5. Nutritional limitations to the early growth of rainforest timber trees in north Queensland

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Abstract

Most of the soils in the humid tropics of north Queensland available for growing rainforest trees are low in available nutrients. The major nutritional deficiencies have been classified according to soil parent material in order to develop a deficiency 'risk' table. From glasshouse trials using soils from across the region, most macronutrients (nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), and sulphur (S)), apart from magnesium (Mg), has been found to be deficient in at least one soil, and every soil studied was deficient in at least one nutrient. Rainforest tree species responded to nutritional deficiencies in different ways and there may be an unrecognised loss in growth potential. Tree growth can be depressed under limiting nutrient supply but remain undiagnosed, as visual deficiency symptoms may not develop. We present a number of techniques to manage nutrients in timely and cost effective ways. These include techniques to ensure a continuous supply of nutrients to the roots during transplanting, rapid tests for deficiencies of N and P, and recognition of visual diagnostic symptoms of deficiency.

Introduction

Many people presume that undisturbed rainforests occur on highly fertile soils with substantial biomass, and high in biodiversity. Rainforests are maintained by the rapid and efficient cycling of nutrients resulting in little loss from such systems. Somewhat unexpectedly, rainforest soils are quite fragile and rapidly degrade after clearing and thus are generally quite poor in an agricultural context; they are often highly weathered, have inherently low fertility and ability to retain nutrients especially if organic carbon (OC) levels decline. Many soils in the humid tropics of north Queensland have little (usually less than 5 cmol$^+$/kg) cation exchange capacity (CEC) (Webb *et al.* 1997). The little CEC that they do have is often dominated by exchange acidity or can be attributed to organic matter. That these soils are able to support luxuriant growth, such as a rainforest, is testament to the recycling and retention abilities of the biomass rather than the soil.

Thus, it should be no surprise that removal of a rainforest also removes a large proportion of nutrients. This can occur through immediate export in logs, subsequent losses through runoff or leaching as there is little vegetation remaining to capture nutrients, or as in the case of N and other volatile nutrients lost from logging residue, as well as from the surface soil and litter, in burning of rainforest residue after clearing (Vitousek and Sanford 1986). Further, it should then be no surprise that to re-establish trees in such landscapes will require an input of nutrients. How these nutrients are applied, and at what rates and times, will contribute to the success of tree, and stand, establishment and growth (Evans 1992).

Plantations established on degraded ex-agricultural land, whether of monocultures of pines for sawn timber or eucalypts for pulp and fibre, uses inputs of nutrients (as fertilisers) to achieve and maintain growth and productivity (Evans 1992). So while it is generally recognised that the nutrient requirements may not match the nutrient supply, nutrients will be required to re-establish trees.

In the Community Rainforest Reforestation Program (CRRP), for example, a prescriptive dose of fertiliser (eg diammonium phosphate; DAP) was often used irrespective of the soil type being planted, its history, or the species being planted because of its affordability, availability and ease of application. There was some direct and indirect evidence that the DAP stimulated a response, in some situations, but research has since shown not necessarily in every situation.

In designed trials, Webb et al (2000a) determined that such a practice could be inappropriate for *Castanospermum australe* (black bean) and *Flindersia brayleyana* (Queensland maple) grown on a soil derived from metamorphic parent material as there was no response to added phosphorus (P), but would be highly appropriate for *Cedrela odorata* (West Indian cedar) and *Agathis robusta* (kauri pine) at the same site. In another example, Reddell *et al.* (1999) have shown that a single field application of well-placed slow-release fertilisers can be hundreds-fold more efficient than field applied fertilisers for the establishment and early growth of *Gmelina arborea* (white beech).

These examples highlight the challenges faced by CRRP staff in the early 1990's, as they considered establishment nutrition; each situation was different. The ability of a particular site to supply required nutrients for tree growth is dependent on many variables. The extent of site degradation, time since clearing/burning of the original vegetation, site management history (agricultural/pastoral/horticultural) including fertiliser history of the site as well as weed control in the establishment phase (up to two years) all have major impacts on fertiliser responses (Webb *et al.* 1997, Bristow *et al.* 2005).

In this paper we highlight the results of research in north Queensland which (a) demonstrates the need to consider appropriate nutrient management in order to achieve good establishment and early growth of planted trees, and (b) led to the development of tools which are currently available to aid in the nutrient management of trees to achieve good establishment and early growth. Where possible, most of the work referred to here has been carried out in north Queensland. In addition, results are presented from tree establishment research in the Solomon Islands, Niue, Fiji, and Samoa.

Nutritional issues in relation to establishment and early growth

Extent, type, and severity of nutrient deficiencies in the wet tropics of north Queensland

In the early 1990's easily accessible published studies describing nutrient relationships for Australian rainforest timber trees, or indeed for any tropical hardwood plantations were limited. Since 1990, the total plantation estate in Australia has increased by 500 000 ha, with much of this area in Australia and worldwide having been reforested with species primarily grown for short-rotation pulp markets (Sedjo 1999, Gerrand *et al.* 2003). During this ten year period it has become clear that there are major nutritional constraints to the growth of timber trees in the humid tropics (Webb *et al.* 1995) including north Queensland (see Table 1, Webb and Reddell 2000, Webb *et al.* 2000a and 2000b). However, it was not always clear from these trials which particular nutrients are limiting tree growth.

In order to characterise the nutrient status of different soils, glasshouse trials have been used as a rapid screening technique to identify 'potential' nutrient deficiencies, which can help with designing effective follow-on field trials. Glasshouse trials test the soils ability to supply sufficient amounts of each of the nutrients essential for plant growth. The level of growth depression compared to a well-fertilised control is an indication of the severity of the deficiency. An example of this methodology is described for *Toona ciliata* (red cedar) in Webb *et al.* (1997). For example, using glasshouse trials with *T. ciliata* grown on a basaltic soil from Malaan on the Atherton tablelands of north Queensland, it is clear that when no nutrients ("Nil") are added that there is poor growth compared to that when adequate quantities of nutrients (Complete) are added (Figure 1).

