RESPONSE OF *EUCALYPTUS DEGLUPTA* TO PHOSPHATE FERTILISER

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CROMER, R.N., TAN, K.C., WILLIAMS, E.R. & RAWLINS, W.H.M. 1992. Response of *Eucalyptus deglupta* to phosphate fertiliser. An experiment was installed in 3 - to 4-y- old plantations of *Eucalyptus deglupta* in the Tawau residency, Sabah, Malaysia. Rock phosphate was applied to plantations on three soil types at five rates of elemental phosphorus (0, 50, 100, 200 and 400 *kg* P ha^{-1}). Height and diameter measurements were made on trees prior to application of fertiliser and at intervals over three subsequent years. Samples of foliage were taken for chemical analysis 12 months after treatments had been applied. Phosphorus concentrations in foliage of unfertilised trees differed between soil types but application of P fertiliser increased foliar P concentrations over all soils. Within each soil type, increases in foliar P concentrations were linearly related to current annual increment in wood volume during the 12 months after samples had been taken. Growth responses were evident within 12 months of fertiliser application and increased thereafter. Three years after treatment, increases in mean annual increment in wood volume were linearly related to the logarithm of the quantity of fertiliser applied, up to a maximum of four m^3 ha^1 at the highest application rate of 400 *kg* P ha^{-1}. Soil type (site quality) had no influence on this relationship. Growth rates of *E. deglupta* in Sabah have been below expectations and establishment of new plantations is not likely to be profitable, even with enhanced growth from P fertiliser. However, marginal returns on investment in P fertiliser application to existing stands on good sites are high and an application of 100 *kg* P ha^{-1} is recommended.

Key words: *Eucalyptus deglupta* - phosphorus fertiliser - plantations - foliage nutrients - internal rate of return - investment

CROMER, R.N., TAN, K.C., WILLIAMS, E.R. & RAWLINS, W.H.M. 1992. Tindak balas *Eucalyptus deglupta* ke atas baja fosfat. Satu kajian telah dijalankan diladang-ladang *Eucalyptus deglupta* yang berumur antara 3 hingga 4 tahun di residensi Tawau, Sabah, Malaysia. Baja fosfat telah digunakan di 3 jenis tanah pada 5 kadar elemen fosforus yang berlainan (0, 50, 100, 200 dan 400 *kg* P ha^{-1}). Ukuran ketinggian dan perepang diambil pada pokok sebelum rawatan pembajaan dan setiap tahun selama 3 tahun berikutnya. Contoh daun diambil untuk analisis kimia 12 bulan selepas lawatan tersebut. Kepekatan fosforus dalam folias pokok yang tidak dibaja berbeza diantara jenis tanah, tetapi penambahan kepekatan P foliar disemua jenis tanah adalah berhubung secara linear pada penambahan tahunan semasa dalam isipadu kayu sepanjang 12 bulan selepas sampel diambil. Kesan tumbesaran adalah jelas dalam masa 12 bulan setelah pembajaan dan meningkat seterusnya. Tiga tahun setelah rawatan, peningkatan pada penambahan tahunan purata isipadu kayu adalah berhubung secara linear dengan logarithma kuantiti pembajaan, hingga tahap maksima $4m^2$ ha^{-1}. Jenis tanah (kualiti tapak) tidak mempengaruhi perhubungan ini. Kadar tumbesaran *E. delupta* di Sabah lebih rendah dari yang dijangkakan dan penubuhan ladang-ladang baru dijangkakan tidak menguntungkan, walaupun dengan tumbesaran yang nyata menggunakan baja P. Walau bagaimanapun, pulangan yang sedikit untuk pembajaan P pada dirian yang sedia ada diatas tapak-tapak yang baik adalah tinggi dan pembajaan 10 *kg* P ha^{-1} adalah dicadangkan.

Introduction

The state of Sabah, Malaysia has been heavily dependent on revenue derived from exploitation of primary dipterocarp forest for almost half a century but income from forest royalties has been declining since a peak in 1979, as reserves are being depleted by commercial logging and clearing for agriculture (Mastan 1984). Development of plantation forests could ensure continued wood supply and employment within the state. Since 1974, growth in world hardwood pulp production has resulted from new mills based on plantation-grown eucalypts, principally in South America and South Africa but with some expansion of existing facilities in Spain and Portugal (Woodbrige, Reed & Associates 1986). The fundamental economic rationale for growing plantations of eucalypts or other tropical and sub-tropical hardwoods is that fast growth enables large wood using industries such as pulp mills to be supported by a relatively small land base, thus minimising harvesting and transport costs of raw material.

Sabah Softwoods Sdn. Bhd. pioneered planting of hardwoods on cleared rainforest sites in southeast Asia in 1974 with *Paraserianthes falcataria* (formerly *Albizia falcataria*), *Eucalyptus deglupta, Gmelina arborea* and, more recently, *Acacia mangium.* This afforestation project covers an area of approximately 61,000 *ha* of logged over forest in the Tawau Residency of Sabah, (4°30' N, 117° 30' E, Figure 1). Growth of *P. falcataria* has generally been good, with mean annual increment in volume (MAIV) ranging from 30 to 60 m^3 ha^{-1} a^{-1} (Mastan 1984). *P. falcataria* has been sold for sawn timber despite small diameter logs, and plantations of this species are economically viable over a rotation of 12 years (Ibbotson 1984). However, growth rates of *E. deglupta* have generally been much lower than *P. falcataria* (Tan and Jones 1982) and the species is no longer being planted. Some 10,000 *ha* had already been established by 1983 and since pulping properties are very good and basic density is higher than *P. falcataria* (Logan 1981), research trials to improve growth in these stands was warranted.

