

# The Significance of Residual Phosphorus and Potassium Fertilizer in Countering Yield Decline in a Fourth Rotation of *Pinus patula* in Swaziland

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## **Abstract**

*Pinus patula* is the main species grown for the production of unbleached kraft pulp on the 60 000 ha Usutu plantation, situated in Swaziland. Trees are harvested on short rotations from sites with low nutrient content and high acidity. In these circumstances sustained production from successive rotations has been an active research focus for nearly fifty years. On part of the Usutu plantation, underlain by gabbro rocks, a 20% growth decline was reported between first and second rotations. This was found to be caused by developing potassium (K) and phosphorus (P) deficiencies. Results from long-term monitoring plots showed that the application of P and K fertilizer in the past corrected the decline in yield. However, the effect of these fertilizer applications on future rotation yields remained unknown. In 1989 a trial was established in a third rotation crop to determine the residual effects of the operational fertilizer application on growth and fertilizer response in the following rotation. During September 1999 a PK factorial treatment combination was applied to the fourth rotation with the residual PK effect occurring as a split plot treatment. In 2004 and 2005 intensive soil, foliar and forest floor sampling was conducted in the trial to ascertain the influence of the residual fertilizer and re-application of P and K on the growth of the current crop.

Analysis of results indicated that in the presence of residual fertilizer, the re-application of only K fertilizer increased volume by 27 m<sup>3</sup> ha<sup>-1</sup> at age seven years. This was statistically similar to the 25.2 m<sup>3</sup> ha<sup>-1</sup> increase from a combined PK application. From these early results it would seem that enough residual P fertilizer remained available to supply the early nutrient demand of the next crop. Although residual K fertilizer also affected some parameters, it was insufficient to supply the requirements of the next crop. We conclude that fertilizer applications to successive crops can be adjusted to allow for benefit from residual P applied in the previous crop.

## **INTRODUCTION**

*Pinus patula* is the main species grown for the production of unbleached kraft pulp on the 60 000 ha Usutu plantation, situated in Swaziland. The plantation areas are characterized by soils with a high level of leaching, low nutrient content, low cation exchange capacity and moderate to strong acidity. Productivity research began in the Usutu Forest in 1968 after concerns that the same decline in productivity could occur as was reported in second rotation, *P. radiata* plantations in

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South Australia at the time. One of the reasons for concern came from observations in the mid-1960s that the foliage of the young second rotation (2R) *P. patula* appeared yellow and unhealthy (Evans, 1975; 1996; 1999a). The silvicultural and tree growing conditions at Usutu lend themselves to test the sustainability of pine plantations over successive rotations, having changed little over time. The comparison of growth over three successive rotations showed there was little significant difference between the rotations. The data, however, did reveal that for a group of plots on the eastern side of the forest (Block A) both height growth and volume per hectare had declined very significantly in the region of 18% in the second rotation (Evans, 1978; 1986; 1999b; Morris, 1987). This effect remained unexplained until Morris investigated associations between sample plots affected and a range of edaphic and lithological parameters (Evans, 1986; 1996; Morris, 1983; 1986). His work revealed that the second rotation plots that showed a growth decline were mostly located on Usushwana complex soils, derived from gabbro parent material. It was found that gabbro-derived soils had a smaller "available" phosphorus (P) pool, fixed P more strongly and supplied less potassium (K) from non-exchangeable reserves than granite-derived soils. This suggested that a developing PK deficiency was responsible for the growth decline.

Elsewhere, the importance of nutrition to sustain forest production has been widely documented. In the southeast USA a 10% to 35% reduction in tree height of second rotation, *P. taeda* and *P. elliotii* was associated with a nutrient deficiency as a result of nutrient removal, particularly phosphate, in timber harvest (Haywood and Tiarks, 1995 and 2002; Tiarks, 1999; Bekele *et al.*, 1999; Rose and Shiver, 2000). In Australia and New Zealand growth of *P. radiata* was also strongly influenced by phosphorus availability (Gentle *et al.*, 1965 and 1986; Ballard, 1978; Turner, 1982; Will, 1985) and to a much lesser extent by potassium availability (Raupach and Hall, 1974; Will, 1985). Significant responses to P fertilizer, with the length of the response on some sites extending into subsequent rotations, were reported on these inherently P deficient soils (Ballard, 1978; Pritchett and Comerford, 1982; Gentle *et al.*, 1986; Harding and Jokela, 1994; Ducey and Allen, 2001; Comerford *et al.*, 2002; Turner *et al.*, 2002).

