

Thirteen-year growth of jarrah (*Eucalyptus marginata*) on rehabilitated bauxite mines in south-western Australia

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Summary

Alcoa's objective is to restore its bauxite mines in south-western Australia to a productive self-sustaining jarrah forest. This paper describes the growth and form of 13-y-old jarrah (*Eucalyptus marginata*) trees established from seed and planted seedlings, and subject to various fertiliser, understorey seed and spacing treatments.

Seeded jarrah had a mean establishment density of 2662 stems ha⁻¹ and a density of 2300 stems ha⁻¹ after 13 y, a survival rate of 86%. Sixty-two per cent of the seeded trees developed into saplings (> 1.5 m tall). The saplings had a mean height of 9.0 m and dbh of 14.4 cm after 13 y. The mean density of potential sawlogs (trees with a single stem to at least 2 m) was 1297 stems ha⁻¹ after 13 y. The presence of tall native legumes (acacias) decreased the percentage of trees that became saplings from 72% to 53%. When N fertiliser was not provided the legumes had a suppressive effect on the basal area and bole volume of potential sawlogs, reducing them to 60% and 57%, respectively, of the values without legumes.

Planted jarrah trees had a mean survival rate over all treatments of 84% after 13 y. Closer tree spacing (particularly 1 m × 1 m) resulted in significantly lower survival (77%) than the wider spacings. Inclusion of tall native legumes with closer tree spacing reduced survival even more (69% at 1 m × 1 m). The mean sapling height across all planted treatments was 9.1 m. The mean dbh was 15.2 cm with 67% becoming saplings. Closer tree spacing had the strongest effect in significantly reducing all of these parameters. Tall native legumes reduced the dbh of the jarrah trees and reduced the overall mean height of all jarrah by limiting the proportion of jarrah that became saplings.

Absence of added N fertiliser also significantly reduced these measures. Basal areas were similar in rehabilitated and unmined forest after 13 y. Mean annual growth increments (1.52 m² ha⁻¹ seeded, 2.72 m² ha⁻¹ planted) were similar to those reported for similar aged regrowth forest (2.62 m² ha⁻¹) and higher than older thinned (0.45 m² ha⁻¹) or unthinned (0.19 m² ha⁻¹) unmined forest. Basal area increments were higher from 8–13 y than 0–8 y, indicating that growth rates were not slowing down over this period.

The optimum stocking rate for jarrah in rehabilitated bauxite mines will be a balance between growth rate, tree form, other

environmental factors and cost considerations. The current rehabilitation prescription aims to establish 1300 stems ha⁻¹ of 'total eucalypts' by broadcast seeding (jarrah and marri — *Corymbia calophylla*). This study indicates that an initial stocking of 1300 stems ha⁻¹ is optimum and meets Alcoa's mine rehabilitation completion criterion of providing at least 300 potential sawlogs ha⁻¹ at 15 y of age.

Keywords: forests; bauxite; mining; rehabilitation; soil treatment; understorey; stand density; survival; growth rate; habit; jarrah; *Eucalyptus marginata*; Western Australia

Introduction

Alcoa World Alumina Australia operates two bauxite mines, at Willowdale and Huntly, in the Darling Plateau of Western Australia. The Del Park mine had operated from 1969 to 1992 and the Jarrahdale mine from 1963 to 1998, but both have now been decommissioned and rehabilitated. Mining takes place within indigenous eucalypt forest dominated by jarrah (*Eucalyptus marginata* Donn ex Smith). Alcoa has been rehabilitating its mines since 1966. Currently, about 550 ha are mined and rehabilitated annually. The objective is to re-establish a jarrah forest ecosystem fulfilling all of the pre-mining land uses including water production, timber, conservation and recreation. Detailed descriptions of the mining and rehabilitation process are provided by Ward *et al.* (1993) and Gardner (2001).

Growth of jarrah in the existing forest (Loneragan 1961; Abbott and Loneragan 1986; Abbott *et al.* 1989) and in response to various silvicultural treatments in the forest (Chandler 1939; Abbott and Loneragan 1983a,b; Abbott and Loneragan 1986; Stoneman *et al.* 1996) has been well documented. These studies show that jarrah is relatively slow growing, particularly in the uncut forest, and that the greatest growth responses occur after thinning. High rates of fertiliser application (Stoneman *et al.* 1996), especially in combination with thinning, may also produce a response. Drought appears to be the main factor limiting jarrah growth (Stoneman *et al.* 1996).

Jarrah has been tested in plantations in South Africa, the USA, India and the West Indies with little success — usually due to poor form and relatively slow growth (Poynton 1979; Abbott and Loneragan 1986). Planted jarrah growing in arboreta in Western Australia has also shown poor form (Abbott and Loneragan 1986). While survival of jarrah has been satisfactory

on bauxite mines, it has often displayed poor form (multiple stems) when planted as seedlings compared with jarrah established from broadcast seed (Ward and Koch 1995).

This study was designed to investigate the development and growth of direct-seeded and planted jarrah seedlings on bauxite mines in response to a variety of rehabilitation treatments. It has been shown (Ward and Koch 1995) that during the first 4 y of growth jarrah seedlings grew faster in rehabilitated areas than in unmined forest, and that 63% of plants when seeded and 66% when planted developed stems with sapling form, that is, stems taller than 1.5 m. Tree heights, the proportion of plants that developed into saplings and the proportion of multiple stems increased where the trees had more resources, for example, through the application of N fertiliser, the reduction of tree density or the planting of a less competitive understorey.

The objectives of this paper are to:

- document and compare the growth of jarrah in seeded and planted rehabilitated areas
- compare the growth of jarrah across fertiliser, understorey seed and spacing treatments
- compare jarrah growth in rehabilitated areas with that in unmined forest
- recommend best practice to establish and grow jarrah in rehabilitated areas.

Methods

Seeded jarrah

The seeded jarrah experiment was based on a randomised block design with four treatments replicated at nine sites (blocks). Two sites were at Jarrahdale (Peacock and Fantail), two at Huntly (Possum and Potoroo), three at Del Park (Scribbly, Bullich and Karri), and two at Willowdale (Scarp North and Wriggly). Mean annual rainfall at all sites is 1200 mm. At each of the nine sites, an area of about 1 ha was divided into four plots to investigate the growth of jarrah from seed. Basal treatments applied to the whole of each experimental area were:

- jarrah seed, broadcast by hand in May–June 1988 at the rate of 2.5 kg ha⁻¹ (32 500 viable seeds ha⁻¹). The one jarrah seedlot was used at all sites. The aim was to establish 2000 jarrah plants ha⁻¹.
- seed of 80 small non-leguminous native understorey species ('minor mix') broadcast at 0.5 kg ha⁻¹
- fertiliser, 500 kg ha⁻¹ of 'Superphosphate No. 1' (41 kg P ha⁻¹, 3.3 kg Cu ha⁻¹, 1.5 kg Zn ha⁻¹ and 0.2 kg Mo ha⁻¹).

The experimental treatments examined two factors, each at two levels ('nil' or 'one') in combination:

- seed of 14 fast-growing native leguminous understorey species ('L') ('major mix'), mostly acacias, many of which grow >2 m high, broadcast at a rate of 2.0 kg ha⁻¹
- additional fertiliser ('F') (diammonium phosphate (DAP), 250 kg ha⁻¹, supplying 43.75 kg N ha⁻¹ and 50 kg P ha⁻¹).

Thus the four treatments were control, L, F and LF.