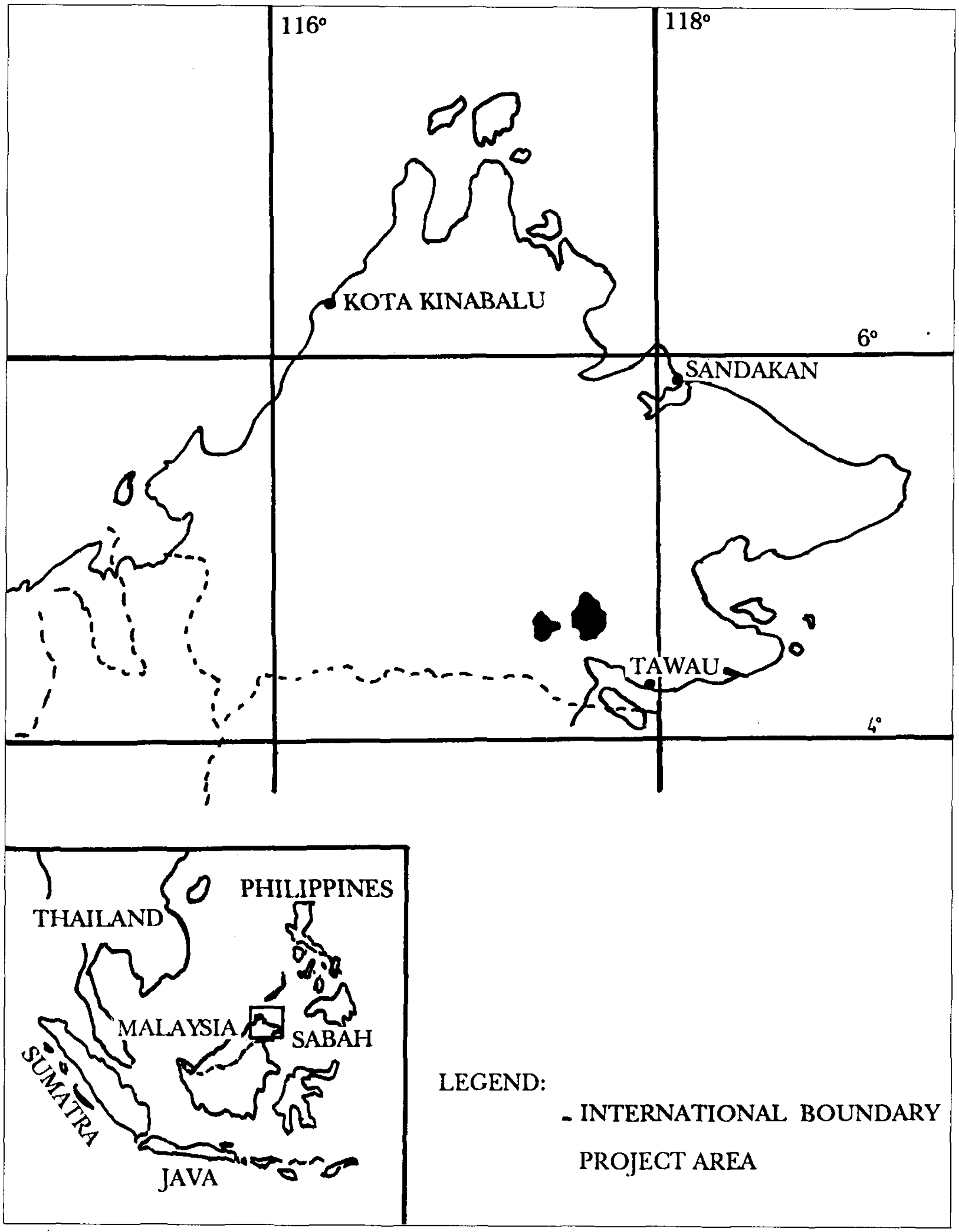

Figure 1. Map showing location of project area managed by Sabah Softwoods Sdn. Bhd. in Sabah, Malaysia

The project area has a humid tropical climate; rainfall distribution is relatively uniform and mean temperature of the coolest month exceeds 27°*C*. Total annual precipitation ranges from less than 2000 *mm* per year in the south (300 *m* elevation) to 2400 *mm* or more in the north (1000 *m* elevation). Despite this high rainfall, estimated evaporation can exceed rainfall for some months of the year, particularly in the south.

Geologically, the greater part of Sabah, particularly that which supported the best dipterocarp forest, was formed from severely folded but relatively soft sedimentary sandstones and mudstones with hills reaching between 100 and 2000 *m* in elevation (Ibbotson 1984). Soils derived from these parent materials are predominantly Acrisols, defined as having an argillic B horizon with a base saturation of less than 50 per cent (Acres *et al.* 1975). Orthic Acrisols are the most widespread soils in Sabah and are found on well or moderately well drained sites on most rock types that occur in the state. They have been sub-divided into soil families based on clay content of the argillic horizon (Wright 1975). Soils derived from sandstone have lower clay contents than those derived from mudstones and hence have lower water-holding capacity and are more prone to water stress during dry periods. Chemical analyses indicate that phosphorus (P) status of Orthic Acrisols is consistently low.

Research on nutrient requirements of rubber (*Hevea braziliensis*) has shown that rock phosphate is equally effective and more economic than alternative soluble forms of P in acid Malaysian soils (Pushparajah *et al.* 1974). Subsequent investigations showed that rock phosphate also had better residual P value than alternatives (Pushparajah *et al.* 1977). Numerous fertiliser trials have been conducted by Sabah Softwoods and preliminary results with *G. arborea* indicated positive growth responses to P alone (Tan and Lee 1984), whilst results from *E. deglupta* were not conclusive.