In order to correct the P and K deficiencies that have developed in successive rotations of *P. patula* on the Usushwana complex, Morris (1987; 1994) recommended the application of 20 kg ha<sup>-1</sup> elemental P and K fertilizer as a spot application at planting, followed by an application of 75 kg ha<sup>-1</sup> elemental P and K fertilizer at pruning as a broadcast application. Continuing measurements have shown that these operational fertilizer applications corrected the decline in yield (Evans, 1996; 1999a). However, the results of the studies by Morris (1986) indicated a need for improving knowledge of the fundamental cycling processes as biogeochemical cycling of nutrients is critical for the maintenance and growth of plantation trees (Scholes, 2002). The trial reported in this paper was specifically designed to determine if the PK fertilizer applied to a gabbro-derived soil in the previous rotation would have any residual benefit that would allow a reduction in the amount of PK fertilizer needed to counter yield decline in subsequent rotations.

## **MATERIALS AND METHODS**

### **Site description**

The trial site is located in the eastern portion of Usutu plantation on gabbro derived soils at an altitude of 1300 m above sea level. A mean annual temperature of 16.3 °C and rainfall of 1421 mm per annum is reported for this land type (Pallett, 1990). The soil on the site consist of a

humic A horizon on a yellow-brown apedal B horizon (Soil classification working group, 1991). Clay content is relatively high, while base saturation is low. According to the USDA soil taxonomy system, this soil would be classified as an Oxisol (Soil Survey Staff, 2006). General soil texture and chemical properties are shown in **Table 1**.

**Table 1: Selected soil properties of trial site.**

Property	Unit	Horizon				
		A	B1	B2	C1	C2
Depth	mm	0-100	100-270	270-470	470-570	570-1500+
Bulk density	Mg m <sup>-3</sup>	0.74	0.87	0.98	1.28	0.93
Texture	-	Clay	Clay	Clay	Clay	Clay
pH (H <sub>2</sub> O)	-	4.3	4.9	5.1	4.8	4.6
Org.C. (WB)*	%	6.8	4.5	3.4	2.4	1.4
P (Bray 2)	mg kg <sup>-1</sup>	4.9	1.7	1.3	0.3	0.3
K	cmol(+) kg <sup>-1</sup>	0.07	0.06	0.03	0.02	0.01
Ca	cmol(+) kg <sup>-1</sup>	0.01	0.03	0.01	0.03	0.02
Mg	cmol(+) kg <sup>-1</sup>	0.08	0.06	0.04	0.03	0.03
Na	cmol(+) kg <sup>-1</sup>	0.05	0.03	0.01	0.03	0.03
CEC	cmol(+) kg <sup>-1</sup>	0.20	0.18	0.09	0.11	0.09
Ex. Acidity	cmol(+) kg <sup>-1</sup>	3.7	1.0	0.2	0.2	0.1
Fe	mg kg <sup>-1</sup>	36.7	23.9	15.7	6.0	4.9
Mn	mg kg <sup>-1</sup>	3.8	2.4	2.1	5.8	9.5
Zn	mg kg <sup>-1</sup>	0.8	1.3	0.6	0.8	0.9
Cu	mg kg <sup>-1</sup>	5.6	6.9	6.2	4.8	4.0

\* Organic carbon content (Walkley Black method).

### Trial description

**Third rotation trial:** In the spring of 1989, the third rotation trial was established in a six-year-old *P. patula* compartment. The genetic stock was first generation seed from Zimbabwe. The trial consisted of 52 plots each 12 x 10 rows in size (at 2.7 m x 2.7 m planting density). Each plot was split into two sub-plots of 6 x 10 rows. A broadcast application of PK fertilizer was randomly allocated to one of each of these pairs of sub-plots. The PK rate was equivalent to 75 kg elemental P and 75 kg elemental K per hectare (Morris, 1999).

