Effects of residual phosphorus and potassium fertiliser on organic matter and soil nutrients in a *Pinus patula* plantation

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Summary

On the Usutu plantation the sustained production from successive *Pinus patula* rotations has been a focus of active research for nearly 50 y. On 13% of the plantation, underlain by gabbro rocks, a 20% growth decline was reported between first (1R) and second (2R) rotations as a result of developing phosphorus (P) and potassium (K) deficiencies. The operational application of fertiliser containing 75 kg P ha^{-1} and 75 kg K ha^{-1} corrected the decline in yield. In 1989 P and K fertiliser was randomly applied, at the above rate, to one half of each of a number of trial plots in a 6-y-old, 3R crop. A 4R trial was re-established on the exact location of the former 3R trial during 1999. In 2004 intensive sampling was conducted to ascertain the influence of the residual fertiliser on the nutrient content of the foliage, forest floor and topsoil in the 4R crop. Fifteen years after the initial fertiliser application, 0.5 M H_2SO_4 extracted $P_{inorganic} + P_{organic}$ in the topsoil was still 41 kg ha^{-1} higher in the fertilised plots than in the control plots. The total forest floor mass was not affected by the residual fertiliser, although the mass of the partially and fully decomposed forest floor litter increased by 3.5 t ha^{-1} (10% level). The residual fertiliser increased the P concentration in only the various needle components and had no effect on any other components or nutrients in the organic matter. We conclude that residual P fertiliser had a greater effect on foliar, forest floor and soil nutrient content than residual K fertiliser.

Keywords: plantations; yield; sustainability; nutrition; fertilizers; phosphorus; potassium; persistence; *Pinus patula*; Swaziland; Usutu

Introduction

The 60 000 ha Usutu plantation is situated 25 km south-west of Mbabane in the western Highveld of Swaziland. It grows pine (mainly *Pinus patula*) as raw material for the production of unbleached kraft pulp. Highly productive sites and the low cost of pulpwood production confer a strategic competitive advantage in the world commodity markets in which pulp is sold. Maintaining wood production from the land in successive rotations is critical to the sustainable supply of low-cost timber to the pulp mill.

Biogeochemical cycling of nutrients is particularly critical for the maintenance and growth of plantation forests on sites that are characterised by a high level of leaching, low nutrient content, low cation exchange capacity and moderate to strong acidity. It is even more important when trees are harvested on short rotations and the crop consists of pine, which is known to modify the soil environment, mostly by decreasing pH, over time (Scholes 2002). Given these circumstances, sustained production from successive rotations has been an active research focus in the Usutu forest for nearly 50 y. A comparison of growth over four rotations showed that over the largest part of the forest the mean height growth was significantly greater over successive rotations (Evans 2005). 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 declined by 18% in the second rotation (Evans 1978, 1986, 1999a). Study of the associations between the affected sample plots and a range of edaphic and lithological parameters revealed that the second-rotation plots, showing a growth decline, were mostly located on Usushwana complex soils, derived from gabbro parent material (Morris 1983, 1986). It was found that gabbro-derived soils had a lower 'available' phosphorus (P) pool, fixed P more strongly and supplied less potassium (K) than granite-derived soils. This suggested that a developing P and K deficiency was responsible for the growth decline on 13% of the Usutu forest.

Elsewhere, the importance of nutrition to sustain forest production has been widely documented. In south-eastern USA, a 10–35% reduction in tree height of second-rotation *P. taeda* and *P. elliottii* was associated with nutrient deficiency as a result of nutrient removal, particularly phosphate, at timber harvest (Haywood and Tiarks 1995, 2002; Tiarks 1999; Bekele *et al*. 1999; Rose and Shiver 2000). Plantations of *P. resinosa* that displayed symptoms of acute K deficiency on glacial outwash sands near Warrensburg, New York, responded positively to the application of potassium (White and Leaf 1964, 1965; Madgewick *et al*. 1970). This significant growth increase, after a single application of K, was still evident after 39 y (Shepard and Mitchell 1990). In Australia and New Zealand, growth of *P. radiata* was also strongly influenced by phosphorus availability (Gentle *et al*. 1965, 1986;

Table 1. Selected soil properties of a soil pit located at the trial site in a fourth rotation *Pinus patula* compartment at Usutu, Swaziland

Property	Unit	Horizon				
		A	B1	B2	C1	C2
Depth	mm	0–100	100–270	270–470	470–570	570–1500+
Bulk density	Mg m^{-3}	0.74	0.87	0.98	1.28	0.93
Texture	–	Clay	Clay	Clay	Clay	Clay
pH (H_2O)	–	4.3	4.9	5.1	4.8	4.6
Org. C (WB)[a]	%	6.8	4.5	3.4	2.4	1.4
P (Bray 2)	mg kg^{-1}	4.9	1.7	1.3	0.3	0.3
P adsorption[b]	mg kg^{-1}	264	225	220	196	553
K	cmol(+) kg^{-1}	0.07	0.06	0.03	0.02	0.01
Ca	cmol(+) kg^{-1}	0.01	0.03	0.01	0.03	0.02
Mg	cmol(+) kg^{-1}	0.08	0.06	0.04	0.03	0.03
Na	cmol(+) kg^{-1}	0.05	0.03	0.01	0.03	0.03
CEC[c]	cmol(+) kg^{-1}	0.20	0.18	0.09	0.11	0.09
Ex. acidity	cmol(+) kg^{-1}	3.7	1.0	0.2	0.2	0.1
Fe	mg kg^{-1}	36.7	23.9	15.7	6.0	4.9
Mn	mg kg^{-1}	3.8	2.4	2.1	5.8	9.5
Zn	mg kg^{-1}	0.8	1.3	0.6	0.8	0.9
Cu	mg kg^{-1}	5.6	6.9	6.2	4.8	4.0

