SOME EFFECTS OF PHOSPHORUS (P) AND POTASSIUM (K) AND RESIDUAL P AND K FERTILIZER ON THE GROWTH OF *PINUS PATULA* AT USUTU, SWAZILAND

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DECLARATION

I declare that this thesis, submitted for the Degree of Doctor of Philosophy at the University of the Witwatersrand, Johannesburg, is the result of my own investigation, unless acknowledged to the contrary in the text. It has not been submitted before for any degree or examination at any other University.

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ABSTRACT

The sustainable production of renewable timber resources is not only important to Sappi and other forestry companies to produce pulp, paper and timber profitably, but to society in general to maintain or improve living standards in an ecological friendly manner. Research on the sustained production from short rotations of *P. patula* on the Usutu plantation has shown that operational application of P and K fertilizer corrected the 20% growth decline that was observed between first and second rotations on about 13% of the plantation that consists of soils derived from gabbro lithology. However, additional trials were established to investigate the magnitude and duration of responses from the application of different amounts of P and K fertilizer at different times of stand development. Results from two of these practical trials are reported here.

Trial R155, a phosphorus (P) by potassium (K) by weed control trial was established to determine the optimum application rate and timing of PK fertilizer. The P and K fertilizer were applied in three amounts, 20/20, 40/40 and 80/80 kg P ha^{-1} and K ha^{-1}. The 40/40 and 80/80 amounts were applied with three different regimes, either applying all of the fertilizer at planting or after pruning (5 years), or splitting the application into a 20/20 application at planting (spot application) and applying the remaining fertilizer at pruning (either 20 or 60 kg of P and K by broadcast application). At cleafelling age (15 years) topsoil (0-100 mm), forest floor litter, stemwood, stembark and foliar samples were collected and chemically analysed to determine the impact of PK fertilization on the nutrient content thereof at rotation age. The fate of the K fertilizer was determined by applying the Rb/K reverse tracer technique, whereby the amount of Rb in the plants was related to the naturally occurring Rb in the soil and used as a “tag” of native soil-K.

Tree survival was not affected by the application of the PK fertilizer. However, the PK fertilizer reduced the coefficient of variation in DBH from 23% to 20%. The application of 80/80 kg P and K per hectare increased DBH from 20.0 to 23.0 cm; tree height from 19.6 to 20.4 m; and volume production by 83 m^3 ha^{-1} (29%). However, the application of 80/80 fertilizer decreased basic wood density by 3% from 0.372 to 0.361 g cm^{-3}. The positive volume growth response was not offset by the slight decrease in timber density as 28 t ha^{-1} (26%) more fibre was produced.

The effect of P fertilizer was more pronounced at the end of the rotation than the effect of K fertilizer. Compared to the control the application of 80/80 PK fertilizer increased the concentration of plant available P (Bray II) in the first 100 mm of the topsoil from 3 mg kg^{-1} to 12 mg kg^{-1} and increased the foliar P level significantly to 0.13%. The foliar P level as well as the concentration of plant available P in the topsoil increased when the fertilizer was applied closer to rotation age. The split application of either 40/40 or 80/80 PK fertilizer increased the stemwood P concentration by 50%, compared to the 23 mg kg^{-1} P that was found on the control plots. Application of the 40/40 and 80/80 amounts of fertilizer increased the mass of the forest floor litter layer by 27 300 kg ha^{-1} (35%) compared to the control. The P and K content (kg ha^{-1}) in the forest floor litter layer, stemwood and stembark were significantly greater on the fertilized plots.

Results from the Rb/K reverse tracer technique showed that none of the applied K remained in the soil at the end of the rotation. In the forest floor litter, 4% of the fertilizer K was found on plots where 80/80 P and K were applied. The results confirmed that within the various plant components fertilizer K contributed more to the amount of K in the wood (28.7%) than to the amount of K in the bark (19.5%) or the foliage (8.5%).

In trial R128, a long-term phosphorus (P) and potassium (K) fertilizer trial, established on gabbro-derived soil, the growth and foliar nutrient response of six-year-old *P. patula* as well as the chemical changes that occurred within the topsoil and forest floor litter were studied in the presence and absence of previously applied (residual) fertilizer. In 1989, when the third rotation (3R) trees were six years old, 75 kg elemental P and K per ha, respectively, was applied to one half of 52 plots as a foundation for a factorial design with applications of 0, 25 and 50 kg P and K per ha, which was superimposed on the 3R trial plots in the following fourth rotation (4R). The 50 kg ha^{-1} applications consisted of two applications of 25 kg ha^{-1}, the first as a spot application at planting in 1999 and the second as a broadcast application after pruning at age 5 years in 2004.

Fifteen years after the initial fertilizer application, 41 kg ha^{-1} more 0.5 M H_2SO_4 extracted $P_{inorganic}$ + $P_{organic}$ was found in the topsoil of the fertilised plots than in the control plots. The residual fertilizer increased the P concentration of the various needle components and had no effect on any other components or nutrients in the organic matter. Furthermore, the results indicated that in the presence of residual fertilizer, the re-application of only K fertilizer increased volume by 27 m^3 ha^{-1} (21.5%) at age seven years. This was statistically similar to the 25.2 m^3 ha^{-1} (20%) increase from a combined PK application. The maximum volume increment over a two year period following post pruning fertilization was achieved when the foliar nutrient concentrations of both nutrients were above the values of 0.14% for P and 0.50% for K, respectively.

The combined results supported the current fertilizer prescription to apply P and K fertilizer to previously unfertilized stands. The changes in nutrient concentration and basic wood density with tree height showed the importance to sample at more than one height to obtain an accurate average or total value for each tree. The results from the present study suggested that increased production will lead to increased nutrient removal, threatening long-term site productivity unless both P and K fertilizer are applied to gabbro-derived soils, which have not received any PK fertilizer application previously. A greater proportion of the K nutrient pool compared to the P nutrient pool was removed from the site during harvesting. The residual fertilizer effects highlighted the importance of knowing the fertilizer application history of a site when new fertilizer trials are established. Furthermore, the results indicated that enough residual P fertilizer remained available to supply the early P demand of the next crop, suggesting that the amount of P fertilizer applied to successive rotations can be reduced. Thus, the re-application of inorganic K fertilizer to the subsequent rotations and conservation of organic material to ensure long-term P cycling will be of utmost importance to produce timber sustainably on the gabbro-derived soils at Usutu. The foliar values for P and K as well as the respective nutrient ratios can be used to monitor the responses to the revised fertilizer prescriptions.

Proverbs 2

Good Things Come From Wisdom

1 My son, accept my words.
Store up my commands inside you.
2 Let your ears listen to wisdom.
Apply your heart to understanding.
3 Call out for the ability to be wise.
Cry out for understanding.
4 Look for it as you would look for silver.
Search for it as you would search for hidden treasure.
5 Then you will understand how to have respect for the Lord.
You will find out how to know God.
6 The Lord gives wisdom.
Knowledge and understanding come from his mouth.

New International Reader's Version Bible

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LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

Symbol	Description
Al	Aluminium
BAI	Basal area increment
Ca	Calcium
CEC	Cation exchange capacity
DBH	Diameter at breast height (1.3 m above soil surface)
df	Degrees of freedom
ddf	Denominator degrees of freedom
Fe	Iron
F-layer	Fermentation layer of forest floor (Oe horizon)
H-layer	Humus layer of forest floor (Oa horizon)
HT	Tree height
H	Hydrogen
K	Potassium
L-layer	Litter layer of forest floor (Oi horizon)
LOI	Loss on ignition
LSD	Least significant difference
Mg	Magnesium
Mn	Manganese
N	Nitrogen
Na	Sodium
ndf	Numerator degrees of freedom
O	Oxygen
OC	Organic carbon
P	Phosphorus
P_i	Inorganic phosphorus
P_o	Organic phosphorus
P_{i+o}	Inorganic and organic phosphorus
Rb	Rubidium
RelHt	Relative tree height (0 at base, 1 at top)
REML	Residual (or restricted) maximum likelihood
SE	Standard error
S-value	Sum of exchangeable cations
3R or 4R	Third rotation or fourth rotation

CONTENTS

CHAPTER 1

INTRODUCTION

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

Geochemical cycling of nutrients is particularly critical for the maintenance and growth of plantation forests on sites like those found at Usutu. These sites are characterised by a high level of leaching, poor 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 (decrease pH mostly) over time (Scholes, 2002). The plant nutritional problems that are associated with acid soil infertility include: reduced levels of N and S; reduced amounts of K, Ca and Mg, through displacement and leaching; reduced availability of P and Mo; increased solubility of metal cations and imbalances, or toxicities, of Al, Mn and sometimes Fe (Barnard and Du Preez, 2004).

Both Evans (1999a, 1999b) and Morris (1986) reported that on a small part of the Usutu Forest, characterized by phosphate-poor soils derived from very slow-weathering gabbro, a volume growth decline had occurred between first and second rotations. This was the first widespread occurrence of a subsequent rotation growth decline to be documented outside the *P. radiata* plantations of South Australia and Victoria (Morris, 1986).

A specific site characteristic namely, soil parent material, was identified as a reason for the 20 percent decline in second rotation productivity (Morris, 1986; 2003; Morris and Smith, 2002). This decline was associated with developing phosphorus (P) and potassium (K) deficiencies on soils derived from gabbro. The evidence to substantiate this statement was:

1. Gabbro-derived soils had a small "available" P pool and fixed P more strongly.

2. Supply of K from non-exchangeable reserves in gabbro-derived soils was found to be inferior to that from granite-derived soils.
3. Needle P and K concentrations were lower in stands located on gabbro-derived soils.
4. Responses to P and K fertilizer, applied at time of planting, were consistently larger on the gabbro-derived soils.

The finding regarding the P-status of the soil was corroborated by Bainbridge *et al.* (1995) and Henry and Smith (2006) who found that phosphorus (P) deficiency is the most widespread and economically important nutrient deficiency in the higher-rainfall eastern parts of southern Africa.

As a result of his study, Morris (1986) determined that changes in management practices were required to maintain productivity of *P. patula* on the gabbro-derived soils in future rotations. He focused his studies on a fertilizer regime to correct P and K deficiencies (Morris, 1987a; 1994a). These studies had a favourable effect as both Evans (1993, 1995 and 2003) and Morris (2003) reported that P and K fertilizer applications to gabbro-derived soils have corrected an otherwise decline in yield. In order to study the effect of fertilizer application to these sites in more detail, additional trials were established with specific focus on optimum amounts of P and K fertilizer, time of application and magnitude and duration of responses that may be expected in the first and subsequently fertilized rotations.

The magnitude and duration of responses to fertilizer are of specific importance as the plant availability of applied fertilizer P tends to be rapidly reduced through reactions with soil components (Bainbridge *et al.*, 1995) and only a small fraction of the P supplied in the fertilizer is normally used by the plants (Fransson and Bergkvist, 2000). However, repeated P fertilisation can lead to P accumulation in the soil (Fransson and Bergkvist, 2000), which might cause adverse environmental effects e.g. eutrophication through losses of dissolved P to groundwater and surface water (Tunney *et al.*, 1997; Payn and Clough, 1989). The probability of this occurring at the Usutu-sites is very low, because of the high buffer capacity of the highly weathered clay soils with high organic matter (Bainbridge *et al.*, 1995).

Previous fertilizer studies have shown that once phosphate requirements have been met, responses to N and K may also occur on many strongly leached forestry soils in the summer rainfall areas (Morris, 1986; Donald *et al.,* 1987; Schutz and De Villiers, 1987;

Herbert and Schönau, 1989; Herbert and Schönau, 1990; Carlson *et al.*, 2000; Carlson, 2000; Campion and Du Toit, 2003). In a large number of trials it was observed that a significant P by K interaction occurred (Grey *et al.*, 1979; Schönau, 1983; Morris, 1986; Donald *et al.*, 1987; Noble and Ramsden, 1992; Carlson *et al.*, 2000) and that the application of K without P resulted in a growth reduction (Donald *et al.*, 1987). Foliar K levels of *P. patula* were significantly correlated with tree growth in studies by Grey *et al.* (1979) and Morris (2003). The soil characteristics of a specific site, and geology by implication, also influenced the response to K (Crous *et al*., 1995; Carlson, 2000; Carlson *et al.* 2000; Campion and Du Toit, 2003; Morris, 2003). Furthermore, the growth response to the application of K was found to be linked to the stand age (Morris, 2003; Herbert and Schönau, 1990), with the greatest responses to K occurring when applied in younger stands, which is consistent with the timing of the peak rate of accretion of this nutrient into organic sinks (Morris, 2003; Herbert and Schönau, 1990).

In his study on soil fertility and long term production of *P. patula* in Swaziland, Morris (1986) indicated a need for improving knowledge of the fundamental cycling processes that could affect nutrient deficiencies. These were the rate of supply of nutrients from slowly available soil reserves, particularly in the subsoil, and the rate of cycling of nutrients through the forest floor.

As part of the continuation of research on the application of PK fertilizer to the gabbro derived soils at Usutu, one trial (R128) was specifically designed by Morris to determine if the PK fertilizer applied in the third rotation (3R) has any residual benefit that would allow a reduction in PK fertilizer application to the next crop. This is a unique trial in forestry research, because it was established with the purpose of measuring fertilizer responses over at least two rotations. In plantation forestry, few site characteristics have been studied in the long term (Nambiar, 1999). Furthermore, global research activity on fertilization of short-rotation softwood plantations has decreased since the mid 1990's as research funding decreased and there was a shift towards a focus on hardwoods rather than softwoods.

Trial R128 was established in 1989, when the 3R *P. patula* trees were six years old, on a site that had never been fertilized before (**Figure 1.1**). A mixture containing 75 kg ha^{-1} elemental P and K fertilizer each was applied to one half of 52 plots as the foundation for a 3 x 3 P and K factorial trial, which was to be superimposed on the 3R trial plots in the following fourth rotation (4R). Thus, in the fourth rotation the growth response to various amounts (0, 25 and 50 kg ha^{-1}) of P and K on their own, and in combination with each other, could be assessed in the presence and absence of residual fertilizer as one half of each main plot of the 4R trial received a PK application in the previous rotation. A schematic trial map is shown in **Appendix 1**, **Figure A1.1**.

In June 2004 it was realised that trial R128 provided the last opportunity to study the residual fertilizer effect at Usutu, since all the commercial plantation areas on the gabbro-derived soils have received at least one application of PK fertilizer. Thus, the study reported on in the first part of the thesis commenced. Samples from the live foliage, senesced needles, forest floor litter and topsoil were collected before the after-pruning fertilizer was applied. During June of the following year live foliage and senesced needles were again sampled to ascertain the fertilizer effects. Unfortunately, at the end of the 3R, no samples were collected from the trial, but the historic tree measurement data were available. These data were analysed for the first time by the author and the results were included in this thesis.

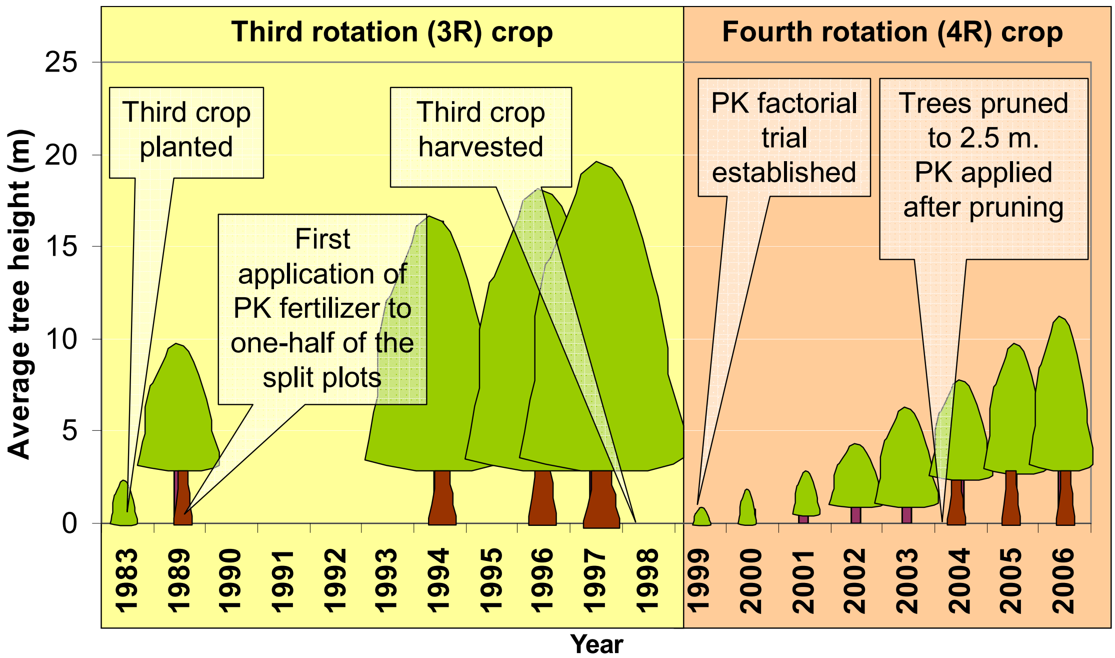


Figure 1.1: Schematic representation of the history of trial R128, a P by K by residual PK fertilizer trial at Usutu. Each tree indicates when trial measurements occurred.

Because no information was available on the influence that PK fertilizer had on the actual timber density or on the nutrient content of the bark or timber at the time of harvesting, the amounts of nutrients that were removed from the R128 trial site at the end of the 3R could not be ascertained. Furthermore, the information from trial R128 was insufficient to determine the period over which a response from the residual P could be expected. In trial R128 the forest floor litter and soil sampling was conducted some years after the harvesting of the 3R crop. This posed the question of how much of the nutrients were laterally re-distributed through the harvest residue. In order to investigate the effects of PK fertilizer on timber density and nutrient content of the components that are exported during harvesting, data from another PK fertilizer trial in block A at Usutu, R155 was used for the second part of the study. This trial was sampled during April 2007 when it reached clearfelling age (15 years) (**Figure 1.2**).

In trial R155, a PK fertilizer by weeding trial, with four replications per treatment, four levels of P and K (0/0; 20/20, 40/40 and 80/80 kg element per hectare) were applied. The fertilizer applications occurred at two different stages of stand development, namely all at planting, all at pruning (age 5 years) or as a split application where 20 kg of P and K per hectare, respectively, was applied at plating and the remaining fertilizer applied after pruning (Morris, 1994b). Significant growth response to different amounts of fertilizer and timing of application were observed close to rotation age (Crous *et al.*, 2005a). Thus, the effects of fertilization could be observed over a range of PK amounts. Furthermore, the results from this trial could be used to predict the amounts of nutrients which were removed from the site during harvesting.

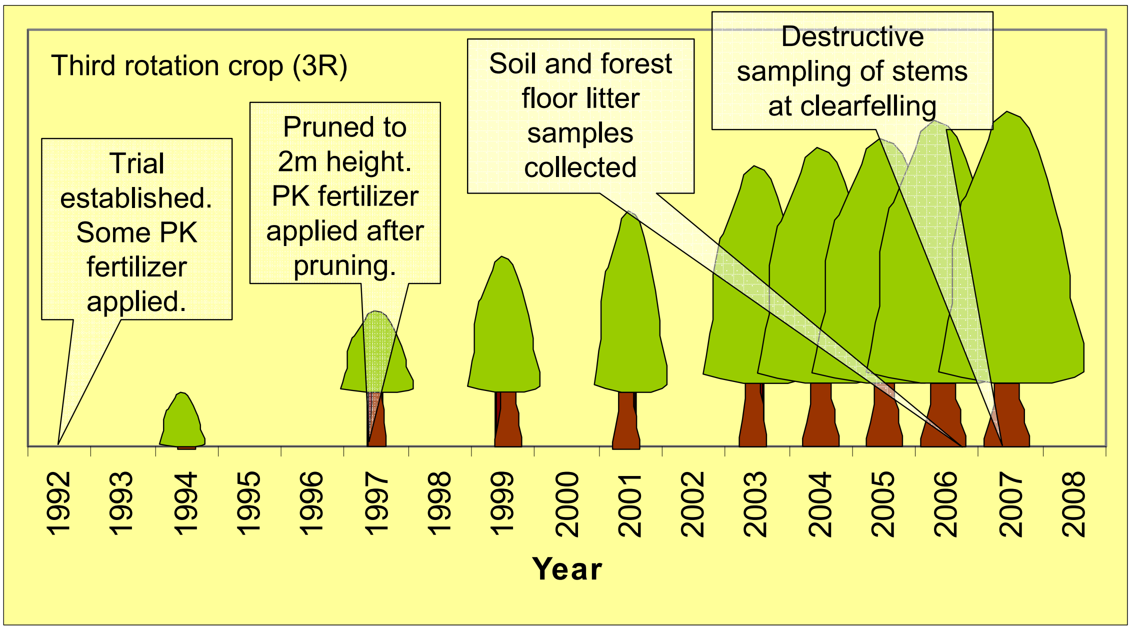


Figure 1.2: Schematic representation of the history of trial R155, a PK fertilizer amount by time of application trial at Usutu. Each tree indicates when trial measurements occurred.

By combining the estimates of nutrient removal from a fertilised site (R155) with the results from trial (R128), predictions could be made about the effect of nutrient removal during crop harvest on the nutrient pools of the different components, which can be used to adjust fertilizer prescriptions for future rotations.

1.1 CONTRIBUTIONS TO SCIENCE

As the human population grows a greater demand for resources is developing, while land availability is decreasing. Timber is a renewable resource that can be grown on land that is not suitable for agriculture as the nutrient demand from plantation trees is lower (trees can utilize nutrients and water to a greater soil depth) than from agricultural crops. Furthermore, plantations can be established on terrain that is unsuitable for agriculture. At the Usutu the trees are grown on short rotations, on soils with relatively poor nutrient status, it therefore provides an excellent opportunity to study the effects of nutrient removal in timber on the tree growth over successive rotations. Furthermore, on sites where developing nutrient deficiencies have been identified previously, the effects of remedial fertilization and adjustments to fertilizer prescriptions for successively fertilized rotations can be studied. The ever increasing cost of world commodities, including fertilizers, will necessitate the optimal application of fertilizer to continue producing timber at a competitive price. The results of this present study can be extrapolated to other forestry areas across the world, and more specifically other forestry areas in southern Africa located on soils derived from basic geology (dolerite, diabase, basalts and other igneous rocks) having similar low P and K contents, where there is a drive to increase production from shorter rotations of tree crops. However, results from one site should not be extrapolated to other sites without appropriate validation (Turner *et al.*, 2001). Many scientists will argue that forest crops under intensive management may behave similarly to agricultural systems. Thus, some of these results might even be applicable to agricultural crops. The increased interest in utilizing tree tops, branches and foliage as bio fuel will lead to increased nutrient removal from plantation sites. Thus, it is necessary to develop models to estimate the nutrient removal in these previously unutilized biomass components in order to do cost-benefit-analyses and to predict possible impacts on nutrient supply as well as the impact on successive tree growth.

Focussing specifically on the Usutu plantation, the main aim of this study was to enhance the knowledge regarding the nutrient requirements of *P. patula* on gabbro-derived soils, to study the interaction between P and K fertilizer and to determine the fate of the applied P and K fertilizers. The growth response to the PK factorial application of fertilizer in the fourth rotation in the presence and absence of residual fertilizer applied in the third rotation of trial R128 indicated that on sites that are fertilized for the first time both P and K fertilizer should be applied. However, on sites where P and K fertilizer was previously applied, a significant amount of residual P fertilizer remained in the topsoil, forest floor litter and foliage. Thus the results indicated that the application of additional K to subsequent rotations will become more important. Correlations between growth and foliar nutrient concentrations were used to investigate critical foliar nutrient concentrations for P and K for *P. patula* trees in the Usutu plantation. The applicability of critical foliar nutrient values in other forestry areas in southern Africa should be assessed in future studies.

The second part of the study, based on results obtained from trial R155 showed that increased amounts of P, K and other macro nutrients are removed from fertilised stands in stembark and stemwood. Furthermore, the Rb/K reverse tracer technique (Hafez and Stout, 1973) was applied for the first time in fertilizer research under southern African forestry conditions to study the fate of K-fertilizer and its distribution in the forest system. This was a substantial contribution to science as relatively little work has been done on the role of potassium in forestry. These results confirmed that a large proportion of the fertilizer-K was removed in the stemwood and stembark at harvesting. Thus the application of increased amounts of K to successive crops will be necessary in order to maintain production from these sites. Furthermore, the results from these two trials contributed substantially to increase the knowledge of nutrient cycling through the forest floor. A reduction in P fertilizer application to successive crops (without a loss in volume production) will lead to financial savings, because the P component comprises 80% of the current fertilizer cost. Furthermore, a lower phosphorus fertilizer usage will also have environmental benefits for planet earth and its human inhabitants, e.g. less risk of eutrophication, reduced contamination of scarce water resources and the conservation of limited phosphorus sources.

1.2 HYPOTHESES AND RESEARCH QUESTIONS

The objectives and associated key questions will be discussed separately for the two trials reported in this document.

Hypotheses 1: The application of P and K fertilizer to gabbro derived soils is necessary to sustain productivity on these sites.

Research questions:

- What was the effect of residual fertilizer on the growth rate on the trees?

- Did an increase in the amount of P and K fertilizer increase tree growth?
- What was the effect of using improved genetic material in the subsequent rotation on tree growth?

Hypotheses 2: The residual PK fertilizer that remained on the site from the application to trees in the third rotation has a positive effect on tree growth, nutrient content of the foliage, forest floor and topsoil in the subsequent rotation:

Research questions

- How much did the residual fertilizer change the amount and chemical composition of the organic material (foliage, litter layers)?
- Was there a difference in the nutrient content of the soil as a result of the residual fertilizer?
- If the P level increased, which P-fractions (organic or inorganic) in the soil were mostly affected?
- Were there significant interactions between tree growth, foliar nutrient and soil nutrient levels?

Hypotheses 3: Tree growth and foliar nutrient concentrations respond differently to the application of P and K to a gabbro-derived soil where P and K fertilizer were previously applied.

Research questions:

- Did the P, K or residual fertilizer increase the nutrient concentration or content of live foliage and senesced needles?
- Did the application of a single element cause a nutrient imbalance in the crop in the presence and absence of residual fertilizer respectively?
- What was the optimum amount and time of application of P and K fertilizer for a site that was fertilised for the first time and for a site that received PK fertilizer during the previous rotation in order to sustain optimum crop production?

Hypotheses 4: The application of PK fertilizer increase the stem taper; increase nutrient content of the stemwood and stembark; and decrease basic wood density along the tree stem.

Research questions:

- Is it possible to quantify and model the variability in macro nutrient content of a) stemwood and b) stembark in relation to relative tree height?

- How has the application of PK fertilizer affected the basic wood density, tree form and nutrient content in relation to relative tree height? Thus, are different models needed to estimate stem form and nutrient content of fertilised trees?

Hypotheses 5: Increasing amounts of PK fertilizer, especially when applied early in the rotation, increase wood production, but decrease basic wood density.

Research questions:

- Did the additional growth associated with the application of increasing amounts of PK fertilizer decrease the basic wood density?
- Was the decrease in density significant and what was the impact on total fibre yield associated with various amounts of PK fertilizer, applied at various times of stand development?

Hypotheses 6: The application of PK fertilizer to a gabbro-derived site increases the nutrient status of the topsoil, forest floor litter and trees at rotation age.

Research questions:

- How did the application of PK fertilizer affect the biomass of the trees and forest floor?
- What chemical changes occurred in the topsoil, live foliage and forest floor litter layer?
- Can the difference in nutrient content of a) stemwood and b) stembark be related to the amount of P and K fertilizer that was applied?

Hypotheses 7: A nutrient budget for gabbro-derived soils can be developed, which can be used to model growth responses to successive fertilizer applications. More nutrients are removed in timber from fertilised stands than unfertilised stands.

Research questions:

- What is the estimated size of the various P and K pools in relation to fertilisation treatments?
- What effect will the additional nutrient removal as a result of increased timber production have on depletion of the nutrient pool in general and the applied fertilizer in particular?
- How can the information on the P and K nutrient pools be used to model growth response to successive fertilizer applications?

Hypotheses 8: A significant proportion of K in the forest floor, soil and tree foliage is supplied by K fertilizer.

Research questions:

- Can the Rb/K reverse tracer technique be used under Southern African forestry conditions? If the technique does not work, what are the reasons for failure?
- If the technique works. What proportion of K in the topsoil, litter, and foliage, is related to K fertilizer?
- Compared to virgin soil, from unplanted, unfertilised areas close to the stand, is there evidence that fertilizer K moved from treated plots into control plots?
- If lateral movement of K did take place, what amount of contamination occurred over a 15 year period?

1.3 STRUCTURE OF THE THESIS

The structure of the thesis is presented in **Figure 1.3**. This chapter supplies a background to the studies, the envisaged contribution to science as well as the hypotheses and key questions to be answered. In Chapter 2 a brief overview of phosphorus and potassium, the two major plant nutrients applied in this trial, is given. Furthermore, a literature review of results from earlier studies provides a background to the current study. The results from the current study are presented in Chapters 3 to 9, which have been written as scientific papers. Therefore, some material has been duplicated in the thesis. Three of these papers have been published (Crous *et al.*, 2007a, 2007b and 2008a), while the other four are in preparation for publication (**Figure 1.3**). Fertilizer has sometimes been spelled as “fertiliser” for publication purposes.

The results from the first trial (R128) that was studied, the P by K by residual PK fertilizer trial, are presented in Chapters 3 to 5. Chapter 3 compares the early results of the fourth rotation with that in the third rotation. Furthermore, the early growth results of the 4R crop related to the application of various amounts of P and K, in different combinations, in the presence and absence of residual PK fertilizer is discussed in Chapter 3. The changes related to the residual PK fertilizer in the trees, topsoil and forest floor litter of the fourth rotation crop are discussed in Chapter 4. These results are based on intensive sampling within a selection of trial plots. In Chapter 5, results from the complete P by K by residual PK fertilizer trial are presented and interactions between foliar nutrient levels and growth responses are investigated.

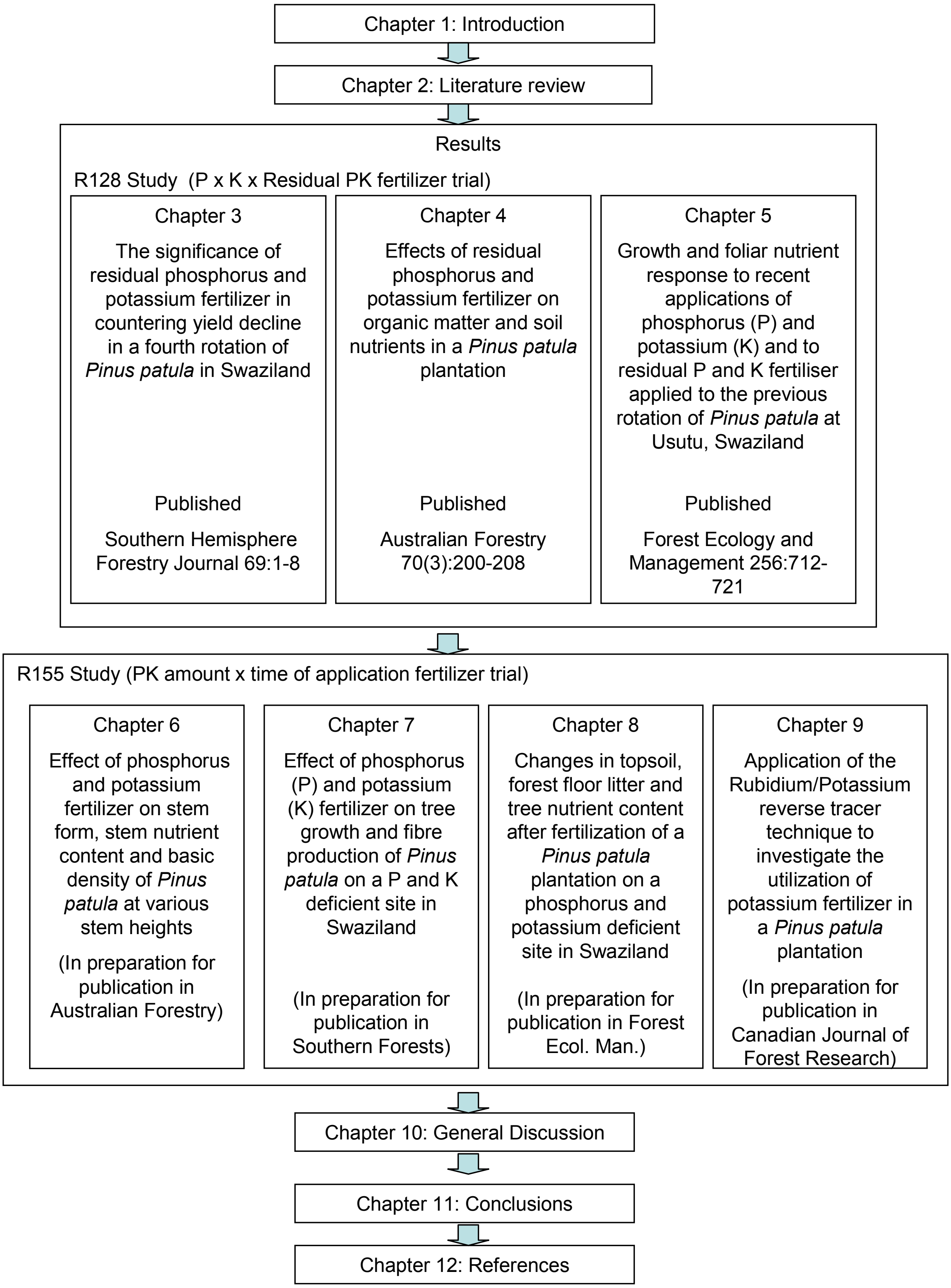


Figure 1.3: Outline of thesis structure.

Results from the second trial (R155), a PK amount by time of application trial, sampled at rotation age are presented in Chapters 6 to 9. Thirty-two trees from selected plots were intensively sampled to determine the effects of fertilization on stem form, stemwood basic density as well as nutrient concentrations and the distribution thereof within the stemwood and stembark. These results are presented in Chapter 6. Effects of the PK fertilizer treatments on tree growth and fibre production in the complete trial are presented in Chapter 7. Chapter 8 reports on the nutrient changes that occurred in the topsoil, forest floor and trees. From the results the size of nutrient pools was estimated on fertilized and unfertilized plots for this site. In Chapter 9 the utilization of the K-fertilizer in particular is investigated with the Rb/K reverse tracer technique. The hypotheses, research questions and general findings from the two trials are discussed in Chapter 10. The overall conclusions are presented in Chapter 11. A list of all publications referred to in this thesis is presented in Chapter 12. Additional information is supplied in the Appendices.

CHAPTER 2

LITERATURE REVIEW

2.1 PHOSPHORUS (P)

2.1.1 The phosphorus cycle

Phosphorus, the element, does not occur by itself in nature. It is always combined with other elements to form phosphates, of which some can be very complex. The word “phosphorus” will be used in this document rather than identifying the particular phosphate. Phosphorus is not a rare element. It is eleventh in order of abundance in the earth’s crust, but the concentration in many rocks is very small (Johnston and Steén, 2000).

Although phosphorus is one of the macro-nutrients essential for plant growth, it is taken up in much smaller amounts than nitrogen or potassium, but its efficiency in soil is very low (Barnard and Du Preez, 2004; FSSA, 1997). Generally virgin soils in South Africa are low in P (Barnard and Du Preez, 2004; Henry and Smith, 2006), with an average total P content of only 0.059% in the topsoil. The phosphate available to plants is even less than this amount (Saayman, 1993). It is thus not surprising that after N, P is one of the most frequently limiting macronutrients for plant growth (Schachtman *et al.*, 1998; Bucher, 2007).

Soluble phosphate from weathering, mineralization or fertilisation is bound to clay particles. As a result the total P content of soil increases with an increase in clay content, if all other factors remain constant. Distribution through the profile is influenced by textural variation, degree of recycling and fertilisation. Soils that formed from homogenous material normally have very low P content in the subsoil because of gradual leaching losses, with higher P content in the topsoil as a result of plant uptake and recycling (Saayman, 1993).

The phosphorus in the soil is composed of roughly 50% inorganic or mineral P, 50% organic P (but can vary between 10 and 90%, depending on organic matter content of the soil) and P in the soil solution (Sharpley, 2000).

Organic forms of P are found in humus and other organic material in the form of inositol phosphates (2 to 50%), phospholipids (1 to 5%), nucleic acids (0.2 to 2.5%) and the forms in which the balance occurs are still unknown (Stevenson, 1982). Plants are unable to absorb organic forms of phosphorus. Phosphorus in organic materials is released by a mineralization process involving soil organisms. The activity of these microbes is highly influenced by soil moisture and temperature, with the highest activity found in warm, well-drained soils. The advantage of organic P is that the phosphorus release through mineralization is slow and somewhat in synchrony with plant needs. This slow release allows plant roots to take up phosphorus before the soil fixation reactions remove it from the available pool. In general, the contribution by mineralization to plant available phosphorus is small, because initial levels are normally low and plant uptake is only one possible fate of the mineralized phosphorus (Brady and Weil, 1996; Saayman, 1993). However, Stevenson (1982) as well as Stewart and Tiessen (1987) reported that amounts and mineralization of organic P is of special importance for the availability of soil P in tropical soils. In these tropical soils pedogenesis has normally reached advanced stages and most of the P from primary minerals has been converted to organic P forms or became occluded in secondary aluminium and iron associated inorganic P forms. Enhanced microbial action in the warmer soils, particularly where distinct wet and dry cycles occur, increases the mineralization of organic P (Sharpley, 2000). Previous studies have shown that relatively large amounts of P (in organic form) are contained in the forest floor litter layer (**Table 2.1**).

Table 2.1: Amount of nutrients contained in the forest floor litter of various *P. patula* compartments in southern Africa.

Regime	Age (years)	Biomass ($t\ ha^{-1}$)	Nutrient content ($kg\ ha^{-1}$) N	P	K	Ca	Mg	Reference
Sawtimber	17 - 37	-	588.9	32.5	38.5	103.2	28.2	Ross *et al.*, 2005
Sawtimber	29	-	614.0	24.4	31.9	40.0	24.9	Carlson and Allan, 2001
Sawtimber	42	-	1442.0	103.0	692.0	19.0	455.0	Dames *et al.*, 2002
Sawtimber	-	-	1045.0	130.0	82.0	229.0	65.0	Schutz, 1990 cited in Dames *et al.*, 2002
Pulpwood	5	54.2	228.1	65.7	27.9	76.1	16.2	Crous *et al.*, 2007b
Pulpwood	11 - 25	-	372.9	22.2	39.4	194.9	45.2	Ross *et al.*, 2005
Pulpwood	12-14 (1R)	43.6	572.4	30.5	33.6	82.9	42.1	Morris, 1986; 1995
Pulpwood	12-14 (2R)	59.9	787.4	41.9	45.2	108.6	55.6	Morris, 1986; 1995
Pulpwood	15 (3R)	77.2	842.0	24.9	39.4	167.0	34.8	Present study (R155) control plots

Inorganic phosphorus occurs in various forms in the soil. As primary phosphate minerals, apatite is the most common phosphate containing mineral in almost all igneous rocks and metamorphic rocks. This mineral group consists of calcium phosphate together with fluorine, chlorine, hydroxyl or carbonate in various amounts (Van der Watt and Van

Rooyen, 1995). It is very resistant to weathering and occurs mainly in the form of small crystals in the silt and clay fractions of soils. This fraction normally contributes very little to the total amount of P in the soil. The weathering of igneous rocks reduces the amount of apatite and promotes the formation of secondary phosphate minerals e.g. Variscite [$Al(OH)_2H_2PO_4$] and Strengite [$Fe(OH)_2H_2PO_4$] as orthophosphate is adsorbed to the mineral surfaces of clays that contain aluminium or iron oxides.

Only a very small portion (less than 0.01%) of the total P in the soil is found in the soil solution, mostly as orthophosphate anions ($H_2PO_4^-$). This is the main form of phosphorus that plants take up (Bidwell, 1979; Saayman, 1993). The solution P concentration (0.02 to 0.08 ppm) is “controlled” by the solubility of inorganic phosphorus minerals, which are highly dependent on solution pH. Phosphorus availability in most soils is normally at a maximum in the pH range 5.5 to 6.5. Mineralization of organic matter can also supply solution phosphorus (Saayman, 1993).

Associations between arbuscular mycorrhizal fungi and plants, as in the case of pines, can improve the uptake of phosphorus from the soil by three to five times (Schachtman *et al.*, 1998) through various mechanisms. The external hyphae of the arbuscular mycorrhizae can extend much further from the root to access a greater volume of undepleted soil. The diameter of the hyphae is also much smaller than most root hairs, allowing access to soil pores that can not be explored by roots. Furthermore, mycorrhizal colonization can stimulate root branching in the host plant that increases the root surface area. P availability can be enhanced through biochemical and physiological characteristics of mycorrhizae as it can acidify the rhizosphere, which can mobilize P in neutral or calcareous soil; excrete chelating agents (citric acid and siderophors) to enhance bioavailable P in acidic soils where P is bound to Fe or Al; and produce phosphatases which have the ability to mobilize P from organic material (Schachtman *et al.*, 1998; Grant *et al.*, 2005; Bucher, 2007).

Phosphate losses from the soil normally occur through harvesting of crops, leaching (but this is only significant in sand and peat soils) erosion and solution in runoff from soil with a very high phosphate content (Saayman, 1993). Morris (1986, 1992) estimated that 45 kg ha^{-1} P is removed in harvest logs over an 18 year rotation with *P. patula* at Usutu. However, values of between 5 to 285 kg ha^{-1} P have been reported (**Table 2.2**). The only net addition of phosphorus in practice is normally as a result of organic or inorganic fertilisation (Saayman, 1993).

The mineral sources of P fertilizer are limited. There is concern that the exploitation of this non-renewable resource to meet current demand is not sustainable. It is predicted that should usage of P fertilizer continue to grow at recent rates, known reserves will only last for the next 100 years (Stevenson and Cole, 1999 in Cardoso, 2002) to 250 years (Johnston and Steén, 2000). These reserves are deposits which can currently be exploited in an economically viable way. However, there are other phosphorus resources (potential reserves), which could be used in future, subject to advances in processing technology or value of the finished product. If these known potential reserves are taken into account, the forecast may be as long as 600 to 1000 years. However large or small the reserves might be, they are finite and must be used efficiently (Johnston and Steén, 2000).

Table 2.2: Amount of nutrients contained in the bole (stemwood and stembark) of various pine species across the world.

Species	Age (years)	Biomass	Nutrient content (kg ha^{-1})					Reference
		(t ha^{-1})	N	P	K	Ca	Mg	
P. patula	15	123	148	6	65	109	27	Present study control plots
P. patula	16	186	174	47	151	110	49	Morris, 1986
P. patula	18	160	194	9	73	166	71	Germishuizen ,1979; cited in Morris, 1986
P. patula	28	117	164	21	45	65	35	Carlson and Allen, 2001
P. patula	25	192	967	158	234	966	119	Singh, 1982
P. patula	34	381	1911	285	478	2101	875	Singh, 1982
P. radiata	29	370	217	31	285	221	66	Madgwick and Webber, 1987
P. radiata	clearfell	143	189	26	200	184	70	Balneaves and Dyck, 1992
P. radiata	31	-	337	38	439	153	107	Payn and Clinton, 2005
P. radiata	32	-	187	28	198	183	69	Payn and Clinton, 2005
P. radiata	26	-	136	22	168	126	97	Payn and Clinton, 2005
P. radiata	27	-	187	36	302	237	80	Payn and Clinton, 2005
P. radiata	42	-	128	38	218	233	73	Payn and Clinton, 2005
P. taeda	22	118	168	17	87	114	31	Rubilar, 2003
P. taeda	19	116	76	8	70	91	31	Rubilar, 2003
P. taeda	22	69	61	5	38	56	15	Tew *et al*., 1986
P. taeda	30	119	123	10	73	137	-	Johnson, 1983
P. elliottii	29	206	189	11	63	170	65	Smith *et. al*., 2008
P. elliottii	clearfell	57	59	5	20	80	17	Riekerk, 1983

About 85% of the world P production comes from sedimentary deposits, which are derived from small particles compacted to a rock-like consistency. The remaining 15% comes from igneous rocks of volcanic origin (Johnston, 2000). Commercially important P deposits in South Africa are confined to the igneous and marine sedimentary geological environments, although the latter are limited. Roughly 95% of the country's production comes from the Phalaborwa Complex, which is particularly insoluble and has proved elusive to technologies other than strong acids for increasing its bioavailablity (Barnard and Du Preez, 2004). It is estimated that this reserve produced 2.8 million tonnes of rock phosphate in 1999, which was approximately 2% of the total world production (Johnston and Steén, 2000). The unitary price of P in fertilizers in South Africa is the highest of all nutrients (Henry and Smith, 2006).

A schematic representation of phosphorus sources and interactions between them in the phosphorus cycle is represented graphically in **Figure 2.1**.

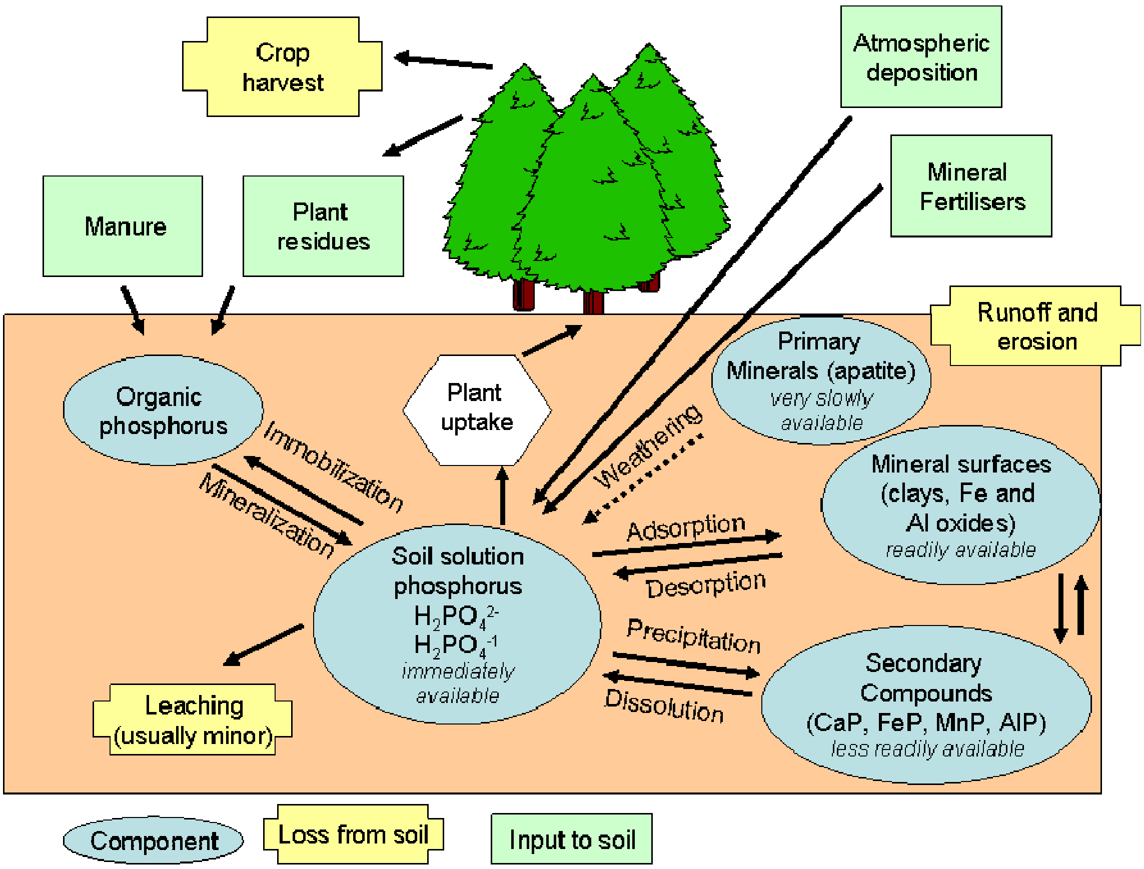


Figure 2.1: The phosphorus cycle. (After "The phosphorus cycle", no date; Johnston, 2000; Sharpley, 2000).

2.1.2 Role in plants

Phosphorus is found in organic compounds (e.g. adenosine triphosphate [ATP], adenosine diphosphate [ADP], deoxyribonucleic acid [DNA], phospholipids, and others) and plant structures. These organic compounds play an important part in the energy-transferring processes of the cell and are involved in many biosynthetic reactions. Therefore deficiency always results in restricted growth. It is also of special importance in cell division, root development and in the ripening of fruits and seeds. Because phosphorus is less mobile in the plant than nitrogen or potassium it cannot be as readily withdrawn from older tissues to benefit the young emerging needles (Binns *et al.*, 1980;

FSSA, 1997, Bidwell, 1979; Marschner, 1986). After uptake by the roots, phosphorus is transported to where it is needed and rapidly incorporated into those molecules for which there is a demand. Growing plants store very little of the simple phosphate ions taken up by the roots so there must be an ample supply in the soil (Johnston, 2000).

2.1.3 Deficiency symptoms in pines

The symptoms of P deficiency are similar for a large number of species: poor height growth coupled with much reduced needle length, reduced needle weight, and loss of older needles. This gives an overall effect of narrow, "thin" crowns in adult trees. There is no marked discoloration, but the needles have normally a dull green colour. Phosphorus deficiency normally develops gradually with a correspondingly slow decline in growth (Binns *et al.*, 1980; Will, 1985; Marschner, 1986). When P is limiting, plants will spend more energy increasing their root volume in order to increase the rate of uptake from the soil (Schachtman *et al.*, 1998).

2.1.4 Solubility of inorganic phosphorus in acid soil and the fate of applied P fertilizer

The plant availability of applied fertilizer P tends to be rapidly reduced through reactions with soil components (Bainbridge *et al.*, 1995; Henry and Smith, 2006). The particular types of reactions that fix phosphorus in relatively unavailable forms differ between soils and are closely related to soil pH (**Figure 2.2**) (Brady and Weil, 1996). Because soils found at Usutu have mostly low pH, only the reactions that occur in acid soils will be discussed.

In acid soils these reactions predominantly involve Al, Fe or Mn, either as dissolved ions, as oxides or as hydrous oxides. The hydrous oxides normally occur as coatings on soil particles and as interlayer precipitates in silicate clays.

The simplest type of phosphorus-fixation reaction to visualise is the simple reaction of $H_2PO_4^-$ ions with dissolved Fe^{3+}, Al^{3+} and Mn^{3+} ions to form insoluble hydroxyl phosphate precipitates. The reaction with aluminium is as follows:

$$\underset{}{Al^{3+}} + \underset{\text{(soluble)}}{H_2PO_4^-} + 2H_2O \leftrightarrow 2H^+ + \underset{\text{(insoluble)}}{Al(OH)_2H_2PO_4}$$

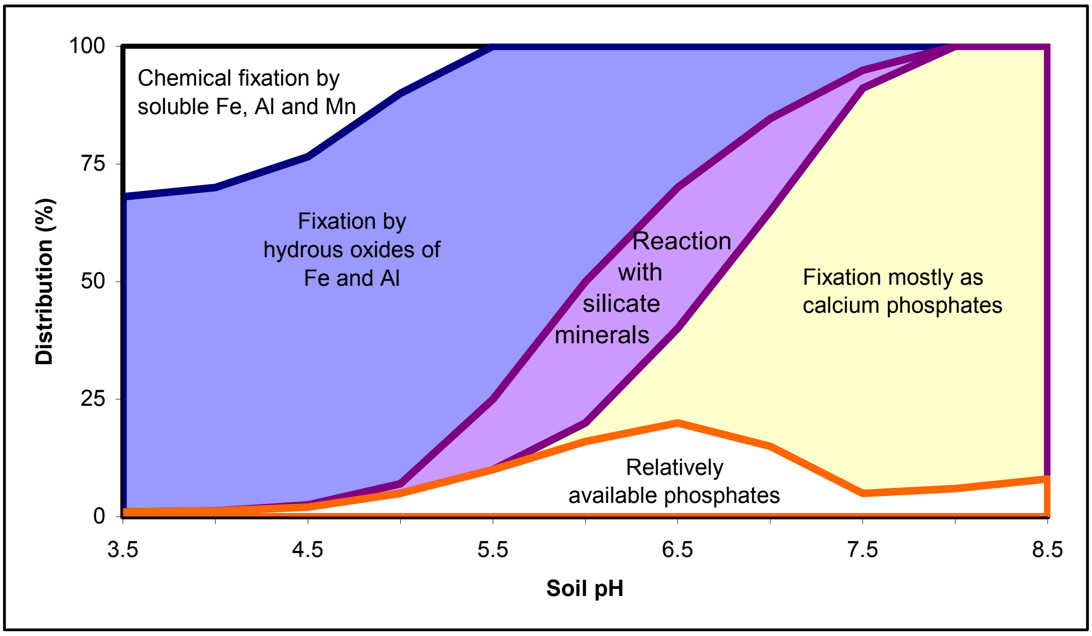


Figure 2.2: Inorganic fixation of added phosphates at various soil pH. Average conditions are postulated. The actual proportion of the P remaining in an available form will depend upon contact with the soil, time for reaction and other factors (after Brady and Weil, 1996).

Recently precipitated hydroxy phosphates are slightly soluble, because they have a large surface area exposed to the soil solution. This is known as the labile phosphorus, because it exhibits a high dissociation rate and can rapidly replenish decreases in solution phosphorus due to plant uptake. Over time the hydroxyl phosphates age and become less soluble. The phosphorus in them then becomes almost completely unavailable to most plants (Brady and Weil, 1996).

Most of the phosphorus fixation in acid soils probably occurs when $H_2PO_4^-$ ions react with, or become adsorbed to the surfaces of insoluble hydrous oxides of iron, aluminium and manganese, such as gibbsite ($Al_2O_3{\cdot}3H_2O$) and goethite ($Fe_2O_3{\cdot}3H_2O$). It is suggested that the reactions happen in several different ways, resulting in different degrees of phosphorus fixation. The $H_2PO_4^-$ anion may be attracted to positive charges that develop under acid conditions on the surfaces of iron and aluminium oxides and broken edges of kaolinite clays. The $H_2PO_4^-$ anions adsorbed by electrostatic attraction to these positively charged sites may be removed by certain other anions such as OH^-, SO_4^{2-} or organic acids (R-COO) in the reversible process of anion exchange. Alternatively, the phosphate ion may replace a structural hydroxyl to become chemically bound to the oxide (or clay) surface. This reaction is reversible, but normally binds the phosphate too tightly to allow it to be replaced by other anions. Thus, the availability of phosphate bound in this manner is very low. Over time, a second oxygen of the phosphate ion may replace a second hydroxyl, so that the phosphate becomes bound to two adjacent aluminium (or iron) atoms in the hydrous oxide surface. This reaction causes the phosphate to become an integral part of the oxide mineral and the likelihood of its release back to the soil solution is extremely small. Finally, as more time passes, the precipitation of additional iron or aluminium hydrous oxide may bury the phosphate deep inside the oxide particle. Such phosphate is termed *occluded* and is the least available form of phosphorus in most soils (Brady and Weil, 1996).

The reactions that rapidly and dramatically reduce the availability of the added phosphorus when a granule of soluble calcium monophosphate ($Ca(H_2PO_4)_2{\cdot}H_2O$) fertilizer is added to moist soil is as follows:

1. The $Ca(H_2PO_4)_2{\cdot}H_2O$ attracts water from the soil. In the moistened granule phosphoric acid is formed by the reaction:
   $Ca(H_2PO_4)_2{\cdot}H_2O + H_2O \rightarrow Ca(HPO_4)\ 2H_2O + H_3PO_4$
2. As more water is attracted, an H_3PO_4-laden solution with a pH of about 1.4 moves outward of the granule. This solution is sufficiently acid to dissolve and displace large quantities of iron, aluminium and manganese.
3. These ions promptly react with the phosphate to form low-solubility compounds as discussed in the previous paragraphs (Brady and Weil, 1996; Saayman, 1993).

2.1.5 Phosphorus-fixation capacity of soils

The phosphorus-fixation capacity of a soil may be conceptualised as the total number of sites on soil particle surfaces capable of reacting with phosphate ions. Soils that remove more than 350 mg P kg^{-1} (approximately 770 kg P ha^{-1}) from solution are generally classified as high phosphorus-fixing soils. These soils tend to maintain low phosphorus concentrations in the soil solution and runoff water (Brady and Weil, 1996).

One way of determining the phosphorus-fixing capacity of a particular soil is to shake a known quantity of the soil in a phosphorus solution of known concentration. After about 24 hours equilibrium will be approached and the concentration of phosphorus remaining in the solution (equilibrium phosphorus concentration [EPC]) can be determined. The difference between the initial and EPC represents the amount fixed by the soil. If this procedure is repeated for a series of solutions, with different initial phosphorus concentrations, the results can be plotted on a phosphorus-fixation curve and the maximum phosphorus-fixation capacity can be extrapolated from the value at which the curve levels off (**Figure 2.3**) (Brady and Weil, 1996).

Phosphorus fixation by soils is not easily reversible. However, some release of phosphorus to solution is likely to occur when soil, containing a portion of phosphorus in relatively soluble form, is exposed to water with a very low phosphorus concentration. This release (or desorption) is indicated in **Figure 2.3** where the curve for soil A crosses the zero fixation line and becomes negative. The solution concentration at which zero fixation occurs, is called the EPC_0. Such desorption helps to re-supply the soil solution phosphorus depleted by plant uptake (Brady and Weil, 1996).

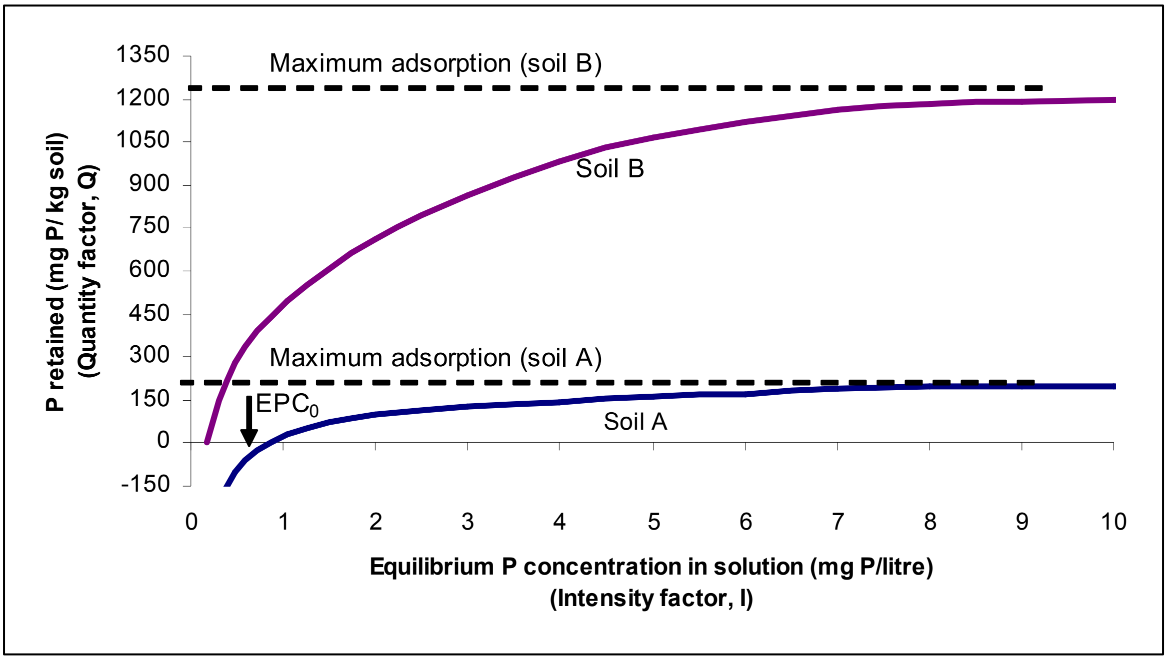


Figure 2.3: Phosphorus-fixation curves of soils with a high (soil A) and low (soil B) P-fixing capacity. (After Brady and Weil, 1996).

