and dead germinated seedlings was counted. Dead seedlings were screened for *Phytophthora* spp.

#### *Topsoil handling*

The topsoil spreading date, ripping date and soil age (direct return or

stockpiled > 3 months) of 2000 and 2001 rehabilitated pits at Huntly and Willowdale was obtained from ARCVIEW and correlated with tree data obtained during Alcoa's routine nine-month botanical monitoring. Soil return date was categorised according to month (October-April, 0-7). Ripping date was also categorised according to month (December-April, 0-5). Analysis was undertaken on all eucalypts.

### *Soil Properties*

The 25 plots established for the temperature experiment were also used to monitor the effect of soil substrate on jarrah emergence and survival. There were five different soil substrates with varying numbers of plots in each (shown in brackets); topsoil (7), yellow sandy overburden (3), orange overburden (6), pit floor (3) and pallid clay (6). Overburden depth was measured at four points in each plot, with two sample points on riplines and two in furrows. Holes were hand-augured until they encountered the clay pit floor. One 20 cm x 20 cm x 20 cm surface sample of soil was taken from each site for soil particle size analysis.

Soil samples were sieved into four different fractions based on particle size; >850  $\mu\text{m}$  (large particles, including gravel), 425 -850  $\mu\text{m}$  (coarse sand), 212 -425  $\mu\text{m}$  (fine sand) and <212  $\mu\text{m}$  (silt and clay). Soil particles sized between 20  $\mu\text{m}$  and 2000  $\mu\text{m}$  are broadly classified as sands (International Particle Size Distribution Scale), however in this study are classified relative to each particle size category.

### *Seed theft*

Seed theft was monitored at Huntly mine by placing three replicates of 50 jarrah seeds at 0 m (forest/rehabilitation border), 20 m and 60 m from the pit edge. There were two 2003 rehabilitated pits, each with two replicates. Seeds were contained in uncovered clear petri dishes that were buried at 1 cm depth so that they lay at the soil surface. Seed were placed in the pits in May 2004 during a week of fine sunny weather (maximum temperature range of 25°C to 29°C). The number of seeds remaining was monitored 24 hours and one week after placement.

### *Statistical Analysis*

Jarrah emergence in seeded plots was adjusted to remove emergence resulting from application of the normal seed mix (average of one plant per 16 m<sup>2</sup> plot). Data were analysed using Analysis of Variance (ANOVA) or variables were tested for correlation in MINITAB

12.12<sup>†</sup>. Δατα εξηβιτινγ νον–νορμαλ διστριβυτιονσ ορ υνεθυαλ πα  
ριανχεσ ωερε λογ, σθυαρε ροοτ ορ χυβιχ ροοτ τρανσφορμεδ βεφορε  
αναλψισ. In χασεσ where the ANOVA assumptions continued to be  
violated following data transformation, treatment differences were  
assessed using the more conservative Kruskal-Wallis nonparametric  
analysis.

## RESULTS

### *Temperature*

The variability in jarrah density was not significantly affected by the within-pit slope categories (upper, middle and lower; Fig. 3). Sites rehabilitated in 2002 had significantly ( $P = 0.000$ ) higher jarrah density (1,594 stems  $\text{ha}^{-1}$ , Fig. 3a) compared with sites rehabilitated in 2003 (867 stems  $\text{ha}^{-1}$ , Fig. 3b). There was no difference in density between the Huntly and Willowdale mines.

The elevation above sea level of pits ranged from 245 m to 410 m, however elevation was uncorrelated with jarrah density (Fig. 4a). Sites rehabilitated in 2001 had significantly ( $P = 0.007$ ) higher jarrah density (2,047 stems  $\text{ha}^{-1}$ ) than sites rehabilitated in 2000 (1,487 stems  $\text{ha}^{-1}$ ) or 2002 (1,594 stems  $\text{ha}^{-1}$ ). The mine site did not have a significant effect on density. Position in the landscape also did not have a significant effect on jarrah density, although there was a trend of lower density at the landscape extremities, such as hilltops and lower slopes (Fig. 4b).

Jarrah emergence in the experimentally seeded plots was highly variable across the 25 different sites, ranging from 2% to 38% with a mean of 15%. Generally, the seedlings emerged six to eight weeks after sowing. The local temperature at the 25 sites varied, with differences of up to 8°C in the weekly maximum temperature and differences of 5°C in the weekly minimum temperature. There was a significant positive correlation ( $P = 0.006$ ) between the average weekly maximum temperature and the emergence of jarrah (Fig. 5a). Sites with warmer weekly maximum temperatures had higher jarrah emergence than sites with cooler weekly maximum temperatures. There was also a significant negative correlation ( $P = 0.001$ ) between the average weekly minimum temperature and the emergence of jarrah (Fig. 5b). Sites with cooler weekly minimum temperatures had higher jarrah emergence than sites with warmer weekly minimum temperatures. The sites with the warmer weekly maximums were also those that had the cooler weekly minimums ( $P = 0.067$ ) (Fig.

5c). The rainfall was fairly consistent over the germination period, apart from one week of dry weather following the sowing of seed (Fig. 6). Rainfall occurred every day for three weeks until 16 July 2003, where there were four consecutive dry days. Another three day break from rain occurred on 23 July and 13 August 2003.