Planted jarrah

The planted jarrah experiment was a split-split plot design replicated at five of the nine sites (Peacock, Possum, Scribbly, Karri and Scarp North) used for the seeded jarrah.

Basal treatments applied to the whole of each experimental area were:

- minor mix seed, as above
- fertiliser, 500 kg ha⁻¹ of 'Superphosphate No. 1', as above.

The experimental treatments examined factorial combinations of:

- seedling density (625, 1250, 2500 or 10 000 trees ha⁻¹, or 4 m × 4 m, 2 m × 4 m, 2 m × 2 m or 1 m × 1 m spacing)
- leguminous understorey ('L') (nil or major mix seed, as above)
- additional fertiliser (0, 50 g, 100 g or 200 g tablets of DAP per tree or 250 kg ha⁻¹ broadcast DAP).

The main-plot treatment was seedling density, the sub-plot treatment was leguminous understorey, and the sub-sub-plot treatment was additional fertiliser. Each of the 40 treatments at each site consisted of ten rows of ten trees. The seedlings were 15–20 cm tall when planted. The DAP tablets were placed about 15 cm from each tree. In total 20 000 seedlings were planted in June 1988.

Monitoring

The density and heights of the trees in each seeded treatment at each site were measured after 1, 2, 5, 8 and 13 y. Sixteen per cent of each plot was sampled by means of permanently marked transects 2 m wide. The heights of the planted trees were measured after 1, 2, 4, 8 and 13 y. Only the data from the central 6 × 6 rows of trees in each planted plot were included in the analysis to allow a buffer strip of two rows of trees around each plot. The mortality rate for each plot was calculated from the total number of dead and missing trees in these central 6 × 6 rows.

For seeded and planted trees >1.3 m tall, the number of stems at heights of 0, 0.5, 1, 2, 4 and 8 m was recorded after 5 (4 in planted), 8 and 13 y. At 8 and 13 y the diameter at breast height over bark (dbhob) of all trees greater than 2 m tall was also measured. At 13 y the bole height of the trees was measured. This is the height at which the bole splits into smaller branches. The bole volume of the trees was calculated from the allometric relationship of Abbott and Loneragan (1986):

$$\text{bole volume (m}^3\text{, under bark)} = \text{basal area (m}^2\text{, over bark)} \\ \times \text{bole length (m)} \times 0.29 \text{ (artificial form factor).}$$

Data analyses

For multi-stemmed trees, the 'total dbhob per tree' was calculated as the square root of the sum of the squares of the diameters at breast height of the individual stems. Saplings were defined as trees that were taller than 1.5 m (Abbott and Loneragan 1986). At the 13-y assessment, potential crop trees were defined as those >3 m tall and with a single stem at 2 m. This fits approximately with the minimum sawlog length of 2.1 m (CALM 1999). Trees

with multiple stems at ground level may also provide future sawlogs if they are form pruned, but these were not included as potential sawlogs in these analyses.

Basal area under bark was derived from diameters overbark using the relationship of Grant *et al.* (1997):

$$\text{bark thickness (mm)} = -10.92 + 28.87 \times \log(\text{dbhob (cm)}).$$

All data were analysed by analysis of variance using MINITAB® version 13.1. For the seeded treatments, the nine sites were used as replicate blocks of a 2 × 2 factorial. The Anderson-Darling normality test was used to decide whether data should be transformed. No transformations were necessary. For the planted treatments the analysis used the split-split plot design with appropriate error terms. The data were tested again for normality but no transformations were necessary.

Results

Seeded jarrah

Tree density and survival

The mean establishment density of seeded areas was 2662 seedlings ha⁻¹, representing a mean establishment rate of 8.2% from applied seed (Table 1). After 13 y the mean density was 2300 ha⁻¹, a mean survival of 86%. There was no significant effect of leguminous understorey or fertiliser on survival during the 13 y.

Despite receiving the same seed application rate per hectare, the mean density of jarrah establishing from seed varied significantly ($P < 0.001$) between sites and ranged from 1104 to 5829 stems ha⁻¹ (Table 1).

Table 1. Density of seeded jarrah at nine sites at ages 1 and 13 y

Site	Density at 1 y (stems ha ⁻¹)	Rate of establishment ^a at 1 y (%)	Density at 13 y (stems ha ⁻¹)
Bullich	5829	17.9	4875
Karri Rd	3825	11.8	2942
Scribbly	3404	10.5	2821
Potoroo	2444	7.5	2176
Possum	2253	6.9	2280
Peacock	2142	6.6	2063
Scarp North	1667	5.1	1346
Wriggly	1292	4.0	971
Fantail	1104	3.4	1229
Mean	2662	8.2	2300
SE	496	1.4	394

^aCalculated from the seedling density at 1 y divided by the seed application rate of 32 500 viable seeds ha⁻¹

Table 2. Attributes of trees growing from seed, at different ages, in response to fertiliser and understorey treatments. Within a row, numbers with the same letter are not significantly different at $P = 0.05$.

Attribute	Treatment				Mean
	Control	L	F	LF	
Survival @ 13 y (%)	83.6	79.2	88.7	98.9	87.6
Percentage which were saplings ^a @					
5 y (%)	49.2b	33.0b	73.2a	56.1ab	52.9
8 y (%)	62.6	55.28	73.7	58.6	62.5
13 y (%)	67.2a	49.6b	75.0a	57.4ab	62.3
Mean height of saplings (m) @					
5 y (m)	2.74c	2.80bc	3.38a	3.14b	3.02
8 y (m)	5.02ab	4.12b	5.76a	5.39ab	5.07
13 y (m)	8.44	8.88	9.22	9.60	9.04
13 y (m) ^b	8.39a	9.11ab	9.11ab	10.48b	9.28
13 y ^a tallest 300 ^c (m)	11.18	10.47	11.73	12.72	11.56
Mean dbhob @					
13 y ^b (cm)	11.43a	13.29ab	12.12a	14.80b	12.90
13 y ^a tallest 300 ^c (cm)	15.55	15.21	15.30	17.83	16.00
Trees of good form ^d :					
Percentage @ 5 y ^b (%)	48.5b	85.5a	44.5b	74.5a	63.3
Percentage @ 13 y ^b (%)	61.8b	69.4a	54.8b	79.5a	66.3
Stocking @ 13 y ^a (no. ha ⁻¹)	1633ab	652a	1647b	875ab	1218
Trees of best form ^e					
Percentage @ 13 y (%)	42.5	30.64	36.98	48.24	39.6

^a Saplings = trees >1.5 m tall

^b Of the trees that were >3 m tall, this is the percentage that had a single stem at a height of 2 m

^c Tallest 300 = the tallest 300 trees ha⁻¹ of good form (i.e. with a single stem at a height of 2 m)

^d Trees with a single stem at a height of 2 m

^e Of the trees that were >6 m tall, this is the percentage that had a single stem at a height of 4 m

Growth and form

Overall, 53% of seedlings reached sapling stage after 5 y and this fraction increased to 62% after 13 y (Table 2). The percentage of trees becoming saplings was significantly greater in the F treatment than in the L treatment at 5 y and at 13 y, but not at 8 y (Table 2). In the L and LF plots, at age 13 y, the percentage of jarrah reaching sapling stage was significantly reduced (54% vs 71% for control and F combined). After about 8 y the percentage of jarrah reaching sapling stage tended to stabilise, although by 13 y the percentage saplings in the L treatment had declined (Table 2). The F treatment had no significant effect on the percentage of jarrah reaching sapling stage at 13 y.

