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Growth response of *Grevillea robusta* A. Cunn. seedlings to phosphorus fertilization in acid soils from Kenya

Nancy Karen Karanja [(1)], Kaleb Adamba Mwendwa [(2)], Felipe Zapata [(3)]

[(1)] Soil Science Department. University of Nairobi. P.O. Box 30197, Nairobi (Kenya). Tel.: +254–02–631643, Fax: +254–02–632121, E-mail: biofix@arcc.or.ke.
[(2)] Kenya Forestry Research Institute. Maseno Agroforestry Research Centre. P.O. Box 25199, Kisumu (Kenya). E-mail: afresmaseno@form-net.com.
[(3)] International Atomic Energy Agency. Wagrammerstrasse, 5. P.O. Box 100. 1400 Vienna (Austria).

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Three experiments were conducted to assess the response of *G. robusta* to phosphorus fertilization using acid soils showing low P levels from Eastern (Gituamba-Andosols) and Western (Kakamega-Acrisols) Kenya. In the first experiment P was applied as Minjingu phosphate rock (MPR-13%P) at 0, 52 and 77 kg P per ha into 5 kg of soil. In the second experiment 2 g vesicular arbuscular mycorrhizae (VAM) soil + root inoculum per 5 kg soil was included in addition to the same MPR rates using Kakamega soil only. In the third experiment, MPR and triple superphosphate (TSP) were added to 5 kg Kakamega soil at a rate of 25.8 mg P per kgsoil, and ^{32}P isotope dilution techniques were used to assess P uptake in the shoot harvested at 3 and 6 MAT (months after transplanting). Application of MPR to the Andosol reduced height and root collar diameter of *G. robusta* significantly ($p < .05$) as compared to the control. Significant increases ($p < .05$) in height and root collar diameter where P was added compared to control were recorded with the Acrisol. Soil interaction with P fertilizer rates was highly significant ($p < .001$) for both height and root collar diameter growth. The roots were not infected with VAM upon harvesting at 12 months. At 3 MAT the percentage P derived from the MPR and TSP was 3% and 6% respectively. P uptake decreased significantly ($p < .05$) between 3 and 6 months. The results indicated that addition of Pfertilizer in the Acrisols was probably required at the early stages of *G. robusta* growth but further research and particularly root studies are required to ascertain the above observations.
Keywords. Acrisols, Andosols, phosphate rock, P uptake, ^{32}P isotope dilution techniques, triple superphosphate, vesicular arbuscular mycorrhizae, *Grevillea robusta*, seedlings, growth.

Effets surla croissance des plantules de *Grevillea robusta* A. Cunn. d'un apport d'engrais phosphaté aux sols acides du Kenya. Trois essais ont été conduits pour évaluer la réponse de *G. robusta* à l'apport de phosphore aux sols particulièrement pauvres en cet élément, prélevés à l'est (Andosols de Gituamba) et à l'ouest (Acrisols de Kakamega) du Kenya. Dans le premier essai, le phosphore était appliqué sous forme de roche phosphatée de Minjingu (MPR, 13 % P) dans 5 kg de sol aux doses de 0, 52 et 77 kg P par ha. Dans le deuxième essai, 2 g d'inoculum (sol + racines) de mycorhizes à vésicules et arbuscules par 5 kg de sol étaient ajoutés aux trois doses de MPR. Cette expérience a été conduite uniquement sur les sols provenant de Kakamega. Dans le troisième essai, la roche phosphatée et le triple superphosphate (TSP) étaient apportés à 5 kg de sol de Kakamega à la dose de 25,8 mg Ppar kgde sol. Les techniques de dilution de ^{32}P ont été utilisées pour évaluer le prélèvement de P dans la biomasse aérienne récoltée à 3 et 6 mois après la plantation. L'application de MPR dans les Andosols a réduit la hauteur et le diamètre au collet de *G. robusta* par rapport au témoin. Dans les Acrisols par contre, une augmentation significative de la hauteur et du diamètre au collet ($p < 0,05$) a été notée dans les pots ayant reçu du phosphore. L'interaction "type de sol – dose de P" s'est révélée très hautement significative ($p < 0,001$) pour la croissance en hauteur et celle du diamètre au collet. Les racines n'étaient pas colonisées par les mycorhizes jusqu'à 12 mois après la plantation. Trois mois après la plantation, les pourcentages de Pissus respectivement de la MPR et du TSPétaient de 3 et 6 %. Le prélèvement de P par les plantules de *G. robusta* a diminué significativement entre 3 et 6 mois. Ces résultats ont montré que l'apport de P dans les Acrisols était probablement nécessaire dans la première phase de développement de *G. robusta*. Cependant, une recherche complémentaire surtout sur le développement des racines est requise.
Mots-clés. Acrisol, Andosol, roche phosphatée, technique de dilution isotopique du ^{32}P, triple superphosphate, mycorhize à vésicules et arbuscules, *Grevillea robusta*, plantule, croissance.