The phosphorus-fixation capacity of a soil is positively related to certain soil properties such as calcium carbonate content, clay content, soil pH and organic carbon content. Most of the compounds with which phosphorus reacts are in the finer soil fractions. Therefore phosphorus availability tends to be the lowest in soils with higher clay contents if all other characteristics (e.g. pH, mineralogy) are the same. Generally, clays with greater anion capacity have a greater affinity for phosphate ions. Thus, the types of clay minerals responsible for phosphorus fixation capacity are in order of increasing extent and degree of fixation:

2:1 clays << 1:1 clays < carbonate crystals < crystalline Al, Fe, Mn oxides < amorphous Al, Fe, Mn oxides, allophone

A relation exists between the above phosphorus-fixing components and soil taxonomy. Vertisols and Mollisols generally are dominated by 2:1 clays and have low phosphorus-fixing capacities. Iron and aluminium oxides are prominent in Ultisols and Oxisols. Therefore, these soils are capable of fixing P more strongly. Andisols are normally characterised by large quantities of amorphous oxides and allophone and have the greatest phosphorus-fixing capacity (Brady and Weil, 1996; Cross and Schlesinger, 1995).

The greatest degree of phosphorus fixation occurs at very low or very high soil pH. As pH increases from below 5 to about 6 the iron and aluminium phosphates become somewhat more soluble (Brady and Weil, 1996; Saayman, 1993; Bidwell, 1979). Organic matter generally has little capacity to fix phosphate ions strongly. Thus soils high in organic matter, especially active fractions of organic matter, generally exhibit relatively low levels of phosphorus fixation. Several mechanisms are responsible. Large humic molecules can adhere to the surfaces of clays and metal hydrous oxide particles, masking the phosphorus-fixation sites and preventing them from interacting with phosphorus ions in solution. Organic acids produced by plant roots and microbial decay can serve as organic anions that compete with phosphorus ions for fixation, because they are also attracted to positive charges and hydroxyls on the surfaces of clays and hydrous oxides. Through another mechanism certain organic acids can entrap reactive Al and Fe in stable organic complexes called chelates. Once chelated, these metals are unavailable for reaction with phosphorus ions in solution (Brady and Weil, 1996).

2.1.6 Determining the availability of different forms of soil phosphorus

As discussed previously, the soil P occurs in a series of “pools” with differing availability to plants. The readily available P can be estimated by different methods of soil analysis, but there is no universal extractant. The quantity of P extracted will vary with the reagent used. The preferred extractant would be one that can adequately distinguish between soils on the basis of the responsiveness of the crop to an application of fertilizer (Johnston, 2000).

Determination of the less readily available P is not routinely done. For specialised studies the less readily available P is normally determined with sequential extraction.

With this procedure phosphate is extracted from the soil with increasingly aggressive reagents (Johnstone, 2000; Cardoso, 2002). A method that is commonly used in the past 10 years (Daroub *et al*., 2000) to determine these empirical fractions was developed by Hedley *et al*. (1982). One advantage of the Hedley fractionations is that the same soil sample is sequentially treated with the various reagents. As a result, one can establish the proportion of labile, non-labile, non-occluded and occluded phosphorus in each sample. Furthermore, it extracts both inorganic P (P_i) and organic P (P_o). The reagents that are normally used are an anion exchange resin to extract bio-available inorganic P; $NaHCO_3$ to extract labile organic and inorganic P; *0.1M* NaOH to extract organic and inorganic P chemisorbed on Fe and Al oxides; *1.0M* HCl to extract P from insoluble apatite minerals and lastly total digestion with H_2SO_4 and H_2O_2 to determine residual P in insoluble minerals (**Table 2.3**). P fractionation has been proved to be critical in understanding P dynamics as the relative contribution of biological processes to the distribution of total soil phosphorus can be estimated by using the Hedley fractionation method (Hedley *et al.*, 1982; Cross and Schlesinger, 1995; Zhang *et al*., 2004).

Table 2.3: Flow chart of the fractionation of soil phosphate. From Hedley *et al.*, (1982); Cross and Schlesinger, (1995).

Extraction	Method	Fraction Name	Extracted Pools
Soil sample	0.5 g soil samples in 50 ml screw cap centrifuge tubes.		
Resin strip	Add 30 ml deionized water plus 0.4 g Dowex 1 x 8-50 anion exchange resin in bicarbonate form, shake 16 h, remove resin bag, centrifuge and discard supernatant.	Resin -P_i	Freely exchangeable P (Plant available P_i)
0.5 M $NaHCO_3$	Add 30 ml 0.5 M $NaHCO_3$ (pH 8.5), shake 16 h, centrifuge and collect supernatant.	Bicarbonate P_i and P_o	Weakly adsorbed P (Plant available P_i and P_o)
0.1 M NaOH	Add 30 ml 0.1 M NaOH , shake 16 h, centrifuge and collect supernatant.	Hydroxide P_i and P_o	P associated with Fe and Al hydrous oxides (Medium term plant available P_i and P_o)
Sonicate 0.1 M NaOH	Add 20 ml 0.1 M NaOH and sonicate in an ice bath at 75W (Brausonic 1510) for 2 min, make to 30 ml volume, shake 16 h, centrifuge and collect supernatant.	Sonicate/ hydroxide P_i and P_o	Physically protected P associated with Fe and Al hydrous oxides (P_i and P_o)
1.0 M HCl	Add 30 ml 1.0 M HCl, shake 16 h, centrifuge and collect supernatant.	Acid P_i	Stable Ca-associated P_i
H_2SO_4 and H_2O_2	Digest with 5 ml H_2SO_4 and H_2O_2	Residue P (P_i and P_o)	P resistant to decomposition

2.1.7 Environmental impact of P fertilizer

Repeated P fertilisation can lead to P accumulation in the soil (Fransson and Bergkvist, 2000), which might cause adverse environmental effects e.g. eutrophication through losses of dissolved P to groundwater and surface water (Tunney *et al.*, 1997; Payn and Clough, 1989). The probability of this occurring at the Usutu-sites is very low, because of the high buffer capacity of the highly weathered clay soils (Bainbridge *et al*., 1995). The most important environmental risk of P fertilizer application at Usutu can result from the erosion of P-rich topsoil. The phosphorus eroded with the soil particles is normally bound to iron oxides and very insoluble under well-aerated conditions. However, prolonged anaerobic conditions can reduce the iron in these complexes from Fe^{3+} to Fe^{2+}, making the iron phosphate complex much more soluble and causing it to release phosphorus in solution. As the eroded phosphorus accumulates in river or other sediments, along with organic material, it can become anoxic and the reducing environment may cause the gradual release of phosphorus. Thus, the eroded phosphorus may aggravate the problem of eutrophication for years to come (Brady and Weil, 1996).

2.1.8 Efficiency, effect and duration of response to P fertilisation

"Past concepts about the behaviour of phosphorus in soil suggested that phosphorus added in fertilizers reacted with other soil constituents and became permanently fixed in soil and therefore unavailable to future crops. It is now known that this is not always the case for many soils. When phosphorus is added to the soil it becomes associated with various soil elements. Although only a small portion of the phosphorus in each application of fertilizer is held weakly, the amount increases as the number of fertilizer applications increase." (Johnston and Steén, 2000).

Phosphorus deficiency has been linked to low production or a decline in production of plantation forests across the world. In the southeast USA a 10% to 35% reduction in tree height of second rotation, *P. taeda* and *P. elliottii* was associated with a nutrient deficiency as a result of nutrient removal, particularly phosphate, with the first crop (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, 1968 and 1986; Ballard, 1978; Turner, 1982; Will, 1985). Some of the trials that proved the importance of P fertilisation on inherently P deficient forest soils will be discussed in more detail.

Polglase *et al.* (1992a, 1992b) studied the release of N and P from decomposing needles and mineralization of N and P from soil organic matter in a fertilizer trial in Florida. *Pinus elliottii* and *P. taeda*, growing on Spodosols, were annually fertilised with nearly all essential mineral elements. The application of fertilizer had a stimulatory effect on specific P mineralization. This suggested that some of the fertilizer P, having been taken up by plants and returned to the soil via decomposition of residues, was converted into organic components that were readily mineralized. Their conclusion was that the rapid recycling of P through organic residues of fertilised plots has the potential to enhance long-term productivity beyond the immediately beneficial effects derived from fertilizer uptake.

Studies to determine the effect of one large application of phosphorus to production in a subsequent crop have been more common with agricultural crops. However, the time frame for agricultural crops is normally much shorter than for forest crops. Therefore, not all the results from agricultural experiments are directly applicable to forestry. This was also the reason why the agricultural fertilisation experiments were not researched extensively for this study. However, some agriculture long-term fertilizer studies showed that the effect of P fertilizer might last for a number of years. As early as 1963, Leamer (1963) reported that rates of between 30 and 235 kg ha^{-1} phosphorus, applied at the beginning of a rotation on an irrigated Springer fine sandy loam affected yield, plant composition and soil tests for several years. Yields were increased for at least the first six of the eight year study period. Increased yields of intervening alfalfa and sorghum crops were obtained until the amount of P applied was removed in the harvested crops.

The objective of a study by Read *et al.* (1973) was also to determine the residual effect of a single large application of phosphate fertilizer on cereal production over a period of several years. The treatments namely, 0, 100, 200 and 400 kg ha^{-1} P were tested in the field as well as in a greenhouse on four different soil types that ranged from clay loam to clay. The production of plant material in the greenhouse was consistent with the findings in the field. The yield of plant material decreased as the available P in the P-fertilised soils decreased. Initially the rate of decrease of the available P was very fast, but became slower and eventually approached that of the control. The level of available P in the control remained fairly constant through the experiment. The total amount of P in the soil was more important to crop production than the placement of the fertilizer. After 19 successive crops, 87, 81 and 70 % of the fertilizer could still be recovered from the 100, 200 and 400 kg ha^{-1} P treated soils, respectively, in the greenhouse study.

The Hoosfield experiment, which formed part of Lawes and Gilbert's Rothamstead classical experiments, clearly demonstrated that the effectiveness of residual P and K fertilizer lasted a long time and that these nutrients did not become irreversibly "fixed" in the soil. After the experiment was started in 1852, residue of P and K accumulated over 20 years as a result of application of farm yard manure (FYM). In 1872, the FYM plots were halved and FYM was only applied to one half of the original plots. When all the plots were again subdivided in 1968 to test four amounts of nitrogen, there were indications that the spring barley was able to utilize the residues more than 100 years later. Although barley yields from the earlier FYM treatments were less than where FYM was being applied each year, the plots with residual P and K were still giving larger yields after another 20 years than soils that were never fertilised (Johnston, 1994).

The duration of response to phosphate fertilisation in forestry had been variable. Some trials showed no response, while others showed improved growth, not only through the rotation of the fertilised crop, but even in the successive rotation. A brief overview of responsive and less responsive forestry trials follows.

Fransson and Bergkvist (2000) investigated the duration of P fertilizer in an acid, medium to fine sand soil in a Norway spruce (*Picea abies*) forest in south-central Sweden. A total of 300 kg ha^{-1} P was applied as superphosphate between 1967, when the trees were 11 years old, and 1988. They found that the P supplied still remained in the soil 10 years after the last fertilisation as relatively soluble P fractions. The added P seemed to be distributed among both the humic and the mineral horizons and across a number of P compounds. The enhancement of the organic P was most pronounced in the top B horizon. There was some evidence that some of the added P was transported to deeper layers.

The fate of broadcast superphosphate applied at rates up to 1400 kg ha^{-1} to a 4-year-old stand of *Pinus radiata* established on a soil with a capacity for retaining phosphorus was studied over a 3 year period by Flinn *et al.* (1982) in Australia. Levels of "available" phosphorus increased markedly within 8 months of application of fertilizer and then remained more or less constant. An increase in the phosphorus content of the above-ground biomass was associated with a significant growth response. Between 44 and 49 % of phosphorus content of the above-ground biomass was contained in the needles. This high proportion of P in the needles, present in biological form, was indicative of the importance of foliage in the phosphorus economy of trees. A reduction in fertilizer efficiency with an increase in the amount of phosphate was recorded. Fertilizer efficiency was 12.2 % for the 73.5 kg ha^{-1} P rate and 8.3% for the 147 kg ha^{-1} P rate respectively. Only 56 and 72% of the applied phosphorus was accounted for three years after application in the surface soil and tree biomass following the broadcast of 700 and 1400 kg ha^{-1} superphosphate respectively. In order to reduce weed stimulation shortly after planting it was concluded that a small localised application of P should be made at planting. A larger broadcast application of P, 3 to 4 years later, should enable satisfactory growth over a significant portion of the rotation on soils where Fe and Al-oxides make a significant contribution to the retention of phosphate (Flinn *et al.*, 1982).

Research had shown that the effect of one P application early in the life of a stand can improve growth through the entire rotation. Pritchett and Comerford (1982) reported significant response in height, diameter, basal area and volume growth to P fertilisation at time of planting that lasted 17 to 20 years. In these experiments one application of 40 kg ha^{-1} P to *P. elliottii*, significantly increased basal area and volume in three of the six trials. Soil properties such as available P content, capacity to retain applied P in the root zone, and soil moisture conditions affected the magnitude and longevity of response to P fertilizers.

In New Zealand, Ballard (1978) reported that a 225 kg ha^{-1} P application to 25-year-*old P. radiata* maintained reasonable foliar P levels after 14 years of the application. Mean basal area in the fertilised plots was 47 m² ha^{-1} opposed to 13.5 m² ha^{-1} in the control plots. Height growth did not appear to be a very sensitive indicator of fertilizer response. Although the treatment differences did significantly affect height growth 16 years after P application, the response declined with age.

Dramatic results were obtained in a trial in the Belanglo State Forest, New South Wales, Australia. A 30-year-old superphosphate experiment with *P. radiata* was assessed to determine the retention of applied P fertilizer over this period. Five rates of superphosphate had been applied, namely 0, 25, 50, 75 and 100 kg ha^{-1} P. The increasing quantities of fertilizer gave increasing growth responses up to 75 kg ha^{-1} P. Thirty years after fertilisation the mean DBH in the control plots was 26.5 cm and those receiving the 100 kg ha^{-1} P was 38.8 cm. The total volume production was 164 m³ ha^{-1} and 489 m³ ha^{-1} for the 0 and 100 kg ha^{-1} P treatments respectively (Turner, 1982). Prior to the establishment of the subsequent crop, sampling was carried out on the standing trees, forest floor and soil to 200 mm to account for redistribution of fertilizer over the course of the experiment. Results indicated significant retention of the phosphate together with accumulations of N, Ca, Mg and K. The accumulation of these elements was considered to be from atmospheric inputs and redistribution from deeper within the soil profile. In this trial phosphorus was retained for a long time. The applied fertilizer could be accounted for at low levels of application, but there were reduced recoveries at the higher application rates. The applied phosphorus was converted predominantly to organic forms, which may be less liable to leaching, but can be considered as major sources of available phosphorus. The application of superphosphate on this site was regarded as a permanent addition to the productive capacity of the site (Forestry Commission NSW, 1986). Elsewhere in the same forest Snowdon and Waring (1990) demonstrated that by the age of 18 years the basal area of unfertilised *P. radiata* trees was 19 $m^2\ ha^{-1}$, compared to 31 $m^2\ ha^{-1}$ for those that received 36 kg ha^{-1} P and 39 $m^2\ ha^{-1}$ for the two highest rates (73 and 96 kg ha^{-1} P at establishment). In 1980, at the age of 18 years, the effects of two thinning types and the application of superphosphate and urea on the subsequent growth was tested. Cumulative basal-area increment for the seven year period following treatments indicated that the initial application of the phosphate fertilizer had a marked residual effect. The increment on the unthinned plots, which had only been fertilised at establishment, was 6.3 $m^2\ ha^{-1}$ greater than that obtained on plots which had never been fertilised. The response to the fertilizer also indicated that site productivity had been improved in the long term by the heavy broadcast application of phosphate (type II response as described by Snowdon and Waring, 1984).

Harding and Jokela (1994) studied the long-term effects of time-of-planting fertilisation on the accumulation and distribution of organic matter and nutrients in a 25-year-old *P. elliottii* stand in north Florida. The three treatments (Control – no fertilizer; NPK mixture of 112, 39 and 45 kg ha^{-1} N, P and K, respectively, using ordinary superphosphate [OSP] and 314 kg ha^{-1} P alone using ground rock phosphate [GRP]) were applied to a poorly drained, P-deficient loamy fine sand. Fertilisation significantly increased total aboveground organic matter accumulation, with levels for the OSP + NK and GRP treatments being 2.5 and 1.8 times greater than the control, respectively. No significant differences were found among treatments in soil organic matter levels (0 – 910 mm). The effects of added fertilizers were also noticeable in the concentration and content of some nutrients in the site biomass, forest floor and soil. Overall increases in the nutrient contents in the combined biomass and forest floor components were greater than the amounts contained in the fertilizers supplied. This suggested enhanced root exploitation, nutrient uptake and cycling in the fertilised plots. The large amount of Ca contained in the GRP fertilizer (± 785 kg ha^{-1} Ca) was still influencing soil nutrient status 25 years after application. Because of enhanced litter decomposition and nutrient cycling by influencing soil organisms and the base content of the litter, the Ca might have had indirect benefits. Foliar data analysis showed that only the high P application rate sustained P levels within the “critical” 800 to 900 mg kg^{-1} range through time. Therefore it was likely that similar sites, previously fertilised with 40 to 80 kg ha^{-1} P will again require treatment when establishing the next rotation of pine (Harding and Jokela, 1994).

Very few studies have tried to determine to what extent a first rotation application of P fertilizer alleviates the need for fertilizer application at establishment of the second crop. Four long-term forestry studies have been reported. A brief summary of each trial and the results are supplied.

In New Zealand, Ballard (1978) reported that the subsequent rotation of *P. radiata* at age 5 years showed a positive response to 225 kg ha^{-1} P that was applied 19 years earlier to the previous crop. The application of P fertilizer to the first rotation on the strongly leached and weathered clay loam soil had significant growth effects as already mentioned. The second rotation experiment had a split-plot design, where the first rotation treatments were used as main plots, with a second rotation application of 17 g $tree^{-1}$ P at planting (equivalent to 52 kg ha^{-1} P) in one of the split-plots. Prior to the planting, soil chemical analysis of the surface 100 mm indicated that only the phosphate values differed between the unfertilised and previous fertilised plots. The Bray 2 and total P levels were 2.0 mg kg^{-1} and 54 mg kg^{-1} respectively in the unfertilised plots, while the values in the previous fertilised plots were 6.4 mg kg^{-1} and 82 mg kg^{-1} respectively. The mean effects of first and second rotation fertilizer (main plot treatments) on collar diameter were small and non-significant for the first 4 years after planting. The treatment differences became more apparent after the 5^{th} growing season. A highly significant interaction between first and second rotation applications was observed. The second rotation application produced a substantial increase in growth on sites, which had received no first rotation application, but suppressed growth on sites which had been fertilised during the first rotation. The foliar P levels in trees which received P in both the first and second rotation were greater than those in trees which received a single application which in turn were greater than the P levels in the trees which received no fertilizer at all. Both first and second rotation applications of P reduced foliar N levels, with the most significant reduction associated with the first rotation application. The lower N status of the old P fertilised plots may have resulted from a greater removal of N in the harvested crop. The reduction in foliar N suggested that an N deficiency limited the response to additional P in the previously fertilised plots. This could explain the reduced response to the application of P in both rotations when compared with an application in either the first or the second rotation.

The results of this trial suggested that it would be possible to reduce the rates or frequency of P fertilizer application to subsequent rotations. It also pointed out that correction of one nutrient deficiency and the associated improved growth can hasten the onset of other nutrient deficiencies.

The second very important residual fertilizer trial was monitored over a 50 year period after establishment in 1947/48 at Penrose State Forest on the southern tablelands of New South Wales in Australia. The site was initially selected because it had previously supported a very poor pine stand in the absence of fertilizer, despite being located in a very favourable climate. The soils were highly weathered, coarse-textured sands to sandy loams derived from quartzitic sandstones which contain intermittent bands of Fe-enriched sandstone. The soil was infertile, with total phosphorus concentrations being generally less than 70 mg kg^{-1} in the top 100 mm of the profile (Gentle *et al.*, 1965, 1986).

The original experiment, established in 1947/48 in a 6-year-old naturally regenerated stand of *P. radiata*, consisted of three treatments. The treatments, namely an untreated control, rock phosphate and superphosphate, each at rates of 96 kg ha^{-1} P, were replicated five times. In 1962/63 the trial was assessed at the age of 16 years before a thinning operation. From this assessment it was reported that the commercial productivity did not differ between the two P sources, and that the volume on the fertilized plots was more than three times that of the untreated plots (Gentle *et al.*, 1965). In January 1965 the forest was destroyed by a wildfire. The trees were harvested and all volumes measured. The replanting of the trial was undertaken in July 1965 with standard nursery stock at a stand density comparable with the stand density in the previous rotation. No additional fertilizer was applied. In 1981 the stand was thinned to a residual basal area of 20 m^2 ha^{-1}, the same as in 1962. Merchantable standing volume and volume removed was estimated. The results were published by Gentle *et al.,* (1986). The trial was reassessed in 1998 prior to final harvesting of the second rotation crop after P fertilizer application (Turner *et al.*, 2002).

Results showed that tree growth responses to the original 1947 fertilisation had been maintained significantly through the two fertilised rotations. The tree height, basal area and volume growth over the 33 year period (from 1965 to 1998) did not differ significantly between the two phosphate treatments, but both treatments increased merchantable standing volume of the second rotation by 50% at the age of 33 years. The pattern of accumulation of merchantable volume showed that the two phosphate treatments diverged from the control prior to and after the thinning (Turner *et al.*, 2002). Such a diverging form of response has been termed a “type II” response by Snowdon and Waring (1984) as it is an indication of a long-term change. Foliage nutrient concentrations indicated that phosphate fertilizer treatments increased P levels from a deficient to a minimum desirable level. The fertilizer also increased foliage calcium levels. Soil phosphorus and calcium levels were raised by fertilizer additions and remained relatively constant since the first analysis in 1962. There was no evidence of vertical movement of phosphate down the soil profile. However, some lateral movement was observed due to litterfall from the fertilised plots into the unfertilised plots. The phosphate treated plots had significantly higher organic matter contents than in the control and it appeared to be increasing over time. This means that the organically related phosphorus was also increasing. Thus, phosphorus availability was likely to become more associated with organic matter mineralization than with inorganic fractions of phosphorus (Turner *et al.*, 2002).

The fertilizer treatments had very little effect on the absolute values of the forest floor mass, but it did reduce the coefficient of variation. There were no significant differences in nutrient content of the aboveground plant material between the two fertilizer treatments, but both were greater than the control. This was mainly because of increased biomass production. The efficiency of the applied phosphate uptake was calculated as 12.8 % and 17.1 % for superphosphate and rock phosphate treatments, respectively, from the additional 12.3 and 16.4 kg ha^{-1} P in the two treatments. Most of the applied phosphorus and calcium could be accounted for in the biomass and soil to a depth of 400 mm. However, levels of nitrogen, magnesium and potassium were higher in the fertilised plots compared with the control. These nutrients were not added in the treatments and it was suggested that is was either transferred from deeper in the profile, nitrogen fixation, or in the case of cations, additional rock weathering from the total pool. It was concluded that for soil with a reasonable level of phosphorus retention (> 200 mg kg^{-1}), phosphorus can be used to increase productivity in the long term and also increase productive capacity of the site for future rotations (Turner *et al.*, 2002).

Wood quality analyses of the first rotation, fire-killed trees showed that basic density, percent latewood and tracheid length did not differ significantly between the control and the fertilizer treatments in this trial (Gentle *et al.*, 1968).

The last two long-term trials that will be discussed in detail were intensively sampled at the beginning of the subsequent rotation to determine the amount, form and bioavailability of the residual phosphorus in the soil and forest floor that could benefit the next rotation. The results of both trials were reported by Comerford *et al.* (2002).

The trial in Glynn County, Georgia, in the USA was established in 1965 on a poorly drained, wet savannah fine-loamy sand. The trial was installed in a newly planted *P. taeda* compartment to evaluate the response to four rates of concentrated superphosphate namely 0, 17.5, 35 and 70 kg ha^{-1} P. Measurements of tree height and diameter were taken at age 20. The stand was harvested in 1992 and replanted with *P. taeda* in 1994, 29 years after the initial fertilizer application (Comerford *et al.,* 2002).

The lowest P fertilisation treatment doubled tree diameter and tree height by age 20 years. The higher P fertilizer rates did not result in significant increases in height or diameter. Stand volume increased seven-fold at the lowest P fertilisation rate and 10-fold at the highest P rate. In 1994, 29 years after P fertilisation, the fermentation horizon (F) showed a trend of increasing total P concentration with increasing fertilizer rate, with an increase of 46 and 58 % over the control where the two highest rates of P were applied. Neither the total P in the litter horizon (L) nor the mass of the L horizon was statistically affected by the treatments, although the absolute values showed an increase. However, the F horizon mass did statistically increase over the control by 239%. The total P in the forest floor, 29 years after fertilisation, accounted for 23, 36 and 15 % of the applied P for the 17.5, 35 and 70 kg ha^{-1} P treatments, respectively. Total mineral soil P in the top 100 mm was significantly increased with the application of 70 kg ha^{-1} P. Increased P in the 0 to 200 mm depth of the mineral soil amounted to 0, 43 and 27 % of the 17.5, 35 and 70 kg ha^{-1} P respectively. Combining the recovery from the soil with that from the forest floor, 26, 79 and 42% of the applied fertilizer was recoverable from their respective fertilizer treatments, 29 years after fertilisation. The surface 100 mm showed a pattern of increasing anion membrane extractable P with increasing P fertilisation. The apparent trend of increased P uptake with increasing fertilizer treatment by *P. taeda* seedlings, grown in pots with soil from the surface 100 mm, was not supported by the statistical analysis.

The second site Comerford *et al.* (2002) investigated was located on the North Island of New Zealand on a highly weathered, clay-textured soil derived from siliceous claystone. In 1973, three replications of a long-term P fertilizer rate study were established in a 6-year-old stand of *P. radiata*. Superphosphate was broadcast at rates of 0, 63, 125 and

250 kg ha^{-1} P. Only the mineral soil was sampled at the site when the trees were 28 years old, 22 years after fertilisation.

At the end of the rotation the unfertilised plots yielded 104 m^3 ha^{-1} of timber, while the plots that received P fertilizer averaged about 540 m^3 ha^{-1}. The application of 125 or 250 kg ha^{-1} P resulted in similar growth (about 550 m^3 ha^{-1}). Anion exchange extractable P was significantly higher for the two higher fertilizer rates compared to the control and lower fertilizer rate. The results from the bioassay indicated that the radiata pine seedlings were able to extract more P from the two highest fertilizer rates. Although significant differences in residual P were detected in the soil as a result of fertilisation, the residual inorganic P in the soil would not likely have been sufficient to meet the early needs of a new plantation. Unfortunately the amount of additional P available in the forest floor was not determined (Comerford *et al.*, 2002).

Some trials only showed a short-term response or none at all to the application of P. Carlson (2000) reported that the response to 150 kg ha^{-1} P lasted only to the fifth year on shale after application of P at age eight years to pines in Mpumalanga. The trials on Highveld granites, and Escarpment sites responded up to seven years after application.

Pritchett and Smith (1972) studied the effect of N, P and K fertilizer application to 28 young *P. elliottii* plantations in the US Lower Coastal Plains on soils that ranged from poorly-drained to excessively well-drained sands to sandy loams in the Spodosol, Ulitsol, Entisol and Inceptisol orders. Applications of P significantly increased heights at age three years in 82% of the 17 trials located on poorly-drained sands, while none of the three located on deep well-drained sands gave significant responses. Ballard and Pritchett (1974) showed that phosphorus retention in these soils was significantly correlated with Al and Fe extracted by soil tests for available phosphorus. They identified sites where excessive leaching losses of P would occur as those with 40 mg kg^{-1} or less of NH_4OAc extractable Al. Later on Ballard and Pritchett (1975) reported that due to leaching or strong retention, a single application of P fertilizer early in the rotation, would not supply nutrients at adequate levels later on in the rotation. Therefore they recommended that only sufficient fertilizer should be supplied at planting to maintain an adequate supply for 5 to 10 years. Re-application of fertilizers later on in the rotation could be based on foliar analysis.

From all these preceding studies of P fertilisation of forests it can be concluded that the period of growth response was variable and difficult to predict. The duration is probably site-specific and dependent on soil characteristics and climate. Previous studies showed that soil parent material has a strong influence on phosphorus availability (Turner *et al.*, 1999). Soil properties such as available P content, capacity to retain applied P in the root zone and soil moisture conditions can affect the magnitude and longevity of response to P fertilizers. The residual P effect will most likely be greater in finer textured soils than in coarse-textured soils. In general the phosphate fertilizer had a low efficiency (5-15%), with a reduction in efficiency with an increase in the amount of fertilizer. On most of the responsive sites, the applied phosphate was converted to organic forms or it became part of the labile pool. These organic forms are less liable to leaching and are a major source of available P. Most of the applied phosphate was found to accumulate in the needles. Studies of subsequent rotations indicated that the residual P occurred in both the mineral soil and forest floor. The largest potential effect appears to be in the forest floor where both the increased amount of inorganic P and P mineralization can provide most of the P needed by a developing pine stand. This showed the importance of leaving the forest floor on site. How long this residual effect lasts and for how long re-fertilisation of a second rotation can be delayed is still uncertain, but there are indications that on some sites the application of phosphorus can be seen as a permanent addition to the productive capacity of the site.

2.1.9 Importance of P fertilisation in Southern African commercial pine forestry

The importance and response to P fertilizer application in South Africa was summarised and reported on previously by various authors. Only a brief summary of the most important results is given below.

Phosphate was identified as the major limiting element for tree growth in Southern Africa (Donald *et al.*, 1984; Morris, 1986, Schutz, 1976; Donald, 1990; Schönau, 1983). With few exceptions, pines treated with P responded positively to treatment. The magnitude of response appeared to be influenced by soil nutrient availability and stand age (Morris, 1986, 2003). At Usutu the lowest soil P availability was associated with the largest response to P fertilizer and the response increased when P was applied to older stands (Morris, 1986, 2003). In other mid-rotation nutritional studies in Mpumalanga, a positive growth response to the application of P at the age of eight years was observed on some, but not all of the trials. The response was mostly delayed by a year, but some trials did respond within the first year after application (Freimond and Allan, 1995; Carlson and Soko, 2000). The basal area increment (BAI) improved by 11% (1.74 m^2 ha^{-1}) in the trial that showed the biggest response, five years after the first fertilizer application (Carlson and Soko, 2000). The magnitude of the responses to the P fertilizer as well as the other elements and factors that initiated the response was variable across the different sites. It was difficult to ascertain exactly which factors had been most instrumental in producing the observed responses (Carlson, 2000; Carlson and Soko, 2000). Soil parent material did prove useful to group sites with similar patterns of response. Analysis of response to a second application (between age 13 and 14 years) of P fertilizer in some of these trials indicated no significant positive response (Campion and Du Toit, 2003).

2.1.10 Summary of P fertilizer research results at Usutu

The largest short term responses were obtained to P when applied at time of planting and after canopy closure. The time of planting application of fertilizer appeared to benefit the young transplants whilst they were establishing an extensive root system (Morris, 1987a). Fertilizer application to established stands indicated that significant responses occurred with P fertilizer when applied to six and eleven-year-old stands but not when applied to three-year-old stands (**Figure 2.4**) (Morris, 2003).

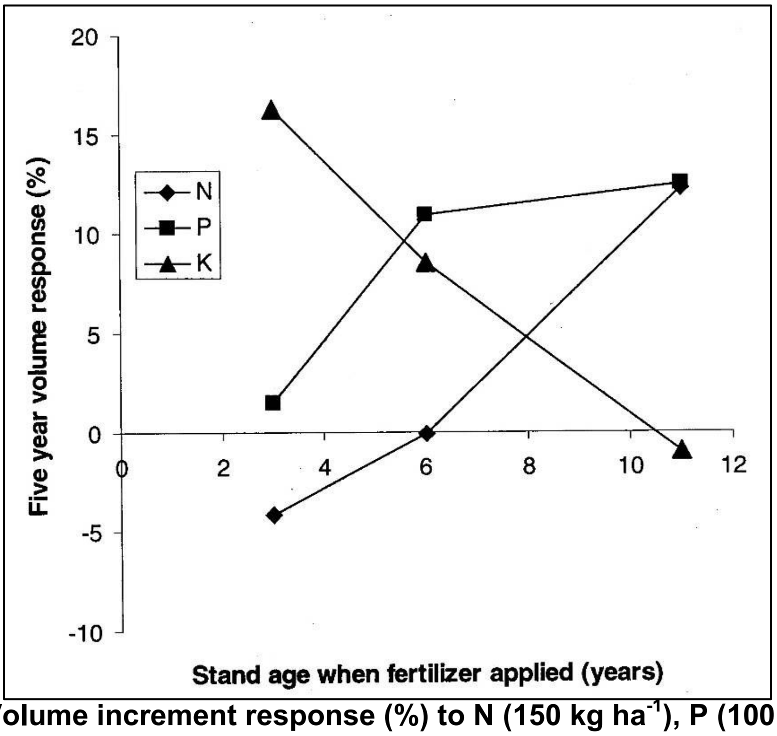


Figure 2.4: Volume increment response (%) to N (150 kg ha^{-1}), P (100 kg ha^{-1}) and K (150 kg ha^{-1}) fertilizer application for five years following application to 3-, 6- and 11-year-old *P. patula* stands at Usutu, (Morris, 2003).

Morris (1986, 1987a) suggested that for a period between planting and age seven years, the demand for P was largely balanced by the soil supply and application of additional P had no significant effect. At the age of eight years the stands reached a maximum P accretion rate and responses to P application became significant again (Morris, 1986).

The mean response to 100 kg ha^{-1} P, applied to six and eleven-year-old stands, was 25 m^3 ha^{-1} over five years in one particular set of trials. Various trials have confirmed that the maximum response was achieved with an application of 50 to 100 kg ha^{-1} P to six and eleven-year-old stands (Morris, 1987a, 2003). Geology had no significant influence on the response to P fertilizer (Morris, 2003).

2.2 POTASSIUM (K)

2.2.1 The potassium cycle

Potassium is normally described as the third most important macro nutrient. It ranks seventh in order of abundance in the earth's crust (Johnston, 2003). Although plants need potassium in relatively large amounts, potassium deficiencies are not common, because most soils have sufficient potassium reserves. Potassium deficiencies have been reported in South Africa on highly leached sandy soils and highly weathered and leached, heavier textured soils (Saayman, 1993).

The potassium status of a soil normally depends on the parent material, degree of weathering and leaching. As a general rule the potassium increases down a soil profile as a result of weathering in the top horizons and leaching to the lower horizons. However, exceptions to this rule occur normally in material with low potassium content. In these soils the A-horizon has higher potassium content than the lower horizons because of base recycling or fertilisation practices (Saayman, 1993).

The behaviour of the potassium in the soil is related to the type and amount of clay and soil organic matter. The type of clay depends on the parent rock and the extent to which the mineral particles have undergone weathering. The clay particles are made up of many layers that are composed of interlocking silicon and oxygen atoms or aluminium and oxygen atoms. In some types of clay (illites) there are spaces between the layers into which positive ions, like potassium, can migrate and be held there by negative charges on the layers. In other clays (kaolinitic) the layers are so tightly bonded together that ions like potassium cannot enter between them. Potassium can be held at the edges of clay layers in both types of clay. The layers also tend to open at the edges, allowing ready ingress of potassium. The positive potassium ions held at the edges of the clay layers and the ions towards the outer edge of any interlayer space can be replaced relatively easily by other positive charged ions. When this occurs the potassium is released into solution. Potassium deeper in the interlayer space can only exchange slowly. The reverse process occurs when the concentration of potassium in the soil solution is increased by the addition of fertilizers. Reserves of potassium can be built up in soils that contain a large proportion of illite or other 2:1-type clays (Johnston, 2003).

Potassium in soil exists in four "pools" related to its availability to plants (**Figure 2.7**). These pools are the soil solution, where it is immediately available, the readily available pool, the slowly available pool and the soil minerals, where it is least available (Johnston, 2003; Brady and Weil, 1996; Saayman, 1993).

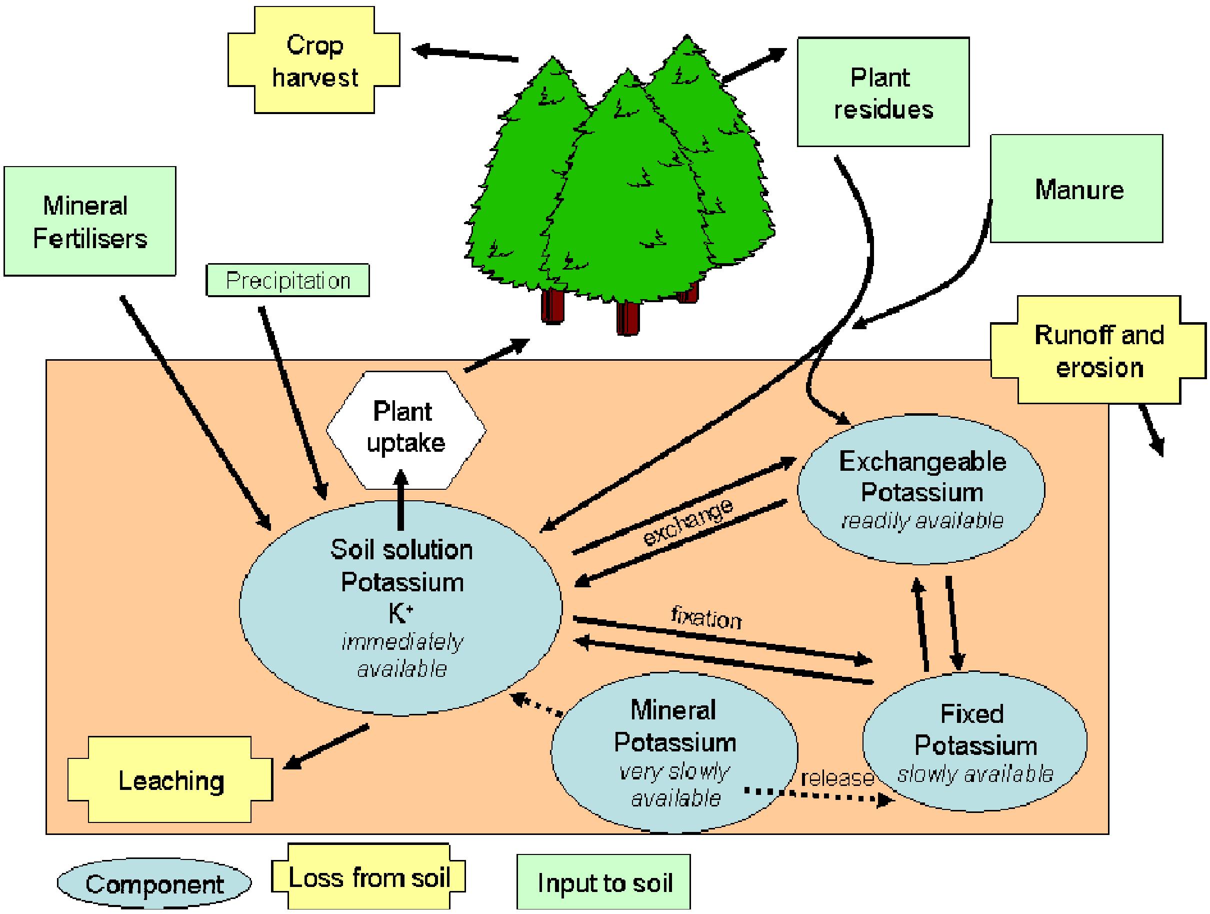


Figure 2.5: The potassium cycle. (After Carpenter *et al*., no date and Krauss, 2002).

Only 1 to 2% of the total soil potassium is readily available. Approximately 90% of the available potassium exists as exchangeable potassium adsorbed on the soil colloidal surfaces. This means that only 0.1 to 0.2% of total soil potassium is found in the soil solution, where it is most readily absorbed by plants, but unfortunately also subject to leaching loss. The soil solution potassium and exchangeable potassium are in dynamic equilibrium. Potassium taken up by plants is immediately replenished from the exchangeable pool. When water-soluble potassium fertilizers are added the soil solution becomes potassium enriched and potassium from the soil solution moves into the exchange complex. The exchangeable potassium is an important buffer mechanism for soil solution potassium (Brady and Weil, 1996; Saayman, 1993).

In the presence of normally expanding clays (e.g. vermiculite, smectite and other 2:1-type minerals) the potassium ions can fit in between the layers in the crystals and become fixed as an integral part of the crystal. These non-exchangeable ions are not readily available to plants, but are in equilibrium with the more available forms and acts as an extremely important reservoir (Brady and Weil, 1996; Saayman, 1993). Etchevers *et al.* (2005) found that the actual release of K from the soluble pool and exchangeable pool depends on initial size of the pool and is independent of the type of soil or previous management practices.

Most (90 to 98%) of the soil potassium is found in relatively unavailable, mineral forms – mostly in feldspars and micas. These minerals are quite resistant to weathering and although they supply only small amounts of potassium each year, the cumulative effect over a period of years is of some importance (Saayman, 1993; Brady and Weil, 1996). The roots of some plants can obtain a proportion of their potassium supply by depleting the potassium ions from the solution around the edges of these minerals, thereby favouring the dissolution of the minerals (Brady and Weil, 1996). Mineralization of plant residues is also an important source of K for plantation trees as the forest floor litter layer contains a large amount of K (**Table 2.1**).

Losses of potassium from the soil occur largely through the removal of plant harvest residues, leaching, and erosion (Saayman, 1993). Plants take up large amounts of potassium, much more than in the case of phosphorus and almost as much as in the case of nitrogen. If most or all of the above-ground plant parts are removed in harvest, the drain on the soil supply of potassium can be very high (Brady and Weil, 1996). Morris (1992) estimated that approximately 151 kg ha^{-1} of potassium is lost through the removal of harvest logs over an 18 year rotation with *P. patula* at Usutu. This corresponded with a figure of 140 kg ha^{-1} for *P. radiata* (Saayman, 1993). In other studies the amount of K removed with the bole was estimated between 20 and 478 kg ha^{-1} (**Table 2.2**). The fact that K is the most soluble and easily absorbed cation in normal soils tends to make it a “luxury” element, often taken up in amounts in excess of actual plant requirements. This makes it difficult to determine the actual plant requirement (Barnard and Du Preez, 2004).

The quantity of potassium that is lost through leaching depends on various factors. Soil texture is important as it affects water holding capacity and has a direct effect on the volume of water that will leach through the profile under given climate conditions. Dense vegetation cover can minimise leaching losses, because it reduces the potassium in the soil solution and reduces potential percolation through reduction of water in the soil profile through transpiration. Soils with a very low cation exchange capacity (CEC) e.g. sandy soils with a low organic material content can lose 50 kg ha^{-1} of potassium per annum as a result of leaching (Saayman, 1993; Brady and Weil, 1996). The soil pH also affects the leaching of potassium from a soil. In acidic soils, where high levels of aluminium cations generally occur on the exchange complex, potassium cannot compete with the aluminium for adsorption sites. As a result leaching of potassium is much higher on soils with a low pH. Liming of these soils can reduce K leaching significantly because the pH will increase as well as the effective CEC when aluminium is replaced by calcium on the exchange complex (complementary ion effect). The type of clay is more important than the amount of clay in the soil in determining potential leaching losses. In clay soils where koalinitic clays dominate, major potassium losses might still occur as opposed to 2:1 type clays that will retain potassium (Saayman, 1993).

Substantial quantities of potassium can be lost through erosion. In most soils the erosion loss of potassium is less serious than in the case of nitrogen or phosphorus, because the potassium content normally increases with soil depth and the proportion lost through erosion is much less (Saayman, 1993).

Additions to the soil occur through atmospheric deposition, mineralization of plant residues and application of manure or inorganic fertilizers. The most common K fertilizer source is the K mined from naturally occurring ore bodies, which were created as sea water evaporated and K salts crystallized to become the beds of K ore being mined today. About 95% of commercially produced K is used in agriculture with a total annual production in excess of 25 million tons (PPI, 2005). There is no evidence that potassium has any adverse effects either in agriculture or in the wider environment (Johnston, 2003).

2.2.2 Role in plants

Plants require relatively large amounts of potassium compared to other elements as it is the most abundant cation in plants. Furthermore, K uptake is closely linked to metabolic activity (Marschner, 1986). Potassium functions more as a regulator of growth than as a direct contributor as it is not a constituent of the organic compounds involved in plant metabolism. As a regulator of growth, K is directly engaged in photosynthesis, the formation of carbohydrates, and the synthesis of proteins. It also has an important role in regulating water conditions within the plant by increasing the osmotic pressure, helping absorption of water and preventing wilt. Plants adequately supplied with potassium can normally better resist drought, frost, insects and pathogens. Potassium is very mobile within the plant and because it is needed in greater concentrations where active growth is taking place, it is withdrawn from the older needles and transferred to the younger ones (Bidwell, 1979; Binns *et al.*, 1980; FSSA, 1997; Marschner, 1986; Krauss and Johnston, 2002).

2.2.3 Deficiency symptoms in pine

Potassium deficiency often causes a change in growth habit. The morphology of young trees is usually affected and in chronic deficiency the death of the apical bud on the leading shoot and on upper side branches can result in a stunted or deformed bushy habit. A potassium deficiency also inhibits photosynthesis and consequently needle colour is lost because of chlorophyll reduction. On young plants the yellowing is confined to the needles at the tips of current shoots. Individual needles show a gradual chlorosis from the green base to the top, which can even become brown. On larger trees the yellowing does not show on current foliage, but it is confined to the older needles and often to the lower branches. This can be used to distinguish between potassium and nitrogen deficiency symptoms (Binns *et al.*, 1980).

2.2.4 Fate of applied K fertilizer and tests of available K

Soil nutrient supply occurs over several months, whereas a soil test gives a single average reading for one ”plant-available pool” at a moment in time. It is especially difficult to determine the plant available K pool, because it is a slow-release pool. Non-exchangeable K supplied by micas and illites and inter-stratified layer clays contributes to the plant-available K in some situations, whereas K fixation by these same minerals and vermiculites reduces plant-available K in others. The same fixation process can occur when K fertilizer is applied to a soil. There is currently no reliable quick-test to tell if non-exchangeable K will be released for plant uptake or if K-fixation will reduce the pool of available K. A simple solution to this problem is unlikely as both reactions are likely to occur at the same time and their net effect on K availability is to vary through the growing season. Their net effect is also likely to differ for different crops. A soil that fixes K under one crop may release non-exchangeable K to another (Fey and Manson, 2004).

An example of the effect of the dynamic exchange processes between the different fractions is supplied by Johnston and co-workers in Krauss and Johnston (2002). In the Garden Clover Experiment in Rothamstead, an addition of 1667 kg K per hectare to the total balance over a period of 10 years increased the content of exchangeable K by only 690 kg ha^{-1} (41% of total balance). If it is assumed that no large amount of K was lost through leaching, almost 60% of the K balance had gone into a pool of K that did not belong to the exchangeable fraction. In the same experiment, the subsequent long-term omission of K resulted in a negative K balance of 1494 kg ha^{-1} K, but the exchangeable K only reduced by 563 kg ha^{-1}, i.e. a reduction by 38%. The other 62% of K removed had to be supplied by K in other soil K pools.

It was found that the release of K from the non-exchangeable pool was linearly related to the content of initial exchangeable K. There was also a close linear relationship between the decrease in exchangeable K and the release of K from the non-exchangeable pool. Thus the evidence suggested that exchangeable K is a good indicator for the likely response of crops to an application of K.

With progressive exhaustion of soil K reserves, applied potassium is more strongly fixed. Crops may fail to respond to normal K dressings, because the applied K is trapped in the interlayer spaces of clay minerals. The K-release to the soil solution from this slowly available fraction cannot cope with the demand of the crops and the crop yield declines. Unfortunately the occurrence of K fixation and resultant absence of crop response is often misleading and worsens the situation. At the same time K depleted soils tend to fix NH_4, which lowers the availability of N (Krauss, 2000).

2.2.5 Duration of response to K fertilisation

Potassium, unlike phosphorus, is normally not strongly adsorbed to soil particles and is more easily leached from the soil (Tisdale *et al*., 1993; Brady and Weil, 1996). Therefore, the duration of response to potassium is believed to be less than that of phosphorus. In theory, due to the dynamic exchange process, the application of K fertilizer could have a residual effect, depending on the soil, climate and crop. To prove this, however, is very difficult. This is partially because exchangeable K is usually measured in soils and this is not always an indication of total K reserves in the soil, as illustrated previously.

Because potassium seldom causes deficiencies in conifer forests, not much research has been conducted on potassium fertilisation in forestry. The best examples of long-term potassium fertilisation studies were found in agricultural research. The long-term experiments at Rothamstead and Woburn indicated that despite application of large amounts of K to the soil (5070 kg ha^{-1} K over a 45-year period and 3330 kg ha^{-1} K over an 83-year period) the effect on soil exchangeable K was a relatively small 28 and 23 mg kg^{-1} K increase respectively (Allison *et al*., 2001). Yin and Vyn (2004) evaluated the residual effect of spring K fertilizer application to previous corn on subsequent soybean from 1997 to 2000. Positive soybean yield responses to residual K fertilizer were observed in only one out of the three years, despite consistent increases in both soil K and soybean leaf K concentrations where K was applied to the previous corn crop. In a study done on French beans (*Phaseolus vulgaris*), Costigan (1988) found that by the time of final harvest there was an increase in pod yield of 54% attributable to the residual potassium, which was applied more than a year previously.

Raupach and Hall (1974) reported K deficiency in *P. radiata* in Australia and were able to correlate foliar K levels with tree growth. K deficiency in *P. radiata* was also reported on limited areas in New Zealand. These were confined to podzolised sands and ultra-basic soils. On the ultra basic soils the deficiency was not as a result of an absolute K deficiency in the soil, but the large quantity of magnesium, which made the uptake of potassium difficult (Will, 1985). In the United States of America, *Pinus resinosa* plantations that displayed symptoms of acute K deficiency on glacial outwash sands near Warrensburg, New York, responded positively to the application of potassium. Tree growth was related to soil and tree potassium content. (White and Leaf, 1964; 1965; Madgwick *et al*., 1970). This significant growth increase after a single application of K was still significant after 39 years (Shepard and Mitchell, 1990). Calculations based on soil rubidium as the “tagging” ion demonstrated that the K fertilizer accounted for 60 % of the foliage potassium after 9 years and 40 % after 23 years. After a 50 year period 36 % of potassium cycling in the fertilised plots and 23 % of the K in nearby unfertilised plots originated from the initial fertilizer application (Stone and Kszystyniak, 1977; Stone 1981). Buxbaum *et al*., (2001) showed that the fertilizer K moved laterally into the control plots. Gray and Kyanka (1974) reported that this growth response to the application of K was associated with a decrease in basic timber density. However, the values reported for the fertilized plots were similar to those found in "normal" stands.

In forestry fertilizer research, conducted in South Africa, Carlson (2000) reported that the response to K appeared more sustained than the response to P and lasted beyond the seventh year, after application of the fertilizer at age eight years to pines in Mpumalanga.

2.2.6 Importance of K fertilisation in Southern African commercial pine forestry

The importance and response to K fertilizer application in South Africa was summarised and reported on previously by various authors. Only a brief summary of the most important results is given here.

Once phosphate requirements have been met, responses to N and K may also occur on many strongly leached forestry soils in the summer rainfall areas (Morris, 1986; Donald *et al.,* 1987; Schutz and De Villiers, 1987; Herbert and Schönau, 1989; Herbert and Schönau, 1990; Carlson *et al.*, 2000; Carlson, 2000; Campion and Du Toit, 2003). In a large number of trials it was observed that a significant P by K interaction occurred (Grey *et al.*, 1979; Schönau, 1983; Morris, 1986; Donald *et al.*, 1987; Noble and Ramsden, 1992; Carlson *et al.*, 2000; Payn *et al.*, 1988). Donald *et al.*, (1987) reported that the application of K without P resulted in a growth reduction. Foliar K levels of *P. patula* were found to be significantly correlated with tree growth in studies by Grey *et al.* (1979) and Morris (2003) conducted in the Transkei and Swaziland, respectively.

Furthermore, the growth response to the application of K was found to be linked to the stand age (Morris, 2003; Herbert and Schönau, 1990), with the greatest responses to K occurring when applied in younger stands. In the mid-rotation fertilizer trial series in Mpumalanga, mentioned earlier, Carlson and Soko (2000) reported that response to the application of K was normally observed two or more years after application, except on the Highveld granite soils where the response was seen within the first year after fertilisation. Five years after the first application, which occurred at age eight years, the biggest response to K was a 23.4% improvement in BAI, which was equivalent to a 3.46

m³ ha^{-1} increase in volume. With the second application of fertilizer at age 13 to 14 years, the response to K was much lower in general (Campion and Du Toit, 2003). Previous research also indicated that the soil characteristics of a specific site, and geology by implication, influenced the response to K (Crous *et al.*, 1995; Carlson, 2000; Carlson *et al.* 2000; Campion and Du Toit, 2003; Morris, 2003).

2.2.7 Summary of K fertilizer research results at Usutu

At Usutu only the stands on gabbro-derived soil showed significant responses to K fertilizer. Responses to K occurred shortly before canopy closure up to the culmination of current annual increment (CAI) (Morris, 1987a), which was consistent with the timing of the peak rate of accretion of this nutrient into organic sinks (Morris, 1986, 2003, Herbert and Schönau, 1990). A trial series established by Morris (2003) confirmed this response pattern. Potassium applied to three and six-year-old stands increased volume increment significantly (**Figure 2.4**), but application to eleven-year-old stands reduced growth (Morris, 1987a, 2003). In one particular study Morris (2003) calculated that the mean response to the application of 150 kg ha^{-1} K to the three and six-year-old stands was 19 m³ ha^{-1} over five years on gabbro-derived soils. The optimum rate of application of K fertilizer to gabbro sites was estimated to be between 50 and 75 kg ha^{-1} K (Morris, 1987a).

2.3 GROWTH DECLINE ON GABBRO SITES AT USUTU (BLOCK A EFFECT)

2.3.1 History

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 South Australia at the time by Keeves (1966) cited by Woods (1990). One of the reasons for concern came from observations in the mid-1960s that the foliage of the young second rotation (2R) *P. patula* at Usutu appeared yellow and unhealthy. Because the silviculture and species stayed relatively the same over rotations and trees are harvested on short 16-year rotations, the conditions lend themselves to test the hypothesis of how sustainable pine plantations might be over successive rotations (Evans, 1975, 1996, 1999b). To quote Evans (1999b): “If declining yields are to characterise plantation forestry – and hence be inherently unsustainable – then the pine plantations at Usutu are a *prima facie* candidate for such problems.”

In 1969/70 Evans established 92 pairs of plots in first and second rotation stands on sites of matching fertility. The rotations were compared at three reference ages namely 6, 10 and 14 years. From 1984 third rotation sample plots were re-established as the old second rotation plots were felled and replanted (Evans, 1996, 1999b).

The comparison of the 1R:2R paired plots showed that although the second rotation height growth and mean tree volume was significantly superior to that of the first rotation at age 6 years, this improvement was not maintained towards the 10 and 14 year assessments. Close to rotation age, there was little significant difference between the rotations. But the data did reveal that for a group of plots on the eastern side of the forest (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; Evans, 1986; Evans, 1999a; Morris, 1987a). 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 a strong association between poor second rotation plots and underlying geology. The second rotation plots that showed a growth decline were mostly located on Usushwana complex soils. This geological igneous complex characterized mainly by gabbro is confined to forest Block A and underlie 13% of the forest in total. Gabbro, in contrast to granite, which is the dominant geology of the other sample plots, is a poor source of phosphate and potassium (**Table 2.4**). This suggested that a developing PK deficiency was responsible for the Block A effect.

The evidence Morris (1986, 1987a) used to substantiate this finding was:

- Gabbro-derived soils had a small "available" P pool and fixed P more strongly. The mineralogy and chemical composition also indicated lower P values in gabbro.
- Supply of K from non-exchangeable reserves in gabbro-derived soils was found to be inferior to that from granite-derived soils. These sources are of increasing importance to successive crops as other, more readily available soil reserves are depleted.
- Needle P and K concentrations were lower in stands located on gabbro-derived soils, reflecting the inferior supply of P and K.
- Responses to P and K fertilizer, applied at time of planting, were consistently larger on gabbro-derived soils compared to those on granite sites.

Table 2.4: Mineralogy and chemical composition of granite and gabbro near the Usutu Forest (After Hunter, 1961 cited by Morris, 2003).

Mineralogy	Granite	Gabbro
Quartz (% Volume)	29	3
K-Feldspars (% Volume)	43	3
Plagioclase (% Volume)	20	55
Biotite (% Volume)	6	Trace
Pyroxenes (% Volume)	<1	34
Olivines (% Volume)	<1	Trace
Apatite	**0.5**	**Trace**
Mg (% Mass)	0.4	4.2
Ca (% Mass)	1.2	7.7
K (% Mass)	**3.3**	**0.4**
P (% Mass)*	**0.092**	**0.014**

2.3.2 PK fertilizer recommendation for compartments situated on the Usushwana complex

In order to correct much of the P and K deficiencies that have developed in successive rotations of *P. patula* on the Usushwana complex, Morris (1987a; 1994a) recommended the application of P and K fertilizer. The operational prescription was to apply 20 kg ha^{-1} elemental P and K fertilizer as a spot application at planting, followed by an application of 75 kg ha^{-1} elemental P and K fertilizer at pruning as a broadcast application. A split application was recommended by Morris (1987a), because the application of all the fertilizer early (at planting) has two major disadvantages. Firstly, the high rates of fertilizer might promote vigorous weed growth, which would increase weeding frequency and costs. Secondly, the full cost of fertilizer application is incurred earlier in the rotation and therefore increases the period before a return on investment is realised. The reason for applying some of the fertilizer at planting was to speed up early growth and to enable prompt pruning and subsequent fertilizer application.

2.3.3 Volume response to operational PK applications

Other researchers also suggested that productivity on these sites could be maintained or enhanced through the implementation of a site-specific management regime that included phosphorus and potassium fertilisation (Fox, 2000). The recommendation to fertilise operational stands on gabbro-derived soils had a favourable effect as both Evans

(1993, 1995 and 2003) and Morris (2003) reported that P and K fertilizer applications have corrected an otherwise decline in yield. Morris (1987a) estimated that the magnitude of response, to a split application of 20 kg ha^{-1} P and K at planting and 75 kg ha^{-1} P and K after pruning, to be an additional 19 to 70 m³ ha^{-1} at rotation age (16 years). This estimate was supported by a later established PK fertilizer trial in which the application of 80 kg ha^{-1} P and K resulted in an additional 64 m³ ha^{-1} volume at the age of 12 years. This volume increment also proved to be cost effective. Most of the response in terms of basal area increment occurred within two years after application in this trial (Crous *et al.*, 2005a).

