THE RELATIONSHIP BETWEEN GROWTH AND FOLIAR NUTRIENT CONCENTRATIONS IN *ACACIA MANGIUM* SEEDLINGS

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PAUDYAL, B. K. & NIK MUHAMAD, M. 2000. The relationship between growth and foliar nutrient concentrations in *Acacia mangium* seedlings. A glasshouse study on Serdang soils (Ultisols) was conducted to examine the relationship between growth parameters and foliar nutrient levels in *Acacia mangium* Willd., a fast-growing species widely planted in Peninsular Malaysia. The results showed a significant and positive relationship between growth parameters and foliar N and K concentrations. Height and diameter increments can be well predicted, separately, by foliar N, P, K concentrations and N:P ratio whereas dry matter production can be predicted by foliar N and K concentrations. The results demonstrated that the optimum foliar concentrations for satisfactory growth of the seedlings could lie within the following ranges: N(mg/kg)–23 500 to 24 700; P(mg/kg)–1400 to 1800; K (mg/kg)–6500 to 7500.

Keywords: *Acacia mangium* - height - diameter - dry matter - nutrients - optimum - foliar

PAUDYAL, B. K. & NIK MUHAMAD, M. 2000. Kaitan antara pertumbuhan dan kepekatan nutrien daun dalam anak benih *Acacia mangium*. Kajian rumah kaca ke atas tanah di Serdang (Ultisol) dijalankan untuk memeriksa kaitan antara parameter pertumbuhan dan kepekatan N dan K daun. Ketinggian dan penambahan garis pusat dapat diramalkan, secara berasingan, melalui N, P, dan K daun dan nisbah N:P manakala pengeluaran kering dapat diramalkan melalui kepekatan N dan K daun. Keputusan menunjukkan bahawa kepekatan daun optimum bagi pertumbuhan anak benih yang memuaskan dapat diletakkan dalam julat yang berikut: N(mg/kg) –23 500 hingga 24 700; P(mg/kg)–1400 hingga 1800; K (mg/kg)–6500 hingga 7500.

Introduction

Acacia mangium Willd. is one of the fast-growing tree species widely planted in Malaysia, which has only marginal and unproductive lands allocated for forest plantation establishment. However, very few studies have been conducted on the nutritional aspects of this species. Most of the nutritional studies in Malaysia have been based on fertiliser trials and earlier fertiliser studies mainly dealt with pine plantations, especially Caribbean pine. Paudyal and Majid (1992) tried to develop the relationship between nutrient requirements and growth parameters of *A. mangium* trees in plantations. The study presented here, however, focuses mainly on the relationship between height, diameter and dry matter growth with nutritional levels of *A. mangium* seedlings in the glasshouse experiment.

In plant analysis, the objective is to establish the relationship between nutrient concentration and growth (or yield), and then use this relationship in comparable situations to establish the nutrient status of a plant or crop. In this way, the nutrient requirement may be assessed (Bates 1971). In recent years, the use of foliar analysis has increased substantially and has been advocated by Everard (1973), Leaf (1973) and Van den Driessche (1974). Its use as a diagnostic tool to determine the nutrient requirements of plants has been established (Ingestad 1960, Madgwick 1964, Everard 1973). The rationale of using foliar analysis is that the concentration of nutrients in the foliage reflects the nutritional status of the tree, and thus its growth potential (Mead 1984).

It is generally known that Malaysian soils are heavily leached and low in nutrients, particularly phosphorus (Fielding 1972). There is a high probability that nutrient deficiencies may occur at early stages of plantation development given the fast growth of *A. mangium*. It is thus critical that studies be conducted on the nutritional levels and its relationship to growth parameters to assess nutritional requirements of this species at the early phase of plantation establishment.

