# EFFECTS OF NITROGEN, PHOSPHORUS AND POTASSIUM ON THE EARLY GROWTH OF *PINUS PATULA* AND *EUCALYPTUS GRANDIS*

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**GOTORE T, MUREPA R & GAPARE WJ. 2014. Effects of nitrogen, phosphorus and potassium on the early growth of *Pinus patula* and *Eucalyptus grandis*.** Effects of various levels of nitrogen (N), phosphorus (P) and potassium (K) applied singly or in combination on *Pinus patula* and *Eucalyptus grandis* tree growth in Zimbabwe were studied. Data were available from eight trials located in areas representative of the commercial forestry areas of Zimbabwe and characterised by varied rainfall patterns, ranging from 750 to 1524 mm per annum. *Pinus patula* growth responses to N fertilisation were small and variable and in some cases caused significant reduction in tree growth. Phosphorus effect showed mixed results, with a positive effect on *P. patula* growth at Nyangui North and Mtao Forests and none at Nyangui South and Charter North. Potassium fertiliser application had no effect on *P. patula* tree growth. The interactions between N and P, N and K, P and K as well as N, P and K were all not significant for *P. patula* growth at all sites. *Eucalyptus grandis* growth was not significantly influenced by N fertiliser application. Trees applied with P had negative response while tree growth was positive to K application at the site with sandy soil texture. Conversely, *E. grandis* tree growth responded positively to P and K fertiliser interactions at the same site. Tree growth responses to N × P × K factorial combinations were only significant ($p < 0.05$) for tree growth at two of four sites. Our results suggested that nutrition was not a major limitation to initial tree growth in provisional silvicultural zones I and III.

Keywords: Forestry, productivity, nutrients, fertiliser prescriptions, soils, Zimbabwe

**GOTORE T, MUREPA R & GAPARE WJ. 2014. Kesan nitrogen, fosforus and kalium terhadap pertumbuhan awal *Pinus patula* serta *Eucalyptus grandis*.** Kesan kepekatan nitrogen (N), fosforus (P) dan kalium (K) sama ada secara tunggal atau kombinasi terhadap pertumbuhan *Pinus patula* dan *Eucalyptus grandis* di Zimbabwe dikaji. Data diperoleh daripada lapan ujian yang dijalankan di lokasi yang mewakili kawasan perhutanan komersial di Zimbabwe dan dicirikan oleh taburan hujan tahunan yang berjulat antara 750 mm hingga 1524 mm. Pertumbuhan *P. patula* terhadap baja N adalah kecil dan pelbagai, malah dalam sesetengah kes menunjukkan pengurangan signifikan dalam pertumbuhan pokok. Kesan P menunjukkan keputusan pelbagai iaitu kesan positif terhadap pertumbuhan *P. patula* di hutan Nyangui Utara dan hutan Mtao tetapi tiada perubahan diperhatikan di Nyangui Selatan dan Charter Utara. Baja K tiada kesan terhadap pertumbuhan *P. patula*. Interaksi antara N dengan P, N dengan K, P dengan K serta N, P dan K tidak signifikan bagi semua *P. patula* di semua tapak. Pertumbuhan *E. grandis* juga tidak dipengaruhi oleh baja N. Pokok menunjukkan gerak balas pertumbuhan negatif terhadap baja P tetapi positif terhadap K di tapak yang mempunyai tanah berpasir. Sebaliknya *E. grandis* menunjukkan gerak balas pertumbuhan positif terhadap kombinasi P dan K di tapak yang sama. Gerak balas pokok terhadap gabungan N × P × K hanya signifikan ($p < 0.05$) bagi pokok di dua daripada empat tapak. Keputusan kajian ini menunjukkan bahawa nutrisi bukanlah faktor pengehad utama bagi pertumbuhan pokok di zon silvikultur sementara I dan III.

## INTRODUCTION

The practice of forest fertilisation has been adopted by forest management organisations worldwide as a biologically sound and cost-effective means to increase tree and stand growth. Fertilisation programmes are well developed for forests in countries around the world, including Australia, New Zealand, South Africa and several forest regions in Europe and North America. Many programmes are directed at ameliorating nutrient deficiencies which adversely affect forest plantation establishment, while others are for the purpose of enhancing growth rates in natural and man-made forests. However, fertilisation has never played a significant role in forest management in Zimbabwe.

 

Zimbabwe lies between latitudes 15° and 23° S and longitudes 25° and 34° E. Most of the country is elevated in the central plateau (high veld), which stretches from the south-west to the north-west at altitudes between 1200 and 1600 m. The country is divided into five provisional silvicultural zones (PSZs) (Barrett & Mullin 1968). Commercial pine and eucalypt forestry is concentrated in PSZs I and III which experience a subtropical to temperate climate due to the modifying effect of altitude with pronounced dry and wet seasons. Predominant species are *Pinus patula* and *Eucalyptus grandis*, covering 88,000 and 17,000 ha respectively (Timber Producers Federation 2010). Minor species include *P. taeda*, *P. elliottii*, *P. kesiya* as well as *E. saligna* and *E. cloeziana* (Forestry Commission 1995).