2.3.4 Continuing research

In order to study the effect of fertilizer application to these sites on the Usushwana complex in more detail, additional trials were established with specific focus on optimum amounts, time of application and magnitude and duration of responses that could be expected. One trial at Usutu (R128) was specifically designed to determine if the PK fertilizer applied to a gabbro-derived soil in the previous rotation had any residual benefit that would allow a reduction in PK fertilizer application to the next crop. This trial was originally established in 1989 in a six-year-old compartment and was felled in 1998/99. The replanted trial formed the basis of the first part of this study (Chapters 3, 4 an 5). This is a very unique trial in forestry research. The relatively long rotation lengths in forestry means that trials are very seldom established with the purpose of measuring responses over one rotation, let alone over two rotations. This was also one of the last opportunities to study the residual fertilizer effect at Usutu, since all the commercial plantation areas on the gabbro-derived soils have received at least one application of PK fertilizer.

Another P and K fertilizer trial, R155, was established with the purpose of determining the optimum rate of P and K fertilizer and the optimum time of application. In this factorial P by K fertilizer by time of application by weeding trial the four levels of P and K (0/0; 20/20, 40/40 and 80/80 kg element per hectare) were applied a) all at planting; b) after pruning at the age of 5 years and c) as a split application where a small amount (20/20) was applied at planting, followed by an application of the remaining fertilizer after pruning. The results from this particular trial are reported in Chapters 6 to 9.

CHAPTER 3

THE SIGNIFICANCE OF RESIDUAL PHOSPHORUS AND POTASSIUM FERTILIZER IN COUNTERING YIELD DECLINE IN A FOURTH ROTATION OF *PINUS PATULA* IN SWAZILAND

The first part of this study was done to determine if the application of P and K fertilizer in the absence and presence of residual PK fertilizer had any significant effect on tree growth, as well as to quantify the differences across all the treatments. In this chapter the growth of the fourth rotation (4R) trees at age 6 years was compared to the growth of the third rotation (3R) trees and results from additional second control treatment plots, established with genetic material similar to the previous rotation (3R) were included in the analyses.

ABSTRACT

Research on the sustained production from short rotations of *P. patula* on the Usutu plantation has shown that operational application of P and K fertilizer corrected the 20% growth decline that was observed between first and second rotations on about 13% of the plantation. In 1989 a trial was established in a third rotation crop to determine if the benefit from residual fertilizer would allow a reduction in application to the next crop. 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 sampling was conducted in the trial. The results indicated that in the presence of residual fertilizer, the re-application of only K fertilizer increased volume by 27 m^3 ha^{-1} (21.5%) at age seven years. This was statistically similar to the 25.2 m^3 ha^{-1} (20%) increase from a combined PK application. From these early results it would appear that enough residual P fertilizer remained available to supply the early nutrient demand of the next crop. Although residual K fertilizer also affected volume growth and foliar nutrient levels, 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 the benefit from residual P applied to the previous crop.

3.1 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 characterised by soils with a high level of leaching, low nutrient content, low cation exchange capacity and moderate to strong acidity. Since afforestation began in the 1950s the silviculture has shown little change. Single species compartments are planted at a stocking rate of 1300 stems per ha; pruned to 2m at age five years to improve access; and no thinning operations are carried out until clear-felling at rotation age of 15 to 17 years. At harvesting only tree stems (with bark) are removed from the site. Harvest residue consisting of foliage, branches and non-utilizable timber are normally left *in situ* and rarely burnt. Clear-felled compartments are re-established with containerized seedlings within one to eight months after harvesting. Site preparation is minimal and only small planting pits are manually prepared shortly before planting. Mechanical and chemical weedings are done regularly until canopy closure at about three years of age.

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 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 four successive rotations showed that over the largest part of the forest the mean height growth was significantly greater in preceding 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 had declined highly significantly in the region of 18% in the second rotation (Evans, 1978; 1986; 1999b). This effect remained unexplained until Morris investigated associations between sample plots affected and a range of edaphic and lithological parameters. 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 (Morris, 1986). 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. Fortunately, only 13% of the forest area is underlain by this geology (Morris, 1986).

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. elliottii* was associated with a 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). In Australia and New Zealand, growth of *P. radiata* was also strongly influenced by P availability (Gentle *et al.*, 1965, 1986; Ballard, 1978; Turner, 1982; Will, 1985) and to a much lesser extent by K availability (Raupach and Hall, 1974; Will, 1985). Significant responses to P fertilizer, with the duration 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 (1987a; 1994a) recommended the application of 20 kg elemental P and K fertilizer per hectare as a spot application at planting, followed by an application of 75 kg elemental P and K fertilizer per hectare 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). Thus, Morris designed a trial specifically 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. The height and volume responses to added of P and K fertilizer, both in the presence and absence of residual fertilizer are reported in the current document.

3.2 MATERIALS AND METHODS

3.2.1 Site description

The trial site is located in the eastern portion of the Usutu plantation on gabbro derived soils at an altitude of 1300m above sea level. A mean annual temperature of 16.3°C and rainfall of 1421mm per annum is reported for this land type (Pallett, 1990). The soil on the site consists 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 of a soil pit located near the trial site are shown in **Table 3.1**.

Table 3.1: Selected soil properties of a soil pit near the trial site.

Soil 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)†	%	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
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‡	$cmol(+)\ kg^{-1}$	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

† Organic carbon content (Walkley Black method).
‡ Cation exchange capacity
# Exchangeable acidity

3.2.2 Trial description

3.2.2.1 Third rotation trial

In the spring of 1989, the third rotation (3R) 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 2.7m x 2.7m planting density). Each plot was divided into two split-plots of 6 x 10 rows. A broadcast application of PK fertilizer was randomly allocated to one of each of these pairs of split-plots. The PK rate was equivalent to 75 kg P and 75 kg K per hectare.

3.2.2.2 Fourth rotation trial

The fourth rotation (4R) *P. patula* trial was re-established in September 1999 at the exact location of the former third rotation PK-fertilizer trial with improved, second generation seed from the Usutu orchards. Each plot was 32.4m x 27m (i.e. 12 x 13 rows at 2.7m x 2.08m). Hence each split-plot consisted of 6 rows by 13 rows.

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 3.2**). 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^{-1} application at planting (spot application of fertilizer in a small pit next to each tree) and a 25 kg ha^{-1} broadcast application after pruning (at age five years) for each element, respectively. Superphosphate (10.5% P) and potassium chloride (50% K) fertilizer 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 3.2: Summary of the fertilizer treatments in the fourth rotation residual fertilizer trial.

Treatment code	Applied at planting (kg ha^{-1})		Applied after pruning (kg ha^{-1})		Total P:K (kg ha^{-1})
	P	K	P	K	
P0K0	0	0	0	0	0:0
P0K25	0	25	0	0	0:25
P0K50	0	25	0	25	0:50
P25K0	25	0	0	0	25:0
P25K25	25	25	0	0	25:25
P25K50	25	25	0	25	25:50
P50K0	25	0	25	0	50:0
P50K25	25	25	25	0	50:25
P50K50	25	25	25	25	50:50
2nd Control (unimproved genetic stock)	0	0	0	0	0:0

3.2.3 Tree growth measurements

3.2.3.1 Third rotation trial

The diameters at breast height (DBH) of the inner 4 x 8 trees in each split-plot were measured with diameter tapes in 1989, 1994, 1996 and 1997. The heights of four randomly chosen trees with above average DBH were measured in each split-plot in 1989. The heights of the same trees were measured during subsequent assessments.

3.2.3.2 Fourth rotation trial

Tree growth measurements, height and DBH over bark, were recorded annually during July. In 2000, 2001 and 2002 only 27 trees (inner 3 x 9) per split-plot were measured. From 2003, 36 trees (inner 4 x 9 trees) per split-plot were measured. Tree height of all lives stems within each measurement plot was measured with a *Vertex* hypsometer and DBH with a diameter tape. A sub-set of four trees with above average DBH (corresponding to measurements in the 3R trial in 1989) was selected per plot to compare dominant plot height of the current rotation with dominant height of the previous rotation at age six years. 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).

3.2.4 Sampling procedure and chemical analysis

3.2.4.1 Foliar samples

The sampling protocol was based on recommendations of Will (1985), Linder (1995) and Louw and Scholes (2003). The foliar 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 five dominant or co-dominant trees per split-plot were bulked for analysis.

3.2.4.2 Chemical analyses

All foliar samples were analyzed in the Institute for Commercial Forestry Research (ICFR) laboratory in Pietermaritzburg. Total nitrogen (N) was determined with the Kjeldahl method. Total P was determined with the molybdenum blue method in an automated segmented flow analyser. Atomic absorption was used to determine the calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K) concentration (Donkin *et. al*., 1993).

3.2.5 Calculations and statistical analyses

Volume estimation for young trees in the fourth rotation trial was performed from DBH and height measurements of all living trees per split-plot using a Max and Burkhart function (Bredenkamp, 2000). Statistical analysis of data was performed with *Genstat 8.1* software using the 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 an 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 analysed 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 (Payne *et al.*, 2005).

3.3 RESULTS AND DISCUSSION

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

The result indicated that in general (except for the second control plots) the mean dominant heights of the 4R trees were superior to those of the 3R trees at the age of six years (**Table 3.3**). When the effect of fertilizer application in the current trial was excluded, by only investigating the differences in the current control plots (improved genetic material), a significant increase in tree height was observed. In the second control plots (unimproved genetic material) the heights in the current rotation were the same as in the previous rotation. However, these results should be treated with caution as they are based on measurements from only a few plots.

Table 3.3: Comparison of dominant tree height of *P. patula* in 1989 (third rotation, 3R) and 2005 (fourth rotation, 4R) at the age of six years.

Source	Dominant height 1989 (3R)		Dominant height 2005 (4R)		df	Paired T-test	Probability
	Mean (m)	SE†	Mean (m)	SE†		α= 0.05	$\mu_1=\mu_2$
All plots excluding second control (Improved genetic material)	9.2	0.1	10.0	0.1	94	8.09	**<0.001**
Current control plots (Improved genetic material)	8.6	0.3	9.8	0.2	7	2.58	**0.036**
Second control plots (Unimproved genetic material)	9.1	0.2	9.1	0.3	5	0.00	1.000

† Standard error of the mean
Statistical significant probabilities ($p<0.05$) are shown in bold

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. This is a view supported by Evans (2005).

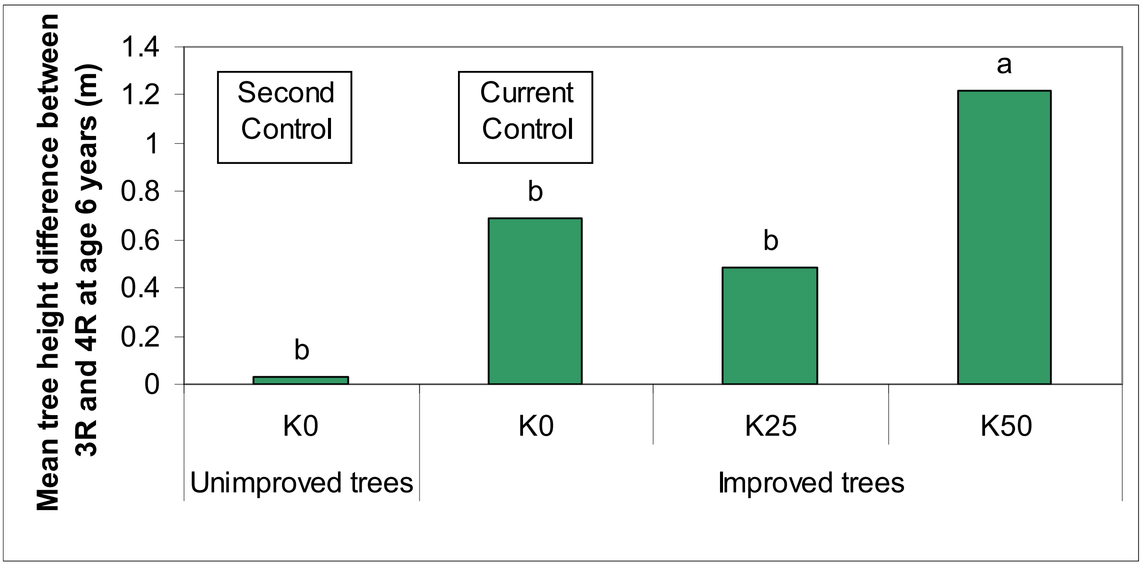


Figure 3.1: Increase in dominant height of *P. patula* trees at age six years in the fourth rotation compared to the third rotation as affected by genetic improvement and the application of K fertilizer. Different letters indicate a difference between the means at p<0.05 significance level.

The ANOVA of height differences between 3R and 4R showed that K application at planting and after pruning (50 kg K ha^{-1}) resulted in a significant increase in tree height in the current rotation (**Figure 3.1**). There was also some indication of a P x K fertilizer interaction. When P and K were applied together at planting and after pruning, 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.

3.3.2 Fourth rotation volume response to P, K and residual PK fertilizer

The ANOVA results showed that the volume response to the respective treatments was very similar from 2004 to 2006 (**Table 3.4**). Of the main treatments, both the K and residual fertilizer treatments had a significant effect on mean plot volume. The third order interaction was highly significant (p<0.05) in 2003, but after the fertilizer application in 2004 the significance declined (**Table 3.4**).

Table 3.4: An ANOVA F-probability table of volume (m³ ha^{-1}) in 2004, 2005 and 2006, and changes in these parameters over a two year period.

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	**0.028**
K	2	5.47	**0.011**	5.71	**0.009**	4.87	**0.017**	3.48	**0.047**
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.Residual_fertilizer Stratum									
Residual_fertilizer	1	8.47	**0.007**	10.74	**0.003**	9.06	**0.006**	7.94	**0.009**
P. Residual_fertilizer	2	0.01	0.991	0.11	0.899	0.37	0.691	1.34	0.278
K. Residual_fertilizer	2	0.09	0.917	0.10	0.904	0.14	0.866	0.20	0.820
P.K. Residual_fertilizer	4	2.71	**0.051**	2.29	**0.085**	2.22	**0.093**	1.73	0.173
Residual	27								
Total	71								

Statistical significant probabilities (p < 0.10) are shown in bold

From 2004 to 2006, increasing amounts of P fertilizer increased the absolute volume growth, but the increases were not statistically significant (**Table 3.5**). However, since 2004, the ANOVA F-value increased (**Table 3.4**) 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 (25 kg P ha^{-1}) 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, where P was applied both at planting and after pruning (50 kg P ha^{-1}), there was a steady increase expressed as a percentage of volume in the control plots from 2004 onwards (**Table 3.5**). This 50 kg P ha^{-1} treatment resulted in a significant 8.8% volume increase at age seven years. The application of P at planting did not affect the absolute volume or volume increment; the response was therefore likely to be the result of 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.

The application of K increased both the absolute volumes since 2004 and the volume increment over the two year period since the application after pruning (**Table 3.5**). It was only the application of the largest amount of K (total of 50 kg K ha^{-1}) that increased the volume significantly over the control. Although both the 25 and 50 kg K ha^{-1} treatments caused an increase in absolute volume, when compared to the control since 2004, the increase expressed as a percentage declined as the stand aged (**Table 3.5**). This also corresponded with results reported by Herbert and Schönau (1990) and Morris (2003), where the maximum response to K occurred when it was applied to younger stands, which is consistent with the timing of the peak rate of accretion of this nutrient into organic sinks (Morris, 1986, 1992). The residual PK fertilizer from the previous rotation also had a significant positive effect on the volume increment (**Table 3.4**). As in the case of K, the absolute volume difference increased, but the relative difference (expressed as a percentage) decreased from 2004 to 2006 (**Table 3.5**).

Table 3.5: Mean volume (m³ ha^{-1}) per main treatment from 2004 to 2006 (across all residual fertilizer treatments in the case of P and K). Different letters indicate differences between the means within each row at p<0.05 significance level.

Year	P0	P25	P50	Volume increase from 25 kg P ha^{-1}		Volume increase from 50 kg P ha^{-1}	
	(m³ ha^{-1})	(m³ ha^{-1})	(m³ ha^{-1})	(m³ ha^{-1})	%	(m³ ha^{-1})	%
2004	55.7 a	56.6 a	58.1 a	0.9	1.7	2.4	4.3
2005	90.6 a	92.1 a	96.6 a	1.5	1.7	6.0	6.5
2006	132.5 a	132.9 a	141.6 a	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 K ha^{-1}		Volume increase from 50 kg K ha^{-1}	
	(m³ ha^{-1})	(m³ ha^{-1})	(m³ ha^{-1})	(m³ ha^{-1})	%	(m³ ha^{-1})	%
2004	52.4 b	56.8 ab	61.2 a	4.4	8.4	8.8	16.8
2005	86.9 b	93.2 ab	99.2 a	6.5	7.5	12.4	14.3
2006	127.9 b	135.0 ab	144.0 a	7.1	5.5	16.1	12.6
Increment 04-06	75.5 b	78.2 ab	82.8 a	2.7	3.5	7.3	9.6

Year	Without residual fertilizer	With residual fertilizer	Volume increase from residual PK fertilizer	
	(m³ ha^{-1})	(m³ ha^{-1})	(m³ ha^{-1})	%
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

The volume response to the P x K factorial combinations was also investigated in the presence and absence of residual PK fertilizer. In 2006 the interaction was only weakly significant at the 10% level and the results must be treated with caution. In plots without residual fertilizer the application of K on its own did not affect volume at all (**Figure 3.2**). Similarly, when either 25 kg P ha^{-1} or 50 kg P ha^{-1} was applied on its own, no significant response occurred. However, when increasing amounts of K were applied with either 25 kg P ha^{-1} or 50 kg P ha^{-1}, there was a linear increase in absolute volume production. Statistical analysis showed that only the application of 50 kg K ha^{-1} with either 25 kg P ha^{-1} or 50 kg P ha^{-1} increased volume significantly (10% level) over the P25K0 and P50K0 treatments, respectively. Compared to the control treatment (P0K0), only the P50K50 treatment increased volume by 19.9 m³ ha^{-1} (only significant at the 10% level), which was equal to a 15.6% increase at age seven years. Again, these results confirmed earlier findings by Morris (1986; 1987a, 1994) that both P and K should be applied to sites on gabbro geology that were not previously fertilized. These results also corresponded with the response to fertilization in the previous rotation, where the application of both 75 kg P ha^{-1} and 75 kg K ha^{-1} at the age of six years increased mean volume by 23 m³ ha^{-1} (11%) at the age of 14 years (Crous *et al.*, 2005a). The greater 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. Results from another 12-year-old fertilizer trial with *P. patula* on the gabbro-derived soils have shown that a split application of PK fertilizer was more beneficial than a single large application after pruning (Crous *et al.,* 2005b).

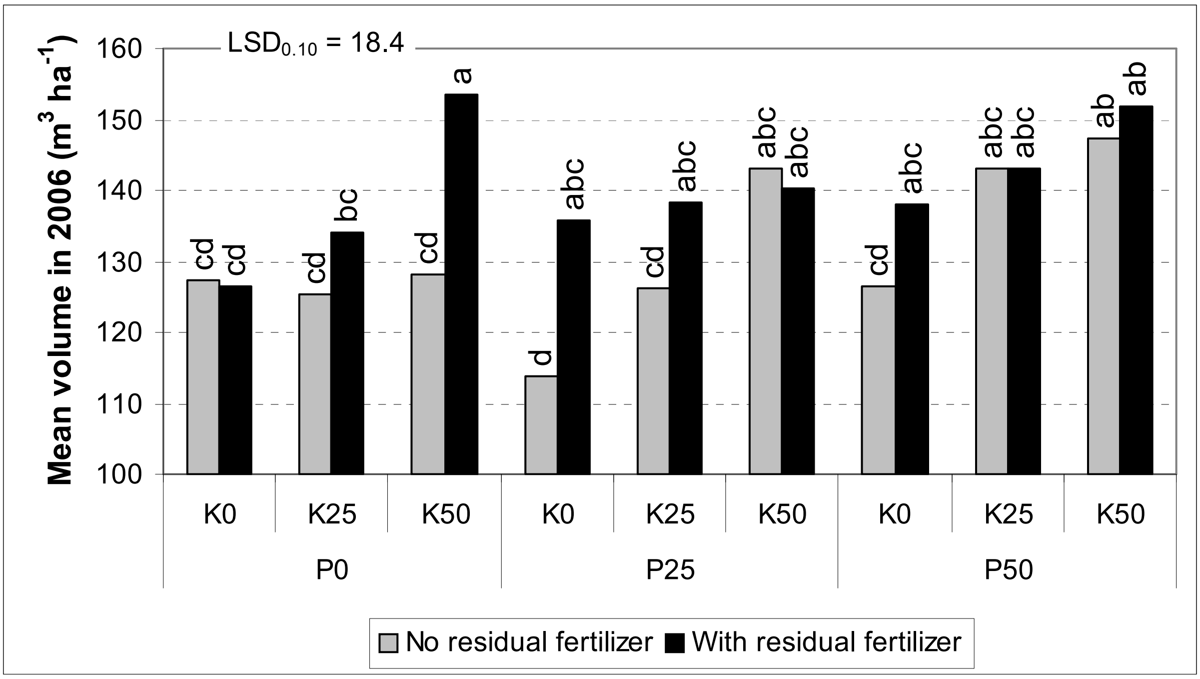


Figure 3.2: The interaction between P, K and residual PK fertilizer on mean *P. patula* volume at age seven years. Different letters indicate a difference between the means at p<0.10 significance level. (Treatment codes are explained in Table 3.2).

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 K ha^{-1} (P0K50) to plots with residual PK fertilizer increased the volume significantly when compared to the control (P0K0). The application of increasing amounts of K with either 25 kg P ha^{-1} or 50 kg P ha^{-1} 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 (**Figure 3.2**). In the presence of residual PK fertilizer a combined application of 50 kg P ha^{-1} and 50 kg K ha^{-1} increased volume by 20% (significant at the 10% level), which was similar to the 21.5% increase achieved by the application of only 50 kg K ha^{-1}. The conclusion drawn 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 to 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 (**Figure 3.2**). 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 was utilized by the trees to respond to the application of either P or K on its own in the successive rotation. Foliar analyses of 2005 collections for these respective fertilizer treatments revealed raised P levels when only K was applied and raised K levels when only P was applied to plots with residual PK fertilizer (**Table 3.6**).

Table 3.6: Foliar P and K levels of six-year-old *P. patula* in relation to 2006 volume production for selected fertilizer treatments. Different letters indicate a difference between the means within each column at p<0.05 significance level.

Treatment	Volume 2006 (m^3 ha^{-1})	Foliar P 2005 (%)		Foliar K 2005 (%)	
P0K50 (no residual fertilizer)	128.2	0.12	c	0.54	ab
P0K50 (with residual fertilizer)	153.5	0.14	ab	0.61	a
P25K0 (no residual fertilizer)	113.8	0.13	bc	0.43	c
P25K0 (with residual fertilizer)	135.7	0.13	bc	0.53	ab
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 Turner *et al.* (2002) reported that an increase in the 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 in studies conducted by Grey *et al.* (1979) and Morris (2003). The response to residual K, 15 years after 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 to 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).

3.4 CONCLUSIONS

The trial reported on in this paper was designed to study the effects of subsequent P and K fertilizer applications to previously fertilized rotations on gabbro-derived geology, which covers about 13% of the Usutu Forest. It was only on these sites that P and K nutritional problems have occurred in the past. Over the rest of the forest, yield of successive crops has been equal or superior to the preceding crop (Evans, 2005).

The comparison of dominant tree height in the trial at six years in the third rotation with 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 the interaction between P, K and the residual PK fertilizer was only weakly statistically significant. In the absence of residual fertilizer, only a combined application of P and K fertilizer at the 50 kg ha^{-1} rate increased volume significantly at the 10% level. On plots where PK fertilizer was applied during the previous rotation the application of only 50 kg K ha^{-1} had a similar positive response as a combined PK application of 50 kg ha^{-1} each. Foliar P and K concentration was also raised to sufficient levels when only 50 kg K ha^{-1} was applied to previously fertilized plots. Thus, the residual P fertilizer was sufficient to supply the early demands of the crop when additional K was supplied. However, there were 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 the early demand of the trees.

It is concluded that fertilizer applications at planting to successive crops can be adjusted to allow for the benefit from residual P applied to the previous crop. The re-application of K at planting will be of utmost importance to maintain volume production in subsequent rotations on the gabbro-derived soils. 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.

Although the tree growth results from the complete trial indicated that the application of fertilizer as well as the residual fertilizer had a significant impact, the effect of the fertilizer on soil nutrients and organic matter remained unknown. This aspect will be addressed in the following chapter.

CHAPTER 4

EFFECTS OF RESIDUAL PHOSPHORUS AND POTASSIUM FERTILIZER ON ORGANIC MATTER AND SOIL NUTRIENTS IN A *PINUS PATULA* PLANTATION

Shortly before the application of fertilizer after pruning, foliar, soil and forest floor litter samples were collected from 12 of the main plots that did not receive any fertilizer in the 4R, but where PK fertilizer was applied to one half of each of these plots in the 3R. Comparison of biomass values and nutrient concentrations and nutrient contents on these plots were used to determine the fertilizer effects that were carried over to the site in the next rotation of plantation trees.

ABSTRACT

On the Usutu plantation the sustained production from successive *Pinus patula* rotations has been an active research focus for nearly fifty years. On 13% of the plantation, underlain by gabbro rocks, a 20% growth decline was reported between first (1R) and second (2R) rotations as result of developing potassium (K) and phosphorus (P) deficiencies. The operational application of fertilizer containing 75 kg P ha^{-1} and 75 kg K ha^{-1} corrected the decline in yield. In 1989 P and K fertilizer was randomly applied, at the above rate, to one half of each of the trial plots in a six year 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 fertilizer on the nutrient content of the foliage, forest floor and topsoil in the 4R crop. Fifteen years after the initial fertilizer application, 0.5 M H_2SO_4 extracted $P_{inorganic}$ + $P_{organic}$ in the topsoil (5 – 100 mm) 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 fertilizer, although the mass of the partially and fully decomposed forest floor litter increased by 3.5 t ha^{-1} (10% level). The residual fertilizer only increased the P concentration of the various needle components and had no effect on any other components or nutrients in the organic matter. We conclude that residual P fertilizer had a greater effect on foliar, forest floor and soil nutrient content than residual K fertilizer.

4.1 INTRODUCTION

The 60 000 ha Usutu plantation is situated 25 km southwest of Mbabane in the western Highveld of Swaziland. It grows pine (mainly *Pinus patula*) as raw material for the production of unbleached kraft pulp. High productivity 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 subsequent rotations is critical to the sustainable supply of low cost timber to the pulp mill.

Bio-geochemical 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 fifty years. The comparison of growth over four rotations showed that over the largest part of the forest the mean height growth was significantly greater in 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 the southeast USA, a 10% to 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; Madgwick *et al.*, 1970). This significant growth increase, after a single application of K, was still evident after 39 years (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; 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 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 (1987a; 1994a) 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} elemental P and K, respectively, at pruning. Continuing measurements have shown that these operational fertilizer 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 fertilizer applied to a gabbro-derived soil in the previous rotation would have any residual benefit. The effect of the residual P and K fertilizer on nutrient content of the current crop's foliage, the forest floor and topsoil is reported here.

4.2 MATERIALS AND METHODS

4.2.1 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 per annum 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). Clay content is relatively high, while base saturation is low. General soil texture and chemical properties for a soil pit near the trial are shown in **Table 4.1**.

Table 4.1: Selected soil properties of a soil pit located at the trial site in a fourth rotation *P. 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

4.2.2 Trial description

4.2.2.1 Third rotation trial

In the spring of 1989, a third rotation trial (3R) was established in a six-year-old *P. patula* compartment. 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 (6 x 10 rows). A broadcast application of P and K fertilizer was randomly allocated to one of each of these pairs of split-plots. The rate was equivalent to 75 kg P and 75 kg K per hectare (Morris, 1999). 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.

4.2.2.2 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-fertilizer 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 x 3K factorial treatments (applied in the 4R) consisted of a combination of 0, 25 and 50 kg elemental P and K per ha. Superphosphate (10.5% P) and potassium chloride (50% K) fertilizer were used. Three additional treatments were imposed to determine the effects of late application and larger amounts of fertilizer. At the age of five years, two of these additional treatments as well as the control treatment had not received any fertilizer 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 fertilizer was applied previously and one where P and K fertilizer was applied in 1989, a total of 24 split-plots were available to study the effect of the residual fertilizer. In 2004 the foliage, forest floor and soil in these plots were intensively sampled.

4.2.3 Sampling procedure and chemical analysis

4.2.3.1 Foliar samples

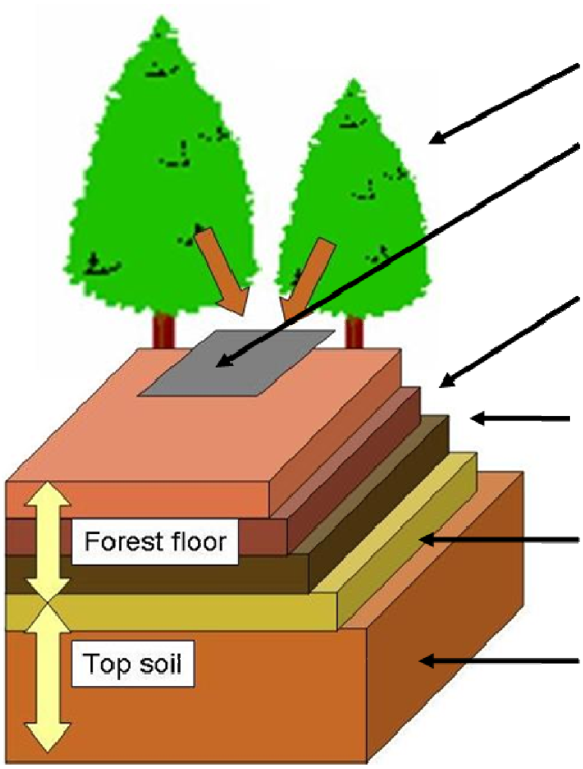
The sampling protocol was based on recommendations of Will (1985), Linder (1995) and Louw and Scholes (2003). The foliage samples were collected during the dormant season (July) from the top third of the crown when the stand was 4.8 years old. Two second-order branches were cut off and the previous season's 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 hours 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 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).

4.2.3.2 Recently senesced needle samples

Needle litterfall was collected over a four month period (from mid July to mid October 2004) prior to the application of the at-pruning fertilizer in two 1.2 x 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.

4.2.3.3 Forest floor samples

Forest litter was sampled in July 2004 over two 0.5 m x 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 (**Figure 4.1**). The fermentation layer (F) consisted of partially decomposed organic material (Van der Watt and Van Rooyen, 1995).



Live foliage from top third of live crown	
Senesced needles collected in litter traps	
Litter (L) Loose easily recognized organic material	Needles
	Dead branches
Fermentation layer (F)	Partially decomposed organic matter
Humus layer mixed with mineral soil (H & A_1)	Completely decomposed litter mixed with top 5 mm mineral soil
Topsoil (A_2)	Remaining mineral soil to a depth of 100 mm

Figure 4.1: Schematic diagram to show the different organic and soil components that were sampled in the fourth rotation (4R) with *P. patula* at age 4.8 years, 15 years after the initial application of 75 kg elemental P and K per hectare, respectively, to the 3R crop at Usutu, Swaziland.

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. Macro nutrient content of the three respective litter components was analysed using the methods described earlier.

4.2.3.4 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 x 0.25 m areas located systematically within each split-plot. Soil samples of the A_2 horizon were taken between a depth of 5 mm to 100 mm. The amount of mineral soil in all the samples was determined by means of loss on ignition analysis. The pH; ammonium acetate extractable Ca, Mg, Na, K (Kalra and Maynard, 1991); and total K, extracted with boiling nitric acid (Helmke and Sparks, 1996), was determined for 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).

4.2.4 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).

4.3 RESULTS AND DISCUSSION

4.3.1 Live foliar samples

The residual P and K fertilizer from the application 15 years earlier increased the P concentration of the live needles by only 50 mg kg^{-1} (**Table 4.2**). The increase in foliar P concentration associated with the application of P fertilizer corresponded with findings by Flinn *et al.* (1982), Turner (1982), Maggs (1985 and 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 fertilizer. However, results from the complete trial, showed that the residual P and K fertilizer increased tree volume per unit area significantly from the age of five years up to age seven years. At the age of seven years residual P and K fertilizer 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.*, 2007a). 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 to show that the concentration of the other nutrients, including K, differed as a result of previous fertilizer. Nutrient ratios of N:P, N:K and P:K were also not significantly affected. The residual fertilizer also had no significant effect on the dry mass of 100 fascicles.

Table 4.2: Nutrient concentration of live foliage collected during the dormant season from 4.8 year old *P. patula* trees at Usutu.

Nutrient or Ratio	Unit	Without residual fertilizer		With residual fertilizer		Paired T-test	Probability
		Mean	SE[a]	Mean	SE[a]	α = 0.05 df = 23	$\mu_1=\mu_2$
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
Statistically significant probabilities (p< 0.10) are shown in bold type

4.3.2 Recently senesced needle samples

The average weight of needles collected over a 14 day period in the litter traps was not affected by residual fertilizer. 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 4.3**). 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 4.3**) with that in the live foliage (**Table 4.2**) 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-year-old stand.

Table 4.3: Nutrient concentration of senesced *P. 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 fertilizer		With residual fertilizer		Paired T-test $\alpha = 0.05$ df = 23	Probability $\mu_1=\mu_2$
		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
Statistically significant probabilities ($p < 0.05$) are shown in bold type

4.3.3 Forest floor samples

The total mass of forest floor was consistent with earlier measurements 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 fertilizer. 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 4.4**). The third rotation fertilizer application increased stem volume of the 3R crop (Crous *et al.*, 2005b; 2008a) 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.

Table 4.4: Oven-dry mass (adjusted for soil contamination) of organic material on the forest floor of a 4.8 year old fourth rotation *P. patula* crop at Usutu.

Layer[a]	Unit	Without residual fertilizer		With residual fertilizer		Paired T-test $\alpha = 0.05$ df = 23	Probability $\mu_1=\mu_2$
		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 and 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 = Humus layer
[b] SE = Standard Error of the mean
Statistically significant probabilities ($p < 0.10$) are shown in bold type

Turner *et al.* (2002) reported that although residual P fertilizer 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 the present study. The present study's 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 fertilizer and those without might also be related to enhanced litter decomposition associated with the application of fertilizer. 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 fertilizer. Maggs and Hewett (1986) showed that superphosphate application to *P. elliottii* on the coastal lowlands of southeast 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 base content of the litter. However, there was no evidence in the present 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 4.5**). The phosphorus concentration increased slightly, but significantly (p = 0.051) in the plots where fertilizer was applied in 1989.

Table 4.5: Nutrient concentration of the needle component in the forest floor L layer, of a 4.8 year old fourth rotation *P. patula* crop at Usutu.

Nutrient	Unit	Without residual fertilizer		With residual fertilizer		Paired T-test	Probability
		Mean	SE[a]	Mean	SE[a]	$\alpha = 0.05$ df = 23	$\mu_1 = \mu_2$
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
Statistically significant probabilities (p< 0.10) are shown in bold type

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 fertilizer in 1989 and those that did not receive fertilizer.

Maggs (1985) also reported that only the needle component of the litter under a *Pinus elliottii* compartment responded positively to the application of P fertilizer.

4.3.4 Soil samples

In the H&A_1 layer neither the soil P (Bray 2 and 0.5M H_2SO_4 extracted P), nor exchangeable soil K concentration expressed per kilogram soil was statistically different, although the absolute values were higher on plots with residual P and K fertilizer. However, when the actual nutrient amount (content) per hectare was calculated, the differences as a result of residual P and K fertilizer were 0.3 kg ha^{-1} for plant available P, 2.5 kg ha^{-1} for 0.5M H_2SO_4 extracted P_i, 7.7 kg ha^{-1} for 0.5M H_2SO_4 extracted P_{i+o} and 1.4 kg ha^{-1} for exchangeable K (significant at the 10% level) (**Table 4.6**). 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 fertilizer. 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 (1974).

Table 4.6: Comparison of soil characteristics of the humus (H) layer mixed with the top 5 mm of soil, 15 years after the initial application of P and K fertilizer to the previous rotation (3R) of *P. patula* at Usutu.

Parameter [a]	Unit	Without residual P and K fertilizer		With residual P and K fertilizer		T-test $\alpha = 0.05$	Proba-bility
		Mean	SE [b]	Mean	SE [b]	df = 23	$\mu_1=\mu_2$
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 (0.5M H_2SO_4)	kg ha^{-1}	12.7	0.93	15.2	1.11	-1.84	**0.079**
P_o (0.5M H_2SO_4)	kg ha^{-1}	41.7	2.27	46.8	2.90	-1.52	0.142
P_{i+o} (0.5M H_2SO_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
Statistically significant probabilities ($p < 0.10$) are shown in bold type

The P_o fraction comprised 76% of the 0.5M H_2SO_4 extracted P pool in the H&A_1 layer. The reason for the very small difference in Bray 2 P and 0.5M H_2SO_4 extracted P_o levels between the plots with residual fertilizer 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 completely contained within the individual plots, a small amount of foliage with higher P levels from fertilised plots was probably mixed with foliage from plots without fertilizer and vice versa. This could have had an effect as Turner *et al.* (2002) reported that they observed lateral movement of phosphate due to litter fall from fertilised plots into the unfertilised plots.

In absolute terms the amount of Ca and Mg also increased (although not significantly) on the plots with residual fertilizer. This observation corresponded with observations of an accumulation of nutrients (even nutrients that were not applied with the fertilizer) 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.

Apart from P, none of the other topsoil (A_2) chemical properties were significantly affected by the residual fertilizer. In the first 5 to 100 mm of topsoil the plant available P, 0.5M H_2SO_4 extracted P_{i+o} and P_o were significantly increased by the residual fertilizer. The increase was a mere 1.3 mg kg^{-1} in the case of plant available P, but the increase in 0.5M H_2SO_4 extracted P_{i+o} was a substantial 44.7 mg kg^{-1} (**Table 4.7**).

Table 4.7: Comparison of some topsoil characteristics (5 to 100 mm depth), 15 years after the initial application of P and K fertilizer to the previous rotation (3R) of *P. patula* at Usutu.

Parameter [a]	Unit	Without residual P and K fertilizer		With residual P and K fertilizer		T-test $\alpha = 0.05$	Probability $\mu_1=\mu_2$
		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 (0.5M H_2SO_4)	mg kg^{-1}	135.2	4.6	144.1	5.4	-1.52	0.143
P_o (0.5M H_2SO_4)	mg kg^{-1}	273.5	14.3	309.3	16.9	-2.72	**0.012**
P_{i+o} (0.5M 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
Statistically significant probabilities ($p < 0.10$) are shown in bold type

This was mainly due to an increase in the organic P fraction. The 0.5M H_2SO_4 extracted P_o fraction contained 68% of the 0.5M 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 fertilizer 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 fertilizer 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. This is a view supported by Polglase *et al.* (1992a and 1992b).

The persistent effect of phosphorus fertilizer was not unexpected as Schönau (1984) reported that residual superphosphate was available to a certain extent for the new crop after a period of 10 years. If the difference in 0.5M 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 fertilizer was 41 kg P per hectare more than on plots that did not receive fertilizer previously. This represented 54.7% of the 75 kg ha^{-1} P that was applied 15 years earlier and was more than the 42% that could be accounted for by Comerford *et al.* (2002) 29 years after the application of 70 kg ha^{-1} P or the 44% reported by Flinn *et al.* (1982) three years 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 years 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 fertilizer moved 11 to 16 m from the edge of fertilised plots over a 50 year period.

4.4 CONCLUSIONS

The results from the present study showed that the residual P fertilizer had a greater effect on the foliage, forest floor and soil nutrient content than the residual K fertilizer. As in other studies, the P fertilizer 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 fertilizer, 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 fertilizer was converted into P_o forms. P_o is less prone to leaching or adsorption and will be a future source of available P to the crop. Thus, the conservation of organic material will be extremely important to ensure long term P cycling.

The 12 intensively sampled plots only investigated changes in foliar nutrients and topsoil nutrients that were associated with residual P and K fertilizer. The effects of the application of P and K fertilizer in the presence and absence of residual PK fertilizer on tree growth and foliar nutrient concentrations will be discussed in the following chapter.

CHAPTER 5

GROWTH AND FOLIAR NUTRIENT RESPONSE TO RECENT APPLICATIONS OF PHOSPHORUS (P) AND POTASSIUM (K) AND TO RESIDUAL P AND K FERTILIZER APPLIED TO THE PREVIOUS ROTATION OF *PINUS PATULA* AT USUTU, SWAZILAND

In this chapter the interaction between foliar nutrient levels in the trial, the fertilizer treatments and the associated response in tree growth will be reported on. Furthermore, the application of critical foliar nutrient levels reported for *P. radiata* in New Zealand will be investigated for use at Usutu to identify P and K nutrient deficiencies. These critical foliar concentrations and ratios can be used in future to monitor changes to fertilizer prescriptions at Usutu.

ABSTRACT

In a long-term phosphorus (P) and potassium (K) fertilizer trial, established on gabbro-derived soil in the Usutu plantation, the growth and foliar responses of six-year-old *P. patula* were studied. In 1989, when the third rotation (3R) trees were six years old, 75 kg elemental P and K per ha, respectively, was applied to one half of 52 plots. In the 4R a factorial design with applications of 0, 25 and 50 kg P and K per ha was superimposed on the previous trial plots. The 50 kg ha^{-1} applications consisted of two applications of 25 kg ha^{-1} at planting in 1999 and after pruning at age 5 years in 2004. The results indicated that on plots fertilised for the first time, the application of 50 kg K ha^{-1} increased the foliar N, P and K concentration and the application of 50 kg P ha^{-1} increased foliar P and K concentration. Volume increment over a two year period was increased by 7 or 8 m^3 ha^{-1} when either foliar P was above 0.14% or K was above 0.50%. The maximum volume increment was achieved when both nutrients were at levels above their respective critical values. In the senesced needles, P fertilizer increased the P concentration, while K fertilizer increased the K concentration, which showed that the application of fertilizer reduced these nutrient deficiencies. There was evidence that the foliar nutrient response to residual P fertilizer was greater than the response to residual K fertilizer. These results suggest that fertilizer application to successive rotations can be adjusted to allow for the benefit of residual P fertilizer. The critical foliar values for P, K as well as the nutrient ratios can be used to monitor the response to revised fertilizer prescriptions.

5.1 INTRODUCTION

Pinus patula is the main species grown on the 60 000 ha Usutu plantation, situated 25 km southwest of Mbabane in the western Highveld of Swaziland, as raw material for the production of unbleached kraft pulp. Almost 50 years of research on sustained production from the forest has shown that height growth has increased over four successive rotations in most of the forest (Evans, 2005). Yet, on about 13% of the forest area, underlain by gabbro geology, both height and volume per hectare had declined significantly by approximately 18% in the second rotation (Evans, 1986) as a result of a developing phosphorus (P) and potassium (K) deficiency (Morris, 1986). Elsewhere, P deficiencies in pine plantations were found to occur widely and have been well documented (Ballard, 1978; Pritchett and Comerford, 1982; Will, 1985; Gentle *et al.*, 1986; Haywood and Tiarks, 1995, Tiarks, 1999). Because K deficiencies are less common in pine plantations and only a few reports exist (Raupach and Hall, 1974; Stone and Kszystyniak, 1977; Will, 1985; Shepard and Mitchell, 1990), there is relatively incomplete knowledge of how important this nutrient is for tree growth (Tripler *et al.*, 2006).

Recommendations by Morris (1987a) to apply 20 kg elemental P and K fertilizer per hectare at planting, followed by 75 kg elemental P and K fertilizer per hectare at pruning (age six years) corrected the decline in yield on the gabbro-derived soils (Evans, 1996). In 1989 a trial was designed to determine if the PK fertilizer that was applied to a gabbro-derived soil in the previous rotation would have any residual benefit on the nutrient status and growth of the current crop. Furthermore, it was important to determine how the residual fertilizer would interact with fertilizer applications to the new crop and to determine if the amount of fertilizer required for the next crop can be reduced without a negative effect on volume production.

The main requirement for an effective operational forest fertilisation programme is a diagnostic system that can accurately identify a site's nutrient status and secondly also predict stand responses to fertilisation amendments (Jokela *et al.,* 1988). Post-fertilisation patterns of fascicle weight and foliar nutrient concentration have been successfully used to diagnose nutrient limitation and stem growth response of coniferous species (Nômmik and Möller, 1981; Valentine and Allen, 1990). Although *P. patula* is the most common pine species in Southern Africa, surprisingly little research has been done on foliar nutrient levels (Louw and Scholes, 2003). The trial established in 1989 provided the opportunity to improve the knowledge about the foliar nutrient concentration of

P. patula in general and the effect of P and K fertilizer on nutrient concentration and tree growth in particular.

It is reported here how new applications of P and K and residual PK fertilizer influenced the nutrient levels in the live and senesced foliage; how nutrient concentration was related to volume increment; and how the data were used to identify critical values for foliar P and K concentrations in the Usutu plantation. The effects of the residual PK fertilizer on volume growth, the forest floor and soil nutrient levels in this trial were reported previously in chapters 3 and 4 (Crous *et al.,* 2007a, 2007b).

5.2 MATERIALS AND METHODS

5.2.1 Site description

The trial site is located in the eastern portion of the Usutu plantation (31°04'48"E, 26°29'24"S) 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 can be expected. About 80% of the annual rainfall is recorded between October and March, with very little precipitation occurring during the winter months. The soil on the site is deeper than 1.5 m and consists of a humic A horizon (0 to 100 mm); a yellow-brown apedal B_1 horizon (101 to 270 mm); red apedal B_2 horizon with no coarse fragments (271 to 470 mm); red saprolytic C_1 horizon (471 to 570 mm) with abundant fine gravel (3 to 5 mm diameter) and a red saprolytic C_2 horizon with no stones and a very small amount of yellow mottling (571 to >1500 mm). According to the USDA soil taxonomy system, this soil would be classified as an Oxisol (Soil Survey Staff, 2006). Although all horizons are classified having a clay texture the clay percentage decreases from 82% in the topsoil (0 to 100 mm) to 67% in the subsoil (570 to 1500 mm). Similarly, the base saturation in the soil declines from 0.20 cmol(+) kg^{-1} in the topsoil to 0.09 cmol(+) kg^{-1} in the subsoil. The plant available P (Bray 2 P-value) of 4.9 mg kg^{-1} in the topsoil is below the "critical" value of 12, as reported by Ballard (1974) for *P. radiata* plantations in New Zealand; this indicates that P deficiency can be expected. The exchangeable K content of the topsoil is very low at 0.07 cmol(+) kg^{-1}. The decrease in exchangeable K with increase in depth is indicative of parent material with low K content (Saayman[1], personal communication, 1993). More details of selected soil properties were published in Crous *et al.*, (2007a).

5.2.2 Trial description

5.2.2.1 Third rotation trial

In the spring of 1989, the third rotation (3R) trial was established in a six-year-old *P. patula* compartment as a foundation to superimpose a factorial P x K x residual PK fertilizer trial in the following rotation. The trial consisted of 52 main plots each 12 x 10 rows in size (at 2.7 m x 2.7 m planting density). Each plot was split into two (6 x 10 rows). A broadcast application of PK fertilizer was randomly allocated to one of each of these pairs of split-plots. The PK rate was equivalent to 75 kg P and 75 kg K per hectare. Thus, the two fertilizer treatments were replicated 52 times each. At clear felling in 1998, 9 years after the first fertilizer application, only tree stems with bark were removed from the site. The remaining harvest residue was left *in situ* and was not burnt, following standard silvicultural practice.

5.2.2.2 Fourth rotation trial

The fourth rotation (4R), *P. patula* trial was re-established in September 1999 at the exact location of the former 3R PK-fertilizer trial. In the new 4R trial design the residual PK effect from the P and K fertilizer applied in 1989 to the 3R crop, occurred as a split-plot treatment within each main plot. The 3P x 3K factorial design, applied at establishment of the 4R, consisted of a combination of 0, 25 and 50 kg elemental P and K per ha (**Table 5.1**). The 25 kg ha^{-1} elemental P or K applications were applied at planting in September 1999 as a spot application of fertilizer in a small pit next to each tree. The 50 kg elemental P or K per ha applications consisted of a 25 kg ha^{-1} application at planting followed by a 25 kg ha^{-1} broadcast application after pruning at the age of five years in October 2004, for each element respectively. The espacement in the 4R was adjusted to 2.7 x 2.08 m (12 x 13 trees per plot) in order to reflect the current operational planting density. Three additional treatments were also included in the design to test the effect of larger amounts of fertilizer as well as late application of fertilizer (**Table 5.1**). As

[1] Saayman, D., Faculty of AgriSciences, Department of Soil Science, University of Stellenbosch.

these 12 treatments were replicated four times it occupied 48 of the original 52 plots. Of the remaining four plots, three were re-established at the 3R espacement with unimproved genetic material to be used as a second control. The boundaries of one plot could not be located with certainty and was excluded from the 4R trial design. Superphosphate (10.5% P) and potassium chloride (50% K) were the sources of P and K in both rotations.

Table 5.1: Summary of the nine main treatments and four additional treatments applied to the fourth rotation (4R) P and K fertilizer trial in a *P. patula* compartment at Usutu, Swaziland

Treatments in trial design	Code	Applied at Planting (Sep 1999) (kg ha^{-1})		Applied after Pruning (Oct 2004) (kg ha^{-1})		Total P:K (kg ha^{-1})
		P	K	P	K	
Main *	P0K0	0	0	0	0	0:0
	P0K25	0	25	0	0	0:25
	P0K50	0	25	0	25	0:50
	P25K0	25	0	0	0	25:0
	P25K25	25	25	0	0	25:25
	P25K50	25	25	0	25	25:50
	P50K0	25	0	25	0	50:0
	P50K25	25	25	25	0	50:25
	P50K50	25	25	25	25	50:50
Additional *	P50K50 Late	0	0	50	50	50:50
	P75K75 Late	0	0	75	75	75:75
	P75K75 Split	25	25	50	50	75:75
2nd Control †	P0K0(2ndCntr)	0	0	0	0	0:0

* Improved genetic material
† Unimproved genetic material

5.2.3 Tree growth measurements

5.2.3.1 Third rotation trial

The diameter at breast height (DBH) of the inner 4 x 8 trees in each split-plot were measured with diameter tapes at the age of six years in August 1989 and thereafter in July 1994, October 1996 and August 1997. The heights of four randomly chosen trees with above average DBH were measured in each split-plot in 1989 with a hypsometer. The heights of the same trees were measured during subsequent assessments.

5.2.3.2 Fourth rotation trial

The first three assessments consisted of tree height measurements of the inner 3 x 9 trees on each split-plot with a height rod at the age of 9, 21 and 33 months, respectively. From the age of 45 months (July 2003) both height and DBH over bark of the inner 4 x 9 trees per split-plot were recorded each year during July. From 2003 tree height was measured with a *Vertex* hypsometer and DBH with a diameter tape.

5.2.4 Sampling procedure and chemical analysis

5.2.4.1 Foliar samples

The sampling protocol was based on recommendations of Will (1985), Linder (1995) and Louw and Scholes (2003). During the dormant season in July 2004, when the 4R crop was almost five years old, and a year later in July 2005 at age six years, foliar samples were collected from five dominant or co-dominant trees per split-plot. Two second-order branches were cut off from the top third of the crown and the previous season's foliage that had reached mature length was collected and bulked on an equal number of needle bundles (fascicles) basis. The foliar samples were dried in a ventilated oven for 72 hours at 70°C. The dry mass of 100 randomly selected fascicles per split-plot sample was also determined. After fine grinding, total nitrogen (N) was determined by the Kjeldahl method. The other macro nutrients were analysed after 2.5 g of the ground samples was dry ashed and taken up in a solution of 0.6N HCl. Phosphorus (P) was determined by the molybdenum blue method in an auto analyzer, while calcium (Ca) and magnesium (Mg), were determined using atomic absorption spectroscopy. Potassium and sodium (Na) were determined by flame emission spectroscopy (Donkin *et al.*, 1993). All concentrations were expressed as a percentage of dry mass. Micro nutrient concentrations were not determined, because earlier studies showed no evidence of micro nutrient deficiencies in *P. patula* planted in the summer rainfall area of Southern Africa (Carlson and Allan, 2001; Louw and Scholes, 2003).

5.2.4.2 Needle litter trap samples

Litterfall was collected in a 1.2 x 1.2 m litter trap made of shade cloth, suspended within a metal frame, on each split-plot. The collection periods in both 2004 and 2005 lasted from the beginning of July to the middle of October as the collection period in 2004 was suspended with the at-pruning fertiliser application. In 2004, one additional litter trap was installed in each of the 24 split-plots that did not receive any fertilizer at planting in the 4R trial. Samples were collected every 14 days and oven dried. An equal number of fascicles from the annual litter trap sample collections were pooled per trap position for chemical analysis similar to the foliage sample analysis.

5.2.5 Calculations and Statistical analysis

A logarithmic transformation of 3R height values was conducted in order to determine the height/DBH relationship with the least squares method of simple linear regression (Bredenkamp, 1993). Volume estimation of trees was performed from DBH and regression height values (3R) or actual height measurements (4R) using a Max and Burkhart function (**Equation 5.1**) with coefficients determined by Kotze (1996) cited in Bredenkamp (2000).

$$V_t = \left(\frac{\pi}{40000}\right) * k * dbh^2 * HT \qquad \text{[Equation 5.1]}$$

where:

$$k = \left(\frac{b_2}{3}\right) + \left(\frac{b_1}{2}\right) - \left(b_1 + b_2\right) + \left(\frac{b_3}{3}\right)\alpha_1^3 + \left(\frac{b_4}{3}\right)\alpha_2^3$$

V_t	=	total under bark tree volume
dbh	=	breast height diameter (cm, over bark)
HT	=	tree height (m)
b_1	=	-3.26841 for *P. patula*
b_2	=	1.50249 for *P. patula*
b_3	=	-1.78287 for *P. patula*
b_4	=	23.7720 for *P. patula*
α_1	=	0.73068 for *P. patula*
α_2	=	0.09391 for *P. patula*

Third rotation data were analysed with a paired t-test (double-sided, α=0.05), because the samples from each treatment were matched or paired in the split-plots. Statistical analyses of 4R data were performed with *Genstat 8.1* software using the Analysis of Variance (ANOVA) procedure (Payne *et al.*, 2005). Differences between the means were further investigated with Fisher's protected LSD multiple comparison test, either at the 5% or 10% level. Product-moment correlations, multiple linear regression and logistic regression were used to investigate the association between absolute foliar nutrient levels, critical foliar levels and observed volume growth responses (Payne *et al.*, 2005).

5.3 RESULTS AND DISCUSSION

5.3.1 Tree growth

5.3.1.1 Third rotation trial

As expected, none of the variables showed a significant difference between fertilised and control plots when the trial was established in 1989. However, at the age of 14 years, tree height, basal area and volume indicated a significant growth difference between fertilised and unfertilised plots in the third rotation (**Table 5.2**).

Table 5.2: Summary of mean growth responses of *P. patula* trees at Usutu in the third rotation (3R) from 1989, when PK fertilizer was applied to one half of each of the 52 plots, up to clear felling in 1997.

Year	Age	Plots	Plots	Difference	T-test	Probability
Mean tree height of measured trees (m)						
1989	6	9.2	9.2	-0.1	0.57	0.572
1994	11	16.3	16.4	0.1	-1.35	0.184
1996	13	17.6	18.0	0.4	-3.90	**<0.001**
1997	14	18.9	19.3	0.5	-3.31	**0.002**
Increment		9.6	10.1	0.5	-3.43	**0.001**
Quadratic mean DBH (cm)						
1989	6	12.3	12.1	-0.2	1.37	0.178
1994	11	18.5	18.8	0.3	-1.31	0.195
1996	13	19.9	20.1	0.2	-1.02	0.311
1997	14	20.5	20.7	0.2	-0.89	0.376
Increment		8.2	8.6	0.4	-2.68	**0.010**
Basal area (over bark) per hectare (m^2 ha^{-1})						
1989	6	13.3	13.0	-0.3	0.85	0.402
1994	11	29.3	30.9	1.6	-2.58	**0.013**
1996	13	33.4	35.1	1.7	-2.33	**0.024**
1997	14	35.0	37.0	2.0	-2.58	**0.013**
Increment		21.7	24.0	2.3	-3.49	**0.001**
Live Stems (Stems ha^{-1})						
1989	6	1115	1125	10	-0.37	0.715
1994	11	1090	1113	23	-0.88	0.384
1996	13	1083	1105	22	-0.83	0.409
1997	14	1070	1101	31	-1.20	0.236
Increment		-45	-24	21	-1.08	0.285
Volume (m^3 ha^{-1})						
1989	6	45.0	44.3	-0.7	0.70	0.490
1994	11	178.5	188.2	9.7	-2.54	**0.014**
1996	13	220.4	236.7	16.3	-3.33	**0.002**
1997	14	250.4	272.5	22.1	-3.97	**<0.001**
Increment		205.4	228.3	22.9	-4.50	**<0.001**

Bold type indicates statistically significant differences at $p<0.05$.

The effect of the PK fertilizer on growth (particularly volume growth) became more apparent towards the end of the rotation as the differences increased to 22.1 m³ ha^{-1} (8.8% increase). Although the difference in quadratic mean DBH was not significant in any single assessment over the rotation, the 0.41 cm increase in DBH growth because of the fertilizer application was significant. The number of live stems per hectare was not affected by the fertilizer.

5.3.1.2 Fourth rotation trial

The 4R data ANOVA results also showed that the fertilizer had no significant effect on survival (**Table 5.3**). The application of P increased the DBH increment and volume increment between age five and seven years significantly (**Table 5.3**). The application of P only at planting did not have any significant effect on DBH or volume when the trees were five years old in 2004 (**Table 5.3**), but after the application of fertilizer in 2004 the F-probability decreased annually (**Table 5.3**), showing that the significant difference in DBH increment and volume increment occurred mostly after the application of P fertilizer at the age of five years. This observation corresponded with findings by Morris (2003) that at Usutu the response to P increased when applied to older stands. In the case of K, the highest rate (50 kg ha^{-1} K) increased the DBH, mean tree height and mean plot volume significantly over all three years. This resulted in a 13% increase (from 127.9 to 144.0 m³ ha^{-1}) in total volume at the age of seven years. The residual PK fertilizer, that remained from the 3R application, had a significant effect on DBH, tree height and volume production over all three years reported (**Table 5.3**). On plots with residual fertilizer, the trees were on average 0.3 m taller, 0.4 cm thicker in diameter and produced 8.9 m³ ha^{-1} more timber at the age of seven years compared to the trees on plots without residual fertilizer, which had a mean height of 10.5 m, a DBH of 14.5 cm and a mean plot volume of 131.2 m³ ha^{-1}. The statistical significance of the P x K x residual fertilizer interaction observed for tree height and mean plot volume decreased from 2004 to almost insignificant levels in 2006 (**Table 5.3**). The mean volume increment between the age of five and seven years also indicated that all three main treatments had a significant effect. The highest rate of P and K (50 kg ha^{-1}), applied as a split application at planting and after pruning, increased the volume increment between the age of five and seven years (**Table 5.3**, **Figure 5.1**). The residual PK fertilizer remaining from the application to the previous rotation also increased the volume increment between 2004 and 2006.