1. INTRODUCTION

Grevillea robusta A. Cunn. was introduced in Kenya as a shade tree for coffee and tea, and from 1910 as a mixture with *Cupressus lusitanica* Mill. (Streets, 1962; Milimo, 1988). The species is currently well accepted in Western (Otieno, 1992) and Central (Kamweti, 1992, 1996) Kenya. *Grevillea robusta* is well established in subtropical and tropical highland environments (Harwood, 1989), and in densely populated zones it is an important source of fuelwood and income from sale of construction timber (Kamweti, 1992). Harwood and Booth (1992) reported that the species is popular with African farmers because it provides viable products, it is easy to propagate and its proteiform roots help it grow in low fertility soils. Further, *G. robusta* does not compete with adjacent crops. Annual growth rates of 2 m in height and 2 cm in diameter over the first 5 years are commonly achieved in a number of countries where climate and soils are suitable (Harwood, Booth, 1992; Kamweti, 1996). Therefore this tree is a good candidate in agroforestry systems. The majority of the areas in Western Kenya and parts of Central Kenya highlands are dominated by acid soils with low levels in phosphorus (P) and nitrogen (N) (FAO, 1986). However TSP and other commercial fertilizers are expensive and unaffordable by the majority of the smallholder farmers who would like to increase their yields on these inherently infertile soils (KARI-KEFRI-ICRAF and Government of Kenya, 1997). Use of phosphate rock has been suggested as an alternative (Chien, Menon, 1993; KARI-KEFRI-ICRAF, GoK, 1997) in replenishing the low P status.

Vesicular arbuscular mycorrhizal (VAM) associations with plant roots play an important role in Pnutrition of plants particularly those growing in soil having low available P (Barea, 1991). Plants infected with VAM on their roots have shown to produce greater plant growth and increased P uptake in P deficient soils by increasing the root surface area (Tinker, 1980). VAM fungi readily absorb soluble phosphate from the labile pool of phosphorus in soils and improve the use of phosphate rock (Barea *et al.*, 1983; Bolan, 1991; Gianinazzi–Pearson, Gianinazzi, 1989). Tinker (1980) estimated that increased P uptake from VAM-inoculation was equivalent to 100 kg of fertilizer per ha. Isotopic labelling (^{32}P) experiments have also indicated that both mycorrhizal and non-mycorrhizal plants utilize the same pool of phosphorus in soil (Gianinazzi–Pearson, Gianinazzi, 1989; Bolan, 1991). However limited research has been conducted to investigate the role of P in the establishment of *G. robusta*, hence information is scarce or unavailable. These glasshouse studies were thus initiated to evaluate *G. robusta* growth response and P uptake after application of P in form of Minjingu phosphate rock (MPR) and after inoculation with VAM and/or triple superphosphate (TSP).