Materials and methods

Potting medium and seedlings

Soil samples belonging to Serdang series (Ultisols) were used as the potting substrate. The samples were collected under 3.5-y-old *A. mangium* stands at Kerling Forest Reserve, Selangor. The samples were taken from the surface down to a depth of 30 cm between the planting rows away from the trees to avoid the influence of previous fertiliser applications. Soil samples were air dried at room temperature (22 °C) and sieved through 2.0 mm opening stainless steel sieve. Soil pH was determined from a 1:2.5 soil/water solution by a glass electrode pH meter. Total N determination was done using the Autoanalyser II following the Kjeldahl's digestion procedure (Bremner 1965). Available P was measured in Bray's No. 1 solution (Olsen & Sommers 1982) and total organic carbon was determined by the Walkley and Black method (1934). Exchangeable K, Ca, and Mg were determined by the atomic absorption spectrophotometer adopting the NH_4OAc leaching method as outlined by Chapman (1965). The physical and chemical properties of the soil are shown in Table 1. Three-month-old *A. mangium* seedlings from Mantin nursery, Negri Sembilan, were used for this study. One seedling per pot was used. The size of the pot was 30.5 cm in diameter and 24 cm in height. After one month in the glasshouse the seedlings were treated with fertiliser application.

Table 1. Physical and chemical properties of the potting medium

Physical	
Coarse sand (%)	40
Fine sand (%)	30
Silt (%)	7
Clay (%)	23
Texture	Sandy clay loam
Chemical	
pH	4.40
Org C (%)	1.41
Total N (%)	0.08
Available P (ppm)	7.23
Exchangeable K (meq %)	18.50
Exchangeable Mg (meq %)	0.74
Exchangeable Ca (meq %)	0.42

Five months after the application of fertiliser, the seedlings were taken out of the pots. This *Acacia* species fixes nitrogen as active nodules were formed during the study. The foliar samples of nine-month-old seedlings were dried in a forced draft oven at 75 ° C for 36 to 72 h. Dried materials were ground in a stainless 'Fritch' Pulverisette mill to pass through 1 mm round hole sieve. The foliar samples were analysed for total N, P, K, Ca, Mg by the wet digestion method (Parkinson & Allen 1975). Total N and P were simultaneously analysed on the original digest by the autoanalyser. K, Ca and Mg were determined by atomic absorption spectrophotometer.

Experimental design and treatments

The basic experimental design for the pot trial was a 4 × 4 × 2 factorial arrangement of treatments based on randomised complete block design with eight replications. There were altogether 256 pots involving 32 treatment combinations. In addition, eight control pots with no fertiliser treatment were also maintained. Nitrogen (as urea) and phosphorus (as P_2O_5) were applied at four levels and potassium (as K_2O) at two levels. The fertilisers applied were urea, triple superphosphate and muriate of potash. The study was conducted in a glasshouse for a period of five months. The pots were watered twice daily to avoid any water stress. The pot positions were arranged randomly and changed systematically at two-week intervals to avoid positional effects within the blocks although it was a randomised complete block design of arrangements. Weeding and loosening of top soils were done regularly to disperse and mobilise the nutrients and prevent the growth of green mould on the surface. The nutrients were applied in solution form as shown in Table 2. The complete dose per treatment was split into two applications at an interval of two months to avoid toxic effects on the young seedlings.

Table 2. Levels of nutrients applied

Commercial fertiliser	Element	Grams added per pot			
		level 1 (100 kg ha^{-1})	level 2 (350 kg ha^{-1})	level 3 (600 kg ha^{-1})	level 4 (800 kg ha^{-1})
Urea (46% N)	N	0.779	2.728	4.677	6.236
Triple superphosphate (48% P_2O_5)	P (P_2O_5)	1.621	5.675	9.729	12.972
Muriate of potash (60% K_2O)	K (K_2O)	1.294	2.588*	-	-

*Note: Level 2 for muriate of potash is 200 kg ha^{-1}.

Growth parameters and data analysis

Height and diameter of the seedlings were measured regularly at two-week intervals for five months. Height and diameter increments were calculated from the difference between final and initial measurements. Initial measurements were taken before the application of fertilisers.

The data were subjected to 3-way ANOVA, analysing the effects of nitrogen, phosphorus and potassium. Tukey's test was used to compare mean values of all the treatments and for the levels of nutrients.