**Fourth rotation trial:** The fourth rotation, *P. patula* trial was re-established in September 1999 on the exact location of the former third rotation PK-fertilizer trial with improved, second generation seed from the Usutu orchards. Each plot was 32.4 m x 27 m (i.e. 13 x 12 rows @ 2.08 m x 2.7 m). Hence each split plot consisted of 6 rows by 13 rows. The inner measured plot consisted of 4 rows by 9 rows giving 36 measured trees per sub-plot.

In the new 4R trial design the residual PK effect occurred as a split plot treatment within each main plot, with four replications of the main plots. The nine main treatments consisted of a 3 P x 3 K factorial application of 0, 25 and 50 kg elemental P or K per ha (**Table 2**). Treatment 1 (0 kg P and 0 kg K application) was the control treatment of the trial. The 50 kg elemental P or K per ha applications consisted of a 25 kg ha<sup>-1</sup> application at planting (spot application of fertilizer in a small pit next to each tree) and a 25 kg ha<sup>-1</sup> broadcast application at pruning for each element respectively. Superphosphate fertilizer (10.5% P) and potassium chloride fertilizer (50% K) were the sources of the P and K. Three additional control plots were established at the previous

planting density with genetic material similar to the material used in the previous rotation (slash line collection).

**Table 2: Summary of the treatments in the 4R trial.**

Treatment Number	Code	Applied at Planting (kg ha <sup>-1</sup> )		Applied after Pruning (kg ha <sup>-1</sup> )		Total P:K
		P	K	P	K	
1	P0K0	0	0	0	0	0:0
2	P0K25	0	25	0	0	0:25
3	P0K50	0	25	0	25	0:50
4	P25K0	25	0	0	0	25:0
5	P25K25	25	25	0	0	25:25
6	P25K50	25	25	0	25	25:50
7	P50K0	25	0	25	0	50:0
8	P50K25	25	25	25	0	50:25
9	P50K50	25	25	25	25	50:50
10	2 <sup>nd</sup> Control (unimproved genetic stock)	0	0	0	0	0:0

### Tree growth measurements

Third rotation trial: The Diameter at Breast Height (DBH) of the inner 4 x 8 trees on each split-plot were measured with diameter tapes in 1989, 1994, 1996 and 1997. The heights of the 4 trees with above average DBH were measured on each split-plot in 1989. The heights of the same trees were measured during subsequent assessments.

Fourth rotation trial: Tree growth measurements, height and DBH over bark, were done annually during July. In 2000, 2001 and 2002 only 27 trees (inner 3 x 9) per sub-plot were measured. From 2003, 36 trees (inner 4 x 9 trees) per sub-plot were measured. Tree height was measured with a *Vertex* hypsometer and DBH with a diameter tape. A sub-sample of four trees with corresponding DBH ranking as measured in the 3R trial in 1989 was selected per plot to compare mean plot height of the current rotation with height of the previous rotation at age six years. This consisted mostly of trees with the largest DBH diameters. Only tree height was used for this comparison, because the fourth rotation was established at a different planting density than the previous rotation. It is known that tree height is not affected as much as diameter growth by stand density (Von Gadow and Bredenkamp, 1992).

### Sampling procedure and chemical analysis

Foliage samples: The sampling protocol was based on recommendations of Will (1985), Linder (1995) and Louw & Scholes (2003). The foliage samples were collected in July 2004 and 2005 from the top third of the crown. Two second-order branches were cut off and the previous season's foliage that had reached mature length was collected. Samples from 5 dominant or co-dominant trees per split-plot were bulked for analysis.

Chemical analyses: All foliar samples were analyzed by the ICFR laboratory in Pietermaritzburg. Total N was determined with the Kjeldahl method. Total P was determined with the molybdenum

blue method in an automated segmented flow analyzer. Atomic absorption was used to determine macro nutrients Ca, Mg, Na, and K (Donkin, *et. al.*, 1993).