There is a dearth of information on nutrient requirements of *E. deglupta* but Lamb (1973) reported a suspected deficiency of P and potassium (K) in *E. deglupta* in the East Sepik District of Papua New Guinea and demonstrated substantial increases in growth following application of fertiliser containing N, P and K. Stands without fertiliser had virtually failed, having poor growth and survival with only a few leaves remaining on live trees. An application of fertiliser which included 55 *kg*P ha^{-1} restored normal crown development and increased foliar P concentrations from 0.8 to 1.2 $mg\,g^{-1}$. Lamb (1977) subsequently observed that foliar P concentrations in most plantations of the species in Papua New Guinea were greater than 1.5 $mg\,g^{-1}$, which probably exceeded the critical value.

A critical foliar nitrogen (N) concentration of 21 $mg\,g^{-1}$ was proposed by Lamb (1977). A preliminary survey of foliar nutrient levels in the four major species was conducted in the Sabah Softwoods project area in 1983. Data for *E. deglupta* indicated that foliar P concentrations in Sabah trees were low by comparison with healthy plantations of the same species in Papua New Guinea and levels in healthy trees were marginal (Table 1). By comparison, N levels were of the same order as those observed by Lamb (1977).

Table 1. Elemental concentrations in the foliage of unhealthy (U) and healthy (H) *Eucalyptus deglupta* aged 5 *y* growing in Sabah, Malaysia, compared with data from Gogol and Keravat in Papua New Guinea (Lamb 1977)

	Sabah U	Sabah H	Gogol (range)	Keravat (range)
Macro-nutrients ($mg\ g^{-1}$)				
Nitrogen	18.2	20.6	6.4-20.4	17.7-33.6
Phosphorus	1.1*	1.5	1.0- 6.9	3.6- 5.4
Potassium	10.1	12.2	4.4-17.8	10.3-14.8
Magnesium	4.6*	2.8	1.3- 4.2	nd
Calcium	3.9	5.8	4.6-14.0	nd
Micro-nutrients ($\mu g\ g^{-1}$)				
Iron	69.4	55.8	32 - 148	nd
Copper	7.8	8.7	2 - 6	nd
Boron	38.2	31.9	15 - 84	nd
Zinc	19.9	21.3	6 - 49	nd
Manganese	543	351	8 - 270	nd

* Significant differences between unhealthy and healthy trees (LSD $p = 0.05$);. nd: Not determined

A collaborative research project between Sabah Softwoods and CSIRO Division of Forest Research (now the Division of Forestry) began in 1984 and field experiments were established to examine the response of *E. deglupta* to addition of phosphate fertiliser. As soils were acid and were expected to have high P sorption characteristics, heavy application rates were included so that an "optimum" intermediate rate might become evident. Trials were set out in established plantations as Sabah Softwoods was not planting new areas of *E. deglupta.*

Methods

Orthic Acrisols are the most common soils in the project area and three representative sites were chosen to represent different clay contents. Soils included in the Kapilit family are largely derived from sandstone and their argillic horizons have less than 25 % clay (Wright 1975). Soils in the Tanjong Lipat family may be derived from either sandstone or mudstone and their argillic horizons have between 25 and 40 % clay (Wright 1975). Typical physical and chemical characteristics of Kapilit and Tanjong Lipat soils from the project area are shown in Table 2.

Three sites were selected within established plantations of *E. deglupta* as follows:

i) Kapilit soil, plantation age four years and one month;
ii) Tanjong Lipat soil (shallow phase) on steep topography, plantation age three years and four months;
iii) Tanjong Lipat soil (deep phase) on gentle topography, plantation age four years and one month.

Table 2. Physical chemical characteristic of a) Kapilit and b) Tanjong Lipat soil families in the Sabah Softwoods project area

Depth (*cm*)	Particle Sand	Size Silt	% Clay	Org. C (%)	Total N(%)	Available P (*ppm*)	pH (H_2O)	Exch. Ca	cation Mg	(*meq* K	%) Na	CEC *meq*%	Base Satn
a) Kapilit													
0- 18	77	9	10	1.6	0.13	4	4.3	0.2	0.1	0.1	tr	6.7	6
18- 45	80	12	5	1.0	0.09	tr	4.6	0.2	0.1	-	tr	4.6	7
45-105	76	11	12	0.5	0.03	1	4.8	0.2	-	-	-	5.1	7
105-110	72	9	17	0.1	-	tr	4.6	0.3	tr	-	-	2.6	12
b) Tajong Lipat													
0- 3	53	29	18	6.1	0.52	7	4.4	1.0	1.6	0.5	tr	1.5	27
3-18	41	34	25	1.0	0.12	2	4.5	0.1	0.1	0.2	-	10.8	5
18-53	36	29	35	0.4	0.06	1	4.2	0.1	0.2	0.1	-	11.5	3
53-85	43	22	35	0.2	0.04	1	4.3	tr	0.1	0.1	-	11.0	2

Twenty-five contiguous plots (five replicates of five treatments), each of 0.02 *ha* and surrounded by one buffer row were set out at each site. Initial stocking was 800 stem per *ha* and each measured plot consisted of four rows of four trees (16 trees or spaces where trees had died). Plots were slashed every six months to reduce competing vegetation. Diameter over bark at 1.3 *m* (DBHOB) of all trees and height of two dominant trees (predominant height = mean height of tallest 100 stems per *ha*) was measured prior to treatment. Plots were allocated to replicates according to pre-treatment basal area and treatments were applied at random within replicates. Christmas Island rock phosphate was applied at five rates of elemental P: 0, 50, 100, 200 and 400 $kg\ ha^{-1}$. There was some evidence of possible boron deficiency from field observation and chemical analysis of foliage (Table 1), so an application of 50 *g* borate per tree (4.5 kg B ha^{-1}) was made to all plots to ensure responses were not influenced by lack of boron.