Site factors play a role in determining species planting sites. For example, *P. patula* thrives better in PSZ I which receives rainfall in all months of the year and experiences relatively low temperatures due to high altitude. *Eucalyptus grandis* is planted predominantly in PSZs II and III because it can be productive in areas with rainfall less than 800 mm per year and on less fertile sites. Soils in PSZs I and III are generally reddish brown sandy loams derived largely from dolerite and granite parent material and are relatively mature due to the combined effects of fairly high temperatures and rainfall (Nyamapfene 1981). Although the soil physical and chemical properties differ both within and between zones, all soils of Zimbabwe are nutritionally poor to moderate, being extremely leached, acidic and low in base cations and phosphorus (P) (Thompson & Purves 1981) as well as nitrogen (N) and sulphur (S) (Grant 1970).

Fertilisers have not been widely used in commercial forestry mainly due to lack of knowledge on the most suitable type and quantity of fertilisers to use for different species and sites. There has been a steady demand for timber products in Zimbabwe, mainly for building construction. Options available to meet the demand include (1) increase funds to buy inputs such as fertilisers in order to improve the productivity of current plantations, (2) increase plantation area through expansion into more marginal areas and (3) a combination of the two. Forestry as a landuse system is now competing with agricultural landuses. Application of fertilisers may maximise returns on investment in new land for forestry.

There has been very little research on forest plantation fertilisation in Zimbabwe. Earlier fertiliser trials for pines and eucalypts were conducted on the dystrophic Kalahari sands at Mtao East (Anonymous 1960). It was reported that application of N, P and potassium (K) fertilisers in combination had better effects on tree growth at Mtao East than any single fertiliser, but P was the most beneficial single element followed closely by calcium, the latter having a marked beneficial effect on survival of trees (van der Lingen 1992). A further trial testing the effects of N, P and K was established at Chibero agricultural station located in PSZ II. Results from that trial were not significant and were difficult to interpret because of the varied nature of the site (van der Lingen 1992). Between 1994 and 1997, several *P. patula* and *E. grandis* fertiliser trials were established at various sites representative of the commercial plantations in Zimbabwe. The specific objectives of the study were to (1) quantify the gain in growth and yield of *P. patula* and *E. grandis* at PSZs I and III following application of various levels of N, P and K, either singly and in combination and (2) determine optimal levels of fertiliser application.

## MATERIALS AND METHODS

### Study site and experimental design

Table 1 provides general information about field trials planted between 1994 and 1997 in Zimbabwe that were examined in this study. The trials covered altitudinal range from 1000 to 1960 m above sea level. Annual rainfall ranged from 753 (PSZ III) to 1524 mm (PSZ I). Within PSZ I, rainfall increased with decreasing altitude. The soils differ across sites and are generally derived from granite and dolerite. Soils in PSZ III are generally sandy to sandy loam, with low water-holding capacity. The trial sites were located in PSZs I and III, representative of the forestry commercial areas of Zimbabwe. *Pinus patula* trials were planted on second rotation sites while *E. grandis* trials, third rotation sites. Two trials were established at each forest in order to cover the altitudinal range of each forest and different soil types. All trials were planted with genetically-improved seeds from the Zimbabwe Forestry Commission Seed Centre in Harare.

**Table 1** Physical characteristics of the *Pinus patula* and *Eucalyptus grandis* fertiliser trial sites

| Trial number | Forest | Provisional silvicultural zone | Species | Date planted (month/ year) | Latitude (S) | Longitude (E) | Altitude (m) | Rainfall (mm year$^{-1}$) | Soil texture | Soil parent material |
|---|---|---|---|---|---|---|---|---|---|---|
| PSV02A | Nyangui North | I | *P. patula* | 12/1994 | 18° 02' | 33° 01' | 1960 | 1200 | Sandy loam | Granite |
| PSV02C | Nyangui South | I | *P. patula* | 12/1994 | 18° 02' | 33° 01' | 1800 | 1200 | Clay loam | Granite |
| PSV04A | Charter North | I | *P. patula* | 01/1997 | 19° 51' | 32° 48' | 1600 | 1400 | Sandy loam | Quartzitic |
| PSV04B | Charter South | I | *P. patula* | 01/1997 | 19° 51' | 32° 48' | 1610 | 1400 | Sandy loam | Quartzitic |
| PSV03A | Mtao East | III | *E. grandis* | 01/1997 | 19° 22' | 30° 38' | 1477 | 753 | Kalahari sandy | Granite |
| PSV03B | Mtao West | III | *E. grandis* | 01/1997 | 19° 22' | 30° 38' | 1477 | 753 | Kalahari sandy loam | Granite |
| PSV03D | Tilbury North | I | *E. grandis* | 01/1997 | 19° 54' | 32° 57' | 1000 | 1524 | Clay loam | Red dolerite |
| PSV03E | Tilbury South | I | *E. grandis* | 01/1997 | 19° 54' | 32° 57' | 1020 | 1524 | Clay loam | Red dolerite |