Table 1 Effect of high and low fertiliser application on the growth of *Eucalyptus pellita* (red mahogany), *E. cloeziana* (Gympie messmate), and *Flindersia brayleyana* (Queensland maple) grown on soil derived from different parent material. Data are the mean and standard error (se) of four replicates.

Species	Tree Age (mths)	Soil Parent Material	Low Fertilisation		High fertilisation	
			Volume (m^3/ha)	se	Volume (m^3/ha)	se
Flindersia brayleyana	17	basalt	0.084	0.018	0.570	0.017
Eucalyptus cloeziana	17	basalt	1.76	0.32	3.56	0.39
Eucalyptus pellita	35	metamorphic	4.4	3.1	39.7	8.8

For details of fertilisers, rates, techniques, etc. see Webb. and Reddell (2000).

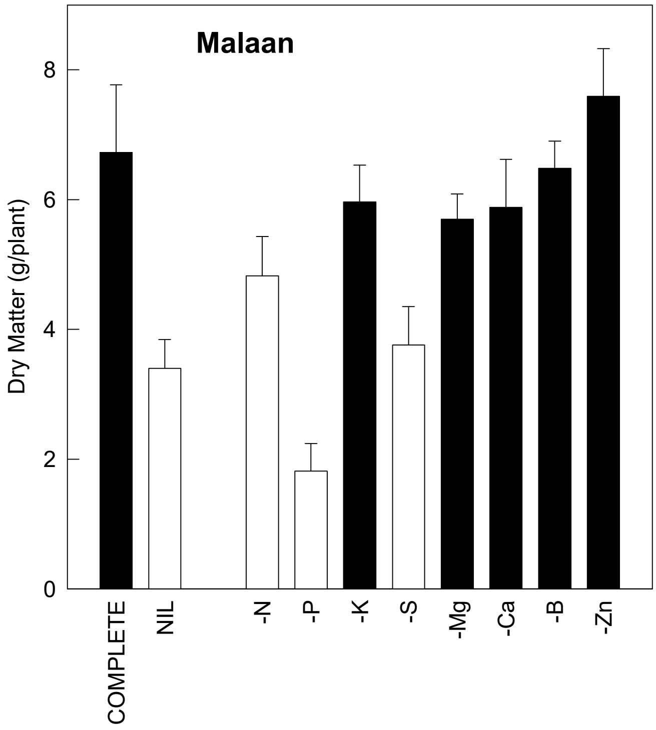

Figure 1 Growth of *Toona ciliata* (red cedar) after four months in an omission pot trial using basaltic soil from Malaan, north Queensland. The treatments applied were a complete nutrient addition as well as complete without: N (= -N); P (= -P); K (= -K); S (= -S); Mg (= -Mg); Ca (= -Ca); B (= -B); and Zn (= -Zn). This trial suggests this species suffers from a P deficiency when grown in this soil. Bars of the same colour are not significantly different when compared to the "Complete" or "Nil" treatments. Error bars represent the standard error of the mean.

Furthermore, these results clearly identify phosphorus ("-P"), as the most severely limiting nutrient in this soil as there is very little growth when P is omitted even when all other essential nutrients have been added. The next most limiting nutrient in this soil is sulphur ("-S"). Similarly, again using *T. ciliata*, another basaltic soil (Eubenangee series) from Innisfail the humid coastal lowlands of north Queensland soil was deficient in N, and to a lesser extent, P, K, and S; and another lowlands granitic soil from Feluga (Thorpe series) was found to be deficient in N and S (Webb *et al.* 1997).

Similar information has been collected using 35 soils from across the humid tropics of north Queensland in glasshouse omission trials. The results of these trials have been summarised by parent material, the severity of the nutrient deficiency, and the number times a particular deficiency was found (Table 2). This firstly shows that P is the most common severe deficiency; occurring in almost every soil tested except those formed on recent basalts. This P deficiency is shared by most tropical soils, especially plantation soils where additions of P and cations are generally required (Folster and Khanna, 1997). It is noteworthy that in soils other that those formed on recent basalts the two soils that did not show P deficiency had recently been in agricultural production with a history of phosphatic fertiliser use. Secondly, this data shows that the deficiencies and severities show some commonality within soils derived from the same parent material.

Table 2 Severity of nutrient deficiencies for tree growth at sites in north Queensland with particular soil types on the basis of parent material. This was determined through glasshouse omission trials *Agathis robusta*, *Castanospermum australe, Cedrela odorata, Eucalyptus grandis, Flindersia brayleyana*, *Gmelina arborea*, *Tectona grandis, Toona ciliata* and *Swietenia macrophylla*. NB. Soils derived from metamorphic rocks have been included as part of the metasediments.

Parent Material	No. of Soils	Extent of growth reduction	
		Severe (> 50%)	Moderate (20 to 50%)
		number of sites at which particular deficiency is present	
Basalt			
recent	2	nil	N-2
older	6	P-5, N-1	N-5, S-3, K-1
Metasediments	7	P-7, Ca-2	Ca-3, Zn-2, N-1, P-1, K-1, S-1
Granites	10	P-9, N-2, Ca-2, S-1, Cu-1	S-6, N-5, Ca-2, Mg-1, Zn-1, Cu-1, B-1
Mixed Alluvium			
well drained	2	P-2, K-1, N-1	K-1, Ca-1, S-1
poorly drained	2	P-2, S-1	N-2, K-1
Acid Volcanics	2	P-2	K-2, Cu-1
Beach Ridges	3	N-3, P-3, S-3, Zn-2, Mo-1	3xK, Zn-1, Mo-1

Key: "P-5" = 5 soils of this parent material were found deficient in phosphorus (P).