DBHOB of all trees and predominant height were measured at six monthly intervals. Volume to a 10 *cm* top diameter was calculated from mean diameter and predominant height using a stand volume equation developed by Sabah Softwoods. Twelve months after fertiliser application, foliage samples were taken from the mid-crown of the four trees in the centre of each plot (youngest fully expanded leaves at the ends of branches) and bulked to form a composite. Samples were dried at 70°*C* and ground to pass a 20 μm screen before dispatch to Canberra. Samples were digested in sulphuric acid and hydrogen peroxide and analysed for nitrogen and phosphorus using automated techniques (Heffernan 1985).

Statistical analyses of data were performed using standard analysis of variance and regression techniques available in the Genstat Statistical Package (Alvey *et al.* 1982).

Results

Foliar nutrients

Foliage samples taken 12 months after treatments had been applied showed that phosphorus concentrations had increased as a result of P fertiliser application

(Figure 2) but there was no significant effect on N concentration. Analysis of variance showed that differences in foliar P between soil types and treatments were both highly significant ($p < 0.001$). Foliar P concentrations for Kapilit and Tanjong Lipat (deep) at 200 $kg\ ha^{-1}$ P were lower than expected for this treatment level. These inconsistencies were not evident when foliar P concentrations were plotted against current annual volume increment (CAIV) during the 12 months after foliage samples were taken (Figure 3), which suggests that this treatment level may not have received the full 200 $kg\ ha^{-1}$ P on those two soils. A regression model of CAIV against leaf P showed there was no significant interaction between leaf P and soil type so a single slope was satisfactory for all soils. The model accounted for 92.4% of the variance:

$$CAIV = a + 37.83\ (\text{leaf P})$$

Where CAIV is in $m^3\ ha^{-1}\ a^{-1}$, leaf P is in $mg\ g^{-1}$ and a is -30.84, -17.13 and -3.75 for Kapilit, Tanjong Lipat (shallow) and Tanjong Lipat (deep) soils respectively. Absolute increases in foliar P concentration over the range of treatments applied was greatest in trees on Kapilit soil, which has a lower clay content than Tanjong Lipat soils. A higher clay content in Tanjong Lipat soils would have resulted in greater adsorption of P, and hence reduced uptake by trees.

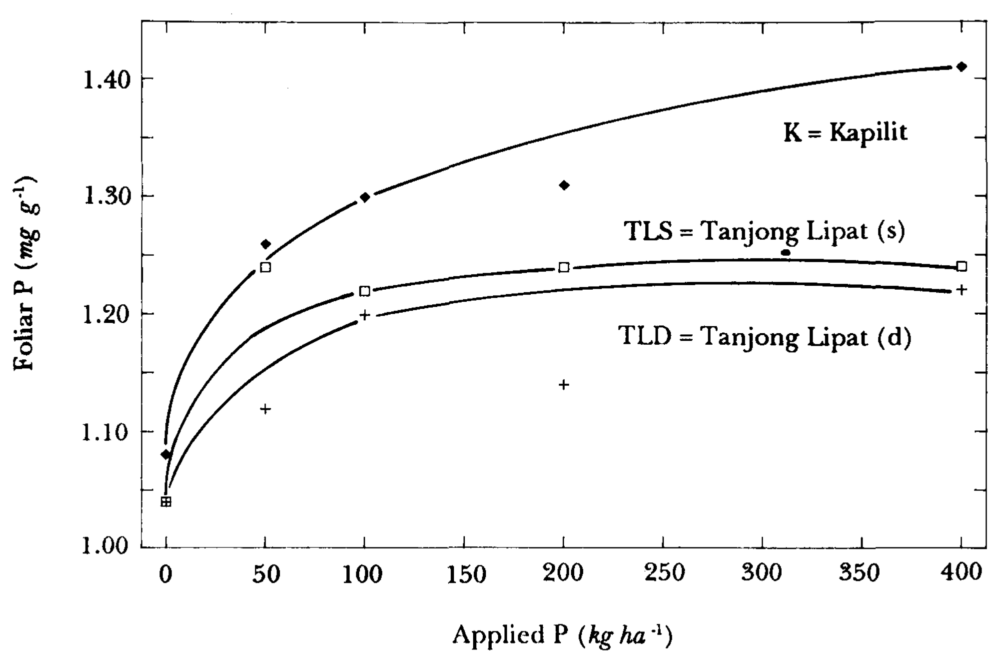

Figure 2. Phosphorus concentration (P) in foliage of *E. deglupta* 12 months after fertiliser treatments had been applied, in relation to rate of fertiliser applied to three soil types; Lines are hand drawn; identity of soils: Kapilit (■), Tanjong Lipat shallow (❐), Tanjong Lipat deep (+)