Details of the number of treatments and fertiliser concentration levels and respective combinations are given in Table 2. Treatments were laid in randomised block design. At all eight sites, tree plots were square with 25 trees planted at a spacing of 3 m × 3 m (*P. patula*) or 2.7 m × 2.7 m (*E. grandis*). The outermost trees of each plot were used as buffers between treatments and measurements were only collected from the nine trees located within the centre of every plot. In all cases, N was applied as urea, P as triple superphosphate and K as potassium sulphate. At planting, fertiliser was applied in a spade slot to a depth of approximately 5 cm (to prevent losses to rain or wind) in a 15-cm radius around each seedling. Regular hand weeding using hoes was carried out to prevent competition from weeds. Details of fertiliser application rates are provided in Table 2. At the two Nyangui Forest sites, four rates of N were applied in a factorial combination with four rates of P for a total of 16 treatment combinations (Table 2); treatments were replicated four times. At the two Charter Forest sites, three rates of N were applied in a factorial combination with three rates of P and K for a total of 27 treatment combinations; treatments were replicated five times. For sites at Mtao and Tilbury Forests, three rates of N were applied in factorial combination with three rates of N, P and K for a total of 27 treatment combinations and treatments were replicated five times.

## Tree growth measurements

Survival at each trial was assessed between ages 1 and 10 years depending on the trial and expressed as percentage of initial total number of trees planted. All height measurements were carried out in meters while diameter at breast height (dbh) was measured in centimeters after the trees were greater than 1.3 m in height. Trees in border rows were not measured.

Two formulae were used to calculate individual tree volume for the two species. *Pinus patula* individual tree volumes ($dm^3$) over bark at the ages of 1, 2, 3 and 7 were estimated using a formula for juvenile pines (Dvorak & Shaw 1992).

$$Vol_i = F \times (Dbh_i)^2 \times Ht_i \qquad (1)$$

where F = 0.35, being the form factor commonly used for tropical pines grown in Southern Africa (Dvorak & Shaw 1992); $Vol_i$ = volume in cubic decimeters ($dm^3$) at age i = 1, 2, 3 or 7 years; $Dbh_i$ = dbh at age 1, 2, 3 or 7 years and $Ht_i$ = height at age 1, 2, 3 or 7 years.

For *E. grandis* individual tree volume was estimated using the formula:

$$V_i = F \text{ x } G \text{ x } Ht_i \qquad (2)$$

where F = 0.51, being the form factor commonly used for tropical eucalypts grown in Southern Africa (Mabvurira & Pukkala 2002); $V_i$ = volume in cubic meters ($m^3$) at age i = 1, 2 or 10 years; G = basal area calculated using the formulae $\pi$ $(dbh_i)/200)^2$; $dbh_i$ = dbh at age 1, 2 or 10 years and $Ht_i$ = height at age 1, 2 or 10 years.

Individual tree volumes in each plot were summed up and divided by the plot area to determine stand volume on a per hectare basis.

**Table 2** Number of fertiliser treatments, replications and fertiliser application rates for *Pinus patula* and *Eucalyptus grandis*

| Trial number | Forest | Species | No. treatments | No. replicates | Nitrogen (g tree$^{-1}$) | Phosphorus (g tree$^{-1}$) | Potassium (g tree$^{-1}$) |
|---|---|---|---|---|---|---|---|
| PSV02A | Nyangui North | *P. patula* | 16 | 4 | 0, 45, 90, 135 | 0, 90, 135, 180 | – |
| PSV02C | Nyangui South | *P. patula* | 16 | 4 | 0, 45, 90, 135 | 0, 90, 135, 180 | – |
| PSV04A | Charter North | *P. patula* | 27 | 5 | 0, 45, 90 | 0, 20, 50 | 0, 20, 50 |
| PSV04B | Charter South | *P. patula* | 27 | 5 | 0, 45, 90 | 0, 20, 50 | 0, 20, 50 |
| PSV03A | Mtao East | *E. grandis* | 27 | 5 | 0, 45, 90 | 0, 20, 50 | 0, 20, 50 |
| PSV03B | Mtao West | *E. grandis* | 27 | 5 | 0, 45, 90 | 0, 20, 50 | 0, 20, 50 |
| PSV03D | Tilbury North | *E. grandis* | 27 | 5 | 0, 45, 90 | 0, 20, 50 | 0, 20, 50 |
| PSV03E | Tilbury South | *E. grandis* | 27 | 5 | 0, 45, 90 | 0, 20, 50 | 0, 20, 50 |

## Statistical analysis

Data from each site were analysed for the effect of each fertiliser treatment, including the interactions, using analysis of variance (ANOVA) procedure in GENSTAT software version 8.1. Analysis of the randomised complete block design used single observed values of dependent variables from each plot (e.g. mean plot height) in an ANOVA which included treatment effects and their interactions (N × P, N × K, P × K and N × P × K) and a random block effect. This analysis assumed that there was no interaction between block and treatment effects (Sokal & Rohlf 1981). Differences between means were further analysed using Fisher's protected least significant difference multiple comparison test at 5% level.