A simple regression was employed to examine the relationship between levels of N, P, K fertiliser (as independent variables) to height and diameter increments, dry matter production, and foliar concentrations of N, P, K, Ca and Mg (as dependent variables). Foliar concentrations of N, P, K, Ca and Mg were correlated with height, diameter and total dry matter production. Coefficients of correlation R derived from correlation analysis were used to identify the nature of correlation between the variables. A stepwise regression analysis was also employed to examine the relationship between the independent (foliar concentrations of N, P, K, Ca and Mg) and dependent variables (height, diameter and dry matter production). This is based on the assumption that growth parameters (height, diameter and dry matter production) are dependent on foliar nutrient concentrations. This regression technique was employed to identify the major foliar nutrient elements affecting seedling growth. Simple regression analysis was employed, separately, between foliar concentrations of N, P, K, foliar ratios N:P, N:K, P:K and growth parameters of height, diameter and dry matter production. This was to evaluate whether growth parameters could be predicted by different foliar nutrients and their ratios.

Results

Relationship between foliar nutrient concentrations and growth

The results of different levels of nutrients on growth parameters and foliar nutrient concentrations are given in Table 3. The results of the correlation analysis are shown in Table 4. They show that height and diameter were positively and highly correlated ($p < 0.01$) with the foliar P and Ca, and K, Mg and N concentrations respectively. Dry matter production, on the other hand, was positively and highly correlated ($p < 0.01$) with N, K and P concentrations in the foliage.

Table 3. Growth parameters and foliar nutrient concentrations

	Growth parameters			Foliar concentrations (mg kg^{-1})				
	Ht(cm)	Dia (cm)	Dm(g)	N	P	K	Ca	Mg
Level of N								
0	20.6c	2.3c	60.2c	19000e	900d	5800c	6300d	1100c
1	57.0b	6.9b	96.3d	20800d	1000d	7000a	6800c	1500a
2	59.7b	6.9b	105.3c	22000c	1200c	7100a	7800a	1600a
3	62.5ab	7.6ab	182.3a	24700a	1800a	7000a	7200b	1400ab
4	70.4a	7.6ab	177.4b	23500b	1400b	6500b	6600c	1400ab
Level of P								
0	20.6c	2.3b	60.2e	19000e	900e	5800c	6300d	1100c
1	62.4a	7.5a	124.1d	19800d	1100d	6800ab	6600c	1300ab
2	59.9a	7.4a	128.1c	21700c	1400c	7000a	7200ab	1400a
3	63.0a	7.3a	140.5b	23500a	1800b	6700b	7500a	1500a
4	64.3a	7.5a	168.6a	22800b	2600a	6700b	6800c	1300b
Level of K								
0	20.6b	2.3b	60.2c	19000c	900b	5800c	6300b	1100b
1	65.3a	7.4a	171.6a	19800b	1100a	7300a	6800a	1200b
2	59.5a	7.4a	109.2b	20700a	1200a	6500b	7000a	1400a

Note: Ht - height, Dia - diameter, Dm - dry matter.
Means with the same letter(s) are not significantly ($p < 0.05$) different as determined by Tukey's test. The test of the means are for levels of each of the nutrients, separately.

Table 4. Coefficients of correlations between foliar nutrient concentrations and tree growth (R value)

Tree growth	Foliar nutrient concentration (%)				
	N	P	K	Ca	Mg
Height	0.59*	0.80**	0.52	0.73**	0.43
Diameter	0.71**	0.58*	0.81**	0.52	0.73**
Dry matter production	0.77**	0.64**	0.66**	0.26	0.51

Note: * - significant ($p < 0.05$), ** - highly significant ($p < 0.01$).

Table 5 shows that all the three nutrients had significant effects on foliar N and P concentrations. Levels of N and P showed significant effects on dry matter matter production whereas levels of N and K had significant effects on height and diameter. Thus, level of N had significant effects on height, diameter, dry matter production and foliar concentrations of N and P. Likewise, level of K showed significant effects on height, diameter and foliar concentrations of N, P, Ca and Mg.