### Calculations and Statistical analysis

Volume estimation for young trees in the fourth rotation trial was made from DBH and height measurements using a Max and Brukhart function (Bredenkamp, 2000; Pienaar and Kotze, 2001). Statistical analysis of data was made with *Genstat 8.1* software Analysis of Variance (ANOVA) procedure. Differences between the means were further investigated with Fisher’s protected LSD multiple comparison test, either at the 5% or 10% level (Ott, 1988). Third rotation height growth was compared with fourth rotation height growth in the new factorial trial with ANOVA. A dummy variable was used to differentiate between the current control plots and the secondary control plots within the ANOVA. The six-year heights measured in 1989 and 2005 were also analyzed with paired T-tests. The difference in height growth between 3R and 4R on the eight split plots comprising the current control and the six split plots comprising the second control was investigated with Residual Maximum Likelihood (REML) analysis.

## RESULTS AND DISCUSSION

### Comparison of height growth in third rotation (3R) with fourth rotation (4R)

The result indicated that in general (excluding the second control plots) the mean heights of 4R trees were superior to that of the 3R trees at the age of six years (**Table 3**). When the effect of fertilizer application in the current trial was excluded by only investigating the differences on the current control plots there was also a significant increase in tree height observable. On the second control plots the heights in the current rotation were the same as in the previous rotation. However, these results should be treated with caution as it is based on measurements of few plots. By using sequential measurements to compare growth of successive rotations there is always the possibility that observed changes might be the result of differences in climatic conditions between rotations (Morris and Smith, 2002). Investigation of total rainfall at Mhlambanyatsi, 4.5 km from the trial site, showed that a total of 7244 mm was recorded in 3R, whilst only 6716 mm was recorded in 4R in the first six years of each rotation respectively. Therefore, the height increase in the fourth rotation can probably be associated with the genetic improvement of the growing stock and the application of fertilizer.

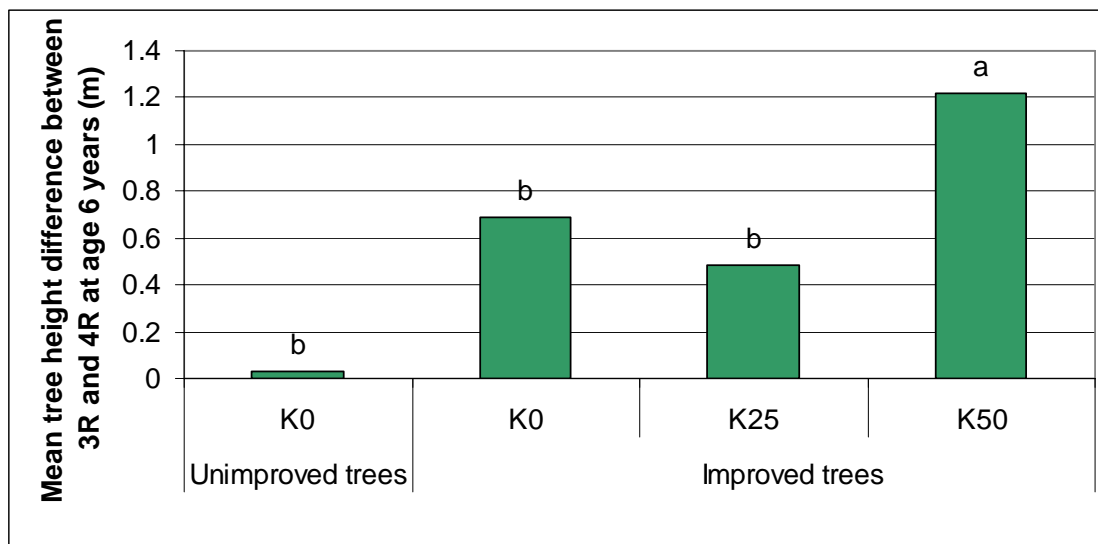
**Table 3: Comparison of mean tree height in 1989 (3R) and 2005 (4R) at the age of six years with paired t-tests.**

Source	Mean Height 1989 (3R)		Mean Height 2005 (4R)		df	Paired T-test $\alpha= 0.05$	Probability: $\mu_1=\mu_2$
	Mean	SE	Mean	SE			
All plots excluding second control	9.2	0.1	10.0	0.1	94	8.09	<0.001
Current control plots	8.6	0.3	9.8	0.2	7	2.58	0.036
Second control plots	9.1	0.2	9.1	0.3	5	0.00	1.000