There was a significant positive linear relationship between total density and density of trees of good form (those with a single stem at 2 m) at 13 y for both seeded and planted trees (Fig. 1). The ratio of trees of good form to total trees was slightly higher for seeded trees than planted trees (0.36 vs 0.33). The density of trees of good form was compared between seeded and planted trees at 625, 1250 and 2500 stems ha^{-1} . Seeded plots with total density values within $\pm 25\%$ of each of the three planted densities were used in the comparison. (A comparison could not be made with the planted density of 10 000 stems ha^{-1} because there were no seeded plots with a similar density). The density of trees of good form was significantly greater in seeded sites than in planted sites at total densities of 625 stems ha^{-1} (467 vs 192 good stems ha^{-1} , $P = 0.001$) and 1250 stems ha^{-1} (756 vs 448 good stems ha^{-1} , $P = 0.019$) but not at a density of 2500 stems ha^{-1} (1330 vs 968 good stems ha^{-1} , $P = 0.089$) (Fig. 1).

The mean height of seeded jarrah reaching sapling stage was 3.0 m at 5 y and 9.0 m at 13 y. There was no significant difference in mean sapling height in response to the L or F treatments at 13 y. However, the mean height of trees of good form in the LF treatment was significantly greater than in the control.

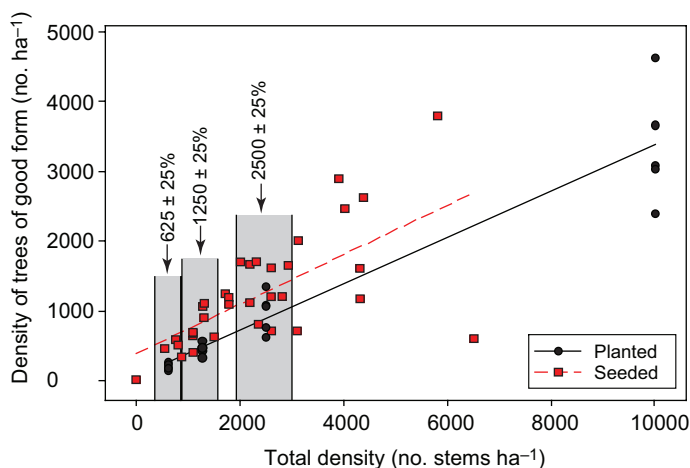


Figure 1. Relationship between total density and density of trees of good form at 13 y. Trees of good form are those >3 m tall with a single stem at 2 m. Seeded trees $r^2 = 0.452$, $P = 0.001$, $n = 36$ (9 sites \times 4 understory/fertiliser treatments). Planted trees $r^2 = 0.905$, $P = 0.0001$, $n = 20$. Density of trees of good form was compared between seeded and planted trees at 625, 1250 and 2500 stems ha^{-1} . Seeded plots with total density values within $\pm 25\%$ of each of the three planted densities were used for comparison, as indicated on the graph.

The percentage of trees of good form and >3 m tall at 5 y and 13 y was significantly greater in the L and LF treatments than in the control and F treatments (Table 2, Fig. 2). However, the stocking of trees of good form was lower with an L understory because a smaller fraction of the total jarrah trees reached sapling stage (Fig. 2). There was no relationship between the density of trees taller than 3 m and the percentage of them with a single stem at 2 m either among plots with legumes or among those without (Fig. 2).

The mean dbhob of trees of good form was 12.9 cm at 13 y. As with height, L and F treatments resulted in trees of good form having larger diameter. The L and LF treatments resulted in a lower stocking of trees of good form than the control and F treatments (Table 2).

The mean height and dbhob of the tallest 300 trees ha^{-1} of good form (likely future sawlogs) were 11.56 m and 16.0 cm respectively, and were not significantly affected by treatment (Table 2).

Basal area and wood volumes

After 13 y the mean basal area of seeded saplings was 22.5 $\text{m}^2 \text{ha}^{-1}$ with a range of 5.6–69.5 $\text{m}^2 \text{ha}^{-1}$ over all plots. The mean bole volume of seeded saplings was 54 $\text{m}^3 \text{ha}^{-1}$ with a range of 0–184 $\text{m}^3 \text{ha}^{-1}$. These large ranges are due to variable densities, not growth rates. The basal area and bole volume of saplings in the F treatment were significantly greater than those in the L treatment (Figs 3a,b).

For seeded saplings the mean annual increment (MAI) in basal area over 13 y was 1.52 $\text{m}^2 \text{ha}^{-1}$ (Table 3) and the mean annual wood volume increment was 4.2 $\text{m}^3 \text{ha}^{-1}$.

Over all treatments the mean stocking of potential sawlogs was 1218 stems ha^{-1} and these had a basal area and bole volume of

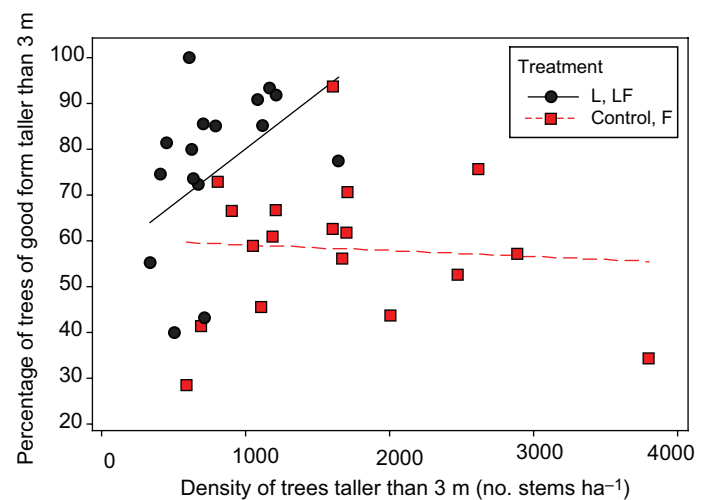


Figure 2. Relationship between density of seeded trees taller than 3 m and the percentage of these that were good form for the understory treatment at 13 y. See the footnote to Table 2 for a definition of the understory treatments. Trees of good form are those > 3 m tall with a single stem at 2 m. Neither of the relationships was significant.

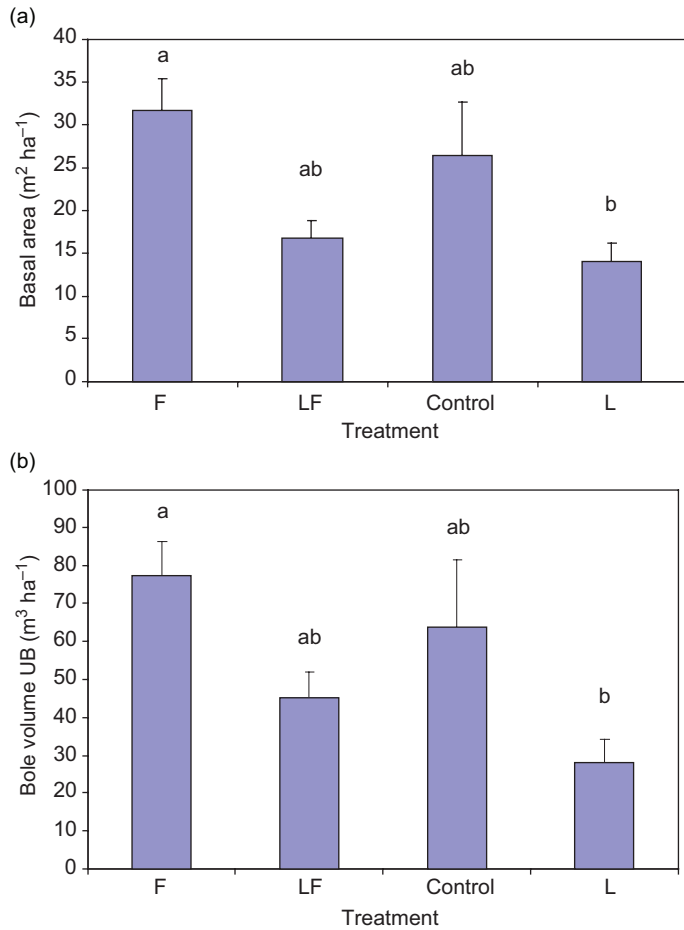


Figure 3. (a) Basal area over bark and (b) bole volume under bark of seeded jarrah saplings after 13 y in response to fertiliser and understorey seed treatments. Error bars are one standard error. Values with the same letter are not significantly different at $P = 0.05$.