Table 5. Simple regression between growth parameters, foliar nutrient concentrations and levels of nutrients

Growth parameter	Regression equation	R^2	F-value	SEE
Level of N				
Height	Ht=33.02+10.51*ln	0.73	8.418*	5.30
Diameter	Dia=4.0+1.13*ln	0.63	5.23*	7.58
Dry matter production	Dm=60.22+32.04*ln	0.89	26.28**	10.22
Foliar N	N=1.95+0.11*ln	0.75	9.40*	8.57
Foliar P	P=0.09+0.01*ln	0.63	5.17*	6.25
Level of P				
Dry matter production	Dm=77.66+23.32*lp	0.85	17.92*	11.53
Foliar N	N=1.91+0.11*lp	0.86	19.12*	9.38
Foliar P	P=0.07+0.04*lp	0.92	38.49**	8.62
Level of K				
Height	Ht=29.01+19.45*lk	0.64	1.78*	9.45
Diameter	Dia=3.15+2.55*lk	0.75	3.0*	12.28
Foliar N	N=1.89+0.08*lk	0.99	16.0**	10.32
Foliar P	P=0.09+0.01*lk	0.96	17.0**	8.32
Foliar Ca	Ca=0.63+0.03*lk	0.94	16.33**	9.87
Foliar Mg	Mg=0.10+0.01*lk	0.96	27.0**	7.32

Note: * – p <0.05, ** – p <0.01, SEE – standard error of estimate, ln–level of N, lp–level of P, lk–level of K.

Table 6 gives the results of the stepwise regression analysis. They showed that height and diameter were significantly ($p < 0.05$) related to foliar N and K concentrations whereas total dry matter production was significantly ($p < 0.01$) related to foliar N concentration only.

Table 6. Stepwise regression between growth parameters and foliar nutrient concentrations

Growth parameters	Regression equation	R^2	F-value	SEE
Height	Ht = -162.96+37.35*N+206.23*K	0.75	4.29*	5.16
Diameter	Dia = -19.77+4.45*N+25.06*K	0.76	4.29*	4.27
Total dry matter	Dm = -261.94+80.04*N	0.59	16.26**	10.32

Note: SEE – standard error of estimate, * – p <0.05, ** – p <0.01.

Nitrogen

Foliar N and foliar P concentrations increased with nitrogen application up to level 3 (600 kg ha^{-1}) but decreased at higher levels (Table 3). There was an increase from 19 000 to 24 700 mg kg^{-1} in foliar N and 900 to 1800 mg kg^{-1} in foliar P concentration for level 3 in comparison with the control. Foliar N and P concentrations at all levels were significantly different ($p < 0.05$) from the control. The uptake of P was greatly enhanced by N application. For foliar K concentration, there was an increase up to level 2 (350 kg ha^{-1}) and decreased afterwards. However, there was no significant difference ($p < 0.05$) in foliar K concentration between levels 1 and 2 although level 1 was significantly different ($p < 0.05$) from the control. An increase from 580 to 710 mg kg^{-1} in foliar K concentration for level 2 relative to the control was observed.

The results of simple regression analysis of the growth parameters on foliar N concentration are given in Table 7. All the growth parameters exhibited a significant linear relationship with foliar N concentration. Height and diameter showed maximum increment at 23 500 mg kg^{-1} N whereas increment in dry matter production was maximum at 24 700 mg kg^{-1} N.

Table 7. Simple regressions

Growth parameter	Regression equation
(A) Between growth parameters and foliar N concentration	
Height	Ht = -11766 +15741*N - 6968.71*N² + 1026.30*N³ (R^2 = 0.83, F-value = 8.15*, RMSE = 7.30, CV = 12.76)
Diameter	Dia = 4513.57 - 2011.90* N + 298.76*N² - 3356.99*1/N (R^2 = 0.88, F-value = 13.45**, RMSE = 0.71, CV = 10.39)
Dry matter production	DM = -622.41+ 509.73*N0.5 (R^2 = 0.62, F-value = 11.46**, RMSE = 25.93, CV = 20.15)
(B) Between growth parameters and foliar P concentration	
Height	Ht = 897.59 - 4759.38*P + 8638.43*P² - 46.50*1/P (R^2 = 0.93, F-value = 19.17**, RMSE = 5.18, CV= 8.96)
Diameter	Dia = 107.90 - 571.24*P+1032.19*P² - 5.60*1/P (R^2 = 0.93, F-value=19.58**, RMSE = 0.61, CV = 8.97)
Dry matter production	DM = 1396.96 - 7031.54*P+13014*P² - 72.61*1/P (R^2 = 0.61, F-value = 2.16ns, RMSE = 33.84, CV = 24.93)
(C) Between growth parameters and foliar K concentration	
Height	Ht = -23959+107629*K-160426*K² + 79553*K3 (R^2 = 0.97, F-value = 56.62**, RMSE = 3.07, CV = 5.35)
Diameter	Dia = 7674.87-11440*K+5678.80*K² - 1709.53*1/K) (R^2 = 0.97, F-value = 51.30*, RMSE = 0.38, CV = 5.66)
Dry matter production	DM = -6892.92 + 21444*K - 16309*K² (R^2 = 0.64, F-value = 4.60*, RMSE = 27.97, CV = 21.75)