Table 5.3: A summary of analysis of variance F-probability values for tree growth measurements between the age of five and seven years in a P x K x residual P and K fertilizer trial with *P. patula* at Usutu, Swaziland

Source	df	Live stems (stems ha^{-1})			Quadratic mean DBH (cm)				Mean tree height (m)				Mean plot volume (m^3ha^{-1})			
		2004	2005	2006	2004	2005	2006	Inc.*	2004	2005	2006	Inc.*	2004	2005	2006	Inc.*
		Probability > F														
Rep	3															
Rep.P.K stratum																
P	2	0.114	0.195	0.195	0.906	0.634	0.114	**<0.001**	0.272	**0.078**	0.330	0.577	0.664	0.250	0.160	**0.028**
K	2	0.345	0.498	0.498	**0.005**	**0.009**	**0.039**	0.115	**0.005**	**0.002**	**0.012**	0.616	**0.011**	**0.009**	**0.017**	**0.047**
P.K	4	0.628	0.521	0.521	0.671	0.556	0.894	**0.073**	0.879	0.681	0.689	0.715	0.938	0.877	0.977	0.994
Residual	24															
Rep.P.K. Residual Fertilizer stratum																
Residual Fertilizer	1	0.241	0.243	0.243	**<0.001**	**<0.001**	**0.005**	0.467	**0.006**	**0.002**	**0.011**	0.390	**0.007**	**0.003**	**0.006**	**0.009**
P. Residual Fertilizer	2	0.250	0.443	0.443	0.598	0.529	0.552	0.280	0.729	0.646	0.748	0.733	0.991	0.899	0.691	0.278
K. Residual Fertilizer	2	**0.072**	0.128	0.128	0.855	0.731	0.743	0.142	0.971	0.990	0.812	0.372	0.917	0.904	0.866	0.820
P.K. Residual Fertilizer	4	0.315	0.349	0.349	0.138	0.131	0.108	0.803	**0.021**	**0.026**	0.119	0.517	**0.051**	**0.085**	**0.093**	0.173
Residual	27															
Total	71															

* Increment between 2004 (age 5) and 2006 (age 7)
Bold type indicates statistically significant differences at p<0.10 between treatment means.

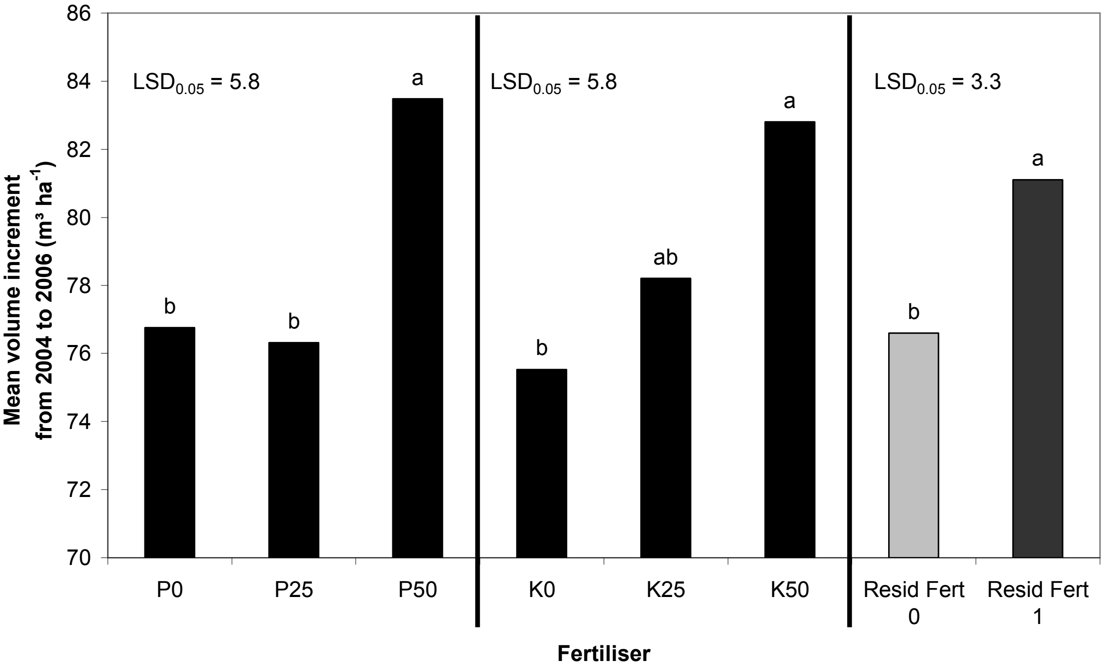


Figure 5.1: Volume increment between the ages of five and six years of *P. patula* trees at Usutu as affected by P and K applied to the present rotation, and by the residual PK fertilizer that remained from application to the previous rotation.

5.3.2 Foliar nutrient concentration

ANOVA results from the complete 4R factorial trial indicated that the N, P and K nutrient concentrations of live foliage collected during July 2005 were significantly affected by P, K and residual PK fertilizer (**Table 5.4**). The application of the lowest rate of K (25 kg ha^{-1}) increased foliar N by 0.06% to 1.67%. A doubling of the amount K did not significantly increase the nitrogen concentration further.

ANOVA results showed that the P and K fertilizer affected the foliar P concentration differently on plots with and without residual fertilizer (**Table 5.4**). This interaction is illustrated in **Figure 5.2a**. On plots without residual fertilizer the P0K25, P25K50, P50K0, P50K25 and P50K50 treatments increased P concentration in the needles when compared to the control treatment. Except for the P0K25 treatment, the increase in needle P concentration was clearly associated with an increase in the amount of P fertilizer that was applied. The increase was also large enough to raise the foliar P levels from marginal to satisfactory when 50 kg P ha^{-1} was applied. The relatively sudden increase in P concentration associated with the application of P fertilizer the previous year corresponded with findings by Flinn *et al.* (1982), Maggs (1985) and Turner *et al.* (2002). Furthermore, as was shown in other studies, the growth response to P fertilizer was reflected in concentrations of P in the foliage (Ballard, 1978; Flinn *et al.*, 1982;

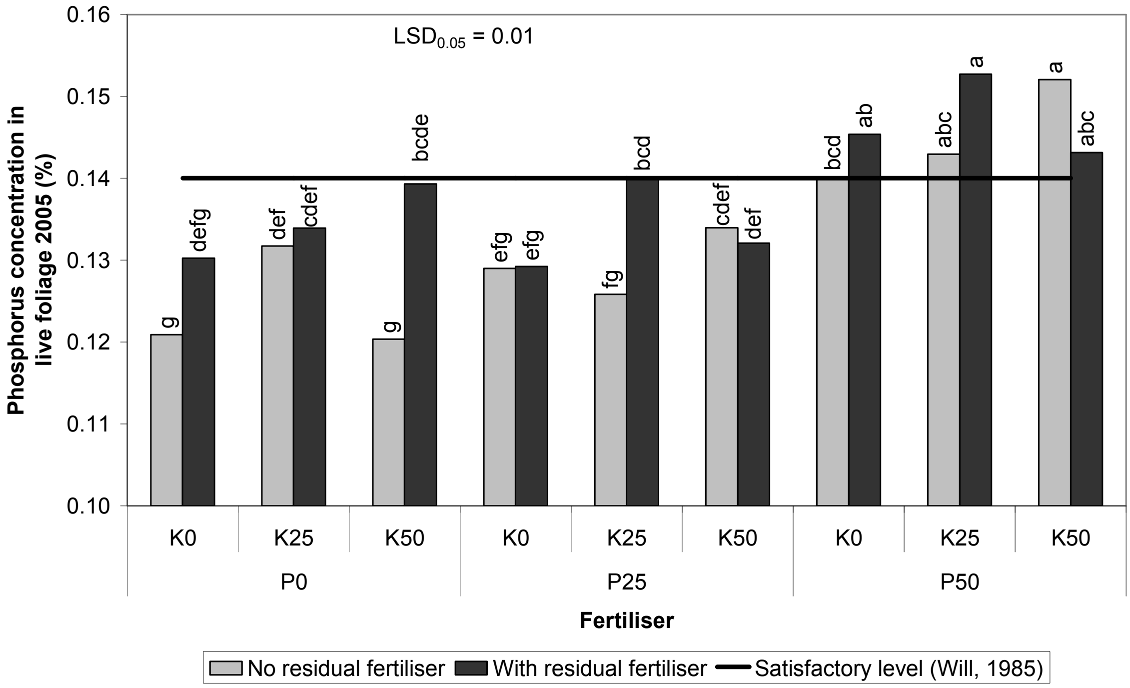
Gentle *et al.*, 1986; Turner *et al.*, 2002). In the presence of residual PK fertilizer, three treatments namely P50K0, P50K25 and P50K50 increased needle P concentration above the level measured in the control (P0K0R1). Investigation of the difference in P concentration that was caused by residual PK fertilizer within treatments showed that the P concentration only differed in the P0K50 and P25K25 treatments. The effect of the residual fertilizer on foliar P concentration where only 50 kg ha^{-1} K was applied (P0K50, with residual PK), confirmed that the foliar P level increased as a result of residual P fertilizer from the previous (3R) rotation when additional K was applied in the current rotation. This observation also corresponded with the significant (5% level) increase in total P content of the topsoil in plots with residual fertilizer, 15 years after the initial application (Crous *et al.*, 2007b).

Table 5.4: A summary of analysis of variance F-probability values for macro nutrient concentrations and ratios in live foliage collected at age six years in a P x K x residual P and K fertilizer trial with *P. patula* at Usutu, Swaziland. The P:N and K:N ratios were expressed on a mass basis as a percentage of N.

Source	df	Macro nutrient concentration in live foliage at age six years								
		%						Ratio		
		N	P	K	Ca	Mg	Na	P:N	K:N	P:K
		Probability > F								
Rep	3									
Rep.P.K stratum										
P	2	0.646	**<.001**	0.686	0.540	0.455	0.976	**<0.001**	0.912	**0.008**
K	2	**0.020**	**0.038**	**0.002**	0.553	0.517	0.328	0.492	**0.058**	**0.010**
P.K	4	0.611	0.961	0.737	0.691	0.733	0.722	0.534	0.484	0.765
Residual	24									
Rep.P.K.Residual Fertilizer stratum										
Residual Fertilizer	1	0.111	**0.004**	0.135	0.506	0.964	0.887	0.107	0.342	0.664
P.Residual Fertilizer	2	0.462	0.163	0.517	0.781	0.837	0.449	**0.016**	0.524	0.233
K.Residual Fertilizer	2	0.463	0.376	0.291	0.284	0.265	0.627	0.980	0.376	0.358
P.K.Residual Fertilizer	4	**0.085**	**0.013**	**0.069**	0.781	0.815	0.917	0.311	0.210	0.154
Residual	27									
Total	71									

Bold type indicates statistically significant differences at p<0.10 between treatment means.

a)



b)

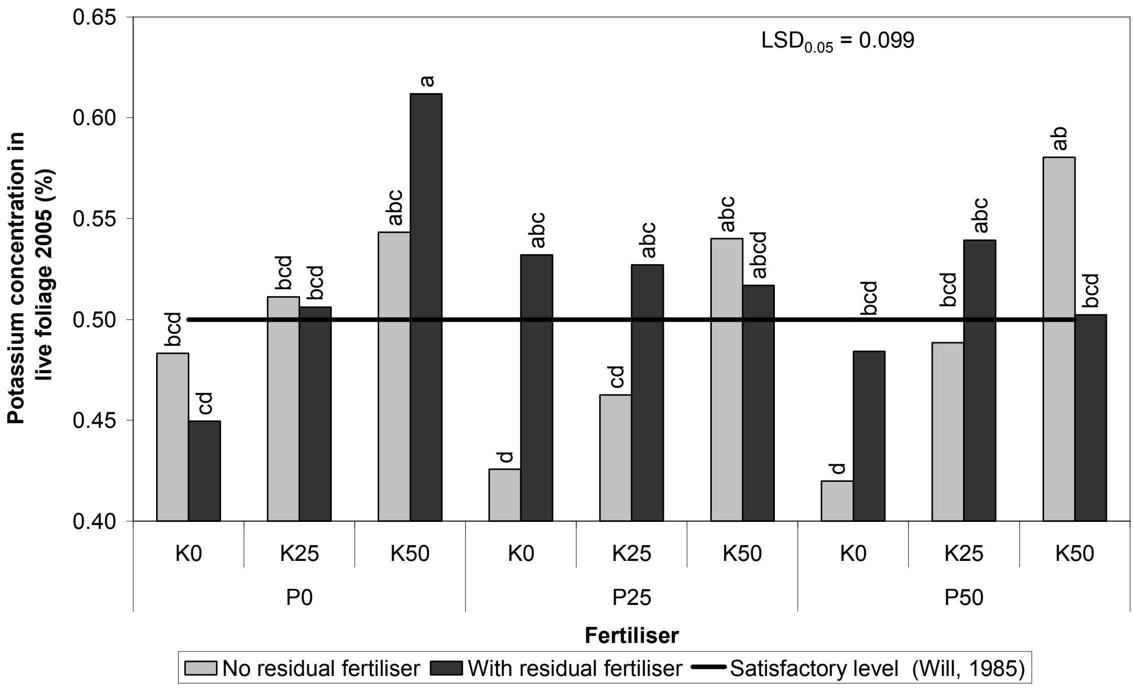


Figure 5.2: Effect of third order interaction between P, K and residual PK on foliar P concentration (a) and on foliar K concentration (b) of six-year-old *P. patula* in a fertilizer trial at Usutu, Swaziland. Different letters indicate a difference between the means at p<0.05 significance level.

Weak evidence from the ANOVA results (p = 0.069) indicated that the K concentration was influenced by a third order interaction between the main treatments (**Table 5.4**). On plots without residual fertilizer the K concentration of the live needles was mainly influenced by the K fertilizer as it caused a linear increase in absolute foliar K concentration regardless of the amount of P that was applied (**Figure 5.2b**). Increases in foliar K following K fertilisation have been observed in 76% of 38 tree studies that were reviewed by Tripler *et al.* (2006). Four of the eight fertilizer treatments (P0K25, P0K50, P25K50 and P50K50) increased foliar K to satisfactory levels. However, on plots with residual PK fertilizer there was only a trend of increasing foliar K with an increase in the application of K when no phosphate fertilizer was applied (P0K0R1, P0K25R1 and P0K50R1). When P was applied with K on the plots with residual fertilizer, no such trend was observed (**Figure 5.2b**). In the P25K0 treatment there was a significant difference between the plots with residual fertilizer and those without (**Figure 5.2b**). Furthermore, on plots with residual fertilizer the absolute foliar K concentration was close to or above the satisfactory level for all treatments except in the control (P0K0R1). This confirmed that the trees were able to take up the residual K fertilizer when P was applied at planting to the subsequent crop. The evidence of a residual K response was unequivocal. Only one example demonstrating that residual K fertilizer influenced foliar K levels over many years was reported in a *Pinus resinosa* ecosystem on glacial outwash sands in New York (Stone and Kszystyniak, 1977; Shepard and Mitchell, 1990; Buxbaum *et al.*, 2001). Nutrient analysis of organic matter and soil nutrients on selected plots in the specific trial indicated that in absolute terms the foliar K concentration was greater on plots with residual PK fertilizer and that the humus on the forest floor mixed with the first 5 mm mineral topsoil contained 1.4 kg ha^{-1} more exchangeable K (Crous *et al.*, 2007b). Therefore the residual fertilizer response can possibly be attributed to efficient recycling and retention of K in the soil.

The ratios between some nutrients were also investigated as Marschner (1986) noted that the optimal ratios between nutrients are as important as absolute values and even more so if one or both are near the deficiency range. The P:N ratio (expressed on a mass basis as a percentage of N) indicated that the response to the application of P was affected by the presence or absence of residual PK fertilizer (**Table 5.4**). On plots without residual fertilizer the 25 kg ha^{-1} P application increased the ratio significantly from 7.5 to 8.0 and the application of 50 kg ha^{-1} caused a further increase over the 25 kg ha^{-1} application to 9.0. In the presence of residual fertilizer the P:N ratio of 8.1 in the control plots was significantly higher than the 7.5 in the control plots without residual PK fertilizer. In the presence of residual PK fertilizer only the 50 kg ha^{-1} application increased the P:N ratio significantly to 8.8. The maximum P:N ratio, associated with the greatest amount of P fertilizer, was still below the optimum level of 10 as recommended for conifers by Linder (1995) as well as the average of 13.1 reported by Louw and Scholes (2003) for *P. patula* in Mpumalanga. However, it was closer to the 8.3 and 9.0 reported by Carlson and Allan (2001) and Dames *et al.* (2002), respectively.

There was weak evidence that the K:N ratio was increased by the application of K fertilizer (only significant at the 10% level) (**Table 5.4**). The K:N ratio of 32.7 in plots where K50 was applied was much smaller than the mean value of 55.9 reported for compartments in Mpumalanga by Louw and Scholes (2003) and 50.3 by Dames *et al.* (2002), but close to the optimal value of 35.0 as reported by Linder (1995). The influence of the application of P and K at pruning and planting was also clearly visible in the P:K foliar ratio for the respective treatments. The application of P50 increased the P:K ratio from 0.26 to 0.30, while the application of K50 reduced the ratio from 0.29 to 0.25.

The ANOVA results of needle mass and nutrient content of 100 needle fascicles showed firstly that none of the main treatments had a significant effect on needle mass and secondly that as in the case with nutrient concentration, P fertilizer only affected the needle P content, while K fertilizer had an effect on needle N and K content. The P fertilizer had to be applied both at planting and after pruning (P50) to increase the foliar P content significantly (p=0.005) from 0.0121 to 0.0146 g per 100 fascicles. Where K was applied, the K25 application had a similar effect as the K50 application on both the needle N and K content values. The N content was increased from 0.150 to 0.168 and 0.165 g per 100 fascicles for the K25 and K50 applications, respectively, while the K content was increased from 0.044 to 0.051 and 0.054 g per 100 fascicles for the K25 and K50 applications, respectively.

5.3.3 Relationship between foliar nutrients and volume growth

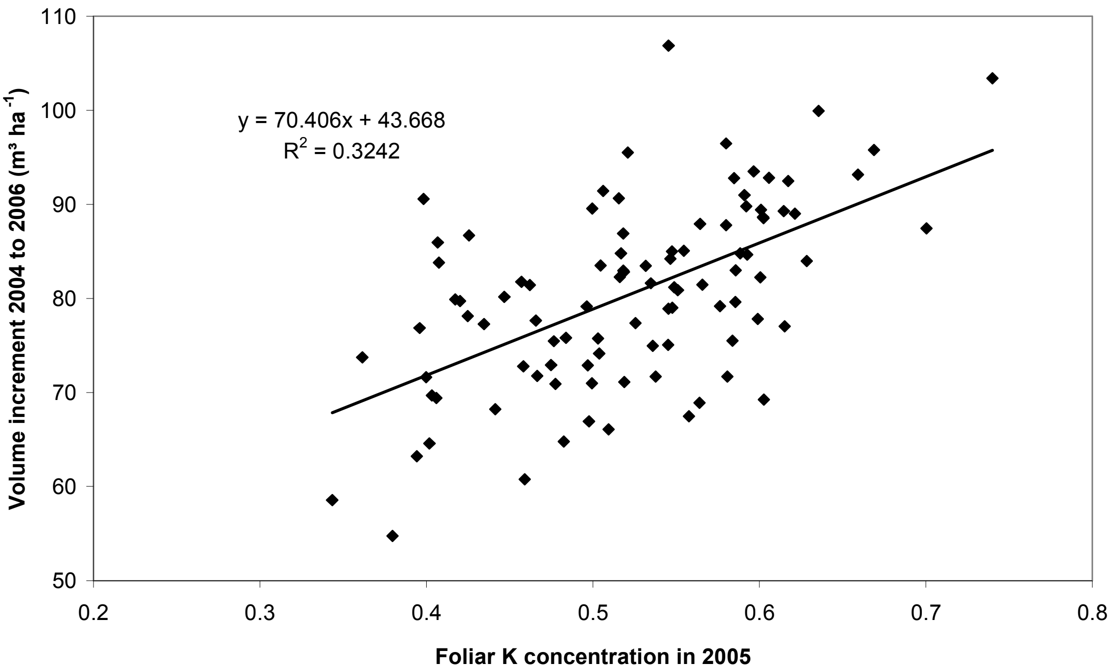
The linear associations between volume increment from age five to age seven years and various foliar nutrient concentrations and ratios (**Table 5.5**) indicated that similar to other studies (Grey *et. al.*, 1979; Louw and Scholes, 2003) the foliar nutrients accounted for a small proportion of the variability in growth. However, some trends could be observed. Increases in foliar K, foliar P, K:N and P:N ratios were generally associated with a greater volume increment (**Figure 5.3a, 5.3b, 5.3c and 5.3d**). Other interesting associations were also observed, for example, significant positive correlations between foliar P and K concentrations and between foliar K and the P:N ratio (**Table 5.5**).

Table 5.5: Correlation matrix showing coefficients (and *p*-value of two sided test in parenthesis) for linear associations between foliar nutrient concentrations and ratios in six-year-old *P. patula* at Usutu, Swaziland, and volume increment over a two year period of the P x K x residual P and K trial. The P:N and K:N ratios were expressed on a mass basis as a percentage of N. (n= 95; Significance levels: *p<0.10, **p<0.01%, ***p<0.001).

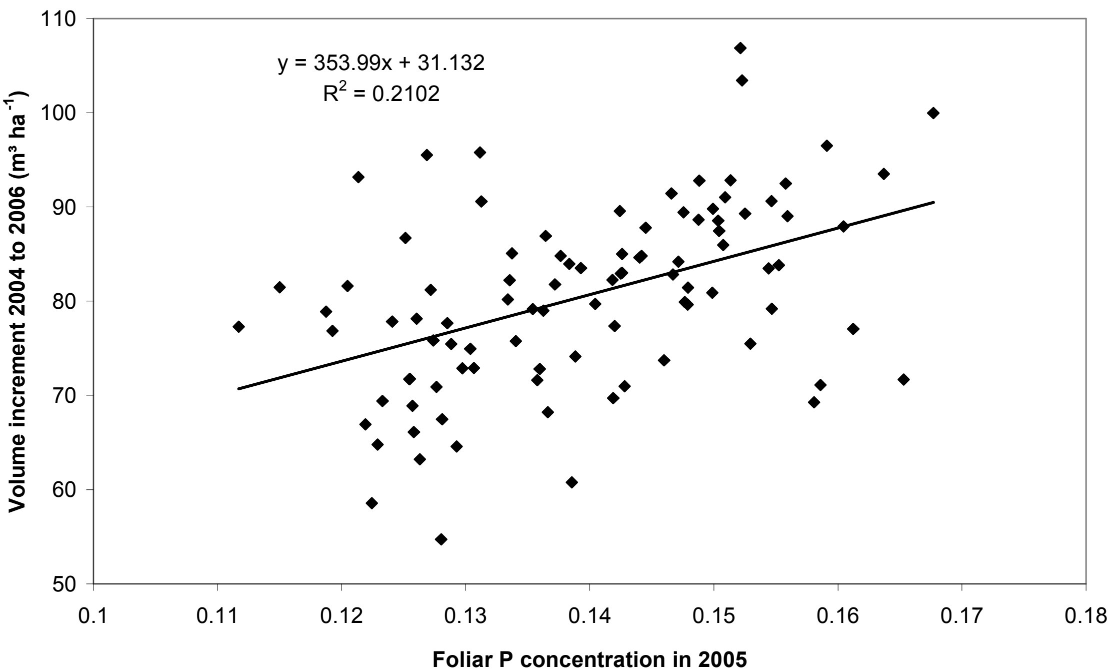
Foliar nutrient concentration or ratio in 2005	Volume increment 2004 to 2006	N	P	K	Ca	Mg	Na	P:N	K:N
N	0.117								
P	0.458*** *(<0.001)*	0.254** *(0.013)*							
K	0.572*** *(<0.001)*	0.275** *(0.007)*	0.403*** *(<0.001)*						
Ca	0.218* *(0.034)*	-0.070	0.130	0.102					
Mg	-0.004	0.091	-0.093	-0.101	0.595*** *(<0.001)*				
Na	-0.167	0.068	-0.095	0.109	-0.165	-0.052			
P:N	0.376*** *(<0.001)*	-0.378*** *(<0.001)*	0.798*** *(<0.001)*	0.215* *(0.036)*	0.174	-0.140	-0.137		
K:N	0.546*** *(<0.001)*	-0.110	0.309** *(0.002)*	0.924*** *(<0.001)*	0.136	-0.131	0.089	0.366*** *(<0.001)*	
P:K	-0.316** *(0.002)*	-0.159	0.178* *(0.085)*	-0.812*** *(<0.001)*	0.020	0.070	-0.198* *(0.055)*	-0.278** *(0.009)*	-0.782*** *(<0.001)*
		Foliar nutrient concentration or ratio in 2005							

Multiple linear regression indicated that the best-fit model that could account for 39% of the variance in volume increment between 2004 and 2006 consisted of the three terms, namely, foliar K, foliar P:N and foliar Na. Individually, foliar K accounted for 32% of the variance and foliar P for 21% of the variance. The effect of residual PK fertilizer, when included in the multiple regression was only significant at the 10% level.

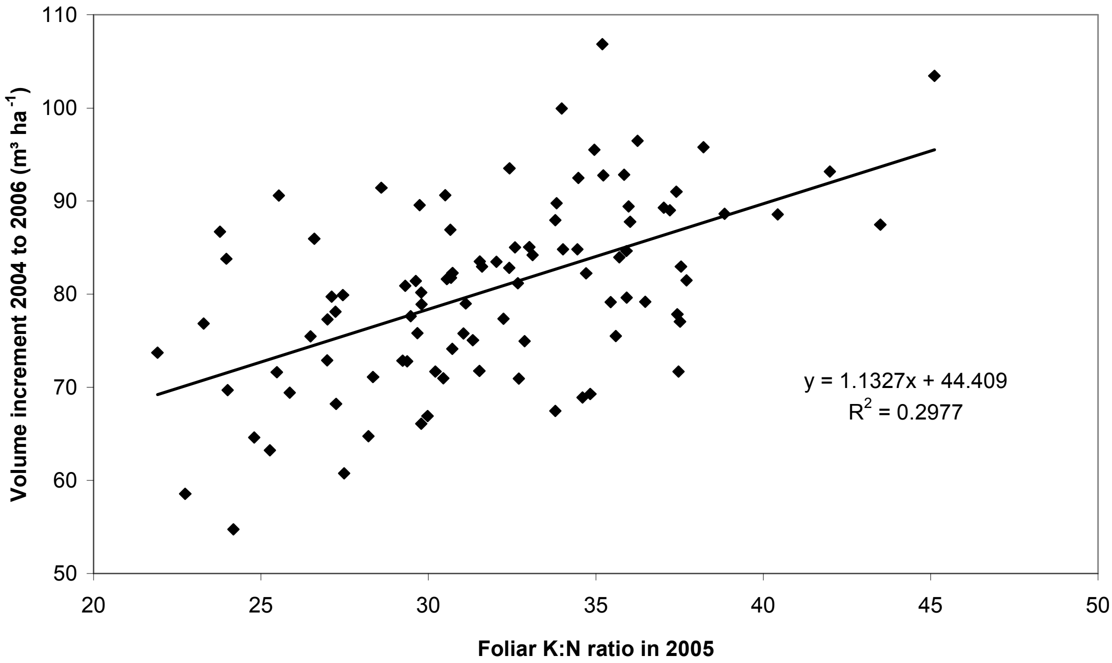
a)


y = 70.406x + 43.668
R2 = 0.3242
Volume increment 2004 to 2006 (m³ ha-1)
Foliar K concentration in 2005
110
100
90
80
70
60
50
0.2
0.3
0.4
0.5
0.6
0.7
0.8

b)


y = 353.99x + 31.132
R2 = 0.2102
Volume increment 2004 to 2006 (m³ ha-1)
Foliar P concentration in 2005
110
100
90
80
70
60
50
0.1
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18

c)



d)

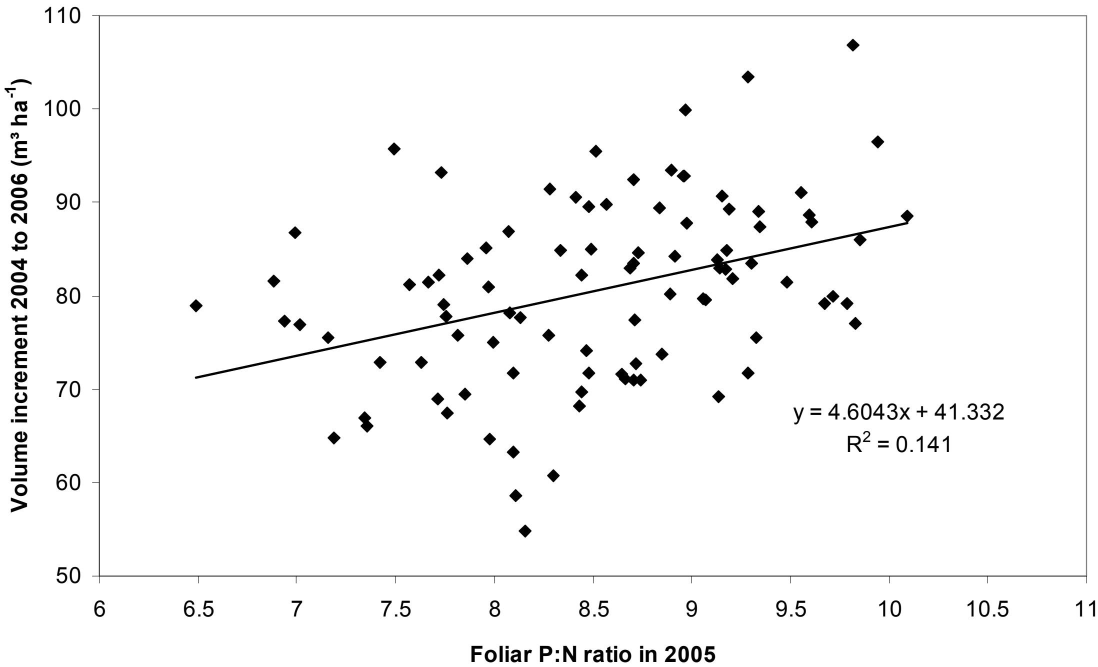


Figure 5.3: Relationship between the foliar K nutrient concentration (a), foliar P nutrient concentration (b), foliar K:N nutrient ratio (c) and foliar P:N nutrient ratio (d) in six-year-old *P. patula* trees and the plot volume growth increment between the age of five and seven years. The P:N and K:N ratios are expressed on a mass basis as a percentage of N.

Because no critical foliar levels have been published for *P. patula* in South Africa, it was decided to test the usefulness of the critical values for *P. radiata* in New Zealand (Will, 1985), as these corresponded well with observed nutrient concentrations in the current trial and previous studies (Grey *et al.,* 1979; Morris, 1986; Carlson and Allan, 2001; Dames *et al.*, 2002; Louw and Scholes, 2003). Log-linear regression showed that the volume increment between the age of five and seven years was significantly higher when either foliar P or foliar K was above the respective critical limits. However, the volume increment was further increased to the maximum when both the foliar P and K concentrations were above the critical values (**Table 5.6**).

Table 5.6: Predicted means and standard errors for *P. patula* volume increment between age five and seven years when foliar P and K were above and below critical levels, respectively in the P x K x residual P and K trial at Usutu, Swaziland. Letters indicate a difference between the means at p<0.05 significance level. The number of records each mean was based on appears in parenthesis.

Foliar K concentration 2005	Foliar P concentration 2005			
	< 0.14%		>= 0.14%	
	Volume increment 2004 to 2006 (m^3 ha^{-1})	Standard Error of Mean	Volume increment 2004 to 2006 (m^3 ha^{-1})	Standard Error of Mean
< 0.50%	72.6 c (26)	1.45	78.9 b (9)	1.91
>= 0.50%	80.3 b (22)	1.54	86.6 a (39)	1.24

These results clearly indicated that the critical P and K foliar values of 0.14% and 0.50%, respectively, can be successfully used to identify deficiencies of these elements in *P. patula* in Swaziland. The nutrient ratios that were associated with the plots where both foliar P and K were above critical were 9.1 for P:N, 34.4 for K:N and 0.26 for P:K. These P:N and K:N values corresponded with the optimum ratios of 10 and 35, respectively, for conifers (Linder, 1995). It should be noted that variation in foliar nutrient concentrations may not only be caused by differences in the availability in the soil, but also by other factors such as stand age, sampling position in the crown and season (Lambert, 1984; Payn and Clough, 1987; Linder, 1995). Thus, caution is necessary when critical values are the only tool for diagnosis of nutrient deficiencies (Louw and Scholes, 2003).

5.3.4 Litter trap nutrient concentration

Only one year after the application of P after pruning (P50), in addition to the application of P at planting, the senesced needles showed firstly a significant (p=0.008) increase in P content from 0.038 to 0.044% and secondly an increase (p=0.003) in the P:N ratio from 5.5 to 6.7. This corresponded with work done by Flinn *et al.*, (1982) on P fertilisation of *P. radiata*. They showed that as early as three months after the application of P fertilizer, the needle P concentration increased by varying amounts throughout the canopy.

At the age of six years the K50 treatment resulted in a significantly ($p<0.001$) greater K concentration of 0.185% compared to 0.118% in the senesced needles on the control plots as well as a greater K:N ratio of 27.8 (K50) compared to 17.0 (K0). Plants normally withdraw nutrients from leaves prior to abscission to redeploy in developing tissue in order to minimize nutrient losses (Killingbeck, 1996; Van Heerwaarden *et al.*, 2003). Thus, there is an assumption that if a plant experiences a deficiency, it will relocate more of the deficient nutrients from the foliage before senescence as these nutrients are immediately available (Aerts, 1996). The comparison of senesced needle K concentrations in 2004 and 2005 clearly indicated that less K was resorbed in the K50 treatment and that the application of K fertilizer thus reduced the K deficiency. Although the results from a selection of plots showed that the residual PK fertilizer had increased the foliar P concentration of senesced needles in 2004 (Crous *et al.,* 2007b), there was no indication that the residual PK fertilizer had any significant effect on the nutrient concentrations of the senesced needles in 2005.

The mass of needles collected over a 14 day period in the litter traps was not affected by any of the treatments or treatment interactions in 2005. One year after the application of the fertilizer the P50 treatment increased the P content of the senesced needles by 19% ($p=0.028$), while the K50 treatment increased the K content by 63% ($p=0.010$).

5.4 CONCLUSIONS

A comparison of nutrient concentration in live foliage in this study, in addition to values reported in other studies confirmed very low P and K concentrations on unfertilized gabbro-derived soil. The foliar samples as well as the litter trap samples indicated that both P and K levels were greater in plots to which P and K fertilizer was applied at planting and after pruning, respectively. These nutrients should remain available to the trees in the short term through internal relocation and in the longer term through mineralization. Investigation of growth response in relation to critical foliar P and K concentrations revealed that volume growth increased when either one of the nutrient concentrations was above the critical level, but that both P and K had to be above the respective critical levels to achieve maximum volume growth.

It was also observed that the P and K fertilizer, which were applied to the 3R crop in 1989, interacted with P and K fertilizer applied to the 4R crop in 1999 and 2004. The results indicated that the re-application of K fertilizer, rather than P fertilizer, to subsequent crops will become more important to maintain the nutrient balance at levels that allow maximum growth. The critical foliar values of 0.14% for P and 0.50% for K as well as the respective optimal nutrient ratios of 10 for P:N and 35 for K:N can be used to monitor the response to revised fertilizer prescriptions.

At the end of the 3R no soil, foliage or timber samples were collected from this trial. The soil and forest litter samples, collected from the 4R crop, could have been "contaminated" during the harvesting operation, as it was impossible to prevent harvest residue from moving into adjacent treatment plots. Furthermore, only tree height and DBH measurements were taken at the end of the 3R. Thus the effect of fertilization on stem form and wood properties could not be investigated. Fortunately, another PK fertilizer trial on similar geology reached clearfelling age in 2007. This supplied the opportunity to investigate the effects that the first application of PK fertilizer to a site had on stem form, stem nutrient content, basic wood density, tree growth, fibre production as well as nutrient changes in the soil and organic material. The results from this trial will be reported in the following four chapters.

CHAPTER 6

EFFECT OF PHOSPHORUS AND POTASSIUM FERTILIZER ON STEM FORM, STEM NUTRIENT CONTENT AND BASIC DENSITY OF *PINUS PATULA* AT VARIOUS STEM HEIGHTS

At the time of clearfelling 32 trees, 16 from the control plots and 16 from a fertilizer treatment resembling the commercial fertilizer application, were sampled at various stem heights in order to determine if the application of PK fertilizer had any significant effect on stem form, stem nutrient content within the stemwood or stembark, as well as the impact thereof on basic wood density at various stem heights. This paper is currently in preparation for publication in the Australian Forestry Journal.

ABSTRACT

The effect of silviculture treatment on volume production, tree form (expression of bole shape in relative terms), basic timber density (based on dry mass and green volume) and stem nutrient content with changes in tree height of *Pinus patula* were investigated by destructively sampling 32 trees in a phosphorus (P) by potassium (K) by weed control trial at rotation age (15 yrs). Sixteen trees were selected covering the DBH range from both the control (no fertilizer applied) and Split 80/80 (20 kg of P and K per ha, respectively, was applied at planting as a spot application, followed by a broadcast application of 60 kg of P and K per ha, respectively, after pruning) treatments. At 15 years of age, the split application of 80/80 PK fertilizer increased the timber production by 32% (89.5 m^3 ha^{-1}) compared to the control. The results showed that fertilization which promoted early tree growth did not change the stem form of the trees. However, it did show that fertilization decreased timber density by 7% at ground level and 5% on average. The nutrient concentration of N, P and K in the stemwood and stembark, increased with an increase in stem height. The changes in nutrient content and basic wood density with tree height highlight the need to sample at more than one height to obtain an accurate average or total value for each tree. The relationship between tree diameter, tree height and nutrient content can be used to estimate total nutrient content of the stemwood and stembark. The increased concentration of P in the wood on fertilized plots, in addition to increased timber production will result in a greater export of nutrients in harvested timber from fertilized compartments compared to unfertilized compartments.

6.1 INTRODUCTION

The 60 000 ha Usutu Forest in Swaziland supplies raw material to a kraft pulp mill, mostly from planted *Pinus patula* trees grown on a 16 year rotation. Long-term growth monitoring showed that 95 kg ha^{-1} of phosphorus (P) and potassium (K) fertilizer, respectively, had to be applied to 13% of the plantation, located on gabbro-derived soils, in order to maintain or increase volume production from these sites in subsequent rotations (Morris, 1986, 1987a, 1994a, 2003; Evans, 2005). However, the effects of the PK fertilizer application on stem form, basic wood density and nutrient content of the stemwood and stembark have not been studied in detail.

Furthermore, the increases in growth rate may change the tree shape, which can have important consequences for forest mensuration and yield assessment (Snowdon and Waring, 1984; Lowell, 1987). It has been found that stem form (expression of bole shape in relative terms) or taper (a measure of the degree of cylindricity of a stem) is related to crown size and to the rate of tree growth (Larson *et al.*, 2001). If fertilization and weeding are applied at planting it can have an effect on tree growth and thus, stem form (Snowdon and Waring, 1984). Some studies with *P. radiata* have shown that the additional growth from fertilizer was unevenly distributed along the stem, producing an increase in the taper (Snowdon *et al.*, 1981; Snowdon and Waring, 1984; Lowell, 1987; Wielinga *et al.*, 2008).

The maintenance of wood quality is just as important as volume production in plantations with very rapid growth rates, where exotic species are used (Jagels, 2006). It has been shown that silviculture operations (weed control, thinning and fertilization) can markedly influence the quality of the wood by changing growth patterns of trees, especially the crown-stem relationship (Larson *et al.*, 2001). However, it is very difficult to predict how wood properties will change as time of application; type and amount of fertilizer have an effect on wood properties (Zobel, 1992). A summary of 44 studies with 16 conifer species showed that fertilizer reduced the basic density of timber and that nitrogen caused the greatest change in wood properties (Zobel and van Buijtenen, 1989 cited in Zobel, 1992). McGrath *et al.* (2003) also reported that the improved growth associated with the application of N, in combination with P, reduced basic wood density temporarily. The application of fertilizer frequently increased the percentage of earlywood and often did not affect the latewood. It was found that N often increased the period of juvenile wood production. In all studies the increased volume from the application of fertilizer more than compensated for the adverse change in wood properties (Zobel, 1992; Beets *et al.*, 2001).

A trial where various amounts of P and K fertilizer was applied to *P. patula* in a factorial design at different times of stand development, with two levels of weed control reached rotation age during 2007. Destructive sampling of 32 selected trees provided information on the effects that PK fertilization had on stem form and mean timber density at various heights along the stem. The aim of this manuscript was to provide answers to the following questions:

1. What effect did the application of fertilizer have on stem form of the trees?
2. How did the mean timber density change from the base to the top of the stem?
3. What was the relationship between mean tree density and density at breast height?
4. Did the application of PK fertilizer affect the nutrient content within the stemwood and stembark at various heights above ground level?

6.2 MATERIALS AND METHODS

6.2.1 Trial establishment

The trial site was situated on Land type 307, in compartment A11 (31°4’12”E, 26°27’37”S), at an altitude of 1250 m a.s.l. on a gentle upper mid-slope position. The previous crop was a 1967 age-class second rotation of *P. patula*. Clearfelling was done in November/December 1991 and tree lengths with bark attached were extracted with a cable skidder. Harvest residue was left *in situ* and was not burnt.

The trial was designed as a 3 x 2 x 2 factorial to test time of application, fertilizer amount and effect of intensive weed control. Two amounts of 0:1:1(17) fertilizer, supplying 40 or 80 kg ha^{-1} each of P and K, were applied either all at time of planting (Early), or as a split with 20 kg ha^{-1} each of P and K at time of planting and the rest following pruning (age 5) (Split), or all as a post-pruning application (Late) (**Table 6.1**). The additional treatments to the factorial combinations were a control, where no fertilizer was applied, and a single application of 20 kg ha^{-1} of P and K, respectively, at time of planting. The eight fertilizer treatments were tested in combination with either routine operational weeding or intensive weeding aimed at removing all competing vegetation. The sixteen treatments were laid out as four complete randomised blocks using 7 x 7 row plots at an espacement of 2.74 m squared.

Table 6.1: The sixteen treatment combinations tested in Trial R155.

TREATMENTS			
Code	Fertilizer amount		Weed Control
	Planting	Pruning	
E40N	40/40	0	Normal
E40I	40/40	0	Intensive
E80N	80/80	0	Normal
E80I	80/80	0	Intensive
S40N	20/20	20/20	Normal
S40I	20/20	20/20	Intensive
S80N	20/20	60/60	Normal
S80I	20/20	60/60	Intensive
L40N	0	40/40	Normal
L40I	0	40/40	Intensive
L80N	0	80/80	Normal
L80I	0	80/80	Intensive
E20N	20/20	0	Normal
E20I	20/20	0	Intensive
CONTRN	0	0	Normal
CONTRI	0	0	Intensive

TREATMENT CODE DESCRIPTION	
	AMOUNT
20/20	20kg elemental P + 20kg elemental K per ha
40/40	40kg elemental P + 40kg elemental K per ha
60/60	60kg elemental P + 60kg elemental K per ha
80/80	80kg elemental P + 80kg elemental K per ha
	TIME
E	All fertilizer applied at planting (Early)
S	Fertilizer applied part at planting (20/20) and the rest post pruning (Split)
L	All fertilizer applied post pruning (Late)
	WEED CONTROL
N	Normal weeding as used operationally
I	Intensive weeding aimed at weed free plots

The trial was planted on 24th March 1992. Fertilizer was applied on 9th April 1992 as spot applications 25 cm from the seedling. The 20/20 amount was applied as a single spot, the 40/40 amount was split between two spots on opposite sides of the seedling and the 80/80 amount was applied in four spots around the seedling. The seedlings were treated with *Bexadust* (active ingredient: Gamma BHC) at the root collar in June, 1992, after a small amount of mortality, associated with the bark beetle, *Hylastes angustatus*, had been observed. However, mortality was minor with less than 5% loss at 17 months after planting, and was unrelated to treatment. The trial was not blanked.

When planted, the site was weed free. Weeding of plots receiving the normal operational treatment was only confined to cut stump chemical control of bugweed (*Solanum mauritianum*) in June, 1993, and again in April, 1994. This was carried out as part of the routine weeding of the surrounding operational stand. The intensively weeded plots received, in addition to the operational treatments, two manual hoeing treatments to remove all weeds on the plots in February and December, 1993. Pruning, to a height of two metres, was done during May 1997 and a broadcast application of fertilizer, following pruning, was done on 11 September 1997.

6.2.2 Trial assessment

6.2.2.1 Tree measurements

All surviving trees of the inner 5 x 5 rows of each plot were assessed for height in June 1994 and height and DBH (Diameter at Breast Height, 1.3 m above the soil surface) in July 1997. In October 1999, May 2001, April 2003, May 2004, April 2005, April 2006 and February 2007 the DBH of all 25 trees was measured, but only 5 trees per plot were assessed in terms of height.

6.2.2.2 Stem measurement and timber samples

Stem form changes and stem nutrient content changes with tree height were only assessed in the control and split 80/80 treatments. The split 80/80 treatment was selected as it resembled the operational fertilizer application prescription. One tree closest to the 12.5th percentile tree, two close to the median and one close to the 87.5th percentile tree were selected per plot prior to clearfelling. These trees, ranging from 15.3 m to 22.7 m in height and 11.2 cm to 35.3 cm in diameter, were left standing when the trial was felled. Shortly after clearfelling the pre-selected trees were destructively sampled. Eight sample discs were collected from each of the 32 trees. A 10 cm thick internodal disk was taken at 0.5, 1.3 and every 3 m thereafter along the stem to the top of the tree. The overbark and underbark measurements of each disc were taken in field. The dry weight of the bark was determined per sample disk after drying at 70 °C for 72 hours in a ventilated oven.

Each stemwood disc was cut into two round discs of 4 cm thickness with a chainsaw. One disc was used for density analysis and the second for nutrient analyses. The basic density of timber samples was determined as it is one of the cheapest and easiest wood properties to measure and provides an indication of both the anatomical characteristics and structural properties of timber (Larson *et al.*, 2001; Stanger *et al.*, 2002). For wood, different definitions of density apply as a decrease in moisture content is associated with a volumetric shrinkage (Simpson, 1993). In the present study the discs used for density analysis were submerged in a dip tank for at least 24 hours until it became fully saturated with water. The green volume of each saturated disc was determined by volume displacement of water. Thereafter the discs were dried in a ventilated oven at 103 °C to a constant weight. The basic timber density was expressed as the dry weight to green volume ratio (Simpson, 1993).

From each wood disc a wedge of timber was cut to sample an equal proportion of earlywood and latewood from each disc, irrespective of the diameter. The wedges were chipped in a hammer mill and thereafter ground in a Wiley mill to pass though a 2 mm sieve. Ground wood from all DBH discs per plot, except from the control and split 80/80 treatments, were bulked into one sample prior to nutrient analyses in order to reduce the expenses. Following fine grinding, the bark samples were bulked similarly to the wood samples. Total nitrogen (N) was determined by the combustion method using a LECO analyser. In this process a suitable aliquot of sample was mixed with a suitable oxidant and thermally decomposed into nitrogen monoxide and other gaseous products. The other macro nutrients were analysed after 2.5 g of the ground samples was dry ashed and taken up in a solution of 0.6N HCl. Phosphorus (P) was determined by the molybdenum blue method in an auto analyzer (Donkin *et al.*, 1993). Potassium (K), calcium (Ca) and magnesium (Mg) concentrations were determined using an Inductively Coupled Plasma Mass Spectrometer (ICP-MS) with an argon shield. All concentrations were expressed as a proportion of dry mass.

6.2.3 Calculations and statistical analyses

Tree volume was calculated by summing the volume of the tree sections. The bottom stem sections were treated as part of a conoid, the mid section as a frustrum of a paraboloid and the top as a cone (Brack, 1999). The dry mass of each section was calculated by multiplying the volume of each section by the density of the bottom disc. A similar approach was used to calculate the nutrient content of each stem portion. Whole tree totals were obtained by summation of the various tree sections.

Due to low levels of weed development in the trial the weed control treatment had only a very small effect on tree growth at the age of 17 months (Morris, 1994b) and none thereafter (Crous *et al.*, 2005a). Therefore, the weed treatment was excluded from the statistical models.

The statistical software program, *GenStat 10.2*, was used to analyse the data (Payne, 2007). T-tests, multiple linear regression, non-linear regression and residual maximum likelihood (REML) mixed models were used for the analyses. Significant differences were tested at the 5% level, unless otherwise stated. Relationships between the various parameters and relative stem height (where 0 is at ground level and 1 is at the top of the stem) were firstly explored with graphical analysis and secondly with regression analysis.

A full versus reduced model approach was used. The most appropriate equation for each parameter was based on best fit (R^2-values) and residuals analyses. Because of the serial correlation in the data caused by repeated measurements of the same experimental units (discs sampled longitudinally along the same tree; Lowell, 1987; Kyriaki, 2004) the assumptions of independence was violated and the use of ordinary regression was not suitable. Lindstrom and Bates (1990) suggested the use of mixed effects models in these situations because of their flexible covariance structure. Thus, the REML algorithm was used where longitudinal data were analysed (Payne *et al.*, 2008).

6.3 RESULTS AND DISCUSSION

6.3.1 Tree growth

A comparison of the number of live stems in the control plots and plots where 80 kg ha^{-1} P and K fertilizer, respectively, was applied as a split application (S80/80) at planting and after pruning, indicated that there was significantly more live stems on the control plots (**Table 6.2**). At the age of 15 years the quadratic mean diameter of the fertilized trees in the S80/80 treatment was 3.2 cm greater and the mean tree height was 1.3 m greater than that of the control plots (**Table 6.2**). At the end of rotation, the S80/80 fertilizer application increased the basal area by 21.6% and mean plot volume by 89.5 m³ ha^{-1} (32%). This volume increase corresponded to estimates of an additional 50 to 70 m³ ha^{-1} based on results from a number of trials by Morris (1987a and 1987b), but were much greater than the additional 22.9 m³ ha^{-1} recorded at the end of the first fertilized rotation (Crous *et al.*, 2008a) or the additional 25.2 m³ ha^{-1} at age seven years of the subsequent fertilized rotation (Crous *et al.*, 2007a) in a separate trial.

Table 6.2: Comparison of tree growth parameters of the *P. patula* trees in the Control plots, where no fertilizer was applied, and the Split 80/80 treatment, where 20 kg P and K ha^{-1}, respectively, were applied at planting in 1992 and a further 60 kg P and K ha^{-1}, respectively, were applied after pruning in 1997.

Parameter	Unit	Fertilizer				Difference		T-test (d.f. = 14)	Prob.: $\mu_1=\mu_2$
		Control	*S.E.*	S80/80	*S.E.*	Value	%		
Live stems (15 yrs)	stems ha^{-1}	1173	*35*	1020	*60*	-153	-13.1	2.21	0.044
DBH (15 yrs)	cm	20.0	*0.40*	23.8	*0.66*	3.8	19.1	-4.940	<0.001
Height (15 yrs)	m	19.6	*0.27*	20.9	*0.27*	1.2	6.2	-3.220	0.006
Basal Area (15 yrs)	m² ha^{-1}	36.8	*1.34*	44.8	*1.26*	7.9	21.6	-4.300	<0.001
Volume (15 yrs)	m³ ha^{-1}	280.1	*10.80*	369.6	*10.30*	89.5	32.0	-5.740	<0.001

6.3.2 Stem form

When the effect of fertilizer on stem form was graphically investigated the results showed that trees sampled in the S80/80 fertilizer plots were both thicker and taller than the trees sampled on the control plots (**Figure 6.1**). A comparison of the DBH-height relationship between treatments indicated that fertilizer had no significant effect on this relationship.

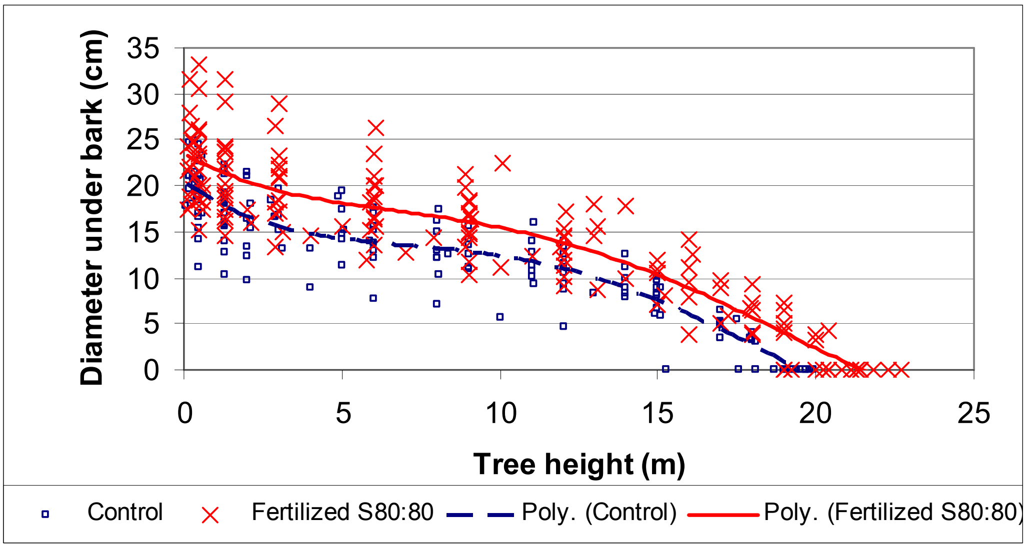


Figure 6.1: Relationship between diameter under bark and tree height in the control and S80/80 fertilizer treatments, respectively, for the 16 *P. patula* trees that were sampled in each treatment at clear felling age.

The effect of fertilizer on stem taper of the 32 intensively sampled trees was investigated by fitting a fourth order polynomial function (Equation 6.1) (Snowdon *et al.*, 1981) with the REML algorithm. Billet heights and under bark diameters were expressed in relative terms.

$$\left({d_{ub}}/{DBH_{ub}} \right)^2 (h) = a_1\, relHT + a_2\, relHT^2 + a_3\, relHT^3 + a_4\, relHT^4 + a_5 + Fertilizer$$

[Equation 6.1]

Where

$d_{ub}/DBH_{ub}\,(h)$ = relative diameter under bark at height (h)
$relHT$ = relative height (h/H)
$Fertilizer$ = 0 for control (0 fertilizer) or 1 for Split 80/80
a_1 to a_5 = coefficients

The fourth order polynomial function fitted the data well and the residual plot indicated that the residuals were roughly symmetrically distributed with variance increasing slightly at the base of the trees (**Figure 6.2**). The inclusion of fertilizer as a variable in the model had no significant effect on the model fit (**Table 6.3**). Furthermore, there was no indication of a significant interaction between fertilizer treatment and other model terms (data not shown).

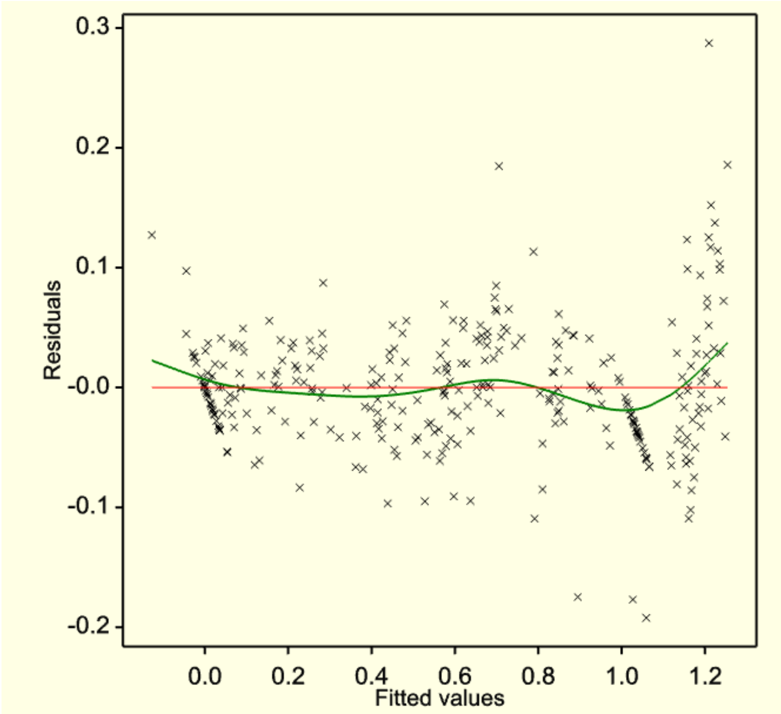


Figure 6.2: Relative underbark diameter residuals for the fourth order polynomial function (Equation 6.1 – refer to text).

Table 6.3: REML variance components analysis statistics and estimated coefficients describing the relationship between relative diameter underbark squared, relative height and fertilizer application (Equation 6.1) of 15-year-old *P. patula* trees.

REML variance component analysis					
Source	df	Sum of Squares	Mean Square	F ratio	Prob.>F
Regression	5	53.156	10.631	2424.6	<0.001
Residual	307	1.3461	0.0044		
Total	312	54.502	0.1747		
Tests for fixed effects					
Fixed term	Wald statistic	ndf	F statistic	ddf	Prob.>F
RelHT	16918.98	1	16918.98	277.8	<0.001
$RelHT^2$	153.34	1	153.34	277.7	<0.001
$RelHT^3$	104.49	1	104.49	277.6	<0.001
$RelHT^4$	145.34	1	145.34	277.5	<0.001
Fertilizer	1.25	1	1.25	27.0	0.272
Estimation of coefficients of reduced model (dropped Fertilizer term)					
Parameter	estimate	*S.E.*			
a_1	-4.202	*0.173*			
a_2	11.46	*0.764*			
a_3	-15.44	*1.168*			
a_4	6.925	*0.574*			
a_5	1.259	*0.0116*			

S.E. = Standard Error
ndf - numerator degrees of freedom
ddf - denominator degrees of freedom

The coefficients that accounted for 97.5% of the variance of the reduced model (Equation 6.1, with the fertilizer term dropped) are presented in **Table 6.3.**

Snowdon *et al.* (1981) reported that fertilizer increased the taper of *P. radiata* trees in four of eight trials in New Zealand and one trial in Australia. Wielinga *et al.* (2008) also found that the application of Nitrogen (N) fertilizer had a significant effect on the stem taper of 29-year-old *P. radiata* trees. In the present study there was no evidence that the application of fertilizer had a statistically significant effect on the stem form. However, it should be noted that these results were based on a small number of trees and that this aspect should be investigated more intensively in future studies.

6.3.3 Basic wood density

Differences in density among individual trees were much greater than the differences due to position within the tree, size of the tree or silvicultural treatment. REML variance analysis showed that density was weakly influenced by the relative height of the sample and fertilizer. However, only 31% of the variance in basic density could be accounted for by the model (Equation 6.2, **Table 6.4** and **Figure 6.3**).

$$Basic\ Density\ (h) = Constant + RelHT + Fertilizer + RelHT.Fertilizer$$

[Equation 6.2]

Where

Fertilizer = 0 for control (0 fertilizer) or 1 for Split 80/80

RelHT = Relative height ($(H-h)/H$)

The relative height of the sample disc had the greatest effect on the basic density of the discs (**Table 6.4**) as it had the largest F-value. In general, basic density decreased with an increase in height along the stem (**Figure 6.3**). Previous studies have also found that density decreases with increasing tree height for pine due to a higher proportion of mature wood lower down (Morris, 1986; Larson *et al.*, 2001). Furthermore, the density changes over the relative height of the stem were influenced by fertilization and interactions between relative height and fertilization (**Table 6.4**). The application of S80/80 fertilizer resulted in a greater decrease in density in the bottom portion of the stem than in the top portion (**Figure 6.3**).