Table 3. Periodic mean annual increment in basal area over bark for seeded jarrah saplings in rehabilitated bauxite mines

Treatment	Basal area increment of all saplings (m² ha⁻¹) for the periods:		
	0–8 y	8–13 y	0–13 y
All seeded treatments	1.22	2.02	1.52
Seeded treatments with legumes (L, LF)	0.65	1.66	1.04
Seeded treatments without legumes (Control, F)	1.79	2.38	2.02

10.4 m² ha⁻¹ and 24.6 m³ ha⁻¹ respectively after 13 y. The addition of DAP fertiliser (F) increased the basal area and bole volume of potential sawlogs after 13 y (Figs 4a,b). When this fertiliser was not provided, the legumes (L) suppressed the basal area and bole volume of potential sawlogs, reducing them to 60% and 57% respectively of the values in the control treatment (Figs 4a,b). When F was provided the basal area and bole volume of potential sawlogs was not significantly affected by L (Fig. 4a,b). Basal area of the tallest 300 single-stemmed trees ha⁻¹ was 6.2 m² ha⁻¹, and was not significantly affected by either F or L (Fig. 5).

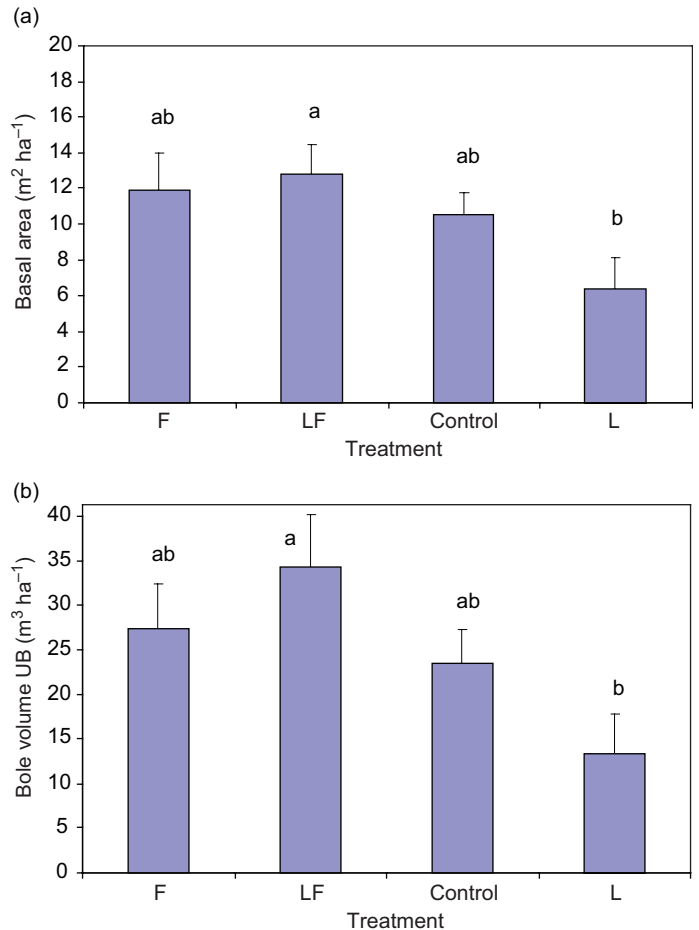


Figure 4. (a) Basal area over bark and (b) bole volume under bark of potential jarrah crop trees in seeded treatments after 13 y in response to fertiliser and understorey seed treatments. Error bars are one standard error. Values with the same letter are not significantly different at $P = 0.05$.

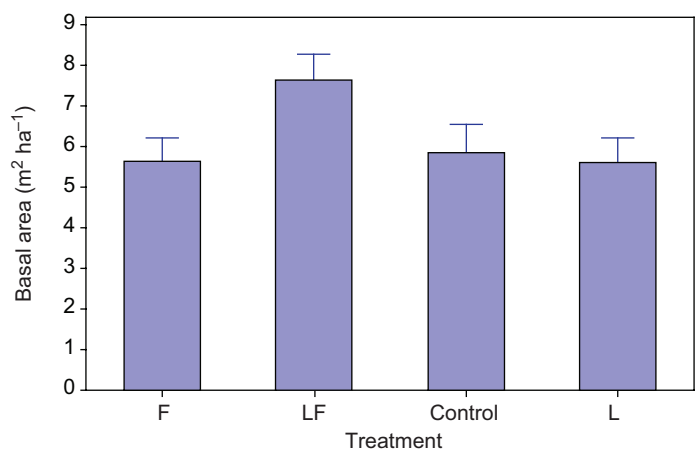


Figure 5. Seeded trees: basal area over bark of the 300 tallest single-stemmed trees ha⁻¹ in response to fertiliser and seed treatment. Error bars are one standard error. There was no significant difference in basal area due to treatment at $P = 0.05$.

Planted jarrah

Survival

Mean survival of planted jarrah over all treatments and all sites was 84.2% at 13 y. Survival rate was most strongly related to the spacing of planted trees, and there was greatest and continuing mortality at the dense spacing of 1 m × 1 m (77.3% survival, Fig. 6). Survival did not vary according to fertiliser type, but was significantly lower at 13 y in treatments with a leguminous understorey (80.7% versus 87.6%). There was a significant interaction between understorey treatment and tree spacing, with much lower survival (68.6%) in the 1 m × 1 m spacing where a leguminous understorey was present, compared with this spacing treatment without the legumes (86.1%, Fig. 7).

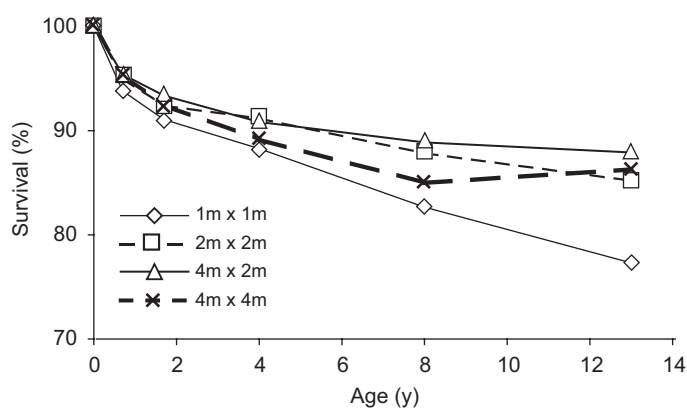


Figure 6. Mean survival in relation to planted tree spacing over 13 y. The 1 m × 1 m spacing had significantly lower survival than the other spacings at 13 y ($P < 0.05$).