On the basis of these commonalities a 'risk assessment' table has been generated to further summarise and integrate the information into a form that could be used by land managers (Table 3). Once again it is quite clear that, independent of soil type, a P deficiency has a very high potential to severely reduce tree growth and that there is a high potential for N deficiency to limit growth in soils in the region.

While these results are not surprising, and add support to the CRRP practice of routinely applying a DAP as a prescriptive fertiliser (if we ignore species differences – see below), they also highlight the potential need to add other nutrients, especially Ca, K and S. These nutrients were rarely added in CRRP plantings unless DAP was not available and another source, or form, of phosphate was used. For example, single super phosphate will also supply calcium and sulphur, and triple super phosphate will also supply Ca.

Table 3 'Risk assessment' table to identify the nutrients that have the most potential to reduce production through insufficient supply. NB. Soils derived from metamorphic rocks have been included as part of the metasediments.

Parent Material	**Deficiency Index**		
	Very High	**High**	**Possibility**
Basalt			
recent	nil	N	
older	P	N, S	K
Metasediments	P	Ca	N, K, S, Zn
Granites	P	N, Ca, S	K, Cu, B, Mg
Mixed Alluvium			
well drained	P	N, K	Ca, S
poorly drained	P	S	N, K
Acid Volcanics	P	K	Cu
Beach Ridges	N, P, S	Zn, Mo, K	

What occurs under glasshouse conditions cannot be directly extrapolated to field situations. Ideally long-term results from field trials are needed and some measure of the overall economics of the situation considered. The CRRP was about reforestation of degraded lands and not necessarily about economic establishment of plantations (see Herbohn *et al.* Chapter 14). Indeed, for those landholders left to tend the young plantings, rapid promotion of growth during the establishment phase, which could lead to more rapid site capture, may be well worth the initial cost and effort.

The usefulness of glasshouse trials, and their limitations, has been confirmed in field trials in north Queensland and overseas, and the standard approach is described in Webb *et al.* (1997). For example, two species grown in a metamorphic soil showed a positive response to P fertiliser, as predicted, but another two did not (Webb *et al.* 2000a). Also, in the Solomon Islands, both *Gmelina arborea* (white teak) and *Tectona grandis* (teak) showed a positive response to P when grown in a soil derived from basalt but with a substantial difference in the magnitude of the response (Figure 2).

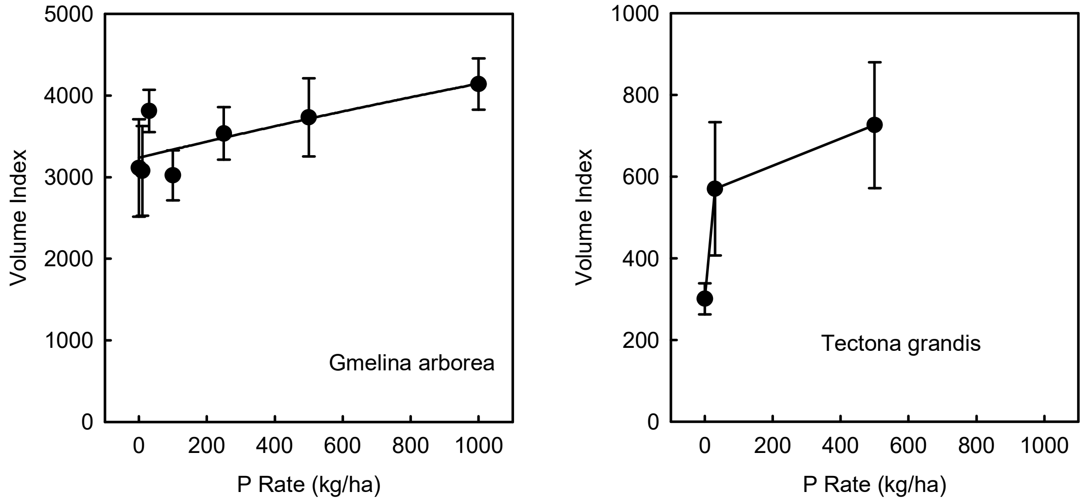

Figure 2 Growth response of *Gmelina arborea* and *Tectona grandis* to increasing phosphorus supply in a field trial on basaltic soil in Kolombangara, Solomon Is. Trees are 27 months old and have been supplied with sufficient amounts of all other essential nutrients. Error bars represent the standard error of the mean. This trial is an example of field testing of nutrient deficiencies first noted in preliminary glasshouse (nursery in this case) trials.

Thus, while glasshouse trials can be a useful indicator of potential nutrient deficiencies, such responses require field confirmation, especially if plantings are for economic gain.

In spite of this information on the severe nutritional limitations to tree growth under glasshouse and field conditions in soils of north Queensland commonly used for tree planting, and the information on which nutrients are most likely to be limiting in those soils, the concept of site specific fertilisation has rarely been adopted. Indeed, these same sentiments have been expressed in regard to the intensively managed tropical pine plantations in Queensland (Simpson 1998). Hopefully, site-specific nutrition research on tropical rainforest species will follow on from examples in other parts of the country with other timber species: viz, boron (B) on *Acacia melanoxylon* (Tasmania blackwood) (Fairweather and McNeil 1997); copper (Cu), zinc (Zn), P, N and other micronutients on *Araucaria cunninghamii* (hoop pine) (Richards 1967, Ryan 1982); manganese (Mn), and Zn (Cameron *et al.* 1986), micronutrients (Schonau and Herbert 1989, Cromer *et al.* 1993), and Cu and other micronutrients (Cromer 1996) on eucalypts.