[a] Org. C (WB) = Organic carbon content (Walkley–Black method)
[b] Derived from Langmuir one-surface regression (Olsen and Watanabe 1957, cited in Henry and Smith 2002)
[c] CEC = Cation exchange capacity; Ex. acidity = Exchangeable acidity

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 fertiliser, with the length of the response on some sites extending into subsequent rotations, were reported on 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^{-1} of elemental P and K, respectively, as a spot application at planting, followed by a broadcast application of 75 kg ha^{-1} of elemental P and K, respectively, at pruning. Continuing measurements have shown that these operational fertiliser applications corrected the decline in yield (Evans 1996, 1999b). However, the studies by Morris (1986) indicated a need for improved knowledge of the fundamental biogeochemical cycling processes that are critical for the maintenance and growth of plantation trees (Scholes 2002). A trial was specifically designed to determine if the P and K fertiliser applied to a gabbro-derived soil in the previous rotation would have any residual benefit. The effect of the residual P and K fertiliser on nutrient content of the current crop's foliage, the forest floor and topsoil is reported here.

Materials and methods

Site description

The trial site is located in the eastern portion of Usutu plantation on gabbro-derived soil at an altitude of 1300 m above sea level. A mean annual temperature of 16.3°C and rainfall of 1421 mm y^{-1} is reported for this land type (Pallett 1990). The soil on the site consists of a humic A horizon over a yellow-brown apedal B horizon (Soil Classification Working Group 1991). This soil would be classified as an Oxisol according to the USDA soil taxonomy system (Soil Survey Staff 2006). The clay content is relatively high, while the base saturation is low. General soil texture and chemical properties for a soil pit near the trial are shown in Table 1.

Trial description

Third-rotation trial

In the spring of 1989, a third-rotation trial (3R) was established in a 6-y-old *P. patula* compartment. The trial consisted of 52 plots each 12 × 10 rows in size (at 2.7 m × 2.7 m planting density). Each plot was split into two (6 × 10 rows). A broadcast application of P and K fertiliser was randomly allocated to one of each of these pairs of split-plots. The rate[1] was equivalent to 75 kg P and 75 kg K ha^{-1}. Measurement plots were separated by an 8.3 m buffer across the contour and 5.4 m along the contour. At clear felling only tree stems and bark were removed from the site. Because of the relatively small size of the plots and limited buffer between measurement plots, harvest residue could not be completely contained within the respective plots during harvesting. The remaining harvest residue was not burnt, but left in situ following usual silvicultural practice.

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[1] Morris, A.R. (1999) Establishment prescription for planting of a residual fertilizer trial on the old R128 trial site. Internal communication. Shaw Research Centre. Sappi Forests Research.

Fourth-rotation trial

A fourth-rotation (4R) *P. patula* trial was re-established in September 1999 at the exact location of the former 3R P and K fertiliser trial. In the new 4R trial design, the residual P and K effect was examined as a split-plot treatment within each main plot, with four replications of the main plot treatments. The 3P × 3K factorial treatments (applied in the 4R) consisted of a combination of 0, 25 and 50 kg ha^{-1} elemental P and K. Superphosphate (10.5% P) and potassium chloride (50% K) fertiliser were used. Three additional treatments were imposed to determine the effects of late application and larger amounts of fertiliser. At the age of 5 y, two of these additional treatments as well as the control treatment had not received any fertiliser in the current rotation. Because these three treatments were replicated four times in the trial and each main plot consisted of two split-plots, one where no fertiliser was applied previously and one where P and K fertiliser was applied in 1989, a total of 24 split-plots were available to study the effect of the residual fertiliser. In 2004 the foliage, forest floor and soil in these plots were intensively sampled.

Sampling procedure and chemical analysis

Foliar samples

The sampling protocol was based on recommendations of Will (1985), Linder (1995) and Louw and Scholes (2003). The foliage samples were collected during the dormant season (July) from the top third of the crown when the stand was 4.8 y old. Two second-order branches were cut off and the previous season's foliage that had reached mature length was collected. The two bulked foliage samples, each from five dominant or co-dominant trees per split-plot, were dried in a ventilated oven for 72 h at 70°C. The dry mass of 100 randomly selected needle bundles (fascicles) per split-plot sample was also determined. Following fine grinding, total N was determined by the Kjeldahl method. After fine grinding and dry ashing, P was determined by the molybdenum blue method. Calcium (Ca) and magnesium (Mg) concentrations were determined using atomic absorption spectroscopy, while K and sodium (Na) were determined by flame emission spectroscopy (Donkin *et al*. 1993).

Recently senesced needle samples

Needle litterfall was collected from mid-July to mid-October 2004 in two 1.2 m × 1.2 m shade cloth bags, suspended within metal frames, on each split-plot. Samples were collected every 14 days and oven dried. The senesced needle samples were pooled per trap position for chemical analysis similar to the foliage sample analysis.

Forest floor samples

Forest litter was sampled in July 2004 over two 0.5 m × 0.5 m areas located systematically within each split-plot. The litter layer (L), consisting of easily recognizable organic material, was separated into needles and branches (Fig. 1). The fermentation layer (F) consisted of partially decomposed organic material (Van der Watt and Van Rooyen 1995). Moist weight of the samples was determined in-field and the dry weight was determined after oven drying. The amount of soil contamination in all the samples was determined by means of loss-on-ignition analysis. Macronutrient content of the three respective litter components was analysed using the methods described earlier.