### *Phytophthora Dieback*

Soil dieback status had no significant effect on eucalypt density in Huntly 2000 and Willowdale 2001 rehabilitated sites, while the effect in Willowdale 2000 and Huntly 2001 rehabilitated sites was inconsistent. In 2000 rehabilitated sites at Willowdale, there was significantly higher eucalypt density in dieback-free sites (2,285 stems ha<sup>-1</sup>) compared with dieback sites (1,717 stems ha<sup>-1</sup>). In contrast, in 2001 rehabilitated sites at Huntly there was significantly higher eucalypt density in dieback sites (2,824 stems ha<sup>-1</sup>) compared with dieback-free sites (2,242 stems ha<sup>-1</sup>).

Jarrah emergence across the 25 different sites was very similar to survival, with 96% of seedlings surviving when re-monitored on 15<sup>th</sup> March 2004. Only six of a total of 32 (4%) dead jarrah seedlings were recovered to screen for the presence of *Phytophthora* spp.; the other dead seedlings could not be found. No *Phytophthora* spp. were isolated from dead seedlings or the surrounding soil. There was also no pre-emergent damping-off of germinated jarrah seeds due to *Phytophthora* spp. The death of germinated seed prior to emergence was caused by restricted growth in the nylon bags and subsequent seed rot. At one site, *P. cinnamomi* and an unknown *Phytophthora* species were isolated from three of the replicate seed bags, resulting in a 1% infection rate. However, this site had relatively high jarrah emergence (32%).

### *Topsoil Handling*

There was no significant correlation between topsoil return date and eucalypt density at Willowdale mine, while the effect of topsoil return date at Huntly was inconsistent. For instance, soil return date was positively correlated with eucalypt density in Huntly 2000 rehabilitated sites (Fig. 7a) but negatively correlated with eucalypt density in Huntly 2001 rehabilitated sites (Fig. 7b). Ripping date also did not significantly correlate with eucalypt density, apart from Huntly 2000 rehabilitated sites where there was a positive correlation (Fig. 7c). Soil age did not significantly affect eucalypt density except at Willowdale 2000

rehabilitated sites, where direct return soil had higher density (2,314 stems ha<sup>-1</sup>) compared with stockpiled soil (1,784 stems ha<sup>-1</sup>).

### *Soil Properties*

In the five different soil substrates (Fig. 8), there was no significant effect of soil properties on jarrah density (Fig. 9). The overburden depth varied from 0 cm to 73 cm, yet was uncorrelated with jarrah density (Fig. 10). Soil texture varied for each of the 25 sites, with the gravel fraction ranging from 53% to 96%, the coarse sand fraction from 4% to 37%, the fine sand fraction from 0 to 17% and the silt and clay fraction from 0 to 12%. Despite the variation, there was no significant correlation between jarrah emergence and each class of particle size (Fig. 11).

### *Seed Theft*

A negligible level of seed theft (< 2%) was recorded 24 hours and one week after seed placement in the field. The distance from the forest edge had no effect on seed theft. However, at one of the 12 sites used in the pre-emergent damping-off experiment, an unidentified animal had torn through nine of the 24 nylon bags and eaten most of the jarrah seeds.

## **DISCUSSION**

High variability in jarrah emergence was observed across the 25 sites at Huntly mine, confirming the variability reported during the routine nine month monitoring programme. Despite high laboratory germination of jarrah seed (83%), the maximum emergence recorded in the field was 38%. In general, field emergence is lower than laboratory germination due to seed desiccation and loss attributed to uncontrolled environmental factors. Most seedlings had emerged six to eight weeks post-sowing, longer than the three weeks to emergence noted under laboratory conditions (Abbott, 1984). Once seedlings had emerged survival was high, indicating it is during the germination phase that factor(s) are causing the observed variability. Similarly, McChesney *et al.* (1995) found few deaths after emergence, implying factors are affecting the seed prior to emergence.

Temperature was the only factor that was significantly correlated with

jarrah density, with the effect occurring at the emergence stage. The highest jarrah emergence occurred on sites that experienced warmer weekly maxima and cooler weekly minima. Whether it was the warmer or cooler temperatures that increased emergence could not be determined, because sites displaying high emergence had both extremes. However, cold air drainage has been shown to reduce jarrah emergence (Gartrell, 1993). Although most species from Mediterranean-type climate regions have maximal germination at temperatures of 10°C to 15°C, the eucalypts appear to form a cline of increasing capacity to germinate at higher temperatures (Bell and Bellairs, 1992). For example, *Eucalyptus oleosa* exhibited maximal germination at 10°C to 20°C, *E. wandoo* also had high germination at 25°C and *E. rudis* had high germination at 30°C (Bell and Bellairs, 1992). High germination was obtained for *E. camaldulensis* and *E. maculata* by incubating the seeds at 35°C to 38°C and 27°C respectively (Grose, 1965). Moisture levels in the seed microsites also have an important influence on the emergence patterns of eucalypts, especially in open environments such as rehabilitated sites (McChesney *et al.* 1995).

In contrast to Gartrell (1993), we found that eucalypt establishment was not related to the position within the pit. Whereas Gartrell (1993) looked at the extremities of upland and lowland sites, the current study used a broader system of slope categorisation for all rehabilitated sites, which may account for the lack of correlation. The slight trend of lower eucalypt establishment at the landscape extremities (hilltops and near valley floors) was non-significant and may be confounded due to the smaller number of pits in these areas.