Note: * – significant ($p < 0.05$), ** – highly significant ($p < 0.01$),
RMSE – root mean square error, CV – coefficient of variation.

Phosphorus

Phosphorus application increased foliar P (Table 3) up to level 4 (800 kg ha^{-1}) and all the levels were significantly different ($p < 0.05$) from the control. There was an increase from 900 to 2600 mg kg^{-1} in foliar P concentration at level 4 relative to the control. The uptake of N was enhanced by P application up to level 3 and declined at higher level. An increase from 19 000 to 23 500 mg kg^{-1} in foliar N was induced by P application. Phosphorus application also induced an increase in foliar K concentration up to level 2 but a decline at higher levels, and all the levels were significantly different ($p < 0.05$) from the control. An increase from 5800 to 7000 mg kg^{-1} in foliar K was recorded at level 2 relative to the control.

The results of simple regression analysis of the growth parameters on foliar P concentration showed that height and diameter were significantly related to foliar P concentration (Table 7). Total dry matter production, however, showed no significant relationship.

Height and diameter recorded maximum increment at 1400 mg kg^{-1} foliar P concentration whereas dry matter production showed maximum increment at 1800 mg kg^{-1} P. However, the results might not be applicable to dry matter matter production as it was not significantly related to foliar P concentration although R^2 value was 0.61.

Potassium

Potassium application increased foliar K concentration by level 1 and decreased afterwards (Table 3). All the levels were significantly different from the control ($p < 0.05$). An increase from 5800 to 7300 mg kg^{-1} was observed in foliar K concentration at level 1. For N, K application enhanced its uptake up to level 2. The increment in foliar N concentration was from 19 000 to 20 700 mg kg^{-1} at level 2 relative to the control. In the case of P, K application increased foliar P concentration from 900 to 1200 mg kg^{-1} at level 2. All the levels were significantly different ($p < 0.05$) from the control although there was no significant difference ($p < 0.05$) between the levels.

The results of simple regression analysis of the growth parameters on foliar K concentrations are given in Table 7. All the growth parameters were significantly related with foliar K concentration.

Height and diameter increments and dry matter production were maximum at 7300 mg kg^{-1} foliar K concentration. However, as there was a significant quadratic relationship ($Y=a+bx+cx^2$) between dry matter production and foliar K concentration, the optimum nutrient concentration (Xo) could be calculated as $Xo = -b/(2*c)$. Based on the generalised concept, a critical nutrient level (Xc) is usually defined as 90 percent of an optimum value, that is, $Xc = 0.9*Xo$ (Binkley 1986, Zhong & Hsiung 1993). Thus, optimum and critical foliar K concentrations for dry matter production are 7000 mg kg^{-1} and 6300 mg kg^{-1} respectively.

N:P ratio

The application of P decreased N:P ratio up to level 4 (Figure 1) whereas the application of N also decreased N:P ratio up to level 3 and increased it at level 4. This shows that the application of P and N both favoured P uptake thereby balancing N:P ratio. The application of K also decreased N:P ratio up to level 2. A N:P ratio of 16.7 was observed for maximum height and diameter increment, whereas for maximum dry matter production, a N:P ratio of 13.7 was recorded. For the seedlings with no fertiliser treatment, a maximum N:P ratio of 21.1 was recorded.

