Aluminium and *Acacia* Plant Growth on Coal Mine Dumps

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Abstract

Colonising native and introduced plant species present on old abandoned dumps in the Collie coal field in south-west Western Australia provide a potential resource for rehabilitation. Coal waste dumps are more acidic than the surrounding forest soils, indicating a potentially toxic presence of aluminium. Some plants exhibit tolerance, and may accumulate, avoid or exclude aluminium. Excluders restrict translocation of the metal bound in root cells. Evolution of tolerance to metal stress may be comparatively rapid and although aluminium has many adverse affects on growth, plants tolerant of its presence also tend to be drought tolerant, an advantage for survival on dumps over dry summers.

Progeny of a dump population of *Acacia decurrens* are contrasted with a non-dump population. Seedlings were subjected to varied concentrations of aluminium in solution and harvested at 10 weeks. *A. decurrens* tolerated low levels of applied aluminium but severe effects on growth were observed at 500 ppm. Plants of dump origin failed to produce greater plant biomass than non-dump plants. However, dump origin plants took up less total aluminium than non-dump plants, indicating an avoidance mechanism. Dump progeny held more of the absorbed aluminium within roots, translocating lower quantities to foliage, suggesting an exclusion mechanism. Decreased tissue nitrogen, phosphorus and calcium coincided with increased aluminium supplied. Calcium decline was the most severe. Trace element and manganese concentrations increased with added aluminium.

Despite an inability to out-perform non-dump progeny, the pattern of nutrient uptake indicates a real difference between the two accessions. In the long run survivors are likely to persist and reproduce if they have successfully avoided uptake of deleterious elements beyond the root systems. It is therefore recommended that collection of seed for use on coal-mine rehabilitation sites should be made from established plants growing on dumps.

Key words: aluminium, tolerance, coal-dump, *Acacia*, progeny

Introduction

It would seem self-evident that selection of plant materials growing on a particular site should prove good candidates for similar sites [1]. Revegetation of coal waste dumps is difficult as they present a harsh environment: inadequate moisture, compaction, low fertility and the presence of heavy metals. Coal waste dumps have low pH relative to surrounding surface soils [2] indicating a high toxic presence of aluminium. Survivors on difficult sites may have exploited a particularly favourable micro-habitat, represent a larger population able to grow on such sites or be a product of natural selection. It is the last that is of greatest interest. Woody species of relatively short life-spans may have undergone natural selection and represent superior material adapted for particular sites.

Rehabilitation procedures for coal mine waste dumps are costly due to need for placement of top-layers, correction of pH, fertilizing, grading and ripping surfaces. Costs of rehabilitation can be reduced if use is made of plants adapted to grow in the conditions provided by the dump [1]. Some ingress of both native and introduced plant species is evident on old dumps and these provide a guide to species suitability for rehabilitation. Potential understorey species of *Acacia* have shown some tolerance to the hostile conditions of Collie mine dumps if lime and fertiliser are applied [3] [4]. A screening technique for acidity tolerance indicated that dump progeny of *Acacia extensa* are more tolerant of acidic conditions than non-dump progeny. Seeds of *Acacia* species taken from dumps are

Table 1. Mean dry weights (g) after 10 weeks growth of *Acacia decurrens* by treatment

Aluminium ppm	Tissue dry weights: Roots	Shoots	Leaves	Total*	Tissue percentage weights: Roots	Shoots	Leaves
	Plants of dump origin						
0	1.327	1.333	3.673	6.333a	21.0	21.0	58.0
200	1.173	1.200	3.307	5.680 a	20.7	21.1	58.2
500	0.727	0.467	1.500	2.694 b	27.0	17.3	55.7
700	0.540	0.400	1.360	2.300 bc	23.5	17.4	59.1
900	0.427	0.233	0.907	1.567 c	27.2	14.9	57.9
100	0.400	0.473	1.187	2.060 bc	19.4	23.0	57.6
1100	0.386	0.367	1.133	1.886 c	20.5	19.5	60.0
	Plants of non-dump origin						
0	1.942	1.417	4.125	7.484 a	25.9	18.9	55.2
200	1.158	0.991	2.825	4.974 b	23.3	19.9	56.8
500	1.042	0.917	2.633	4.592 b	22.7	20.0	57.3
700	1.017	0.842	2.233	4.092 bc	24.9	20.6	54.5
900	0.300	0.475	1.283	2.058 cd	14.6	23.1	62.3
1000	0.275	0.400	1.183	1.858 cd	14.8	21.5	63.7
1100	0.242	0.325	0.875	1.442 d	16.8	22.5	60.7