Diseases caused by *Phytophthora* spp. were not responsible for the observed variability in the density of nine-month-old jarrah seedlings, and *P. multivora* was not isolated from germinating seeds or perished seedlings. Despite the presence of *P. cinnamomi* in rehabilitated sites, the early eucalypt stocking rates are high and overall mortality is generally low (Colquhoun and Petersen, 1994). The removal of caprock during the mining process actually increases the resistance of rehabilitated sites to dieback infection due to sub-optimal moisture and temperature conditions for pathogen proliferation (Colquhoun and Hardy 2000). While *P. multivora* has caused both pre- and post-emergent damping-off of jarrah in rehabilitated sites (Woodman, 1993), we found no evidence that damping-off is the factor responsible for variable jarrah establishment. Woodman (1993) studied the germination of jarrah and five understorey species in plots containing, *P. cinnamomi*, *P. multivora* and control treatments and found that average emergence was 40% lower in the *P. multivora* treatment. Furthermore, *P. multivora* was recovered from 44% of dead jarrah seedlings. The early mortality of eucalypt species in forest sites has also been attributed to damping-off (Mwanza and Kellas, 1987; Stoneman *et al.*, 1994). The lack of *P. multivora* infection in this study could be due to seasonal variation in temperature and pathogen activity. The pathogen is able to survive for long periods as dormant propagules in the soil, making it extremely difficult to identify contaminated locations and control the pathogen (Colquhoun and Hardy, 2000). In addition, the pre-emergent damping-off experiment was conducted in one-year-old

rehabilitation rather than newly rehabilitated sites, which may have reduced pathogen activity compared with freshly disturbed soil.

Although soil return date, ripping date and soil age exhibited significant correlations with jarrah density in certain mine and year combinations, there was no consistency in the correlation patterns. The month of ripping should not affect the germination of applied seed so long as seeding occurs immediately after soil cultivation (Ward *et al.* 1996), as is the practice for all rehabilitated sites. Ripping late in the season (April) reduces the density of species establishing from the topsoil compared with ripping in December or February (Ward *et al.*, 1996), however jarrah is a bradysporous species and the broadcast seed mix is the main source of return. For this reason, soil age is also unlikely to affect jarrah density, despite numerous studies reporting on the importance of fresh topsoil to increase species richness and abundance (Bellairs and Bell, 1993; Dixon and Meney, 1994; Koch *et al.*, 1996; Norman and Koch, 2005b). Although the time between soil return and the beginning of the germination season ranged from zero to six months, there was no effect on eucalypt establishment.

Despite the large variation in overburden depth between sites, there was no relationship with jarrah survival. The depth of the returned overburden (or the depth to the clay pit floor) influences the amount water available to plants during the summer drought. Soil composed of gravel and coarse material has a limited capacity to hold water due to low porosity, while clay has higher porosity (Craze and Hamilton, 1991). While water storage capacity of the growing medium is not vital during the rainfall season, it will have an effect during the summer drought, because plants survive by accessing soil stored water. Most jarrah mortality occurs in later spring and summer (November to February) as soil water deficits develop and soil temperatures rise, with little further mortality in March (Stoneman *et al.*, 1994).

Jarrah plants growing on sites with a shallow layer of overburden have more water available than jarrah growing on deep overburden, as the taproot can reach the clay to access the stored water. However, jarrah mortality from October to March was negligible. Although survival is higher on clay, germination may be lower because germinating seeds may be unable to exert the greater pressure required to extract water held in clay compared with larger soil particles. The variability in emergence was unrelated to the soil substrate or particle size of the surface soil.

Seed predation was generally absent from the newly rehabilitated sites, however the presence of an unidentified animal eating seeds from pre-emergent damping-off experiment was noted in one-year-old rehabilitated sites. It appears seed predation is minimal in newly rehabilitated sites, probably due to the absence of ant populations and a vegetative cover for fauna. In the jarrah forest, over 40% of jarrah seeds did not germinate because they were harvested and presumably eaten (Abbott, 1984). Similarly, Grant (1997) found high levels of ant predation of jarrah and eastern Australian eucalypt seed following burning in 13-year-old rehabilitation, however the sites were older and already colonised with ants. Grant (1997) found that either most or no seeds were removed, indicating that once ants did find the seeds they tended to remove the entire sample. Seed theft due to ants, mammals and birds did not occur in newly rehabilitated areas and is not the cause of the variability observed in jarrah establishment.

## **CONCLUSIONS**

None of the measured parameters adequately explained the variability in establishment of jarrah from seed in rehabilitated bauxite mines. There was some positive correlation to sites with higher maximum and lower minimum temperatures but most of the variability was not explained by temperature. Once established, most jarrah seedlings survived over the first summer, indicating that establishment and not first summer mortality is highly variable.