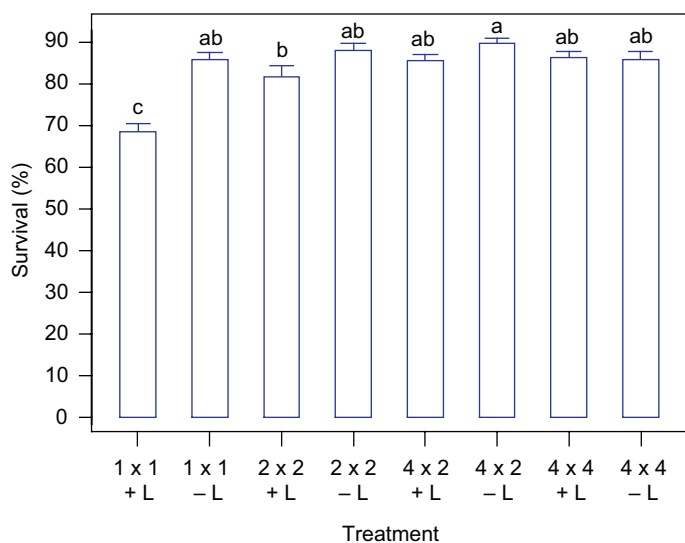


Figure 7. Planted tree survival after 13 y showing interaction between tree spacing and understorey seed. Treatments with the same letter are not significantly different at $P = 0.05$. Error bars are one standard error.

Growth

Over all planted treatments the mean sapling height was 9.1 m and dbhob 15.2 cm, and 67% of the trees became saplings. Planted trees at 13 y had significantly lower height, dbhob and fraction of trees as saplings where no DAP fertiliser was applied (Table 4). The mean basal area of all planted trees was 35.4 m² ha⁻¹, representing a mean annual increment of 2.72 m² ha⁻¹ (Table 5). There was a trend of increasing basal area and bole volume at higher levels of fertiliser application, but the differences were significant only between the lowest and higher rates of fertiliser application (Table 4). Understorey legumes (L) reduced the mean height of all jarrah by reducing the percentage of jarrah that became saplings, but did not affect the height of jarrah saplings (Table 4). The tallest 300 single-stemmed trees ha⁻¹ had a larger mean diameter, height and bole volume when grown with DAP fertiliser, and were also larger in the leguminous understorey treatments than in plots without this understorey (Table 4).

Closer tree spacing significantly reduced height and dbhob. However, the basal area and bole volume of single-stemmed trees increased significantly at closer tree spacing (Table 5). For saplings, closer spacing increased the percentage that was single-stemmed, but closer spacing also decreased the percentage of trees that became saplings. This dual effect resulted in similar percentages of total trees becoming single-stemmed at 2 m height. The tallest 300 single-stemmed trees ha⁻¹ had a larger mean diameter, height and bole volume at wider spacings, except for 4 m × 4 m which had less than 300 single-stemmed trees ha⁻¹. Bole volume was significantly lower at the widest spacing of 4 m × 4 m but was the same for all spacings of 4 m × 2 m and closer (Table 5). Closer spacing resulted in more small-diameter trees. At 1 m × 1 m spacing there were very few trees with a dbhob ≥ 20 cm (Fig. 8). As the spacing widened the diameter of the trees increased until at 4 m × 4 m more than half the trees had a dbhob ≥ 20 cm (Fig. 8).

Discussion

Growth rates compared to forest

Comparing growth rates of jarrah in the rehabilitated mined areas to those in the unmined forest is difficult because the mined areas are a 'new' ecosystem with no pre-existing overstorey. Growth in the unmined forest on the other hand is variously affected by tree age, logging history, stand density and other factors. The best comparison may be with heavily cut-over forest sites over the same age range. Regrowth in those sites has similar growth rates to the mined areas (cut-over 2.26 m² ha⁻¹ y⁻¹ from 0 to 10 y (Stoneman *et al.* 1988), mined and seeded 1.52 m² ha⁻¹ y⁻¹, mined and planted 2.72 m² ha⁻¹ y⁻¹). As expected, old forest has lower growth rates (0.19 m² ha⁻¹ y⁻¹). Mean annual increments (MAIs) of bole volumes under bark of 4.2–4.7 m³ ha⁻¹ in mined sites are also more typical of heavily cut or clearfelled forests at regrowth stages (4–8 m³ ha⁻¹ Parkes 2001; Cromer *et al.* 2002). Older cut-over jarrah forest (1.8–2.3 m³ ha⁻¹ y⁻¹) or uncut high quality forest (1.2 m³ ha⁻¹ y⁻¹) have lower volume increments (Abbott *et al.* 1989).

The high growth rate of jarrah in the first 13 y is probably due to the greater availability of water and other resources in the newly

Table 4. Mean measurements of planted trees in response to fertiliser and understorey type after 13 y. Within columns and treatment types, numbers with the same letter are not significantly different at $P = 0.05$.

Treatment	All trees		Saplings ^a		Tallest ^b 300			Trees with single stem at 2 m ht	
	Ht (m)	Dbhob (cm)	Ht (m)	Frequency (%)	Ht (m)	Dbhob (cm)	BAob (m ² ha ⁻¹)	BAob (m ² ha ⁻¹)	Bole vol. (m ³ ha ⁻¹)
Fertiliser									
0	5.5 b	13.3 b	7.8 b	54.2 c	9.2 b	13.7 b	4.6 b	8.1 a	16.6 b
¹ Broadcast	7.5 a	15.4 a	9.3 a	64.3 b	10.7 ba	15.5 ba	5.9 ab	13.1 a	28.0 ab
² 50	8.2 a	15.6 a	9.5 a	69.5 ab	11.4 a	16.3 a	6.4 a	15.0 a	33.1 a
² 100	8.5 a	15.9 a	9.5 a	72.4 ab	11.3 a	16.0 a	6.3 a	14.8 a	32.6 a
² 200	8.6 a	15.8 a	9.3 a	74.3 a	11.5 a	16.3 a	6.5 a	15.1 a	33.2 a
Understorey									
Minor only	8.0 a	15.6 a	9.0 a	72.6 a	10.4 b	14.9 b	5.4 b	11.5 b	23.1 b
Major and minor	7.3 b	14.7 b	9.2 a	61.3 b	11.3 a	16.3 a	6.4 a	15.0 a	34.3 a
Mean	7.6	15.2	9.1	66.9	10.9	15.6	5.9	13.2	28.7

^aSaplings = trees >1.5 m tall^bTallest 300 = the tallest 300 trees ha⁻¹ of good form (i.e. with a single stem at a height of 2 m)¹Broadcast fertiliser at 250 kg ha⁻¹²g tree⁻¹**Table 5.** Tree measurements in relation to planted tree spacing after 13 y. Measures are averages of all sites and all other treatments. In rows, numbers with the same letters are not significantly different at $P = 0.05$.

