
Ray E. Worley, S. A. Harmon, and R. L. Carter²

University of Georgia
Coastal Plain Experiment Station, Tifton

Abstract. Concentration of pecan roots in the 15-45 cm layer of soil and lower soil pH, P, and K in the 15-30 cm layer than in adjacent layers indicate that pecan trees are feeding primarily in this zone. Fertilization with N-containing complete fertilizers or NH₄NO₃ reduced soil pH gradually, and continued annual application gradually affected deeper soil layers. Phosphorus and K applications affected soil pH very little.

Continued annual applications of P gradually built up residual soil P (measured one year later) to high levels at all layers sampled for old trees over a 10-year period. When P applications were based on topsoil P levels, subsoil P level was not affected over a 5-year period.

Applications of K usually increased residual soil K, but rate effects were slow to appear in old trees and were often erratic. Rates of K were readily reflected in residual soil K levels at depths to 70 cm when rates were based on topsoil K level.

Conflicting reports on the response of pecan to fertilization suggest that the soil concn of fertilizer nutrients determines to a great extent the response that a tree will give to added fertilizer. Since pecan tree roots occupy a tremendous volume of soil (8), more information is needed concerning the effect that different fertilization practices have on soil pH, P, and K throughout the soil profile. Since leaf analysis and soil analysis are seldom correlated (10), the trees might be feeding in an area below that normally sampled. A comparison of P and K concn at different depths in the soil profile should give an indication of the movement of these nutrients in soils under pecan trees.

Materials and Methods

Three groves were used. 1) The Kennedy Grove of 'Stuart' trees approximately 40 years old was spaced 21 x 21 m in Tifton loamy sand. Fertilizer treatments, which began in 1962, were 0, 448 kg/ha (400 lb/acre) biennially and 448, 896, and 1344 kg/ha (400, 800, and 1200 lb/acre) annually of commercially mixed 10-4.4-8.3 (N-P-K). Nine single tree replications were used in a completely randomized design. The trees were fertilized prior to the initiation of treatments, and their appearance was good. Dolomite at 2.2 metric T/ha was applied to all plots in 1963. Twelve 2.5 x 15 cm soil plugs were taken on July 31, 1962, and thereafter, at the end of each growing season in January or February just prior to fertilizer application. For example, data for the 1963 season were from soil sampled in January 1964. In 1968, 1970, and 1971 soil was sampled at 15-cm intervals to 75 cm at 4 locations under each tree.
tree using a motorized 2.5 cm diam soil auger. Samples were then sent to the state soil testing laboratory where routine soil tests were run. Soil pH was determined from a 1:1 soil:water extract. Phosphorus and K were extracted with 0.05 N HCl - 0.025 N H₂SO₄ solution for 5 min, and K was determined colorimetrically using an ammonium molybdate-stannous chloride reagent. Potassium was determined by flame photometry. The upper limits of the soil test for P were 177 (1961), 202 (1962-1964), 212 (1965-1970), and 400 kg/ha (1971). Treatment, soil depth, and year differences were compared using a computerized least squares analysis of variance program with Duncan's multiple range test (UG 3090CT).

2) The Voigt 'Stuart' Grove consisted of 21-year-old trees spaced 24 x 24 m growing in a Leefield sand near Waycross, Georgia. Fertilizer treatments (expressed as g N-P-K/cm circumference) were: 1) 18-8-15, 2) 36-16-30, 3) 45-16-59, 4) 89-16-59 applied each spring; (for lb/inch, divide by 18). Nutrient sources were from commercially mixed 10-4.4-8.3, 0-4.4-16.6, and NH₄NO₃. Treatments 5 and 6 were identical to 1 and 4, respectively, until 1964 when the P and K applications were discontinued. Beginning in 1963, treatment of no lime, dolomite, and calcite were superimposed on each fertilizer treatment. Dolomite or calcite was applied in winter or early spring of each year at the rate of 2.2 metric T/ha (1 T/acre) for each tree when the soil pH dropped below 6.0 for dolomite and calcite treatments. The experimental design was a split plot with fertilizer treatments replicated twice in whole plots of 12 trees each and limestone treatments replicated 12 times in subplots of 4 trees each. The soil sample each year consisted of a composite of 12 plugs from each tree in the 0-15 cm and 15-30 cm layers. In addition, after the 1961, 1968, and 1970 seasons, a composite of 4 plugs was taken from each tree at 15-cm intervals to 75 cm, and analysis was similar to the Kennedy Grove. Each tree was an experimental unit.