* values in columns with the same letter are not significantly different at $p < 0.05$ using the Duncan test

Table 2. Elemental concentration in *Acacia decurrens* not subjected to aluminium treatment and to the lowest level (200 ppm aluminium)

Tissue	N	P	Ca	Mn	Fe	Zn	Cu	Al
	%			ppm				
Treatment : Control								
Source: dump origin								
Root	2.21	0.60	0.45	205	1065	57	66	2071
Shoot	1.37	0.34	0.28	19	91	13	9	165
Leaf	2.93	0.41	0.56	26	52	6	6	267
Source: non-dump origin								
Root	2.20	0.63	0.41	219	1126	6	63	1000
Shoot	1.42	0.30	0.32	126	424	95	51	101
Leaf	2.80	0.45	0.57	54	100	14	20	279
Treatment : 200 ppm aluminium								
Source: dump origin								
Root	1.41	0.22	0.19	1803	1131	287	41	2600
Shoot	0.61	0.23	0.24	101	93	43	10	160
Leaf	1.01	0.17	0.38	97	79	16	5.7	315
Source: non-dump origin								
Root	1.80	0.33	0.12	1406	772	7.2	70	3133
Shoot	1.09	0.29	0.52	1297	658	291	57	118
Leaf	0.58	0.30	0.45	464	156	20	16	609

consistently of heavier mean weight than those from the forest [1]. Several overstorey *Eucalypts* can also be grown with suitable amendments [3] but the longer life-spans of large trees indicate that provenance testing may be more useful in selecting material for difficult sites.

Despite the high toxicity of aluminium at low pH, tolerance has been noted in some plants [5]. If a population of plants evolves in a soil that has an excess of a certain heavy metal, tolerance of that metal will be a trait of that population. An aluminium tolerant population will presumably possess traits that allow the species to deal with the stress caused by aluminium. This may involve aluminium accumulation sites in the tissues, restriction of entry (exclusion) by precipitation at the root surface or restriction of translocation. Some species restrict the translocation of the metal by binding in the root cells [6]. This group includes some legumes [5], a group of which *Acacia* is a member. Accumulators may absorb metals such that concentration in the plant is higher than in soil. Tea is an accumulator and may have leaf concentrations exceeding those of the substrate. The notion of tolerance does not imply that growth is better under good conditions.

The work reported examined the effects of aluminium on *Acacia decurrens*, with respect to growth, nutrient uptake and translocation. *A. decurrens* is an eastern Australian tree reaching 10 m with a 5 m crown now commonly seen in south-west Western Australia as semi-naturalised. It grows well on coal-mine dumps at Collie. These traits of hardiness render *A. decurrens* a prime candidate for mine dump rehabilitation.

Methods

Seeds of *Acacia decurrens* from the Collie area were taken from a dump source, Stockton, and a non-dump source, Westralia Block. Stockton seeds were 50% heavier in weight, confirming trends noted earlier for species of *Acacia* growing on dumps [1]. Seedlings were raised in moistened sand trays until the first leaf opened and then transferred to pots with a coarse, sterile sand as a growth medium. Seedlings were allocated to treatments, consisting of a control and six aluminium levels, each with 15 replicates. Concentrations of 200, 500, 700, 900, 1000 and 1100 ppm aluminium were obtained by dissolving hydrated aluminium chloride in de-ionized water. Aluminium solutions were applied three times a week, using 50-100 ml per application per plant. Hoagland's nutrient solution No. 2 was added once a week to all treatments, on a day that aluminium was not supplied. The control treatment received only nutrient solution.