SE: Standard error of the mean

The 3R:4R comparison of mean tree height on the current control plots (improved genetic material) and the second control plots (original genetic material and original planting density) showed a significant difference on the current and second control plots, but the residual fertilizer

had no significant effect on height growth of trees in any of the two types of control plots. The ANOVA of height differences between 3R and 4R showed that K application at planting and after pruning ( $50 \text{ kg ha}^{-1} \text{ K}$ ) resulted in a significant increase in tree height in the current rotation (**Figure 1**). There was also some indication of a P x K fertilizer interaction. When P and K were applied together at planting and after pruning, the tree height increased significantly over the treatment where only P was applied both at planting and at pruning. There was no indication that the residual fertilizer had any effect on this subset of height measurements.



**Figure 1: Potassium application at pruning and planting improved mean tree height significantly in the fourth rotation compared to the third rotation. Different letters indicate a significant difference between the means at the 5% significance level.**

#### Seven year growth responses to PK fertilizer applied in fourth rotation

The ANOVA results showed that the volume response to the respective treatments was very similar from 2004 to 2006 (**Table 5**). Of the main treatments, both the K and residual fertilizer treatments had a significant effect on mean plot volume. The third order interaction, although declining as the stand aged, was still significant at the 10% level in 2006.

From 2004 to 2006 increasing amounts of P fertilizer increased the absolute volume growth, but the increases were not statistically significant (**Table 4**). However, since 2004 the ANOVA F-value increased and this was reflected in the significant effect that the P applied after pruning had on the volume increment between 2004 and 2006. The P application only at planting did not have any significant effect on the volume response in any particular year or on the volume increment over the two years. In contrast, the treatment where P was applied both at planting and after pruning ( $50 \text{ kg ha}^{-1} \text{ P}$ ) showed a steady increase from 2004 in volume response expressed as a percentage of volume in the control plots. The application of P fertilizer at planting and after pruning resulted in a significant 8.8 % volume increase at age seven years. The application of P at planting did not affect the actual volume or volume increment, therefore the response was likely from the application of P after pruning. Morris (2003) reported that response to fertilizer was dependent on stand age and showed that the response to P application increased when applied to stands older than four years.

**Table 4: Mean volume (m<sup>3</sup> ha<sup>-1</sup>) per main treatment from 2004 to 2006. Letters indicate significant differences at the 5% significance level between means within each row.**

Year	P0	P25	P50	Volume increase from 25 kg ha <sup>-1</sup> P		Volume increase from 50 kg ha <sup>-1</sup> P	
	(m <sup>3</sup> ha <sup>-1</sup> )	(m <sup>3</sup> ha <sup>-1</sup> )	(m <sup>3</sup> ha <sup>-1</sup> )	(m <sup>3</sup> ha <sup>-1</sup> )	%	(m <sup>3</sup> ha <sup>-1</sup> )	%
2004	55.7	56.6	58.1	0.9	1.7	2.4	4.3
2005	90.6	92.1	96.6	1.5	1.7	6.0	6.5
2006	132.5	132.9	141.6	0.4	0.3	9.1	6.8
Increment 04-06	76.8 b	76.3 b	83.5 a	-0.5	-0.7	6.7	8.8

Year	K0	K25	K50	Volume increase from 25 kg ha <sup>-1</sup> K		Volume increase from 50 kg ha <sup>-1</sup> K	
	(m <sup>3</sup> ha <sup>-1</sup> )	(m <sup>3</sup> ha <sup>-1</sup> )	(m <sup>3</sup> ha <sup>-1</sup> )	(m <sup>3</sup> ha <sup>-1</sup> )	%	(m <sup>3</sup> ha <sup>-1</sup> )	%
2004	52.4 b	56.8 ab	61.2 a	4.4	8.4	8.8	15.5
2005	86.9 b	93.2 ab	99.2 a	6.3	7.2	12.3	13.2
2006	127.9 b	135.0 ab	144.0 a	7.1	5.6	16.1	11.9
Increment 04-06	75.5 b	78.2 ab	82.8 a	2.7	3.6	7.3	9.4