Possible failure to recognise loss in growth potential

Whilst we have the ability to test soils both in glasshouse and field experiments for their ability to supply the necessary nutrients to support acceptable growth rates (Webb *et al.* 1995, Webb *et al.* 1997, Keenan *et al.* 1998, Webb and Reddell 2000, Webb *et al.* 2000a, 2000b) it is more common that small-scale tree growers will rely on observation and experience to determine if their trees are nutritionally healthy and therefore growing at an acceptable rate. Such observation may well be the basis for any decision to supply supplementary fertilisation.

In north Queensland, with so many species being grown and with trees from any one species potentially being obtained from quite genetically diverse stocks (see Lott *et al.* Chapter 3), it is difficult to establish an 'acceptable' or even 'expected' growth rate by which to judge the health of a stand. For example, the growth rate of young plantations of *Eucalyptus pellita* (red mahogany) in Australia and the South Pacific can range anywhere from 1 m/year to almost 5 m/year even though specific symptoms of ill-health may not have been apparent at the lower growth rates (Webb and Reddell 2000). Furthermore, this variation will continue as a result of genetic improvement and thus it is necessary to update acceptable growth rates. For example, for young plantation material Harwood *et al.* (1997) discuss a 10% increase in volume growth of second generation seed of selected provenances of *E. pellita*, and a 20-30% increase in volume growth over natural populations.

Thus, growers are usually dependent on their own previous experiences, or that of others, as to what constitutes a healthy stand. To a large extent, this is a judgement made on the physical appearance of the stand.

Unfortunately, reliance on simple appearance of a stand carries the possibility that the grower will fail to recognise a loss in growth potential. Whilst the use of visual symptoms of nutritional deficiencies can be a powerful tool in diagnosing and managing nutrient deficiencies in agricultural crops as well as trees (see Webb *et al.* 2001a), there are times when it may not adequately diagnose a reduction in growth rate as a result of a nutritional deficiency (Webb and Reddell 2000).

Nutritional deficiencies appear when the rate of growth exceeds the rate at which particular nutrients can be absorbed from the soil to support that growth. This results in tissues that have an inadequate supply of a particular nutrient to carry out the metabolic functions for which that nutrient is responsible. This is then manifested in a metabolic imbalance that results in the production of symptoms. A classic example is the yellowing of leaves in response to nitrogen deficiency because of a lack of protein for chlorophyll formation.

The production of symptoms is quite common when there is a gross imbalance of nutrients. However, we have found that when all nutrients are in balance, but are simply supplied at lower rates, growth rate may be reduced but no symptoms are apparent (Webb and Reddell 2000).

As an example, there is little evidence from their appearance, if assessed in isolation of the other treatments that the *Eucalyptus pellita* trees grown at lower nutrient supply (see Webb and Reddell 2000) are experiencing any nutritional stress. However, it is clear from comparison with trees grown at a higher nutrient supply (Webb and Reddell 2000) that they are not are not growing at their maximum potential. Furthermore, in spite of the large differences in growth rate, we were unable to detect any difference between these treatments through nutritional, biochemical, and physiological tests that should reflect differences in growth rate or levels of nutrition (Webb and Reddell 2000).

These results suggest that a vast number of trees may be growing at rates lower than their genetic potential and that this loss in production will not be realised.

Different species, different responses

For purposes of efficiency, we have used a single species, *Toona ciliata* (red cedar), to characterise the nutritional status of many of the soils reported above. However, it is quite clear from a number of experiments that different species may behave quite differently under the same edaphic and climatic conditions. Webb *et al.* (2000a) clearly showed that at the same site, *Cedrela odorata* (West Indian cedar) and *Agathis robusta* (kauri pine) responded to P fertilisers but *Castanospermum australe* (black bean) and *Flindersia brayleyana* (Queensland maple) did not.

At another site *A. robusta* showed little effect of fertiliser for at least two years yet *C. australe* responded immediately (Keenan *et al.* 1998). In the Solomon Islands, *Gmelina arborea* showed only a small response to added P fertiliser whereas added P more than doubled the volume of *Tectona grandis* (Figure 2).