At ten weeks plants were harvested, divided into roots, shoots and leaves and dried in a 105°C oven for 24 hours prior to weighing. After weighing, plants were ground into a fine powder and composition of 8 elements (N, P, Ca, Mn, Fe, Zn, Cu and Al) determined by conventional methods.

Results

Dry weight

Plants of dump origin did not grow as well as those of forest origin in the absence of added aluminium (Table 1), yielding 81% of the dry weight of the latter, despite having a larger seed resource base. The major difference was a heavier root mass (+46%) in non-dump progeny. Shoots (+6.3%) and leaves (+12.3%) were similar. Al treatment at the lowest level (200 ppm) did not cause a significant reduction in dump progeny weight but depressed weight to two thirds of the control in non-dump progeny. Non-dump progeny were heavier than dump plants over the range 500-900 ppm.

Foliage ranged between 55 and 64% of total dry weight. Each component declined with increased Al, similar to that of total dry weight. Roots of dump progeny were heavier than non-dump plants at 900 ppm and greater, but leaves and shoots were not heavier in the dump set until 1000 ppm. The % of dry weight contained in roots declined in non-dump progeny from 26% in control to 15% at 900-1000 ppm Al. In contrast, % weight of dump plant roots increased from 21% of total dry weight to 27% at 500 and 900 ppm and then declined to 20% (Table 1).