Table 6.4: REML statistics and coefficients describing the relationship between basic timber density, fertilizer application and relative tree height (Equation 6.2 – refer to text) of 15-year-old *P. patula* trees.

REML variance component analysis					
Source	df	Sum of Squares	Mean Square	F ratio	Prob.>F
Regression	3	0.1338	0.04460	39.1	<0.001
Residual	250	0.2851	0.00114		
Total	253	0.4189	0.00165		
Tests for fixed effects					
Fixed term	Wald statistic	ndf	F statistic	ddf	Prob.>F
RelHT	244	1	244	221.7	<0.001
Fertilizer	5.87	1	5.87	12.8	0.031
RelHT.Fertilizer	6.01	1	6.01	220.7	0.015
Estimation of coefficients					
Parameter	Coefficient	*S.E.*			
Constant (Control)	0.4102	*0.00586*			
RelHT (Control)	-0.0820	*0.00648*			
Constant (S80/80)	0.3818	*0.00546*			
RelHT (S80/80)	-0.0599	*0.00902*			

ndf - numerator degrees of freedom
ddf - denominator degrees of freedom

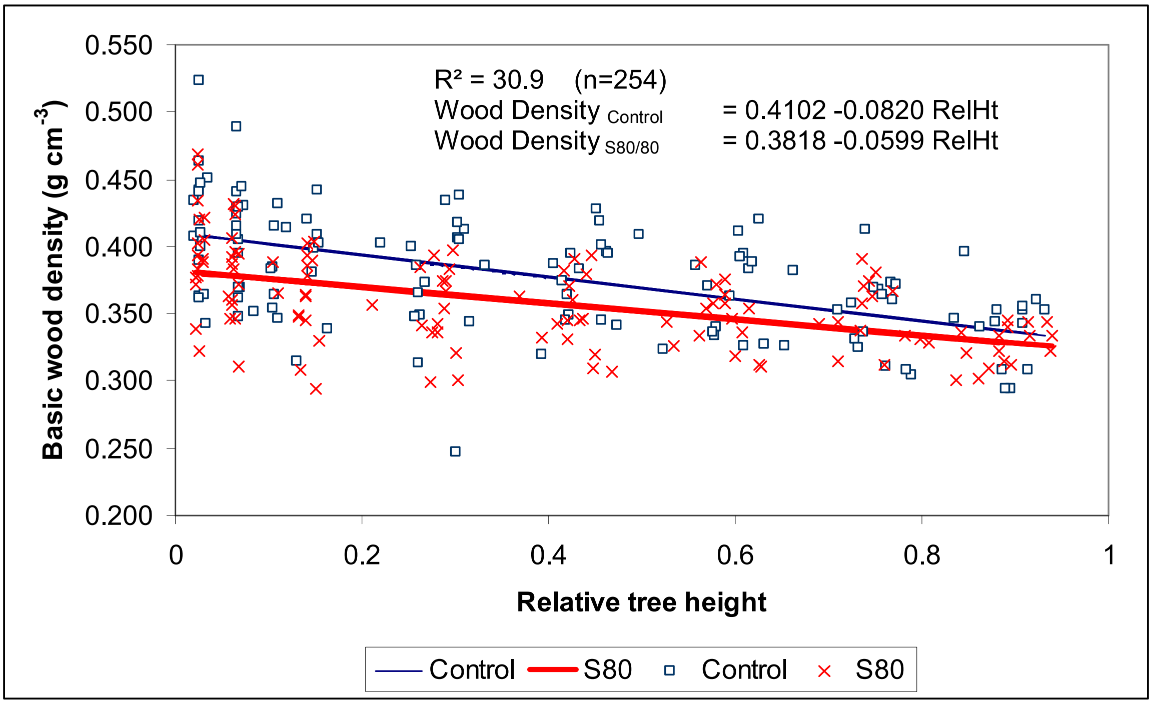


Figure 6.3: The relationship of basic wood density to relative tree height in mature *P. patula* trees at Usutu on control (Control) and Split 80/80 (S80) treatment plots.

The mean timber density, predicted from the regression model, decreased by 6.9% (from 0.4102 in the control to 0.3818 g cm^{-3} in the S80/80 treatment) at the base of the tree, by 5% (from 0.3782 to 0.3584 g cm^{-3}) in the middle and by 2% in the top from (0.3282 to 0.3219 g cm^{-3}).

The 7% to 2% density decrease associated with fertilization in the present study was slightly less than the density decrease of 8% reported by McKinnell and Rudman (1973) after application of 188 kg K ha^{-1} to *P. radiata* or the 9% decrease in density (Wielinga *et al.,* 2008) associated with a 128% volume increase (Waterworth *et al.*, 2007) in the Biology of Forest Growth study with *P. radiata* where 400 kg N ha^{-1}, 200kg P ha^{-1}, 100 kg K ha^{-1} and irrigation were applied (Benson *et al.*, 1992). Gray and Kyanka (1974) reported a 5.5% decrease in basic wood density of *P. resinosa* after the application of 225 kg ha^{-1} KCl. In the southern USA intensive site preparation with fertilization and weed control increased merchantable stem volume of *P. taeda* trees by 81 to 120 %, but reduced basic timber density by 6 to 10% (Clark *et al.*, 2004; Clark *et al.*, 2006). Cown and McConchie (1981) found that the application of N and P fertilizer decreased the whole-tree density of *P. radiata* by 5% across the stem. In their study the largest response was recorded in the year following treatment, when mean density dropped by 20, 18 and 12% at the butt, 6 m above ground and 12 m above ground, respectively. This decrease in density reduction with an increase in tree height corresponded to the trend observed in the S80/80 treatment in the present study. In trials where density across each disc was assessed per ring the reduction in mean timber density was ascribed to three possible causes. Firstly, fertilization normally increased growth in conifers during spring resulting in a higher proportion of low-density earlywood (Gray and Kyanka, 1974; Larson *et al.*, 2001; Albaugh *et al.*, 2004). Secondly, the increased growth in the first few years of the tree increased the diameter of the juvenile wood core, which is characterised by timber with lower density than mature wood (Clark *et al.*, 2004; Clark *et al.*, 2006, Mora *et al.*, 2007). Thirdly, the density can decrease after fertilization because of a reduction in latewood density (Clark *et al.*, 2004) associated with increased photosynthetic efficiency (Larson *et al.*, 2001). Because the basic wood density in the present study was calculated across the whole disc, the specific cause for the decrease in density associated with fertilization could not be established. The lowering of timber density can have an influence on the pulp characteristics, for example, higher burst and tensile strengths, but lower tear factor, opacity and bulk (McKinnell and Rudman, 1973; Clark *et al.*, 2006). A lower timber density will also result in lower yields per digester charge in batch processes, which will have an economic penalty (Clark *et al.*, 2006).

Correlations between the timber density data and tree parameter data showed that the average timber density was not related to any tree characteristics (DBH, height or volume) (**Table 6.5**).

Table 6.5: Correlation matrix of average density of the 32 intensively sampled trees and tree characteristics of the 15-year-old *P. patula* at Usutu, Swaziland. P-values in italics with bolded values referring to significant differences at p<0.05 level.

DBH (over bark)	-0.1515 *0.408*				
Timber dry mass	-0.1093 *0.552*	0.9660 ***<0.001***			
Timber volume	-0.2539 *0.160*	0.9588 ***<0.001***	0.9861 ***<0.001***		
Tree height	-0.1693 *0.354*	0.817 ***<0.001***	0.8001 ***<0.001***	0.7986 ***<0.001***	
Timber density at breast height	0.8774 ***<0.001***	-0.0428 *0.816*	-0.0189 *0.918*	-0.1473 *0.421*	-0.055 *0.765*
	Average Density	DBH (over bark)	Timber dry mass	Timber volume	Tree height

Density measurements of the DBH discs gave a good indication of the density of the complete tree, as can be seen in the correlation matrix (**Table 6.5**) and **Figure 6.4** below. It also showed that the density at DBH was greater than the average density, because of the density decline with an increase in tree height (as shown earlier).

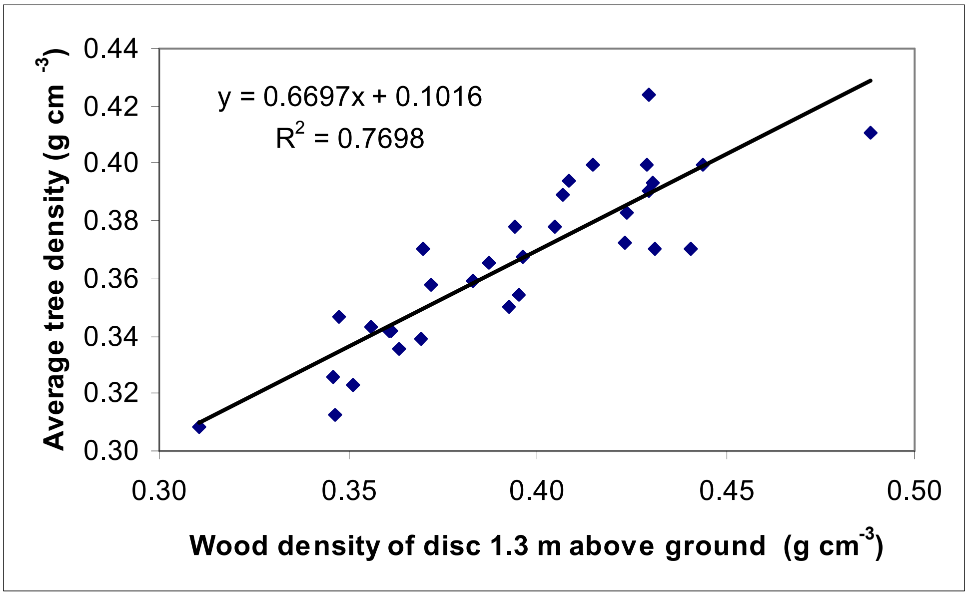


Figure 6.4: Relationship between density at breast height and average density of the entire 15-year-old *P. patula* trees at Usutu, Swaziland.

Because there was clear evidence that mean timber density decreased with an increase in tree height (probably because of an increase in the proportion of juvenile wood associated with the growth increase) a function was developed to estimate the density of the entire stem from a sample collected at breast height (Equation 6.3).

$$Avg.\ basic\ density\ of\ entire\ tree = 0.6697(Basic\ density\ at\ 1.3\ m) + 0.1016$$ [Equation 6.3]

This function can be used to adjust breast height density values in order to estimate timber production per unit area from breast height samples and total volume production estimates.

6.3.4 Stemwood nutrients

Earlier work by Morris (1986) and Rubilar *et al.* (2005) indicated that the concentration of some stemwood nutrients differ at various heights along the stem. Therefore, an attempt was made to investigate the nutrient content changes with height between fertilized and unfertilized trees in the present study. Equations that were used with great success to model nutrient changes with tree height in *P. taeda* by Rubilar *et al.,* (2005) were fitted to the present data (Equations 6.4 and 6.5). The significance of the fixed terms in the REML model is shown in **Table 6.6a**. The best fit model, goodness of fit (R^2- values) and coefficients are shown in **Table 6.6b**.

$$y = (a + b\ Log_{10}(1\text{-}RelHT))*Fertilizer$$ [Equation 6.4]

$$y = (a + b\ (1\text{-}RelHT) + c\ (1\text{-}RelHT)^2)*Fertilizer$$ [Equation 6.5]

The application of PK fertilizer increased the P and Ca concentration of the stemwood equally over the whole tree length (**Table 6.6a**). None of the interactions between fertilizer and relative tree height was significant (**Table 6.6a**).

Table 6.6: REML significance of fixed effects (a) and regression models, estimated coefficients and their associated standard errors (b) to describe the relationship between nutrient concentration in the stemwood and relative tree height in a PK fertilizer trial at Usutu, Swaziland.

a)

Fixed effect	Nutrient (Prob. >F)				
	N	P	K	Ca	Mg
Log(1-RelHt)	**<0.001**	**<0.001**	**<0.001**	-	**<0.001**
(1-RelHt)	-	-	-	**0.008**	-
$(1\text{-RelHt})^2$	-	-	-	**<0.001**	-
Fertilizer	0.682	**<0.001**	0.396	**0.042**	0.306
Log(1-RelHt).Fertilizer	0.801	0.062	0.365	-	0.693
(1-RelHt).Fertilizer	-	-	-	0.626	-
$(1\text{-RelHt})^2$.Fertilizer	-	-	-	0.151	-

Bold type indicates statistically significant differences at $p<0.05$.

b)

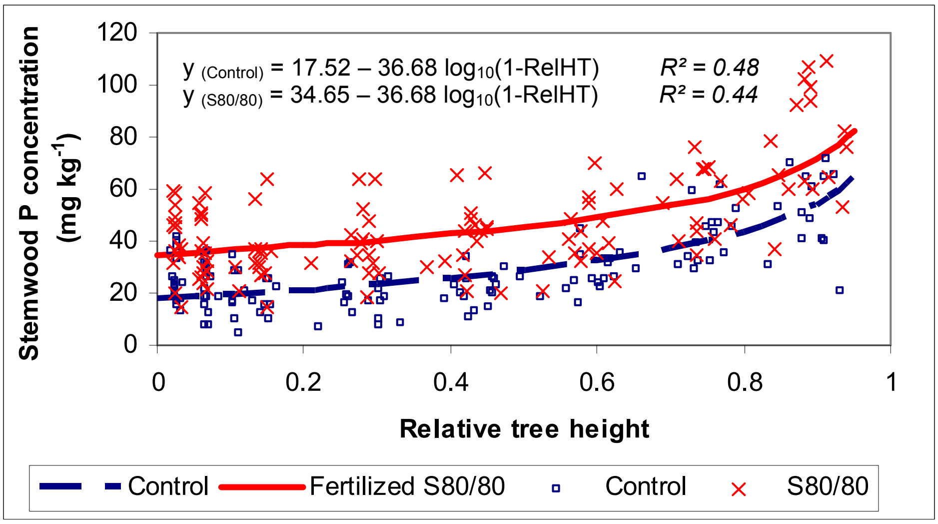
Wood nutrient concentration	Unit	Model	Fertilizer	Adjusted R^2	Model parameters					
					a	*S.E.*	b	*S.E.*	c	*S.E.*
N	mg kg^{-1}	A	ns	0.247	900.8	*32.1*	-361.4	*28.9*	-	-
P	mg kg^{-1}	A	None	0.475	17.52	*3.31*	-36.68	*1.96*	-	-
			Split 80/80	0.439	34.65	*3.31*	-36.68	*1.96*	-	-
K	mg kg^{-1}	A	None	0.501	375.3	*10.8*	-177.4	*8.54*	-	-
Ca	mg kg^{-1}	B	None	0.023	361.3	*14.9*	177.8	*37.5*	-176.6	*32.72*
			Split 80/80	0.074	402.8	*14.9*	177.8	*37.5*	-176.6	*32.72*
Mg	mg kg^{-1}	A	ns	0.110	113.9	*7.95*	-27.52	*2.83*	-	-

Model A $y = a + b\ Log_{10}(1\text{-}RelHT)$ S.E. = Standard Error

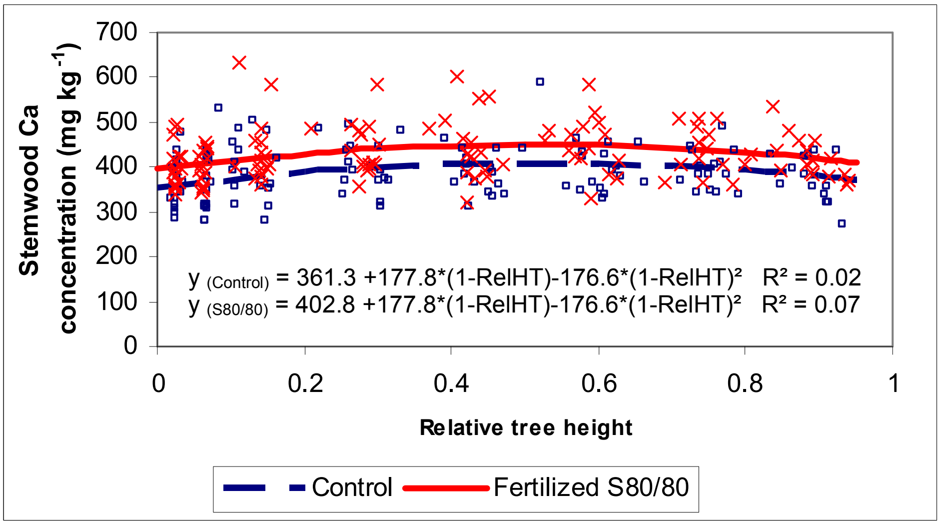
Model B $y = a + b(1\text{-}RelHT) + c(1\text{-}RelHT)^2$ ns = not significant

$RelHT$ = relative tree height

The relationship between the respective nutrient concentrations in the stemwood with tree height showed a similar trend for N, P and K and corresponded with findings by Rubilar *et al.* (2005) (**Figure 6.5a**). There was a general increase in concentration of these mobile elements towards the top of the tree. However, the model fit for N and Mg stemwood concentrations in the present study (**Table 6.6b**) were lower than those reported by Rubilar *et al.* (2005). These changes in nutrient concentration with tree height indicate that serious errors can be made if whole tree nutrient content is estimated from samples collected only at breast height (Rubilar *et al.*, 2005).



a



b

Figure 6.5: Stemwood nutrient concentration of P (a) in relation to tree height was significantly affected by the application of PK fertilizer. Nitrogen and K showed a similar trend, but were not affected by the application of fertilizer. Relatively immovable Mg and Ca showed a weak trend with relative tree height (b) in the 15-year-old *P. patula* trees at Usutu.

The concentration of Ca and Mg, relatively immobile elements, showed a poor relationship with tree height (**Table 6.6b** and **Figure 6.5b**).

The effect of nutrient concentration differences on whole tree stemwood nutrient content and its allometric relationship with tree diameter and height was investigated with an equation that were used by Tew *et al.* (1986), and Rubilar *et al.* (2005) (Equation 6.6).

$$\log_{10}(y) = (a + b \log_{10}(DBH^2HT))*Fertilizer \qquad \text{[Equation 6.6]}$$

where

DBH = over bark diameter at breast height (cm)

HT = tree height (m)

a and b = coefficients

The results showed that tree height and tree DBH could be used with great success to estimate timber mass per tree as well as the respective nutrient contents of the trees as the fitted models could account for 88 to 93% of the variation (**Table 6.7**). It was only in the case of total P content per tree where the application of PK increased the amount significantly. In the case of K and Ca, where a significant increase in concentration was seen, the decrease in timber density associated with the application of fertilizer probably negated the increase in nutrient concentration.

Table 6.7: Regression coefficients and associated standard errors for estimating mass of timber and macro nutrients in 15-year-old *P. patula* trees with Equation 6.6 (refer to text).

Component (y)	Unit	Fertilizer	Adjusted R^2	*a*		*b*	
				Coefficient	*S.E.*	Coefficient	*S.E.*
Timber mass	kg $tree^{-1}$	ns	0.932	-4.62	*0.175*	0.91	*0.044*
N	kg $tree^{-1}$	ns	0.882	-4.88	*0.025*	0.98	*0.064*
P	kg $tree^{-1}$	None	0.901	-7.14	*0.350*	1.15	*0.091*
		Split 80/80		-6.98	*0.351*	1.15	*0.091*
K	kg $tree^{-1}$	ns	0.936	-5.25	*0.182*	0.98	*0.046*
Ca	kg $tree^{-1}$	ns	0.913	-4.96	*0.198*	0.90	*0.050*
Mg	kg $tree^{-1}$	ns	0.864	-5.76	*0.273*	0.97	*0.069*

S.E. = Standard Error
ns = not significant

6.3.5 Stembark mass

Stembark mass was associated with bark thickness and underbark diameter of 254 discs collected from the 32 intensively sampled trees. The multiple linear regression supplied a model (Equation 6.7) that could account for 91% of the variance. Both the model and level of fit was very similar to results reported by Morris (1986) in a study of 76 billets. The inclusion of the fertilizer treatment in the model had no significant effect.

$$M = 0.001547\,(DIA)^2 + 1.9308\,(BT) - 0.4242 \qquad \text{[Equation 6.7]}$$

Where,
M = bark mass in kg per meter of stem
DIA = Diameter underbark (cm)
BT = Bark thickness (cm)

The total bark mass of each tree, based on the sum of all the billets, was also associated with DBH and tree height as these two parameters can easily be measured for each tree. A model used by Tew *et al.* (1986) and Rubilar *et al.* (2005) (Equation 6.8) could account for 77.2% of the variance when fitted to the data from the 32 trees. Inclusion of the fertilizer treatment in the model did not increase the goodness of fit of the model, which showed that the fertilizer had no significant effect on the bark mass.

$$Log_{10}(TBM) = -1.848 + 0.7488\ Log_{10}(DBH^2.HT) \quad \text{[Equation 6.8]}$$

Where,
TBM = Total bark mass per tree (kg)
DBH = Diameter at breast height overbark (cm)
HT = Tree height (m)

When bark mass per relative length of stem was plotted against relative tree height, a strong exponential relationship was observed (**Figure 6.6**). When this relationship was further investigated with non-linear regression, the inclusion of DBH² overbark significantly improved the fit by decreasing the sum of squares. The best fit model (Equation 6.9) could account for 88.5% of the variance.

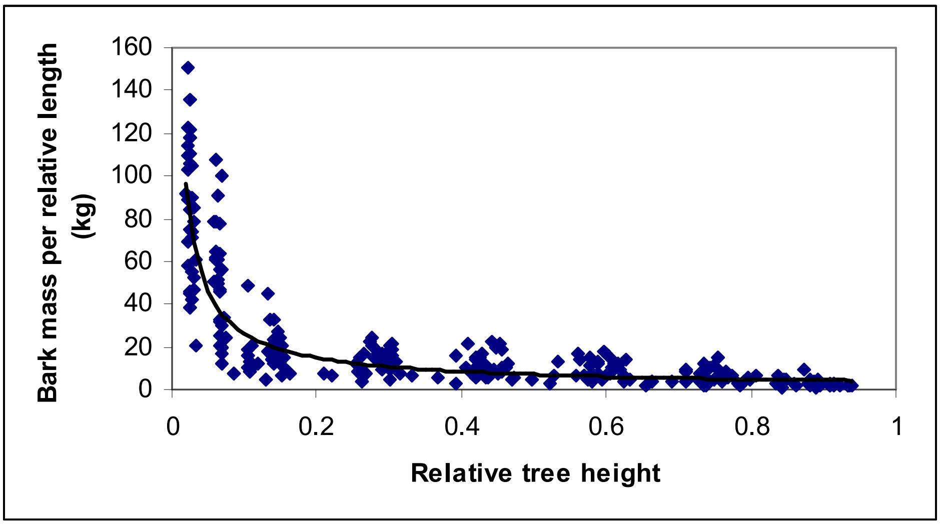


Figure 6.6: Relationship between bark mass per relative length of stem and relative tree height in 15-year-old *P. patula* trees at Usutu, Swaziland.

$$BM_{relHT} = 1.128 \times relHT^{-0.7296} + 0.009525 \times DBH_{ob}^2 \times relHT^{-0.7296} \quad \text{[Equation 6.9]}$$

Where,
BM_{relHT} = Bark mass per relative tree height (kg per relative m height)
$relHT$ = relative Height = (measurement height [h]/ total tree height [H])
DBH_{ob} = Diameter at breast height, overbark (cm).

The area underneath the graph gave an indication of total bark mass associated with each tree. Through integration of Equation 6.9 a function was derived to determine bark mass from the base of the stem up to any specified height (Equation 6.10). This same formula can be used to calculate the bark mass between any two reference points along the stem.

$$TBM_{removed} = \int_{rel\ StumpHT}^{rel\ TopHT} f(BM_{relHT}) \quad d(relHT)$$
$$= [(1.128 + 0.009525 \times DBH_{ob}^2) \times 3.6982 \times relHT^{0.2704}]_{rel\ StumpHT}^{rel\ TopHT}$$

[Equation 6.10]

Where,

$TBM_{removed}$ = bark mass removed with utilizable timber (kg)
BM_{relHT} = Bark mass per relative tree height (kg per relative height)
$relHT$ = relative Height = measurement height [h]/ total tree height [H]
$rel\ StumpHT$ = relative stump height = stump height [h_{stump}] / total tree height [H]
$rel\ TopHT$ = height where diameter reach utilizable limit = 1 for total tree length
DBH_{ob} = Diameter at breast height, over bark (cm).

When Equation 6.10 was used to calculate total bark mass of 32 of the sample trees the goodness of fit, based on least squares, was slightly less than the estimate from Equation 6.9. Comparison of predicted values and actual values with both functions showed that Equation 6.10 tended to slightly over estimate bark mass of the smaller trees. However, Equation 6.10 is more useful as it can estimate bark mass of any stem portion, as long as the total tree height and DBH overbark is known.

6.3.6 Stembark nutrients

Equations 6.5 and 6.11 were used to model nutrient concentration changes in the stembark from the base to the top of the trees. The significance of fixed terms for the complete model is shown in **Table 6.8a**. In the case of N and Mg the fertilizer treatment was not significant and there was also no significant interaction between fertilizer and N and Mg nutrient content along the stem. Although there was some indication of an interaction between relative height and fertilizer treatment in the P and K concentrations (**Table 6.8a**) the inclusion of fertilizer treatment in the model did not significantly improve the level of fit (significant reduction in error sum of squares). Therefore the fertilizer term was excluded from the N, P, K and Mg models. The respective reduced models, level of fit and coefficients are shown in **Table 6.8b**.

$$y = (a + b(1-RelHT) + c(1-RelHT)^2 + d(1-RelHT)^3)*Fertilizer \qquad \text{[Equation 6.11]}$$

Table 6.8: REML significance of fixed effects (a) and regression models, estimated coefficients and their associated standard errors (b) to describe the relationship between nutrient concentration in the stembark and relative tree height in a PK fertilizer trial at Usutu, Swaziland.

a)

Fixed effect	Nutrient (Prob. >F)				
	N	P	K	Ca	Mg
(1-RelHt)	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
$(1\text{-RelHt})^2$	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
$(1\text{-RelHt})^3$	-	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Fertilizer	0.459	0.102	0.757	**0.027**	0.437
(1-RelHt).Fertilizer	0.073	0.623	0.188	0.062	0.775
$(1\text{-RelHt})^2$.Fertilizer	0.587	0.203	0.089	**0.016**	0.101
$(1\text{-RelHt})^3$.Fertilizer	-	**0.012**	**0.042**	**0.005**	0.151

Bold type indicates statistically significant differences at p<0.05.

b)

Bark nutrient	Unit	Model	Fertilizer	Adj. R²	Model parameters							
					a		*b*		*c*		*d*	
					Coef.	*S.E.*	Coef.	*S.E.*	Coef.	*S.E.*	Coef.	*S.E*
N	%	B	ns	0.626	0.5236	*0.0207*	-0.03602	*0.07837*	-0.2788	*0.06832*	-	-
P	mg kg^{-1}	C	ns	0.614	744.9	*43.6*	-1636	*303.0*	3097	*642.6*	-2175	*392.6*
K	mg kg^{-1}	C	ns	0.573	3414	*256*	-6601	*1373*	14919	*2911*	-11420	*1779*
Ca	mg kg^{-1}	C	None	0.430	4883	*1039*	-22084	*7525*	75140	*15921*	-56559	*9729*
	mg kg^{-1}	C	S80/80	0.494	6836	*991*	-40239	*10480*	129671	*22220*	-94770	*13575*
Mg	mg kg^{-1}	C	ns	0.438	2015	*236*	-5336	*1440*	17501	*3074*	-14309	*1893*

Model B $y = a + b(1\text{-}RelHT) + c(1\text{-}RelHT)^2$
Model C $y = a + b(1\text{-}RelHT) + c(1\text{-}RelHT)^2 + d(1\text{-}RelHT)^3$
Adj. = Adjusted
S.E. = Standard Error
ns = not significant
RelHT = relative tree height

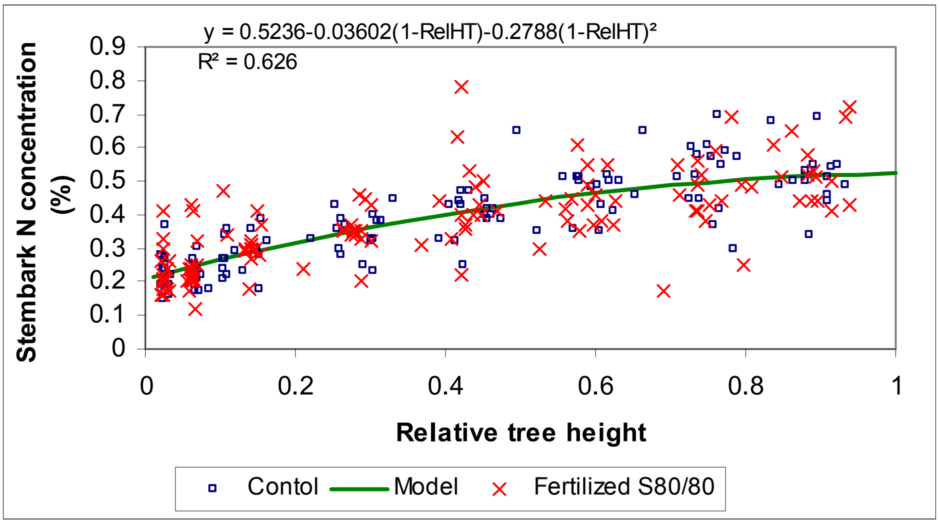
In the case of the relatively mobile nutrients (N, P and K), the concentration of these nutrients in the stembark increased from the base toward the top of the tree (**Figures 6.7a** and **6.7b**). Fitting separate models for the Ca concentration, depending on the fertilizer treatment, significantly (p<0.001) improved the degree of fit. The concentration of Ca in the stembark at the bottom of the trees was significantly greater on the S80/80 fertilized plots, compared to that on the unfertilized plots (**Figure 6.7c**). The general trend of an increase in the N, P and K concentrations with an increase in height along the stem corresponded with the findings by Rubilar *et al.*, (2005).

The allometric relationship between the measured trees and nutrient content was also determined. These results are presented in **Table 6.9**. The model fit for the bark nutrient content was lower than that of the stemwood content, but could still account for a large percentage of the variation.

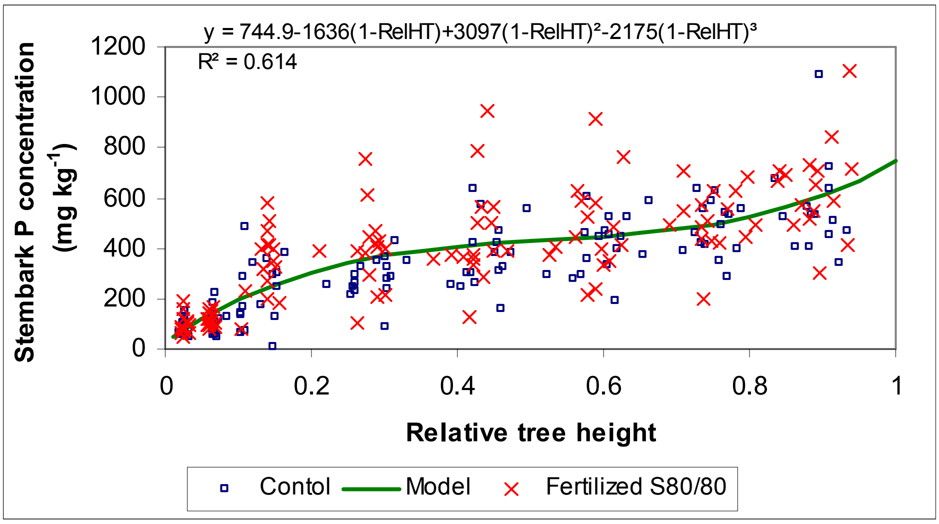
Table 6.9: Regression coefficients and associated standard errors for estimating macro nutrients in stembark of 15-year-old *P. patula* trees with Equation 6.7 (refer to text).

Component (y)	Unit	Fertilizer	Adj. R^2	*a*		*b*	
				Coefficient	*S.E.*	Coefficient	*S.E.*
Barkmass	kg tree^{-1}	ns	0.772	-1.848	*0.288*	0.749	*0.073*
N	kg tree^{-1}	ns	0.733	-4.576	*0.345*	0.810	*0.087*
P	kg tree^{-1}	ns	0.551	-6.054	*0.574*	0.906	*0.145*
K	kg tree^{-1}	ns	0.530	-4.801	*0.517*	0.782	*0.130*
Ca	kg tree^{-1}	ns	0.590	-4.720	*0.520*	0.887	*0.131*
Mg	kg tree^{-1}	ns	0.541	-5.579	*0.608*	0.940	*0.153*

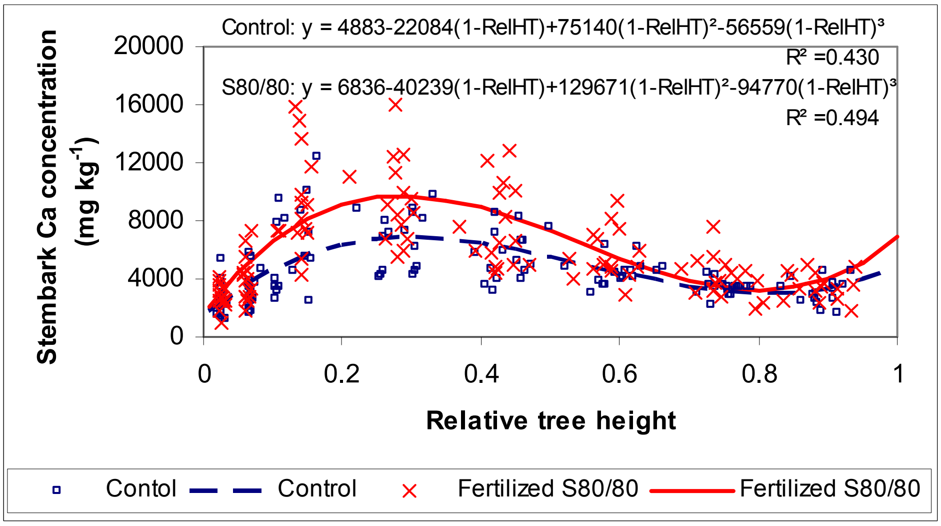
S.E. = Standard Error
Adj. = Adjusted
ns = not significant



a)



b)



c)

Figure 6.7: Stembark N concentration increased from the bottom to the top of the stem (a). Stembark P (b) and K concentrations showed a similar increasing trend towards the top of the trees. Stembark Mg and Ca (c) showed a similar trend, but in the case of Ca the application of P and K fertilizer increased the Ca concentration in the bottom half of 15-year-old *P. patula* trees at Usutu.

6.4 CONCLUSIONS

Similar to results from other trials, the application of PK fertilizer improved tree growth significantly. Furthermore the PK fertilizer had a more pronounced effect on the P-levels in the soil and biomass components than the K-levels.

The stem diameter data from 32 intensively sampled trees did not show a significant change in tree shape as a result of fertilization. However, these results are based on a small number of trees and this aspect will have to be studied in more detail in future.

The results demonstrated that silvicultural practices that promote early tree growth, and by implication increases the proportion of juvenile timber with a lower basic density, can decrease the average tree density by 5%. The decrease in basic density with tree height highlights the need to sample at more than one height or to convert breast height measurements to average tree values with a regression function.

The nutrient content changes with height in the stemwood and stembark (especially for the mobile elements e.g. N, P and K) means that samples should be collected at various heights or that values obtained from samples collected at breast height should be adjusted. The relationship between tree diameter, tree height and nutrient content can be used to estimate total nutrient content of the stemwood and stembark. The increase in P concentration of the stemwood throughout the stem necessitated the use of separate functions to estimate total tree P content from easily measured tree parameters. The increase in stemwood P concentration associated with the application of PK fertilizer in addition to increased timber production will result in a substantial increase in the amount of nutrients removed from the site in the harvested crop.

The investigation of changes within the tree stems on the fertilized and unfertilized plots gave an indication of changes associated with the highest rate of fertilizer application, but the response to different amounts as well as time of application was not investigated. In the following chapter the effect of all the fertilizer treatments on tree growth and basic wood density will be presented.

CHAPTER 7

EFFECT OF PHOSPHORUS (P) AND POTASSIUM (K) FERTILIZER ON TREE GROWTH AND FIBRE PRODUCTION OF *PINUS PATULA* ON A P AND K DEFICIENT SITE IN SWAZILAND

In the previous chapter the basic wood density changes as well as the nutrient changes in stemwood and stembark, as well as the impact PK fertilization had on these parameters, were modelled from ground level to the top of the tree. In this chapter, some of these models will be used to adjust values from samples collected at DBH to reflect whole-tree values. Subsequently, the effect of P and K fertilizer on tree growth and fibre production associated with increasing amounts of fertilizer and application at different times of stand development will be investigated. This paper is currently in preparation for publication in *Southern Forests: A Journal of Forest Science*.

ABSTRACT

A trial, determining the optimum application rate and timing of PK fertilizer to counter a growth decline observed in *P. patula* stands located on the gabbro-derived soils (underlying 13% of the plantation area) of the Usutu Forest, was sampled at rotation age (15 years). The P and K fertilizer was applied in three amounts, 20/20, 40/40 and 80/80 kg P and K per hectare. The 40/40 and 80/80 amounts were applied a) all at planting; b) all after pruning at the age of 5 years; and c) as a split application where 20 kg of P and K per ha, respectively was applied at planting as a spot application and the remaining fertilizer applied after pruning as a broadcast application. Tree survival was not affected by either the amount or time of application of the fertilizer. The increase in tree growth and dry timber production were more related to the amount of fertilizer that was applied than to the time of application, although the early fertilizer application produced more timber than the late fertilizer application. The application of 80/80 kg P and K per hectare significantly increased DBH from 20.0 to 23.0 cm; tree height from 19.6 to 20.4 m; and volume production by 83 m^3 ha^{-1} (29%). Furthermore the application of fertilizer resulted in a more uniform DBH distribution. These results support the current fertilizer prescription on previously unfertilized stands. However, compared to the control the application of 80/80 fertilizer decreased basic wood density by 3% from 0.3718 to 0.3610 g cm^{-3}. Fortunately, the positive volume growth response to the application of fertilizer

outweighed the disadvantage of a slight decrease in timber density as 28 t ha^{-1} (26%) more fibre was produced as a result of fertilization. In order to maximise fibre yield per unit area, the application of PK fertilizer to previously unfertilized gabbro-derived soil at the current recommended rate should continue.

7.1 INTRODUCTION

The 60 000 ha plantations of Usutu Forest in Swaziland supplies raw material to a kraft pulp mill, mostly from planted *Pinus patula* trees grown on a 16 year rotation. Long-term growth monitoring showed that 95 kg ha^{-1} phosphorus (P) and potassium (K) fertilizer, respectively, had to be applied to 13% of the plantation area, located on gabbro-derived soils, in order to maintain or increase volume production from these sites in subsequent rotations (Morris, 1986, 1987a, 1994a, 2003; Evans, 2005). After initial studies showed that the application of PK fertilizer improved growth, further studies were conducted to determine the optimum application rate of the post-pruning fertilizer application if a small amount of PK fertilizer is applied at planting to *P. patula* on the gabbro-derived soils (Morris, 1987a).

In exotic species plantations with very rapid growth rates the maintenance of wood quality is just as important as the maintenance of timber production (Jagels, 2006). Therefore, the increase in volume production after fertilization should be investigated in association with wood quality changes, e.g. basic timber density. The amount of fertilizer, time of application and fertilizer type can have an effect on wood properties (Zobel, 1992) by changing growth patterns of trees, especially the crown-stem relationship (Larson *et al.*, 2001). A summary of 44 studies with 16 conifer species showed that, in general, fertilizer reduced the basic density of the timber. The decrease in density was mostly related to an increased period of low density juvenile wood production after fertilization (especially when nitrogen fertilizer was applied), and to an increase in the percentage of low density earlywood compared to higher density latewood (Zobel and van Buijtene, 1989 cited in Zobel, 1992; Beets *et al.*, 2001).

A trial where various amounts of P and K fertilizer was applied to *P. patula* in a factorial design at different times of stand development, with two levels of weed control reached rotation age during 2007. The tree measurements before clearfelling and destructive sampling at clearfelling provided information on the effects that PK fertilization had on tree growth and on the mean basic timber density of the stemwood at the age of15 years.

7.2 MATERIALS AND METHODS

7.2.1 Trial establishment

The trial site was situated on Land type 307, in compartment A11 (31°4'12"E, 26°27'37"S), at an altitude of 1250 m a.s.l. on a gentle upper mid-slope position. The previous crop was a 1967 age-class second rotation of *Pinus patula*. Clearfelling was done in November to December 1991 and tree lengths were extracted with a cable skidder. Harvest residue was left *in situ* and was not burnt.

The trial was designed as a 3 x 2 x 2 factorial to test time of application, fertilizer amount and effect of intensive weed control. Two amounts of 0:1:1(17) fertilizer, supplying 40 or 80 kg ha^{-1} each of P and K, were applied either all at time of planting (Early), or as a split with 20 kg ha^{-1} each of P and K at time of planting and the rest following pruning (age 5) (Split), or all as a post-pruning application (Late) (**Table 7.1**). The additional treatments to the factorial combinations were a control, where no fertilizer was applied, and a single application of 20 kg ha^{-1} of P and K, respectively, at time of planting. The eight fertilizer treatments were tested in combination with either routine operational weeding or intensive weeding aimed at removing all competing vegetation. The sixteen treatments were laid out as four complete randomised blocks using 7 x 7 row plots at an espacement of 2.74 m squared (Morris, 1994b).

Table 7.1: The sixteen treatment combinations tested in a trial at Usutu where PK fertilizer was applied to *P. patula* trees.

TREATMENTS			
Code	Fertilizer amount		Weed Control
	Planting	Pruning	
E40N	40/40	0	Normal
E40I	40/40	0	Intensive
E80N	80/80	0	Normal
E80I	80/80	0	Intensive
S40N	20/20	20/20	Normal
S40I	20/20	20/20	Intensive
S80N	20/20	60/60	Normal
S80I	20/20	60/60	Intensive
L40N	0	40/40	Normal
L40I	0	40/40	Intensive
L80N	0	80/80	Normal
L80I	0	80/80	Intensive
E20N	20/20	0	Normal
E20I	20/20	0	Intensive
CONTRN	0	0	Normal
CONTRI	0	0	Intensive

TREATMENT CODE DESCRIPTION	
	AMOUNT
20/20	20kg elemental P + 20kg elemental K per ha
40/40	40kg elemental P + 40kg elemental K per ha
60/60	60kg elemental P + 60kg elemental K per ha
80/80	80kg elemental P + 80kg elemental K per ha
	TIME
E	All fertilizer applied at planting (Early)
S	Fertilizer applied part at planting (20/20) and the rest post pruning (Age 5 years) (Split)
L	All fertilizer applied post pruning (Age 5 years) (Late)
	WEED CONTROL
N	Normal weeding as used operationally
I	Intensive weeding aimed at weed free plots

The trial was planted on 24th March 1992. Fertilizer was applied on 9th April 1992 as spot applications 25 cm from the seedling. The 20/20 amount was applied as a single spot, the 40/40 amount was split between two spots on opposite sides of the seedling and the 80/80 amount was applied in four spots around the seedling. The seedlings were treated with *Bexadust* (active ingredient: Gamma BHC) at the root collar in June, 1992, after a small amount of mortality, associated with the bark beetle, *Hylastes angustatus*, had been observed. However, mortality was minor with less than 5% loss at 17 months after planting, and was unrelated to treatment. The trial was not blanked.

When planted, the site was weed free. Weeding of plots receiving the normal operational treatment was only confined to cut stump chemical control of bugweed (*Solanum mauritianum*) in June, 1993, and again in April, 1994. This was carried out as part of the routine weeding of the surrounding operational stand. The intensively weeded plots received, in addition to the operational treatments, two manual hoeing treatments to remove all weeds on the plots in February and December 1993. Pruning, to a height of two metres, was done during May 1997 and the broadcast application of fertilizer, following pruning, was done on 11 September 1997.

7.2.2 Sampling procedure and chemical analyses

7.2.2.1 Tree growth measurements

All surviving trees of the inner 5 x 5 rows of each plot were assessed for height in June 1994 and height and DBH (Diameter at Breast Height, 1.3 m above the soil surface) in July 1997. In October 1999, May 2001, April 2003, May 2004, April 2005, April 2006 and February 2007 the DBH of all 25 trees was measured, but only five trees per plot were assessed in terms of height.

7.2.2.2 Timber and bark samples

In order to do a more intensive analysis of tree density and nutrient content, four trees per plot were selected prior to clearfelling. The four trees included one closest to the 12.5th percentile tree, two close to the median and one close to the 87.5th percentile tree. These were left standing when the trial was felled. Following clearfelling of the unmarked trees a 10 cm billet was collected at breast height from each of the remaining trees per plot by destructive sampling. As some of the marked trees were felled or damaged during harvesting, the mean values of each fertilizer treatment were based on the results from 12 to 22 trees over the DBH range (**Table 7.2**) in stead of the planned 32 trees. The overbark and underbark measurements of each disc were taken in field. The dry weight of the bark from each disc was determined after drying at 70 °C for 72 hours in a ventilated oven.

The basic density of timber samples was determined as it is one of the cheapest and easiest wood properties to measure and provides an indication of both the anatomical characteristics and structural properties of timber (Larson *et al.*, 2001; Stanger *et al.*, 2002). For wood, different definitions of density apply as a decrease in moisture content is associated with a volumetric shrinkage (Simpson, 1993). In the present study the discs used for density analysis were submerged in a dip tank for at least 24 hours until it became fully saturated with water. The green volume of each saturated disc was determined by volume displacement of water. Thereafter the discs were dried in a ventilated oven at 103 °C to a constant weight. The basic timber density was expressed as the dry weight to green volume ratio (Simpson, 1993).

Table 7.2: Number of trees destructively sampled per fertilizer amount and time of application in the 15-year-old *P. patula*, PK fertilizer trial at Usutu.

Time of application	Parameter	Fertilizer amount			
		0/0	20/20	40/40	80/80
Control	Nr. Trees	19	-	-	-
	Min. DBH	11.2			
	Max. DBH	26.9			
Early	Nr. Trees	-	21	12	21
	Min. DBH		12.2	13.3	14.8
	Max. DBH		28.1	25.6	29.5
Late	Nr. Trees	-	-	14	22
	Min. DBH			20.2	13.6
	Max. DBH			27.9	27.2
Split	Nr. Trees	-	-	16	22
	Min. DBH			15.8	16.3
	Max. DBH			27.8	35.3

7.2.3 Calculations and statistical analysis

A logarithmic transformation of height values was conducted in order to determine the height/DBH relationship in the trial with the least squares method of simple linear regression (Bredenkamp, 1993). Utilizable volume estimation was performed from actual DBH measurements and regression heights using a Schumacher and Hall function (Bredenkamp, 2000).

There was clear evidence that mean timber density decreased with an increase in tree height in this trial, as was found in other trials (Morris, 1986; Wielinga *et al.*, 2008), therefore a model was developed to estimate the density of the entire stem from a sample collected at breast height (**Equation 7.1**)(Chapter 6).

$$\text{Avg. basic density of entire tree} = 0.6697(\text{Basic density at 1.3 m}) + 0.1016 \quad \text{[Equation 7.1]}$$

Dry timber production was estimated by multiplying the total stem volume produced by the estimated basic wood density per plot (after the average breast height density was adjusted). The stem bark mass was estimated per plot by the association between DBH, tree height and bark mass (**Equation 7.2**), as reported in Chapter 6.

$$Log_{10}(TBM) = -1.848 + 0.7488\, Log_{10}(DBH^2.HT) \quad \text{[Equation 7.2]}$$

Where,

TBM = Total bark mass per tree (kg)
DBH = Diameter at breast height (cm)
HT = Tree height (m)

In order to analyse the data of the complete trial simultaneously a dummy variable (named “Contrast”) was used to distinguish between the Control treatment; the additional E20/20 treatment; and the factorial treatment combinations. Because the weed treatment had no significant effect from age 5 on any of the growth parameters (Crous *et al.*, 2005a), this treatment was excluded from most statistical models, except in the case of basic tree density analysis. On six plots all the trees were felled during harvesting. Subsequently these plots were treated as missing values in the analyses of bark mass and basic wood density. Analysis of Variance procedure (ANOVA) and multiple linear regression of the statistical software program, *GenStat 10.2*, were used for data analyses (Payne, 2007).

7.3 RESULTS

7.3.1 Tree growth

The effect of fertilizer treatments on the relationship between tree height and tree diameter was investigated with multiple linear regression. The results indicated that from the age of 7.6 years in 1999 (**Table 7.3**) the application of fertilizer affected the relationship of DBH to height significantly and from the increase in R^2-values it is clear that the relationship became stronger as the trees matured.

Table 7.3: Diameter at breast height vs. tree height regression coefficients for the function $lnHT = a.DBH^{-1}+b_{(fertilizer\ amount)}$ where HT = tree height (m) and DBH = diameter overbark at breast height (cm)

Year	Model fit (R^2)	a		Constant (b)							
				0/0		20/20		40/40		80/80	
		Estimate	Prob.>t	Estimate	Prob.>t	Estimate	Prob.>t	Estimate	Prob.>t	Estimate	Prob.>t
1997	0.402	-5.5900	**<0.001**	2.5232	**<0.001**	2.5232	**<0.001**	2.5232	**<0.001**	2.5232	**<0.001**
1999	0.357	-7.7160	**<0.001**	2.8415	**<0.001**	2.8069	0.099	2.8296	0.493	2.8496	0.637
2001	0.346	-5.2290	**<0.001**	2.8788	**<0.001**	2.8811	0.884	2.9083	**0.022**	2.9142	**0.006**
2003	0.415	-5.7720	**<0.001**	3.0798	**<0.001**	3.0746	0.713	3.1019	0.058	3.1152	**0.003**
2004	0.406	-5.1380	**<0.001**	3.1048	**<0.001**	3.1070	0.859	3.1285	**0.022**	3.1457	**<0.001**
2005	0.472	-6.0690	**<0.001**	3.1867	**<0.001**	3.1989	0.339	3.2143	**0.009**	3.2321	**<0.001**
2006	0.475	-6.6770	**<0.001**	3.2640	**<0.001**	3.2728	0.522	3.2854	**0.059**	3.3042	**<0.001**
2007	0.488	-6.3020	**<0.001**	3.2801	**<0.001**	3.2746	0.668	3.2946	0.171	3.3122	**0.003**

The application of fertilizer did not change the slope of the regression line significantly, but did increase the intercept. Generally, an increase in fertilizer amount was associated with an increase in tree height.

The ANOVA results of various tree growth parameters that were measured from 1997 to 2007 are presented in **Table 7.4**. Although the fertilizer amount had a weakly significant effect ($p < 0.10$) on the number of live stems between 1997 and 2004, the effect declined and was insignificant at the 10% level from 2005 onwards (**Tables 7.4** and **7.5**). All other growth parameters were significantly affected by the fertilizer and responded almost similarly to the fertilizer application (**Table 7.4**). A significant difference was observed for the contrast between the control treatment and fertilized treatments, which became stronger as the trial progressed, as can be seen in the decrease in F-probability levels (**Table 7.4**) from 1997 to 2007. As could be expected, the time of application had a greater effect when the trial was young, but declined towards clearfelling age. Just before harvesting the time of application only had an effect on quadratic mean diameter, where the late application of PK fertilizer after pruning produced trees with a smaller DBH than the split application where the fertilizer was split in two applications – at planting and after pruning (**Table 7.5**). The effect of applying different amounts of fertilizer generally increased towards clearfelling age and resulted in significant increases in tree diameter, basal area and volume production per unit area. In terms of basal area and volume the 80:80 treatments performed better than the 40/40 treatments, which in turn performed better than the control treatment (**Table 7.5**). The 80/80 fertilizer amount resulted in an 83 m^3ha^{-1} (29%) volume increase at rotation age compared to the control treatment.

Table 7.4: A summary of analysis of variance F-probability values for tree growth parameters for all measurements from 1997 to 2005 when the *P. patula* trees in the PK fertilizer trial were almost 15 years old.

		Probability >F							
Live stems (spha)		Year measured							
Source of variation	df	1997	1999	2001	2003	2004	2005	2006	2007
REP stratum	3	0.131	0.134	0.124	0.107	0.191	0.250	0.228	0.098
REP.*Units* stratum									
Contrast	2	0.206	0.240	0.244	0.227	0.269	0.436	0.384	0.543
Contrast.Amount	1	0.053	0.063	0.067	0.067	0.066	0.121	0.146	0.238
Contrast.Time	2	0.111	0.102	0.123	0.166	0.176	0.239	0.322	0.242
Contrast.Amount.Time	2	0.644	0.593	0.543	0.500	0.525	0.445	0.552	0.547
Residual	53								
Total	63								
Quadratic mean diameter (cm)									
Source of variation	df	1997	1999	2001	2003	2004	2005	2006	2007
REP stratum	3	0.098	0.960	0.960	0.954	0.971	0.847	0.923	0.825
REP.*Units* stratum									
Contrast	2	**0.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**
Contrast.Amount	1	0.217	**0.003**	**0.002**	**<.001**	**<.001**	**<.001**	**0.001**	**0.003**
Contrast.Time	2	**<.001**	**<.001**	**0.001**	**0.001**	**0.003**	**0.010**	**0.020**	**0.026**
Contrast.Amount.Time	2	**0.005**	**0.047**	0.063	0.052	0.075	0.075	0.120	0.135
Residual	53								
Total	63								
Mean tree height (m)									
Source of variation	df	1997	1999	2001	2003	2004	2005	2006	2007
REP stratum	3	**0.013**	**<.001**	0.457	0.233	0.574	0.452	0.954	0.889
REP.*Units* stratum									
Contrast	2	**0.001**	**0.046**	**0.002**	**0.001**	**0.001**	**<.001**	**0.005**	**0.004**
Contrast.Amount	1	0.527	0.476	0.886	0.424	0.123	0.126	0.151	0.146
Contrast.Time	2	**<.001**	**0.043**	0.077	0.546	0.154	0.246	0.391	0.241
Contrast.Amount.Time	2	**0.033**	**0.016**	0.190	0.334	0.553	0.519	0.603	0.894
Residual	53								
Total	63								
Basal area (m^2ha^{-1})									
Source of variation	df	1997	1999	2001	2003	2004	2005	2006	2007
REP stratum	3	**<.001**	**0.025**	**0.041**	**0.045**	0.095	0.212	0.151	0.217
REP.*Units* stratum									
Contrast	2	**0.047**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**
Contrast.Amount	1	0.727	0.139	0.100	0.051	**0.033**	**0.026**	**0.032**	**0.024**
Contrast.Time	2	**<.001**	**<.001**	**0.027**	**0.026**	**0.048**	0.125	0.099	0.151
Contrast.Amount.Time	2	**0.024**	**0.044**	0.095	0.098	0.154	0.236	0.235	0.240
Residual	53								
Total	63								
Volume per plot (m^3ha^{-1})									
Source of variation	df	1997	1999	2001	2003	2004	2005	2006	2007
REP stratum	3	**<.001**	**0.041**	**0.048**	0.058	0.111	0.259	0.189	0.274
REP.*Units* stratum									
Contrast	2	**0.038**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**
Contrast.Amount	1	0.789	**0.007**	**0.037**	**0.006**	**0.002**	**0.001**	**0.001**	**0.001**
Contrast.Time	2	**<.001**	**<.001**	**0.017**	**0.013**	**0.029**	0.074	0.055	0.098
Contrast.Amount.Time	2	**0.020**	**0.022**	0.073	0.068	0.117	0.168	0.162	0.172
Residual	53								
Total	63								

Bold type identifies statistically significant differences at $p<0.05$.

Table 7.5: Growth response of *P. patula* at age 15 years to the application of various amounts of P and K fertilizer and time of application in a trial at Usutu, Swaziland. Different letters indicate a significant difference between means at p<0.05 or p<0.10 level.

Fertilizer amount	Control	Time of application: Early	Split	Late	Average	Statistical significance
Live stems (stems ha^{-1})						
0/0	1173				1173	
20/20		1106			1106	
40/40		1179	1113	1126	1140	
80/80		1113	1019	1140	1091	
Quadratic mean DBH (cm)						p<0.05
0/0	20.0				20.0	C
20/20		21.7			21.7	B
40/40		21.1	22.3	21.6	21.7	B
80/80		23.3	23.8	21.7	23.0	A
Average	20.0 c	22.2* ab	23.1 a	21.6 b		
Mean tree height (m)						p<0.05
0/0	19.6				19.6	B
20/20		19.4			19.4	B
40/40 & 80/80		20.3	20.7	20.2	20.4	A
Basal area (m^2 ha^{-1})						p<0.05
0/0	36.81				36.81	C
20/20		40.43			40.43	BC
40/40		41.26	42.88	41.01	41.72	B
80/80		46.89	44.75	41.87	44.51	A
Volume (m^3 ha^{-1})						p<0.05
0/0	286.1				286.1	C
20/20		316.1			316.1	BC
40/40		329.7	345.7	329.0	334.8	B
80/80		389.8	373.6	344.0	369.1	A
Basic wood density (g cm^{-1}) (6 missing values)						p<0.10
0/0	0.3718				0.3718	AB
20/20		0.3754			0.3754	A
40/40		0.3723	0.3652	0.3694	0.3689	B
80/80		0.3685	0.3585	0.3560	0.3610	C
Dry timber production (t ha^{-1}) (6 missing values)						p<0.05
0/0	109.3				109.3	D
20/20		123.7			123.7	BC
40/40		124.9	131.6	123.3	126.6	B
80/80		147.6	138.2	126.8	137.5	A
Average	109.3 d	136.2* a	134.9 ab	125.1 bc		
Stembark mass (t ha^{-1}) (6 missing values)						p<0.05
0/0	13.71				13.71	B
20/20		14.42			14.42	AB
40/40 & 80/80		15.97	15.84	15.18	15.66	A

* Excluding early 20/20 treatment

The effect of the fertilizer treatments on the stand structure was also investigated by analyzing the coefficient of variation of the DBH and tree height data. The ANOVA results showed that the fertilizer treatments had no effect on the tree height distribution. However, there were strong evidence (p=0.034) that the coefficient of variation of the DBH data in the fertilized plots (19.18% for the early 20/20 treatment and 20.12% for the factorial 40/40 and 80/80 treatments) were significantly lower than the 23.21% of the control treatment plots.

7.3.2 Basic timber density, dry wood production and mass of stembark

The ANOVA analysis results indicated that basic timber density was only weakly influenced by the amount of fertilizer (**Table 7.6**). At the 10% significance level the application of the highest amount of PK fertilizer caused a decrease in timber density of 0.0161g cm^{-3} compared to the control treatment (**Table 7.5**).

There was a significant increase of 16% in the dry timber production over the control when 40/40 fertilizer was applied and a significant increase of 8.6 % when 80/80 fertilizer was applied (**Tables 7.5** and **7.6**). There was weak evidence (**Table 7.6**) that the time of application had a significant effect on dry timber production in this trial. The early and split application of the 40/40 and 80/80 amounts produced significantly more fibre per hectare than the late application of the same amounts of fertilizer (**Table 7.5**). The stem-bark mass was significantly greater (14%) on the plots that received 40/40 and 80/80 amounts of P and K fertilizer, compared to the control plots (**Tables 7.5** and **7.6**). There was no indication of an interaction between fertilizer amount and time of application in the basic timber density, dry timber production or stembark mass (**Table 7.6**).