## **ACKNOWLEDGEMENTS**

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## REFERENCES

- Abbott, I. (1984). Emergence, early survival, and growth of seedlings of six tree species in Mediterranean forest of Western Australia. *Forest Ecology and Management* **9**: 51-66.
- Bell, D. T. and Bellairs, S. M. (1992). Effects of temperature on the germination of selected Australian native species used in the rehabilitation of bauxite mining disturbance in Western Australia. *Seed Science and Technology* **20**: 47-55.
- Bellairs, S. M. and Bell, D. T. (1993). Seed stores for restoration of species rich shrubland vegetation following mining in Western Australia. *Restoration Ecology* **1**: 231-240.
- Boersma, J. G., Cooke, D. E. L. and Sivasithamparam, K. (2000). A survey of wildflower farms in the south-west of Western Australia for *Phytophthora* spp. Associated with root rots. *Australian Journal of Experimental Agriculture* **40**: 1011-1019.
- Bunny, F. J. (1996). *The biology, ecology and taxonomy of Phytophthora citricola in native plant communities in Western Australia*. PhD Thesis. Murdoch University: Perth.
- Colquhoun I. J., and Hardy G. E. St. J. (2000). Managing the Risks of Phytophthora Root and Collar Rot During Bauxite Mining in the *Eucalyptus marginata* (Jarrah) Forest of Western Australia. *Plant Disease*. **84**:116-127.
- Colquhoun, I. J. and Petersen, A. E. (1994). The impact of plant disease on mining. *The Journal of the Royal Society of Western Australia*, **77**: 151-158.
- Croton, J. T. and Reed, A. J. (2007). Hydrology and Bauxite Mining on the Darling Plateau. *Restoration Ecology Supplement*. **15**:S40-S47.
- Craze, B. and Hamilton, G. J. (1991). Soil physical properties. In 'Soils – their properties and management'. (Eds.) P. E. V. Charman and B. W. Murphy. Soil Conservation Commission of New South Wales: Sydney. pp. 147-164.
- Dixon, K. W. and Meney, K. A. (1994). Seed quality for minesite

rehabilitation. In '*National Workshop on Native Seed Biology for Revegetation*'. (Eds. S. B. Bellairs and L. C. Bell). Australian Centre for Minesite Rehabilitation and The Chamber of Mines and Energy of Western Australia Inc. pp. 15-19.

ESRI (1996) Environmental Systems Research Institute Inc

ArcView  
with GIS  
3.2a for  
Windows  
1996.  
ESRI  
Redlands,  
California.

- Gartrell, C. (1993). *The germination and early establishment ecology of Eucalyptus marginata Donn ex Smith (jarrah), Eucalyptus calophylla R. Br. Ex Lindley (marri), Eucalyptus diversicolor F. Muell. (karri) and Eucalyptus patens Benth. (blackbutt)*. Honours thesis. Botany Department. The University of Western Australia: Perth.
- Grant, C. (1997). *Fire ecology in rehabilitated bauxite mines in the jarrah (Eucalyptus marginata) forest of south-western Australia*. PhD Thesis. The University of Western Australia: Perth.
- Grose, R. J. (1965). *Germination responses of seeds of Victorian eucalypts*. Forestry Technical Paper No. 16. Forests Commission of Victoria: Victoria.
- Koch, J. M., Ward, S. C., Grant, C. D. and Ainsworth, G. L. (1996). Effects of bauxite mine restoration operations on topsoil seed reserves in the jarrah forest of Western Australia. *Restoration Ecology* **4**: 368-376.
- Lockley, I. R. and Koch, J. M. (1996). *Response of two Eucalypt species to fertilizer application on rehabilitated bauxite mines in Western Australia*. Environmental Department Research Bulletin No. 27. Alcoa World Alumina Australia: Perth.
- Majer, J. D. (1978). *Studies on invertebrates in relation to bauxite mining activities in the Darling Range – a review of the first eighteen months research*. Environmental Department Research Bulletin No. 3. Alcoa World Alumina Australia: Perth.
- Mattiske Consulting Pty. Ltd. (2001). *Nine month botanical monitoring of 2000 rehabilitated areas at Jarrahdale, Huntly and Willowdale*. Mattiske Consulting Pty. Ltd.: Perth. (available from Alcoa on request).
- Mattiske Consulting Pty. Ltd. (2002). *Nine month botanical monitoring of 2001 rehabilitated areas at Jarrahdale, Huntly and Willowdale*. Mattiske Consulting Pty. Ltd.: Perth. (available from Alcoa on request).
- McChesney, C. J., Koch, J. M. and Bell, D. T. (1995). Jarrah forest

restoration in Western Australia: canopy and topographic effects.  
*Restoration Ecology* **3**: 105-110.