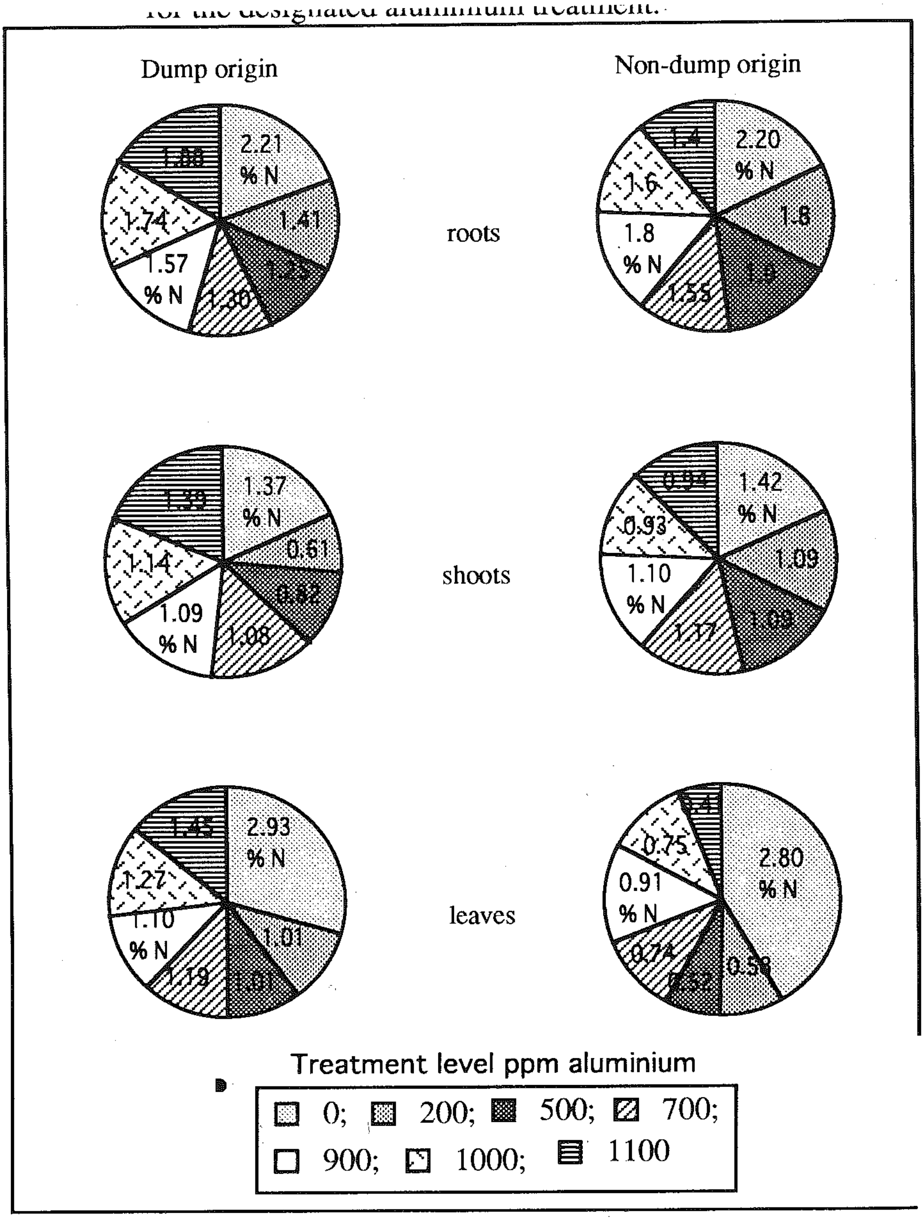

Figure 1. Proportional distribution of nitrogen in *Acacia decurrens* by treatments Numbers represent % tissue N for the designated aluminium treatment

In the non-dump set root growth declined more rapidly than leaves and shoots and was only 15% of control at 900 ppm. This contrasted with plants of dump origin where shoot and leaf contribution to dry weight fell markedly and roots declined less as a proportion of control weight such that they were 55 % of control at 500 ppm. At 1100 ppm dump roots were 29 % of the control, more than twice the proportion in non-dump plants. Dump plant root dry weights declined consistently and were at higher proportions of control than non-dump progeny over the range 900-1100 ppm. Dump plant shoots and leaves did not differ over the range of 700-1100 from that attained at 500 ppm. At 900 ppm both shoots and leaves in the dump set were of lower weight than at the two more severe levels of aluminium.

% Nitrogen content

Untreated plants had tissue N > 2 % in both foliage and roots (Table 2). Aluminium treatment was associated with a reduction in tissue N concentration (Figure 1). Levels of N were < 1% in shoots of dump plants treated at 200-500 ppm aluminium. All other levels for dump plants were > 1%, and roots and leaves were never < 1% N. Non-dump progeny had very low leaf nitrogen contents (< 1 %) at all levels of aluminium, as did shoots at the two highest aluminium levels. Collectively, nitrogen levels rose slightly over the range of aluminium applied to dump progeny but the pattern was more obscure with non-dump progeny.

% Phosphorus and calcium content

P and Ca levels declined with increased aluminium. The greatest change in P content was from zero to 200 ppm aluminium (Table 2). Non-dump plants had a two stage decline and after 500 ppm aluminium P concentrations stabilised at around 0.2 %. Foliar P in dump plants progressively declined over the range of added aluminium. In dump progeny Ca levels were very low at all aluminium levels for all tissues. Levels stabilised after 500 ppm aluminium. Ca was also very low at all levels in non-dump plant roots. Leaf and shoot Ca levels were adequate until after the 700 ppm aluminium level.

Aluminium content

Root Al contents in dump progeny stabilised after the 500 ppm treatment at around 6000 ppm aluminium. Dump plant foliar Al increased with treatment level from 300 ppm at the lowest treatment to > 900 at 900 ppm Al, and then fell away to 6-700 at higher treatment levels. Both roots and leaves of non-dump progeny had much higher concentrations than dump progeny, with root levels between 8000 and 10000 ppm after the 500 ppm treatment. Non-dump plant foliar Al rose from 600 ppm at the lowest Al treatment to around 2000 ppm for all other treatment levels.