## RESULTS

### *Pinus patula*

ANOVA F-probability values for main effects and interactions of *P. patula* are presented in Tables 3 and 4. The number of live stems per hectare at Nyangui and Charter Forests was not affected by fertiliser application (data not provided) and survival was greater than 95%. Growth responses to fertilisation were small and none of the variables showed significant growth response to N fertiliser alone at Nyangui (Table 3). At Charter North, height, dbh and volume at age 2 showed significant reduction in growth response to N (Table 4). A similar reduction in height occurred at age 2 at Charter South. P fertiliser application increased tree growth ($p < 0.05$) at ages 1, 2, 3 and 7 years after planting at Nyangui North but had no effect at Nyangui South (Table 3). For example, volume at age 7 years at Nyangui North was 24% greater in plots receiving 90 g P tree$^{-1}$ than unfertilised plots. However, there were no significant differences between the different amounts of P fertiliser application, suggesting that P fertiliser application of 90 g tree$^{-1}$ may be optimal for tree growth at Nyangui North. Growth response to P fertiliser application at Charter North was generally insignificant. Dbh and volume at ages two years from planting at Charter South responded positively to P fertiliser application ($p < 0.05$). P concentration at 50 g tree$^{-1}$ resulted in over 25% increase in volume compared with unfertilised plots (Table 4). At Charter North and South, none of the variables showed significant growth response to K fertiliser application (Table 4). The interactions between N and P, N and K, P and K as well as N, P and K were all non-significant at all sites ($p > 0.05$) (Tables 3 and 4).

### *Eucalyptus grandis*

ANOVA F-probability values for main effects and interactions of *E. grandis* are presented in Tables 5 and 6. The number of live stems per hectare at all four sites (Mtao and Tilbury Forests) was 98% and did not appear to be affected by fertiliser application (data not presented). Tree growth responses to N and P fertilisers alone at Mtao and Tilbury Forest Estates are shown in Tables 5 and 6. *Eucalyptus grandis* growth was not significantly influenced by N fertiliser application at Mtao and Tilbury Forest Estates. Significant differences in height and dbh growth at 2 years were detected between plots fertilised with P or K at Mtao East. Growth response to P or K fertiliser application at 20 g tree$^{-1}$ was significantly different compared with the controls (with no fertiliser application) but not significantly different with the application of 50 g tree$^{-1}$. No significant differences in growth response were observed for either fertiliser applications for any traits at age 10 years, except for height of trees receiving P fertiliser. Height, dbh and volume at Mtao Forest were not significantly affected by either N and P or P and K fertiliser interactions (Table 5). Nitrogen and K fertiliser interactions at Mtao Forest Estate were only significant in one trial at Mtao East for height at age 10 years. A combination of N × K at 45 g tree$^{-1}$ and 20 g tree$^{-1}$ respectively resulted in 10% greater in height growth at age 10 years compared with other fertiliser combinations. Dbh at 2 years old also showed a positive response to P and K fertiliser interactions at Mtao East. Tree growth responses to N × P × K factorial combinations were only significant ($p < 0.05$) for height at 2 years at Mtao West (Table 5). Tree growth responses to N × P × K factorial combinations were also significant ($p < 0.05$) for height and dbh at age 1 year at Tilbury North (Table 6). Other significant responses were for dbh at age 2 years at both sites in Tilbury Forest (Table 6).

 

**Table 3** Mean height (HT), diameter at breast height (DBH) and volume (VOL) responses of *Pinus patula* to varying levels of single nitrogen (N) and phosphorus (P) fertiliser applications and their respective F-probability levels at Nyangui Forest