Measure	Tree spacing				Mean
	1 m × 1 m	2 m × 2 m	2 m × 4 m	4 m × 4 m	
Stocking of single-stemmed trees ^a (number ha ⁻¹)	3360 a	968 b	448 c	192 d	
Mean dbhob of single-stemmed trees (cm)	8.7 d	12.2 c	14.9 b	17.6 a	13.4
Mean dbhob tallest 300 ^b (cm)	14.7 b	15.5 ab	16.6 a		
Mean dbhob of all trees (cm)	8.7 d	13.5 c	17.5 b	21.0 a	15.2
Total basal area all trees (m ² ha ⁻¹)	54.1 a	35.5 b	30.1 b	21.7 c	35.4
Total bole volume all trees (m ³ ha ⁻¹)	64.1 a	64.5 a	65.8 a	50.4 b	61.2
Percentage of all trees that are single-stemmed (at 2 m height) (%)	33.6 ab	38.7 a	35.8 ab	30.7 b	34.7
Percentage of saplings that are single-stemmed (at 2 m ht) (%)	71.0 a	56.6 b	46.8 c	40.7 d	53.5
Height all trees (m)	4.8 d	6.9 c	8.9 b	10.1 a	7.6
Height of saplings (m)	6.5 d	8.7 c	10.0 b	11.0 a	9.1
Height tallest 300 (m)	10.8	10.8	10.8		
Percentage of all trees that are saplings (%)	47.3 c	68.4 b	76.6 a	75.4 ab	66.9
Basal area single-stemmed trees (m ² ha ⁻¹)	24.6 a	13.7 b	9.0 c	5.6 c	13.2
Basal area tallest 300 (m ² ha ⁻¹)	5.2 b	5.8 ab	6.7 a		
Bole volume single-stemmed trees (m ³ ha ⁻¹)	46.7 a	31.1 b	22.1 bc	14.7 c	28.7
Basal area MAI 0–8 y all trees (m ² ha ⁻¹)	2.49 a	1.92 b	1.71 b	1.19 c	1.83
Basal area PMAI 8–13 y all trees (m ² ha ⁻¹)	6.83 a	4.02 b	3.28 b	2.44 c	4.14
Basal area MAI 0–13 y all trees (m ² ha ⁻¹)	4.16 a	2.73 b	2.32 b	1.67 c	2.72

^aSingle-stemmed trees are defined as those over 3 m tall and of good form (i.e. with a single stem at a height of 2 m)^bTallest 300 = the tallest 300 trees ha⁻¹ of good form (i.e. with a single stem at a height of 2 m)

created forest. As excess water in the rehabilitated mined areas is used by the new jarrah trees it is expected that growth will slow. The Periodic MAI (PMAI) of basal area over bark in the planted trees was higher in the 8–13 y period (4.14 m² ha⁻¹) than in the 0–8 y period (1.83 m² ha⁻¹). This is consistent with basal area growth of regrowth jarrah in the unmined forest which only decreases after basal area (under bark) exceeds about 20 m² ha⁻¹ (Stoneman *et al.* 1989). The mined sites in this study are just reaching this value (9–36 m² ha⁻¹ under bark) and hence may be expected to have a lower PMAI at the next measurement. It is not known exactly at what age water deficits are likely to limit tree growth. In a catchment that had been partially cleared, mined

and rehabilitated streamflow increased for 10–14 y (Ruprecht and Stoneman 1993), indicating extra available soil water for this period. Mining removes the lateritic caprock layer and the rehabilitated areas are deep ripped to 1.5 m, which may promote this rapid early growth. A question often asked is: 'Is jarrah tree growth on rehabilitated bauxite mines sustainable in the long term?' Thirteen years cannot be considered long term, but growth rates do not appear to be limited by any intrinsic factors in the rehabilitated bauxite mines, and at 13 y of age are controlled by the same environmental and silvicultural factors affecting eucalypt forests elsewhere in southern Australia.

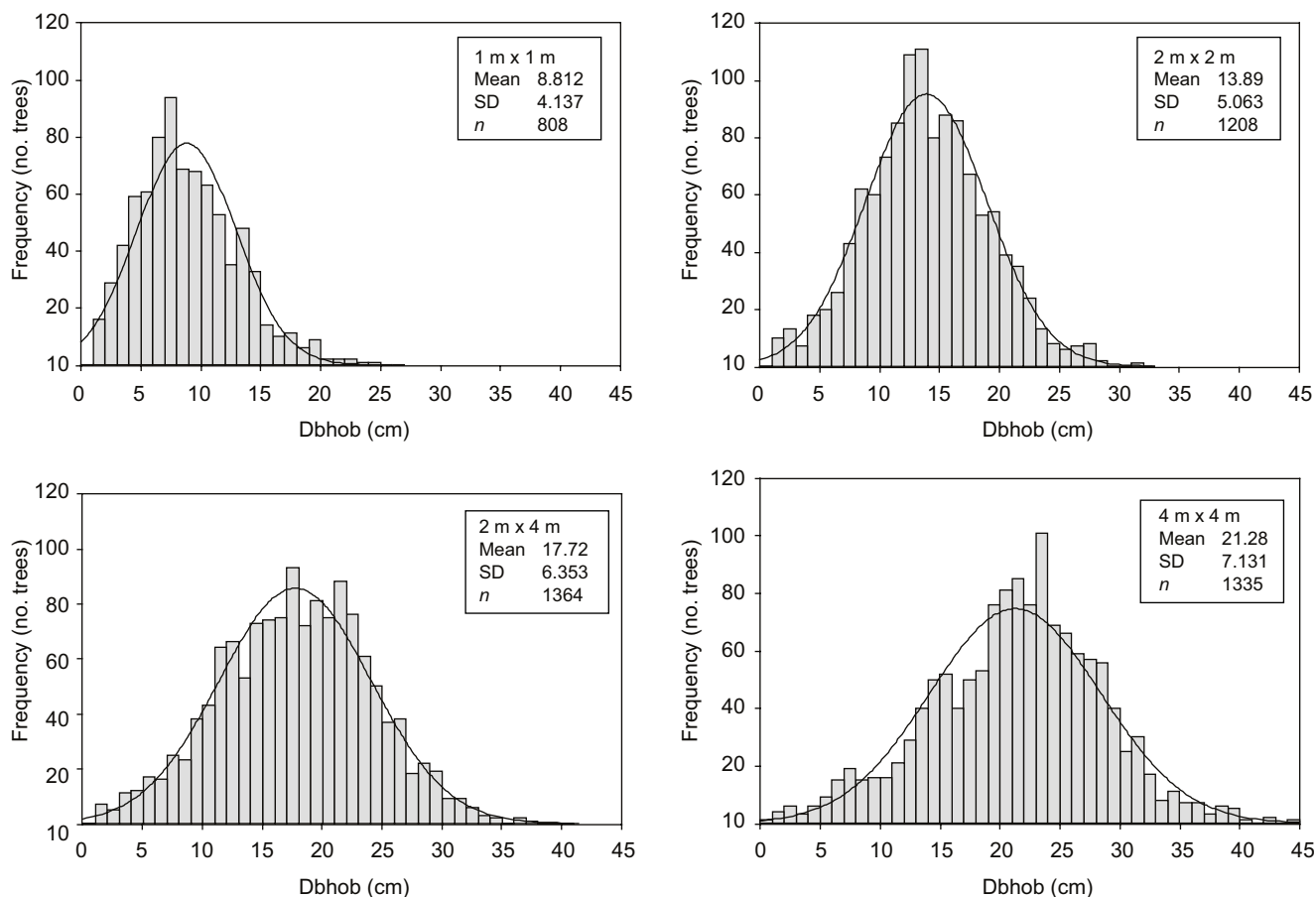


Figure 8. Frequency histograms and normal curves of tree diameter at breast height over bark at the four different tree spacings

Effect of tall native legumes

The decline, in the period from 8 to 13 y, in the percentage of saplings in the seeded treatment with a leguminous understorey and no additional fertiliser (L) was caused by higher mortality of saplings in this treatment. This suggests that the saplings in this treatment were less able to compete with the vigorous legumes. At 5 and 13 y the leguminous understorey also had a strong effect on the form of the seeded trees, resulting in significantly more single-stemmed trees. Similarly in the planted treatments, the proportion of single-stemmed trees increased as competition became more intense through closer tree spacing or the large legumes. The proportion of single-stemmed trees at 2 m height was greater than at 4 m height, particularly in response to the legumes. The legumes helped produce single-stemmed jarrah trees, but when the trees grew out of the understorey canopy (about 3 m high) the trees then developed more multiple stems. Although the rehabilitation prescription has changed since 1988 and the density of legumes has been reduced, the DAP fertiliser with legumes (i.e. LF in the seeded experiment) is the most similar treatment to Alcoa's current practice and produces 79% of trees over 3 m tall with a single stem at 2 m (good form) and 48% of trees over 6 m tall with a single stem at 4 m in the seeded sites. At a mean stocking rate of 2300 stems ha^{-1} , this is equivalent to 1049 and 637 stems ha^{-1} after 13 y. These are potential future sawlogs at least to a minimum standard of 2.1 m. At this density, however, the growth rate of individual trees is already slowing and the stands would require thinning if wood production is to

be optimised. Silvicultural treatments including thinning to different densities and controlled burning are currently being investigated in 10–15-y-old rehabilitated bauxite mines.