2. MATERIAL AND METHODS

2.1. Characteristics of soil and tree seedlings

Surface soils (0–20 cm) were randomly collected from experimental farms in Gituamba (Andosols) in E. Kenya, (pH 1:5 soil to H_2O 4.2, carbon = 5.9%, available P-Olsen = 2.5mg·kg^{-1}, exchangeable Al = 2.1 cmol·kg^{-1}, C.E.C. = 22.3 cmol·kg^{-1}) and Kakamega (Acrisols) in W. Kenya (pH 1:5 soil to H_2O 4.3, carbon = 1.8%, available P-Olsen = 2.1 mg·kg^{-1}, exchangeable Al = 1.0 cmol·kg^{-1} and C.E.C. = 3.2 cmol·kg^{-1}). *G. robusta* seeds were pregerminated on sterile water-agar Petri dishes and after emergence were transferred into sterilized sand trays for 3 weeks. Thereafter seedlings were transplanted, one per pot (30 cm height × 15 m diameter) containing 5 kg of soil.

2.2. Establishment of glasshouse experiments

2.2.1. Experiments I and II: assessing growth of the tree seedlings due to P application and VAM inoculation. *In experiment I*, Minjingu PR (12.9% P and 40% CaO) was applied at the rates of 0 (PR_0), 52 (PR1) and 77 (PR2) kg P per ha (equivalent to 0, 400 and 600 kg Minjingu PR per ha) and mixed thoroughly with the two soils before transplanting the one month old seedlings. The design of the experiment was completely randomized and replicated three times.

In experiment II, the treatments were PR_0, PR1, PR2, PR_0 + VA-mycorrhizae, PR1+VAM and PR2+VAM. Minjingu PR was applied and mixed thoroughly with the Kakamega soil. About 200 ml of water was added (to approximately 80% field capacity) and the set-up left for a week to allow for equilibration. The VAM inoculation method described by Wilson *et al.*, (1991) was adopted at a rate of 2 g of inoculum per pot. The inoculum consisted of a mixture of roots and soil from *Acacia tortilis* spp. *tortilis* and was added approximately quarter-way down the soil in the pots. A basal nutrient solution containing 200 mg N (NH_4NO_3), 400 mg K ($K_2SO_4.7H_2O$) and 400 mg Mg ($MgSO_4.7H_2O$) was applied to each pot at transplanting. The experiment was replicated four times in a completely randomized design.

In experiment I, height and root collar diameter were recorded at 21 weeks after transplanting (WAT), the 21 WAT is a general recommendation age for transplanting tree seedlings to the field by the Forest Department in Kenya).

In experiment II, the height and root collar diameter were recorded at 12 months after transplanting (12 MAT) after which the seedlings were destructively harvested. Shoot dry weight was determined after drying the materials at 80 °C in an oven for 24 hrs. One centimeter root sections obtained from seedlings grown in experiment II were stained to assess VAM infection using the methods described by Phillips and Hayman (1970) and Koske and Gemma (1989). The grid intercept method of Tennant (1975) was used to quantify the infection. The remaining portions of roots were oven dried at 80 °C for 24 hrs for root dry weight determination.

2.2.2. Experiment III: procedures for labelling the P fertilized experiment. In experiment III, ^{32}P isotope dilution techniques were applied to discriminate between soil and fertilizer derived phosphorus in the plant material. Two fertilizers, MPR and TSP, were used and applied at one rate of 25.8 mg P per kg soil, equivalent to 52 kg P per ha and the Acrisol from Kakamega used as the test soil. The treatments included

(a) soil alone as the control
(b) soil + Minjingu PR and
(c) soil + TSP.

To all the pots, 20 ml of a 10 ppm KH_2PO_4 solution labelled with an activity of 50µCi ^{32}P per kg soil (or 185 × 104 Bq ^{32}P per kg soil) were then uniformly applied over the soil surface immediately after transplanting the three week old seedlings. Small amounts of distilled water were added to each pot to wash down the phosphate fertilizer. The soils were constantly watered to approximately field capacity. The experimental design was completely randomized with 3 replications for each of the destructive harvests done at 3 and 6 months after transplanting (3 and 6 MAT). Coinciding with the first destructive harvest of shoots at 3 MAT, a similar amount and activity of ^{32}P labelled solution was again uniformly added onto the soil surface of 3 month old seedlings which constituted the second destructive harvest of shoots to be carried out at 6 MAT. To reduce contamination risk with radio-isotope, root data were not collected because this would have involved washing the soil from the harvested roots.