The non-dump plants consistently translocated a higher proportion of Al to foliage, in excess of 30%. Non-dump progeny had higher contained total aluminium (mg) in foliage. Dump progeny consistently retained a higher proportion of absorbed Al within roots, but for all treatments dump roots had lower amounts of total Al than non-dump progeny.

In the absence of aluminium, non-dump progeny contained more N, P, Ca, Mn, Fe, Zn and Cu. Levels were similar in each of roots, shoots and leaves for N, P and Ca. Ca and N levels were greatest in leaves and lowest in shoots (Table 2). Phosphorus was highest in roots and least in shoots.

Trace element content

Non-dump progeny had more Mn, Fe, Zn and Cu but the dump plants had 44% more Al. Dump plants held more of total plant Al, Fe, Mn, Zn and Cu in roots than did non-dump plants. Dump plants consistently had more Al, Fe, Mn, Zn and Cu in leaves than stems. Non-dump plants had more Fe in stem than leaves, little Zn in roots and most in stems.

With exposure to the lowest level of aluminium, non-dump progeny continued to take up more of most elements considered (Table 2). Dump plants had slightly more N

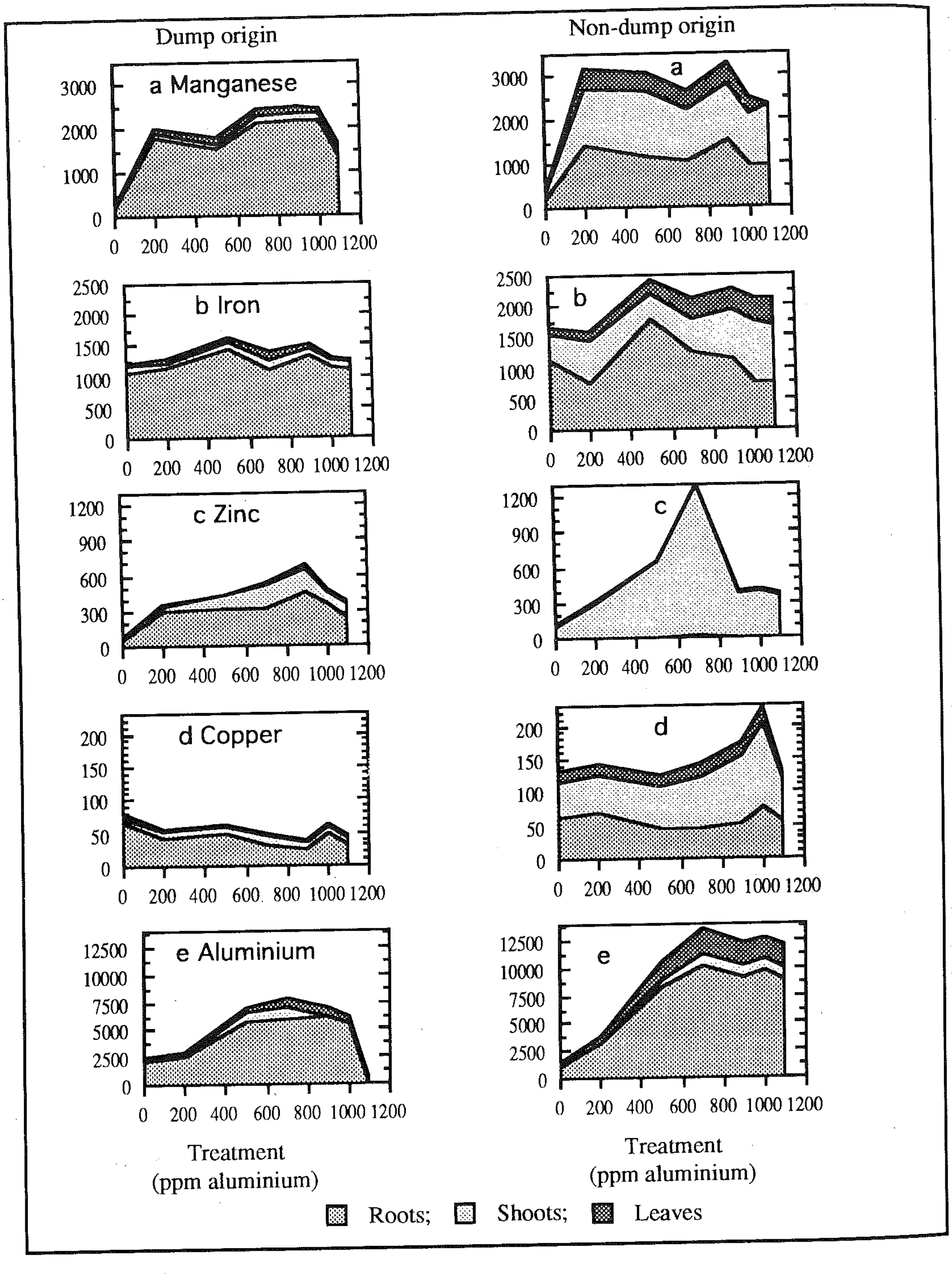

Figure 2. **Trace elements (ppm) in tissues of *Acacia decurrens* grown in seven treatment levels of aluminium. (ppm aluminium)**

and Zn. Considerably more Al (+46%), and P (+58%) went into non-dump plants. Dump plants continued to hold more of total plant Al, Fe, Mn, Zn and Cu in the roots in comparison with non-dump plants.

Most of the trace elements taken up by dump progeny remained in the roots (Figure 2). Levels of Cu and Fe in roots were high, although these levels were not affected by aluminium treatment. For each of roots, shoots and leaves, concentrations of Cu and Fe were similar to the zero aluminium levels, or less (in the case of Cu in roots). Aluminium treatment was associated with increased levels of Mn and Zn in all plant parts. Mn levels in roots were well over 1000 ppm, but in shoots and leaves, where levels also increased with aluminium compared to the control, concentrations were between 100 and 160 ppm. Zn levels were high in all roots (> 250 ppm) and shoots (> 100 ppm) at aluminium concentrations of 500 ppm or more.