| Fertiliser level ($g\ tree^{-1}$) | | Nyangui North (PSV02A) | | | | | | | Nyangui South (PSV02C) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | HT1 (m) | HT2 (m) | HT3 (m) | HT7 (m) | DBH3 (cm) | DBH7 (cm) | VOL7 ($dm^3\ ha^{-1}$) | HT1 (m) | HT2 (m) | HT3 (m) | HT7 (m) | DBH3 (cm) | DBH7 (cm) | VOL7 ($dm^3\ ha^{-1}$) |
| N | 0 | 0.9 a | 1.5 a | 3.0 a | 10.9 a | 3.5 a | 17.8 a | 141.7 a | 0.9 a | 1.6 a | 3.5 a | 11.3 a | 4.3 a | 16.3 a | 132.1 a |
| | 45 | 0.9 a | 1.6 a | 3.1 a | 11.0 a | 3.7 a | 18.1 a | 150.7 a | 1.1 a | 1.8 a | 3.7 a | 11.5 a | 4.8 a | 16.9 a | 143.0 a |
| | 90 | 1.1 a | 1.6 a | 3.2 a | 11.0 a | 3.7 a | 17.8 a | 146.4 a | 1.1 a | 1.8 a | 3.8 a | 11.8 a | 4.9 a | 17.3 a | 150.6 a |
| | 135 | 0.9 a | 1.5 a | 3.0 a | 10.8 a | 3.5 a | 17.5 a | 141.2 a | 1 a | 1.8 a | 3.8 a | 11.7 a | 4.9 a | 17.2 a | 148.1 a |
| | F-probability | 0.353 | 0.275 | 0.174 | 0.178 | 0.195 | 0.311 | 0.376 | 0.285 | 0.125 | 0.351 | 0.159 | 0.456 | 0.127 | 0.521 |
| P | 0 | 0.8 a | 1.4 a | 2.8 a | 10.6 a | 3.1 a | 17.0 a | 128.6 a | 1.0 a | 1.7 a | 3.6 a | 11.4 a | 4.6 a | 16.6 a | 136.9 a |
| | 90 | 1.0 b | 1.6 b | 3.2 b | 11.2 a | 3.7 b | 18.5 b | 159.7 b | 1.1 a | 1.7 a | 3.7 a | 11.6 a | 4.7 a | 16.9 a | 139.4 a |
| | 135 | 0.9 b | 1.6 b | 3.2 b | 11.0 a | 3.8 b | 17.9 b | 146.7 b | 1.0 a | 1.7 a | 3.6 a | 11.3 a | 4.6 a | 16.8 a | 139.4 a |
| | 180 | 1.0 b | 1.6 b | 3.1 b | 11.0 a | 3.7 b | 17.8 ab | 144.4 ab | 1.1 a | 1.8 a | 3.8 a | 11.9 a | 5.0 a | 17.6 a | 158.1 a |
| | F-probability | < **0.001** | **0.037** | **0.009** | 0.184 | **0.007** | **0.014** | 0.021 | 0.067 | 0.115 | 0.179 | 0.239 | 0.236 | 0.521 | 0.743 |
| N × P | F-probability | 0.138 | 0.286 | 0.143 | 0.168 | 0.083 | 0.274 | 0.188 | 0.167 | 0.189 | 0.246 | 0.197 | 0.359 | 0.741 | 0.652 |

Within columns, means followed by the same letter do not differ significantly ($p < 0.05$), bold values identify significant F-probability values; 1, 2, 3 and 7 correspond to the ages of trees

**Table 4** Mean height (HT), diameter at breast height (DBH) and volume (VOL) responses of *Pinus patula* to varying levels of single nitrogen (N), phosphorus (P) and potassium (K) fertiliser applications and their respective F-probability levels at Charter Forest

| Fertiliser level ($g\ tree^{-1}$) | | Charter North (PSV04A) | | | | | Charter South (PSV04B) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | HT1 (m) | HT2 (m) | DBH1 (cm) | DBH2 (cm) | VOL2 ($dm^3\ ha^{-1}$) | HT1 (m) | HT2 (m) | DBH1 (cm) | DBH2 (cm) | VOL2 ($dm^3\ ha^{-1}$) |
| N | 0 | 1.2 a | 2.7 c | 0.4 a | 3.2 c | 1.5 b | 1.7 a | 3.1 b | 1.02 a | 3.8 a | 2.2 a |
| | 45 | 1.2 a | 2.5 b | 0.4 a | 2.9 b | 1.3 a | 1.7 a | 2.9 ab | 1.04 a | 3.6 a | 2.2 a |
| | 90 | 1.2 a | 2.2 a | 0.4 a | 2.6 a | 1.1 a | 1.7 a | 2.7 a | 1.04 a | 3.4 a | 2.0 a |
| | F-probability | 0.083 | **< 0.001** | 0.273 | **< 0.001** | **< 0.001** | 0.969 | **0.004** | 0.976 | 0.056 | 0.374 |
| P | 0 | 1.1 a | 2.4 a | 0.4 a | 2.8 a | 1.2 a | 1.6 a | 2.9 a | 1.0 a | 3.4 a | 1.9 a |
| | 20 | 1.2 ab | 2.4 a | 0.4 a | 2.9 a | 1.3 a | 1.7 a | 2.8 a | 1.0 a | 3.4 a | 2.0 a |
| | 50 | 1.2 b | 2.5 a | 0.5 a | 3.1 a | 1.4 a | 1.7 a | 3.1 a | 1.1 a | 3.9 b | 2.5 b |
| | F-probability | **0.048** | 0.278 | 0.098 | 0.088 | 0.076 | 0.199 | 0.1 | 0.079 | **0.018** | **0.017** |
| K | 0 | 1.20 a | 2.6 a | 0.4 a | 3.0 a | 1.4 a | 1.6 a | 2.9 a | 1.0 a | 3.5 a | 2.1 a |
| | 20 | 1.15 a | 2.4 a | 0.4 a | 2.8 a | 1.2 a | 1.7 a | 2.9 a | 1.1 a | 3.6 a | 2.3 a |
| | 50 | 1.19 a | 2.5 a | 0.4 a | 2.9 a | 1.3 a | 1.7 a | 2.9 a | 1.0 a | 3.6 a | 2.1 a |
| | F-probability | 0.345 | 0.125 | 0.303 | 0.158 | 0.170 | 0.737 | 0.935 | 0.551 | 0.851 | 0.569 |
| N × P | F-probability | 0.742 | 0.528 | 0.629 | 0.849 | 0.731 | 0.387 | 0.18 | 0.689 | 0.465 | 0.721 |
| N × K | F-probability | 0.181 | 0.995 | 0.130 | 0.861 | 0.423 | 0.253 | 0.862 | 0.323 | 0.796 | 0.643 |
| P × K | F-probability | 0.772 | 0.935 | 0.332 | 0.907 | 0.613 | 0.351 | 0.709 | 0.462 | 0.631 | 0.503 |
| N × P × K | F-probability | 0.274 | 0.331 | 0.116 | 0.206 | 0.106 | 0.559 | 0.561 | 0.707 | 0.479 | 0.598 |