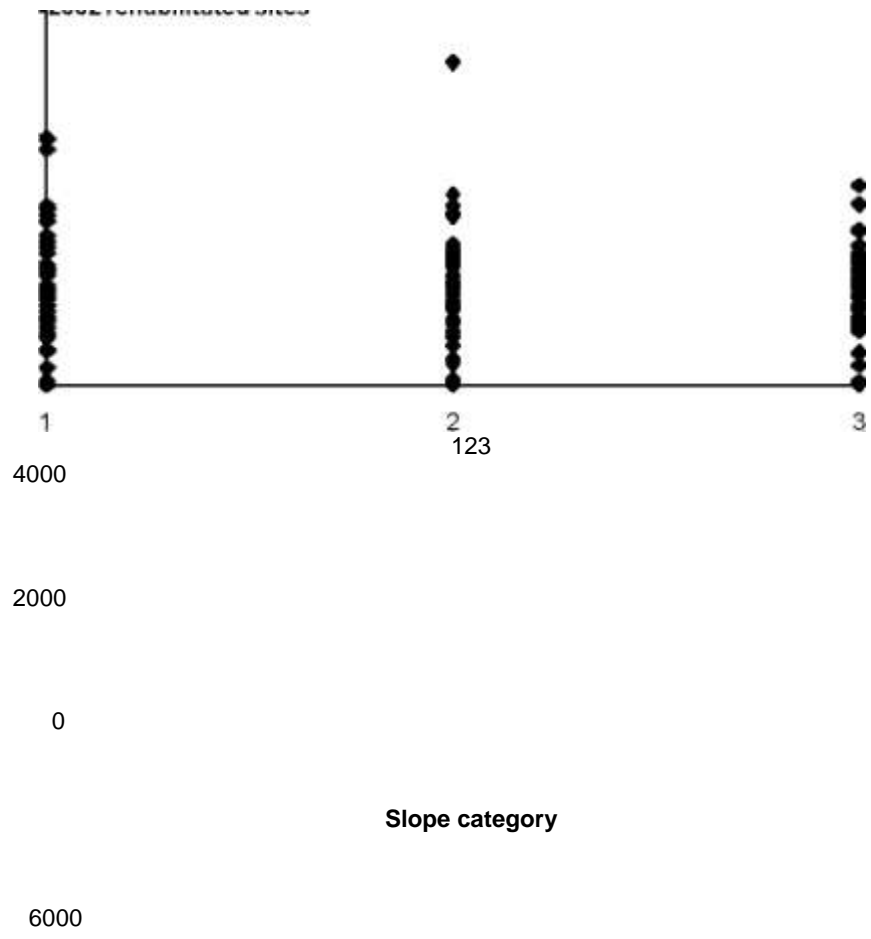
Mwanza, E. J. M. and Kellas, J. D. (1987). Identification of the fungi associated with damping-off in the regeneration of *Eucalyptus obliqua* and *E. radiata* in a central Victorian forest. *European Journal of Forest Pathology* **17**: 237-245.

- Norman, M. and Koch, J. M. (2005a). *The effect of fertiliser application and timing on jarrah and marri growth, density and form in nine-year-old bauxite mine rehabilitation*. Environmental Department Research Note No. 21. Alcoa World Alumina Australia: Perth.
- Norman, M. A. and Koch, J. M. (2005b). *Differences in species abundance between sites rehabilitated with direct return and stockpiled soil*. Environmental Department Research Bulletin No. 33. Alcoa World Alumina Australia: Perth.
- Scott, P. M., Burgess, T. I., Barber, P. A. Shearer, B. L., Stukely, M. J. C., Hardy, G.  
E. St. J. and Jung, T.(2009). *Phytophthora multivora* sp. nov., a new species recovered from declining *Eucalyptus*, *Banksia*, *Agonis* and other plant species in Western Australia. *Persoonia* **22**: 1–13.
- Stoneman, G. L., Dell, B. and Turner, N. C. (1994). Mortality of *Eucalyptus marginata* (jarrah) seedlings in Mediterranean-climate forest in response to overstorey, site, seedbed, fertilizer application and grazing. *Australian Journal of Ecology* **19**: 103-109.
- Ward, S.C., Koch, J.M. and Ainsworth, G.L. (1996). The effect of timing of rehabilitation procedures on the establishment of a jarrah forest after bauxite mining. *Restoration Ecology* **4**: 19-24.
- Woodman, G. J. (1993). Damping-off of indigenous jarrah forest plant species by *Phytophthora cinnamomi* and *Phytophthora citricola* in bauxite pit rehabilitation in the northern jarrah forest. Hons. Thesis. Murdoch University: Perth.

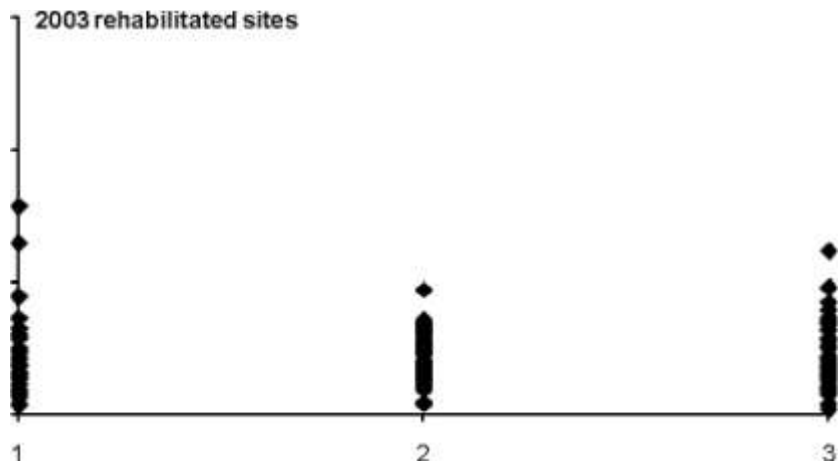
**2002 rehabilitated sites**

(a) 6000

**Jarraah density/ha**



(b)