3) The Voigt 'Desirable' Grove of 4-year-old trees was spaced 18 x 18 m on Albany, Leefield, and Plumer sands near Waycross, Georgia, in an area approximately 1/4 mile from the 'Stuart' Grove. These were poorly drained soils, but trees were planted on ridges approx 2.3 m higher than the valleys that were used for drainage between the trees. Nitrogen and P rates were 0, 56, and 112 kg/ha (0, 50, 100 lb/acre); K rates were 0, 112, and 224 kg/ha (0, 100, 200 lb/acre). The N treatments were all applied annually; but for P and K, the 0-15 cm soil test level was deducted from the respective treatment level, and the difference was the amount applied each spring. Fertilizer sources were ammonium nitrate (33.5% N), superphosphate (8.8% P), and muriate of potash (50% K). Soil was sampled at the 0-15 and 15-30 cm layer annually similar to the 'Stuart' Grove. Deeper samples were collected at 15 cm intervals to 75 cm in 1967 and 1970. Chemical and statistical analysis was the same as that for the Kennedy Grove. The main effect treatments were in a complete factorial arrangement with 4 replications in a randomized complete block design; thus main effects were replicated 36 times.

**Results**

**Soil pH.** Data for topsoil pH is presented as an average of the first 5 years and last 5 years of the study for the 2 older groves. In the Kennedy Grove increasing rates of complete fertilizer

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**Table 1. Soil pH under pecan trees as affected by fertilizer, lime, depth, and time.**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate of 10-4.4-8.3</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>(kg/ha)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0-15 cm</td>
<td>15-30 cm</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1962-66</td>
</tr>
</tbody>
</table>

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**Voigt 'Stuart' Grove - Waycross, Ga.**

<table>
<thead>
<tr>
<th>Depth</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-15 cm</td>
<td>15-30 cm</td>
</tr>
</tbody>
</table>

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**Limestone treatment**

<table>
<thead>
<tr>
<th>No.</th>
<th>0</th>
<th>15-30 cm</th>
<th>30-45 cm</th>
<th>45-60 cm</th>
<th>60-75 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No lime</td>
<td>5.72a</td>
<td>5.65a</td>
<td>5.5a</td>
<td>5.0a</td>
</tr>
<tr>
<td>2</td>
<td>Dolomite</td>
<td>5.98b</td>
<td>5.63b</td>
<td>5.24b</td>
<td>5.60b</td>
</tr>
<tr>
<td>3</td>
<td>Calcite</td>
<td>6.07b</td>
<td>5.71c</td>
<td>5.5c</td>
<td>5.25b</td>
</tr>
</tbody>
</table>

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**Voigt 'Desirable' Grove - Waycross, Ga.**

<table>
<thead>
<tr>
<th>Depth</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-15 cm</td>
<td>15-30 cm</td>
</tr>
</tbody>
</table>

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**Notes:**

- Treatments 5 and 6 were identical to 1 and 4, respectively, until 1964.
- Beginning in 1963, 2.2 metric T/ha lime was added annually when soil test pH was <6.0.
- Duncan's multiple range test, within columns, at 5% level.
decreased soil pH, but the differences between the 0, 448 biennially, and 448 kg/ha annually treatments were not significant at depths below 15 cm. The lowering of soil pH by high rates of fertilization could be detected to the 60-75 cm depth in both 1968 and 1971 (Table 1). In the Voigt 'Stuart' Grove a treatment-by-year interaction was apparent. In 1961, after the first year of fertilizer treatments, treatment differences were not significant at any depth. In the top 15 cm, differences were not consistent until 1966 when increasing rates of N lowered pH. The 1967-70 average showed typical pH values after 1966 (Table 1). By 1968 pH was lowered significantly to the 30 cm level by the high N rates, but the change was not significant at the 30-60 cm level. By 1970 significant lowering of pH at high N levels was apparent at all depths to 75 cm (Table 1). The addition of P and K at the same level of N (Treatments 1 vs. 5 and 4 vs. 6) seldom caused significant changes in pH. The soil became more acid as depth increased in 1961, but by 1968 and 1970 the pH of the 15-30 cm layer was lower than that in the 15 cm layer immediately above and below (Fig. 1).