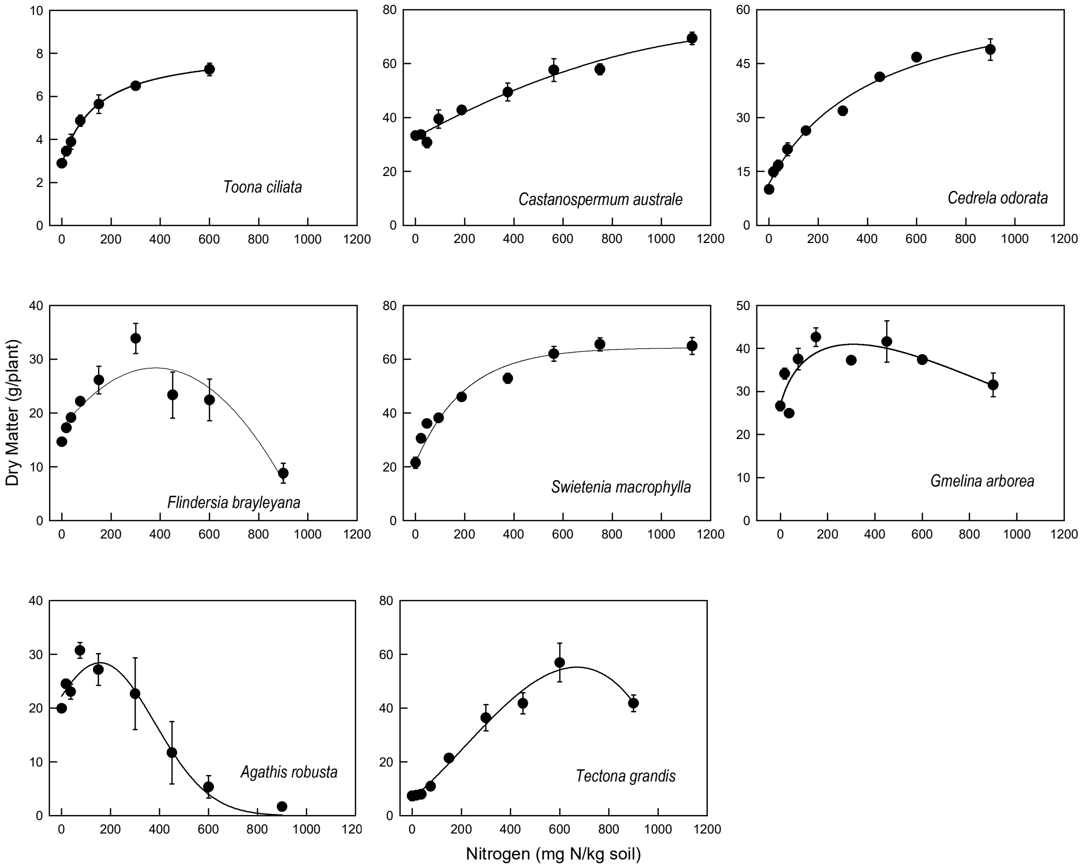

Figure 3 Dry matter response of rainforest timber species to nitrogen addition in a basaltic soil when grown under glasshouse conditions. Plants were harvested after growing for: 11 months, *Agathis robusta*; 12 months, *Castanospermum australe,* 13 months *Cedrela odorata,* 7 months, *Flindersia brayleyana*; 4 months, *Gmelina arborea*, 13 months, *Tectona grandis;* 7 months *Toona ciliata*; and 9 months *Swietenia macrophylla*.

Table 4 External requirements of N and P to achieve 90% of maximum growth*.

Species	N requirement (mg/kg)	P requirement (mg/kg)
Agathis robusta	45	32
Castanospermum australe	992	192
Cedrela odorata	741	56
Flindersia brayleyana	189	171
Gmelina arborea	187	222
Swietenia macrophylla	375	54
Tectona grandis	504	273
Toona ciliata	405	42

** N response was on a basaltic soil (PinGin series) from the Atherton Tablelands with a history of P fertilisation; P response was on a metamorphic soil (Galmara schist) from the humid coastal lowlands.*

The nutritional requirements for maximum growth also vary widely. In pot trials with a number of species, the pattern of response to N levels was markedly different among the different species grown (Figure 3).

This has resulted in 20-fold differences in external concentrations of N required for maximum growth (Table 4). Similar results have been found for P on the same species. However, the relative ranking for N differs from that for P (Table 4).

Visual symptoms of nutritional stress also vary widely among species. While some nutrient deficiencies result in visual symptoms that are common among many species (e.g. Fe deficiency) others are not as diagnostic. For example K and Mg deficiency symptoms are quite different in *F. brayleyana* but quite similar in *Gmelina arborea* (Figure 4). These results highlight the caution that is needed when extending the results for one species to another.

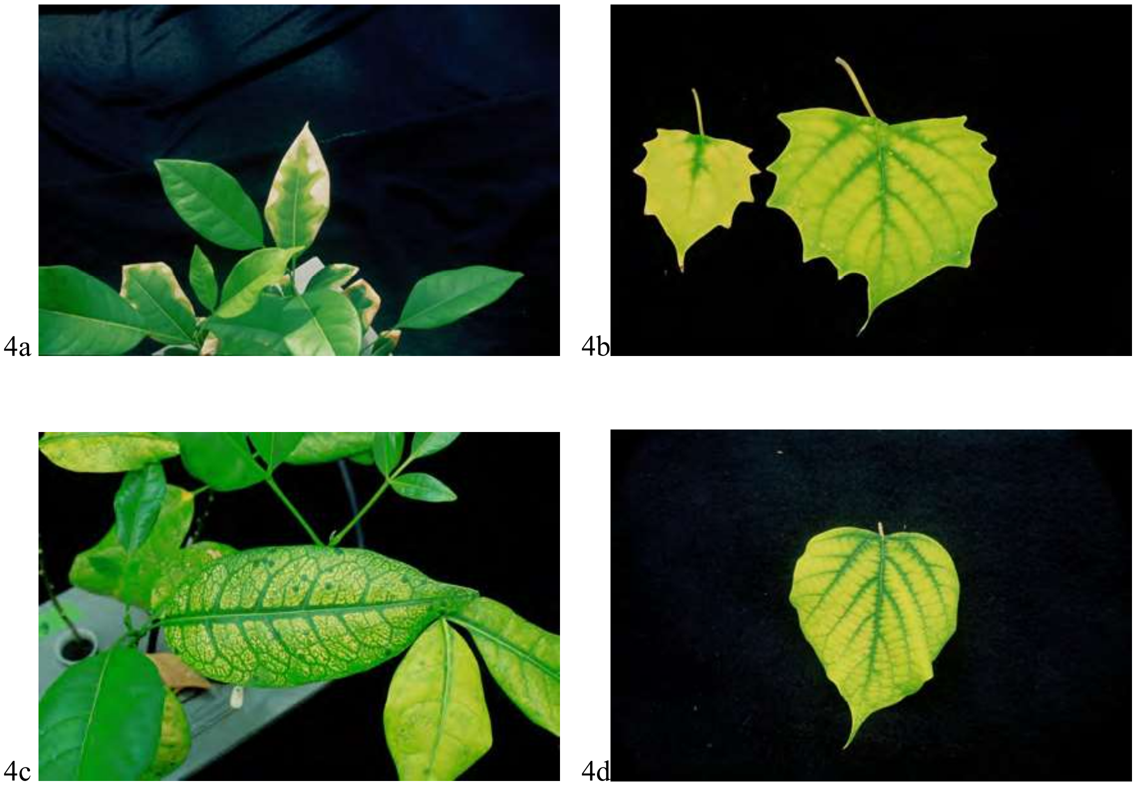

Figure 4 Potasssium (upper) and magnesium (lower) deficiency symptoms in *Flindersia brayleyana* (left, 4a & 4c) and *Gmelina arborea* (right, 4b and 4d).