Year	Without residual fertilizer	With residual fertilizer	Volume increase from residual PK fertilizer	
	(m <sup>3</sup> ha <sup>-1</sup> )	(m <sup>3</sup> ha <sup>-1</sup> )	(m <sup>3</sup> ha <sup>-1</sup> )	%
2004	54.6 b	59.0 a	4.4	8.1
2005	89.5 b	96.7 a	7.2	8.0
2006	131.2 b	140.1 a	8.9	6.8
Increment 04-06	76.6 b	81.1 a	4.5	5.8

**Table 5: ANOVA F-probability table of volume (m<sup>3</sup> ha<sup>-1</sup>) in 2004, 2005 and 2006 and changes in these parameters over two years.**

Source	df	Volume							
		2004		2005		2006		Increment 2004-06	
		F	Prob >F	F	Prob >F	F	Prob >F	F	Prob >F
Rep	3	5.23		3.93		3.33		1.87	
Rep.P.K Stratum									
P	2	0.42	0.664	1.47	0.250	1.98	0.160	4.14	<b>0.028</b>
K	2	5.47	<b>0.011</b>	5.71	<b>0.009</b>	4.87	<b>0.017</b>	3.48	<b>0.047</b>
P.K	4	0.20	0.938	0.30	0.877	0.11	0.977	0.06	0.994
Residual	24	2.02		1.83		2.01		2.03	
Rep.P.K.Fertilizer-residue Stratum									
Fertilizer (residue)	1	8.47	<b>0.007</b>	10.74	<b>0.003</b>	9.06	<b>0.006</b>	7.94	<b>0.009</b>
P. Fert-residue	2	0.01	0.991	0.11	0.899	0.37	0.691	1.34	0.278
K. Fert-residue	2	0.09	0.917	0.10	0.904	0.14	0.866	0.20	0.820
P.K. Fert-residue	4	2.71	<b>0.051</b>	2.29	<b>0.085</b>	2.22	<b>0.093</b>	1.73	0.173
Residual	27								
Total	71								

The application of K increased both the actual volumes since 2004 and the volume increment over the two year period since the application after pruning. It was only the application of the largest amount of K (total of 50 kg ha<sup>-1</sup> K) which increased the volume significantly over the control. Although both the 25 and 50 kg ha<sup>-1</sup> K treatments caused an increase in absolute volume, when compared to the control since 2004, the increase expressed as a percentage of plot volume

declined as the stand aged. This also corresponded with results reported by Herbert and Schönau (1990) and Morris (2003) that the maximum response to K occurred when applied in younger stands, which is consistent with the timing of the peak rate of accretion of this nutrient into organic sinks. The residual PK fertilizer from the previous rotation also had a significant positive effect on the volume increment. As in the case of K the absolute volume difference increased, but the relative difference (expressed as a percentage of plot volume) decreased from 2004 to 2006.

The response to the P x K factorial combinations was also investigated separately in the presence and absence of residual PK fertilizer. On plots without residual fertilizer the application of K on its own did not affect volume at all (**Figure 2**). When either 25 kg ha<sup>-1</sup> P or 50 kg ha<sup>-1</sup> P was applied on its own, again no significant response occurred. However, when increasing amounts of K was applied with either 25 kg ha<sup>-1</sup> P or 50 kg ha<sup>-1</sup> P, there was a linear increase in absolute volume production. Statistical analysis showed that only the application of 50 kg ha<sup>-1</sup> K with either 25 kg ha<sup>-1</sup> P or 50 kg ha<sup>-1</sup> P increased volume significantly (10% level) over the P25K0 and P50K0 treatments respectively. Compared to the control treatment (P0K0), only the P50K50 treatment increased volume significantly by 19.9 m<sup>3</sup> ha<sup>-1</sup>, which was equal to a 15.6 % increase at age seven years. Again, these results confirmed earlier findings by Morris (1986, 1987, 1994) that both P and K should be applied to sites on gabbro geology that was not previously fertilized. It also corresponded with the response to fertilizer application in the previous rotation, where the application of both 75 kg ha<sup>-1</sup> P and 75 kg ha<sup>-1</sup> K at the age of six years increased mean volume by 23 m<sup>3</sup> ha<sup>-1</sup> (11%) at the age of 14 years (Crous *et al.*, 2005a). The bigger response in the current rotation might be related to the earlier application of the PK fertilizer as a small application at planting, followed by a broadcast application after pruning. In another trial it has been shown that a split application of PK fertilizer was more beneficial than a single large application after pruning (Crous *et al.*, 2005b).