Soil samples

The humus layer (H), consisting of fully decomposed organic material, could not be separated from the top 5 mm of mineral soil (A_1 horizon). Thus, these two layers (H&A_1) in the litter-to-soil transition zone were sampled together and treated as soil with a high organic material content (40%). All soil samples were collected from two 0.25 m × 0.25 m areas located systematically within each split-plot. Soil samples of the A_2 horizon were taken at a depth of 5–100 mm. The amount of mineral soil in all the samples was determined by loss-on-ignition analysis. The pH; ammonium acetate extractable Ca, Mg, Na and K; as well as total K (extracted with boiling nitric acid), was determined for

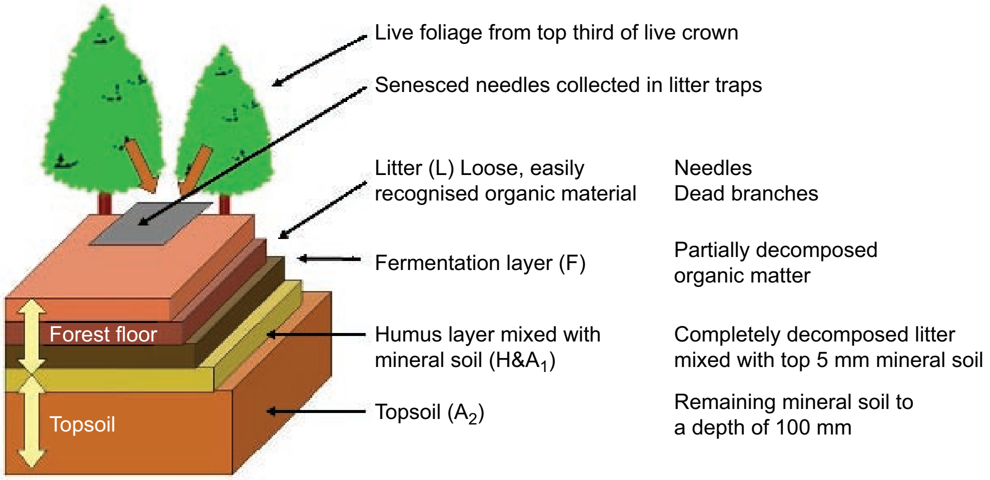

Figure 1. Schematic diagram of the different organic and soil components that were sampled in the fourth rotation (4R) of *Pinus patula* at age 4.8 y, 15 y after the initial application of 75 kg ha^{-1} elemental P and K, respectively, to the 3R crop at Usutu, Swaziland

each sample. The plant-available P was determined with Bray 2 extraction, as these P values have shown a good correlation with pine growth in other studies (Ballard 1974; Payn and Clough 1988). Soil P in the form of calcium phosphates was extracted with 0.5 M H_2SO_4 to determine the inorganic P fraction (P_i) (before digestion) and total P (P_{i+o}) (after digestion of organic material) respectively. The organic P fraction (P_o) was calculated as the difference between P_{i+o} and P_i (Kuo 1996). Organic carbon was determined with the Walkley–Black method (Kalra and Maynard 1991).

Statistical analysis

Data were statistically analysed with Genstat 8.1 software. The paired *t*-test procedure, with a confidence level of 95%, was used because the samples from each treatment were matched or paired in the split-plots (Ott 1988).

Results and discussion

Live foliar samples

The residual P and K fertiliser from the application 15 y earlier increased the P concentration of the live needles by only 50 mg kg^{-1} (Table 2). The increase in foliar P concentration associated with the application of P fertiliser corresponded with findings by Flinn *et al.* (1982), Turner (1982), Maggs (1985, 1988) and Turner *et al.* (2002). A comparison of tree growth data from the 12 intensively sampled plots indicated that only the mean diameter at breast height (DBH) increased ($P = 0.052$) as a result of the residual fertiliser. However, results from the complete trial showed that the residual P and K fertiliser increased tree volume per unit area significantly from the age of 5 y up to age 7 y. At the age of 7 y residual P and K fertiliser increased total volume by 8.9 m^3 ha^{-1} above the 131.2 m^3 ha^{-1} recorded in the control plots (Crous *et al.* 2007). In other studies it was also found that an increase in needle P was associated with a significant growth response (Ballard 1978; Flinn *et al.* 1982; Pritchett and Comerford 1982; Turner 1982; Gentle *et al.* 1986; Harding and Jokela 1994; Turner *et al.* 2002). No evidence was found that the concentration of the other nutrients, including K, differed as a result of previous fertiliser. Nutrient ratios of N:P, N:K and P:K were also not significantly affected. The residual fertiliser also had no significant effect on the dry mass of 100 fascicles.

Recently senesced needle samples

The average weight of needles collected over a 14-day period in the litter traps was not affected by residual fertiliser. The analysis of litter trap needles indicated that the P concentration in the needlefall from the trees was higher as a result of the P that was applied in the previous rotation (Table 3). The N, K and Ca concentrations also tended to be higher, but the variability of the data was such that these differences could not be shown to be statistically significant. A comparison of nutrients in the senesced needles (Table 3) with those in the live foliage (Table 2) indicated that in absolute terms more N, P and K was resorbed in the unfertilised plots, but these differences were not statistically significant. On the fertilised, plots 46% of the N and P was translocated. The P resorption figure corresponded with that reported by Dames *et al.* (2002) in a 42-y-old stand.

Forest floor samples

The total mass of forest floor was consistent with earlier observations for stands of *P. patula* of similar age and altitude at Usutu (Morris 1993, 1995). The total forest floor mass was not statistically significantly affected by the residual fertiliser. There was, however, a 3.5 t ha^{-1} increase (significant at the 10% level) in the organic matter component of the H&A_1 layer (Table 4). The third-rotation fertiliser application increased stem volume of the 3R crop (Crous *et al.* 2005) and therefore it can be assumed that the amount of all aboveground biomass would have increased as well. This in turn would also have increased the amount of harvest residue from the 3R. After clear felling, the harvest residue became humus that formed most of the H-layer at the time of the study.

Turner *et al.* (2002) reported that although residual P fertiliser did not affect the absolute values of the forest floor mass, it did reduce the coefficient of variation. With the exception of the variation in the F-layer, similar results were seen in our study.