In experiment III, P uptake and other isotopically derived parameters were determinated. At each harvest the shoots of the seedlings to which ^{32}P was applied were cut into small sections and oven dried at 80 °C for 24 hours to obtain dry weight. This was followed by subsampling into 2 g portions and placed into oven dried porcelain dishes. The samples were moistened by a little distilled water and dry ashed in a muffle furnace at 450 °C. After cooling, the ash were dissolved using 20 ml of 1 M HCl; 10 ml of this solution was used for plant tissue P determination by colorimetric method. The rest was transferred to vials for Cerenkov counting to assess ^{32}P activity using Scintillation counter model LSC Packard 2000. The following formulae were used (Zapata, Axmann, 1995) to derive isotopically determined parameters:

$$SA = \frac{\text{degradation per minute (dpm)}}{(\text{mg P} / 2)} \quad (1)$$

where
SA= specific activity of plant material and
mg P/2 is used because only half the sample is used in the P determination;

$$\%\ \text{Pdfs} = \frac{\text{SA plant (in presence of fertilizer)} \times 100}{\text{SA plant (in absence of fertilizer)}} \quad (2)$$

where
% Pdfs = the percentage of P in the plant material derived from the soil; the assumption in this method is that the higher the P availability from fertilizer (Minjingu PR or TSP) to the plant, the more it will dilute the SA of the material;

$$\%\ \text{Pdff} = \left(1 - \frac{\text{Pdfs}}{100}\right) \times 100 \quad (3)$$

where
% Pdff = percentage of P in the plant material derived from the respective fertilizers; the assumption made here was that the plant absorbs P in direct proportion to its availability and that the ratio of availability of soil P and labelled carrier ^{32}P was unaffected by the addition of fertilizer.

The actual amount in the plant material derived from the fertilizers was determined as follows:

$$\text{AAPf} = \text{Total P uptake} \times \%\ \text{Pdff} \quad (4)$$

where
AAPf = actual amount of P in mg taken up by the seedlings from the fertilizers.

The relative availability of Minjingu PR was then determined as follows:

$$\text{RAID} = \frac{\text{AAPf (MPR)}}{\text{AAPf (TSP)}} \quad (5)$$

where
RAID = relative availability (of Minjingu PR compared to TSP) as determined by isotope dilution,
AAPf (MPR) = actual amount of P in plant derived from Minjingu phosphate rock as determined by isotope dilution,
AAPf (TSP) = actual amount of P in plant derived from TSP as determined by isotope dilution.

2.3. Statistical analysis.

The data at 21 WAT (*Experiment I*), 12 MAT (*Experiment II*), 3 and 6 MAT (*Experiment III*) were subjected to analysis of variance (ANOVA) using the Genstat 3.22 computer software package (Genstat 5 Committee, 1993), while least significant differences (l.s.d.) were used to compare the means.

3. RESULTS AND DISCUSSION

3.1. Experiment I: height and root collar diameter of 21 week-old seedlings

Results for height and root collar diameter for experiment I are shown in **Table 1**. When the soil types and P rates were separated during the data analysis, a significant reduction of up to 1.5 times of both parameters is observed upon addition of P fertilizer to Gituamba soil (Andosols) compared to the control. With the Kakamega soil (Acrisols) there was a significant increase in height and root collar diameter of up to 1.5 times when Pwas applied compared to the control. Soil and P rates interaction were significant ($p < .001$) confirming that the two soils behaved differently to P application. Futhermore growth response to P application in Kakamega soils still remained lower than that recorded in the Gituamba control.