Lime applications, as expected, increased or prevented a large decrease in soil pH. By the end of 1963 the unlimed plots were more acid in the 0-15 cm level than calcite-limed plots, and by 1964 both calcite and dolomite-limed plots were significantly less acid than unlimed plots. Unlimed plots reached a low of 5.3 in the topsoil, but there was year-to-year fluctuation. Annual adjustments in topsoil pH by lime kept limed plots near 6.0. The pH was increased for limed over unlimed plots at all depths studied by 1970, and the pH was higher on calcite-limed than dolomite-limed plots.

In the young 'Desirable' Grove lowering of pH by increasing application levels of N was readily apparent and affected the soil to greater depths with time (Table 1). By the end of 1967, the second year of the study, soil pH was not lowered significantly below the 30 cm level; but by 1971 increasing N had lowered pH in the 45 cm level but did not lower it significantly at greater depths. The lowering of pH in the 15-30 cm layer below that of adjacent layers was not evident by 1967, but by 1970 it was apparent. Phosphorus treatments had no significant effect on soil pH in any layer in any year. Increasing K rates increased soil pH significantly only in 1970 and only in the topsoil. Residual soil P. Residual soil P was high (&gt; 67 kg/ha) under all trees and at all depths in the Kennedy 'Stuart' Grove (Table 2) even when no P was applied during the test period. Soil P was so high in the topsoil that it often exceeded the range for P used by the soil testing laboratory which analyzed the samples. For this reason, few treatment comparisons were significantly different for the 0-15 cm level. Changes in the max levels of P preclude comparisons across years. An extension of the max range of P in 1971 revealed extremely high P levels for all plots. Increasing the P rate increased soil P in the 45-60 cm and 60-75 cm levels. The soil P level was lower in the 15-30 cm level in 1970 and 1971 than in adjacent layers (Table 2 shows 1971 data).

In the Voigt 'Stuart' Grove, soil P was extremely low at depths below 30 cm at the end of 1961; however, in the topsoil, residual soil P was high (&gt; 67 kg/ha) according to Georgia soil test standards in all years even when P applications had been discontinued for 7 years. Fertilizer treatment differences were not significant in any layer until 1965 when plots receiving no P applications contained less P in the 1-15 cm layer than the other plots. By 1970 each increment of soil P application increased residual soil P above that of the previous increment in this layer. The combined 4-year averages (Table 2) illustrate these trends. By 1968, P applications increased soil P through the 45-60 cm level, and by 1970, plots receiving the highest P rate contained up to 4 times as much residual P in the 60-75 cm level as those plots where P was omitted. Lowering of the soil P level in the 15-30 cm layer below that of the adjacent layers was evident in 1970 only for Treatments 1 and 2. Limestone treatments had little effect on soil P except to increase topsoil P slightly for the 1967-70 average.

In the Voigt 'Desirable' Grove no P was applied unless the soil P level in the topsoil was below the treatment level. The initial soil P level was so high that only a few plots required applications for the 56 kg/ha treatment level. For this reason, residual soil P was never significantly different between the 0 and 56 kg/ha treatments (Table 2). By the third year (1968), residual topsoil P in plots receiving the P12 treatment level was significantly greater than that in the other plots (not shown), and this trend was well apparent in 1970 (Table 2). Differences due to P treatments were not significant in deeper soil layers. Soil P was medium (35-67 kg/ha) or higher in all layers in all years for all treatments. In 1967, after the second year of treatment, soil P appeared to be higher in the 15-30 cm layer than in adjacent layers, but by 1970 soil P was less in this layer than in adjacent layers. The N and K treatments affected soil P very little. In 1970 the highest K level reduced soil P from 62 to 52 kg/ha in the 0-15 cm level and from 52 to 35 kg/ha in the 15-30 cm level.