In the presence of residual P and K fertilizer, the trees responded differently to the application of K. Increasing amounts of K alone increased absolute mean volume in the presence of residual PK fertilizer, while it had no response in the absence thereof. When no P was applied, only the application of 50 kg ha<sup>-1</sup> K (P0K50) increased the volume significantly when compared to the control (P0K0). The application of increasing amounts of K with either 25 kg ha<sup>-1</sup> P or 50 kg ha<sup>-1</sup> P on plots with residual PK fertilizer increased absolute volume production, as in the case of plots without residual PK fertilizer, but the effect was less prominent. A combined application of 50 kg ha<sup>-1</sup> P and 50 kg ha<sup>-1</sup> K increased volume by 20 %, which was similar to the 21.5 % increase achieved by the application of only 50 kg ha<sup>-1</sup> K in the presence of residual PK fertilizer. The conclusion made from this response was that the trees were able to utilize the residual P fertilizer from the previous rotation and responded positively when additional K was applied in the current rotation. Elsewhere, it has been demonstrated that growth responses to P fertilizer can persist for many years (Pritchett and Comerford, 1982; Turner, 1982; Tisdale *et al.*, 1993) and even over successive rotations (Ballard, 1978; Gentle *et al.*, 1986; Turner *et al.*, 2002).

At the 10 % significance level the main difference within the P x K combination treatments as a result of residual PK fertilizer was observed in the P0K50 and P25K0 treatments. This again suggested that the residual P fertilizer in the case of the P0K50 treatment and residual K fertilizer in the case of the P25K0 treatment were utilized by the trees to respond to the application of either P or K on its own. Foliar analysis of 2005 collections for these respective fertilizer

treatments revealed raised P levels when only K was applied to plots with residual PK fertilizer and raised K levels when only P was applied (Table 6).

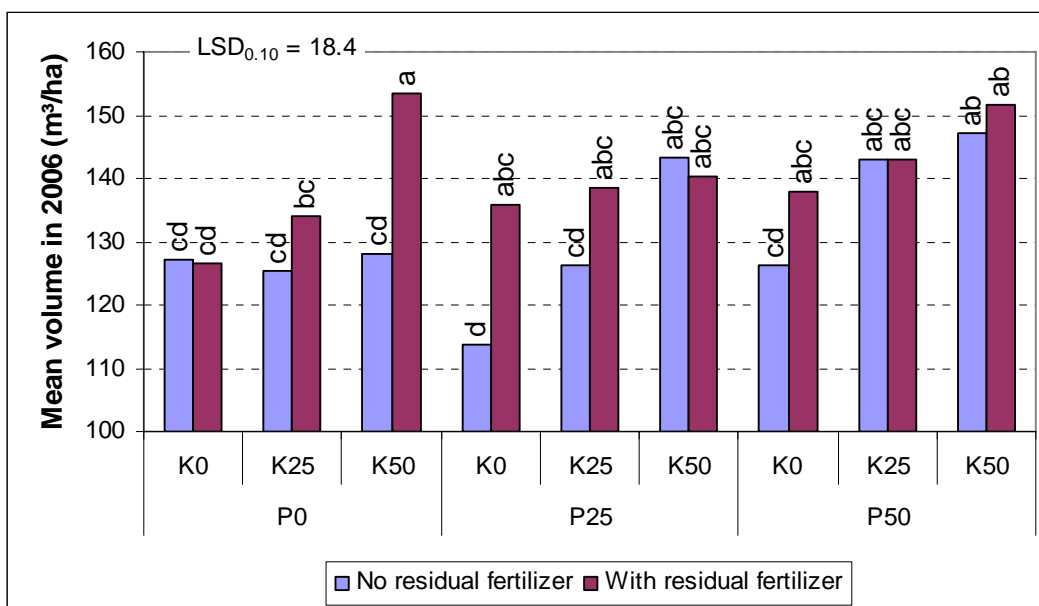


Figure 2: The interaction between P, K and residual PK fertilizer on mean volume at age seven years. Different letters indicate a significant difference between the means at the 10% significance level.