Jarrah density/ha

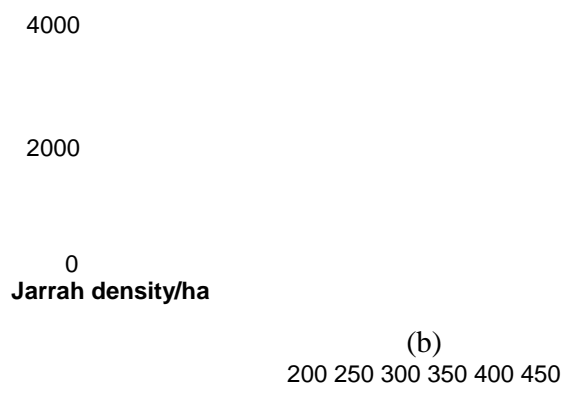
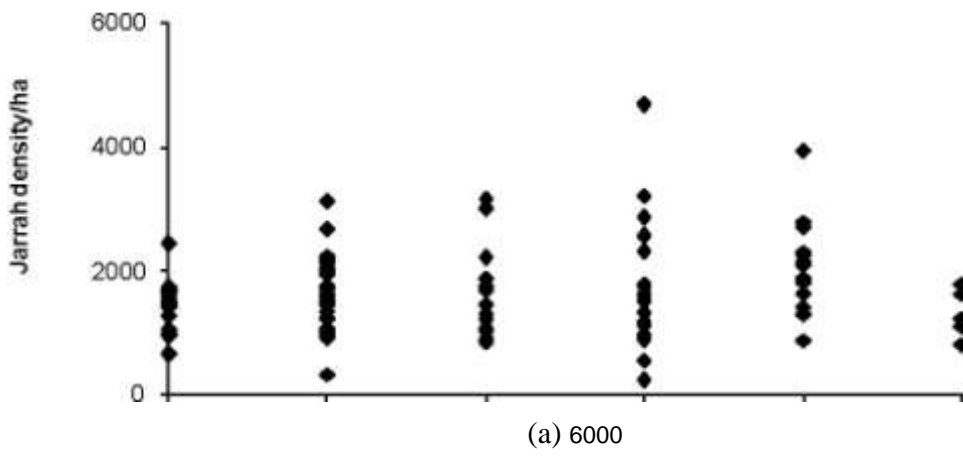
4000

2000

0

**Slope category**

**Figure 3:** Jarrah density (stems ha<sup>-1</sup>) in relation to within-pit slope in (a) 2002 and (b) 2003 rehabilitated pits at Huntly and Willowdale mines (pooled). Pits were divided into upper (1), middle (2) and lower (3) slope areas.



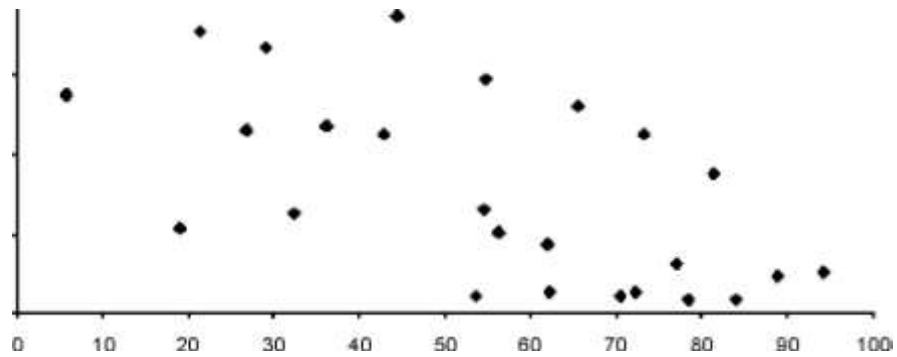
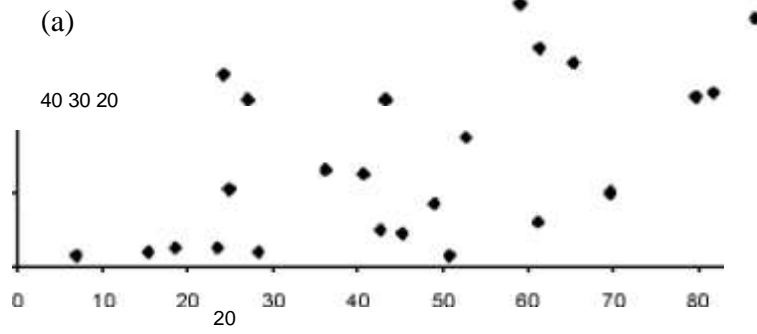
Elevation above sea level (m)

123456

Slope category

**Figure 4:** Jarrah density (stems ha<sup>-1</sup>) in relation to (a) elevation above sea level and

(b) position in the landscape. For position in the landscape, pits were assigned a slope category from 1 (hilltop) to 6 (lower slope near valley floor).



Temperature (°C) Emergence (%)  
 Emergence (%)

0 10 20 30 40  
 50 60 70 80  
 90 100

Maximum  
 temperature  
 (range  
 standardised)