Residual soil K. Residual soil K in the Kennedy Grove was medium (67-168 kg/ha) or higher for all treatments and at all depths. Topsoil K levels responded erratically to fertilizer treatments. In 1966-1969 residual soil K increased with increasing fertilizer treatments, but differences were not significant in 1970 and 1971 (see examples, Table 3). Consistent trends were more apparent in the deeper layers. In 1968 residual soil K was reduced with depth through the first 3 layers, but by
1971 soil K in the 15-30 cm layer became lower than that for all other layers. Data for 1970 (not shown) was similar to that for 1971.

In the Voigt 'Stuart' Grove soil K in the 0-15 cm level was medium or higher for all treatments in all years except for Treatment 5 in 1966. When K was applied annually, soil K was in the medium range or higher after 1965 at all profile depths except for the 45-60 cm layer in 1970; but when K application was omitted (after 1963), soil K became extremely low in the 15-30 cm layer to a greater extent being exhausted from the 15-30 cm layer to a greater extent being exhausted from the 15-30, 45-60, and 60-75 cm layers by 1970 (Table 3). Fertilizer treatments did not affect the soil K concn at any depth in 1961, but by 1964 differences began to segregate. In most years, soil K became lower with depth at least through the first 4 layers, but by 1970 the 15-30 cm layer was depleted below that of the other layers.

The soil K level was lower in the 15-30 cm layer than in adjacent soil K. Increasing the level of K treatment increased the residual K in each layer of the soil each year that it was analyzed (Table 3). The 1967 soil samples indicated that soil K became lower with depth at least through the first 4 layers, but by 1970 the 15-30 cm layer was depleted below that of the other layers.

### Root distribution.
Since it appeared that nutrients were being exhausted from the 15-30 cm layer to a greater extent than other layers, a 1.5 x 6 m trench was dug under a tree in the Kennedy Grove to determine the area of concn of feeder roots. This tree was typical of those in the Kennedy and Voigt 'Stuart' Groves. Most of these small roots were found in the 15-45 cm layer and relatively few were found in the topsoil (Table 4).

### Correlations with leaf P and K.
Correlation coefficients for both leaf P and K with soil P and K, respectively, were usually significant and positive for each soil layer, except the 15-30 cm layer for K in 1969 and the 60-75 cm layer for P in 1970, for 'Desirable' Grove samples (Table 5). Leaf P was best correlated with soil P in the 30-45 and 45-60 cm layers in 1970, and leaf K was best correlated with soil K in the 15-30 and 30-45 cm layers in 1970. In the Voigt 'Stuart' Grove, correlations varied from significantly negative to significantly positive depending on years, but no negative r's were found after 1965 (Table 5). In the Kennedy 'Stuart' Grove in 1971, these correlations were not significant for any layer. Even when the r's were significantly positive, only a small amount of the variation in leaf P or K
could be accounted for by soil levels of these nutrients. Yield was seldom consistently correlated significantly with soil test levels in any study.

**Discussion**

Repeated applications of fertilizer caused a reduction of soil pH apparently due to the N component in the fertilizer as reported by Lewis and Fowler (7). Nitrification of the NH₄⁺ ions releases H⁺, and crop removal and leaching of the NO₃⁻ ion with its basic cation further reduces soil pH (9). This process is a slow process, which progresses to deeper layers with time and was apparent in the Kennedy Grove to 75 cm by the 7th year on these sandy soils. Calcite, which was ground finer than dolomite, was slightly more effective in reducing soil acidity than dolomite. There was no evidence that high pH caused by overliming often brings on Zn deficiency (6). Since the groves in the study were apparently well fertilized prior to the initiation of the treatments, the initial P level was high in the topsoil in all groves, and high levels of soil P in the topsoil of trees receiving no P application shows that leaching of P is not great; however, gradual increases in the soil P level at greater depths with increasing fertilizer application indicates that applied P moves into the subsoil of these sandy soils slowly. Low application rates as for the Voigt 'Desirable' Grove caused little movement beyond the topsoil after 5 years. Penetration of P in our soils under large trees was apparently faster than that reported for Yoholo loam (2). The lack of yield and growth response to P applications indicates that P was not deficient and supports the results of Alben and Hammar (1), who obtained yield responses to applied P only when soil P was extremely low.