Table 2. Nutrient concentration of live foliage collected during the dormant season from 4.8-y-old *Pinus patula* trees at Usutu

Nutrient or ratio	Unit	Without residual fertiliser		With residual fertiliser		Paired *t*-test $\alpha = 0.05$ df = 23	Probability[b] $\mu_1 = \mu_2$
		Mean	SE[a]	Mean	SE[a]		
N	%	1.565	0.040	1.614	0.024	–1.36	0.189
P	%	0.111	0.002	0.116	0.002	–2.04	**0.053**
K	%	0.380	0.010	0.379	0.010	–0.03	0.978
Ca	%	0.231	0.007	0.236	0.009	–0.44	0.663
Mg	%	0.085	0.007	0.078	0.006	–0.49	0.630
Na	%	0.007	0.000	0.008	0.001	–1.45	0.162
N:P	–	14.260	0.470	14.070	0.360	0.47	0.644
N:K	–	4.174	0.130	4.324	0.131	–0.91	0.370
P:K	–	0.295	0.008	0.308	0.006	–1.28	0.213

[a] SE = Standard error of the mean

[b] Bolding identifies the presence of significant differences between treatment means at $P < 0.08$

Table 3. Nutrient concentration of senesced *Pinus patula* needles collected in litter traps between July and October 2004 in the P and K residual study plots at Usutu

Nutrient	Unit	Without residual fertiliser		With residual fertiliser		Paired *t*-test $\alpha = 0.05$ df = 23	Probability[b] $\mu_1 = \mu_2$
		Mean	SE[a]	Mean	SE[a]		
N	%	0.771	0.046	0.857	0.030	–1.65	0.112
P	%	0.054	0.002	0.062	0.003	–2.89	**0.008**
K	%	0.157	0.008	0.176	0.011	–1.66	0.111
Ca	%	0.336	0.020	0.360	0.208	–0.78	0.441
Mg	%	0.072	0.003	0.073	0.002	–0.19	0.850
Na	%	0.012	0.001	0.011	0.001	0.40	0.696
N:P	–	14.400	0.800	14.060	0.410	0.36	0.724
N:K	–	5.228	0.369	5.288	0.362	–0.11	0.912
P:K	–	0.365	0.022	0.379	0.025	–0.43	0.669

[a] SE = Standard error of the mean

[b] Bolding identifies the presence of significant differences between treatment means at $P < 0.08$

Table 4. Oven-dry mass (adjusted for soil contamination) of organic material on the forest floor of a 4.8-y-old fourth rotation *Pinus patula* crop at Usutu

Layer[a]	Unit	Without residual fertiliser		With residual fertiliser		Paired *t*-test $P = 0.05$ df = 23	Probability[c] $\mu_1 = \mu_2$
		Mean	SE[b]	Mean	SE[b]		
L layer (needles)	t ha^{-1}	9.8	0.60	9.4	0.56	0.50	0.621
L layer (branches)	t ha^{-1}	6.6	0.84	6.7	0.73	–0.08	0.933
F layer	t ha^{-1}	6.6	0.58	6.0	0.63	0.72	0.479
H&A_1 layer	t ha^{-1}	31.1	2.00	34.6	1.90	–1.86	**0.076**
Total forest floor	t ha^{-1}	54.2	2.26	56.7	2.42	–1.08	0.290

[a] L= Litter layer; F = Fermentation layer; H&A = Humus layer plus A_1 horizon

[b] SE = Standard error of the mean

[c] Bolding identifies the presence of significant differences between treatment means at $P < 0.08$

Our finding of an increase in H-layer mass, but no increase in the L-layer mass, corresponded with the results from a study in Georgia, USA, by Comerford *et al.* (2002). The reason why no difference was observed between the total forest floor mass on plots with residual fertiliser and those without might also be related to enhanced litter decomposition associated with the application of fertiliser. Both Gentle *et al.* (1986) and Harding and Jokela (1994) suggested that the rate of decomposition can accelerate due to increased nutrient content of forest floor litter as a result of fertiliser. Maggs and Hewett (1986) showed that superphosphate application to *P. elliottii* on the coastal lowlands of south-eastern Queensland had an effect on forest floor microbial activity as the P fertilizer increased rates of non-symbiotic nitrogen fixation in the forest floor. Furthermore, an increase in Ca from the gypsum component in superphosphate could affect nutrient cycling by influencing micro-flora and fauna succession and the base content of the litter. However, there was no evidence in our study or that of Maggs (1985, 1988) that the superphosphate had any effect on the Ca content of the forest floor components.

The nutrient content of the needle portion of the forest floor also reflected the same response as the live foliage and litter trap samples (Table 5). The phosphorus concentration was slightly higher ($P = 0.051$) in the plots where fertiliser was applied in 1989.

No nutrient differences could be detected in the dead branches that formed part of the forest floor. The nutrient content of the partially decomposed organic matter was the same in plots that received fertiliser in 1989 and those that did not receive fertiliser. Maggs (1985) also reported that only the needle component of the litter under a *P. elliottii* compartment responded positively to the application of P fertiliser.

Soil samples

In the H&A_1 layer neither the soil P (Bray 2 and 0.5 M H_2SO_4-extracted P), nor exchangeable soil K concentration expressed per kilogram soil, was significantly different, although the absolute values were higher on plots with residual P and K fertiliser. However, when the actual nutrient amount (content) per hectare was calculated, the differences as a result of residual P and K fertiliser were 0.3 kg ha^{-1} for plant available P, 2.5 kg ha^{-1} for 0.5 M H_2SO_4-extracted P_i, 7.7 kg ha^{-1} for 0.5 M H_2SO_4-extracted P_{i+o} and 1.4 kg ha^{-1} for exchangeable K (significant at the 10% level) (Table 6). This increase was directly related to the significant increase in the organic material mass of the H&A$_1$ layer as a result of the residual P and K fertiliser. The 7.7 kg ha^{-1} P and 1.4 kg ha^{-1} K represented 10.3% and 1.9% of the 75 kg ha^{-1} P and K that was applied in 1989, respectively. The Bray 2 P-values in the H&A$_1$ layer were close to the 'critical' value of 12 as reported by Ballard (1978).