Non-dump progeny took up greater quantities of trace elements over the range of aluminium treatment, but retained smaller proportions in roots than dump plants. Whereas root levels of Mn, Fe and Cu were similar between accessions each of these and Zn had much higher shoot and leaf concentrations in non-dump compared with dump progeny. For both Mn and Cu non-dump plants had similar root and shoot concentrations. High levels of Mn, Fe and Cu were present in non-dump roots and shoots. Very little Zn was retained in roots of non-dump plants with high concentration in shoots, and leaf levels also generally higher than in roots. Shoot Zn peaked at 1300 ppm in the 700 ppm aluminium treatment along with Al.

Discussion

Common symptoms of a plant intolerant to metal stress are : membrane damage, inhibition of root growth and alteration of enzyme activity [6]. Plants must be able to tolerate both nutrient deficient conditions and the presence of heavy metals in order to colonise coal mine waste dumps [2]. Since pot trials beg a number of questions concerning reality, the work described does not indicate that seedling establishment in nature will necessarily differ between accessions. In practice, mine-site rehabilitation involves over-sowing of seed to maximise the chances of successful lodgement. Even at the lowest level of aluminium used it is clear that growth of *A. decurrens* is depressed. The dump source plants did not grow better in the best conditions.

Nitrogen present in the plant is generally inversely proportional to the concentration of aluminium. Aluminium is bound in plant roots, but nitrogen in shoots is less than in roots. It is noted that Al treatment affected foliar nitrogen levels most severely in the non-dump progeny. Greater N reduction in shoots than roots is because aluminium affects root pressure, reducing translocation of nitrogen to shoots and leaves [7]. Nitrogen levels in roots were the least effected as Al does not bind directly with nitrogen but with an enzyme mediator of nitrogen absorption. Al also interferes with amino acid inter-conversion, changing the nitrogen forms translocated in sap [7], [8]. Thus, while nitrogen content of the roots increased slightly (dump progeny), leaf nitrogen content was reduced (non-dump progeny) as a result of reduced root pressure and Al interference in translocation.