Within columns, means followed by the same letter do not differ significantly ($p < 0.05$), bold values identify significant F-probability values; 1 and 2 correspond to the ages of trees

**Table 5** Mean height (HT), diameter at breast height (DBH) and volume (VOL) responses of *Eucalyptus grandis* to varying levels of single nitrogen (N), phosphorus (P) and potassium (K) fertiliser applications and their respective F-probability levels at Mtao Forest

| Fertiliser level ($g\ tree^{-1}$) | | Mtao East (PSV03A) | | | | | Mtao West (PSV03B) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | HT2 (m) | HT10 (m) | DBH2 (cm) | DBH10 (cm) | VOL10 ($m^3\ ha^{-1}$) | HT2 (m) | HT10 (m) | DBH2 (cm) | DBH10 (cm) | VOL10 ($m^3\ ha^{-1}$) |
| N | 0 | 7.8 a | 16.8 a | 7.4 a | 15.4 a | 268 a | 6.7 a | 17.9 a | 6.9 a | 15.4 a | 283 a |
| | 45 | 7.7 a | 16.9 a | 7.3 a | 15.0 a | 248 a | 6.9 a | 17.8 a | 7.1 a | 15.7 a | 303 a |
| | 90 | 7.6 a | 16.8 a | 7.4 a | 15.5 a | 265 a | 6.3 a | 17 a | 6.6 a | 15.3 a | 313 a |
| | F-probability | 0.786 | 0.946 | 0.92 | 0.612 | 0.571 | 0.054 | 0.370 | 0.153 | 0.721 | 0.919 |
| P | 0 | 8.0 b | 17.7 b | 7.7 b | 15.9 a | 285 a | 6.7 a | 17.8 a | 7.0 a | 15.7 a | 294 a |
| | 20 | 7.4 a | 16.1 a | 7.1 a | 14.8 a | 237 a | 6.4 a | 17.3 a | 6.6 a | 15.5 a | 324 a |
| | 50 | 7.6 ab | 16.8 ab | 7.3 ab | 15.1 a | 258 a | 6.8 a | 17.6 a | 7.0 a | 15.3 a | 280 a |
| | F-probability | **0.016** | **0.004** | **0.013** | 0.134 | 0.065 | 0.297 | 0.763 | 0.272 | 0.806 | 0.839 |
| K | 0 | 7.3 a | 16.9 a | 7.1 a | 15.2 a | 255 a | 6.5 a | 17.2 a | 6.7 a | 15.5 a | 309 a |
| | 20 | 7.9 b | 16.7 a | 7.7 b | 15.4 a | 263 a | 6.8 a | 17.9 a | 7.0 a | 15.9 a | 287 a |
| | 50 | 7.8 b | 17.0 a | 7.3 ab | 15.2 a | 262 a | 6.6 a | 17.6 a | 6.9 a | 15.1 a | 303 a |
| | F-probability | **0.014** | 0.875 | **0.036** | 0.93 | 0.919 | 0.398 | 0.529 | 0.471 | 0.459 | 0.598 |
| N × P | F-probability | 0.552 | 0.847 | 0.298 | 0.211 | 0.514 | 0.375 | 0.614 | 0.626 | 0.565 | 0.831 |
| N × K | F-probability | 0.311 | **0.036** | 0.434 | 0.238 | 0.156 | 0.385 | 0.803 | 0.189 | 0.913 | 0.841 |
| P × K | F-probability | 0.325 | 0.616 | **0.047** | 0.668 | 0.959 | 0.818 | 0.833 | 0.533 | 0.759 | 0.759 |
| N × P × K | F-probability | 0.557 | 0.314 | 0.451 | 0.685 | 0.758 | **0.048** | 0.209 | 0.128 | 0.122 | 0.139 |

Within columns, means followed by the same letter do not differ significantly ($p < 0.05$), bold values identify significant F-probability values; 2 and 10 correspond to the ages of trees