The P$_o$ fraction comprised 76% of the 0.5 M H$_2$SO$_4$-extracted P pool in the H&A$_1$ layer. The reason for the very small difference in Bray 2 P and 0.5 M H$_2$SO$_4$-extracted P$_o$ levels between the plots with residual fertiliser and those without might be the result of harvest residue from fertilised plots that ended up on unfertilised plots after harvesting the third-rotation crop. Because harvest residue could not be contained completely within the individual plots, a small amount of foliage with higher P levels from fertilised plots was probably mixed with foliage from plots without fertiliser and vice versa. This could have had an effect, as Turner *et al.* (2002) had observed lateral movement of phosphate due to litter fall from fertilised plots into unfertilised plots.

In absolute terms the amount of Ca and Mg also increased (although not significantly) on the plots with residual fertiliser. This observation corresponded with observations of an accumulation of nutrients (even nutrients that were not applied with the fertiliser) on fertilised plots by Forestry Commission NSW (1986), Nowak *et al.* (1991) and Harding and Jokela (1994). In these studies the accumulation was attributed to increased nutrient cycling in the fertilised plots and redistribution of nutrients from deeper in the soil profile because of enhanced root exploitation.

Table 5. Nutrient concentration of the needle component in the forest floor L layer, of a 4.8-y-old fourth-rotation *Pinus patula* crop at Usutu

Nutrient	Unit	Without residual fertiliser		With residual fertiliser		Paired *t*-test $\alpha = 0.05$ df = 23	Probability[b] $\mu_1 = \mu_2$
		Mean	SE[a]	Mean	SE[a]		
N	%	1.081	0.018	1.080	0.016	0.05	0.964
P	%	0.066	0.003	0.073	0.003	–2.06	**0.051**
K	%	0.103	0.008	0.104	0.006	–0.09	0.926
Ca	%	0.505	0.032	0.488	0.035	0.62	0.541
Mg	%	0.079	0.002	0.075	0.003	1.29	0.210
Na	%	0.006	0.001	0.006	0.000	0.12	0.907

[a] SE = Standard error of the mean

[b] Bolding identifies the presence of significant differences between treatment means at $P < 0.08$

Table 6. Comparison of soil characteristics of the humus (H) layer mixed with the top 5 mm of soil (A$_1$), 15 y after the initial application of P and K fertiliser to the previous rotation (3R) of *Pinus patula* at Usutu

Parameter[a]	Unit	Without residual fertiliser		With residual fertiliser		*t*-test $\alpha = 0.05$ df = 23	Probability[c] $\mu_1 = \mu_2$
		Mean	SE[b]	Mean	SE[b]		
CEC	cmol(+) kg^{-1}	1.36	0.215	1.48	0.306	–0.59	0.564
Org. C (WB)	%	17.82	1.250	17.49	1.050	0.23	0.824
pH (KCl)	–	3.70	0.037	3.73	0.038	–0.42	0.681
Exc. acidity	cmol(+) kg^{-1}	6.12	0.318	6.05	0.101	0.13	0.898
P (Bray 2)	mg kg^{-1}	11.32	1.310	12.60	1.210	–0.81	0.427
Exchangeable K	kg ha^{-1}	5.5	0.43	6.9	0.51	–2.27	**0.033**
Total K	kg ha^{-1}	12.4	0.95	13.4	0.71	–0.09	0.400
Ca	kg ha^{-1}	12.0	2.00	13.5	2.72	–0.75	0.458
Mg	kg ha^{-1}	4.1	0.82	5.6	1.56	–0.92	0.366
Na	kg ha^{-1}	0.2	0.02	0.2	0.02	–2.52	**0.019**
P (Bray 2)	kg ha^{-1}	1.0	0.10	1.3	0.10	–1.93	**0.066**
P$_i$ (0.5 M H$_2$SO$_4$)	kg ha^{-1}	12.7	0.93	15.2	1.11	–1.84	**0.079**
P$_o$ (0.5 M H$_2$SO$_4$)	kg ha^{-1}	41.7	2.27	46.8	2.90	–1.52	0.142
P$_{i+o}$ (0.5 M H$_2$SO$_4$)	kg ha^{-1}	54.4	2.73	62.1	3.50	–1.83	**0.080**

[a] CEC = Cation exchange capacity; Org. C (WB) = Organic carbon content (Walkley–Black method); Exc. acidity = Exchangeable acidity; P$_i$ = Inorganic P fraction; P$_o$ = Organic P fraction

[b] Standard error of the mean

[c] Bolding identifies the presence of significant differences between treatment means at $P < 0.08$

Apart from P, none of the other topsoil (A_2) chemical properties were significantly affected by the residual fertiliser. In the first 5–100 mm of topsoil, the plant-available P, and 0.5 M H_2SO_4-extracted P_{i+o} and P_o, were significantly increased by the residual fertiliser. The increase was a mere 1.3 mg kg^{-1} in the case of plant-available P, but the increase in 0.5 M H_2SO_4-extracted P_{i+o} was a substantial 44.7 mg kg^{-1} (Table 7).

This was mainly due to an increase in the organic P fraction. The 0.5 M H_2SO_4-extracted P_o fraction contained 68% of the 0.5 M H_2SO_4-extracted P_{i+o} in the A_2 component and accounted for 75% of the difference in P between plots with and without fertiliser when the fractions in the H, A_1 and A_2 layers were combined. This corresponded with findings by Fransson and Bergkvist (2000) that a large proportion of the inorganic P in the fertiliser was converted into organic P forms. The P contained in organic material, which is less prone to leaching and adsorption, became a major source of available P for future growth — a view supported by Polglase *et al*. (1992a,b).