Simple solutions using available technologies to improve establishment and early growth

The results presented above serve to highlight some of the issues faced by tree planters when considering a fertiliser strategy. While it is probably not practical to carry out experiments like those described above in order to determine the particular nutrient issues for a particular site and species being planted, these results and those presented below may aid in either avoiding nutrient deficiencies or managing those that are detected. For example, knowledge of soil parent material and site history may help in deciding what longer term nutritional issues will need to be addressed.

Slow release fertilisers

Although there are differences in the nutritional status of different sites, and differences between species in the way they respond to nutritional stress, there are some simple solutions that can improve establishment and early growth.

The first of these is to provide a continuous supply of nutrients to young plants especially during the transition from nursery to field. In many situations, planting material may be quite low in nutrients because of the length of time they are in the nursery or deliberate management decision used to 'harden up' the seedlings. Immediately after planting, roots need to develop to exploit the resources of the soil around them. Often the soils lack one or more nutrients, which may need to be supplied as fertilisers. These nutrients are usually applied to the surface or in a small slot for ease and efficiency of operation. In either case, these nutrients will have no effect until they come in contact with a root and are absorbed. This could take many weeks depending on many factors such as the growth rate of roots, the original location of the nutrient, the type of nutrient and form that is used, or rainfall to move the nutrient through the soil profile. This is likely to be when a young plant is most vulnerable to competition from other vegetation for resources. It is also a time that they have minimal resources with which to compete.

Universally in tropical forest plantations, establishment silvicultural recommendations for weed control are to maintain the tree rows free of weeds for the first couple of years, to remove competing vegetation allowing the trees to achieve rapid site capture. These recommendations extend for growing rainforest species (Subtropical Farm Forestry Association 2001, Bristow *et al.* 2005). With judicious weed control, careful individual tree application of fertilisers can be effective. Evidence for tropical eucalypts exists to suggest that this sort of technique is far less responsive when inadequate weed control is used (Keenan and Bristow 2001). The CRRP experience showed that these recommendations were not often followed; weed control was generally poor and thus competing grasses and weeds regularly received the fertilisers that were meant for the trees.

An alternative technique where nutrients can be packaged in pots in the nursery phase, then buried underground can be an efficient and effective way of delivering establishment nutrients to tree plantations. Studies have shown that by providing continuous access to nutrients through the planting phase, substantial improvements to early growth (to age two years) can be achieved (Woods *et al.* 1998, Reddell *et al.* 1999, Webb and Reddell 2000, Webb *et al.* 2000b). In general this has been done by providing a large amount of long-term slow release fertiliser in a medium that will facilitate the planting of the slow release fertiliser with the root ball and intact.

A good example of the use of this technique comes from work in the Solomon Islands with *Gmelina arborea* (Reddell *et al.* 1999). In brief, coir (composted and ground coconut husks) is mixed with both commercially available short-term (four to five month release time) and long-term (nine month release time) slow release fertilisers in reasonably large quantities (10- 20 g/L coir). The *G. arborea* cuttings used are usually only kept in the nursery for 6 weeks, after which they are transported to the field for planting. In this experiment, no field fertiliser was added to the trees. An important part of the planting process is to keep the root ball intact to minimise disturbance and maximise the retention of the slow release fertiliser around the roots. Although the fertiliser had no effect after six weeks in the nursery, there was an effect some six months later in the field (Figure 5). This effect was even more pronounced after 14 months (Reddell *et al.* 1999).

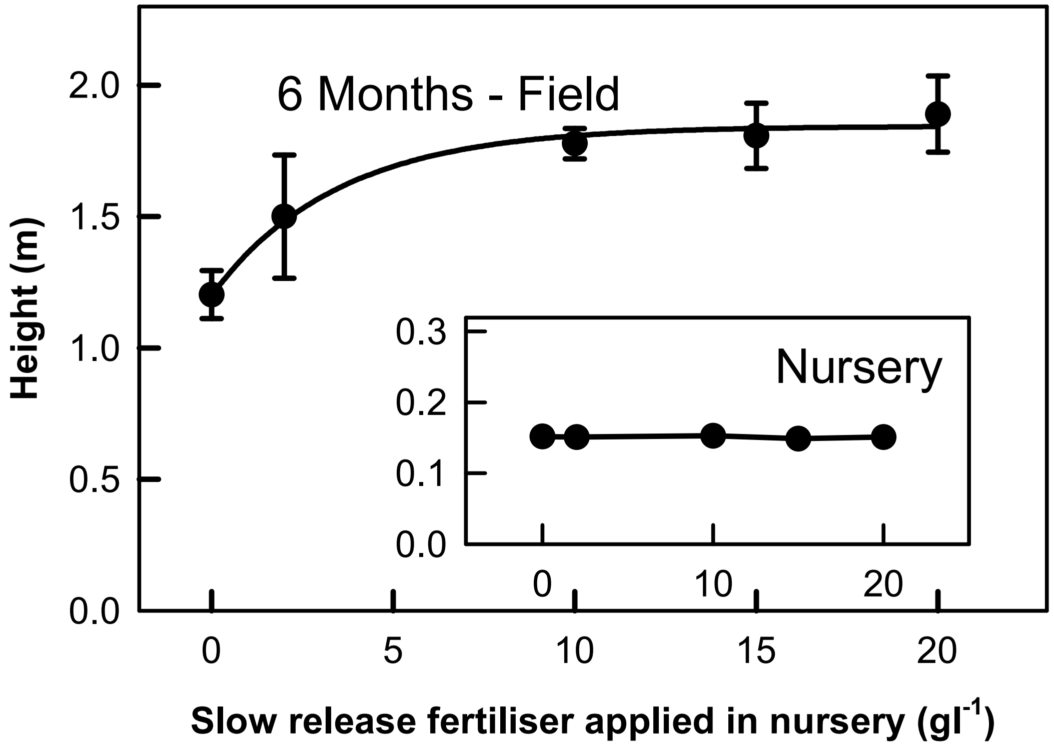

Figure 5 Effect of nursery-applied slow release fertiliser (details of fertiliser in Reddell and Webb 1999) on subsequent field growth of *Gmelina arborea.*