Aluminium affects nutrient availability to the plant generally and may cause Ca deficiency [9], [10]. Calcium levels were the most severely affected of the macro-nutrients. Both non-dump and dump progeny exhibited dramatic falls in Ca, primarily in the leaves. Al binds with the Ca binding protein, calmodulin. This inhibits the uptake of Ca into the plant. Calcium levels in the leaves dropped more than in the roots probably due to a decrease in root pressure which, in turn, would diminish translocation from the roots to the upper sections of the plant. Therefore, any decrease in nutrient levels of the roots will be magnified in the leaves. N and P levels, although severely affected, were not as diminished as Ca in the roots. Al binds directly with P at the root surface and in the intercellular spaces. Thus it may still be absorbed into the roots but translocation is inhibited [11] and plant tops may be P deficient.

The seed of *A. decurrens* was taken from self-sown trees established many years earlier on an un-restored waste dump. These were of heavier weight compared with seed from the non-dump plants, confirming trends noted earlier for species of *Acacia* [1]. Because dump spoils have little or no organic material, seeds must have enough stored energy to allow germinants to reach a stage at which they are not vulnerable to desiccation. Analysis has shown that dump seeds of *A. decurrens* have higher nutrient contents (N, P) than non-dump seeds [12]. The heavier seed weights translate into a total seed N advantage for dump seed of 113%, and for P of 224% of the amounts in non-dump seed. Dormancy may also be increased by a thicker seed coat allowing a delay in germination until favourable conditions prevail. Because dump conditions are biased toward larger seeds, the genetic code of plants growing on the dump may, in turn, be altered such that fewer small seeds are produced. The demonstrated characteristics - production of heavier seeds, higher nutrient content of seeds and, possibly, a thicker seed coat - suggest that selective forces operate within mine dump populations which maximise the chance of survival in such a harsh environment.

In contrast to a growth advantage found when grown in acidic solution culture for *Acacia extensa* of dump origin, with heavier seed [1], under the present trial conditions there were no clear dry weight production advantages for *A. decurrens* plants of dump origin. Since *A. extensa* is a species of relatively fast growth and short life-span, the seeds which were taken from plants long established on an old, naturally colonised dump would represent a number of generations of growth on that dump. At the lowest level of aluminium supplied, dump *A. decurrens* plants were heavier in total dry weight than non-dump plants. In addition to nutrient differences, dump seed had 27% more Mn composition, 32% more Zn and 45% more Al than non-dump seed, with resultant absolute differences (due to seed weight) of 91, 99 and 119% respectively in the levels of contained metals [12]. These seed levels may be implicated in reduced uptake of metal ions, at least at lower levels of applied aluminium.

In the absence of aluminium, dump progeny took up more Al. With aluminium supplied, the dump plants accumulated less Al, indicating some avoidance mechanism may have been operating. Within the plants, aluminium was mainly held in roots with lower proportions in shoots and stems, suggesting an exclusion mechanism. Leaf accumulation in non-dump plants was higher than in plants of dump origin. Roots in dump plants took up to 6,000 ppm Al and had < 1,000 ppm in foliage, whereas non-dump plants accumulated up to 10,000 ppm Al in roots and > 2000 ppm in foliage.

There were no deaths over the trial. Field trials must account for both establishment and survival of progeny [13]. Persistence of progeny on a dump is surely the best measure of tolerance. For example some Collie dumps have a number of severely stunted trees of *Allocasuarina fraseriana* present. Despite an inability to out-perform non-dump progeny, the pattern of elemental uptake indicates a real difference between the two accessions. In the long run survivors are likely to persist and reproduce if they have successfully avoided uptake of deleterious elements beyond the root systems. It is therefore recommended that collection of seed for use on coal-mine rehabilitation sites should be made from established plants growing on dumps.