The persistent effect of phosphorus fertiliser was not unexpected, as Schönau (1984) reported that residual superphosphate was available to a certain extent for the new crop after 10 y. If the difference in 0.5 M H_2SO_4-extracted P_{i+o} in the H, A_1 and A_2 layers is taken into account, the P in plots with residual P and K fertiliser was 41 kg P ha^{-1} more than on plots that did not receive fertiliser previously. This represented 55% of the 75 kg ha^{-1} P applied 15 y earlier, and was more than the 42% accounted for by Comerford *et al*. (2002) 29 y after the application of 70 kg ha^{-1} P or the 44% reported by Flinn *et al*. (1982) 3 y after the application of 63 kg ha^{-1} P. This result indicates that the amount of P applied to subsequent fertilised crops can possibly be reduced, because some P from the initial application will remain available to the next crop.

Potassium, on the other hand, is more easily leached in the soil profile than phosphorus (Tisdale *et al*. 1993; Brady and Weil 1996). After a period of 15 y it was expected that the applied K would have became distributed over a much larger depth in the soil profile and is possibly the reason why the difference was insignificant. It also might have moved laterally as Buxbaum *et al*. (2001) have shown that K fertiliser moved 11–16 m from the edge of fertilised plots over a 50-y period.

Conclusions

The results from our study showed that the residual P fertiliser had a greater effect on the foliage, forest floor and soil nutrient content than the residual K fertiliser. As in other studies, the P fertiliser had a significant positive effect on the P concentration of all needle components (live foliage, senesced needles and litter layer needles), while it had no significant effect on any other component or nutrient. Fifteen years after the application of the P fertiliser, it still had a positive effect, although small, on the plant-available P fraction in the first 100 mm of topsoil. However, a significant proportion of the inorganic P fertiliser was converted into P_o forms. P_o is less prone to leaching or adsorption and will be a future source of available P for the crop. Thus, the conservation of organic material will be extremely important to ensure long-term P cycling.

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Table 7. Comparison of some topsoil characteristics (5–100 mm depth), 15 y after the initial application of P and K fertiliser to the previous rotation (3R) of *Pinus patula* at Usutu

Parameter[a]	Unit	Without residual P and K fertiliser		With residual P and K fertiliser		*t*-test $\alpha = 0.05$	Probability[c] $\mu_1 = \mu_2$
		Mean	SE[b]	Mean	SE[b]		
CEC	cmol(+) kg^{-1}	0.48	0.078	0.36	0.039	1.55	0.134
Exc. acidity	cmol(+) kg^{-1}	2.86	0.148	2.77	0.111	0.51	0.615
Exchangeable K	cmol(+) kg^{-1}	0.07	0.003	0.07	0.004	–0.05	0.961
Total K	cmol(+) kg^{-1}	0.15	0.007	0.16	0.007	–0.29	0.776
Ca	cmol(+) kg^{-1}	0.12	0.019	0.12	0.020	0.63	0.535
Mg	cmol(+) kg^{-1}	0.11	0.007	0.12	0.017	–0.84	0.412
Na	cmol(+) kg^{-1}	0.05	0.003	0.05	0.003	–0.54	0.593
Org. C (WB)	%	6.71	0.317	6.55	0.247	0.34	0.740
pH (KCl)	–	3.81	0.033	3.83	0.027	–0.37	0.717
P (Bray 2)	mg kg^{-1}	3.06	0.348	4.34	0.613	–1.84	**0.079**
P_i (0.5 M H_2SO_4)	mg kg^{-1}	135.2	4.6	144.1	5.4	–1.52	0.143
P_o (0.5 M H_2SO_4)	mg kg^{-1}	273.5	14.3	309.3	16.9	–2.72	**0.012**
P_{i+o} (0.5 M H_2SO_4)	mg kg^{-1}	408.7	15.5	453.4	18.8	–2.76	**0.011**

[a] CEC = Cation exchange capacity; Org. C (WB) = Organic carbon content (Walkley-Black method); Exc. acidity = Exchangeable acidity; P_i = Inorganic P fraction; P_o = Organic P fraction

[b] Standard error of the mean

[c] Bolding identifies the presence of significant differences between treatment means at $P < 0.08$

References

Ballard, R. (1974) Use of soil testing for predicting phosphate fertiliser requirements of radiata pine at time of planting. *New Zealand Journal of Forestry Science* **4,** 27–37.

Ballard, R. (1978) Effect of first rotation phosphorus applications on fertiliser requirements of second rotation radiata pine. *New Zealand Journal of Forestry Science* **8,** 135–145.

Bekele, A., Hundall, W.H. and Tiarks, A.E. (1999) Vector analyses identify loblolly pine (*Pinus taeda* L.) phosphorus deficiency on a Beauregard soil. In: Heywood, J.D. (ed.) *Proceedings of the Tenth Biennial Southern Silvicultural Research Conference*, 16–18 February 1999, Shreveport, LA. Gen. Tech. Rep. SRS-030. US Department of Agriculture Forest Service, Southern Research Station, Asheville, NC, pp. 474–479. http://www.treesearch.fs.fed.us/pubs/1171.

Brady, N.C. and Weil, R.R. (1996) *The Nature and Properties of Soils.* Prentice-Hall International Inc., Upper Saddle River, New Jersey.

Buxbaum, C.A.Z., Nowak, C.A. and White, E.H. (2001) Long-term soil nutrient dynamics and lateral nutrient movement in fertilized and unfertilized red pine plantations. *Biogeochemistry* **55,** 269–292.

Comerford, N.B., McLeod, M. and Skinner, M. (2002) Phosphorus form and bioavailability in the pine rotation following fertilization. P fertilization influences P form and potential bioavailability to pine in the subsequent rotation. *Forest Ecology and Management* **169,** 203–211.