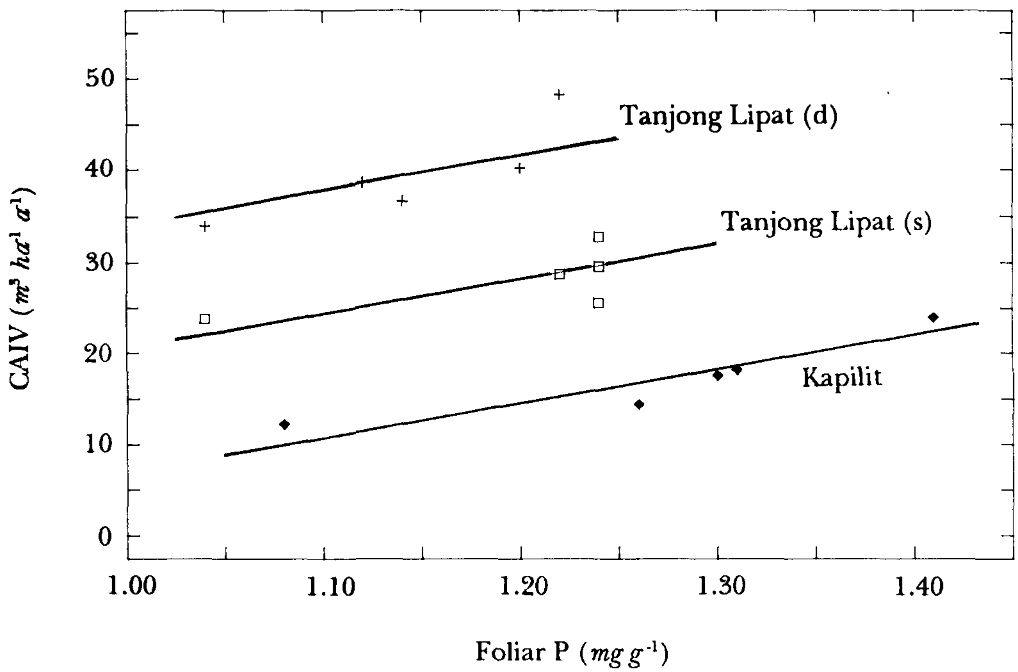

Figure 3. Phosphorus concentration (P) in foliage of *E. deglupta* 12 months after fertiliser treatments had been applied, in relation to current annual increment in wood volume (CAIV) on three soil types; variance accounted for was 92.4%, identity of soils as given in Figure 2

Growth

Tree growth characteristics three years after fertiliser had been applied are shown in Table 3, including predominant height, diameter at breast height over bark, mean annual increment in basal area, and number of stems *per ha*. Differences between soil types were significant in all cases. P fertiliser had little influence on height growth or number of stems *per ha*, differences after three years being non-significant. Treatment had a highly significant effect on diameter and basal area growth, both of which increased with increasing quantity of P fertiliser. Soil × treatment interaction was not significant for any growth parameter so data have been averaged over soil types and treatments. Whilst there was no treatment effect on number of trees *per ha*, considerable mortality occurred in some plots during the third year after treatment which contributed to a marked reduction in CAIV during this period (Figure 4).

Maximum increases in MAIV and CAIV observed over the three years following application of fertilizer to the three soils are shown in Figure 4. Lines show growth in unfertilised controls compared with the heaviest treatment of 400 kg ha^{-1} P. A significant treatment response in MAIV was not apparent during the first 12 months, but otherwise, overall differences in MAIV and CAIV between treatments and soils were highly significant in most cases ($p < 0.001$). Application of 400 kg ha^{-1} P resulted in substantial increases in CAIV which subsequently improved MAIV by about 4 m^3 ha^{-1} a^{-1} over all soils. Culmination of MAIV (intersection of MAIV and CAIV curves), in unfertilised treatments occurred between 6.5 *y* (Kapilit soil) and 7*y* (Tanjong Lipat deep) and fertilisation has extended this only slightly (Figure 4).

Table 3. Growth of *E. deglupta* 3 *y* after fertiliser treatments had been applied; a) Treatment effects, b) soil type effects; predominant height = mean height of tallest 100 stems *per ha*, DBHOB = diameter over bark at 1.3 *m*, MAI BA = mean annual increment in basal area

(a)	Treatment (*kg* P ha^{-1})					
	0	50	100	200	400	Sig. +
			All	soils		
Predom height (*m*)	19.2	19.6	20.2	19.9	20.3	NS
DBHOB (*cm*)	15.1	15.2	16.1	16.0	16.6	***
MAI BA ($m^2 ha^{-1} a^{-1}$)	1.8	1.9	1.9	2.0	2.1	***
Stems per *ha*	693	711	649	667	680	NS

(b)	Soil type			
	Kapilit	Tanjong Lipat (shallow)	Tanjong Lipat (deep)	Sig. +
Predom ht (*m*)	18.8	20.5	20.3	***
DBHOB (*cm*)	14.8	15.7	16.9	***
MAI BA ($m^2 ha^{-1} a^{-1}$)	1.6	2.2	2.1	***
Stems per *ha*	652	717	671	**

\+ Significance level of soil or fertiliser effects; NS not significant; ** $p < 0.01$; *** $p < 0.001$; Soil treatment interaction was not significant in any instance

In order to derive a response curve for economic analysis, differences in MAIV between fertilised and unfertilised plots three years after treatments had been applied were calculated and data subject to regression analysis to derive a rate response over all soils (Figure 5). As statistical analyses had indicated that there was not a significant soil × fertiliser interaction, this calculation was valid. However, as there was some doubt if the full 200 $kg\ ha^{-1}$ P had been applied to two soils (Figure 2 and 3), these points were omitted and the following equation resulted:

$$D\ MAIV = 4.6 + 1.4\ (\ln P) \qquad r^2 = 0.89$$

where: P = Rate of elemental phosphorus applied ($kg\ ha^{-1}$); D MAIV = Increase in mean annual increment in volume to 10 *cm* top diameter ($m^3\ ha^{-1}\ a^{-1}$).

This equation indicates that increases in MAIV of: 0.9, 1.8, 2.8 and 3.8 $m^3\ ha^{-1}\ a^{-1}$ would result from applications of 50, 100, 200 and 400 $kg\ ha^{-1}$ P respectively. The change in MAIV occurred in the three years after application of fertilizer but represents a difference over the full period since planting (six years and four months to seven years and one month). Inclusion of site as an additional factor in the equation did not improve the fit of the regression.