Table 7.6: A summary of analysis of variance F values and associated probabilities for basic timber density, dry timber production and bark mass of 15-year-old *P. patula* trees in a fertilizer amount by time of application factorial trial at Usutu.

Source of variation	df (m.v.)	Wood basic density (g cm^{-3})		Dry timber production (t ha^{-1})		Bark mass (t ha^{-1})	
		F	Prob. > F	F	Prob. > F	F	Prob. > F
REP stratum	3	0.54	0.657	0.43	0.732	1.53	0.219
REP.*Units* stratum							
Contrast	2	2.27	0.114	9.82	**<0.001**	6.10	**0.004**
Contrast.Amount	1	3.60	**0.064**	7.55	**0.008**	2.81	**0.099**
Contrast.Time	2	1.70	0.195	3.12	**0.053**	1.09	0.345
Contrast.Amount.Time	2	0.46	0.633	2.25	0.117	0.72	0.491
Residual	47 6)						
Total	57 (6)						

m.v. = missing value

Bold type indicates statistically significant differences at p<0.10.

7.4 DISCUSSION

7.4.1 Tree growth

The application of PK fertilizer had no significant impact on the number of live stems at rotation age, similar to findings in another PK trial (R128) that have reached rotation age (Crous *et al.*, 2008a). All other growth parameters were significantly affected by the application of fertilizer. In general, the highest application (80/80) increased DBH by 15%, mean tree height by 5%, basal area by 21% and volume per hectare by 29% at the age of 15 years. This volume increase corresponded to estimates of an additional 50 to 70 $m^3 ha^{-1}$ based on results from a number of trials by Morris (1987a and 1987b), but were much greater than the additional 22.9 $m^3 ha^{-1}$ or the 25.2 $m^3 ha^{-1}$ that was reported by Crous *et al.* (2007a and 2008a), respectively. Investigation of the effect of fertilization on the stand structure showed that the DBH distribution was more uniform on the fertilized plots as the coefficient of variation decreased, confirming findings by Schönau (1989). The results also showed that the fertilizer increased growth over the life of the trees and not only temporarily after application. The difference in volume production per unit area between trees that received the split 80/80 application and the control increased towards clearfelling age. This clearly indicated that the fertilizer increased the stand productivity – a type II response as defined by Snowdon and Waring (1984).

The significance of the time of application of the fertilizer on volume production decreased after the post-pruning application in 1997 and four years later it was not significant any more. In contrast, the amount of fertilizer that was applied had a significant impact on volume production from 1999 to the end of the rotation.

7.4.2 Basic timber density dry wood production and mass of stembark

The application of the 80/80 amount of PK fertilizer decreased timber density by 3% (**Table 7.5**) compared to the control treatment. Comparison of basic density changes with height in 16 trees sampled on the control plots to 16 trees sampled on S80/80 plots indicated that average basic density at breast height (1.3 m) was 7% lower on the fertilized plots (Chapter 6), which was slightly more than the 3% observed in the analysis of the results from the complete trial. The density decrease of 3% was also less than the reduction of 8% reported by McKinnell and Rudman (1973) after application of 188 kg K ha^{-1} to *P. radiata* or the 5.5% reduction reported by Gray and Kyanka (1974) after application of 112 kg K ha^{-1} to *P. resinosa.* In Australia, the 128% volume increase

(Waterworth *et al.*, 2007) reported in the Biology of Forest Growth study with *P. radiata,* where 400 kg N ha^{-1}, 200kg P ha^{-1}, 100 kg K ha^{-1} and irrigation were applied (Benson *et al.*, 1992), was associated with a 9 % decrease in basic density (Wielinga *et al.,* 2008). In the southern USA intensive site preparation with fertilization and weed control increased merchantable stem volume of *P. taeda* trees by 81 to 120 %, but reduced basic timber density by 6 to 10% (Clark *et al.*, 2004; Clark *et al.*, 2006). Cown and McConchie (1981) and Woollons *et al.*, (1995) cited in McGrath *et al.* (2003) reported a 5% decrease in fertilized *P. radiata* wood in New Zealand and New South Wales, Australia, respectively. The lowering of timber density can have an influence on the pulp characteristics, for example, higher burst and tensile strengths, but lower tear factor, opacity and bulk (McKinnell and Rudman, 1973; Clark *et al.*, 2006). A lower timber density will also result in lower yields per digester charge in batch processes, which will have an economic penalty (Clark *et al.*, 2006).

In trials where density across each disc was assessed per ring the reduction in mean timber density was due to 1) an increase in the earlywood content as fertilization normally increased growth in conifers during spring resulting in a higher proportion of low-density earlywood (Gray and Kyankan, 1974; Larson *et al.*, 2001; Albaugh *et al.*, 2004) or 2) because increased growth in the first few years increased the diameter of the juvenile wood core, which is characterised by timber with lower density than mature wood (Clark *et al.*, 2004; Clark *et al.*, 2006, Mora *et al.*, 2007) or 3) because of a reduction in latewood density (Clark *et al.*, 2004) associated with increased photosynthetic efficiency (Larson *et al.*, 2001). Gray and Kyanka (1974) as well as Cown and McConchie (1981) mentioned that nutrient deficiencies may affect wood properties because of abnormally slow radial growth and that the response after fertilization might be a reversion to the wood properties of “normal” stands.

Results from the complete trial (data not shown) and 32 trees where stem discs were analysed at various stem heights (Chapter 6) showed that the weed treatment had no effect on the mean timber density.

Despite the negative effect on basic timber density, the total dry timber production (fibre) increased significantly by 16% where 40/40 fertilizer was applied and 26% where 80/80 fertilizer was applied, due to the increase in timber volume production. The early application of fertilizer produced 8% more dry timber than the late application, but only 1% (not statistically significant) more than the split application. These results confirm that the current commercial prescription to apply a small amount of PK fertilizer at planting, followed by a larger application after pruning, is the most effective, because it increases production significantly while the largest proportion of fertilizer cost is incurred later into the rotation and early weed growth is not stimulated too much by a small application of fertilizer at planting (Morris, 1994a).

The 13.7 tons per hectare of bark in the control plots corresponded with values of 14.2 t ha^{-1} reported by Morris (1992) for 15-year-old *P. patula* trees at Usutu and 12.9 and 13.7 t ha^{-1} reported in 19 and 22-year-old *P. taeda*, respectively (Rubilar, 2003). The bark mass was not affected to the same extent as wood production by the application of fertilizer and the application of the 40/40 and 80/80 amounts increased the bark mass by 14%, compared to the control.

7.5 CONCLUSIONS

The PK fertilizer increased growth over the life of the trees and not only temporarily after application, indicating that the fertilizer increased the stand productivity – a type II response as defined by Snowdon and Waring (1984). Furthermore the application of fertilizer resulted in a more uniform DBH distribution. The results supported the current prescription to apply 20 kg P and K per ha, respectively, at planting, followed by a broadcast application of 75 kg P and K per ha, respectively, after pruning to stands located on gabbro-derived soils that have not been fertilized during an earlier rotation. A split application increased production similarly to an early application, while the largest proportion of fertilizer cost was incurred later into the rotation and early weed growth was not stimulated too much by a small application of fertilizer at planting, before canopy closure occurred.

Although the application of fertilizer decreased the mean density of the timber the additional volume production from the application of PK fertilizer far outweighed the disadvantage of a slight (3%) reduction in density. Therefore, in order to maximise fibre yield per unit area, the application of PK fertilizer to previous unfertilized soil located on gabbro parent material should continue at the current recommended rate.

In the following chapter, which is a continuation of analysis of results for the complete R155 trial, the impact of the PK fertilizer application on forest floor litter, soil nutrients and tree nutrient content will be discussed.

CHAPTER 8

CHANGES IN TOPSOIL, FOREST FLOOR LITTER AND TREE NUTRIENT CONTENT AFTER FERTILIZATION OF A *PINUS PATULA* PLANTATION ON A PHOSPHORUS AND POTASSIUM DEFICIENT SITE IN SWAZILAND

In chapter 4 the effects that residual P K fertilizer had on soil, forest floor and foliar nutrients 15 years after the application of fertilizer to trial R128 were reported. However, these results were based on samples collected a few years after the clearfelling of the original trial. In the trial results (R155) reported in this chapter the soil and forest floor litter samples were collected before clearfelling and foliar and wood samples at clearfelling, minimizing the effects of harvest residue cross contaminating plots. From the earlier work (R128, chapter 3 to 5) it was impossible to estimate the amounts of nutrients that were removed from the site in the fertilized crop, which was now possible by using data from trial R155. This paper is currently in preparation for publication in Forest Ecology and Management.

ABSTRACT

A major goal for sustainable forestry management is to prevent a decline in soil fertility as it contributes towards the site's production capacity. A study of the amount of nutrients contained in foliage, forest floor litter and topsoil was used to determine the impact of PK fertilization on nutrient cycling at rotation age. In a phosphorus (P) by potassium (K) by weed control trial, the P and K fertilizer was applied in three amounts, 20/20, 40/40 and 80/80 kg P and K per ha. The 40/40 and 80/80 amounts were applied with three different regimes, either applying all of the fertilizer at planting or after pruning (5 years), or splitting the application into a 20/20 application at planting (spot application) and applying the remaining fertilizer at pruning (either 20 or 60 kg of P and K by broadcast application). In a further treatment a 20/20 application of fertilizer was applied at planting with no further application at pruning. At clearfelling age (15 years) topsoil, forest floor litter, stemwood, stembark and foliar samples were collected and chemically analysed. The effect of P fertilizer was more pronounced at the end of the rotation than the effect of K fertilizer. Compared to the control the application of 80/80 PK fertilizer, increased the concentration of plant available P (Bray II) in the first 100 mm of the topsoil from 3 mg kg^{-1} to 12 mg kg^{-1} and increased the foliar P level significantly to 0.13%. The foliar response at rotation age to the PK fertilizer as well as the concentration of plant

available P in the topsoil increased when the fertilizer was applied closer to rotation age. The split application of either 40/40 or 80/80 PK fertilizer increased the stemwood P concentration by 50%, compared to the 23 mg kg^{-1} P that was found on the control plots. Application of the 40/40 and 80/80 amounts of fertilizer increased the mass of the forest floor litter layer by 27 300 kg ha^{-1} (35%) compared to the control. Although the P and K concentrations were not significantly affected in the forest floor litter layer, the P and K contents were significantly greater on the fertilized plots. The highest amount of PK fertilizer significantly increased the amount of nutrients that were removed from the site in stemwood and stembark. A greater proportion of K compared to P of the applied P and K was removed from the site, indicating that the re-application of K in the subsequent rotations will become more important.

8.1. INTRODUCTION

The 60 000 ha Usutu Forest in Swaziland supplies raw material to a kraft pulp mill, mostly from planted *Pinus patula* trees grown on a 16 year rotation. Long-term growth monitoring showed that 95 kg ha^{-1} phosphorus (P) and potassium (K) fertilizer, respectively, had to be applied to 13% of the plantation, located on gabbro-derived soils, in order to maintain or increase volume production from these sites in subsequent rotations (Morris, 1986, 1987, 1994, 2003; Evans, 2005). Further studies were conducted to determine the optimum application rate of the post-pruning fertilizer application if a small amount of PK fertilizer is applied at planting to *P. patula* on the gabbro-derived soils (Morris, 1987). This trial reached clearfelling age (15 years) in 2007.

According to Dyck and Beets (1987) the long-term site productivity is affected by nutrient reserves, amount of nutrients removed in harvesting and post-harvesting site preparation. Previous studies have shown that substantial amounts of nutrients are contained within the harvested timber crop (**Table 2.2**). A major goal for sustainable forestry management is to prevent a decline in soil fertility as it contributes towards the site's production capacity (Nambiar, 1996). In the short-term soil fertility is related to the pool of nutrients available for plant nutrition, while soil fertility in the medium- to long-term is related to the fluxes of elements (Ranger and Turpault, 1999). Thus, the losses of nutrients associated with removal in crop harvests need to be quantified in order to determine its effect on the nutrient pools and subsequently on the long-term production capacity of the site (Carlson and Allan, 2001).

The results from the trial reported on in this paper were used to verify the growth response to the application of PK fertilizer on the gabbro-derived soils (Chapter 7), as the results from various compartments are needed to estimate responses in other similar compartments (Binkley, 2008). In addition, destructive sampling of a selection of trees provided information on the effects fertilization had on mean timber density, stembark and stemwood nutrient contents (Chapter 6). In this document the chemical analysis of foliage, forest floor and topsoil provided information on the longer-term effects of the application of PK fertilizer on nutrient cycling and the effects on the site nutrient balance. The amounts of nutrients that are exported in the harvested crop were estimated in order to determine the impact on the nutrient pools and thus on growth of the subsequent crop.

8.2 MATERIALS AND METHODS

8.2.1 Trial establishment

The trial site was situated on Land type 307, in compartment A11 (31°4'12"E, 26°27'37"S), at an altitude of 1250 m a.s.l. on a gentle upper mid-slope position. The previous crop was a 1967 age-class second rotation of *Pinus patula*. Clearfelling was done in November to December 1991 and tree lengths were extracted with a cable skidder. Harvest residue was left *in situ* and was not burnt. The site had not been fertilized before.

The trial was designed as a 3 x 2 x 2 factorial to test time of application, fertilizer amount and effect of intensive weed control. Two amounts of 0:1:1(17) fertilizer, supplying 40 or 80 kg ha^{-1} each of P and K, were applied either all at time of planting (Early), or as a split with 20 kg ha^{-1} each of P and K at time of planting and the rest following pruning (age 5) (Split), or all as a post-pruning application (Late) (**Table 8.1**). The additional treatments to the factorial combinations were a control, where no fertilizer was applied, and a single application of 20 kg ha^{-1} of P and K, respectively, at time of planting. The eight fertilizer treatments were tested in combination with either routine operational weeding or intensive weeding aimed at removing all competing vegetation. The sixteen treatments were laid out as four complete randomised blocks using 7 x 7 row plots at an espacement of 2.74 m squared.

The trial was planted on 24th March 1992, after two days of rain, using nine-month-old *P. patula* stock raised from OP seed of Zimbabwe clone 48. Fertilizer was applied on 9th April 1992 as spot applications 25 cm from the seedling. The 20/20 amount was applied as a single spot, the 40/40 amount was split between two spots on opposite sides of the seedling and the 80/80 amount was applied in four spots around the seedling. The seedlings were treated with *Bexadust* (active ingredient: Gamma BHC) at the root collar in June, 1992, after a small amount of mortality, associated with the bark beetle, *Hylastes angustatus*, had been observed. However, mortality was minor with less than 5% loss at 17 months after planting, and was unrelated to treatment. The trial was not blanked.

Table 8.1: The sixteen treatment combinations tested in a trial at Usutu where PK fertilizer was applied to *P. patula* trees.

TREATMENTS			
Code	Fertilizer amount		Weed Control
	Planting	Pruning	
E40N	40/40	0	Normal
E40I	40/40	0	Intensive
E80N	80/80	0	Normal
E80I	80/80	0	Intensive
S40N	20/20	20/20	Normal
S40I	20/20	20/20	Intensive
S80N	20/20	60/60	Normal
S80I	20/20	60/60	Intensive
L40N	0	40/40	Normal
L40I	0	40/40	Intensive
L80N	0	80/80	Normal
L80I	0	80/80	Intensive
E20N	20/20	0	Normal
E20I	20/20	0	Intensive
CONTRN	0	0	Normal
CONTRI	0	0	Intensive

TREATMENT CODE DESCRIPTION	
	AMOUNT
20/20	20kg elemental P + 20kg elemental K per ha
40/40	40kg elemental P + 40kg elemental K per ha
60/60	60kg elemental P + 60kg elemental K per ha
80/80	80kg elemental P + 80kg elemental K per ha
	TIME
E	All fertilizer applied at planting (Early)
S	Fertilizer applied part at planting (20/20) and the rest post pruning (Age 5 years) (Split)
L	All fertilizer applied post pruning (Age 5 years) (Late)
	WEED CONTROL
N	Normal weeding as used operationally
I	Intensive weeding aimed at weed free plots

When planted, the site was weed free. Weeding of plots receiving the normal operational treatment was only confined to cut stump chemical control of bugweed (*Solanum mauritianum*) in June, 1993, and again in April, 1994. This was carried out as part of the routine weeding of the surrounding operational stand. The intensively weeded plots received, in addition to the operational treatments, two manual hoeing treatments to remove all weeds on the plots in February and December, 1993. Pruning, to a height of two metres, was done during May 1997 and a broadcast application of fertilizer, following pruning, was done on 11 September 1997.

8.2.2 Sampling procedure and chemical analyses

8.2.2.1 Tree growth measurements

All surviving trees of the inner 5 x 5 rows of each plot were assessed for height in June 1994 and height and DBH (Diameter at Breast Height, 1.3 m above the soil surface) in July 1997. In October 1999, May 2001, April 2003, May 2004, April 2005, April 2006 and

February 2007 the DBH of all 25 trees was measured, but only 5 trees per plot were assessed in terms of height.

8.2.2.2 Timber and bark samples

In order to do a more intensive analysis of basic wood density and nutrient content, four trees per plot were selected prior to clearfelling. The four trees included one closest to the 12.5th percentile tree, two close to the median and one close to the 87.5th percentile tree. These were left standing when the trial was felled. Following clearfelling of the unmarked trees a 10 cm billet was collected at breast height from each of the remaining trees per plot with destructive sampling. As some of the marked trees were felled during harvesting, the mean values of each fertilizer treatment were based on the results from 12 to 22 trees, representing the DBH range (**Table 8.2**). The overbark and underbark measurements of each disc were taken in field. The dry weight of the bark was determined per sample disc after drying at 70 °C for 72 hours in a ventilated oven.

Table 8.2: Number of trees destructively sampled per fertilizer amount and time of application in the 15-year-old *P. patula*, PK fertilizer trial at Usutu.

Time of application	Parameter	Fertilizer amount 0/0	20/20	40/40	80/80
Control	Nr. Trees	19	-	-	-
	Min. DBH	11.2			
	Max. DBH	26.9			
Early	Nr. Trees	-	21	12	21
	Min. DBH		12.2	13.3	14.8
	Max. DBH		28.1	25.6	29.5
Late	Nr. Trees	-	-	14	22
	Min. DBH			20.2	13.6
	Max. DBH			27.9	27.2
Split	Nr. Trees	-	-	16	22
	Min. DBH			15.8	16.3
	Max. DBH			27.8	35.3

Each disc was cut into two round discs with a chainsaw. One disc was used for density analysis and the second for nutrient analyses. The basic density of timber samples was determined as it is one of the cheapest and easiest wood properties to measure and provides an indication of both the anatomical characteristics and structural properties of timber (Larson *et al.*, 2001; Stanger *et al.*, 2002). For wood, different definitions of density apply as a decrease in moisture content is associated with a volumetric shrinkage (Simpson, 1993). In the present study the discs used for density analysis were submerged in a dip tank for at least 24 hours until it became fully saturated with water. The green volume of each saturated disc was determined by volume displacement of water. Thereafter the discs were dried in a ventilated oven at 103 °C to a constant weight. The basic timber density was expressed as the dry weight to green volume ratio (Simpson, 1993).

From each wood disc a wedge of timber was cut to sample an equal proportion of earlywood and latewood from each disc, irrespective of the diameter. The wedges were chipped in a hammer mill and thereafter ground in a Wiley mill to pass though a 2 mm sieve. An equal amount of ground wood from all DBH discs, except from the Control and split 80/80 treatments, were bulked into one sample per plot prior to nutrient analyses. Following fine grinding, the bark samples were bulked similarly to the wood samples. Total nitrogen (N) was determined by the combustion method using a LECO analyser. In this process a suitable aliquot of sample was mixed with a suitable oxidant and thermally decomposed into nitrogen monoxide and other gaseous products. The other macro nutrients were analysed after 2.5 g of the ground samples was dry ashed and taken up in a solution of 0.6N HCl. Phosphorus (P) was determined by the molybdenum blue method in an auto analyzer (Donkin *et al.*, 1993). Potassium, calcium (Ca) and magnesium (Mg) concentrations were determined using an Inductively Coupled Plasma Mass Spectrometer (ICP-MS) with an argon shield. All concentrations were expressed as a proportion of dry mass. The P:N and K:N nutrient ratios were expressed on a mass basis as a percentage of N (Linder, 1995).

8.2.2.3 Foliar samples

Live foliage was collected from the top third of the crown from each of the trees that were destructively sampled after clearfelling during April/May 2007. The previous season's foliage that had reached mature length was collected from the top third of the crown (Will, 1985; Linder, 1995 and Louw and Scholes, 2003) and bulked per plot on an equal number of needle bundles (fascicles) basis. The foliar samples were dried in a ventilated oven for 72 hours at 70°C immediately following collection. After fine grinding the macro nutrient concentrations were analysed using the methods described earlier.

8.2.2.4 Forest floor samples

The forest floor mass was systematically sampled over two 0.5 x 0.5 m areas per plot, below tree numbers 8 and 17 on each plot. The wet mass of each sample was determined in field with a hanging scale. The various humus layers (L, F and H layers) were bulked as one sample and the wet weight of this sub-sample was accurately determined at the research station immediately after collection in field. After drying for 72 hours at 70 °C the dry weight was determined. Macro nutrient concentrations were analysed using the methods described earlier.

8.2.2.5 Soil samples

The first 100 mm of mineral soil was collected with a soil core sampler from 10 locations per plot and bulked. The soil sampling was conducted during July 2006, prior to disturbance of the soil and forest floor during the harvesting operation. The sampling was systematically conducted below the same tree numbers in each plot, which were initially randomly determined. To compare soil parameters in the trial with those from surrounding areas, bulked soil samples were collected from an adjacent planted compartment (in an area where no fertilizer had been applied) and virgin soil samples were collected from a natural grassland area (firebreak) below the trial. Each sample was immediately air dried, sieved through a 2 mm sieve, placed in an air-tight container and archived for analysis one year later.

The pH and ammonium acetate extractable Ca, Mg, Na, and K were determined for each sample as described by Donkin *et al.* (1993). The plant-available P was determined with Bray II 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). Total soil N was determined by the Kjeldahl-method (Kalra and Maynard, 1991). $HN0_3$ - extraction described by Hafez and Stout (1973) was used to determine the "total" K concentration. Organic Carbon was determined by means of loss on ignition analysis (Donkin, 1991; Kalra and Maynard, 1991).

8.2.3 Calculations and statistical analysis

The allometric relationships between biomass and nutrient content that were developed from selected treatments in the trial (Chapter 6) were used to estimate nutrient content of stemwood and stembark on each plot.

In order to analyse the data of the complete trial simultaneously a dummy variable (named "Contrast") was used to distinguish between the Control treatment; the additional E20/20 treatment; and the factorial treatment combinations. Due to low levels of weed development in the trial the weed control treatment had only a very small effect on tree growth at the age of 17 months (Morris, 1994b) and none thereafter (Crous *et al.*, 2005a). On six plots all the trees were felled during harvesting. Subsequently these plots were treated as missing values. The statistical software program, *GenStat 10.2*, Analysis of Variance procedure (ANOVA), t-test, multiple linear regression as well as non-linear regression, was used for data analyses (Payne, 2007).

8.3 RESULTS

8.3.1 Top soil nutrients

A comparison of soil parameters assessed within the trial, with those from virgin grassland soil and an adjacent unfertilized stand indicated that in absolute terms soil N, exchangeable K, Ca, Mg and the S-value was greater in the grassland and unfertilized plantation than in the control plots or S40/40 and S80/80 fertilized plots in the trial (**Table 8.3**).

Table 8.3: Comparison of soil parameters from an adjacent grassland area, unfertilized stand and selected trial treatments from the 15-year-old *P. patula* PK fertilizer trial at Usutu.

Parameter	Unit	Grassland		Unfertilized		Control		S40/40		S80/80	
		Mean	*SE*	Mean	SE	Mean	*SE*	Mean	*SE*	Mean	*SE*
N	%	0.27	*0.024*	0.27	*0.032*	0.20	*0.013*	0.22	*0.011*	0.20	*0.011*
P Bray II	mg kg^{-1}	0.43	*0.105*	1.70	*0.415*	2.79	*0.342*	3.27	*0.343*	9.96	*2.353*
P_i (0.5M H_2SO_4)	mg kg^{-1}	40.2	*1.04*	53.9	*3.01*	55.5	*6.15*	61.5	*5.35*	79.5	*10.87*
P_o (0.5M H_2SO_4)	mg kg^{-1}	189.9	*27.30*	201.5	*25.60*	150.1	*9.03*	159.5	*15.48*	180.1	*30.40*
P_{i+o} (0.5M H_2SO_4)	mg kg^{-1}	230.1	*28.40*	255.3	*28.60*	205.6	*14.10*	221.0	*20.10*	259.6	*39.90*
K Exch.	cmol(+)kg^{-1}	0.18	*0.015*	0.17	*0.030*	0.09	*0.011*	0.08	*0.005*	0.09	*0.004*
K (HNO_3 extracted)	cmol(+)kg^{-1}	0.23	*0.040*	0.20	*0.011*	0.11	*0.008*	0.10	*0.007*	0.10	*0.005*
Ca	cmol(+)kg^{-1}	0.59	*0.175*	0.92	*0.045*	0.36	*0.044*	0.33	*0.030*	0.37	*0.029*
Mg	cmol(+)kg^{-1}	0.33	*0.060*	0.36	*0.085*	0.13	*0.012*	0.14	*0.011*	0.13	*0.014*
Na	cmol(+)kg^{-1}	0.09	*0.000*	0.15	*0.040*	0.08	*0.014*	0.06	*0.010*	0.08	*0.011*
S-value	cmol(+)kg^{-1}	1.19	*0.255*	1.59	*0.055*	0.65	*0.072*	0.61	*0.043*	0.67	*0.055*
OC	%	4.87	*0.024*	5.23	*0.370*	5.33	*0.124*	5.60	*0.294*	5.50	*0.109*

SE – Standard Error of the mean
S-value – Sum of exchangeable cations
OC – Organic carbon

The plant available P increased from the grassland to the unfertilized plantation to the control plots and further as P and K fertilizer was applied. On the other hand soil K levels decreased from the grassland soil to the unfertilized plantation and fertilized plots (**Table 8.3**).

Although the ANOVA results (**Table 8.4**) indicated that the soil N content was significantly affected by the amount of fertilizer, investigation of least significant differences at the 5% level between treatment means could only identify a significant difference between the 0.21% found in the 40/40 treatments and 0.19% found in the 80/80 treatments. The plant available P (Bray II) increased when it was applied closer to rotation age. However, the largest amount of fertilizer had the greatest influence on plant available P (**Table 8.5**). The time of application affected the organic, inorganic and total Ca-phosphate fractions that were extracted with sulphuric acid (**Table 8.5**). The greatest fertilizer amount increased the soil Ca-levels significantly (**Table 8.5**).

Table 8.4: A summary of analysis of variance F-probability values for nutrient concentrations in topsoil (0-100 mm) in a 15-year-old PK fertilizer trial.

Source	d.f.	Soil nutrients (mg kg^{-1})								
		N	P (Bray II)	0.5M H_2SO_4 extracted			K	Ca	Mg	Na
				P_i	P_o	P_{i+o}				
		Probability > F								
REP stratum	3	0.239	0.322	0.326	**0.000**	**0.000**	0.094	**0.000**	**0.007**	0.409
REP.*Units* stratum										
Contrast	2	0.722	0.244	0.233	0.809	0.483	0.846	0.996	0.720	0.885
Contrast.Amount	1	**0.031**	**0.047**	0.167	0.793	0.259	0.181	**0.017**	0.375	0.252
Contrast.Time	2	0.520	**0.007**	**<0.001**	**0.014**	**0.002**	0.496	**0.026**	0.915	0.251
Contrast.Amount.Time	2	0.624	0.173	0.212	0.362	0.174	0.341	0.762	0.404	0.257
Residual	53									
Total	63									

Bold type indicates statistically significant differences at $p<0.05$.
P_i = Inorganic P fraction; P_o = Organic P fraction

Table 8.5: Summary of the soil nutrients in the control plots and detail of soil P and Ca concentrations that were significantly affected by the application of PK fertilizer to *P. patula* trees at Usutu. Different letters indicate a significant difference between means at p<0.05.

Parameter	Amount	Time of application				Average	Statistical significance
		Control	Early	Split	Late		
N (%)		0.20					
P Bray II (mg kg^{-1})							
	0/0	2.8				2.8	B
	20/20		2.3			2.3	B
	40/40		2.9	3.3	8.3	4.8	B
	80/80		2.0	10.0	23.0	11.6	A
	Average	2.8 b	2.5* b	6.6 b	15.6 a		
P_i (0.5M H_2SO_4) (mg kg^{-1})		55.5 b	51.3* b	70.5 b	129.0 a		
P_o (0.5M H_2SO_4) (mg kg^{-1})		150.1 ab	132.8* b	169.8 a	131.7 b		
P_{i+o} (0.5M H_2SO_4) (mg kg^{-1})		205.6 ab	184.1 b	240.3a	260.7a		
K Exch. (cmol(+)kg^{-1})		0.089					
K HNO_3 Extr.(cmol(+)kg^{-1})		0.106					
Ca (cmol(+)kg^{-1})							
	0/0	0.359				0.359	AB
	20/20		0.363			0.363	AB
	40/40		0.300	0.325	0.365	0.330	B
	80/80		0.353	0.370	0.453	0.392	A
	Average	0.359 ab	0.326* b	0.348 ab	0.409 a		
Mg (cmol(+)kg^{-1})		0.126					
Na (cmol(+)kg^{-1})		0.078					
Organic Carbon (%)		5.33					

* Excluding Early 20/20 treatment; P_i = Inorganic P fraction; P_o = Organic P fraction

8.3.2 Forest floor mass and nutrients

The ANOVA results (**Table 8.6**) indicated that none of the macro nutrient concentrations in the forest floor litter was significantly affected by the application of the PK fertilizer. However, the forest floor litter mass was significantly increased by 27 300 kg ha^{-1} (35%) as a result of the 40/40 and 80/80 PK fertilizer treatments, compared to the control (**Table 8.6** and **Figure 8.1**). The P content of the forest floor litter increased significantly by 61% over that in the control when 40/40 and 80/80 amounts of P and K were applied (**Table 8.6** and **Figure 8.1**). The amount of K in the forest floor litter was 50% more on the plots that received fertilizer, compared to that on the control plots (**Table 8.6** and **Figure 8.1**).

Table 8.6: A summary of analysis of variance F-probability values for nutrient concentrations in forest floor litter underneath 15-year-old *P. patula* trees in a PK fertilizer trial.

Source	df	Nutrient concentration (%)					Forest floor litter mass	Nutrient content (kg ha^{-1})				
		N	P	K	Ca	Mg		N	P	K	Ca	Mg
		Probability >F										
REP stratum	3	**0.013**	**0.004**	0.562	**0.001**	**0.001**	0.198	0.162	**0.039**	0.349	**0.009**	**0.004**
REP.*Units* stratum												
Contrast	2	0.413	0.067	0.205	0.265	0.307	**0.013**	0.081	**0.010**	**0.039**	0.108	0.065
Contrast.Amount	1	0.961	0.659	0.430	0.587	0.354	0.109	0.116	0.132	0.559	0.089	0.612
Contrast.Time	2	0.680	0.545	0.454	0.702	0.170	0.235	0.196	0.265	0.430	0.553	0.193
Contrast.Amount.Time	2	0.514	0.254	0.862	0.935	0.864	0.701	0.821	0.337	0.611	0.733	0.763
Residual	53											
Total	63											

Bold type indicates statistically significant differences at p<0.05.

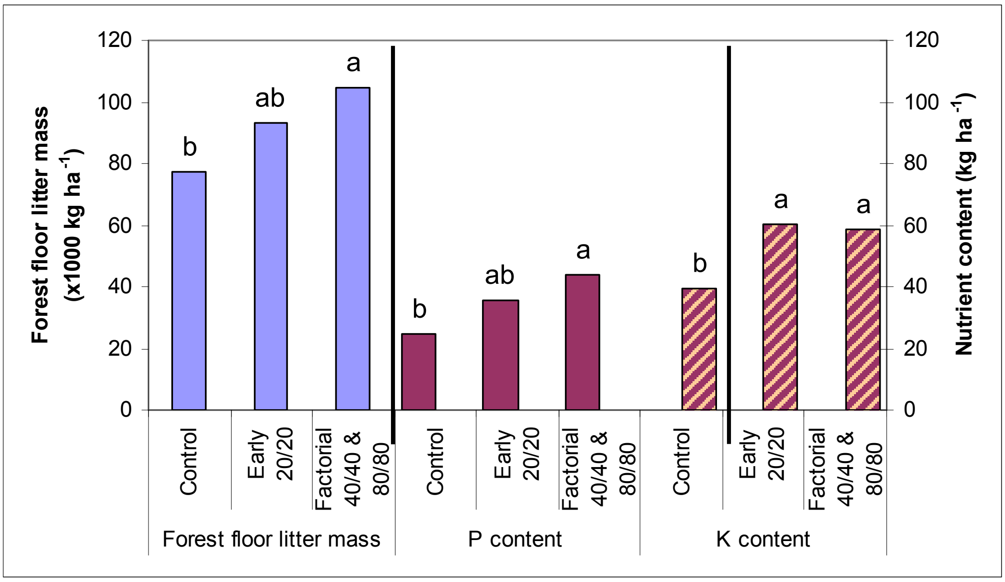


Figure 8.1: Forest floor litter mass; P content and K content of the forest floor litter as affected by the application of 0, 20 or 40 and 80 kg P and K ha^{-1}, respectively, underneath a 15-year-old *P. patula* stand at Usutu. Different letters indicate a significant difference between the means of each component at p<0.05.

8.3.3 Foliar nutrients

The ANOVA results showed that the application of the P and K fertilizer only affected the foliar P and Ca concentration and had no effect on the other nutrients (**Table 8.7**). The foliar Ca concentration of the treatments where 40/40 or 80/80 kg PK was applied were significantly greater at 0.327% compared to the level of 0.250% that was recorded on the control plots. The amount of fertilizer had a greater effect on foliar P levels than the time of application. Only the application of the greatest amount increased the foliar P levels significantly (**Table 8.8**).

Table 8.7: A summary of analysis of variance F-probability values for nutrient concentrations and ratios of live foliage from *P. patula* trees at Usutu, collected at age 15 years in a PK by amount by time of application fertilizer trial.

Source	d.f.	m.v.	Foliar nutrient concentration (%) or nutrient ratio							
			N	P	K	Ca	Mg	P/N	K/N	P/K
			Probability >F							
REP stratum	3		0.138	**0.001**	**0.001**	0.217	0.018	**0.008**	0.052	**0.015**
REP.*Units* stratum										
Contrast	2		0.521	**0.018**	0.873	**0.050**	0.168	**<0.001**	0.388	**0.010**
Contrast.Amount	1		0.835	**0.008**	0.571	0.062	0.250	**0.002**	0.551	**0.011**
Contrast.Time	2		0.150	**0.014**	0.449	0.164	0.328	**0.023**	**0.020**	**0.002**
Contrast.Amount.Time	2		0.735	0.141	0.298	0.219	0.316	0.276	0.603	0.488
Residual	45	(8)								
Total	55	(8)								

m.v. = number of missing values
Bold type indicates statistically significant differences at p<0.05.

Table 8.8: Summary of the foliar nutrient concentration and foliar nutrient ratios in 15-year-old *P. patula* trees that were recorded in a PK fertilizer trial at Usutu. Different letters indicate a significant difference between means at p<0.05.

Parameter	Fertilizer amount	Time of application				Average	Statistical significance
		Control	Early	Split	Late		
Foliar N%	0/0	1.927					
Foliar P%	0/0	0.104				0.104	B
	20/20		0.111			0.111	B
	40/40		0.108	0.116	0.122	0.115	B
	80/80		0.116	0.145	0.127	0.129	A
	Average	0.104 b	0.112* b	0.131 a	0.125a		
Foliar K%	0/0	0.451					
Foliar Ca%	0/0	0.250					
Foliar Mg%	0/0	0.081					
Foliar P:N†	0/0	5.37					C
	20/20		5.86			5.86	BC
	40/40		5.92	6.12	6.68	6.24	B
	80/80		6.41	7.41	7.17	7.00	A
	Average	5.37 c	6.16* b	6.77 a	6.92 a		
Foliar K:N	Average	23.4 ab	25.13* ab	22.7 b	25.8 a		
Foliar P:K	0/0	0.231				0.231	B
	20/20		0.253			0.253	B
	40/40		0.233	0.278	0.266	0.259	B
	80/80		0.266	0.319	0.277	0.287	A
	Average	0.231 c	0.249* bc	0.299 a	0.272 b		

* Excluding early 20/20 treatment
† Expressed on a mass basis as a percentage of N

However, at clearfelling the foliar P levels were significantly greater in the 40/40 and 80/80 treatments that received some fertilizer after pruning (late and split), compared to the early and control treatments (**Table 8.8**). Compared to the late application of fertilizer, the split application reduced the foliar K:N ratio significantly. The effect of the fertilizer on the foliar P concentration also affected the P:N and P:K foliar ratios (**Table 8.7**). The P:N ratio increased significantly with the application of 40/40 and 80/80 PK fertilizer, respectively (**Table 8.8**). The split and late applications increased the P:N ratio significantly, compared to the early treatment, which in turn was also significantly greater than the control treatment. The foliar P:K ratio was increased when the highest amount of fertilizer was applied (**Table 8.8**).

8.3.4 Stem wood nutrients

8.3.4.1 Nutrient concentration

Of the 5 macro-nutrients that were analysed in the stemwood 1.3 m above the ground only P and Mg were affected by the application of PK fertilizer (**Table 8.9**).

Table 8.9: A summary of analysis of variance F-probability values for macro nutrient concentration of 15-year-old *P. patula* stemwood discs collected at 1.3 m above ground in an amount by time of application PK fertilizer trial at Usutu.

Source	d.f.	Wood nutrient concentration ($mg\ kg^{-1}$) 1.3 m above ground				
		N	P	K	Ca	Mg
		Probability > F				
REP stratum	3	0.059	0.429	**<0.001**	0.155	**<0.001**
REP.*Units* stratum						
Contrast	2	0.674	**0.001**	0.213	0.197	**0.039**
Contrast.Amount	1	0.061	0.202	0.937	0.283	0.425
Contrast.Time	2	0.142	**0.002**	0.076	0.111	0.144
Contrast.Amount.Time	2	0.138	0.175	0.690	0.323	0.651
Residual	47 (6 mv)					
Total	57 (6 mv)					

Bold type indicates statistically significant differences at p<0.05.
mv = missing values

Compared to the control the application of 40/40 and 80/80 PK fertilizer increased the P concentration of the stemwood significantly (**Figure 8.2**). The results also showed that the split application increased the stemwood P concentration to a greater extent than an early application. The Mg concentration of the stemwood at 1.3 m above the ground increased to 206.6 mg kg^{-1} when 40/40 and 80/80 PK fertilizer was applied, compared to the 113.1 mg kg^{-1} measured in the control treatment. The mean concentrations of macro nutrients measured in the stemwood of the control treatment are shown in **Table 8.10**.

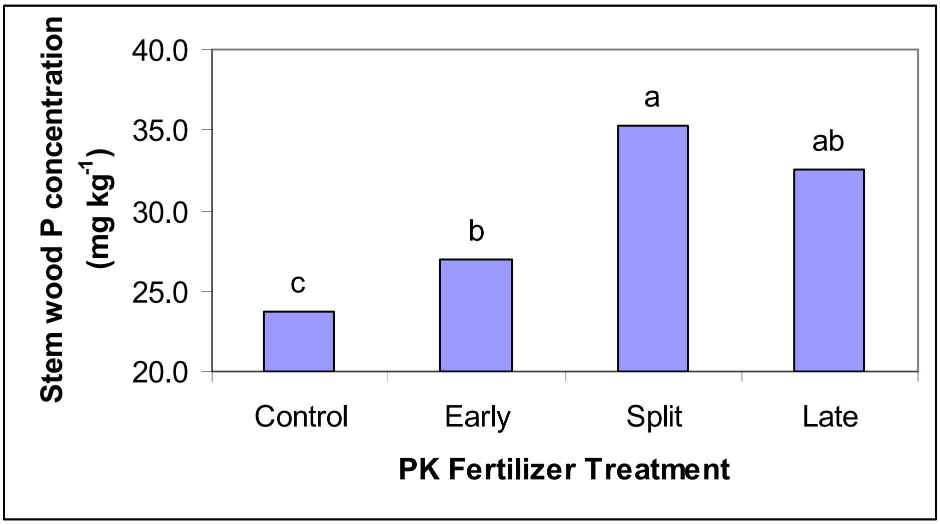


Figure 8.2: The stemwood P concentration of 15-year-old *P. patula* as affected by the time of application of 40/40 and 80/80 PK fertilizer at Usutu. Letters indicate a significant difference at p<0.05.

Table 8.10: Macro-nutrient concentration of 15-year-old *P. patula* stemwood on the control plots of a PK fertilizer trial at Usutu.

Nutrient	Unit	At 1.3 m above ground		Over entire stem	
		Concentration	*S.E.*	Concentration	*S.E.*
N	mg kg^{-1}	857.2	*45.7*	960.0	*37.4*
P	mg kg^{-1}	23.7	*2.3*	25.0	*1.47*
K	mg kg^{-1}	373.7	*16.3*	401.5	*10.8*
Ca	mg kg^{-1}	381.3	*12.0*	387.8	*11.9*
Mg	mg kg^{-1}	113.1	*7.2*	117.4	*4.9*

S.E. = standard error

8.3.4.2 Nutrient content

Calculation of the estimated amount of each respective macro-nutrient contained in the stemwood portion per plot indicated that the amount of nutrients in the wood per hectare increased with an increase in the amount of PK fertilizer that was applied (**Table 8.11** and **Table 8.12**). The time of application only had a significant effect on the amount of P contained in the stem wood. The split and early applications of 40/40 and 80/80 amounts contained significantly more P than the late application, which in turn contained significantly more P than the control. The N, K, Ca and Mg amounts in the stemwood increased in the same proportions as more fertilizer was applied (**Figure 8.3**). However, the amount of P contained in the stemwood almost doubled when 80/80 PK fertilizer was applied.

Table 8.11: A summary of analysis of variance F-probability values for estimated macro nutrient content (kg ha^{-1}) in stemwood of 15-year-old *P. patula* trees in an amount by time of application PK fertilizer trial at Usutu.

Source	d.f.	Wood nutrient content (kg ha^{-1})				
		N	P	K	Ca	Mg
		Probability > F				
REP stratum	3	0.341	0.605	0.345	0.294	0.338
REP.*Units* stratum						
Contrast	2	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Contrast.Amount	1	**0.019**	**<0.001**	**0.018**	**0.031**	**0.019**
Contrast.Time	2	0.144	**0.033**	0.143	0.195	0.148
Contrast.Amount.Time	2	0.303	0.116	0.302	0.355	0.307
Residual	47					
Total	56					

Bold type indicates statistically significant differences at p<0.05.

Table 8.12: Estimated mass of the macro nutrients per hectare contained in the stemwood portion of 15-year-old *P. patula* trees for each of the fertilizer rates applied to the trial at Usutu. Different letters indicate a significant difference between means at p<0.05.

Amount PK Fertilizer	Estimated mass of nutrients contained in stem wood (kg ha^{-1})									
	N		P		K		Ca		Mg	
0/0	101.9	c	2.7	c	43.6	c	43.5	c	12.6	c
20/20	111.0	bc	3.1	c	47.5	bc	46.9	bc	13.7	bc
40/40	118.3	b	4.0	b	50.6	b	49.8	b	14.6	b
80/80	128.1	a	5.2	a	54.9	a	53.5	a	15.8	a

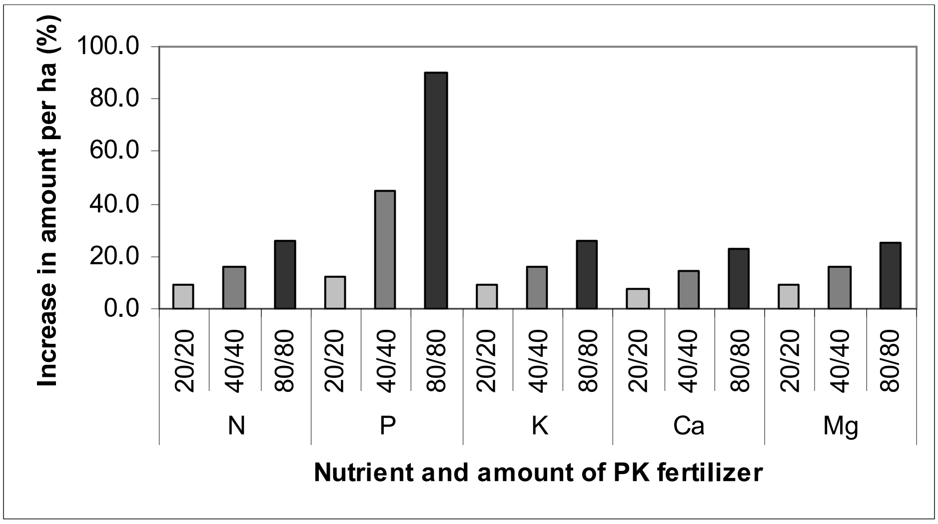


Figure 8.3: Proportional increase in amount of nutrients contained in the stem wood of the respective PK fertilizer treatments in comparison to the control treatment in a 15-year-old *P. patula* fertilizer trial at Usutu.

8.3.5 Stem bark nutrients

8.3.5.1 Nutrient concentration

The significant effect of amounts of PK fertilizer on the N concentration of the stembark observed in the ANOVA results (**Table 8.13**) was as a result of a significantly lower N concentration on plots that received 40/40 P and K fertilizer, compared to those that received the 80/80 treatment (**Figure 8.4**). The bark P concentration was significantly lower in the 20/20 and 40/40 treatments than in the control or 80/80 treatments (**Figure 8.4**).

Table 8.13: A summary of analysis of variance F-probability values for macro nutrient concentration of 15-year-old *P. patula* stembark collected at 1.3 m above ground in an amount by time of application PK fertilizer trial at Usutu.

Source	d.f.	Bark nutrient concentration (mg kg^{-1}) 1.3 m above ground				
		N	P	K	Ca	Mg
		Probability > F				
REP stratum	3	**0.022**	<0.001	**0.026**	0.511	0.051
REP.*Units* stratum						
Contrast	2	0.903	**0.005**	0.060	0.939	0.106
Contrast.Amount	1	**0.008**	**0.021**	0.247	0.879	0.487
Contrast.Time	2	0.238	**0.002**	0.067	0.056	0.923
Contrast.Amount.Time	2	0.872	0.225	0.431	0.844	0.409
Residual	47 (6 mv)					
Total	63 (6 mv)					

Bold type indicates statistically significant differences at p<0.05
mv = missing value

The time of application had a significant effect on the bark P concentration (**Table 8.13**). The P concentration increased (not statistically significant) from 66.1 mg kg^{-1} in the case of the early 40/40 and 80/80 treatments to 76.5 mg kg^{-1} in the late 40/40 and 80/80 treatments and increased significantly ($p<0.05$) to 94.0 mg kg^{-1} in the split 40/40 and 80/80 treatments, which was similar ($P<0.05$) to the 95.5 mg kg^{-1} observed in the control treatment. The means for stembark nutrient concentrations of the control plots at 1.3 m above ground level and the average across the stem are shown in **Table 8.14**.

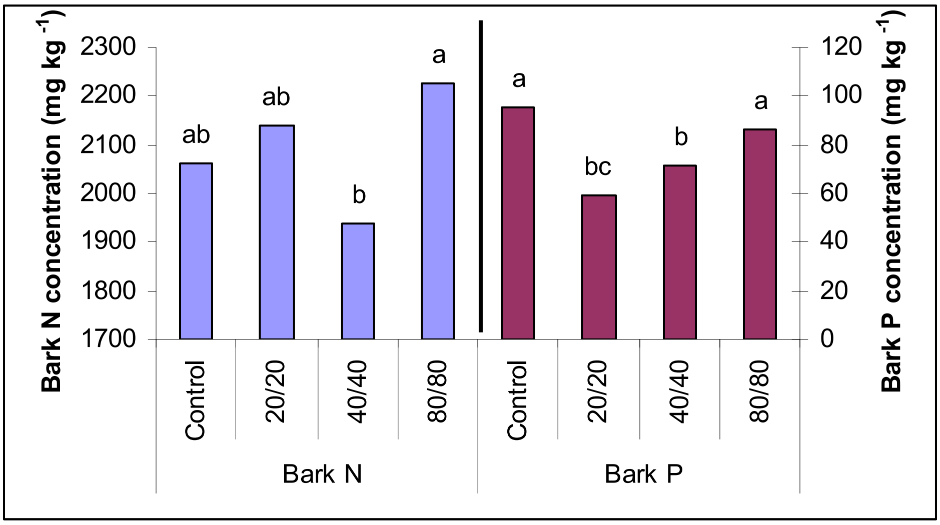


Figure 8.4: Stembark N and P concentration as affected by the application of 0, 20 or 40 and 80 kg P and K ha^{-1}, respectively, underneath a 15-year-old *P. patula* stand at Usutu. Different letters indicate a significant difference between the means of each component at $p<0.05$.

Table 8.14: Macro-nutrient concentration of 15-year-old *P. patula* stembark on the control plots of a PK fertilizer trial at Usutu.

Nutrient	Unit	At 1.3 m above ground		Over entire stem	
		Concentration	*S.E.*	Concentration	*S.E.*
N	mg kg^{-1}	2063	*56.6*	3266	*121*
P	mg kg^{-1}	96	*11.2*	247	*2.3*
K	mg kg^{-1}	725	*125.2*	1510	*14.3*
Ca	mg kg^{-1}	2888	*267*	4317	*292*
Mg	mg kg^{-1}	362	*47.1*	1077	*9.5*

S.E. = standard error

8.3.5.2 Nutrient content

The ANOVA results of the bark nutrient content showed that there was a significant difference between the control treatments and the combined 40/40 and 80/80 factorial treatments (**Table 8.15**) in all five macro nutrients. When more than 40/40 P and K was applied, the stembark contained a significantly greater amount of nutrients, compared to the control treatment (**Table 8.16**). In the case of P, Ca and Mg there were significantly more nutrients in the stembark of the 80/80 treatment compared to that in the control treatment (**Table 8.16**). Comparison of absolute values of each element (**Table 8.16**) showed that the amounts decreased in the following order: Ca > N > K > Mg >> P.

Table 8.15: A summary of analysis of variance F-probability values for estimated macro nutrient content (kg ha^{-1}) in stembark of 15-year-old *P. patula* trees in an amount by time of application PK fertilizer trial at Usutu.

Source	d.f.	Bark nutrient content (kg ha^{-1})				
		N	P	K	Ca	Mg
		Probability > F				
REP stratum	3	0.244	0.299	0.232	0.286	0.320
REP.*Units* stratum						
Contrast	2	**0.002**	**<0.001**	**0.003**	**<0.001**	**<0.001**
Contrast.Amount	1	0.063	**0.031**	0.077	**0.035**	**0.024**
Contrast.Time	2	0.279	0.192	0.309	0.207	0.167
Contrast.Amount.Time	2	0.433	0.353	0.459	0.367	0.328
Residual	53					
Total	63					

Table 8.16: Estimated mass of the macro nutrients per hectare contained in the stembark portion of 15-year-old *P. patula* trees for each of the fertilizer rates applied to the trial at Usutu. Different letters indicate a significant difference between means at p<0.05.

Amount	Estimated mass of nutrients contained in stembark (kg ha^{-1})									
PK Fertilizer	N		P		K		Ca		Mg	
0/0	45.8	b	3.6	c	21.2	b	65.5	d	14.6	c
20/20	48.6	b	3.9	bc	22.4	b	70.4	c	15.8	bc
40/40	53.1	a	4.1	b	24.4	a	74.8	b	16.8	b
80/80			4.4	a			80.1	a	18.1	a

8.3.6 Nutrient pools

The nutrient concentrations and biomass mass values determined in this study (current chapter and chapter 7) and earlier studies (Morris, 1986; 1992 and Crous *et al.,* 2007b) were used to estimate the amount of nutrients in the biomass components and first 1 m of soil for two selected treatments (control and split 80/80) in the trial. The results are shown in **Table 8.17**. Comparison of the total nutrient pool sizes indicate that N was the most abundant followed by P, Ca, K and Mg. The sum of the nutrients contained in the stembark and stemwood were used as an estimate of the amount of nutrients that was removed at harvesting (**Table 8.17**).

Table 8.17: Estimated nutrient pools in aboveground biomass components and first 1 m of soil in two selected treatments of a 15-year-old *P. patula* PK fertilizer trial at Usutu plantation, located on gabbro-derived soil.

Component	Control treatment						Split 80/80 treatment					
	Mass	Nutrients (kg ha^{-1})					Mass	Nutrients (kg ha^{-1})				
	t ha^{-1}	N	P	K	Ca	Mg	t ha^{-1}	N	P	K	Ca	Mg
Soil (0-0.10 m)	750.0	1530.0	154.2	31.0	54.1	11.5	750.0	1474.5	194.7	30.9	55.6	12.0
Soil (0.1-1.0 m) †	9240.0	4620.0	2143.7	144.5	425.9	115.1	9240.0	4620.0	2143.7	144.5	425.9	115.1
Litter forest floor	77.2	842.0	24.9	39.4	167.0	34.8	121.2	1255.0	56.8	64.5	324.0	56.6
Stem wood	109.3‡	101.9	2.7	43.6	43.5	12.6	138.2‡	130.4	5.4	55.9	54.1	16.1
Stem bark	13.7‡	45.8	3.6	21.2	65.5	14.6	15.8‡	54.8	4.5	25.1	80.9	18.4
Foliage	8.5§	164.1	10.1	38.4	21.3	6.9	10.4§	203.3	15.0	47.6	34.7	11.0
Live branches §	17.3	49.4	6.9	44.2	24.3	13.0	20.9	59.4	8.3	53.2	29.2	15.6
Dead branches §	28.2	49.3	4.8	3.4	40.3	11.3	29.1	51.0	5.0	3.5	41.7	11.7
Total	10244.3	7402.5	2351.0	365.7	841.9	219.7	10325.8	7848.4	2433.4	425.1	1046.0	256.4
Nutrients removed in crop	123.0	147.7	6.3	64.8	109.0	27.2	154.2	185.2	9.9	81.0	135.0	34.5
% nutrients removed in crop		*2.0*	*0.3*	*17.7*	*12.9*	*12.4*	*1.5*	*2.4*	*0.4*	*19.0*	*12.9*	*13.5*
Nutrients remaining after harvest		7254.8	2344.6	300.9	732.9	192.5		7663.2	2423.5	344.2	911.0	221.9
Difference between Control and Split 80/80							81.5	445.9	82.4	59.4	204.1	36.6
Additional removal from fertilized plots								37.6	3.5	16.2	26.0	7.3

§ Values estimated from Morris 1986, 1992
† Crous *et al.*, 2007a
‡ Chapter 7

8.4. DISCUSSION

8.4.1 Soil nutrients

The application of P fertilizer clearly had an effect on soil P levels. The application of 80/80 fertilizer increased the plant available P significantly in the soil. However, this was mostly as a result of the application of P closer to clearfelling age (application at pruning) compared to the application at planting. This was not unexpected as inorganic P is easily adsorbed by soil (Brady and Weil, 1996). Another possibility is that the trees had more time to take up the applied P when it was applied at planting. This idea is supported by the inorganic P fraction results that showed significantly more P_i where the fertilizer was applied after pruning, as well as the observation that the greatest amount of P_{i+o} was also found in plots where the fertilizer was applied after pruning (**Table 8.4**). The effect on the soil Ca levels can be linked to the P application, because the single superphosphate that was applied, contained a significant amount of Ca.

Soil-K was not significantly affected by the application of fertilizer. In fact, the amount of K decreased in absolute terms from the grassland to the unfertilized plantation and even further in the control plots and fertilized plots of the trial. Morris (1986) also found that in absolute terms, the exchangeable K decreased from soils under a grassland area to that under a first rotation crop and even further underneath a second rotation crop. The decrease in the amount of K in the fertilized plots was probably related to the application of P and K together in this trial. Previous results have shown that the trees were not able to utilize applied K unless P was also applied (Morris 1986, 1987a; Crous *et al.*, 2007a, 2008a). The small buffer area between the plots (consisting of only 4 tree rows) might not have been enough to prevent trees growing on the control plots from taking up P that was applied to the treatment plots, either by extending roots into the adjacent plots or by lateral movement of P by litter fall as was observed by Turner *et al.* (2002). Thus, as the trees obtained more P, a greater proportion of K was probably taken up by the trees. Furthermore a large amount of Ca (160 kg ha^{-1}) was applied with the P in the form of single superphosphate. As a result of the complementary ion effect the K^+ ions was less tightly held by the colloids and could leach more easily (Tisdale *et al.*, 1993; Barber, 1995; Brady and Weil, 1996).

8.4.2 Forest floor nutrients

The forest floor mass underneath the 15-year-old trees in this study was consistent with earlier results reported for stands of *P. patula* of similar age and altitude at Usutu (Morris, 1995). The application of fertilizer did not only increase the stemwood mass in the present study (**Table 7.5**), but also increased the mass of the forest floor litter. Phosphorus and calcium were the only nutrients that were found in significantly greater amounts in the forest floor litter layer in plots where more than 40/40 P and K fertilizer were applied. The total amount of nutrients within the forest floor litter of the control plots corresponded to that reported in other trials of similar age (**Table 2.1**).

8.4.3 Foliar nutrients

Both the foliar P and K concentrations (**Table 8.6**) in the control treatment were below the critical values of 0.14 % and 0.50 %, respectively, for *P. patula* at Usutu (Crous *et al.,* 2008a). This is indicative of the P and K deficiency that occurs on gabbro-derived soils (Morris, 1986). However, the application of PK fertilizer increased the foliar P levels significantly. As the amount of fertilizer increased, the foliar P-levels increased as well. The treatments, where some or all of the P was applied after pruning, had a greater effect on the foliar P values than the treatments where P was applied at planting. Thus, it was only the 80/80 split PK application that raised the foliar P concentration above the critical value. This confirmed the earlier finding by Morris (2003) that the response to P increased when P was applied to older trees. Although the foliar P:N ratio increased with an increasing amount of fertilizer, even the greatest value of 7.4, reported for the S80/80 treatment was still significantly less than the optimum value of 10 as reported by Linder (1995) for conifers. The foliar K:N values of less than 30 (as suggested by Linder, 1995) were also indicative of a potassium deficient site.

8.4.4 Stemwood nutrients

All the stemwood nutrient concentrations, except the P concentration, corresponded with values reported for *P. patula* in southern Africa (Morris, 1992; Carlson and Allan, 2001; Ross *et al.*, 2005; Dames *et al.*, 2002). The P value of 23.7 mg kg^{-1} measured in the current study's control plots was between five and ten times less than the values of 220, 120 and 200 mg kg^{-1}, respectively, reported by Morris (1992), Carlson and Allan (2001) and Dames *et al.* (2002). However, it corresponded to values for *P. patula* reported by Germishuizen (1979) cited in Morris (1986), Ross *et al.* (2005) and for *P. taeda* in the

USA by Rubilar *et al.*, 2005. A review of mineral nutrient concentrations in wood by Meerts (2002) showed that the P concentration in heartwood ranged from 2 to 870 mg kg^{-1}, but that it was rare to see concentrations greater than 100 mg kg^{-1}. The proportion of heartwood to sapwood can have a significant effect on average stemwood concentrations as heartwood generally has a 92% lower P concentration, 75% lower N and K concentration than the sapwood (Meerts, 2002). Thus, sampling method can have a significant impact on nutrient content values.