**Table 6** Mean height (HT), diameter at breast height (DBH) and volume (VOL) responses of *Eucalyptus grandis* to varying levels of single nitrogen (N), phosphorus (P) and potassium (K) fertiliser applications and their respective F-probability levels at Tilbury Forest

| Fertiliser level ($g\ tree^{-1}$) | | Tilbury North (PSV03D) | | | | | Tilbury South (PSV03E) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | HT1 (m) | HT2 (m) | DBH1 (cm) | DBH2 (cm) | VOL2 ($m^3\ ha^{-1}$) | HT1 (m) | HT2 (m) | DBH1 (cm) | DBH2 (cm) | VOL2 ($m^3\ ha^{-1}$) |
| N | 0 | 5.6 a | 11.2 a | 5.1 a | 9.9 a | 84 a | 5.9 a | 11.9 a | 5.0 a | 8.0 a | 52 a |
| | 45 | 5.6 a | 11.3 a | 4.9 a | 10.0 a | 83 a | 5.9 a | 11.7 a | 5.0 a | 7.9 a | 49 a |
| | 90 | 5.4 a | 10.9 a | 4.7 a | 9.6 a | 79 a | 5.9 a | 11.6 a | 4.9 a | 7.9 a | 50 a |
| | F-probability | 0.828 | 0.873 | 0.501 | 0.721 | 0.594 | 0.973 | 0.620 | 0.853 | 0.803 | 0.499 |
| P | 0 | 5.4 a | 11.1 a | 4.7 a | 9.7 a | 78 a | 5.5 a | 11.2 a | 4.5 a | 7.4 a | 44 a |
| | 20 | 5.4 a | 11 a | 4.8 a | 9.7 a | 83 a | 6.1 b | 11.8 b | 5.1 b | 8.1 b | 53 b |
| | 50 | 5.8 a | 11.3 a | 5.2 a | 10.0 a | 85 a | 6.3 b | 12.1 b | 5.3 b | 8.3 b | 55 b |
| | F-probability | 0.089 | 0.661 | 0.139 | 0.523 | 0.089 | **< 0.001** | **0.005** | **< 0.001** | **0.004** | **< 0.001** |
| K | 0 | 5.4 a | 10.9 a | 4.9 a | 9.7 a | 81 a | 5.9 a | 11.7 a | 4.9 a | 8.0 a | 51 a |
| | 20 | 5.5 a | 11.1 a | 4.8 a | 9.7 a | 80 a | 6.0 a | 11.9 a | 5.1 a | 8.0 a | 52 a |
| | 50 | 5.7 a | 11.5 a | 5.0 a | 10.2 a | 86 a | 5.9 a | 11.5 a | 5.0 a | 7.8 a | 48 a |
| | F-probability | 0.617 | 0.221 | 0.638 | 0.25 | 0.314 | 0.922 | 0.353 | 0.815 | 0.477 | 0.428 |
| N × P | F-probability | 0.218 | 0.449 | 0.245 | 0.528 | 0.489 | 0.966 | 0.553 | 0.682 | 0.671 | 0.890 |
| N × K | F-probability | 0.515 | 0.164 | 0.816 | 0.401 | 0.812 | 0.511 | 0.461 | 0.462 | 0.755 | 0.717 |
| P × K | F-probability | 0.809 | 0.923 | 0.860 | 0.849 | 0.959 | 0.591 | 0.549 | 0.75 | 0.783 | 0.842 |
| N × P × K | F-probability | **0.016** | 0.099 | **0.042** | **0.044** | 0.219 | 0.051 | 0.057 | 0.065 | **0.048** | 0.234 |

Within columns, means followed by the same letter do not differ significantly ($p < 0.05$), bold values identify significant F-probability values; 1 and 2 correspond to the ages of trees

## DISCUSSION

Generally, small or no responses were obtained in applied fertilisers. For example, a single application of N did not have significant effect on *P. patula* grown at Nyangui Forest or *E. grandis* grown at Tilbury and Mtao Forests. Surprisingly, N application had negative effect on tree growth at Charter Forest, resulting in reduced growth compared with unfertilised trees. Our results suggested that N may not be a limiting factor to tree growth in the first few years after planting and may be readily available in the soil. Tropical forests are generally known to sustain levels of N cycling, N loses and N:P ratios in leaves and litter (Vitousek 1984, 2004). Unfortunately, no initial detailed soil and foliar nutrient analyses were carried out to confirm nutrient status of the soils in the study area. Warmer and wetter tropical climates such as those experienced in PSZs I and III enhance N mineralisation and plant N-use efficiency (Schlesinger & Andrews 2000). Other factors such as amount of water available to trees also determine tree growth. One of the problems of applying fertilisers to young plants on sandy soils such as at Mtao Forest is that much of the fertiliser cannot be immediately utilised by the plants and is inevitably leached from the site. It should be noted that it is not the amount of fertiliser applied to the soil that matters, but the amount absorbed (uptake) by the tree which determines growth.