High levels of soil K under old trees caused treatment

**Table 3. Residual soil K (kg/ha) under pecan trees as affected by fertilizer, lime, depth, and time.**

<table>
<thead>
<tr>
<th>Treatment No.</th>
<th>N-P-K</th>
<th>Rate of 10-4.4-8.3 (kg/ha)</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>179aW 148aW 090aW 125aW 130aW 123aW 115aW 111aW</td>
<td>1968</td>
</tr>
<tr>
<td>2</td>
<td>448 biennially</td>
<td>194b 160a 153b 102a 127a 138b 129a 139a 128a 122ab</td>
<td>1969</td>
</tr>
<tr>
<td>3</td>
<td>448 annually</td>
<td>193b 160a 168b 103a 140ab 175c 139b 146ab 134a 137c</td>
<td>1970</td>
</tr>
<tr>
<td>4</td>
<td>896 annually</td>
<td>203ab 161a 160ab 124b 146ab 159abc 144ab 143ab 140a 132ab</td>
<td>1971</td>
</tr>
<tr>
<td>5</td>
<td>1344 annually</td>
<td>211b 156a 183b 113ab 165b 169bc 166b 170b 164b 144b</td>
<td>1972</td>
</tr>
</tbody>
</table>

**Table 4. Fresh roots removed from a 1.5 x 6 m area underneath a large pecan tree by root size and depth - Kennedy 'Stuart' Grove, Tifton, Ga.**

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Root size (cm diam)</th>
<th>Fresh wt of roots (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5-2.5</td>
<td>10-4.4-8.3</td>
<td>10-4.4-8.3</td>
</tr>
<tr>
<td>2.5-5</td>
<td>10-4.4-8.3</td>
<td>10-4.4-8.3</td>
</tr>
<tr>
<td>5-7.5</td>
<td>10-4.4-8.3</td>
<td>10-4.4-8.3</td>
</tr>
</tbody>
</table>

Table 5. Correlation coefficients (r’s) for pecan leaf P and K with soil P and K at various depths.

<table>
<thead>
<tr>
<th>Variables correlated and year</th>
<th>Soil depth (cm)</th>
<th>0-15</th>
<th>15-30</th>
<th>30-45</th>
<th>45-60</th>
<th>60-75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaf P with soil P - 1967</td>
<td></td>
<td>.37</td>
<td>.28</td>
<td>.37</td>
<td>.22</td>
<td>.25</td>
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<tr>
<td>Voigt 'Desirable' Grove</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Correlation coefficients²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leaf K with soil K - 1967</td>
<td></td>
<td>.62</td>
<td>.71</td>
<td>.55</td>
<td>.53</td>
<td>.55</td>
</tr>
<tr>
<td>Voigt 'Stuart' Grove</td>
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<tr>
<td>Correlation coefficients²</td>
<td></td>
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<tr>
<td>Leaf P with soil P - 1962</td>
<td></td>
<td>-.05</td>
<td>.05</td>
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<td>Leaf K with soil K - 1962</td>
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<td>Correlation coefficients²</td>
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</tbody>
</table>

²Least significant r, 5% level = .20 for the 'Desirable' Grove and .33 for the 'Stuart' Grove.

Differences in residual soil K were readily apparent in the 'Desirable' Grove because treatments were based on the topsoil K. These sandy soils also apparently did not retain large amounts of K. Also, the soils under these young trees did not have heavy rates of fertilizer applied prior to treatment initiation as did the large trees.

High levels of P and K in the topsoils of plots that have received low or no application of these elements for several years, high amounts of feeder roots in the 15-45 cm area, depletion of P and K from the 15-30 cm layer after several years and lowering of pH in the 15-30 cm area suggests that there is recycling of nutrients in the soils. Apparently the roots mine the subsoil, particularly the 15-20 cm layer, and redeposit the nutrients on the surface through leaching of nutrients from the leaves and through decomposition of leaves and shucks.

Literature Cited