The tallest 300 single-stemmed trees ha^{-1} are likely to represent the future sawlogs (criteria for completion of rehabilitation require a minimum of 300 stems ha^{-1} potential sawlogs at 15 y of age). A tall leguminous understorey resulted in these trees having larger mean diameter, height and bole volume than those in smaller understorey vegetation.

The competitive effect of the leguminous understorey was evident both in the early growth of the jarrah and at 13 y of age. Some of the legumes used in the 1988 seed mix live longer than 13 y and can grow into small trees (e.g. *Acacia longifolia*, *A. celsa*, *A. saligna* and *A. myrtifolia*). The current understorey seed mix contains only shorter-lived acacias that do not grow into trees. In addition, the amount of seed of acacias and other vigorous native legumes has been reduced from 2 kg ha^{-1} in 1988 to less than 0.4 kg ha^{-1} in 2005. The reduction has been made because the acacias and other vigorous legumes:

- do not appear to confer any benefits to the jarrah trees and reduce tree growth even after 13 y
- represent a fire hazard by providing a large amount of aerated fuel
- reduce access to rehabilitated areas, and

- give a structure and appearance unlike that of the surrounding unmined forest.

A moderate stocking of acacias and vigorous legumes is being retained because these plants:

- are a natural and common component of the jarrah forest flora
- provide rapid vegetation cover to prevent erosion
- create litter
- build up soil organic carbon
- fix atmospheric nitrogen, and
- provide fauna habitat.

Growth of both seeded and planted jarrah was significantly affected by fertiliser, understorey competition and planting spacing at age 4 y (Ward and Koch 1995). Of the various treatments, however, only planting spacing significantly affected survival. There appeared to be some self-thinning occurring at the closest spacing. This was particularly noticeable in the tall leguminous treatments where the intraspecific competition between jarrah trees and the added competition from the legumes would have been most intense. Competing legumes have previously been shown to reduce eucalypt growth in rehabilitated bauxite mines (Majer and Sawyer 1981; Koch 1987). We believe that competition for soil moisture is the likely cause of reduced growth and higher tree mortality. Stoneman (1992) and Stoneman *et al.* (1994) found that water stress limited jarrah seedling growth in glasshouse experiments and concluded that competition for water was the major factor controlling jarrah seedling growth in the forest.

Comparison of seeded and planted jarrah trees

After 13 y the growth of seeded and planted jarrah trees was the same. Jarrah established from seed had a higher proportion of single stems, particularly at lower densities of around 1500 trees ha^{-1} or less. Seeded jarrah had high establishment variability (the range across the experimental sites was 1104 to 5829 ha^{-1}). This was mainly caused by lower establishment success in sites where there was a long delay between soil tillage and seed broadcasting. Ward and Koch (1995) discussed this and it has since been addressed by changing our procedures to seeding immediately after tillage in all rehabilitated areas. The higher proportion of single stems, the lower cost and the more natural appearance of seeded jarrah makes it the preferred method of establishment in rehabilitated bauxite mines.

Fertiliser

At four years the fertiliser treatments had significantly different effects on tree growth, with each increment in fertiliser producing extra growth for the planted trees (Ward and Koch 1995). By 13 y most of the fertiliser effects had disappeared, the only growth difference being between the no-DAP treatment and all treatments receiving DAP. Early growth tended to be better when fertiliser was placed as a tablet next to each tree rather than being broadcast, even though the rate per hectare was lower in the tablet application. The broadcast DAP application supplied 43.75 kg N ha^{-1} and 91 kg ha^{-1} elemental P and produced good growth after 13 y. Current fertiliser application rates are 72 kg N ha^{-1}

and 80 kg ha^{-1} elemental P as broadcast DAP, but it is likely the N component of this could be reduced without reducing tree growth.

Best tree density for rehabilitated areas?

About one third of all planted trees were single-stemmed at 2 m regardless of density, although this fraction decreased at the lowest density (i.e. 4 m \times 4 m spacing). The better form at higher densities was partially offset by the smaller percentage of the trees that reached sapling stage. At lower densities (625 and 1250 stems ha^{-1}) the larger number of seeded trees of good form compared to similar planted trees is likely to have been due to an interaction between the leguminous understorey and the faster early growth of the planted trees. Planted trees are about one year ahead of seeded trees in their early growth and are consequently larger and less affected by the competing leguminous understorey. Outgrowing the leguminous understorey may allow more multiple stems to develop in the planted trees. At higher densities (2500 stems ha^{-1}) competition from neighbouring trees leads to better form in the planted trees.

Closer tree spacing gives higher basal area simply due to the higher density, but the size (diameter) of individual trees is small. At the closest spacing the trees do self-thin to some extent (23% mortality at 13 y) but the density is still too high to yield useful timber products.

Bole volume is the same for tree spacings of 2 m \times 4 m and closer (around 65 $\text{m}^3 \text{ha}^{-1}$, Table 5), but is significantly less at 4 m \times 4 m spacing (50 $\text{m}^3 \text{ha}^{-1}$). This could indicate that the resources of the site were fully exploited at all of the higher densities after 13 y, but not fully exploited at that age at 4 m \times 4 m spacing. If we interpret this as meaning that the 4 m \times 4 m spacing is suboptimal for wood volume production, then the 2 m \times 4 m or 2 m \times 2 m spacing seems to be the logical choice for early stocking rate. The 2 m \times 2 m spacing is showing increased mortality and a significant decrease in growth rate, and would need to be thinned at about this age if timber production was to be given priority.

CALM's current silvicultural objective is to maintain a high stand density in regrowth until maximum bole length is achieved, and then thin to maintain maximum stand basal area growth with the fewest possible stems per hectare. For the existing jarrah forest this is an under-bark basal area of 15 $\text{m}^2 \text{ha}^{-1}$ (Stoneman *et al.* 1996). In a stand 13 y old, the emphasis would be on developing bole length. The over-bark basal areas at 13 y in the current study were, for all trees, 14–54 $\text{m}^2 \text{ha}^{-1}$, and for potential sawlog trees (tallest 300 single-stemmed trees ha^{-1}), 6.7 $\text{m}^2 \text{ha}^{-1}$ at 2 m \times 4 m and 5.8 $\text{m}^2 \text{ha}^{-1}$ at 2 m \times 2 m. When the over-bark values for all trees are converted to under-bark values they are 9–36 $\text{m}^2 \text{ha}^{-1}$. These values span the optimum basal areas for growth in the jarrah forest. The rehabilitated sites, however, are much younger than a thinned forest, and so a higher basal area may be appropriate. Thus the 2 m \times 4 m spacing (1250 stems ha^{-1}) with a mean under-bark basal area of 22.1 $\text{m}^2 \text{ha}^{-1}$ appears to be an appropriate stocking at 13 y.