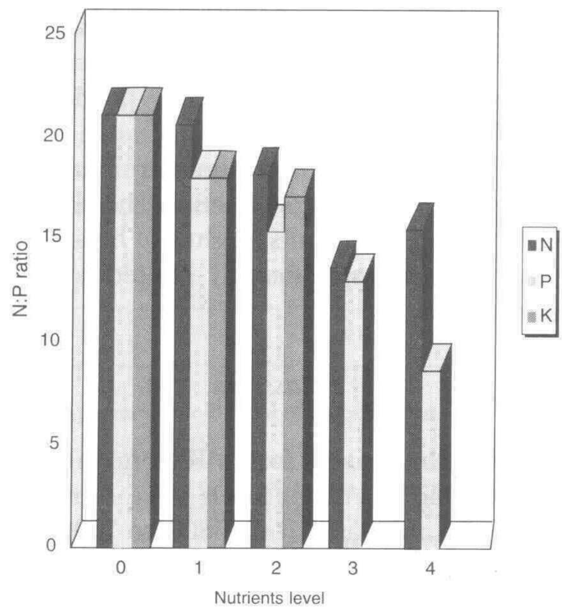

Figure 1. Nutrient levels and N:P ratio

The results of simple regression analysis of the growth parameters on N:P ratio are shown in Table 8. The results show that height and diameter but not dry matter production were significantly related to N:P ratio.

N:K ratio

The application of N and P decreased N:K ratio by level 1 (Figure 2) and increased it afterwards up to level 3 with a slight decline at level 4. However, K application decreased N:K ratio by level 1 and increased it afterwards.

Table 8. Simple regressions

Growth parameters	Regression equation
(A) Between growth parameters and N:P ratio	
Height	Ht = -1204.49 + 98.89*N:P-2.48*$N^2:P^2$+ 5204*1/N:P (R^2= 0.89,F-value = 19.91**, RMSE = 5.06, CV = 8.63)
Diameter	Dia = -140.58 +11.64*N:P- 0.29$N^2:P^2$+602.58*1/N:P (R^2= 0.91,F-value = 26.06**, RMSE = 0.53, CV = 7.66)
Dry matter production	DM = 82.35 + 352.13*N:P (R^2= 0.25,F-value = 1.12ns, RMSE = 33.25, CV = 26.38)
(B) Between growth parameters and N:K ratio	
Height	Ht = 813.55-478.11*N:K + 75.17*$N^2:K^2$ (R^2= 0.19,F-value = 0.98ns, RMSE = 13.11, CV = 22.35)
Diameter	Dia = 84.28-48.96*N:K + 7.70*$N^2:K^2$ (R^2= 0.14,F-value = 0.53ns, RMSE = 1.61, CV = 23.14)
Dry matter production	Dm = 3364.56 - 2076.72*N:K + 331.08*$N^2:K^2$ (R^2= 0.51,F-value = 4.22*, RMSE = 30.50, CV = 22.90)
© Between growth parameters and P:K ratio	
Height	Ht = 43.99+65.10*P:K (R^2= 0.12, F-value = 1.15ns, RMSE = 13.63, CV = 23.35)
Diameter	Dia = 5.34+7.18*P:K (R^2= 0.10, F-value = 0.97ns, RMSE =1.63, CV = 20.38)
Dry matter production	Dm = 76.0+248.69*P:K (R^2= 0.23, F-value = 2.45ns, RMSE = 35.64, CV = 27.21)

Note: ns – not significant ($p < 0.05$) *– significant ($p < 0.05$),
RMSE – root mean square error, CV – coefficient of variation.

The results of simple regression analysis of the growth parameters on N:K ratio (Table 8) show that only dry matter production was significantly related to N:K ratio. However, the R^2 value of 0.5 clearly indicates that only 51% of the variability could be explained by the regression model and is thus less reliable. The maximum height and diameter increments were recorded for N:K ratio of 3.6 and maximum dry matter production was recorded for N:K ratio of 3.5.

P:K ratio

The application of N enhanced P:K ratio up to level 3 (Figure 3) and the ratio declined at higher levels of N. Phosphorus application increased P:K ratio up to level 4 (800 kg ha^{-1}). Potassium application, however, produced no effect on P:K ratio by level 1 and increased it by level 2.