Phosphorus had positive effect on *P. patula* growth at Nyangui and Charter Forests. Soils in these forests are mature (Thompson & Purves 1981) and may experience P deficiencies given that they are now on second rotation forests. Tropical soils become depleted in P with age (LeBauer & Treseder 2008). On the basis of tree growth, we recommend that 90 g P $tree^{-1}$ be applied during planting of *P. patula* stands at Nyangui Forest and 50 g P $tree^{-1}$ at Charter Forests. However, more work should be conducted to determine if a concentration of less than 90 g P $tree^{-1}$ will produce similar or better growth. From this study, it appeared that *E. grandis* grown at Mtao East had negative response to the low rate of P application. In fact there were significant differences in growth between fertilised and unfertilised plants (Table 5). It is not clear what may have caused such a difference. Other studies have shown that if P is applied too close to the roots, it may burn some of the roots, leading to poor uptake of nutrients (Weinbaum et al. 1995). Potassium application had significant effect on *E. grandis* only at Mtao East but not on *P. patula*. For *E. grandis*, we recommend an application of 20 tree$^{-1}$ each of P and K at planting time. However, since 20 g tree$^{-1}$ of P or K was the lowest rate applied, and similar to P application for *P. patula*, a lower rate should be tested.

With little research on forest fertiliser use in Zimbabwe, there is scarce information for comparison. Fertiliser trials for both pines and eucalypts were only conducted on the dystrophic Kalahari sands at Mtao Forest (Anonymous 1960). Results from those studies suggested that a combination of several fertilisers had better effects on tree growth than any single fertiliser (van der Lingen 1992). Likewise, in the current study, 10-year-old *E. grandis* height growth at Mtao East responded positively (10% increase) to N × K fertiliser combination compared with unfertilised trees. *Eucalyptus grandis* height and dbh growth at 1 year also responded positively to N × P × K fertiliser combinations at Tilbury North and Tilbury South. Plant responses to fertiliser combinations often exceed response to N alone (Harpole et al. 2007). However, none of the fertiliser combinations provided positive growth response for *P. patula* growth at Nyangui and Charter Forests. It is also possible that lack of *P. patula* response to fertiliser combination is due to positive effects of tree-breeding programme, e.g. use of genetically improved *P. patula* material.

Factors that are known to limit seedling survival and early growth include rainfall, weed control, inherent soil fertility and plant genetics. It appeared that none of these factors limited plant growth in this study. Both *P. patula* and *E. grandis* were well matched to the site conditions for optimal growth in Zimbabwe. For example, *P. patula* was grown in PSZ I which received over 1000 mm rainfall per annum while *Eucalyptus grandis,* in PSZs I and III which received above 700 mm rainfall per annum. There was no possible competition for nutrients from weeds as weeding was carried during the first year of planting at all sites.

Often it is difficult to compare tree responses to fertiliser application across different studies in other countries because soil and climatic environments may be different. We can only make some broad generalisations with regards to *P. patula* and *E. grandis.* Our results corresponded with findings by Crous et al. (2008) who reported that in order to correct P deficiencies that had developed in successive rotations of *P. patula* grown in Swaziland, an application of 20 kg ha$^{-1}$of P (~ 20 g tree$^{-1}$) as spot application at planting was recommended. However, *P. patula* stands in South Africa are grown in gabbro-derived soils compared with sandy loams from dolerite and granite parent material in Zimbabwe. The only similarity is that both studies were conducted on second rotation sites.

One advantage of P application at planting is that it is likely to benefit trees from planting time through to rotation age. For example, Pritchett and Comerford (1982) reported significant response in height, diameter, basal area and volume growth of *Pinus taeda* to P fertilisation at time of planting that lasted 17 to 20 years in south-eastern USA. Soil properties such as available phosphate content, capacity to retain applied phosphate in the root zone and soil moisture conditions often affect the magnitude and longevity of response to P fertilisers (Crous et al. 2008). Soils at Nyangui and Charter Forests readily adsorb P (Thompson & Purves 1981). However, addition of P at planting increased growth and, therefore, increased the availability of P in the short term. This would result in increased P-uptake which promoted uptake of other nutrients through rapid development of roots (Bennett et al. 1996). Studies in Australia have shown that eucalypt response to P is largest when nutrient is made available to plants during the earliest growth phases (Bennett et al. 1996). Evidently, requirements vary widely amongst different sites because of differences in soil and variations in seasonal climatic conditions.

## CONCLUSIONS AND FUTURE PERSPECTIVES

This study is the first comprehensive study on forest fertilisation on second- and third-rotation sites in Zimbabwe. Our results suggested that nutrition was not currently a major limitation to tree growth in PSZs I and III. It is also possible that second- and third-rotation problems have been masked by positive effects of tree-breeding programme, e.g. use of genetically improved material and improvements in silvicultural techniques such as weed control during first year of planting. Second-rotation problems, as diagnosed in parts of South Africa and Australia, have been attributed to adverse changes in both chemical and physical properties of soil following one or more rotations of forest stands. These problems did not exist in PSZs I and III or they have not been fully recognised. However, these problems may surface as forestry expands into more marginal areas (PSZs IV to VI). The long-term effect of fertiliser on pine and eucalypt timber yields on these and similar sites remain to be determined.

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