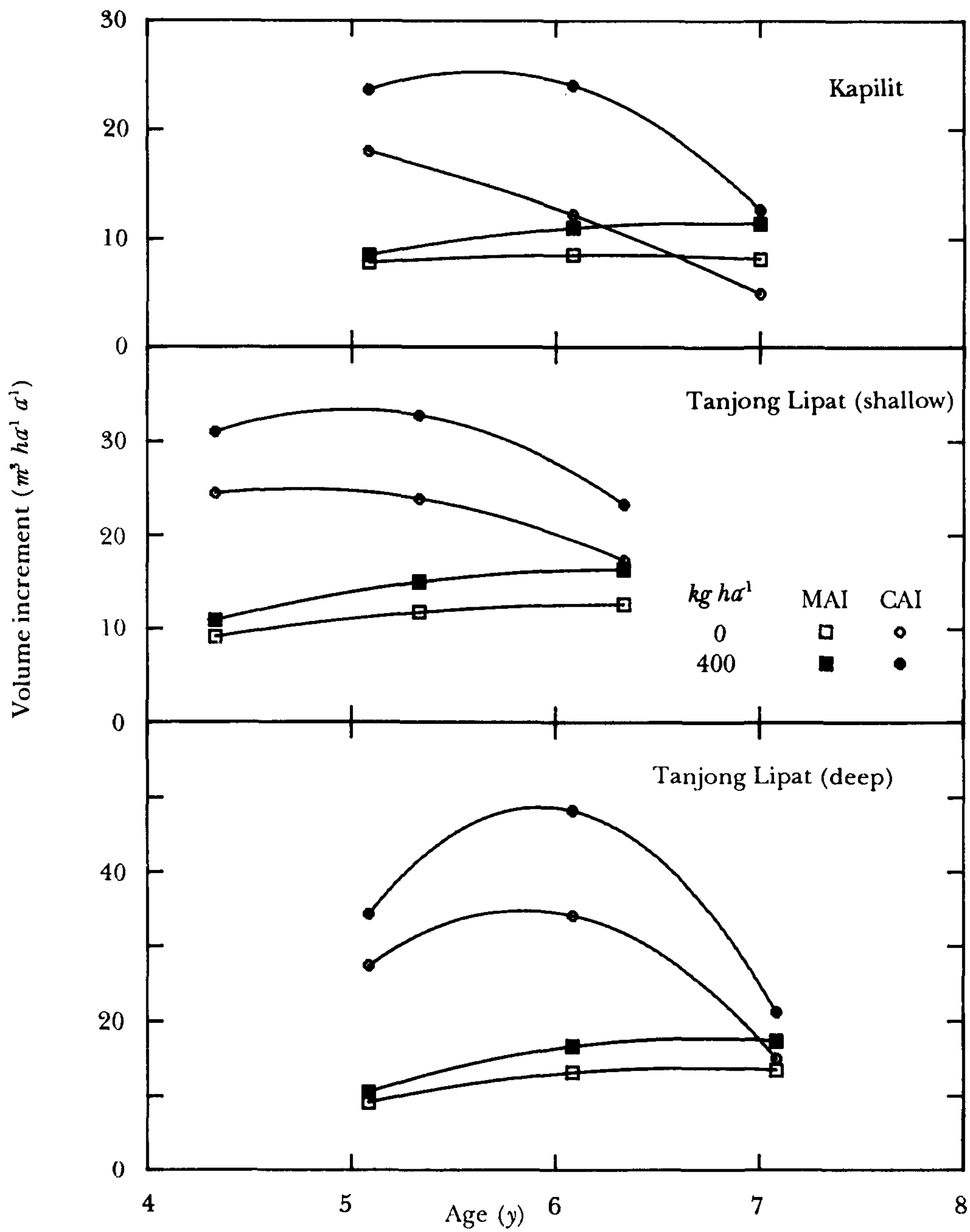

Figure 4. Response in current annual increment (CAIV) and mean annual increment (MAIV) in merchantable wood volume of *E. deglupta* over three years following application of 400 *kg ha*$^{-1}$ elemental phosphorus to three soil types; response in MAIV after 12 months was not significant, all other responses were very highly significant ($p < 0.001$)