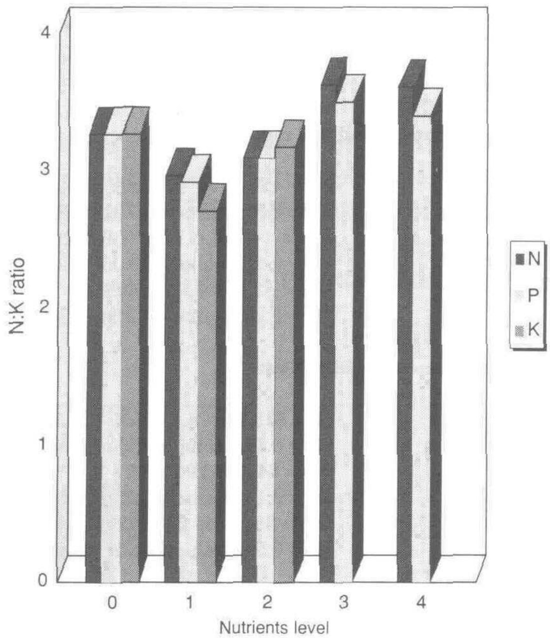

Figure 2. Nutrient levels and N:K ratio

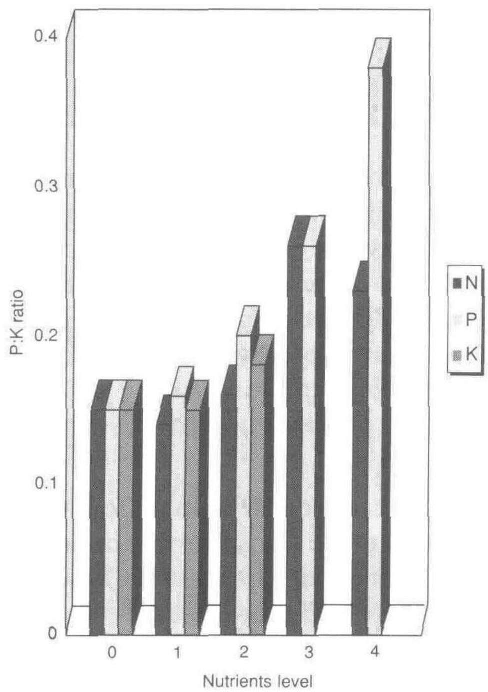

Figure 3. Nutrient levels and P:K ratio

The results of simple regression analysis of the growth parameters on P:K ratio are given in Table 8. The results indicate that none of the growth parameters were significantly related to P:K ratio. The maximum height and diameter, however, were observed for P:K ratio of 0.21 and maximum dry matter production for a ratio of 0.25. Given the insignificant nature of the relationship between growth parameters and P:K ratio, it is difficult to ascertain optimum P:K ratio for enhancing growth.

Discussion

The addition of mineral nutrients to improve growth in forest stands is an established forest management practice in many parts of the world. The beneficial effects of forest nutrition have been well documented by several authors (Miller & Cooper 1973, Crane 1982, Bolstad & Allen 1987, Herbert 1990). The results from this study are in agreement with the earlier findings by other researchers, where application of fertilisers resulted in better growth.

The results of simple regression analysis showed that all the three nutrients had positive and significant effects on foliar N and P concentrations. Nitrogen showed significant effects on all the growth parameters (height, diameter and dry matter production). Phosphorus and potassium had significant effect on dry matter production at all levels and no significant effect on height and diameter after level 1. The results also demonstrated that urea and P_2O_5 both at 600 kg ha^{-1} could be considered optimum for the growth parameters. Potassium at 100 kg K_2O ha^{-1} could be considered sufficient to boost the growth.

The results of simple regression analysis indicated a positive and significant relationship between all the growth parameters and foliar N concentration. In earlier studies, Srivastava and Chin (1978), however, showed a negative linear relationship between foliar N concentration and height. Abang Naruddin (1981) indicated a positive but insignificant linear relationship between foliar N concentration and height, diameter and total dry matter production for *Pinus caribaea* seedlings. The results of this study agree with those of Drechsel *et al.* (1991) who reported significant relationship between height growth and foliar N level for *Tectona grandis* in Liberia.