Current criteria for the completion of rehabilitation of bauxite mines specify that there will be a minimum of 300 stems ha^{-1} of

potential timber logs at 15 y of age (DMPR 2002). Timber harvesting guidelines specify a minimum log length of 2.1 m (CALM 1999). In this experiment the density of trees over 3 m tall with a single stem at a height of 2 m can be used as an indication of potential sawlog production. For planted trees, densities of 2 m × 4 m and closer exceed the requirement of 300 stems ha⁻¹ for potential sawlogs (448 stems ha⁻¹) (Table 5) but the 4 m × 4 m spacing does not (192 stems ha⁻¹). Seeded trees exceed the requirement for potential sawlogs even at lower total densities of 500–800 stems ha⁻¹. Basal area and dbhob of the tallest 300 trees ha⁻¹ of good form (likely future sawlogs) are also greater at 2 m × 4 m spacing than at closer spacings. The current rehabilitation prescription aims to establish 1300 stems ha⁻¹ of total eucalypts by seeding (jarrah and marri). This gives an average of >700 potential sawlogs ha⁻¹ and therefore seems to be the appropriate density to provide enough future sawlogs, allowing for some patchiness but without overstocking.

In addition to producing a future sawlog crop, the rehabilitated areas must satisfy the other forest land uses of water production, conservation and recreation. The best fertiliser regime for fulfilling all of the above land use objectives appears to be the use of both N and P fertiliser to ensure good early growth of jarrah. The inclusion of N minimises the early suppressive effect of the leguminous understorey. As discussed earlier, the rate of seeding of large, fast-growing legumes has been reduced to a value between the '+L' and '-L' treatments used in this experiment. This should ensure that the benefits of the legumes are not outweighed by the undesirable effects of high legume density. The trees should be established from seed, at an initial density of 800–1500 stems ha⁻¹, to satisfy a nominal target of 1300 stems ha⁻¹.

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References

- Abbott, I. and Loneragan, O. (1983a) Growth rate of jarrah (*Eucalyptus marginata*) in relation to site quality in cut over forest, Western Australia. *Australian Forestry* **46**, 91–102.
- Abbott, I. and Loneragan, O. (1983b) Response of jarrah (*Eucalyptus marginata*) regrowth to thinning. *Australian Forest Research* **13**, 217–229.
- Abbott, I. and Loneragan, O. (1986) *Ecology of Jarrah* (*Eucalyptus marginata*) in the Northern Jarrah Forest of Western Australia. Bulletin No. 1. Dept of Conservation and Land Management, Perth, WA, 137 pp.
- Abbott, I., Dell, B. and Loneragan, O. (1989) The jarrah plant. In: Dell, B., Havel, J.J. and Malajczuk, N. (eds) *The Jarrah Forest: A Complex Mediterranean Ecosystem*. Kluwer, Dordrecht, Netherlands, Chapter 4, pp. 41–51.
- CALM (1999) *Manual of Management Guidelines for Timber Harvesting in Western Australia*. Department of Conservation and Land Management, Perth, WA, 79 pp.
- Chandler, W.G. (1939) Thinning experiments in jarrah coppice (*Eucalyptus marginata*). *Australian Forestry* **4**, 69–78.
- Cromer, R.N., Turnbull, C.R.A., LaSala, A.V., Smethurst, P.J. and Mitchell, A.D. (2002) *Eucalyptus* growth in relation to combined nitrogen and phosphorus fertiliser and soil chemistry in Tasmania. *Australian Forestry* **65**, 256–264.
- DMPR (Department of Mineral and Petroleum Resources) (2002) *Alcoa World Alumina Australia Darling Range Bauxite Mine Rehabilitation Completion Criteria*. DMPR, Perth.
- Gardner, J.H. (2001) Rehabilitating mines to meet land use objectives: bauxite mining in the jarrah forest of Western Australia. *Unasylva* **207**, 3–8.
- Grant, C.D., Koch, J.M., Bell, D.T. and Loneragan, W.A. (1997) Tree species response to prescribed burns in rehabilitated bauxite mines in Western Australia. *Australian Forestry* **60**, 84–89.
- Koch, J.M. (1987) Nitrogen accumulation in a rehabilitated bauxite-mined area in the Darling Range, Western Australia. *Australian Forest Research* **17**, 59–72.
- Loneragan, O.W. (1961) Jarrah (*Eucalyptus marginata* Sm.) and karri (*Eucalyptus diversicolor* F.v.M.) regeneration in southwest Western Australia. MSc(For) thesis, University of Western Australia.
- Majer, J.D. and Sawyer, A. (1981) Competition between understorey and planted *Eucalyptus* species in rehabilitated bauxite mined areas. *Mulga Research Centre Annual Report* **5**, 69–70.
- Parkes, T. (2001) Predicting long term growth responses and economic benefits. In: Connell, M.J., Raison R.J. and Brown, A.G. (eds) *Intensive Management of Regrowth Forest for Wood Production in Australia*. Proceedings of the National Workshop 18–20 May 1999, Orbost, Victoria. CSIRO Forestry and Forest Products, Canberra, pp. 34–38.
- Poynton, R.J. (1979) *Tree Planting in Southern Africa. Volume 2. The Eucalypts*. Department of Forestry, Republic of South Africa, 882 pp.
- Ruprecht, J.K. and Stoneman, G.L. (1993) Water yield issues in the jarrah forest of south-western Australia. *Journal of Hydrology* **150**, 369–391.
- Stoneman, G.L. (1992) Factors affecting the establishment of jarrah (*Eucalyptus marginata*) from seed in the northern jarrah forest of Western Australia. PhD thesis, Murdoch University, Australia.
- Stoneman, G.L., Rose, P.W. and Borg, H. (1988) *Recovery of Forest Density after Intensive Logging in the Southern Forest of Western Australia*. Technical Report No. 19, Department of Conservation and Land Management, Perth.
- Stoneman, G.L., Bradshaw, F.J and Christensen, P. (1989) Silviculture. In: Dell, B., Havel, J.J. and Malajczuk, N. (eds) *The Jarrah Forest*. Kluwer, Netherlands, Chapter 18, pp. 335–355.
- Stoneman, G.L., Turner, N.C. and Dell, B. (1994) Leaf growth, photosynthesis and tissue water relations of greenhouse-grown *Eucalyptus marginata* seedlings in response to water deficits. *Tree Physiology* **14**, 633–646.
- Stoneman, G.L., Crombie, D.S., Whitford, K., Hingston, F.J., Giles, R., Portlock, C.C., Galbraith, J.H. and Dimmock, G.M. (1996) Growth and water relations of *Eucalyptus marginata* (jarrah) stands in response to thinning and fertilization. *Tree Physiology* **16**, 267–274.
- Ward, S.C. and Koch, J.M. (1995) Early growth of jarrah (*Eucalyptus marginata* Donn ex Smith) on rehabilitated bauxite mines in south west Australia. *Australian Forestry* **58**, 65–71.
- Ward, S.C., Slessar, G.C. and Glenister, D.J. (1993) Environmental resource management practices of Alcoa of Australia Limited. In: Woodcock, J.T. and Hamilton, J.K. (eds) *Australasian Mining and Metallurgy*. Second edition, Vol. **1**, 104–108.