Although these rates of application are large by nursery media standards they are very small compared to routinely used rates of field applied fertiliser. For example, the amount of P added at the top rate in the nursery is some 300-fold less than that commonly added as field applied P. Because these soils in the Solomon Island have a high P-sorption capacity, these surface-applied P fertilisers are often ineffective. This approach has been so successful in the Solomon Islands that the plantation company no longer applies fertiliser post planting; instead they now control their fertiliser management in the nursery.

Similar trials in Australia have also shown considerable benefit of improving the availability of nutrients to tree roots during early growth. At a number of sites and on a range of soil types in north Queensland improving nursery and subsequent field nutrition has resulted in a doubling of height in six months (Webb and Reddell 2000) compared to the standard fertilisation practice. By 24 months the relative height differences had lessened but the stem volume of the well-fertilised tree was still more than double that of the tree fertilised using the standard practice.

Diagnosis by Symptoms

Sometimes growth rate may be depressed in young trees even though there are no symptoms of nutrient deficiency. This usually occurs when all nutrients are low in availability. However, when just one or two are out of balance we will often get visual symptoms, which, because of their particular feature, may be diagnostic of a particular nutrient deficiency. This information is captured in a book of descriptions and colour photographs depicting common nutrient deficiencies in young trees (Webb *et al.* 2001a). A second book is currently in production that will provide symptoms for *Castanospermum australe*, *Flindersia brayleyana* and *Agathis robusta*.

Although symptoms can be a useful technique for diagnosing nutritional problems, they should not be relied on as a sole management tool because by the time symptoms become visible it is often the case that stand or tree production has suffered. It is recommended remedial measures be applied in advance of visual symptoms appearing. Site and land use history, soil characteristics and nutrient deficiencies common to north Queensland soils presented as a 'risk assessment' in Table 3, may be a starting point.

Rapid Diagnostic Tests

In addition to traditional chemical analysis of nutrients to diagnose nutritional status of tropical timber trees (see Boardman *et al.* 1997), Webb *et al.* (2001b) have also developed rapid tests for determining N and P status using 'test strips'. These tests are rapid (a couple of minutes to complete) and while they may not provide the same degree of precision in determining the level of deficiency as tissue nutrient analysis, they have been used quite successfully in a "trouble shooting" sense to determine the nature of a problem and suggest a solution. For example, in the Solomon Islands, *Eucalyptus deglupta* (kamerere) seedlings in the nursery were quite chlorotic, suggesting nitrogen deficiency. However, when the sap was tested with a nitrate test strip it was clear that nitrogen deficiency was not the problem. Further investigation suggested iron deficiency as likely and a subsequent experiment with a foliar application of iron chelate confirmed this. Had traditional chemical nutrient analysis been undertaken, by the time the results would have been available the trees would have probably already left the nursery and been planted in a poor condition. Further, the cause of the condition (in this case, slow release fertiliser without added micronutrients) would not have been recognised and could have possibly re-occurred.

Conclusions

When developing a fertiliser strategy to achieve good establishment and early growth it is important to consider the:

- site and land use history, and soil characteristics;
- type of fertiliser, i.e. the nutrient needed;
- amount of fertiliser required;
- chemical form of that fertiliser (i.e. nutrient release rate);
- timing of application;
- site of application; and
- species being fertilised.

From a commercial point of view, it is also important to consider the cost/benefit of such a strategy, however it is important to consider more that just timber production as the benefit. That is, one should also consider the consequences of such a strategy in terms of its ability to reduce the costs of silvicultural activities. Trees with adequate nutrients grow better, capture the site more efficiently and shade out competing grasses and weeds. The ensuing increased tree growth, and consequent reduced weed control costs, can offset high fertilisation costs; which is part of good establishment silviculture.

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References

Boardman, R., Cromer, R. N., Lambert, M.J. and Webb, M.J. 1997. Forest plantations, In (Eds) Reuter, D.J. and Robinson, J.B. *Plant Analysis – an interpretation manual*. Collingwood. pp. 503-566. CSIRO Publishing.

Bristow, M., Annandale, M. and Bragg, A. 2005. Growing Rainforest Timber Trees: a farm forestry manual for north Queensland. JVAP Manual Series No. 4., RIRDC Publication No. 03/010, Rural Industries Research and Development Corporation, Canberra.

Cameron, D.M., Rance, S.J. and Williams, E.R. 1986. Nutrition studies with irrigated *Eucalyptus camaldulensis* and *Anthocephalus chinensis* on a cracking clay in northern Australia. *Tropical Agriculture*, 63 (1): 11-16.

Cromer, R.N. 1996. Research to increase and sustain productivity of hardwood plantations in Australia. *Australian Forest Grower*, 19 (1): Special Liftout Section No. 35.

Cromer, R.N., Cameron, D.M., Rance, S.J., Ryan, P.A. and Brown, M. 1993. Response to nutrients in *Eucalyptus grandis*. 1. Biomass accumulation. *Forest Ecology and Management*, 62: 211-230.

Evans, J. 1992. Plantation Forestry in the Tropics. 2nd Edition Oxford University Press, Oxford.