Phosphorus application increased foliar N and P concentrations. However, foliar N concentration declined after level 3 (600 kg P_2O_5 ha^{-1}). This might have been caused by antagonistic effect of higher dosage of P on N uptake as reported for spruce seedlings (Hoffman 1967), Scots pine (Smilde 1973) and Caribbean pine seedlings (Chai 1980). P application increased foliar K level up to level 2 (350 kg P_2O_5 ha^{-1}) and declined afterwards. This shows that P application, especially at higher doses, had an inhibitory effect on foliar K level. The increase in foliar P level as a result of P application has also been observed by Abang Naruddin (1981) for Caribbean pine seedlings. Foliar P concentration showed a significant relationship with height and diameter increment but a non-significant relationship with dry matter production. The study of Raupach *et al.* (1975) and later works by Chai (1980) and Abang

Naruddin (1981) showed a positive and significant relationship between foliar P concentration and height increment and dry matter production for Caribbean pine seedlings.

The application of K enhanced foliar K concentration up to level 1 (100 kg K_2O ha^{-1}) and declined at higher level. For foliar P and N, K application increased their concentrations. Thus, K application showed positive effects on foliar N, P and K concentrations. However, Abang Naruddin (1981) reported no increase in foliar K concentration for Caribbean pine seedlings by the addition of K. This might, as the author suggested, be due to dilution effect of the element as it is vital for the synthesis of proteins and amino acids (Leaf 1968). The results of the present study showed differences with earlier findings. The studies by White (1954), Chai (1980) and Abang Naruddin (1981) indicated no correlation between K foliar concentration and growth of seedlings. A significant relationship, however, was observed between foliar K concentration and all the growth parameters in the present study. This is probably due to the fact that K plays an important role in boosting growth of *A. mangium* seedlings.

The results of this study also showed that N:P ratio was important for predicting growth response to fertilisers. Height and diameter increments were significantly related to N:P ratio. Although there was a significant relationship between N:K ratio and dry matter production, the R^2 value of 0.5 only makes it a less reliable model. No correlation was found between P:K ratio and growth parameters. In the present study, the optimum N:P ratio lies between 13 and 17. In earlier studies, Raupach (1967) reported N:P ratio of 5–16 for radiata pine seedlings, 9.3 for Caribbean pine (Abang Naruddin 1981), around 13 for *Eucalyptus grandis* (Schonau & Herbert 1983) and 7.68 for *Cunninghamia lanceolata* (Zhong & Hsiung 1993). The conclusions obtained, however, are based on the assumption that nutrients other than N, P, K are not limiting growth, which may not be true.

The stepwise regression analysis technique gave a better understanding of the relationship between foliar nutrient concentrations and growth parameters. The positive and significant contributions of foliar N and K to the regression models emphasise the importance of these nutrients in explaining variations in height and diameter increments. However, earlier works by Raupach *et al.* (1975) and Abang Naruddin (1981) reported foliar P to be significantly related to growth parameters. It might be possible that foliar N levels were quite low to show any significant relationship with the growth parameters. In the present study, the insignificant contribution of foliar P to the growth parameters might have been caused by dilution effect, the fact that P is of prime importance for root development (Schonau & Herbert 1989). However, simple regression analysis performed on foliar P only does show a significant effect on height and diameter increments. The regression analysis also showed that height and diameter increments could well be predicted by foliar N, P and K concentrations and by N:P ratio, separately. Total dry matter production, however, could be predicted separately by foliar N and K concentrations only.

The present study shows that optimum level of foliar P concentration was 1400–1800 mg kg^{-1} and the deficiency level could lie below 900 mg kg^{-1}. The optimum level of N could be assumed to lie between 23 500 and 24 700 mg kg^{-1} and the level that would show deficiency is below 19 000 mg kg^{-1}. For potassium, the optimum level could range between 6500 and 7000 mg kg^{-1} and signs of deficiency should occur below 5800 mg kg^{-1}.

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