The Gituamba soils are volcanic soils which typically have amorphous alumino-silicates and humus-Al complexes that have a very high capacity to sorb P(Buresh *et al*., 1997; Van Wambeke, 1995). This sorption tends to be essentially irreversible, and even high rates of P application do not satisfy the P sorption capacity (Espinosa, 1992). However P fixed by amorphous material in Gituamba Andosols was probably easily extracted by *G. robusta* through its special root structures (Skene *et al.*, 1996). This may have accounted for the poor response to P application. Moreover, the reduction in growth observed with larger P applications may be due to toxic amounts of exchangeable Al^{3+} released from the mineralising organic matter-Al complexes influenced by the Ca^{2+} ions from Minjingu PR that contains 40% CaO as it solubilised to release nutrients into the soil solution. Such an effect of Ca^{2+} on organic matter-Al complexes in Andosols has also been reported by Le Mare and Leon (1989).

The seedlings in the control of Kakamega level had poor growth compared to those of Gituamba control because of inherently low Plevel in Acrisols (Okalebo, 1987). The positive response to P application was probably due to the low organic matter levels which were unable to supply sufficient P through mineralization (Harrison, 1987). Buresh *et al.*, (1997) reported that a decrease in soil organic matter is likely to lead to a reduction in supply of plant available P. However, the low response to P fertilization in Kakamega soils when compared to the Gituamba control could be explained by high Al content (approx. 37%) in the Acrisols. This high Al content could have sorbed the applied P from Minjingu PR or directly affected the growth of *G. robusta* seedlings.

Table 1. Effect of P fertilization on the height and root collar diameter increase of *G. robusta* after 21 weeks while growing in two acid soils from Kenya (Experiment I) — *Effet de la fertilisation en Psur l'accroissement en hauteur et en diamètre au collet de jeunes plants de* G. robusta *après 21 semaines de croissance sur deux types de sols acides du Kenya.*

P rate	Soil type			
	Gituamba	Kakamega	Gituamba	Kakamega
($kg \cdot ha^{-1}$)	Height (cm)		Root collar diameter (cm)	
0	31.8	15.9	0.6	0.3
52	15.4	27.6	0.4	0.6
77	18.3	28.7	0.4	0.5
l.s.d. soil x P rates	9.8***(**1**)		0.1***	

(**1**) *** = $p < .001$

3.2. Experiment II: dry matter production, height and root collar diameter of 12 month-old seedlings

Results of experiment II on seedlings growing in Kakamega soils are shown in **table 2**. There were no significant differences in response in terms of height, root collar diameter, root and shoot dry weights to P application or VAM inoculation by *G. robusta*. No VAM infection was detected on the root samples and the seedlings looked healthy with no signs of nutrient deficiencies. The results though inconclusive, imply that mycorrhizal inoculation is not necessary when *G. robusta* are grown in acidic soils. There was however no trend in Minjingu PR addition and VAM inoculation at 12 MAT.

3.3. Experiment III: the height, root collar diameter and P uptake as estimated through isotope dilution method of 3 month-old and 6 month-old seedlings

Minjingu PR and TSP gave significant improvement on seedling height (for Minjingu PR only), root collar diameter, P uptake above the control (**Table 3**). Addition of phosphate fertilizers to the poor soil probably enhanced root proliferation hence increased P uptake by the fertilized tree seedlings. Although

Table 2. Effect of P application as Minjingu PR and VAM inoculation on height, root collar diameter, shoot and root dry weight of *G. robusta* after 12 months while growing in Kakamega soil (Experiment II) — *Effets d'un apport de P, pour une application de roche MPR combinée ou non à une inoculation de mycorrhizes VA, sur la hauteur, le diamètre au collet et les poids secs des parties aériennes et racinaires de plants de* G. robusta *ayant crû sur sol de Kakamega (Acrisol) durant 12 mois.*