Fairweather, J.R. and McNeil, D. 1997. Early growth response of Acacia melanoxylon to superphosphate, lime and boron. *Australian Forestry*, 60 (3): 202-206.

Folster, H. and Khanna, P.K. 1997. Dynamics of Nutrient Supply in Plantation Soils. In (Eds) Nambiar, E.K.S. and Brown, A.G. *Management of Soil, Nutrients and Water in Tropical Plantation Forests*. Canberra. pp. 339-378. ACIAR.

Gerrand, A., Keenan, R.J., Kanowski, P. and Stanton, R. 2003. Australian forest plantations: an overview of industry, environmental and community issues and benefits. *Australian Forestry*, 66 (1): 1-11.

Harwood, C.E., Alloysius, D., Pomroy, P., Robson, K.W. and Haines, M.W. 1997. Early growth and survival of *Eucalyptus pellita* provenances in a range of tropical environments, compared with *E. grandis*, *E. urophylla* and *Acacia mangium*. *New Forests* 14: 203-219.

Keenan, R., Hambleton, A., Robson, K. and Webb, M. 1998. Growth response of rainforest cabinet timber species to fertilizer application in north Queensland plantations. In (Eds) Schulte, A. and Ruhiyat, D. *Soils of Tropical Forest Ecosystems*. pp.107-114. Springer, Berlin.

Keenan, R.J. and Bristow, M. 2001. Effects of site preparation, weed control and fertilisation on the early growth of planted eucalypts on a farm forestry site sin north Queensland. In (Ed) Grodecki, A. *Managing and Growing Trees training conference*. Kooralbyn, Queensland, 2001. pp. 131-135. Queensland Department of Natural Resources and Mines.

Reddell, P., Webb, M., Poa, D. and Aihuna, D. 1999. Incorporation of slow-release fertilisers into nursey media. *New Forests*, 18:277-287.

Richards, B.N. 1967. Introduction of the rain-forest species *Araucaria cunninghamii* Ait. to a dry schlerophyll forest environment. *Plant and Soil*, 27: 201-216.

Ryan, P.A. 1982. Results of fertilising and weed control experiments in the establishment of hoop pine plantations. In *Report of a meeting of the Australian Forestry Council's Research Working*

Group 5: Establishment of Coniferous Plantations. Mt Gambier, South Australia, 20-23 September 1982. Australian Forestry Council.

Schonau, A.P.G. and Herbert, M.A. 1989. Fertilizing eucalypts at planation establishment. *Forest Ecology and Management* 29: 221-244.

Sedjo, R.A. 1999. The potential of high-yield plantation forestry for meeting timber needs: recent performance, future potentials, and environmental implications. *New Forests* 17: 339-359.

Simpson, J. 1998. Site specific fertiliser requirements of tropical pine plantations. In (Eds) Schulte, A. and Ruhiyat, D. *Soils of tropical forest ecosystems*. Springer, Berlin. pp 115-124.

Subtropical Farm Forestry Association. 2001. Farm Forestry manual and planner for subtropical eastern Australia. Subtropical Farm Forestry Association, Lismore.

Vitousek, P.M. and Sanford, R.L. 1986. Nutrient Cycling in Moist Tropical Forest. *Annual Review of Ecology and Systematics* 17: 137-167.

Webb, M.J., Poa, D., Hambleton, A. and Reddell, P.W. 1995. Identifying and solving nutritional problems in establishing plantations of high-value cabinet timbers: a case study in the Solomon Islands, Volume 4. In *Soils and Plantation Forestry. Proceedings of the International Congress on Soils of Tropical Forest Ecosystems. Third Conference on Forest Soils*. Balikpapan, Indonesia, 29 Oct – 3 Nov 1995. pp. 148-165.

Webb, MJ., Reddell, P., Hambleton, A. and Mazza, G.M. 1997. Nutritional constraints to growth of Australian red cedar (*Toona ciliata*) seedlings in five north Queensland soils. *Australian Forestry*, 60 (1): 46-52.

Webb, M.J. and Reddell, P. 2000. Demonstration of the potential effects of nursery nutrients – Tropical cabinet timber trees. RIRDC Publication No. 00/119. Rural Industries Research and Development Corporation, Canberra.

Webb, M.J., Reddell, P., Hambleton, A and Robson, K. 2000(a). Growth response of four tropical plantation timber species to increasing phosphorus supply and assessment of phosphorus requirements using foliar diagnosis. *New Forests* 20:193-211.

Webb, M.J., Reddell, P. Pauku, R., Bevu, T. and Pouli, T. 2000(b). Inadequate nutrition: A major (and often unrecognised) limitation to tree growth in the humid tropics of north Queensland and the south western Pacific, pp. 257-260. In (Eds) Snell, A. and Vise, S. *Proceedings of the Australian Forest Growers Biennial conference: Opportunities for the New Millennium*. Cairns, 4-6 Sept 2000. Australian Forest Growers.

Webb, M.J., Reddell, P. and Grundon, N.J. 2001a. A Visual Guide to Nutritional Disorders of Tropical Timber Species: *Swietenia macrophylla* and *Cedrela odorata*. Australian Centre for International Agricultural Research, Canberra.

Webb, M.J., Reddell, P., Nath, S. and Srivastava, R.J. 2001b. Determining P and N status of a tropical timber species (teak): assessment of 'quick' chemical tests and a root phosphatase assay, pp. 706-707. In (Eds) Horst, W.J. and others. *Plant Nutrition – food security and sustainability of agro-ecosystems through basic and applied research*. Kluwer Academic Publishers, Dordrecht/ Boston/ London.

Woods, P.V., Peseta, O. and Webb, M.J. 1998. Effectiveness of organic potting media for raising mahogany (*Swietenia macrophylla*, King) seedlings in Western Samoa. *Journal of Tropical Forest Science* 10: 552-560.