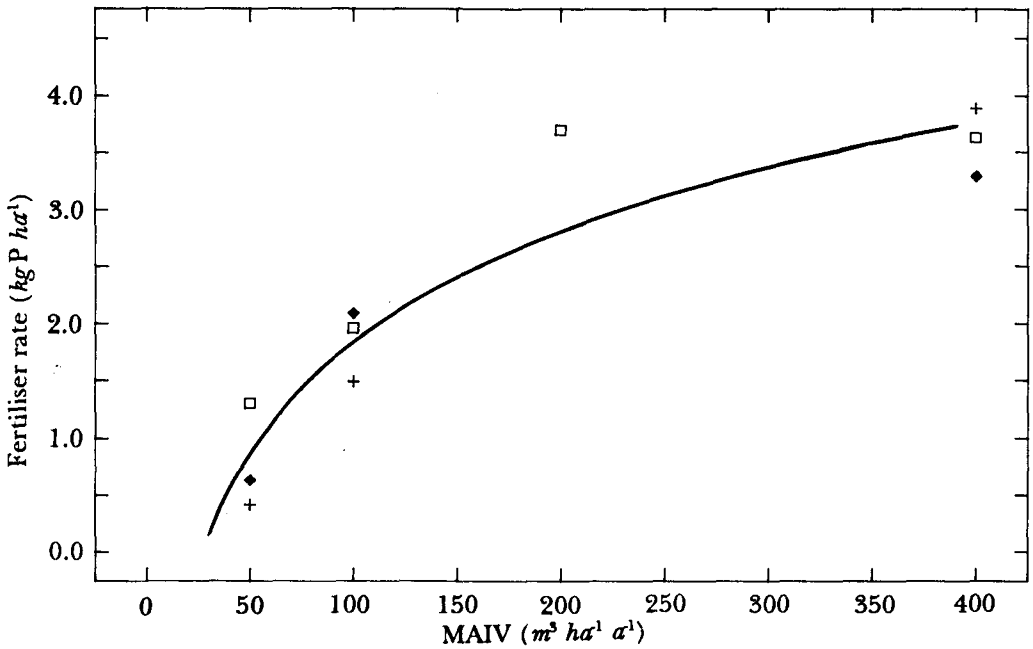

Figure 5. Increase in mean annual increment in wood volume of *E. deglupta* in relation to rate of fertilizer applied to three soil types ($r^2 = 0.89$); identity of soils as given in Figure 2.

Economic analysis

Only small differences in yields were apparent between unfertilised trees on the deep and shallow phases of Tanjong Lipat soils, so these sites were combined for purposes of economic analysis. Increments defined by the regression equation were rounded and added to unfertilised yields to produce the growth data shown in Table 4.

Table 4. Estimated mean annual increment in volume at 8 *y* (m^3 ha^{-1})

	Treatment (*kg* P ha^{-1})					
	0	50	100	200	300	400
Soil						
Kapilit	9	10	11	11.9	12.5	12.9
Tanjong Lipat	15	16	17	17.9	18.5	18.9

An 8 *y* rotation was used as the basis for economic analysis. Data were available from trees aged 6 *y* 4 *mth* on one site and 7 *y* on two sites and extrapolation to 8 *y* introduced little uncertainty, particularly as comparative data for older trees across a range of site classes were available.

At 8 *y*, *E. deglupta* has a basic density of 360 *kg* m^{-3} and a 70 % moisture content (wet basis) which was assumed to be constant over all treatments and sites. Considered as chips for export as a pulpwood source, *E. deglupta* has a relatively low basic density compared with wood from older natural forests and this will produce relatively low money values per cubic metre or wet tonne. Similarly, relatively slow growth and small stems at harvest resulted in high harvesting costs. Value of wood at stump from the poorest site (Kapilit) with no fertiliser was compared with the other sites (Tanjong Lipat) at the highest fertiliser level and results are shown in Table 5. Actual values for harvesting and transport costs in Table 5 are illustrative only to show gain from fertiliser due to increased stem size and consequent reductions in harvesting costs. Over the range of mean stem volumes encountered, harvesting costs are strongly influenced by tree size.

Table 5. Estimated yields, prices, costs and value at stump of *E. deglupta* (prices in RM = Malaysian $)

	Kapilit (nil P)	Tanjong Lipat (400 kg P ha^{-1})
MAIV (m^3 ha^{-1} a^{-1})	9.0	18.9
Yield at harvest (m^3 ha^{-1})	72.0	151.0
Density (kg m^{-3})	360	360
Yield at harvest (t ha^{-1} dry)	25.9	54.4
Mean stem volume (m^3)	0.10	0.22
Chip sale price (RM t^{-1} dry)	225	225
Chip sale price (RM m^{-3})	81	81
Chip sale price (RM t^{-1} wet)	67	67
Less Chipping (RM t^{-1} wet)	-14	-14
Less Harvesting (RM t^{-1} wet)	- 51	-33
Less Transport (RM t^{-1} wet)	-11	-8
Total (RM t^{-1} wet)	-76	-55
Value at stump* (RM t^{-1} wet)	-8	13
Value at stump (RM ha^{-1})	-728	2404

* columns do not add due to rounding

Plantation establishment costs were estimated at RM1426 ha^{-1} and when accumulated at 4 and 10% real interest rates for eight years, amount to RM1842ha^{-1} and RM3056 ha^{-1} respectively. By comparison, sales value at stump are at best RM2404 ha^{-1} (Table 5). When annual maintenance costs are added to establishment and other costs, a plantation programme based on *E. deglupta*, with or without fertiliser must be of doubtful profitability. Thus fertiliser does not seem to provide a solution to relatively low yields in *E. deglupta*.

However, fertiliser application to pulpwood plantations of *E. deglupta* which are already in existence, might be profitable. As initial establishment costs have already been "sunk", annual maintenance charges continue to accrue and the value of any gain in yield from fertiliser may exceed application costs. Marginal gains in yield and costs associated with extra fertilising are shown in Table 6. Fertiliser produces larger stems, thus reducing harvesting costs which is reflected in higher value of wood at the stump. Rates of return on 100 kg phosphorus fertiliser ha^{-1} on Tanjong Lipat soils were high, with a 29 % real internal rate of return before tax on the initial 50 kg and 38 % on the second 50 kg (100 kg P ha^{1} total). Rates of return on fertiliser investment for Kapilit soil were low at all levels of fertiliser, reflecting low initial yields, small tree sizes and thus low value at stump.

Table 6. Marginal gain and costs associated with fertilising *E. deglupta* over an 8 *y* rotation

	Treatment (*kg* P ha^{-1})				
	50	100	200	300	400
Tanjong Lipat					
Additional yield at harvest	8	8	7.2	4.8	3.2
Additional value at stump at year 8 (RM ha^{-1})*	615	466	287	200	138
Ferterliser cost at year 4 (RM ha^{-1})**	151	124	238	231	231
IRR (%)***	29	38	5	negative	negative
Kapilit					
IRR (%)	3	14	negative	negative	negative

* Values at constant price; increase in mean stem volume from fertiliser application results in reduced harvesting costs for the whole crop, not just the additional yield from fertilising; ** Includes cost of application which is not directly proportional to quantity applied; *** Internal rate of return based on constant prices; negative. Negative internal rate of return.