The stemwood P concentration was more affected by the amount of applied fertilizer than by the time of application. However, there was evidence to show that the stemwood P concentration of the split application (where a small amount was applied at planting, followed by a larger amount after pruning) was significantly greater than where the same amount of fertilizer was all applied at planting. The results from the complete trial (**Table 8.9**) showed that it was only the P concentration in the timber that was affected by the application of PK fertilizer. Therefore the increase in the amount of nutrients contained in the stem wood was mostly as a result of an increase in the amount of biomass produced.

8.4.5 Stembark nutrients

The stembark contained significantly greater concentrations of macro nutrients than the stemwood. A comparison of nutrient concentrations found in the present study with those reported in other studies showed that the stembark P concentration was less than half reported by Morris (1986) and Carlson and Allen (2001). The concentrations of N, K and Mg were also lower in the present study, compared to the values reported by Morris (1986) and Carlson and Allen (2001), while the Ca concentration was greater. The stembark N and P concentrations were similar to that reported by Germishuizen (1979) cited in Morris (1986), but the K, Ca and Mg concentrations were less. The stembark concentrations of all five macro nutrients in the present study were greater than concentrations reported for 22-year-old *P. taeda* in the USA by Rubilar *et al.*, (2005).

Although the ANOVA results (**Table 8.13**) indicated that there were some differences between the treatment means of the N and P concentrations, a closer investigation did not show any significant trend in the case of the stembark N concentration (**Figure 8.4**). The stembark P concentration decreased when 20/20 P and K fertilizer was applied and increased to a value similar to that of the control treatment when 80/80 P and K was applied (**Figure 8.4**). Despite the fact that the stembark concentrations changed little, significantly greater amounts of macro nutrients were contained in the stembark of fertilized trees compared to that of the control treatment (**Tables 8.15** and **8.16**).

8.4.6 Nutrient pools

Nambiar and Kallio (2008) cautioned that uncertainties are contained in the calculation of nutrient pools, especially when nutrients in specific components are expressed as a percentage of the total site nutrient capital. This is because the nutrient pools that are available over the life of a stand of trees or the depth from which and to which nutrients are cycled in the soil-tree system are difficult to quantify. In the present study the trees probably utilized nutrients from soil depths greater than 1 m and possibly from adjacent plots as the buffer areas between plots were small. Thus, the percentages reported in this document should be used with caution and should only be used to compare relative changes in the pools at rotation age.

Shepard and Mitchell (1990) found that above-ground biomass accounted for 66% of the ecosystem K of a red pine plantation. On the fertilized plots the biomass had higher levels of K due to efficient cycling and enhanced retention in vegetation, highlighting the important role that biomass played in the biogeochemistry of K on K-deficient soils. The present study confirmed this finding as 52% of the K pool (to a soil depth of 1 m) was found in the above-ground biomass pools on the control plots (**Table 8.17**). All the additional K (59.4 kg ha^{-1}) found on the fertilized plots was in the biomass components as the amount of K in the topsoil was similar. Of the additional K, 42% was found in the litter, 20% in the stemwood, 6% in the bark and 30% in the foliage and live branches. A large amount of K (64.8 and 81.0 kg ha^{-1} on the control plots and split 80/80, respectively) was removed from the site at harvesting in stemwood and stembark. This comprised 17.7% and 19%, respectively, of the K pool on the control and split 80/80 plots up to a soil depth of 1 m. It supports the finding by Morris (1986) that harvested log removal is the most important factor in K losses. Although the stembark made up only 12% of the biomass harvested from the site, the bark contained 33% of the K that was removed from the site. Stembark also contributed significantly to the amount of other macro nutrients that was removed from the site.

In the case of P, the soil contained 98% of the total pool (to 1 m soil depth), with only small amounts found in the biomass components. Of the estimated additional 82.4 kg P ha^{-1} that was found on the plots where 80 kg P and K ha^{-1} was applied, 49% was contained in the topsoil, 38.7% in the forest floor litter and 6% in the live foliage. This confirmed earlier findings that the residual P fertilizer that remained in the topsoil as well as P cycled through mineralization of organic material is a major source of available P for future growth (Schönau, 1984; Maggs 1988, Polglase *et al.*, 1992a,b; Flinn, *et al*, 1982; Comerford *et al.*, 2002; Crous *et al.*, 2007b). Only a small proportion of P (0.4%) was removed from the 80/80 fertilized site during crop harvest. Thus, it is expected that the initial fertilizer application will have a persistent effect and that application of P to the subsequent rotations can be significantly reduced. However, it should be noted that over time the P will become immobile through adsorption and precipitation (Schachtman *et al.*, 1998), which will lower its efficiency. Currently it is unknown for which period the trees will obtain sufficient P from the residual fertilizer. This aspect should be addressed in future studies.

Large amounts of Ca and Mg that accounted for substantial proportions of the respective nutrient pools were also removed from the site during harvesting (**Table 8.17**). As 160 kg Ca ha^{-1} was applied together with the P in the superphosphate, there is a bigger possibility that Mg deficiencies can develop on these sites in future.

8.5 CONCLUSIONS

The effect of P fertilizer was more pronounced at the end of the rotation than the effect of K fertilizer. This was seen in the increased levels of P in the soil and foliage. The stemwood P concentration did not increase with an increase in the amount of fertilizer, but it did increase when the fertilizer was applied later in the rotation. It is speculated that the comparative amounts of nutrients taken up from the soil will be larger that the amounts being made available by long-term mineralization and weathering. However, additional inputs from other sources, e.g. wet and dry deposition are unknown. Therefore, it seems reasonable to suggest that a decline in productivity is eventually inevitable unless P and K fertilizer are added. A similar amount of K was removed from the site than the amount that was applied as fertilizer. Only a small portion of the P that was applied was removed in the harvested crop. This showed that the application of K fertilizer to subsequent fertilized rotations will become more important to sustain production on the gabbro-derived soils of Usutu.

The results indicated that the effects of P application on soil and stemwood nutrient concentrations were more significant than the effects of K fertilization. However, without the application of K, the application of P had little effect on tree growth and, as indicated in Chapter 5, the application of K to the subsequent rotation became more important. Furthermore, very little work has been done on the importance of K fertilization in forestry. Thus, a technique where rubidium is used as an “isotope” of K was applied to determine the fate of the applied K. These results are reported in the next chapter.

CHAPTER 9

APPLICATION OF THE RUBIDIUM/POTASSIUM REVERSE TRACER TECHNIQUE TO INVESTIGATE THE UTILIZATION OF POTASSIUM FERTILIZER IN A *PINUS PATULA* PLANTATION.

Potassium, although it is known to be important for tree growth, is very seldom one of the most limiting nutrients and therefore most fertilizer research in the past has focused on N and P fertilization. However, on the gabbro-derived soils the application of K in association with P is of utmost importance to maintain volume production (Chapters 3, 5 and 7). This rather unique incidence of a significant response to K fertilizer led to a more in-depth study to determine the fate of the applied fertilizer K in this ecosystem by using naturally occurring Rb as a tracer for K. This paper is currently in preparation for publication in the Canadian Journal of Forestry Research.

ABSTRACT

A trial, investigating the effects of various amounts of phosphorus (P) and potassium (K) fertilizer applied at different stages of stand development to *Pinus patula* on gabbro-derived soils supplied the ideal opportunity to determine the fate of the applied K fertilizer, by applying the rubidium/ potassium (Rb/K) reverse tracer technique. Because plants take up and translocate Rb as readily as K, the amount of Rb in the plants is related to the naturally occurring Rb in the soil and can therefore be used as a "tag" of native soil-K. The fertilizer was applied in three amounts, 20/20, 40/40 and 80/80 kg P and K per ha, respectively. The 40/40 and 80/80 amounts were applied with three different regimes, either applying all of the fertilizer at planting or after pruning (5 years), or splitting the application into a 20/20 application at planting (spot application) and applying the remaining fertilizer at pruning (either 20 or 60 kg of P and K by broadcast application). In a further treatment a 20/20 application of fertilizer was applied at planting with no further application at pruning. At the age of 15 years, samples from the topsoil, forest floor litter, stembark, stemwood and live foliage were collected in the trial. Topsoil was also collected from an adjacent grassland area and unfertilized plantation area. Chemical analyses indicated that the K fertilizer used had low enough Rb levels to make use of the "reverse-tagging" of fertilizer-K with natural occurring soil-Rb. A comparison of the HNO_3 extractable K values showed that the amount of K decreased from 88.5 mg kg^{-1} in soils in the grassland to 76.0 mg kg^{-1} in soil in the unfertilized plantation and to 41.3 mg kg^{-1} in soil in the control plots of the trial. As more P and K were applied, the

amount of K in the soil decreased further in absolute terms. Thus, none of the applied K remained in the soil at the end of the rotation. None of the K from fertilizer in the forest floor litter remained in the 20/20 and 40/40 applications, but 4% of the K was found on plots where 80/80 P and K were applied. Although there were indications that the Rb and K concentrations within the stembark and stemwood decreased as a result of the application of P and K fertilizer, the results confirmed that within the various plant components fertilizer-K contributed more to the amount of K in the wood (28.7%) than to the amount of K in the bark (19.5 %) and foliage (8.5%). Thus, the Rb/K-reverse tracer technique proved to be useful in determining the fate of the applied K fertilizer. It confirmed that a large amount of the applied K was removed from the site in stemwood and stembark. Therefore, the application of K fertilizer to the subsequent rotations will be of utmost importance for sustainable production of timber on the gabbro-derived soils at Usutu.

9.1 INTRODUCTION

Nutrient cycling is very important for the conservation of nutrients in plantations, which in turn is critical for long-term sustainable crop production (Scholes, 2002). On 13% of the Usutu Forests in Swaziland, confined to the gabbro-derived soils, a growth decline of 18% has been observed in the second rotation (Evans, 1978, 1986, 2005). This was mainly due to the development of P and K deficiencies (Morris, 1986). The application of P and K fertilizer to these sites corrected the decline in yield (Evans, 1996). However, the fate of the applied fertilizer has not been studied in much detail. A study on the effect of recent applications of P and K fertilizer and residual PK fertilizer on the growth of the subsequent crop indicated that a significant amount of residual P from the previous rotation was still present in the topsoil and forest floor litter under the subsequent rotation, but that very little of the originally applied fertilizer-K remained (Crous *et al.,* 2007b). The growth and foliar results indicated that the application of K to previously PK fertilized stands is becoming more important (Crous *et al.*, 2007b, 2008a). A trial testing the effect of various amounts of PK fertilizer applied at different stages of stand development to *Pinus patula* on the gabbro-derived soils, provided the ideal opportunity to determine the fate of the applied fertilizer, especially the K fertilizer.

Although it is known that K plays a critical role in the physiological balance and overall health of trees, there is limited knowledge of the importance of this nutrient for tree growth and its dynamics in a forest ecosystem (Tripler *et al.,* 2006). The present study investigated the use of the “Rubidium (Rb)/ K reverse tracer” technique, described by Hafez and Stout (1973), to investigate the relationship between plant-K and soil-K as well as to determine the fate of the applied K fertilizer in this specific trial at Usutu. These results were then compared to values obtained from adjacent grassland and an unfertilized plantation. This novel technique has been used to estimate the persistence of K in other forest systems as it is innocuous, economical and suitable for large plot application and for relatively long time spans (Stone and Kszystyniak, 1977 and Stone, 1978 and 1981). Despite a difference in molecular weight, Rb^+ and K^+ are so nearly alike (monovalent cations with similar hydrated ion radius) that they have almost isotope-like characteristics. These two elements occur together in all rocks and soils. The Rb content of soils is largely inherited from the parent rocks. Therefore soils derived from granites and gneisses have normally higher Rb contents than sandy and organic soils. The bonding forces of Rb to silicates appear to be stronger than those of K (Baligar and Barber, 1978a) and over time the Rb/K ratio of the soil increases (Kabata-Pendias and Pendias, 2000).

The Rb/K reverse tracer technique depends upon plant species as well as the concentration of K and Rb ions in solution (Hafez and Rains, 1972). Because plants take up and translocate Rb as readily as K (Collander, 1941), the amount of Rb in the plants is related to the naturally occurring Rb in the soil and can therefore be used as a “tag” of native soil-K (Hafez and Stout, 1973). Commercial K fertilizers normally contain very little Rb in relation to the amount of K in the soil. Consequently, additions of K fertilizer reduce the Rb/K ratio in the root environment and in the plant if the fertilizer-K is taken up by the plant. The proportion of fertilizer-K in any component can be estimated from its Rb/K ratio, provided that the Rb/K ratio of the control is known and that the Rb content of the K fertilizer is known or assumed negligible (Hafez and Stout, 1973). Furthermore, it is assumed that K and Rb remain independent of each other in the soil. Ryan and Miller (1978) questioned the technique, as fertilization with K may reduce the absolute amount of Rb taken up by plants as a result of competitive uptake, which in turn can increase the leaching loss of naturally occurring Rb from the system. Stone (1978) supplied additional information showing that the application of K did not affect the naturally occurring Rb and that the concern expressed by Ryan and Miller (1978) was unfounded. However, later studies by Tyler (1997) and Drobner and Tyler (1998) indicated that the uptake of Rb^+ by the common acid woodland sedge, *Carex pilulifera,* increased when K^+ was deficient and that the Rb concentration in the shoots decreased when K fertilizer was applied to the soil. Baligar and Barber (1978b) also reported that the application of K did not affect the Rb/K ratio in the solution phase, but that it did decrease the exchangeable Rb and increased the nonexchangeable Rb. Unless the plants only absorb K and Rb from the solution phase, which does not always occur (Baligar and Barber, 1978a, 1978c), the application of the Rb/K reverse tracer technique will incorrectly estimate the proportion of fertilizer-K in the various components.

Differences in biomass concentrations of Rb and K in *Picea abies* on different sites have been attributed to variability in soil adsorption properties (Wyttenbach *et al.,* 1995). It has also been proposed in the past that the uptake of Rb^+ is positively related to acid soil conditions as displacement of Rb^+ by H^+ from the ligand might increase the amount of Rb^+ in the soil solution at lower pH levels (Tyler, 1997). However, later studies by Drobner and Tyler (1998) clearly showed that plant uptake of Rb and K was unaffected by acidity over the 3.6 to 5.0 pH range. Nyholm and Tyler (2000) attributed increased Rb concentrations in tissue of a wide range of vascular plants and fungi to a shortage or low availability of K^+ in acid soils, which favours uptake of closely related Rb^+.

The reverse tracer technique was applied in the present study, which is unique in southern African forestry, to determine the fate of the K fertilizer that was applied in a PK fertilizer trial.

9.2 MATERIALS AND METHODS

9.2.1 Trial design

The trial site was situated on Land type 307, in compartment A11 (31°4'12"E, 26°27'37"S), at an altitude of 1250 m a.s.l. on a gentle upper mid-slope position. The previous crop was a 1967 age-class second rotation of *Pinus patula*. Clearfelling was done in November to December 1991 and tree lengths with bark attached were extracted with a cable skidder. Harvest residue was left *in situ* and was not burnt.

The trial was designed as a 3 x 2 x 2 factorial to test time of application, fertilizer amount and effect of intensive weed control. Two amounts of 0:1:1(17) fertilizer, supplying 40 or 80 kg ha^{-1} each of P and K, were applied either all at time of planting (Early), or as a split with 20 kg ha^{-1} each of P and K at time of planting and the rest following pruning (age 5) (Split), or all as a post-pruning application (Late) (**Table 9.1**). The additional treatments to the factorial combinations were a control, where no fertilizer was applied, and a single application of 20 kg ha^{-1} of P and K, respectively, at time of planting. The eight fertilizer treatments were tested in combination with either routine operational weeding or intensive weeding aimed at removing all competing vegetation. The sixteen treatments were laid out as four complete randomised blocks using 7 x 7 row plots at an espacement of 2.74 m squared (Morris, 1994b). There were only four buffer rows between measurement plots.

Table 9.1: The sixteen treatment combinations tested in Trial R155.

TREATMENTS			
Code	Fertilizer amount		Weed Control
	Planting	Pruning	
E40N	40/40	0	Normal
E40I	40/40	0	Intensive
E80N	80/80	0	Normal
E80I	80/80	0	Intensive
S40N	20/20	20/20	Normal
S40I	20/20	20/20	Intensive
S80N	20/20	60/60	Normal
S80I	20/20	60/60	Intensive
L40N	0	40/40	Normal
L40I	0	40/40	Intensive
L80N	0	80/80	Normal
L80I	0	80/80	Intensive
E20N	20/20	0	Normal
E20I	20/20	0	Intensive
CONTRN	0	0	Normal
CONTRI	0	0	Intensive

TREATMENT CODE DESCRIPTION	
	AMOUNT
20/20	20kg elemental P + 20kg elemental K per ha
40/40	40kg elemental P + 40kg elemental K per ha
60/60	60kg elemental P + 60kg elemental K per ha
80/80	80kg elemental P + 80kg elemental K per ha
	TIME
E	All fertilizer applied at planting (Early)
S	Fertilizer applied part at planting (20/20) and the rest post pruning (Split)
L	All fertilizer applied post pruning (Late)
	WEED CONTROL
N	Normal weeding as used operationally
I	Intensive weeding aimed at weed free plots

The trial was planted on 24th March 1992. Fertilizer was applied on 9th April 1992 as spot applications 25 cm from the seedling. The 20/20 amount was applied as a single spot, the 40/40 amount was split between two spots on opposite sides of the seedling and the 80/80 amount was applied in four spots around the seedling. The seedlings were treated with *Bexadust* (active ingredient: Gamma BHC) at the root collar in June, 1992, after a small amount of mortality, associated with the bark beetle, *Hylastes angustatus*, had been observed. However, mortality was minor with less than 5% loss at 17 months after planting, and was unrelated to treatment. The trial was not blanked.

When planted, the site was weed free. Weeding of plots receiving the normal operational treatment was only confined to cut stump chemical control of bugweed (*Solanum mauritianum*) in June, 1993, and again in April, 1994. This was carried out as part of the routine weeding of the surrounding operational stand. The intensively weeded plots received, in addition to the operational treatments, two manual hoeing treatments to remove all weeds on the plots in February and December, 1993. Pruning, to a height of two metres, was done during May 1997 and the broadcast application of fertilizer, following pruning, was done on 11 September 1997.

9.2.2 Sampling

9.2.2.1 Fertilizer

The fertilizer in the trial was applied as a commercial 0:1:1 (17) mixture of which the K-component most likely came from KCl. Because that specific batch of fertilizer was not analysed, recently acquired 0:1:1 (28) and KCl fertilizer was sampled to determine the Rb content of the fertilizer.

9.2.2.2 Wood and Bark

In order to do a more intensive analysis of basic wood density and nutrient content, four trees per plot were selected prior to clearfelling. The four trees included one closest to the 12.5th percentile tree, two close to the median and one close to the 87.5th percentile tree. These were left standing when the trial was felled. Following clearfelling of the unmarked trees a 10 cm billet was collected at breast height from each of the remaining trees per plot with destructive sampling. As some of the marked trees were felled during harvesting, the mean values of each fertilizer treatment in the complete trial were based on the results from 12 to 22 trees over the DBH range (**Table 9.2)**.

Table 9.2: Number of trees destructively sampled per fertilizer amount and time of application in the 15-year-old *P. patula*, PK fertilizer trial at Usutu.

Time of application	Parameter	Fertilizer amount			
		0/0	20/20	40/40	80/80
Control	Nr. Trees	19	-	-	-
	Min. DBH	11.2			
	Max. DBH	26.9			
Early	Nr. Trees	-	21	12	21
	Min. DBH		12.2	13.3	14.8
	Max. DBH		28.1	25.6	29.5
Late	Nr. Trees	-	-	14	22
	Min. DBH			20.2	13.6
	Max. DBH			27.9	27.2
Split	Nr. Trees	-	-	16	22
	Min. DBH			15.8	16.3
	Max. DBH			27.8	35.3

Stem nutrient content changes with tree height were only assessed in the control and split 80/80 treatments. The split 80/80 treatment was selected as it resembled the operational fertilizer application prescription. Eight sample discs were collected from each of the 32 trees. A 10cm thick internodal disc was taken at 0.5, 1.3 and every 3 m thereafter along the stem to the top of the tree. The overbark and underbark measurements of each disc were taken in field. The dry weight of the bark was determined per sample disc after drying at 70 °C for 72 hours in a ventilated oven.

Each disc was cut into two round discs with a chainsaw. One disc was used for density analysis and the second for nutrient analyses. From each wood disc a wedge of timber was cut to sample an equal proportion of earlywood and latewood from each disc, irrespective of the diameter. The wedges were chipped in a hammer mill and thereafter ground in a Wiley mill to pass though a 2 mm sieve. Ground wood from all DBH discs, except from the control and split 80/80 treatments, were bulked into one sample per plot prior to nutrient analyses. Following fine grinding, the bark samples were bulked similarly to the wood samples.

9.2.2.3 *Foliage*

Live foliage was collected from the top third of the crown from each of the trees that were destructively sampled after clearfelling during April/May 2007. The previous season's foliage that had reached mature length was collected from the top third of the crown (Will, 1985; Linder, 1995 and Louw and Scholes, 2003) and bulked per plot on an equal number of needle bundles (fascicles) basis. The foliar samples were dried in a ventilated oven for 72 hours at 70°C immediately following collection. After fine grinding the macro nutrient concentrations were analysed.

9.2.2.4 Forest floor samples

The forest floor mass was systematically sampled over two 0.5 x 0.5 m areas per plot, below tree numbers 8 and 17 on each plot. The wet mass of each sample was determined in field with a hanging scale. The organic matter layers (litter-, fermentation- and humus-layers) were bulked as one sample per plot and the wet weight of this sub-sample was accurately determined at the research station immediately after collection in field. After drying for 72 hours at 70 °C the dry weight was determined.

2.2.5 Soil samples

The first 100 mm of mineral soil was collected with a soil core sampler from 10 locations per plot and bulked. The soil sampling was conducted during July 2006, prior to disturbance of the soil and forest floor during the harvesting operation. The sampling was systematically conducted below the same tree numbers in each plot, which were initially randomly determined. To compare soil parameters in the trial with those from surrounding areas, replicated bulked soil samples consisting of ten soil cores each were collected from an adjacent unfertilized area under 3R *P. patula* and from a natural grassland area. The soil from the unfertilized 3R *P. patula* was collected in trial R149 located in compartment A11.11 approximately 400 m to the north of trial R155. Large plots consisting of 25 x 50 tree rows did not receive any fertilizer in this *P. patula* genotype x fertilizer trial and nutrient movement from adjacent fertilized areas could be excluded. The virgin soil samples were collected from a firebreak under grassland next to the road reserve, located 70 m to the west of the trial. According to the Swaziland 1:50 000 geological map (Government of Swaziland, 1968), all samples were collected on the same gabbro geology. Each soil sample was immediately air dried, sieved through a 2 mm sieve, placed in an air-tight container and archived for analysis one year later.

9.2.3 Chemical analyses

9.2.3.1 Fertilizer samples

Of each sample, 2.5 g was taken up in a solution of 0.6N HCl (Donkin *et al.*, 1993; Helmke and Sparks, 1996). Potassium and Rb were determined by ICP-MS with an argon shield gas. All concentrations were expressed as a percentage of dry mass.

9.2.3.2 Soil samples

The same method of extraction described by Hafez and Stout (1973) was used to determine the Rb and K concentrations. A 5 g soil sample was digested by boiling in 25 ml 1N $HN0_3$ for 10 minutes. This solution was filtered and washed with 0.1N HNO_3. After appropriate dilution, using a standard addition method, the K and Rb values were read on an Inductively Coupled Plasma Mass Spectrometer (ICP-MS) with an argon shield gas. All concentrations were expressed as a percentage of dry mass.

9.2.3.3 Biomass samples

Of each sample, 2.5 g of the ground material was dry-ashed and taken up in a solution of 0.6N HCl (Donkin *et al.*, 1993). Potassium and Rb were determined by ICP-MS with an argon shield gas. All concentrations were expressed as a percentage of dry mass.

9.2.4 Calculations

To calculate the proportion of fertilizer-K that was taken up by a K-fertilized plant, Hafez and Stout (1973) developed Equation 9.1, which includes a Rb-discrimination correction factor as the Rb/K ratio within plant parts can differ (Hafez and Rains, 1972).

% K from fertilizer = 100 $(Rb/K_{control} – Rb/K_{fertilized})/(Rb/K_{control} – Rb/K_{fertilizer}/n)$ [Equation 9.1]

Where n = $(Rb/K_{soil\ control})/(Rb/K_{plant\ control})$

However, if the Rb to K ratio is very small in the fertilizer, the equation can be reduced to:

% K from fertilizer = $100\ (Rb/K_{control} - Rb/K_{fertilized})/(Rb/K_{control})$ [Equation 9.2]

9.2.5 Statistical analyses

Due to low levels of weed development in the trial the weed control treatment had only a very small effect on tree growth at the age of 17 months (Morris, 1994b) and none thereafter (Crous *et al.*, 2005a). Therefore, the weed treatment was excluded from the statistical models. In order to analyse the data of the complete trial simultaneously a dummy variable (named "Contrast") was used to distinguish between the Control treatment; the additional E20/20 treatment; and the factorial treatment combinations.

The statistical software program, *GenStat 10.2* was used to analyse the data (Payne, 2007). T-test, Analysis of Variance (ANOVA), multiple linear regression, non-linear regression and residual maximum likelihood (REML) mixed models, were used for the analyses. Relationships between the various parameters and relative stem height (where 0 is at ground level and 1 is at the top of the stem) were firstly explored with graphical analysis and secondly with regression analysis. The most appropriate equation for each parameter was based on best fit (R^2-values) and residuals analyses. Because of the serial correlation in the data from the 32 intensively sampled trees, caused by repeated measurements of the same experimental units (discs sampled longitudinally along the same tree) (Lowell, 1987; Kyriaki, 2004) the assumptions of independence was violated and was the use of ordinary regression not suitable. Lindstrom and Bates (1990) suggested the use of mixed effects models in these situations because of their flexible covariance structure. Thus, the REML algorithm was used where longitudinal data were analysed (Payne *et al.*, 2008).

9.3 RESULTS

9.3.1 Rb content of fertilizers

The Rb/K ratio in the 0:1:1 (28) fertilizer sample collected at Usutu was similar to the average value reported in KCl fertilizer by Hafez and Stout (1973) when they investigated the Rb content of various K sources (**Table 9.3**).

Table 9.3: Comparison of Rb/K ratios in fertilizer samples from Usutu with previous results.

Fertilizer		K ($g\ kg^{-1}$)	Rb ($mg\ kg^{-1}$)	Rb/K ($x10^3$)	Source
KCl (50)	Average	500	28	0.055	Hafez and Stout (1973)
(n=15)	Min	473	8	0.015	
	Max	540	59	0.118	
0:1:1 (28)		147	7	0.048	Present study
KCl (50)		492	88	0.179	

9.3.2 Rb and K content and Rb/K ratios

The ANOVA results indicated that the Rb concentration of the stemwood, stembark and forest floor components differed significantly as a result of the application of increasing amounts of PK fertilizer (**Table 9.4a**).

Table 9.4: A summary of analysis of variance F-probability values for Rb concentrations (a) and Rb/K ratios (b) in the soil, forest floor litter, foliage, wood and bark of 15 year old *P. patula* trees in a PK fertilizer by amount by time of application trial at Usutu, Swaziland.

a)

Source	d.f.	Top soil (HNO_3-extracted) ($mg\ kg^{-1}$)	Forest floor litter ($mg\ kg^{-1}$)	d.f.	Bark at 1.3 m ($mg\ kg^{-1}$)	Wood at 1.3 m ($mg\ kg^{-1}$)	d.f.	Foliage ($mg\ kg^{-1}$)
		Probability > F			Probability > F			Prob. > F
REP stratum	3	0.021	0.089	3	0.033	0.130	3	0.163
REP.*Units* stratum								
Contrast	2	0.885	**0.009**	2	**<0.001**	**<0.001**	2	0.329
Contrast.Amount	1	0.962	**0.036**	1	**0.004**	**0.001**	1	0.699
Contrast.Time	2	0.381	0.381	2	0.084	**<0.001**	2	0.598
Contrast.Amount.Time	2	0.783	0.609	2	0.144	**<0.001**	2	0.518
Residual	53			46			43	
Total	63			57			53	

b)

Source	d.f.	Top soil (HNO_3-extracted) ($mg\ kg^{-1}$)	Forest floor litter ($mg\ kg^{-1}$)	d.f.	Bark at 1.3 m ($mg\ kg^{-1}$)	Wood at 1.3m ($mg\ kg^{-11}$)	d.f.	Foliage ($mg\ kg^{-1}$)
		Probability > F			Probability > F			Prob. > F
REP stratum	3	0.153	0.076	3	0.	**<0.0001**	3	0.761
REP.*Units* stratum								
Contrast	2	0.965	**0.017**	2	**0.025**	0.144	2	0.318
Contrast.Amount	1	0.777	**0.012**	1	**0.001**	0.417	1	0.466
Contrast.Time	2	0.983	0.734	2	0.541	0.742	2	0.295
Contrast.Amount.Time	2	0.606	0.394	2	**0.019**	0.318	2	0.920
Residual	53			46			43	

Bold type indicates statistically significant differences at p<0.05.

In the case of stemwood Rb there was also evidence of an interaction between the amount of fertilizer and time of application (**Table 9.4a**). The ANOVA results of the Rb/K ratios in various components indicated that the PK fertilizer treatment only had a significant effect on the Rb/K ratio of the forest floor litter and stembark components (**Table 9.4b**).

A comparison of the HNO_3 extractable K in the control plots to that in an unfertilized stand and to a natural grassland area next to the trial indicated that the amount of K decreased from 88.5 mg kg^{-1} in the grassland to 76.0 mg kg^{-1} in the unfertilized plantation and to 41.3 mg kg^{-1} in the control plots of the trial (**Table 9.5**). Even on plots where K was applied, the HNO_3 extractable K in the top soil was less than that observed in the control treatment in absolute terms (**Table 9.5**). The HNO_3 extractable Rb was similar in the grassland soil, the unfertilized plantation and the fertilizer trial plots. As a result, the Rb/K ratio was greater in the topsoil in the fertilizer trial treatments than in the soil in the unfertilized stand or grassland, although not statistically significant. In the stemwood and stembark the Rb concentration was significantly lower in the fertilized treatments compared to that in the control treatment (**Table 9.5**).

Table 9.5: Potassium, rubidium as well as the K/Rb ratio for the different components that were assessed in a 15-year-old PK fertilizer trial in a *P. patula* plantation at Usutu, Swaziland. Different letters indicate a significant difference between the means at p<0.05.

Parameter and source	Amount PK fertilizer	Top soil (HNO_3-extracted)	Forest floor litter	Stem-bark	Stem-wood	Foliage
K (mg kg^{-1})						
Grassland	0	88.5 a	nd	nd	nd	nd
Unfertilized plantation	0	76.0 a	nd	nd	nd	nd
Trial	0	41.3 b	529	725	374	4509
	20	38.9 b	661	536	334	4396
	40	38.1 b	577	505	309	4459
	80	38.3 b	540	574	311	4551
Rb (mg kg^{-1})						
Grassland	0	4.468	nd	nd	nd	nd
Unfertilized plantation	0	4.592	nd	nd	nd	nd
Trial	0	4.789	3.36 bc	4.51 a	2.83 a	27.8
	20	4.508	5.35 a	2.26 c	1.14 c	25.3
	40	4.491	4.18 b	2.22 c	1.16 c	25.1
	80	4.512	3.31 c	3.22 b	1.63 b	24.5
Rb/K (x10^3)						
Grassland	0	54.3	nd	nd	nd	nd
Unfertilized plantation	0	60.3	nd	nd	nd	nd
Trial	0	122.1	6.35 b	6.04 a	7.59	6.14
	20	119.1	8.12 a	4.38 b	4.71	5.73
	40	125.8	7.14 a	4.52 b	5.41	5.67
	80	121.8	6.10 b	5.68 a	6.11	5.45

nd = not determined

Both the K and Rb concentrations differed greatly between the various components. However, the Rb/K ratios of the biomass components were very similar in size (**Table 9.5**). The Rb/K ratio in the stembark was significantly lower when 20/20 and 40/40 amounts of fertilizer were applied, compared to that of the control and the 80/80 amount (**Table 9.5**). In the forest floor litter, the opposite was observed as the Rb/K ratio of the 20/20 and 40/40 treatments was significantly greater than that of the control and 80/80 treatments.

9.3.3 Estimated amount of K from fertilizer

9.3.3.1 Complete trial

Although not all of the Rb/K ratios differed significantly as a result of different amounts of fertilizer or different times of application, the percentage of K that came from fertilizer was calculated for each fertilizer amount and component. However, it should be noted that some of the values might be over-estimated because of a greater decrease in Rb concentration than K concentration of some components on fertilized plots. These results indicated that where 40/40 P and K were applied, the amount of extractable K in the soil decreased compared to the amount of K in the control plots (**Figure 9.1**) and resulted in a negative value (-3%) for the estimated amount of K that originated from the fertilizer.

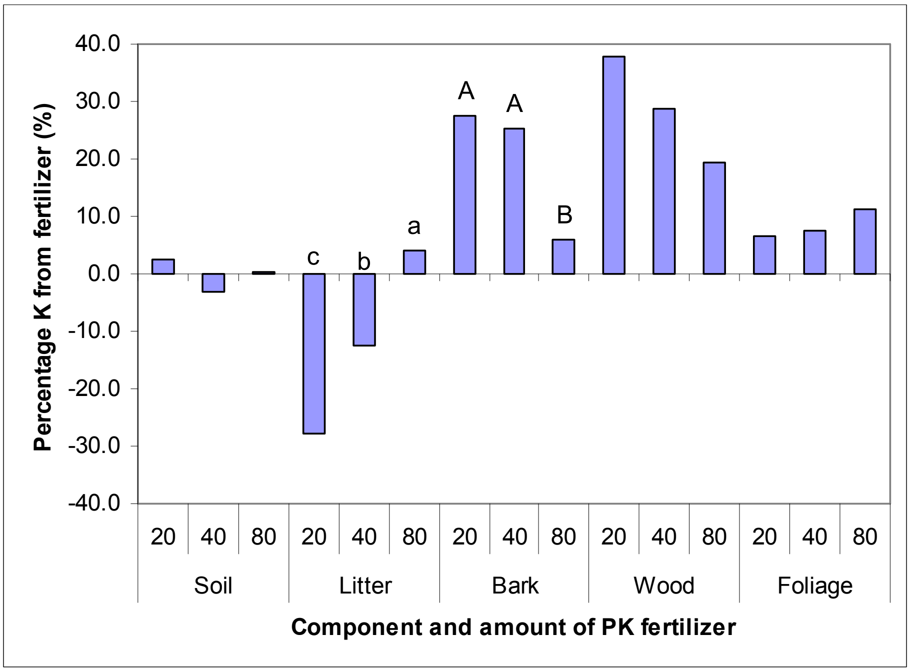


Figure 9.1: Estimated percentage of K from the applied fertilizer in each component based on the Rb/K ratios observed in 15-year-old *P. patula* trees at Usutu Swaziland and a PK fertilizer trial.

The percentage of K from fertilizer in the forest floor litter was also negative in the 20/20 and 40/40 applications, but increased to a positive amount of 3.9% on plots where the greatest amount of P and K was applied. Of the various tree components, the fertilizer-K contributed mostly to the amount of K in the wood (28.7%), followed by 19.5% of the K in the bark and 8.5% of the K in the foliage across all fertilizer treatments.

9.3.3.2 Intensively sampled trees

The results from the 32 intensively sampled trees, 16 from the control treatment and 16 from the S80/80 treatment indicated that there was no significant difference between the stemwood Rb concentration of the fertilized and unfertilized (control) trees (**Figure 9.2** and **Table 9.6a**).

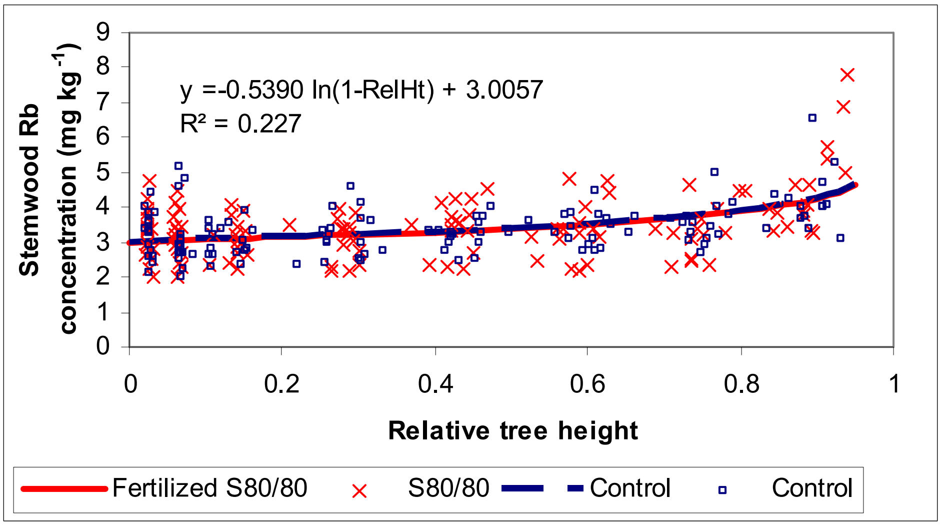


Figure 9.2: Stemwood Rb concentration increased towards the top of the tree, but was not significantly affected by the application of PK fertilizer in 15-year-old *P. patula* trees at Usutu.

Large variability was observed for the Rb/K ratio within the stemwood at different heights, which resulted in a poor model fit (low R^2-value for regression). Although, there were indications from the graphical analysis that the Rb/K ratio was greater in the control treatment compared to that in the S80/80 treatment (**Figure 9.3**) the REML analysis could not detect any differences when the various sources of variance and co-variance was taken into account (**Table 9.6b**).

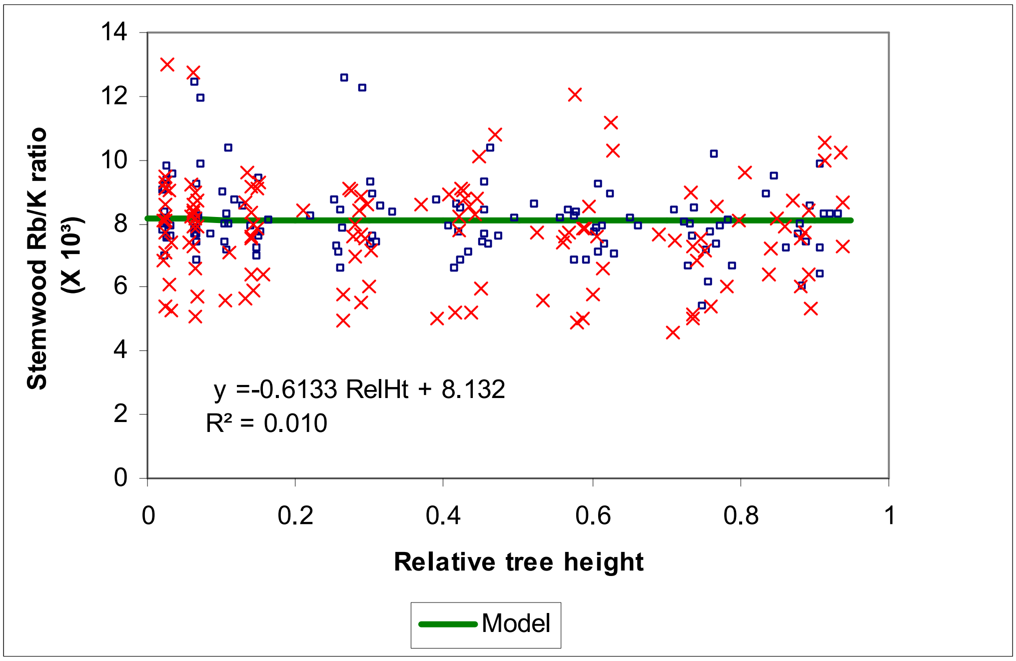


Figure 9.3: The stemwood Rb/K ratio was not significantly affected by the application of PK fertilizer and it changed very little from the base to the top of the 15-year-old *P. patula* trees.

Table 9.6: Results from fixed effects tests for stemwood Rb (a) and stemwood Rb:K ratio (b) with REML of 15-year-old *P. patula* trees at Usutu.

a)

Fixed effect	F	df	Prob >F
Log(1-RelHt)	142.62	222.9	**<0.001**
Fertilizer	0.04	9.1	0.854
Log(1-RelHt).Fertilizer	3.00	222.9	0.084

b)

Fixed effect	F	df	Prob >F
RelHt	9.66	220.8	**0.002**
Fertilizer	0.6	9.1	0.459
RelHt.Fertilizer	1.09	220.8	0.298

Bold type indicates statistically significant differences at p<0.05.

The stembark Rb concentration also showed a large variability, but the general trend was for the concentration to increase from the base of the tree towards the top (**Figure 9.4**). The REML analysis indicated that there was no significant difference between the stembark Rb concentration of fertilized and unfertilized trees across the length of the trees (**Table 9.7a**). Inclusion of fertilizer in the model did not significantly improve the model fit (p = 0.500).

The Rb/K ratio did not show any relationship with height (**Figure 9.5**) and was not significantly affected by the application of P and K fertilizer (**Table 9.7b**). Inclusion of fertiliser in the model did not improve the level of fit (p = 0.120).

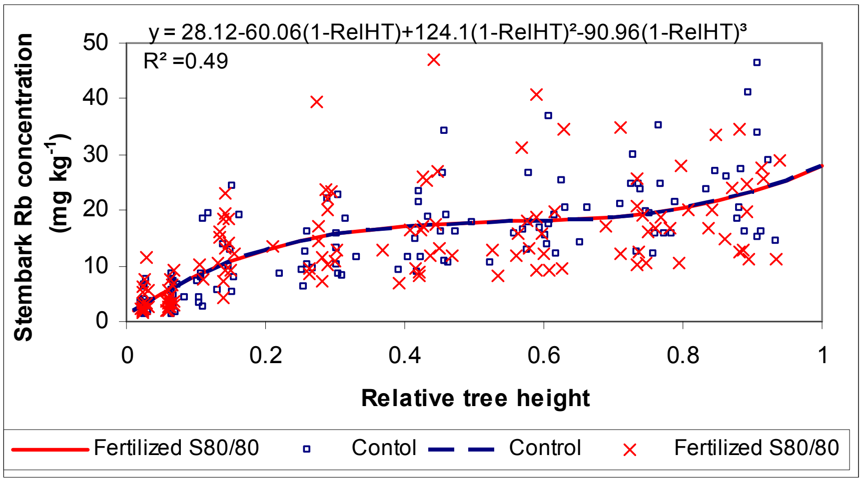


Figure 9.4: Stembark Rb concentration increased towards the top of the tree and was not significantly affected by the application of PK fertilizer in 15-year-old *P. patula* trees at Usutu.

Table 9.7: Results from fixed effects tests for stembark Rb (a) and stembark Rb:K ratio (b) with REML of 15-year-old *P. patula* trees at Usutu.

a) Rb

Fixed effect	F statistic	df	Prob. >F
(1-RelHt)	455.75	215	**<0.001**
(1-RelHt)2	34.04	214.8	**<0.001**
(1-RelHt)3	24.78	214.7	**<0.001**
Fertilizer	0.03	8.9	0.856
(1-RelHt).Fertilizer	8.17	215	**0.005**
(1-RelHt)2.Fertilizer	4.01	214.8	**0.047**
(1-RelHt)3.Fertilizer	1.28	214.7	0.259

b) Rb:K

Fixed effect	F statistic	df	Prob. >F
(1-RelHt)	110.46	218.2	**<0.001**
Fert	0.43	9.3	0.529
(1-RelHt).Fert	10.97	218.2	**0.001**

Bold type indicates statistically significant differences at $p<0.05$.

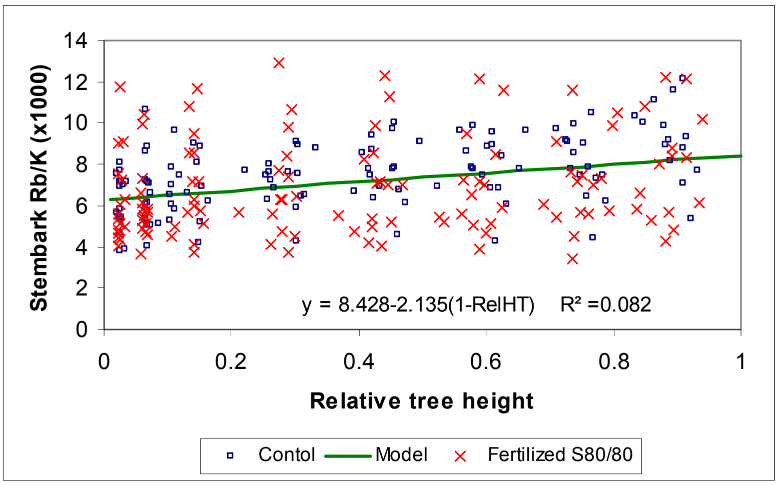


Figure 9.5: The stembark Rb/K ratio in the 15-year-old *P. patula* trees was not significantly affected by the application of PK fertilizer or the relative tree height of the sample.

9.4 DISCUSSION

The Rb/K ratio in the Usutu KCl fertilizer was slightly greater than the maximum reported in an earlier study by Hafez and Stout (1973), but it was nonetheless 682 times smaller than the Rb/K ratio observed in the top soil of the control plots. If the arbitrarily set standard of a Rb/K-value of 0.044 x 10^{-3} or less is applied (Hafez and Stout, 1973), the K-fertilizer that was used in the present study had marginal Rb/K values (0.048 x 10^{-3} for 0:1:1 fertilizer), but the Rb level was still deemed low enough to make use of the "reverse-tagging" of fertilizer-K with naturally occurring soil-Rb.

As mentioned earlier, a comparison of the HNO_3-extractable K in the control plots to that in an unfertilized stand and a natural grassland area next to the trial indicated that the amount of K decreased from the grassland to the unfertilized plantation and even further in the control plots and fertilized plots of the trial. Morris (1986) also found that in absolute terms the exchangeable K decreased from soils under a grassland area to that under a first rotation crop and even further underneath a second rotation crop. The decrease in the amount of K in the fertilized plots was probably related to the application of P and K together in this trial. Previous results have shown that the trees were not able to utilize applied K unless P was also applied (Morris 1986, 1987; Crous *et al.*, 2007a, 2007b, 2008a). The soil Rb levels in the unplanted grassland, the unfertilized stand and the trial were very similar (**Table 9.5**), while the soil-K levels decreased from the grassland to the unfertilized stand and to the trial control plots and remained similar despite the application of increasing amounts of P and K fertilizer. In the present study the buffer area between the plots (consisting of only four tree rows) might not have been enough to prevent trees growing on the control plots from taking up P that was applied to the treatment plots, either by extending roots into the adjacent plots or by lateral movement of P by litter fall as was observed by Turner *et al.* (2002). This probably allowed the trees to utilize more of the small amount of K that was available in the soil on the control plots. Furthermore a large amount of Ca (160 kg ha^{-1}) was applied with the P in the form of single superphosphate. As a result of the complementary ion effect the K^+ ions was less tightly held by the colloids and could leach more easily (Tisdale *et al.*, 1993; Barber, 1995; Brady and Weil, 1996). There was no evidence that K fertilizer moved laterally into adjacent plots in the present study, as was found in a study with *P. resinosa* on glacial sands in Washington (Buxbaum *et al.*, 2001).

The ANOVA results from the fertilizer trial showed no significant differences in the K concentration between treatments within any of the components. In the case of Rb, the stemwood and stembark concentration was decreased by the application of the P and K fertilizer. This corresponded to the findings by Tyler (1997). However, in the present study the absolute K concentration in the stembark and stemwood also decreased with an increase in the amount of P and K fertilizer that was applied. The large amount of Ca that was applied with the superphosphate could have limited K^+ uptake as it is known that high levels of Ca^{2+} can have an antagonistic effect on biomass K concentrations (Tomlinson *et al.*, 1990; Brady and Weil, 1996; Wilkinson, 2000). Despite the fact that one of the assumptions of the Rb/K technique was questionable, it was decided to calculate the various Rb/K values as well as the amount of K that originated from the fertilizer as the absolute values of K were also lower (not statistically significant) in the stembark and stemwood.

The stembark and forest floor litter Rb/K ratios differed significantly between some of the fertilizer treatments (**Tables 9.4b** and **9.5**), indicating that it was only in these two components where the amount of K that originated from the applied fertilizer differed significantly (**Figure 9.1**). In the forest floor litter, consisting mostly of dead needles, the amount of K from the fertilizer changed from negative values in the 20/20 and 40/40 treatments to 4% in the 80/80 treatment (**Figure 9.1**). This was a much lower percentage than the 41 and 21% reported by Stone and Kszystyniak (1977). The trend in the present study was probably caused by increased internal K translocation before needle senescence on the plots where 20/20 PK was applied, compared to the control. Aerts (1996) reported that plants experiencing a deficiency will translocate a greater amount of the deficient nutrient from the live foliage before senescence. As more PK fertilizer was applied in the present study, the K deficiency was further reduced, which probably reduced the retranslocation of K, leading to a small amount of fertilizer-K being recycled through the forest floor on plots where the greatest amount of fertilizer was applied. An opposite trend was seen in the stembark. The percentage of K originating from fertilizer was much less in the 80/80 treatment than in the 20/20 or 40/40 treatments (**Figure 9.1**).

Unlike the report by Stone (1981) that the proportion of fertilizer-K to total K in the stem and branches was only slightly less than in foliage, the Rb/K ratios in the present study indicated that the utilization of fertilizer-K differed between the various components. The largest percentage of fertilizer-K was found in the stemwood (27.8%), followed by that in the stembark (19.5%). It is these two components, which will be removed from the site during crop harvest. This corresponds to findings by Morris (1986) that harvested log removal is the most important pathway for K losses in the Usutu plantation. The 8.5% fertilizer-K that was found in the live foliage 10 years after the last fertilizer application was less than the 25% to 60% found 5 to 12 years after application of fertilizer by Stone and Kszystyniak (1977) and Stone (1981). There were also interesting trends when the absolute values were investigated. In the stem components there was a trend of decreasing fertilizer-K utilization with an increase in PK fertilizer, while the percentage K from fertilizer increased in the foliage and forest floor litter as the amount of PK fertilizer increased.

The K and Rb concentration changed over the length of unfertilized and fertilized tree stems showing that both nutrient concentrations increased from the base to the top of the tree (Chapter 6). However, neither the K nor the Rb concentration or the Rb/K ratio was significantly affected by the application of fertilizer. The large variation between the trees and variation between samples within the trees was probably responsible for the poor model fit. Thus, the data from the stem analysis of 32 trees could not be used to calculate the percentage of K that originated from fertilizer within the stembark and stemwood longitudinally across the stem.

9.5 CONCLUSIONS

Although there were indications that the Rb and K concentrations within the tree stems decreased as a result of the application of P and K fertilizer, the results from the Rb/K reverse tracer technique confirmed that a large amount of fertilizer-K was contained in the stemwood and stembark at the end of the rotation. A small amount of fertilizer-K could also be found in the live foliage and forest floor litter on the plots where 80/80 P and K fertilizer was applied. Although the percentage of fertilizer-K within the stemwood and stembark decreased with an increase in the amount of PK that was applied, the total amount of K uptake on fertilized plots probably exceeded the amount that was applied. This was reflected in the low percentage of fertilizer-K that could be found in the topsoil and forest floor litter on the fertilized plots as well as a significant decrease in soil-K levels underneath unfertilized plantation areas compared to the adjacent grassland area. It is recommended that future trials should be designed with a larger buffer area between treatment plots. We conclude that the application of K fertilizer to the subsequent rotations will be of utmost importance for sustainable production of timber on the gabbro-derived soils at Usutu.

Even though a lot of assumptions were made the application of the Rb/K reverse tracer technique definitely increased the knowledge of utilization of the fertilizer-K in this particular ecosystem. The combined results from the two trials will be discussed in the following chapter.

CHAPTER 10

GENERAL DISCUSSION

10.1 HYPOTHESES AND RESEARCH QUESTIONS

10.1.1 Hypotheses 1

The application of P and K fertilizer to gabbro-derived soils is necessary to sustain productivity on these sites.

- *What was the effect of the residual fertilizer on the growth rate of the trees?*

By using 24 paired samples from the 12 intensively sampled plots the power of the T-test was not always sufficient to establish differences relating to the residual fertiliser effect. In the case of tree growth, only 12 paired samples were available and natural variability in tree growth further reduced the power of the test. The only growth difference that was statistically significant (at the 10% level) was an increase in quadratic mean DBH from 2003 to 2004 (data not shown). However, the results from the complete trial indicated that between the ages of five and seven years the DBH, tree height and mean plot volume were increased by the residual fertilizer (**Tables 3.4, 3.5** and **5.3**). At the age of seven years, the residual PK fertilizer produced an additional 6.8% (8.9 m^3 ha^{-1}) timber (**Table 3.5).** The effect of the fertilizer treatment on stand structure was also investigated as Schönau (1989) reported that fertilization can increase stand uniformity through providing each seedling with an equal supply of nutrients at the start. The results showed that neither the DBH distribution nor the height distribution, based on analyses of the coefficient of variation per plot, was significantly affected by the fertilizer treatments (data not shown).

- *Did an increase in the amount of P and K fertilizer increase tree growth?*

Yes. Tree height was significantly (5% level) increased by the application of K since 2003. At age six years both the 25 and 50 kg ha^{-1} application of potassium increased tree height significantly when compared to the control. However, one year later, at age seven years, only the 50 kg ha^{-1} application of potassium increased tree height significantly. This observation corresponded with the decline in response to K as trees mature as reported by Morris (2003) (**Figure 2.6**). In addition, as the trees got taller, it became more difficult to measure tree heights very accurately, which might have contributed to the reduction in the significance level. A P by K by residual fertiliser interaction affected mean tree height between the ages of three and six years. At the age of six, tree height of the P0K50 and P25K0 treatments were significantly increased on plots with residual fertiliser as opposed to plots without residual fertiliser. In the case of the P0K50 treatment, the residual P fertiliser might have provided the tree with P to enable it to utilize the large amount of K applied in the subsequent rotation. On plots without any residual P fertiliser the application of 50 kg ha^{-1} K did not have any effect, because P remained at deficient levels and was therefore limiting growth. The difference in height growth between plots with and without residual fertiliser of the P25K0 treatment is possibly due to residual K fertiliser from 3R that remained available to the trees in the fourth rotation. The residual K fertiliser prevented the trees from developing a nutrient imbalance when only P was applied at planting and enabled them to utilize the additional P fertiliser. Although the absolute values showed the same trend at age seven years, the relative difference became smaller and the third order interaction was no longer statistically significant. Turner (1982) concluded that height growth did not appear to be a sensitive indicator of fertiliser response as the response declined with age in a superphoshate fertiliser trial.

As in the case with tree height, the significance of the potassium effect on DBH seemed to decrease as the trees mature. At the ages of six and seven years, only the 50 kg ha^{-1} K application increased mean DBH significantly by 0.72 and 0.55 cm $tree^{-1}$, respectively. The lack of a DBH response to P fertilisation was unexpected as many other studies have shown that P fertiliser can increase mean tree diameter significantly (Ballard, 1978; Turner, 1982; Comerford *et al.*, 2002). At age four and five (2003 and 2004) a significant P by K by residual fertiliser interaction was observed when the application of fertiliser at planting was investigated. Investigation of this interaction at five years of age showed that the residual fertiliser affected the P0K25 treatment. On the plots with residual fertiliser the application of only K at planting increased DBH significantly over the control. This increase was similar to when both P and K was applied at planting on plots with residual fertiliser. These results suggested that potassium was the most limiting nutrient followed by phosphorus on plots with residual PK fertiliser, probably because the trees were able to utilise some of the residual phosphorus remaining in the soil from the application to the previous rotation.

Thus, in rotations fertilized for the first time, the application of increasing amounts of P and K fertilizer was associated with an increase in volume growth in absolute terms.

These results confirmed earlier findings by Morris (1986, 1987a, 1994a) that both P and K should be applied to sites on gabbro geology that have not been fertilised in previous rotations. In the following (second) fertilized rotation, the application of the greatest amount of K fertilizer increased the timber volume to the same extent as a combined P and K application, suggesting that only K has to be applied to the subsequent rotations as long as residual P fertilizer is available.

- *What was the effect of using improved genetic material in the subsequent rotation on tree growth?*

The comparison of the tree heights of the current control plots (improved genetic material) with those from the second control plots (unimproved genetic material), showed that there was no significant difference in the 3R (t =-1.13, 12 df, p=0.281). However, in the 4R an increase of 0.75 m (t=2.11, 12 df, p=0.056) in tree height (**Table 3.3**) was observed in the control plots established with improved genetic material, compared to the control plots where unimproved material was planted (9.81 m vs. 9.06 m). It should be noted that these results should be treated with caution as they are based on measurements from only a few plots.

10.1.2 Hypotheses 2

The residual PK fertilizer that remained on the site from the application to trees in the third rotation has a positive effect on the nutrient content of the foliage, forest floor and topsoil in the subsequent rotation.

- *How much did the residual fertilizer change the amount and chemical composition of the organic material (foliage, litter layers)?*

The residual fertilizer increased the P concentration of the live foliage, senesced needles and needle component in the forest floor litter layer by 0.005% (p=0.053), 0.008% (p=0.008) and 0.007% (p=0.051), respectively. Therefore, as was shown in other studies, the effects of P fertilizer could be seen in the needle components (Ballard, 1978; Flinn *et al.*, 1982; Gentle *et al.*, 1986; Polglase *et al.*, 1992a; 1992b; Fransson and Bergkvist, 2000; Lopez-Zamora, 2001; Comerford *et al.*, 2002; Turner and Lambert, 1987; Turner *et al.*, 2002).

In absolute terms, the forest floor mass increased by 2.5 t ha^{-1} in plots with residual fertiliser. This was mainly because of a 3.5 t ha^{-1} increase, significant at the 10% level, in the H and soil-transition layer. 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 the study reported in this document. The results of an increase in H-horizon mass corresponded with the results from a study in Georgia, USA by Comerford *et al.* (2002). However, it differed in that Comerford *et al.* (2002) observed neither a difference in the P content nor the mass of the L horizon. In the Usutu study there was a significant increase in the P-content of the needle component of the L-layer as showed in the preceding paragraph.

- *Was there a difference in the nutrient content of the soil as a result of the residual fertilizer?*

When the actual nutrient amount per hectare in the H&A_1 layer was calculated, the plant available P increased by 0.3 kg ha^{-1}, 0.5M H_2SO_4 extracted P_i increased by 2.5 kg ha^{-1}, 0.5M H_2SO_4 extracted P_{i+o} increased by 7.7 kg ha^{-1} and exchangeable K increased by 1.4 kg ha^{-1} (significant at the 10% level) (**Table 4.6**). This increase was directly related to the significant increase in the mass of the H layer and soil transition layer as a result of the residual PK 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.