Table 6: Foliar P and K levels confirmed that the trees were able to utilize residual P and K fertilizer. Different letters indicate a significant difference between the means at the 5% significance level within each column.

Treatment	Volume 2006 m³ ha⁻¹	Foliar P 2005 %	Foliar K 2005 %
P0K50 (no residual fertilizer)	128.2	0.12 d	0.54 abc
P0K50 (with residual fertilizer)	153.5	0.14 abc	0.61 a
P25K0 (no residual fertilizer)	113.8	0.13 cd	0.43 d
P25K0 (with residual fertilizer)	135.7	0.13 cd	0.53 abc
Critical level *		0.14	0.50

\* Will, 1985

The foliar P and K levels were related to the volume response. Maximum volume was produced when both the P and K foliar concentrations were above the critical values. Conversely, the minimum volume was produced when the foliar concentrations of both P and K were below the critical value. The response to residual P fertilizer was not unexpected as Flinn *et al.* (1982), Turner (1982), Pritchett and Comerford, (1982), Harding and Jokela, (1994) and Tuner *et al.* (2002) reported that an increase in P content of above ground biomass (mostly the needle portion), as a result of phosphate fertilizer, was associated with a significant growth response. Similarly foliar K levels of *P. patula* were significantly correlated with tree growth studies by Grey *et al.* (1979) and Morris (2003). The response to residual K, 15 years after the application to the previous crop, can possibly be attributed to efficient recycling and K retention in the soil. Potassium fertilizer can be adsorbed on soil colloidal surfaces and fixed between crystal layers of

expanding clays (Brady and Weil, 1996). Because of the dynamic exchange process between the different K pools the K fertilizer that was applied in the previous rotation could theoretically be released from the non-exchangeable and fixed pools if the soil solution K and exchangeable pools become depleted (Fey and Manson, 2004). Krauss and Johnston (2002) demonstrated that only 41% of K fertilizer that was applied over a 10 year period was found in the exchangeable pool, while the balance must have gone into the non-exchangeable and fixed pools. Only one other example demonstrating retention of K fertilizer, in a *P. resinosa* ecosystem in New York for up to 39 years after a single application, was found in the literature (Stone and Kszystyniak, 1977; Shepard and Mitchell, 1990 cited by Fox, 2000).

## CONCLUSIONS

The comparison of mean tree height at six years at the establishment of the trial in the third rotation with mean tree height in the fourth rotation showed no evidence of a growth decline in the subsequent rotation. Considering that rainfall over the first six years was almost similar in both rotations, the observed improved growth in the fourth rotation was probably related to both the use of improved genetic material and the application of PK fertilizer.

Volume growth results from the age of four years indicated that there was a consistent interaction between P, K and the residual PK fertilizer. In the absence of residual fertilizer, only a combined application of P and K fertilizer at the 50 kg ha<sup>-1</sup> rate increased volume significantly. On plots where PK fertilizer was applied during the previous rotation the application of only 50 kg ha<sup>-1</sup> K had a similar positive response as a combined PK application of 50 kg ha<sup>-1</sup> each. Foliar P and K concentration was also raised to sufficient levels when only 50 kg ha<sup>-1</sup> K was applied to previously fertilized plots. Thus, the residual P fertilizer was sufficient to supply in the early demands of the crop when additional K was supplied. However, there are indications that the role of P might become more important as the trees mature and that the residual P fertilizer might not be sufficient to supply the demand until the end of the rotation. Both the tree growth and foliar analyses indicated that the trees were able to utilize some residual K fertilizer, but that it was insufficient to supply in the early demand.

It is concluded that that fertilizer applications at planting to successive crops can be adjusted to allow for benefit from residual P applied in the previous crop. The re-application of K at planting will be of utmost importance to maintain volume production in subsequent rotations. The trial is still too young to adjust recommendations for application after pruning as there are indications that application of a small amount of P with K might be more beneficial than the application of K alone. Nevertheless, a reduction in the amount of P applied to successive rotations on previously fertilized sites is unlikely to cause a decline in growth, but will have considerable economic benefits as P fertilizer is much more expensive than K fertilizer. These results also proved that sustainable production is possible on the gabbro-derived soils through site-specific management.

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