Conclusions

Exposure of *A. decurrens* to aluminium solutions inhibited growth. Al tended to accumulate in higher concentrations within the roots of all exposed plants while relatively small concentrations were translocated to the shoots and leaves. However, seedlings of the non-dump source absorbed more Al in total, and dump progeny retained more in the roots and translocated less to the leaves. This supports the theory that legumes, such as *Acacia,* bind heavy metals in the roots, inhibiting translocation to the shoots and leaves. Countering the potentially severe effects of Al toxicity may be achieved by selecting propagation material from successfully established dump populations. This is likely to lead to more efficient methods of re-vegetating environments, such as coal mines and other mine waste dumps, in which heavy metals proliferate. Instead of treating the secondary effects of metal toxicity such as nutrient deficiencies, steps can be taken to treat the problem at the source. Time, money and energy would be saved by the relatively simple expedient of collecting seed for use in mine-site rehabilitation from those dumps already colonised successfully.

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References

[1] Fox, J. E. D., Easton-Groves, J., Elliott, J. L. & Owens, B. K. (1988). Tolerant populations of naturally regenerating species. pp 372-386, Proceedings: Australian Mining Industry Council, Environmental Conference, Darwin, September 1988.

[2] Bartle, J. R. & Ritches, J. R. H. (1978). Rehabilitation after mining in the Collie coal field. pp. 1-5. In : J. E. D. Fox (Ed.) Rehabilitation of Mined Lands in Western Australia. Proceedings of a meeting held in Perth, 11th October 1978. W. A. Institute of Technology. 122 pp.

[3] Doronila, A. I. & Fox, J. E. D. (1990). Tree and shrub establishment on coal mine interburden. Mulga Research Centre Journal 10, 28-37.

[4] Koch, J. M. & Bell, D. T. (1985). Native legume establishment on acidic coal mining overburden at Collie, Western Australia. Environmental Geochemistry & Health. 7, 141-144.

[5] Aniol, A. & Gustafson, J. P. (1989). Genetics of tolerance in agronomic plants. pp. 255-267. In : Shaw, A. J. (Ed.) Heavy Metal Tolerance in Plants: Evolutionary Aspects. C. R. C. Press, Boca Raton, Florida.

[6] Barcelo, J. & Poschenreider, C. (1990). Plant water relations as affected by heavy metal stress. Journal of Plant Nutrition. 13, 1-37.

[7] Gomes, M. M. S., Cambria, J. & Sant'anna, R. (1985). Aluminium effects on uptake and translocation of nitrogen in sorghum. Journal of Plant Nutrition Botany 8, 457-465.

[8] Miyasaka, S. C., Kochian, L. V., Sharff, J. E. & Foy, C. D. (1989). Mechanisms of aluminium tolerance in wheat. Plant Physiology. 91, 118-119.

[9] Schaeffer, H. J. & Walton, J. D. (1990). Aluminium ions induce oat protoplasts to produce an extracellular (1-3) B-D-glucan. Plant Physiology 94, 577-584.

[10] Zhang, G. & Taylor, G. J. (1990). Kinetics of aluminium uptake in Triticum aestivum L. Plant Physiology. 94, 577-584.

[11] Clarkson, D. T. (1969). Metabolic aspects of aluminium tolerance and possible mechanisms for resistance. 381-397, In (ed.) Rorison, I. H. Ecological Aspects of Mineral Nutrition. Blackwell Scientific Publications, Oxford.

[12] Hughes, M. P. & Fox, J. E. D. (1993). Phytotoxic effects of aluminium on Paraserianthes lophantha and Acacia decurrens. Mulga Research Centre Journal 11, 57-73.

[13] Egerton-Warburton, L. M., Griffin, B. J. & Lamont, B. B. (1993). Pollen-pistil interactions in Eucalyptus calophylla provide no evidence of a selection mechanism for aluminium tolerance. Australian Journal of Botany 41, 541-552.