Treatments	**Height** (cm)	**Root collar diameter** (cm)	**Shoot dry weight** (g/plant)	**Root dry weight** (g/plant)
PR_0	66.3	1.8	94.7	34.1
PR_0 + M(**1**)	75.0	1.9	102.4	36.6
PR_1(**2**)	77.5	1.8	93.5	44.0
PR_1 + M	76.2	1.8	66.5	38.5
PR_2	70.8	1.8	79.4	35.9
PR_2 + M	72.7	1.7	103.2	36.4
l.s.d. (p < .05)	12.3ns(**3**)	0.2ns	29.9ns	13.4ns

(**1**) M = VAM inoculum.
(**2**) PR_1, PR_2 = Minjingu phosphate rock.
(**3**) ns= not significant.

Table 3. Effect of two sources of Pon the height, root collar diameter, shoot dry weight and P uptake of *G. robusta* at 6 months after transplanting into Kakamega soil (Experiment III) — *Effets de deux sources de P sur la hauteur, le diamètre au collet, le poids sec des parties aériennes ainsi que sur le prélèvement en P de plants de* G. robusta *âgés de 6 mois après transplantation sur sol de Kakamega (Acrisol).*

P sources	**Height** (cm)	**Root collar diameter** (cm)	**Shoot dry weight** (g/plant)	**P uptake** (mg P/plant)
PR(**1**)	38.1	0.5	8.0	2.0
TSP(**2**)	31.2	0.6	8.5	2.0
Control	30.0	0.5	6.8	1.2
l.s.d. (p < .05)	6.1*	0.1*	1.8ns(**3**)	0.7*

(**1**) PR = Minjingu phosphate rock.
(**2**) TSP = Triple superphosphate.
(**3**) ns=not significant.

height, root collar diameter and shoot dry weight increased between 3 and 6 MAT, P uptake declined significantly with increase in age of the tree seedlings (**Table 4**). The reduction of P uptake at 6 MAT was probably due to a dilution effect of growth (i.e increase in tissue biomass). Jarrel and Beverly (1981) reported that there is a dilution effect on P due to additional growth because dry matter usually

Table 4. Effect of P application on height, root collar diameter, shoot dry weight and P uptake of *G. robusta* after P application at 3 and 6 months after transplanting into Kakamega soil (Experiment III) — *Effets de l'application de P sur la hauteur, le diamètre au collet, le poids sec des parties aériennes et le prélèvement en P de plants de* G. robusta *(application de P à 3 et 6 mois après transplantation - MAT - sur sol de Kakamega).*

Harvest period	**Height** (cm)	**Root collar diameter** (cm)	**Shoot dry weight** (g/plant)	**P uptake** (mg P/ plant)
3 MAT(**1**)	16.5	0.3	1.0	2.6
6 MAT	49.7	0.8	14.6	0.9
l.s.d. (p<.001)	5.0***	0.1***	1.5***	0.6***

(**1**) Months after transplanting.

accumulates faster than P uptake. However, at both 3 and 6 MAT P uptake by *G. robusta* from the two sources were not significantly different (**Table 5**).

Of the total P taken up by the seedlings only 3% (0.09 mg P) was derived from rock-Pand 6% (0.18 mg P) from TSP at 3 MAT. This supports observations made in experiments I and II that *G. robusta* showed a preference for inherent soil derived P. The relative availability of Minjingu PR as determined by isotope dilution (RAID) value was 50 % as effective as TSP in supplying P to *G. robusta* seedlings. At 6 MAT the negative results for % Pdff and AAPf could mean that no more P was taken up from either Minjingu PR or TSP between 3 and 6 MAT and as such, it was assumed that all the P in the plant was derived from the inherent soil P. It is possible that the isotope dilution method assumptions could not hold with 6 months old seedlings and therefore the method may not be suitable for fast growing perennials older than 3 months and confined to pots. Kato *et al.*, (1994) reported that % Pdff in the plant seems to be affected by various soil and or plant borne factors. However, similar studies conducted with five fast growing tree species gave consistent % Pdff results (Mwendwa *et al.*, 1997–1998).