Crous, J.W., Morris, A.R. and Khoza, S. (2005) R128: Rotation-age growth response to a post-pruning application of PK fertilizer on a gabbro site at Usutu. Research Document 20/2005, Sappi Forests Research, Ngodwana 1209, Republic of South Africa.

Crous, J.W., Morris, A.R. and Scholes, M.C. (2007) The significance of residual phosphorus and potassium fertilizer in countering yield decline in a fourth rotation of *Pinus patula* in Swaziland. *Southern Hemisphere Forestry Journal* **69,** 1–8.

Dames, J., Scholes, M.C. and Straker, C.J. (2002) Nutrient cycling in a *Pinus patula* plantation in the Mpumalanga province, South Africa. *Applied Soil Ecology* **20,** 211–226.

Donkin, M.J., Pearce, J. and Chetty, P.M. (1993) *Methods for Routine Plant Analysis in the ICFR Laboratories*. ICFR Bulletin 06/93. Institute for Commercial Forestry Research, Pietermaritzburg.

Ducey, M. and Allen, H.L. (2001) Nutrient supply and fertilization efficiency in midrotation loblolly pine plantations: a modeling analysis. *Forest Science* **47,** 96–102.

Evans, J. (1978) A further report on second rotation productivity in the Usutu Forest, Swaziland. *Commonwealth Forestry Review* **57,** 253–261.

Evans, J. (1986) Productivity of second and third rotations of pine in the Usutu Forest, Swaziland. *Commonwealth Forestry Review* **65,** 205–214.

Evans, J. (1996) The sustainability of wood production from plantations: evidence over three successive rotations in the Usutu Forest, Swaziland. *Commonwealth Forestry Review* **75,** 234–239.

Evans, J. (1999a) S*ustainability of Forest Plantations: The Evidence*. The Department for International Development, London, UK, 64 pp.

Evans, J. (1999b) Sustainability of plantation forestry: impacts of species change and successive rotations of pine in the Usutu Forest, Swaziland. *Southern African Forestry Journal* **184,** 3–70.

Evans, J. (2005) Growth rates over four rotations of pine in Swaziland. *International Forestry Review* **7,** 305–310.

Flinn, D.W., James, J.M. and Hopmans, P. (1982) Aspects of phosphorus cycling in radiata pine on a strongly phosphorus-adsorbing soil. *Australian Forest Research* **12,** 19–35.

Forestry Commission, NSW (1986) *Research Report 1983 & 1984*. Soils and nutrition. Forestry Commission of New South Wales, Sydney, pp. 17–34.

Fransson, A. and Bergkvist, B. (2000) Phosphorus fertilisation causes durable enhancement of phosphorus concentrations in forest soil. *Forest Ecology and Management* **130,** 69–76.

Gentle, S.W., Humphreys, F.R and Lambert, M.J. (1965) An examination of a *Pinus radiata* phosphate fertiliser trial fifteen years after treatment. *Forest Science* **11,** 315–324.

Gentle, S.W., Humphreys, F.R. and Lambert, M.J. (1986) Continuing growth response of *Pinus radiata* to phosphatic fertilizers over two rotations. *Forest Science* **32,** 822–829.

Harding, R.B. and Jokela, E.J. (1994) Long-term effects of forest fertilization on site organic matter and nutrients. *Soil Science Society of America Journal* **58,** 216–221.

Haywood, J.D. and Tiarks, A.E. (1995) Growth reductions in short-rotation loblolly and slash pines in central Louisiana — 10th year results. In: Edwards, M.B. (ed.) *Proceedings of the Eighth Biennial Southern Silvicultural Research Conference*. 1–3 November 1994, Auburn, AL., Gen. Tech. Rep. SRS-1. USDA Forest Service, Southern Research Station, Asheville, NC., pp. 268–274.

Haywood, J.D. and Tiarks, A.E. (2002) Response of second-rotation southern pines to fertilizer and planting on old beds — fifteenth-year results. In: Outcalt, K.W. (ed.) *Proceedings of the Eleventh Biennial Southern Silvicultural Research Conference*. Gen. Tech. Rep. SRS-48. US Department of Agriculture Forest Service, Southern Research Station, Asheville, NC, pp. 497–502.

Henry, P.C. and Smith, M.F. (2002) Phosphorus sorption study of selected South African soils. *South African Journal of Plant and Soil* **19,** 61–69.

Kalra, Y.P. and Maynard, D.G. (1991) *Methods Manual for Forest Soil and Plant Analysis.* Information report NOR-X-319. Forestry Canada, Northwest region. Northern Forestry Centre, Edmonton, Alberta, 116 pp.

Kuo, S. (1996) Total organic phosphorus. In: Sparks, D.L. (ed.) *Methods of Soil Analysis. Part 3. Chemical Methods.* Soil Science Society of America, Madison, USA, Chapter 32, pp. 874–876.

Linder, S. (1995) Foliar analysis for detecting and correcting nutrient imbalances in Norway spruce. *Ecological Bulletins* **44,** 178–190.

Louw, J.H. and Scholes, M.C. (2003) Foliar nutrient levels as indicators of site quality for *Pinus patula* in the Mpumalanga escarpment area. *Southern African Forestry Journal* **197,** 21–30.

Madgewick, H.A.I., White, E.H., Xydias, G.K. and Leaf, A.L. (1970) Biomass of *Pinus resinosa* in relation to potassium nutrition. *Forest Science* **16,** 154–159.

Maggs, J. (1985) Litter fall and retranslocation of nutrients in a refertilized and prescribed burned *Pinus elliottii* plantation. *Forest Ecology and Management* **12,** 253–268.

Maggs, J. (1988) Organic matter and nutrients in the forest floor of a *Pinus elliottii* plantation and some effects of prescribed burning and superphosphate addition. *Forest Ecology and Management* **23,** 105–119.

Maggs, J. and Hewett, R.K. (1986) Nitrogenase acticity (C_2H_2 reduction) in the forest floor of a *Pinus elliottii* plantation following superphosphate addition and prescribed burning. *Forest Ecology and Management* **14,** 91–101.