0 10 20 30 40 50 60 70 80 90 100

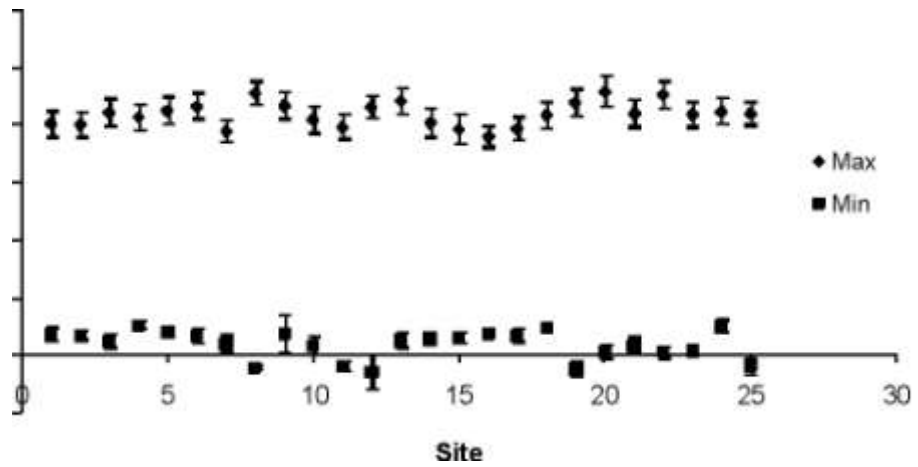
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(b) 40  
 30

a t u r e  
 ( r a n g e  
 s t a n d  
 a r d i s e d )  
 (c) 30 25 20 15 10 5  
 0 -5

**Figure 5:** Jarrah emergence (%) in relation to the range standardised weekly average

(a) maximum temperatures and (b) minimum temperatures at the sites from July to September 2003. The average weekly maximum and minimum temperatures for each site (c).



**Daily  
Rainfall  
(mm)**

60 50  
40 30  
20 10  
0



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us ra n  
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15 ll 6<sup>t</sup>  
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June ig m to  
16-30 u m A

ugust

15<sup>th</sup>

2003 at

Huntly

mine

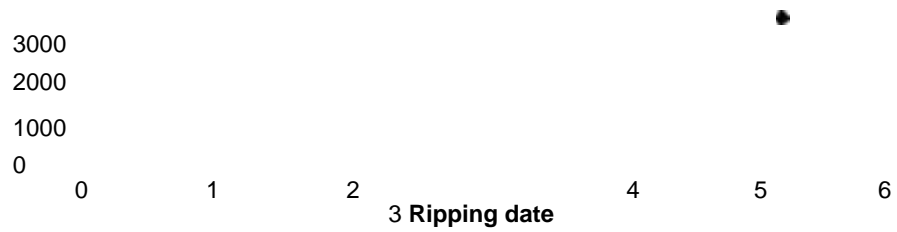
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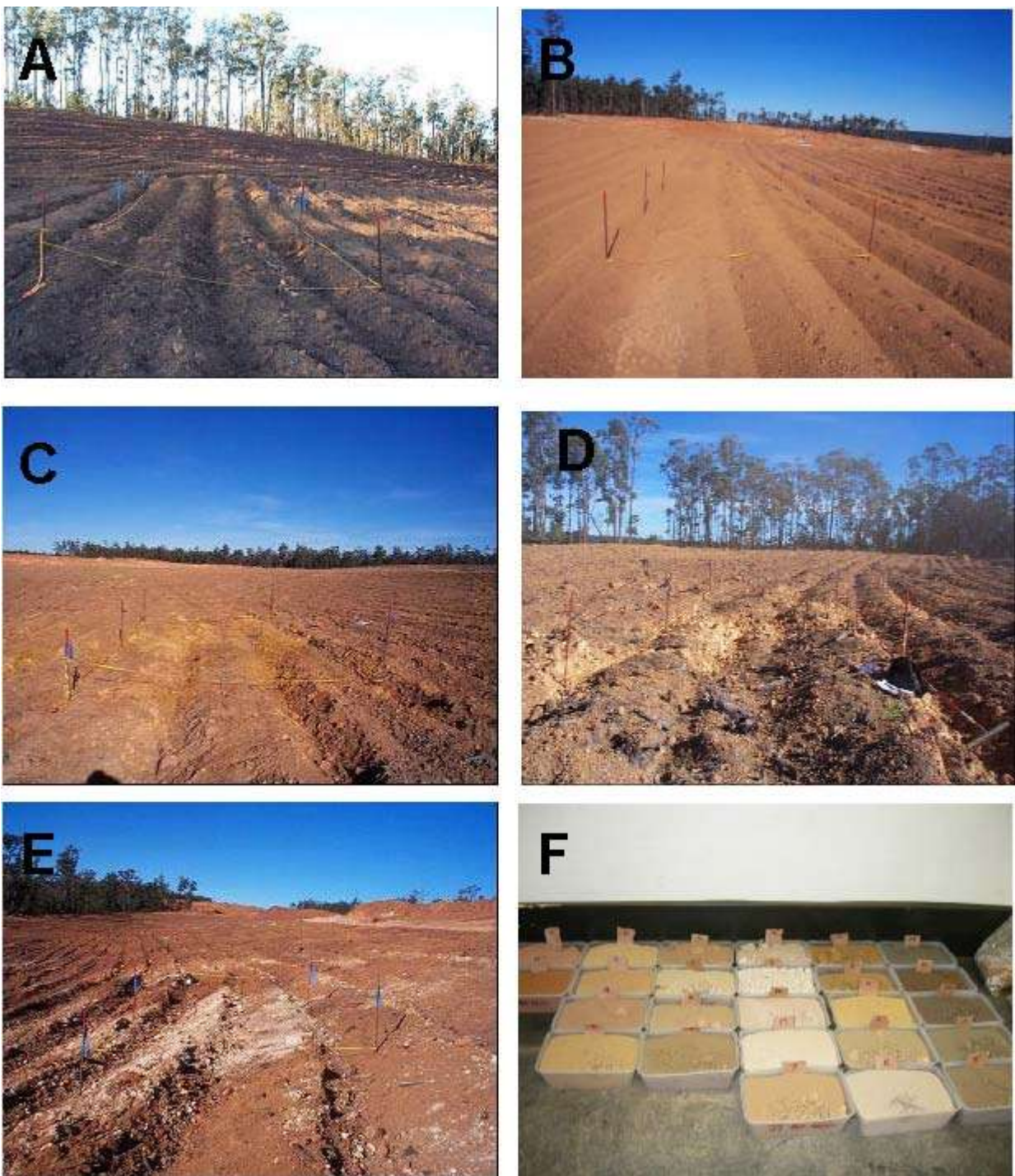
15