Discussion

Intensively managed plantations can be seen as potential alternative sources of wood to replace dwindling resources from native forests, or to enable natural areas which might otherwise be harvested, to be reserved for conservation purposes (*e.g.* Cameron & Penna 1988). However, fast-growing plantations, harvested on short rotations can rapidly deplete soil nutrient reserves and lead to a decline in yields within a few rotations. Theoretical nutrient balances developed for several tropical and sub-tropical plantation species using different harvesting systems on both low and high fertility soils indicated that high yields could not be maintained without supplemental nutrient applications on some soils (Jorgensen & Wells 1986).

Clearing of tropical forests and burning residues is known to lead to loss of N and other elements but appropriate management can reduce the risk of nutrient loss and declining fertility (Chijioke 1980). Thus management should ensure that all slash from harvesting and cleaning operations is left on site and that burning at the beginning of second and subsequent rotations is discouraged. Growth and nutrition of *E. deglupta* planted into sites which had been burnt were compared with those planted into unburnt sites in Papua New Guinea (Lamb 1976a). Seedlings established using an enrichment planting technique (no burning) grew more vigorously and had higher N concentrations in their foliage than those planted into a cleared and burnt site, reinforcing the need to conserve nutrients on site. In Sabah, burning is required following initial clearing to ensure good establishment of the first crop but conservative management methods including high lead logging and no burning for second rotation establishment have been practiced by Sabah Softwoods for some years.

Growth rates of *E. deglupta* plantations in Sabah range from 8 to 20 m^3 ha^{-1} a^{-1} (Mastan 1984) and have been less than those reported for plantations of the species in some other locations. Mean annual volume increment of *E. deglupta* at

Keravat in Papua New Guinea ranged from 32 to 37 m^3 ha^{-1} a^{-1} at ten years (Lamb 1976b) and similar high rates of growth have been reported from Costa Rica (Lugo *et al.* 1988). However, Jacobs (1981) noted that *E. deglupta* occurs naturally between latitudes 9°N and 11°S in areas which receive between 3750 and 5000 *mm* of rainfall per *annum.* Whilst low soil fertility has clearly inhibited growth in Sabah, rainfall amount and distribution may also be less than optimum for growth of *E. deglupta.*

Apart from the work of Lamb in Papua New Guinea during the 1970s, there has been little research on relationships between growth and nutrition of *E. deglupta.* Lamb (1976c) found that soils in the Gogol Valley in Papua New Guinea were moderately fertile and suggested that the only element likely to limit plant growth was nitrogen. Subsequent research confirmed a deficiency of N and a strong relationship was developed between height growth and foliar nitrogen concentration of *E. deglupta* from Gogol and Keravat plantations (Lamb 1977).

Results from the fertiliser trial presented here, in conjunction with data from Papua New Guinea (Lamb 1973), show clearly that rate of phosphorus supply has limited growth of *E. deglupta* in the project area on the three soils included in this study. Absolute increases in growth were similar at similar rates of applied P in the three soils, despite probable differences in adsorption characteristics and hence uptake. It is also possible that *E. deglupta* would respond to nitrogen following removal of P limitations but this has not been tested. In the present study, fertiliser was applied to plantations aged from 3 *y* 4 *mth* to 4 *y* 1 *mth,* so we can only speculate on potential growth responses which might have occured had fertiliser been applied at time of planting. Waring (1973) reported that a delay of 4 *y* in application of fertiliser, halved basal area growth in *Pinus radiata* at 8 *y* of age, compared with the same quantity applied at planting. Differences in volume growth were even greater.

Efforts to increase early growth of fast-growing tropical hardwoods and thus promote rapid canopy closure are critical to assist in control of competing weeds and an enhanced response would be expected if fertiliser were applied at time of planting. Responses reported here can therefore be considered conservative in comparison with potential responses from application of P at planting. Competing vegetation was controlled by slashing in the present experiment but weed growth is rapid and some competition for light, water and nutrients would no doubt have occurred.

Given that growth rates of *E. deglupta* in Sabah have been less than expected, establishment of new plantations of the species for pulpwood production appears to be of doubtful profitability. Growth rates can be improved by application of P fertiliser but responses from an application at three or four years of age are insufficient to make plantation establishment profitable as increment lost by age three or four cannot be recovered. Application of P fertiliser at time of planting would increase aggregate growth responses and would improve the chance of a positive return on investment on good sites but on poor sites, return on investment was negative, even with added fertiliser.

Lack of profitability at the Kapilit site is related to small stem size at eight years and consequent high cost of harvesting. Harvesting costs change rapidly in response to stem size at this level of diameter. If rotation length is increased to 12 years (at the same MAIs) to produce larger stems, internal rates of return for Kapilit increased to 17, 22 and 10% per *annum* for the marginal investment in the first 50 *kg*, the next 50 kg and the next 100 *kg* P. However, rates of return for fertiliser investment on Tanjong Lipat soils were lower than they were at eight years as the delay in returns outweights the savings due to harvesting larger stems.

Thus marginal returns on investment in fertiliser application to existing stands on good sites is high and an application of 100 *kg* P ha^1 is recommended. By comparison, marginal returns on investment on poor sites are low but use of fertiliser may make tip the balance from a stand which cannot be harvested economically to one which is worthwhile.

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