Morris, A.R. (1983) *The Relationship between the Block A 'Second Rotation Decline' Phenomena and Geology at the Usutu Forest.* Forest Research Report No. 44. Usutu Pulp Company. Swaziland.

Morris, A.R. (1986) Soil fertility and long term productivity of *Pinus patula* in the Usutu Forest, Swaziland. PhD thesis, University of Reading, UK, 398 pp.

Morris, A.R. (1987) *Recommendations for Fertilizer Application to* Pinus patula *Stands on the Usushwana Igneous Complex*. Forest Research Document 19/87. Usutu Pulp Company. Swaziland.

Morris, A.R. (1993) Forest floor accumulation under *Pinus patula* in the Usutu Forest, Swaziland. *Commonwealth Forestry Review* **72,** 114–117.

Morris, A.R. (1994) *Current Prescriptions for Operational Fertilizer Applications in the Usutu Forest*. Forest Research Document 7/94. Usutu Pulp Company, Swaziland.

Morris, A.R. (1995) Forest floor accumulation, nutrition and productivity of *Pinus patula* in the Usutu Forest, Swaziland. *Plant and Soil* **168–169,** 271–278.

Nowak, C.A., Downard, Jr., R.B. and White, E.H. (1991) Potassium trends in red pine plantations at Pack Forest, New York. *Soil Science Society of America Journal* **55,** 847–850.

Ott, L. (1988) *An Introduction to Statistical Methods and Data Analysis.* Third edition. PWS-Kent Publishing Company, Boston, 835 pp.

Pallett, R.N. (1990) *Forest Land Types of the Usutu Forest Swaziland*. Forest Research Document 4/90. Usutu Pulp Company. Swaziland.

Payn, T.W. and Clough, M.E. (1988) Differential fertilisation of pine plantations on acid forest soils. *Southern African Forestry Journal* **147,** 16–25.

Polglase, P.J., Jokela, E.J. and Comerford, N.B. (1992a) Nitrogen and phosphorus release from decomposing needles of southern pine plantations. *Soil Science Society of America Journal* **56,** 914–920.

Polglase, P.J., Comerford, N.B. and Jokela, E.J. (1992b) Mineralization of nitrogen and phosphorus from soil organic matter in southern pine plantations. *Soil Science Society of America Journal* **56,** 921–927.

Pritchett, W.L. and Comerford, N.B. (1982) Long-term response to phosphorus fertilization on selected southeastern coastal plain soils. *Soil Science Society of America Journal* **46,** 640–644.

Raupach, M. and Hall, M.J. (1974) Foliar levels of potassium in relation to potassium deficiency symptoms in radiata pine. *Australian Forestry* **36,** 204–213.

Rose, C.E. and Shiver, B.D. (2000) *A Comparison of First and Second Rotation Dominant and Codominant Heights for Flatwoods Slash Pine Plantations.* PMRC Technical Report 2000–2. Plantation Management Research Cooperative, University of Georgia, Athens, 15 pp.

Scholes, M.C. (2002) Biological processes as indicators of sustainable plantation forestry. *Southern African Forestry Journal* **195,** 57–62.

Schõnau, A.P.G. (1984) Fertilisation of fast growing broadleaved species. In: Grey, D.C., Schõnau, A.P.G. and Schutz, C.J. (eds) *Proceedings of the IUFRO Symposium on Site and Productivity of Fast Growing Plantations*. Vol. 1. Pretoria and Pietermaritzburg. South African Forest Research Institute, Pretoria, pp. 253–268.

Shepard, J.P. and Mitchell, M.J. (1990) Nutrient cycling in a red pine plantation 39 years after potassium fertilization. *Soil Science Society of America Journal* **54,** 1433–1440.

Soil Classification Working Group (1991) *Soil Classification: A Taxonomic System for South Africa.* Memoirs on the Agricultural Natural Resources of South Africa No.15, Department of Agricultural Development, Pretoria, 257 pp.

Soil Survey Staff (2006) *Keys to Soil Taxonomy*. Tenth edition. United States Department of Agriculture. US Government Printing Office, Washington, DC, 341 pp.

Tiarks, A.E. (1999) Nutrient management in pine forests. *Proceedings of the Fifteenth Annual ARK-LA-TEX Forestry Forum*, 9 March 1999, Shreveport, LA, pp. 1–6. http://www.srs.fs.usda.gov/pubs/ja/uncaptured/ja_tiarks002.pdf.

Tisdale, S.L., Nelson, W.L., Beaton, J.D. and Havlin, J.L. (1993) *Soil Fertility and Fertilizers.* Fifth edition. Prentice Hall, New Jersey.

Turner, J. (1982) Long-term superphosphate trial in regeneration of *Pinus radiata* at Belanglo State Forest, NSW. *Australian Forest Research* **12,** 1–9.

Turner, J., Lambert, M.J. and Humphreys, F.R. (2002) Continuing growth response to phosphate fertilizers by a *Pinus radiata* plantation over fifty years. *Forest Science* **48,** 556–568.

Van der Watt, H.v.H. and Van Rooyen, T.H. (1995) *A Glossary of Soil Science*. Second edition. The Soil Science Society of South Africa, Pretoria.

White, E.H. and Leaf, A.L. (1964) Soil and tree potassium contents related to tree growth I: HNO_3 extractable soil K. *Soil Science* **98,** 395–402.

White, E.H. and Leaf, A.L. (1965) Soil and tree potassium contents related to tree growth II: Tissue K as determined by total tree analysis techniques. *Soil Science* **99,** 109–114.

Will, G. (1985) *Nutrient Deficiencies and Fertilizer Use in New Zealand Exotic Forests*. FRI Bulletin No. 97. Forest Research Institute, New Zealand Forest Service, Rotorua, New Zealand, 53 pp.