These soils are high P fixing and it is possible that all the P applied as Minjingu PR or TSP was fixed immediately after application. As the soil retained more strongly newly added cation (anion) than the one it had before (Duchaufour, 1991), the plant had to exploit the P retained in the soil using other mechanisms, such as cluster roots (Skene *et al.*, 1996). These structures (roots) cling onto soil clods with nutrient patches, and probably exudate citrates which move in rhizosphere for the mobilization of iron phosphates and acquisition of P (Gardener *et al.*,

Table 5. Effect of two P sources on the P uptake, %Pdfs, %Pdff, AAPf and RAID of *G. robusta* at 3 and 6 MAT — *Effets de deux sources de Psur le prélèvement de cet élément, le % en Pdérivé du sol (% Pdfs), le % en P dérivé de l'engrais (% Pdff), la quantite effective de P provenant de l'engrais (AAPf) et la disponibilité relative déterminée par dilution isotopique (RAID) pour des plants de* G. robusta *âgés de 3 et 6 mois après transplantation (MAT).*

P source	**Total P uptake** (mg·plant^{-1})	**%Pdfs** (**1**)	**%Pdff** (**2**)	**AAPf** (mg) (**3**)	**RAID** (**4**)
	3 MAT				
Minjingu PR	3.1	97	3	0.09	50%
TSP(**5**)	3.0	94	6	0.18	n/a (**6**)
Control	1.7	n/a	n/a	n/a	n/a
l.s.d.(p<.05-P sources)	1.5				
	6 MAT				
Minjingu PR	1.0	124	-24	-22.8	n/a
TSP	1.0	135	-35	-35.0	n/a
Control	0.7	n/a	n/a	n/a	n/a
l.s.d. (p<.05-P sources)	0.60				

(**1**) Percent of phosphorus in plant material derived from soil.
(**2**) Percent of phosphorus in plant material derived from fertilizer.
(**3**) Actual amount of P taken up by the seedlings (% Pdff x Total P uptake) from fertilizer.
(**4**) Relative availability of Minjingu PR as determined by isotope dilution.
(**5**) Triple superphosphate.
(**6**) n/a = value not applicable.

1983). It was observed during this study through low power microscopy that *G. robusta* root had such cluster roots. Skene *et al.* (1996) suggested that these roots occur at fixed distances and provide *G. robusta* with the opportunity of growing in soils of low available phosphate. Grierson and Attiwell (1989) showed that cluster roots produce hydrogen ions, reductants and possible chelating agents. *G. robusta* has been shown by gas chromatography/mass spectrometry that it exudes citrate from the cluster roots, which are specifically designed for nutrient patches exploration, exploitation and exportation (Skene *et al.*, 1996). Some species with cluster roots exude as much as 23 % of the total plant dry weight as citrate (Dinkelaker *et al.*, 1989).

4. CONCLUSIONS

The application of Minjingu PR to Kakamega Acrisols improved the growth of *G. robusta* seedlings at the early stage. The failure to get a response with Gituamba soil was attributed to some availability to *G. robusta* of fixed P in Andosols and to the toxic effect of exchangeable Al^{3+} consecutive to Ca^{2+} input. VAM inoculation may not be necessary with *G. robusta* and none of the seedlings were infected with VAM. Through use of isotope dilution techniques it was observed that availability of P from Minjingu PR was a half of that from soluble TSP. The reduction of P uptake at 6 MAT was probably due to a dilution effect of growth. *G. robusta* was shown to be able to utilize inherent soil P even in the absence of external P sources e.g Minjingu PR and TSP. This ability to mine unavailable P is due to the specialized cluster roots. The ability of *G. robusta* to perform well in low available P and acidic Andosols is interesting. However, P fertilization might still be necessary in Acrisols at the early stages of growth of *G. robusta*. The ability of this tree to discriminate against fertilizer P and to form cluster roots requires that further investigations to establish the nature of this discrimination and also to ascertain whether cluster root formation is an adaptability mechanism should be done.

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