**Eucalypt density/ha**

**Figure 7:** Correlation of eucalypt density (stems ha<sup>-1</sup>) and (a) Huntly 2000 soil return date, (b) Huntly 2001 soil return date and (c) Huntly 2000 ripping date. Soil return date is categorised from October to April (0-7) and ripping date is categorised from December to April (0-5).





**Figure 8:** Twenty-five sites were established on five different soil types ranging from a) topsoil, b) sandy yellow overburden, c) orange overburden, d) pit floor and e) white pallid clay. The colour variation within each group is illustrated in the soil trays (f).

**Jarrah emergence (%)**

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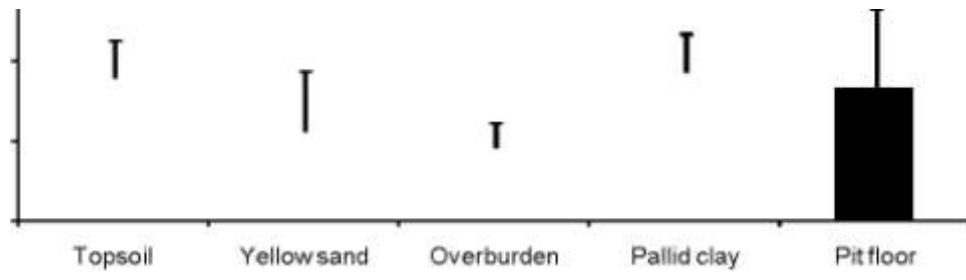
0

2

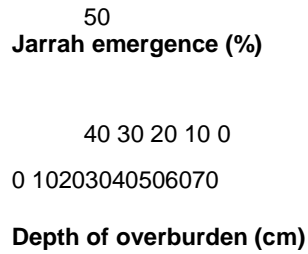
0

1

0

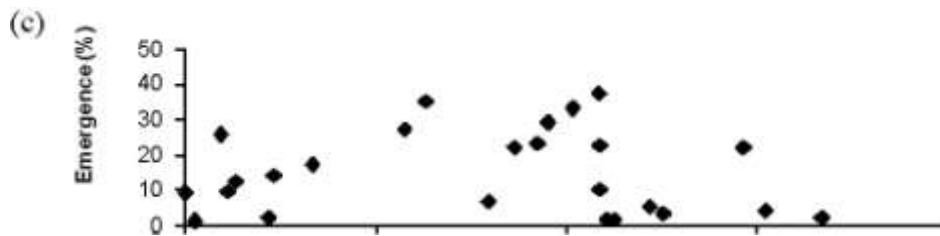
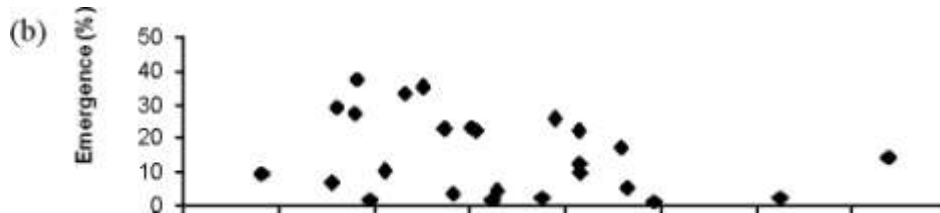


**Figure 9:** Jarrah emergence (%) on five different soil substrates; topsoil, yellow sand, overburden, pallid clay and pit floor. There was no significant effect of soil substrate on jarrah establishment ( $P > 0.05$ ).



**Figure 10:** Jarrah establishment (%) in relation to the depth of overburden (cm). There was no significant correlation between jarrah establishment and the depth of overburden ( $P > 0.05$ ).





30

Emergence (%)

20 10 0

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%)  
)

50 60 70 80 90 100

Percentage of gravel (>850um) in soil

0 5 10 15 20 25 30 35 40

Percentage of coarse sand particles (425-850um) in soil

0 5 10 15 20

Percentage of fine sand particles (212-425 um) in soil

0 0.5 1 1.5 2 0

(d) 50 40 30 20 10



Percentage of silt and clay particles (<212 um) in soil

Figure 11: Jarrah emergence (%) in relation to different particle sizes;

(a) >850 μm (gravel), (b) 425 – 850 μm (coarse sand), (c) 212 – 425 μm (fine sand) and (d) <212 μm (silt and clay). There was no significant correlation between jarrah emergence and soil particle size (P > 0.05).

▪ (τ)Z<sub>f</sub><sup>s</sup>

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.....  
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