In the first 100 mm of topsoil the plant available P increased by a mere 1.3 mg kg^{-1}, but the increase in 0.5M H_2SO_4 extracted P_{i+o} was a substantial 44.7 mg kg^{-1} on plots where fertiliser was applied during the previous rotation. Neither the exchangeable K nor the HNO_3-extracted K of the top soil was significantly affected by the residual fertiliser. Potassium, compared to P, is more easily leached down the soil profile than phosphorus (Tisdale *et al.*, 1993; Brady and Weil, 1996). After a period of 15 years it was expected that the applied K would have became distributed over a much larger depth in the soil profile. Another possibility is that the applied K was taken up by the trees as previous studies have shown that plants can accumulate significant amounts of K in stemwood and stembark (**Table 2.2**). In absolute terms the amount of Ca and Mg also increased in the topsoil of the residual fertiliser plots. 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.

- *If the P level increased, which P-fractions (organic or inorganic) in the soil were mostly affected?*

In the humus-soil transition layer, both the plant available P and the inorganic P fractions were significantly greater on plots that were previously fertilized. In the topsoil plant available P and organic P fractions were significantly greater where fertilizer was applied 15 years earlier.

In the preceding section it has been shown that the total P level of both the H&A_1 layer and topsoil increased significantly as a result of the residual fertiliser. In the H&A_1 layer, the main statistical difference was observed in the 0.5M H_2SO_4 extracted P_i, which increased by 2.5 kg ha^{-1} on previously fertilised plots. However, in absolute terms the increase in 0.5M H_2SO_4 extracted P_o on fertilised plots was almost twice as large at 5.1 kg ha^{-1}.

In the A_2 soil the absolute increase in 0.5M H_2SO_4 extracted P_i was not statistically significant. However, the 0.5M H_2SO_4 extracted P_o increased significantly by 35 mg kg^{-1} and 0.5M H_2SO_4 extracted P_{i+o} were also significantly greater on plots with residual PK fertiliser (**Table 4.7**). The 0.5M H_2SO_4 extracted P_o contained 66 % and 67 % of the 0.5M H_2SO_4 extracted P_{i+o} in unfertilised and fertilised plots respectively.

The combined results from the H, A_1 and A_2 layers indicated that an additional 41 kg ha^{-1} P were found on the plots with residual PK fertilizer, representing 54.7 % of the 75 kg ha^{-1} P that was applied 15 years earlier. Approximately 22% of the additional P on fertilised plots was found in the inorganic P fraction and 75% was found in the organic P fraction. This suggested that the largest portion of the fertiliser, applied in inorganic P form, was cycled through the vegetation or converted into organic P forms by soil microbes such as fungi, bacteria and nematodes. It further showed that the P in the organic material, which is less liable to adsorption, became a major source of available P for the subsequent crop.

- *Were there significant associations between tree growth, foliar nutrient and soil nutrient levels?*

The correlation matrix of various topsoil and foliar analysis variables with mean tree plot volume (**Appendix 2**, **Table A2.4**) indicated that there was weak evidence of a negative correlation (correlation coefficient of -0.25, p = 0.09) between plot volume at age five years and the foliar P:K ratio. In their study, Louw and Scholes (2003 and 2006) could correlate site index (tree height at a specific reference age) with various soil variables and foliar nutrient levels e.g. foliar K, foliar Ca, soil N mineralization, foliar N:K ratio, foliar N:P ratio, etc. In the present study the foliar N:P ratio was significantly correlated with the foliar N:K ratio. Foliar P was positively correlated with foliar K, magnesium cations in the soil and, as expected, the plant available P (Bray 2) in the topsoil. The positive correlation between foliar K and exchangeable K in the soil was only significant at the 5% level. Furthermore, the foliar K was also positively correlated with the organic carbon content of the top soil and magnesium content of the top soil. The association between organic carbon and plant available P and K nutrients in the soil (r = 0.44 and r = 0.66, respectively) highlighted the importance of organic material in the P and K nutrient cycles within the plantation forests at Usutu.

10.1.3 Hypotheses 3

Tree growth and foliar nutrient concentrations respond differently to the application of P and K on sites where P and K fertilizer were applied previously.

- *Did the P, K or residual fertilizer increase the nutrient concentration or content of live foliage and senesced needles?*

Foliar P values were affected by a P by K by residual fertilizer interaction (**Table 5.4**). On plots without residual fertilizer, both P and K had to be applied (in the greatest amounts) to increase the foliar P significantly in the live needles. On plots without residual fertilizer the K concentration of the live needles was mainly influenced by the K fertilizer as it caused a linear increase in absolute foliar K concentration regardless of the amount of P that was applied. However, on plots with residual PK fertilizer there was only a trend of increasing foliar K when no P fertilizer was applied (**Figure 5.2**). On plots with residual fertilizer the absolute foliar K concentration was close to or above the satisfactory level for all treatments except in the control. Only one year after the application of P after pruning, in addition to the application of P after planting, did the senesced needles show firstly a significant increase in P concentration and secondly an increase in the P:N ratio. At the age of 6 years the K50 treatment resulted in a significantly greater K concentration in the senesced needles on the control plots as well as a greater K:N ratio.

- *Did the application of a single element cause a nutrient imbalance in the crop in the presence and absence of residual fertilizer respectively?*

Some evidence was found from the 2004 data that in the absence of residual PK fertiliser the application of only P fertiliser without K fertiliser decreased the quadratic mean DBH and basal area at the age of five years. Furthermore, the mass of 100 needle fascicles and dry weight of needles collected in litter traps also decreased significantly when only P was applied at planting. Valentine and Allan (1990) showed that post-fertilisation patterns of fascicle weight and foliar nutrient concentration were related to nutrient limitation and stem growth response of coniferous species that have one needle flush each year. Because of the reduction in fascicle mass, the application of only P at planting affected the N, P and K content of the live and dead needles significantly, but not the respective nutrient concentrations. At the age of seven years the application of only P at planting on plots without residual fertiliser still had a negative effect in absolute terms on basal area, volume, potassium concentration in the live foliage, and dry weight of 100 needle fascicles, but none of these differences were statistically significant.

The treatments were the maximum amount of P and K were applied were associated with the highest foliar nutrient levels as well as maximum volume growth response (**Figure 5.2** a and b; **Table 5.6**). Both P and K had to be applied in order to increase foliar nutrient levels of P and K above their critical concentrations of 0.14% for P and 0.5% for K, respectively. “Critical concentration” in this sense refers to the minimum acceptable foliar concentration and not to the concentration associated with 90% of the optimum yield as defined by Bevege and Richards (1972) and Richards and Bevege (1972). Comparison of foliar sample results to these “critical” values can be used to identify a need to apply fertilizer before the stands experiences severe nutritional deficiencies. However, these values should not be used to predict the magnitude of the fertilizer response. Furthermore, it should be noted that foliar critical values should not be the only tool for diagnosis of nutrient deficiencies (Louw and Scholes, 2003) as the variation in foliar nutrient concentrations may not only be caused by differences in the availability of the nutrients in the soil, but also by other factors, such as stand age, sampling position in the crown , season (Lambert, 1984; Payn and Clough, 1987; Linder, 1995), silvicultural management practice and climatic conditions (Xu *et al.*, 1995).

There was no evidence that the application of K alone caused a growth reduction as reported by Donald *et al.*, (1987).

- *What was the optimum amount and time of application of P and K fertilizer for a site that was fertilised for the first time and for a site that received PK fertilizer during the previous rotation in order to sustain optimum crop production?*

On plots without residual PK fertiliser, only the combined application of the largest amount of P and K, namely 50 kg ha^{-1} elemental P and K respectively, produced a significant volume increase compared to the control P0K0 treatment. The results from the

R128 study confirmed earlier findings that a combined application of P and K fertiliser is needed to obtain a significant increase in volume on sites that were not previously fertilised (Morris, 1986; 1987a; 1994a).

From the information available up to age seven years there was strong evidence that the re-application of K at planting was extremely important on sites which have previously received PK fertiliser, because remaining residual P fertiliser could be utilized by the plants. Key evidence to substantiate this statement was the fact that the response to the application of only 50 kg ha^{-1} K was similar to the increase obtained by a combined application of 50 kg ha^{-1} P and K, respectively. Review of other P residual fertiliser studies showed that the response to residual P remained until all the applied P was removed from the soil (Leamer, 1963; Read *et al.*, 1973). Unfortunately it is unknown if the nutrient content of the timber, which was removed from the site with harvesting, increased as a result of the application of P and K fertiliser in the previous rotation. Furthermore, some of the P may become occluded over time and thus unavailable to the plants. In this case re-application of P will have to take place sooner, but it is likely that a reduced amount to what is currently prescribed will be sufficient to obtain a response. There were indications that the response to P was increasing as the trees aged. Morris (2003) reported that the response to the application of P at the age of 6 was much higher than the response at age 3 years. Gholz *et al.* (1985) also demonstrated that the maximum uptake of P occurred at age 8 years in a *P. elliottii* stand. Therefore, a small application of P might be necessary after pruning just before maximum nutrient demand occurs.

10.1.4 Hypotheses 4

The application of PK fertilizer increase the stem taper; increase nutrient content of the stemwood and stembark; and decrease basic wood density along the tree stem.

- *Is it possible to quantify and model the variability in macro nutrient content of a) stemwood and b) stembark in relation to relative tree height?*

Yes, the stemwood concentration changes of N, P and K could be modelled with reasonable accuracy. In the stemwood the concentration of the relatively immobile elements, Ca and Mg did not change much with an increase in height. The models that were fitted could account for only 5% and 11% of the variation of Ca and Mg, respectively. The concentration of the more mobile nutrients N, P and K showed a trend of increasing concentration toward the top of the tree. The model to describe the change in the N concentration could only account for 24% of the variation. However, the models for P and K could account for 45% and 50% of the variation, respectively (**Table 6.6b**).

The stembark nutrient changes along the stem could also be modelled. The models could account for 63% of the variance in N, for 61% of the variance in P, for 57.3% of the variance in K and for 44% of the variance in Mg. The stembark Ca concentration was significantly affected by the application of P and K fertilizer and separate models were developed. The model for stembark Ca in unfertilized trees could account for 43% of the variation, while the model for the split 80/80 treatment could account for 49% of the variation (**Table 6.8b**). All five macro nutrients showed an increasing trend in concentration with an increase in height along the stem.

- *How has the application of PK fertilizer affected the basic wood density, tree form and nutrient content in relation to relative tree height? Thus, are different models needed to estimate stem form and nutrient content of fertilised trees?*

Basic wood density decreased by 5% on average as a result of fertilization. Furthermore, the basic wood density decreased from the bottom to the top of the tree, probably because of an increase in the proportion of juvenile wood to mature wood towards the top of the tree. However on the fertilized plots the density decrease was less pronounced as the basic wood density of the fertilized trees were much lower at the base of the tree (7% less), compared to that at the top (2% less) (**Figure 8.3**) A model was developed to estimate total tree density from breast height density measurements, which can be used in future work.

The data did not show that silvicultural practices promoting tree growth (e.g. fertilization) changed the stem form. The nutrient concentration of the more mobile elements N, P and K increased towards the top of the trees. The concentration of P and Ca was significantly greater in the stemwood of fertilized trees, while the concentration of only Ca was greater in the bottom stembark of fertilized trees. However, when the allometric relationship between DBH, tree height and nutrient contents was investigated, only the application of P increased the P nutrient content of the stemwood of the trees, which necessitated the use of a different model (**Table 6.3**).

10.1.5 Hypotheses 5

Increasing amounts of PK fertilizer, especially when applied early in the rotation, increase wood production, but decrease basic wood density.

- *Did the additional growth associated with the application of increasing amounts of PK fertilizer decrease the basic wood density?*

Yes, the application of increasing amounts of PK fertilizer increased volume production and decreased basic wood density. The highest amount of fertilizer decreased basic wood density by 3% from 0.3718 to 0.3610 g cm^{-3}, but increased timber production by 29% (83 m³ ha^{-1}).

- *Was the decrease in density significant and what was the impact on total fibre yield associated with various amounts of PK fertilizer, applied at various times of stand development?*

The application of 20/20 fertilizer did not affect the timber density significantly, but the density in the 40/40 treatment decreased and it decreased further in the 80/80 treatment (**Table 7.5**). The time of application had no significant effect on timber density. The additional volume growth associated with the application of PK fertilizer far outweighed the disadvantage of a slight decrease in basic timber density as the 80/80 treatment increased fibre production by 28 t ha^{-1} (26%). Fibre production increased with increasing amounts of fertilizer and the early application of fertilizer had a greater effect than the late application of fertilizer. There was no statistical difference between the volume response to the early application of fertilizer and the split application.

10.1.6 Hypotheses 6

The application of PK fertilizer to a gabbro-derived site increases the nutrient status of the topsoil, forest floor litter and trees at rotation age.

- *How did the application of PK fertilizer affect the biomass of the trees and forest floor?*

The application of PK increased the biomass of the trees and the forest floor. The split 80/80 application increased the production of stemwood by 26.4% (28.9 t ha^{-1}), the production of stembark mass by 15.5% (2.13 t ha^{-1}) and the production of forest floor litter by 35% (27.3 t ha^{-1}). The mass of the forest floor litter was positively correlated to the volume of timber produced at rotation age, the foliar P/N and P/K ratios and the foliar

P concentration (**Appendix 3, Table A3.1**). The volume of timber produced was positively correlated to the foliar P/K ratio, while in trial R128 (**Appendix 2, Table A2.4**) and in the study by Louw and Scholes (2003) there was a negative correlation. In trial R155 the volume produced was positively correlated to the foliar P/N ratio and foliar P concentration. The soil N concentration and soil-K concentration were positively correlated to the organic content of the soil. This highlighted the importance of organic matter in the cycling of N and K as well.

- *What chemical changes occurred in the topsoil, live foliage and forest floor litter layer?*

At clearfelling greater amounts of the plant available P (Bray 2) in the topsoil were detected when the largest amount of PK fertilizer was applied, compared to the control treatment. As could be expected, the highest plant available P levels occurred in plots that received fertilizer closest to harvesting, i.e. the late application (**Table 8.5**). Soil Ca followed a similar trend, mainly because superphosphate contained a significant amount of Ca. The application of the 80/80 P and K fertilizer increased the foliar P concentrations to a level above that of the control, which was also close to the critical value of 0.14% (**Table 8.8**). None of the concentrations of the other nutrients in the live foliage was significantly affected by the application of P and K fertilizer. Although the nutrient concentration in the forest floor litter layer was not affected by fertilizer (**Table 8.6**), the P and K content increased significantly as a result of fertilization (**Table 8.6** and **Figure 8.1**).

- *Can the difference in nutrient content of a) stemwood and b) stembark be related to the amount of P and K fertilizer that was applied?*

a) The estimated mass of all 5 macro nutrients (N, P, K, Ca and Mg) contained in the stemwood was significantly increased by the application of 40/40 PK fertilizer and doubling of this amount of fertilizer further increased the amount of nutrients within the tree stems (**Table 8.12**).

b) In the case of stembark N and K the application of 40/40 or 80/80 PK fertilizer increased the amount of these two nutrients within the stembark component. The P, Ca and Mg concentration of the 40/40 amount was significantly greater than that of the control and application of 80/80 fertilizer increased it even further (**Table 8.16**).

10.1.7 Hypotheses 7

A nutrient budget for gabbro-derived soils can be developed, which can be used to model growth responses to successive fertilizer applications. More nutrients are removed from the fertilized sites.

- *What is the estimated size of the various P and K pools in relation to fertilisation treatments?*

All the additional K (59.4 kg ha^{-1}) found on the fertilized plots was contained in the biomass components as the amount of K in the topsoil was similar (**Table 8.17**). Of the additional K, 42% was found in the litter, 20% in the stemwood, 6% in the bark and 30% in the foliage and live branches. A large amount of K (64.8 and 81.0 kg ha^{-1} on the control plots and split 80/80, respectively) was removed from the site at harvesting in stemwood and stembark. This comprised 17.7% and 19%, respectively, of the K pool on the control and split 80/80 plots up to a soil depth of 1 m.

In the case of P, the soil contained 98% of the total pool (to 1 m soil depth), with only small amounts found in the biomass components (**Table 8.17**). Of the estimated additional 82.4 kg P ha^{-1} that was found on the plots where 80 kg P and K ha^{-1} was applied, 49% was contained in the topsoil, 39% in the forest floor litter and 6% in the live foliage.

- *What effect will the additional nutrient removal as a result of increased timber production have on depletion of the nutrient pool in general and the applied fertilizer in particular?*

Because the application of P and K increased timber production, the timber and bark on fertilized plots contained a greater amount of macro nutrients (**Tables 8.12** and **8.15**), which will lead to greater nutrient removal from fertilized sites. The results indicated that as a result of fertilization (split 80/80 treatment) an additional 37.6 kg ha^{-1} N, 3.5 kg ha^{-1} P, 16.2 kg ha^{-1} K, 26.0 kg ha^{-1} Ca and 7.3 kg ha^{-1} Mg will be removed at timber harvest (**Table 8.17**). However, looking at the total amount of nutrients removed at crop harvest, only 12.4% of the applied P will be removed, while all`` of the applied K will be removed from the site. If the amount of nutrients contained in the crop is expressed as a percentage of the total pool to a soil depth of 1 m, only 0.4% of the P pool is depleted, while 19% of the available K pool is depleted.

- *How can the information on the P and K nutrient pools be used to model growth response to successive fertilizer applications?*

The results from the estimates of nutrient pools in fertilized and unfertilized plots in the R155 study confirmed observations from the R128 study that a large portion of the applied P remained on the site after the first rotation that can supply in the P demand of the next crop. However, a very large proportion of the available K on the site was removed in crop harvest, indicating that the application of additional K will become more important in subsequent rotations.

10.1.8 Hypotheses 8

A significant proportion of K in the forest floor, soil and tree foliage is supplied by K fertilizer.

- *Can the Rb/K reverse tracer technique be used under Southern African forestry conditions? If the technique does not work, what are the reasons for failure?*

Analyses of Southern African fertilizer sources showed that K-fertilizers contained only a small amount of Rb (**Table 9.3**), which made it possible to apply the technique. One had to assume that the application of K did not have an effect on the uptake of Rb or on the solution and exchangeable Rb in the soil. The technique failed to a certain extent in that the Rb concentrations of the forest floor litter, stembark and stemwood was affected by the application of fertilizer (**Tables 9.4a** and **9.5**). However, in previous studies K was applied as a single nutrient. In the present study K was applied with P as well as Ca (because single superphosphate contains large amounts of Ca), which could have had an impact on the exchangeable K and Rb in the soil and consequently on the uptake of these nutrients.

- *If the technique works. What proportion of K in the topsoil, litter, and foliage, is related to K fertilizer?*

The level of K in the soil was 7% lower on the fertilized plots, compared to that of the control plots. This was probably because the trees were able to utilize more than the applied K when the P deficiency was alleviated by the application of P fertilizer. Results from the other components showed that 28.7% of the K in the wood, 19.5% of the K in the bark and 8.5% of the K in the foliage originated from fertilizer.

- *Compared to virgin soil, from unplanted, unfertilised areas close to the stand, is there evidence that fertilizer K moved from treated plots into control plots?*

There was no evidence that K fertilizer moved from fertilized plots into control plots, as the K levels in the control plots were lower than that of the unplanted and unfertilized stand.

- *If lateral movement of K did take place, what amount of contamination occurred over a 15 year period?*

There was no evidence that K moved laterally in this trial. However, the trial site being located on clay soil differed drastically from the sandy soil where lateral movement of K fertilizer was reported by Buxbaum *et al.*, (2001).

10.2 COMBINED RESULTS FROM R128 AND R155

The results from the two trials (R128 and R155) in the present study, both located on gabbro-derived soils on the Usushwana-complex, complemented each other as both contributed to the understanding of the processes that were responsible for the growth responses. This approach is recommended by Binkley (2008) as he cautioned about applying results from a single trial, located on one specific site, to all other similar sites. The results from R155 were used to establish the effects of various amounts and time of application of PK fertilizer on the tree growth, changes in timber properties, stem form and nutrient pools in the topsoil and some biomass components at the end of the first fertilized rotation. Trial R128 was unfortunately not intensively sampled at the end of the first fertilized rotation (3R). However, measurements and samples from the subsequent trial (4R), supplied valuable information on the residual effects of fertilizer that was applied in the previous rotation and how future fertilizer prescriptions can be adjusted.

Both trials showed a positive growth response to the application of P and K fertilizer. The application of 75 kg ha^{-1} elemental P and K, respectively, at the age of 6 years to the 3R crop of R128 increased height by 5%, basal area by 10% and volume by 11% (22.9 m^3 ha^{-1}) (**Table 5.2**) at the clearfelling age of 14 years. This response, although highly significant, was less than the additional 30 to 70 m^3 ha^{-1} measured in other similar trials (Morris 1987a, 1994a). The successive (4R) rotation of trial R128 indicated that on plots that received PK fertilizer for the first time the application of 50 kg ha^{-1} elemental P and K, respectively, increased the volume production by 15.6% (20 m^3 ha^{-1}) at the age of seven years (**Figure 3.2**). In trial R155 the application of 80/80 kg ha^{-1} elemental P and K, respectively, 20/20 applied at planting and 60/60 at the age of 6 years to the 3R crop of R155 on a previously unfertilized site increased volume production by 29% (83 m^3 ha^{-1}) at the age of 15 years. These results supported the recommendation to apply both

P and K fertilizer to gabbro-derived soils, which have not received any PK fertilizer application previously (Morris, 1987a, 1994a).

In trial R128 neither the DBH distribution nor the height distribution, based on analyses of the coefficient of variation per plot, was significantly affected by the fertilizer treatments. However, in trial R155 the application of fertilizer reduced the coefficient of variation of the DBH values from 23.2% in the control treatment plots to 20.1% in the factorial 40/40 and 80/80 plots. Theoretically, stands with a more uniform structure should be more efficient in utilizing resources, which should increase their productivity compared to stands with a large variation in stand structure (Binkley *et al.*, 2002)

Volume growth results from the age of four years of the 4R crop in trial R128 indicated that there was a consistent interaction between P, K and the residual PK fertilizer, remaining from the application to the 3R crop. In the presence of residual PK fertilizer the application of only 50 kg ha^{-1} K increased volume by 21.5% (27 m^3 ha^{-1}) at age seven years. This was statistically similar to the 20% (25.2 m^3 ha^{-1}) increase from a combined PK application of 50 kg ha^{-1} each (**Figure 3.2**). The foliar P and K concentrations were also raised to sufficient levels when only 50 kg ha^{-1} K was applied to previously fertilised plots (**Figures 5.2a** and **5.2b**).

The analysis of 32 tree stems, 16 each from the control and split 80/80 treatments of trial R155, indicated that the enhanced growth as a result of fertilization did not change the shape of the stems (**Table 6.3**), but that the basic wood density decreased (**Table 6.4** and **Figure 6.3**). However, these effects were small compared to the additional volume production and as a result a significantly greater amount of fibre was produced on the fertilized plots (**Table 7.5**). Because the basic wood density and nutrient concentrations of the mobile nutrients (N, P and K) within the stembark and stemwood changed with an increase in tree height, models were developed to estimate the average basic wood density and total nutrient content based on the allometric relationship between values obtained from samples collected at breast height, tree height and tree diameter at breast height (DBH).

The application of P fertilizer significantly increased the P concentration of the live foliage in both trials (Tables **5.2a** and **8.8, A3.1**). As was shown in other studies, the growth response to P was reflected in concentrations of P in the foliage (Ballard, 1978; Flinn *et al.*, 1982; Gentle *et al.*, 1986; Xu *et al.*, 1995; Turner *et al.*, 2002). The results from the recently senesced needles from trial R128 showed that in absolute terms less P was resorbed on sites where fertilizer was applied (data not shown). As a result, the P content of the needle component of the forest floor in trial R128 and the complete forest floor of trial R155 (consisting mostly of dead needle material) increased significantly on plots where P was applied (**Table 4.5** and **Figure 8.1**). In the other biomass components, sampled in trial R155, the application of P inceased the stemwood and stembark P concentrations (**Tables 8.9** and **8.13**). On the split 80/80 fertilized plots of trial R155 only 9.9 kg P ha^{-1} was contained within the stemwood and stembark portions, indicating that only 0.4% of the P pool within the biomass and first 1 m of topsoil was removed at harvesting (**Table 8.17**). Although the effect of P fertilizer on the nutrient concentration and content of the biomass components were greater than the effect of K fertilizer, strong evidence was found that the K concentrations also increased.

In trial R128, on previously unfertilized plots, the application of increasing amounts of K significantly increased the K concentration of the live foliage (**Figure 5.2b**). The resorption of potassium before senescence was only 66% in plots where 50 kg K ha^{-1} was applied, compared to the 74% in the control plots when the 4R crop of trial R128 was six years old (data not shown). Although the K content of the forest floor was not significantly increased in trial R128, the application of K fertilizer significantly increased the K content of the forest floor of trial R155 (**Figure 8.1**). In trial R155 the foliar and stembark K concentrations in samples collected at the end of the rotation were not significantly affected by the application of K ten years earlier (**Tables 6.6b** and **8.9**). However, the content within the stemwood and stembark were significantly increased (**Tables 8.12** and **8.16**) by the application of increasing amounts of P and K fertilizer in trial R155. On the split 80/80 treatment plots the stembark contained 25.1 kg K ha^{-1} and the stemwood 55.9 kg K ha^{-1}. Thus, the 81 kg K ha^{-1} removed at crop harvest comprised 19% of the K pool contained in the biomass and first 1 m of topsoil (**Table 8.17**).

In the 4R crop of trial R128 very little of the K that was applied could be accounted for in the foliage, forest floor and soil. The exchangeable K content was significantly greater in plots with residual fertilizer, but this could only account for 1.9% of the fertilizer that was applied in 1989 to the 3R crop. The HNO_3-extracted K concentration in the topsoil was greater in absolute terms on the previously fertilised plots, but the power of the test was not sufficient to show this statistically. The results at the end of the first fertilized rotation (R155) showed that the trees took up a significant amount of K when P and K fertilizer were applied. This was also evident in the topsoil as the absolute levels of exchangeable K in the soil was lower in the fertilized plots, compared to that of the control plots and an unfertilized stand adjacent to the trial (**Table 8.3**). The earlier trial (R128) as well as earlier studies by Morris (1987) also showed that a combined application of P and K is necessary to elicit a positive growth response on the gabbro-derived soils. The chemical analysis of biomass components at rotation age on fertilized and unfertilized plots in trial R155 showed that a greater amount of K than P were removed from the site in stembark and stemwood at harvest (**Table 8.17**). The Rb/K reverse tracer technique results confirmed that a large proportion (28.7%) of K in the stemwood originated from the fertilizer (**Figure 9.1**) in trial R155. On the fertilized plots a greater amount of K was removed from the site than the amount that was applied as fertilizer during the rotation (101%). This suggested that the fertilizer prescription might have to be adjusted to apply more K to the subsequent crops in order to maintain volume production in subsequent rotations.

Only 12% of the P that was applied was removed from the site in the crop harvest in trial R155. According to the results from a P adsorption study that was conducted on soil samples from a soil pit next to trial R128 (**Appendix 2.2**) the maximum P adsorption was above 200 mg kg^{-1}. This indicated that the soil has the potential to retain large amounts of P (Turner *et al.*, 2002) and that P applications should increase the productive capacity of the site for future rotations. The results from the PK residual trial (R128) confirmed the observations from trial R155 as the additional 41 kg ha^{-1} elemental P that was found in the soil layers in plots with residual P fertilizer accounted for almost 55 % of the amount of P that was applied 15 years earlier to the previous crop. The greatest proportion of the residual P occurred in organic fractions, indicating that the inorganic P fractions were converted into organic P. The organic P is less liable to leaching or adsorption and will be a major source of available P to the following crops. Therefore, the conservation of organic material on these sites will be extremely important to ensure the long term benefits of P cycling through organic residues to subsequent crops. The combined results indicated that the residual P should be sufficient to supply the demands of at least the next three to five rotations. It is concluded that fertilizer applications at planting to successive crops can be adjusted to allow for the benefit from the residual P that remained from the application to the previous crop. A reduction in the amount of P applied to successive rotations on previously fertilised 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. Furthermore the investment in P fertilizer can be seen as a relatively permanent addition to soil nutrient status and forest site quality on the gabbro soils. A reduction in P applications in subsequent rotations will also have an environmental benefit in that it will prevent over fertilisation with P, which can have a detrimental effect through eutrophication. The economic benefit of a reduction in the amount of P fertilizer in successive rotations will be discussed in the next section.

10.3 ECONOMIC BENEFIT OF APPLYING FERTILIZER TO THE GABBRO-DERIVED SOIL

Since December 2006, the price of superphosphate fertilizer increased by 317% (**Figure 10.1**). The price of other fertilizers increased similarly over the same time period. These increases were related to the increase in the oil price and increased demand from the Far East, China in particular. Furthermore, the phosphate reserves on earth are finite (Johnston and Steén, 2000) and the relatively cheap sources of phosphate are almost depleted. This increase in fertilizer cost necessitated a review of the cost-benefit (Morris, 1987a) of applying more expensive P and K fertilizer to pines on the gabbro-derived soils. Various volume response scenarios ranging from pessimistic to optimistic were investigated and for each of these the cost of additional timber was calculated at the current fertilizer cost. The time value of money was excluded from the calculations, because the plantation resource was assumed to be normalised in age class and in rotation. Therefore, current fertilizer prices as well as timber prices were used in all calculations similar to the method used by Morris (1987a). The respective fertilizer prices per ton excluding VAT and transport, at time of writing, were R 10 692 for KCl (50%) and R 8 769 for superphosphate (10.5%).

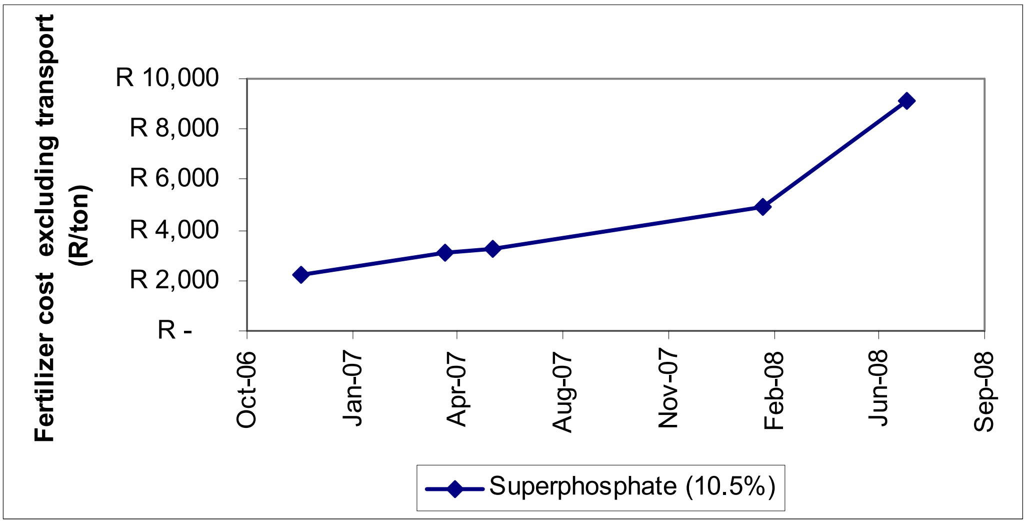


Figure 10.1: The price of superphosphate fertilizer increased by 317% over the past two years.

The cost-benefit analysis showed that as a result of the increase in the cost of fertilizer, the application of P and K fertilizer to pines was not economically feasible for the worst case scenario if the calculation was done over only one rotation, as the cost of the additional timber was more than the current cost of timber (**Table 10.1a**). At the average and maximum response scenarios application of P and K at each rotation was still economical.

However, the results from trial R155 showed that only a small amount of the fertilizer P was removed from the site at harvesting (**Table 8.17**). The response observed in trial R128 confirmed that a significant amount of residual P remained from the earlier application and that the trees were able to utilize this fertilizer (**Figure 5.1**).Thus, the application of PK fertilizer to previously unfertilized stands should be seen as a capital investment as it increased the long-term site productivity.

The results from trial R155 showed that a large amount of fertilizer K was removed at harvesting (**Table 8.17**). The response in the successive rotation of trial R128 also indicated that the greatest response on previously fertilizer plots occurred when only additional K fertilizer was applied. These results suggested that the prescriptions for fertilizer application to subsequent fertilized crops can be adjusted, for example, by applying P only every fourth rotation. This will have a huge economic benefit as the cost of superphosphate comprised 80% of the fertilizer cost shown in **Table 10.1a**. If the fertilizer prescription is adjusted, even the worst case scenario will be highly profitable over four rotations (**Table 10.1b**). At current fertilizer prices the cost of the additional timber will be R181 per m³ at the worst case scenario and R54 per m³ at the best case scenario (**Table 10.1b**), which is significantly less than the current cost of timber.

Table 10.1: Cost-benefit calculation of application of PK fertilizer to pines growing on basic soil parent material over one rotation (a) and four rotations where P and K is applied in the first rotation and only K in the subsequent three rotations (b).

a) One rotation with P and K fertilizer.

	Volume Gain Scenario		
	Min.	Avg.	Max.
Volume gain at clearfelling 16 yrs (m³ ha^{-1})	23.0	50.0	77.0
Application cost (1.5 units ha^{-1})	R 158	R 158	R 158
Fertilizer cost per ha (95 kg P and K respectively ha^{-1})	R 9,965	R 9,965	R 9,965
Total Fertilizer cost per ha	R 10,123	R 10,123	R 10,123
Cost of additional timber (R m^{-3})	**R 440**	**R 202**	**R 131**

Shading indicates a cost of more than R250 m^{-3}

b) One rotation with P and K fertilizer and three rotations with only K fertilizer.

	Volume Gain Scenario		
	Min.	Avg.	Max.
Volume gain at clearfelling 16 yrs (m³ ha) x 4 rotations	92.0	200.0	308.0
Application cost (1.5 units ha^{-1}) x 4 rotations	R 630	R 630	R 630
Fertilizer cost per ha (95 kg P ha^{-1}, 380 kg K ha^{-1})	R 16,060	R 16,060	R 16,060
Total Fertilizer cost per ha	R 16,690	R 16,690	R 16,690
Cost of additional timber (R m^{-3})	**R 181**	**R 83**	**R 54**

CHAPTER 11

CONCLUSIONS AND FUTURE RESEARCH

The results from the two studies showed that the application of P and K fertilizer to the gabbro-derived soils prevented a growth decline in the 3R crops, and combined with planting genetically improved material, even led to improved production from these sites in the following rotation (4R) of trial R128. The results from the present study suggest that increased production will lead to increased nutrient removal, threatening long-term site productivity unless both P and K fertilizer are applied to gabbro-derived soils, which have not received any PK fertilizer application previously. The evidence from the 32 intensively sampled trees was insufficient to show that fertilization changed the stem form of the trees, which can have significant implications for growth and yield modelling. This aspect should be studied in more detail in future. In addition to the quantity of timber produced, the quality of the wood from fertilized trees is also important.

As was found in other studies, silvicultural practices that enhanced tree growth (fertilization in the present study) decreased the basic wood density, but the additional volume increase far outweighed the disadvantage of a slight decrease in density. A slight density reduction will have an insignificant effect on the final product or production process. The basic wood density decreased towards the top of the trees, possibly because of an increase in the proportion of juvenile wood to mature wood. Thus, samples should be collected at various heights or DBH values should be converted with an appropriate model to obtain average values of basic wood density per tree. The same applies for the nutrient concentration of the mobile elements N, P and K within the stemwood and stembark as these concentrations increased towards the top of the tree.

The fertilizer P should remain for long periods in the soil, because the gabbro-derived soils have a high P adsorption capacity. In trial R128, 55% of the applied P could be found 15 years after the application of 75 kg P ha^{-1} and 87% of the applied P could be found ten years after the application of 80 kg P ha^{-1} in trial R155. These results suggested that the application of P fertilizer to successive crops can be reduced to allow for the benefit of residual P fertilizer. Over time the efficiency of the P fertilizer will decrease as a result of adsorption and precipitation. Thus, the frequency and amount of future P fertilizer applications will have to be assessed. A reduction in the P fertilizer usage will result in large financial savings and will have environmental benefits (lower risk of eutrophication, reduced risk of contamination of scarce water resources and the conservation of limited phosphorus sources).

In contrast to P, very little to none of the applied K fertilizer could be found on the respective sites after the first fertilized rotation. Calculation of the amount of K contained in various biomass and soil components showed that a significant amount of K was taken up by the trees and removed from the site in the stemwood and stembark at crop harvest. These results suggested that the application of increased amounts of K fertilizer will be of utmost importance to produce timber sustainably on the gabbro-derived soils at Usutu.

The response to applying K with decreased amounts of P in subsequent rotations should be tested in at least one other trial before revising the current operational fertiliser application prescriptions. Therefore, in January 2008 a 2P by 3K factorial trial was re-establish on the former PK amount by time of application by weeding trial (R155). By re-applying 0 and 50 kg ha^{-1} P and 0, 50 and 100 kg ha^{-1} K in a factorial combination in the presence of the historic 0/0, 40/40 and 80/80 kg ha^{-1} PK fertiliser application, it should be possible to model the growth and soil nutrient response to the re-application of fertiliser in subsequent rotations more accurately. Furthermore, the results will be used to determine the exact P:K fertiliser ratio necessary to achieve the maximum volume production in subsequent fertilised rotations. The relatively small size of the plots (7 x 7 trees) might be a limitation to future work, but it must be remembered that the trial was not designed to study long-term responses to fertilisation over more than one rotation. It is suggested that future trials should be designed with a plot size of 40 m x 40 m with larger buffer areas (more than 10 m) between treatment plots. It will, however, increase the size of the trials and reduce uniformity within the trial sites. The larger number of trees will increase the accuracy of modelling responses.

As a result of nutrient removal of harvested crops; impacts of silvicultural operations, e.g. fertilizer applications; and the modification of the soil environment by the trees themselves, the soil nutrient levels change over time. Thus, it is necessary to measure soil nutrient levels at the start of any fertilizer trial as well as to compare the nutrient levels to that of other stands. Nutrient levels recorded at the end of a fertilizer trial can be used to determine the impact of the fertilizer applications and can assist in identifying possible future deficiencies that might develop. It is especially important if the previous fertilizer history of a site is unknown, as residual fertilizer from earlier applications might be present, making it impossible to extrapolate results from a trial to other similar, but unfertilized sites. If the changes in soil nutrient levels are quantified, fertilizer prescriptions can be adjusted over successive rotations.

The results from the two trials reported on in this thesis contributed substantially to increase the knowledge of nutrient cycling through the forest floor. The P fractionation results from both trials showed that over time the inorganic P fertilizer was converted into organic P forms, which are less prone to leaching and adsorption. Because the organic P will be an important source of P to the subsequent crops, the conservation of organic material (forest floor litter and harvest residue) will be extremely important to ensure long-term P cycling on these sites. The organic material also played an important role in the cycling of K. Thus, the current silvicultural practice of not burning any harvest residue on the Usutu forest should continue in order to preserve the nutrients contained within the organic material. If a wild fire occurs all possible measures will have to be taken to prevent erosion of the ash and topsoil as these components will contain a large amount of the plant available P and K. In the event of a serious wildfire, followed by erosion, the re-application of P and K fertilizer to the gabbro-derived sites might be necessary. The use of harvest residue from the gabbro-derived soils as a source of bio-fuel should be discouraged.

Gabbro is of very limited extent in South African forestry plantations. However, the applicability of the findings from this study to other *P. patula* stands on soils originating from basic geologies (dolerite, diabase, basalts and other igneous rocks) having similar low P and K contents in Mpumalanga, Swaziland and Natal should be investigated. It is likely that P and K nutrient deficiencies might be developing and that remedial fertilization could enhance volume production significantly on these sites. However, results from one site should not be extrapolated to other sites without appropriate validation. Most soils under plantation forestry in South Africa are highly weathered with a low pH and are strongly P-fixing. Many of the principles with respect to P chemistry might be widely applicable within the Southern African forestry industry.

Foliar nutrient values, nutrient ratios and growth data from permanent sample plots can be used to identify developing nutrient deficiencies; to identify compartments that will respond to P and K fertilization; and to monitor continuously the response to the revised fertilizer prescriptions at Usutu. The results from this study and previous studies can be used as a baseline for future forest ecosystem studies and the development of nutrient management models.

CHAPTER 12

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APPENDIX 1

TRIAL MAPS

Figure A1.1: R128 schematic trial map.

R155 - PK Fertiliser amount x time of application trial
Compartment A11

		1 S40N 1	2 L80N 1	3 L40N 1	4 CONTRN 2	5 S40I 2	6 CONTRI 2	7 L40N 2	8 E40I 2
		9 L40I 1	10 CONTRI 1	11 L80I 1	12 L80N 2	13 S40N 2	14 L40I 2	15 E80N 2	16 E40N 2
17 S40I 1	18 E20N 1	19 CONTRN 1	20 S80N 1	21 E20I 1	22 E20I 2	23 E20N 2	24 E80I 2	25 L80I 2	26 S80I 2
27 E40I 1	28 S80I 1	29 E40N 1	30 E80I 1	31 E80N 1	32 S80N 2	33 L80N 4	34 S80I 4	35 S40I 4	36 E20I 4
37 E40I 3	38 CONTRI 3	39 L40N 3	40 E20I 3	41 S80N 3	42 S40I 3	43 E80I 4	44 S40N 4	45 CONTRI 4	46 L40N 4
47 E80I 3	48 S40N 3	49 L80I 3	50 L40I 3	51 E80N 3	52 S80I 3	53 E40N 4	54 E80N 4	55 CONTRN 4	56 L40I 4
		57 L80N 3	58 E20N 3	59 CONTRN 3	60 E40N 3	61 E20N 4	62 E40I 4	63 L80I 4	64 S80N 4

To Malkerns ROUTE 3 To Mhlambanyati

Planted 1992

TREATMENTS

Code	Fertiliser rate		Weed Control
	Planting	Pruning	
E40N	40/40	0	Normal
E40I	40/40	0	Intensive
E80N	80/80	0	Normal
E80I	80/80	0	Intensive
S40N	20/20	20/20	Normal
S40I	20/20	20/20	Intensive
S80N	20/20	60/60	Normal
S80I	20/20	60/60	Intensive
L40N	0	40/40	Normal
L40I	0	40/40	Intensive
L80N	0	80/80	Normal
L80I	0	80/80	Intensive
E20N	20/20	0	Normal
E20I	20/20	0	Intensive
CONTRN		0	Normal
CONTRI		0	Intensive

20/20	20kg P + 20kg K per ha
40/40	40kg P + 40kg K per ha
60/60	60kg P + 60kg K per ha
80/80	80kg P + 80kg K per ha
E	All fertiser applied at planting
S	Fertiliser applied part at planting (20/20) and rest post pruning
L	All fertiser applied post pruning
N	Normal weeding as used operationally
I	Intensive weeding aimed at weed free plots
(green box)	Plots identified for intensive sampling

Figure A1.2 Schematic map of PK fertilizer amount by time of application trial (R155) at Usutu.

APPENDIX 2

ADDITIONAL INFORMATION –TRIAL R128

A2.1 Soil pit information:

A soil pit was dug next to plot 14 and 16 in an area next to trial R128. This specific location was selected to obtain samples of all the different soil layers where no fertiliser was previously applied. The stand next to the trial received an operational PK application at planting, but due to the layout of the trial, it was unlikely that the area between plots 9 and 45 received operational fertiliser (**Figure A1.1**). Each horizon was classified according to the soil taxonomic classification system of South Africa (Soil Classification Working Group, 1991). After fresh surfaces were dug on three sides of the soil pit, samples were collected from each diagnostic horizon for chemical and textural analyses. Total major elements were determined by means of X-ray fluorescence (XRF). Bulk density was determined by the core method as described by Kalra and Maynard (1991). Undisturbed soil cores of each horizon were collected by means of a metal core sampling cylinder of known volume from three sides of the soil pit. The samples were dried in a ventilated oven for 72 hours at 70°C to constant weight. The oven-dried weight of the soil sample divided by the volume of the cylinder gave the bulk density.

The soil in the trial area can best be described as a Kranskop 1100 (Soil Classification Working Group, 1991). The humic A horizon is classified as thin and because the clay content does not increase markedly from the A to the B1 horizon, the soil is classified as non-luvic. Details of the diagnostic soil horizons are shown in **Table A2.1**, while results of the bulk density and chemical analyses appear in **Table A2.2** and **Table A2.3**.

Table A2.1: Soil pit profile description at trial R128.

Horizon	Depth (mm)	Description	Diagnostic Horizon
A	0-100	Brown to dark brown; well drained clay soil; no coarse fragments	Humic A
B1	100-270	Yellow-brown colour; clay soil; no coarse fragments; apedal structure	Yellow-brown apedal B
B2	270-470	Red apedal clay with no coarse fragments	Red apedal B
C1	470-570	Red colour with no signs of mottling or wetness. Abundant (80%) fine, rounded, gravel (3-5mm) and 5% coarse gravel in the horizon.	Unspecified
C2	570-1500(+)	Red saprolite with yellow mottling, no coarse fragments.	Unspecified

Table A2.2: Soil texture and results of soil chemical analysis for each diagnostic horizon of the soil pit at trial R128.

Property	Unit	Horizon				
		A	B1	B2	C1	C2
Bulk density	Mg m^{-3}	0.74	0.87	0.98	1.28	0.93
Silt	%	14	12	13	9	10
Clay	%	82	81	80	71	67
Sand	%	4	7	7	20	23
Texture	-	Clay	Clay	Clay	Clay	Clay
pH (H_2O)	-	4.3	4.9	5.1	4.8	4.6
pH (KCl)	-	3.7	4.1	4.5	5.0	5.0
Org.C. (WB)*	%	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
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	cmol(+) kg^{-1}	0.2	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	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

Table A2.3: Total major element analysed via X-ray fluorescence of each diagnostic horizon of the soil pit at trial R128.

Horizon	SiO_2 %	Al_20_3 %	Fe_20_3 %	Mn0 %	Ca0 %	Na_20 %	K_20 %	$Ti0_2$ %	P_20_5 %	Cr_20_3 %	Ni0 %	Total %
A	37.67	30.41	27.56	0.05	0.00	0.18	0.06	2.87	0.21	0.05	0.01	99.23
B1	37.20	30.96	28.20	0.14	0.00	0.05	0.04	2.88	0.18	0.05	0.02	99.88
B2	34.10	30.50	31.19	0.05	0.00	0.07	0.03	2.85	0.13	0.07	0.01	99.15
C1	34.80	29.50	31.74	0.19	0.00	0.00	0.03	2.77	0.14	0.07	0.01	99.40
C2	34.42	31.80	29.38	0.10	0.00	0.00	0.02	3.10	0.16	0.04	0.01	99.18

Table A2.4: Correlations between selected top soil variables, tree growth and foliar nutrient levels in trial R128, a P by K by residual PK trial with *P. patula* at Usutu. (*Significance levels: coefficient only = 0.10, * = 0.05, ** = 0.01, *=0.001*).**

1	Volume 2004	1.00																
2	Foliar N		1.00															
3	Foliar P			1.00														
4	Foliar K			0.45 **	1.00													
5	Foliar Ca		0.34 *			1.00												
6	Foliar Mg			-0.32 *			1.00											
7	Foliar N:P		0.76 ***	-0.70 ***				1.00										
8	Foliar N:K		0.51 ***	-0.49 ***	-0.72 ***			0.69 ***	1.00									
9	Foliar P:K	-0.25	-0.28	0.25	-0.74 ***		-0.27	-0.35 *	0.43 **	1.00								
10	P Bray2 (soil)			0.37 **	0.30 *	0.44 **					1.00							
11	Exch. K^+ (soil)			0.27	0.32 *			-0.31 *	-0.43 **		0.24	1.00						
12	Ca^{++} (soil)					0.31 *							1.00					
13	Mg^{++}(soil)			0.44 **	0.29 *		-0.25	-0.26	-0.27		0.40 **	0.51 ***	0.31 *	1.00				
14	CEC (soil)					0.30 *						0.35 *	0.97 ***	0.51 ***	1.00			
15	O.C. (soil)			0.29 *	0.34 *			-0.29 *	-0.34 *		0.44 **	0.66 ***	0.28	0.25	0.34 *	1.00		
16	Ex. Acid (soil)				0.26				-0.26		0.38 **					0.73 ***	1.00	
17	pH (H_2O)															-0.45 **	-0.68 ***	1.00
		Volume 2004	Foliar N	Foliar P	Foliar K	Foliar Ca	Foliar Mg	Foliar N:P	Foliar N:K	Foliar P:K	P Bray2 (soil)	Exch. K^+ (soil)	Ca^{++} (soil)	Mg^{++} (soil)	CEC (soil)	O.C. (soil)	Ex. Acid (soil)	pH (H_2O)
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17

A2.2 Soil P-adsorption

Phosphorus fixation curves were constructed to determine the maximum phosphorus-fixation capacity of the soil, because soil adsorption reactions can rapidly decrease the availability of phosphorus to plants and thus decrease the utilization of fertiliser P. A series of phosphorus solutions of increasing concentration, ranging from 20 to 300 mg l^{-1}, were mixed with a known quantity of soil and the concentration of the P remaining in solution was determined when equilibrium was reached. The adsorbed P was calculated as the difference between the initial concentration of P added and the final concentration of P in the supernatant. The P adsorbed at each addition was plotted against the concentration of P remaining in the solution (Henry and Smith, 2002; 2004; 2006). The two most commonly isotherm equations were used to model P adsorption (Kinniburgh, 1986). The isotherms for the Freundlich (Russel and Prescott, 1916 cited in Henry and Smith, 2002) and Langmuir (Langmuir, 1916 cited in Nelson, 2001; Wikipedia, 2006; Olsen and Watanabe, 1957 cited in Henry and Smith, 2002) models (**Equations A1** and **A2**) were fitted mathematically with the non-linear regression functionality (Kinniburgh, 1986) within *Genstat 8.1* software. The form of the fitted regression equations was:

Langmuir one surface: $Y = Alx/(1+Blx)$ [Equation A1]

Freundlich : $Y = Afx^{Bf}$ [Equation A2]

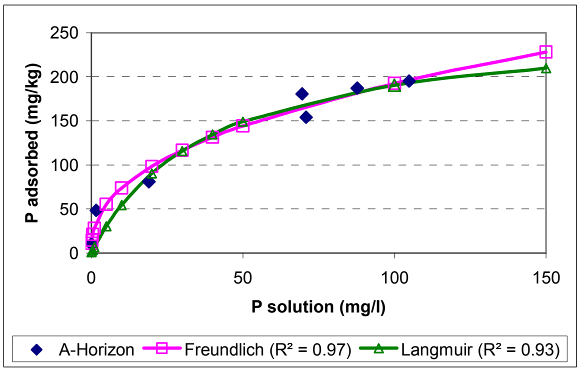
Regression analysis results of the two equations to estimate the P isotherms are shown in **Table A2.5** and graphically represented in **Figure A2.1**. The R^2 values were generally high and showed that the fitted equations could account for a large portion of the variability. The maximum phosphate fixation capacity for each soil horizon was estimated from the Al/Bl relationship of the Langmuir equation coefficients (Henry and Smith, 2002). This indicated a general decrease in maximum adsorption from 264 mg kg^{-1} in the A-horizon down the profile to 196 mg kg^{-1} in the C1 horizon. The maximum adsorption in the C2 horizon, the saprolitic layer, was very high at 553 mg kg^{-1}.

Table A2.5: Estimated regression coefficients for P-adsorption graphs and indication of fit for each horizon of a soil pit next to trial R128, a P by K by residual PK fertilizer trial with *P. patula* at Usutu, Swaziland.

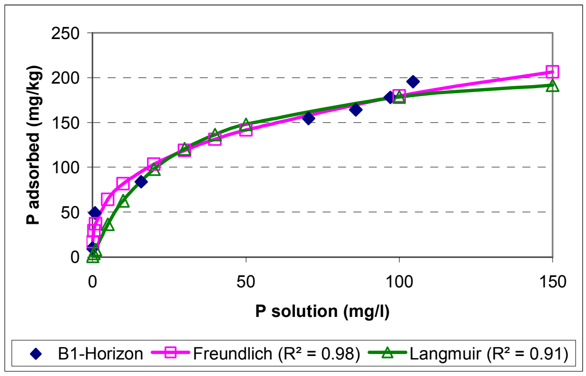
Horizon	Langmuir one surface $Y = Alx/(1 + Blx)$				Freundlich $Y = Afx^{Bf}$		
	Al	Bl	R^2 (n = 7)	Adsorption maximum (Lm) (mg kg^{-1})	Af	Bf	R^2 (n = 7)
A	6.86	0.0260	0.93	263.8	28.11	0.4179	0.97
B1	8.69	0.0387	0.91	224.7	37.14	0.3422	0.98
B2	14.24	0.0646	0.84	220.4	47.24	0.3103	0.87
C1	11.19	0.0572	0.84	195.6	46.53	0.2765	0.92
C2	4.21	0.0076	0.89	553.2	12.22	0.6470	0.90

The P-adsorption isotherms indicated that the equilibrium phosphorus concentration was very close to 0 for all five horizons as no remaining P was found when solutions ranging from 0.1 to 20 mg l^{-1} were applied. Results obtained with solutions of 150, 200 and 300 mg l^{-1} were consistently outliers in all five samples and were therefore excluded from the regression analysis. Of the two models fitted, the Freundlich equation fitted the data the best when the percentage of variance that could be accounted for (R^2) was used as a measure of fit (**Table A2.5**). However, the Langmuir equation also fitted well and could account for more than 84% of the variation in all the horizons. Some researchers believe the Langmuir equation is more useful, because the isotherm has a theoretical basis. The Bl-coefficient is theoretically related to the energy of bonding of the adsorbed P onto the surface and from the Al/Bl relationship, the adsorption maximum of the soil (Lm) can be calculated (Henry and Smith, 2002).

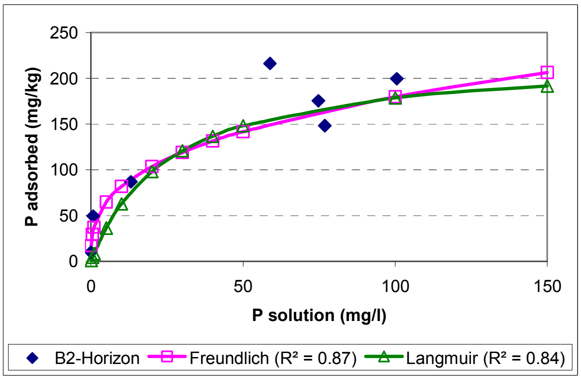
In the R128 study the A-horizon had an Lm of 264 mg $kg^{-1}$and this decreased to 196 mg kg^{-1} in the C1-horizon. The C2-horizon, consisting of saprolite, had the highest maximum adsorption of 553 mg kg^{-1}. Based on these values this soil can be classified as a phosphorus fixing soil and will tend to maintain low phosphorus concentrations in the soil solution. The high fixation capacity is probably related to the high levels of aluminium and iron in the soil minerals (**Table A2.3**), clay minerals dominated by crystalline Fe, Al and Mn oxides in the Oxisol and low pH (Brady and Weil, 1996; Cross and Schlesinger, 1995). Theoretically the topsoil (100 mm deep A-horizon) was capable of adsorbing all of the 75 kg ha^{-1} P that was applied in 1989 as this was equal to 101 mg kg^{-1} based on the 0.74 Mg m^{-3} bulk density of the A-horizon. The phosphorus fixation level of more than 200 mg kg^{-1}, the critical value as determined by Turner *et al.* (2002), suggested that phosphorus fertiliser will be strongly adsorbed, increasing the productive capacity of the site for future rotations.



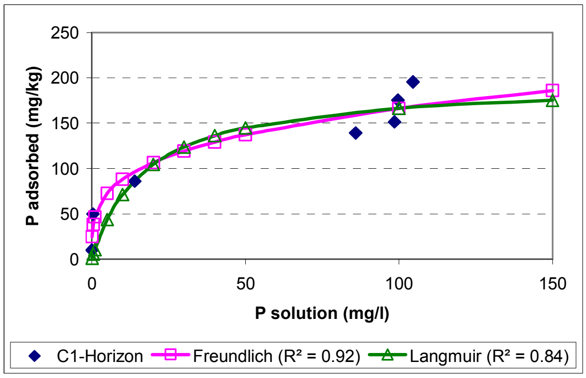
a) A-horizon



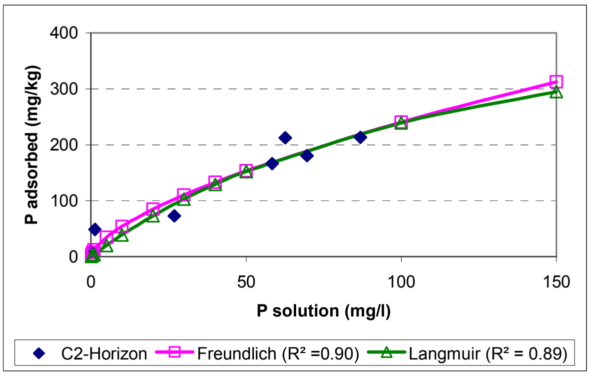
b) B1-horizon



c) B2-horizon



d) C1-horizon



e) C2-horizon

Figure A2.1: P-adsorption graphs for the five soil horizons sampled in the soil pit next to trial R128 a P by K by residual PK fertilizer trial with *P. patula* at Usutu.

Appendix 3: Additional information trial R155

Table A3.1: Correlations between selected topsoil variables, tree growth and foliar nutrient levels in trial R155, a P by K by residual PK trial with *P. patula* at Usutu at cleafelling age of 15 years. (*Significance levels: coefficient only = 0.10, * = 0.05, ** = 0.01, *=0.001*).**

Foliar N%																					
Foliar P%	0.3453 **	0.4910 ***																			
Foliar K%		0.3478 **	0.4963 ***																		
Foliar Ca%	0.2551		0.2370																		
Foliar Mg%	0.2872 *	0.3566 **	0.4874 ***	0.2738 *	0.6255 ***																
Foliar P:N	0.4506 ***		0.8270 ***	0.3533 **		0.3362 *															
Foliar K:N		-0.4111 **		0.7067 ***			0.4184 **														
Foliar P:K	0.3780 **	0.2828 *	0.7225 ***	-0.2331	0.2461	0.3267 *	0.6375 ***	-0.4215 **													
Forest floor Litter mass	0.4971 ***		0.3977 **				0.4430 ***		0.3929 **												
Soil N				-0.2615			-0.2923 *	-0.3045 *													
Soil P_i							0.3179 *	0.3016 *													
Soil P_o		0.2323	0.3430 *					-0.3054 *	0.4547 ***	0.2552											
Soil P_{i+o}			0.3614 **				0.3861 **		0.3460 **			0.7796 ***	0.6238 ***								
Soil P BrayII							0.3323 *	0.2512				0.9511 ***		0.7438 ***							
Soil K										-0.2275	0.4365 ***	0.4352 ***	-0.2291		0.2955 *						
Soil Ca								0.2689 *	-0.2961 *						0.2404	0.3634 **					
Soil Mg																0.3352 *	0.7560 ***				
Soil Na																	0.3271 *	0.2614			
Soil OC	0.2277										0.4613 *0.0004*					0.2787 *					
Soil S value								0.2560	-0.3211 *		0.2682 *	0.2498			0.2246	0.6247 ***	0.9260 ***	0.8244 ***	0.2624		
	Vol ha^{-1} 07	Foliar N%	Foliar P%	Foliar K%	Foliar Ca%	Foliar Mg%	Foliar P:N	Foliar K:N	Foliar P:K	Forest floor Litter mass	Soil N	Soil P_i	Soil P_o	Soil P_{i+o}	Soil P BrayI	Soil K	Soil Ca	Soil Mg	Soil Na	Soil OC	Soil S value