POTASSIUM CYCLING IN A FERTILIZED SLASH PINE (*Pinus elliottii* var. *elliottii* Engelm.) ECOSYSTEM IN FLORIDA

By

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Major Department: Soil Science

The effect of applied K on the growth and K cycle in a 13-year-old slash pine plantation was examined. Potassium chloride at rates of 0, 48, 96, and 192 kg K/ha with a basal application of diammonium phosphate (DAP) at 224 kg/ha was applied to 0.04 ha plots. An additional treatment receiving no fertilizer was established as a check plot. There were three replications of the five treatments. Annual nutrient input from rainfall to the system under study was 1.6 kg K/ha, 7.2 kg Na/ha, 4.6 kg Ca/ha, 1.3 kg Mg/ha, and 0.2 kg P/ha.

While no growth response to K treatments was detected, DAP increased the first flush needle lengths in the 1973 growing season by 10%.

Tree tissue, litterfall, throughfall, stemfall, soil, soil water, ground water, and ground cover nutrient concentrations were examined throughout the 17-month experimental period. Final nutrient contents were determined by total tree harvest. Root biomass and nutrient contents were estimated using published data for slash pine growing on similar soils.

Differences in K concentration in current and new growth were significant within 30 days following treatment, with the high K concentrations corresponding to the high K treatment rate. Sodium, Ca, Mg, and P concentrations were not affected by K or DAP application.

Losses of nutrients from the tree crowns by leaching and litterfall were small and amounted to only 4 to 8 kg K/ha/yr. Calcium losses approached 25 kg/ha/yr, while Mg and P losses were lower than K. Throughfall P contents were smaller than rainfall and indicated direct foliar uptake of P from the rainfall.

Up to 82% of the K in the oldest needles on the tree appeared to be translocated from the needles to other parts of the tree before abscission. Litterfall did not lose additional K as it was incorporated into the forest floor.

Total tree biomass amounted to 100 t/ha at the conclusion of the study. Volume increment determinations provided an estimate of 10 t/ha/yr net increase in tree biomass for the duration of the experiment. Ground cover provided little total biomass, but contained 29% as much K as the total trees.

Recovery of applied K ranged from 68% of the lowest K application rate to 29% of the highest application rate.

INTRODUCTION

Mineral cycling plays an important role in the continued maintenance of nutrition in forest ecosystems, as well as contributing to the processes of forest soil development. Under conditions of nutritional stress, whether through natural deficiencies in the system, by continued depletion by harvest, or by other means, the mineral cycle must adjust to low nutrient levels. Premature loss of needles, visual foliage changes, and suppressed growth are visual signs of adjustments to nutrient deficiencies in Pinus species, particularly with phosphorus (P) (Pritchett and Llewellyn, 1966; Will, 1968), but also common symptoms in potassium (K) deficient areas (Heiberg and White, 1951; Raupach and Hall, 1972). In less severe cases of nutrient deficiencies, growth response to added K is taken as presumptive evidence of deficiency (Pritchett and Smith, 1969; Hall and Parnell, 1961).

Growth responses in slash pine are well documented for nitrogen (N) and P in marine deposited sands of the southeastern Coastal Plain of the United States (Pritchett and Llewellyn, 1966) and current use of N and P fertilizers is increasing to meet the increasing demand for pulp and lumber (Pritchett and Gray, 1974). Potassium deficiences are less evident in this area, although K levels in foliage and soil are sometimes extremely low. It is not yet known how increased tree growth resulting from P and N fertilization will affect the K nutrition of forests of this area, but in a series of experiments conducted by the Cooperative Research in Forest Fertilization (CRIFF) program little or no growth

response was obtained when additions of 88 kg/ha of K were made to N and P fertilizer treatments.

Large areas of the Coastal Plain are currently in forests, with over half of the approximately 80 million forested hectares in the 13 southeastern states supporting pine forests. In Florida alone, it is estimated over 4 million ha of slash pine forest on "flatwood" soils will respond to application of N and P fertilizer (Pritchett and Gray, 1974). These soils are characterized by coarse textures, acid reaction, inherently low levels of fertility, and somewhat poor drainage (drainage class 2) (Pritchett and Smith, 1974). Because of the low total K contents and absence of K-bearing primary minerals in these soils (Zelazny and Carlisle, 1971), the ability to supply K to forest trees over long periods is of interest, particularly in light of responses to K found in agronomic crops in Florida. In addition, shortened rotation times and whole tree harvest methods may result in a rapid and serious deplation of nutrients on forest sites of naturally low fertility (Malkonen, 1973).

The objectives of this study were to:

1. Determine the response of slash pine to applied K on a flatwoods soil.
2. Examine the K cycle in reference to foliage, litterfall, throughfall, stemflow, rainfall, soil water, ground water, and soil nutrient concentrations as affected by K fertilization.
3. Model the long range K needs for slash pine production on flatwood soils.

LITERATURE REVIEW

The Role of Potassium in Plant Nutrition

Physiological Function of K

While N and P are constituents of plant protoplasm and undergo many complex organic combinations in the synthesis of compounds necessary to plant growth, K does not. Potassium is generally found as a soluble inorganic salt in tissues in relatively large amounts and appears to have rather specific functions that cannot be replaced completely by even closely related elements, such as sodium (Na) and lithium (Li) (Tisdale and Nelson, 1966; Mustanoja and Leaf, 1965; Baule and Fricker, 1970).

These functions include;

a) production and translocation of carbohydrates,

b) conversion of reduced N compounds to protein,

c) uptake of nitrate and other anions, water uptake and transpiration, and

d) enzymatic action enhancement. Potassium and other monovalent cations may serve as cofactors for as many as 46 known enzymes for animals, microorganisms, and higher plants (Gauch, 1972).

Potassium Uptake

Potassium presumably is taken up by plants through a process of "active transport" that allows uptake against a concentration gradient (Epstein, 1955). Some evidence suggests that mycorrhizal associations enhance K uptake in trees (Harley, 1959; Rosendahl, 1942; Baule and Fricker, 1970).

Role of K in Disease and Insect Resistance in Forests

While K is generally credited with increased disease and insect resistance in trees (Weetman and Hill, 1973), results have been ambiguous in many CRIFF experiments. Potassium added as a supplement to 88 kg/ha rates of N and P reduced insect damage from 17% without added K to 12% in 5 locations, but had little effect on the incidence of Cronartium fusiforme (Pritchett and Smith, 1972). It was also found that K alone has been able to give height growth increases without concomitant increase in rust infection. When N was added with K, higher rust incidence often resulted over that of the K alone (Pritchett and Smith, 1972).

Distribution of K in Trees

Because K occurs in trees in the ionic form, it appears to be quite soluble and leaching of K from foliage occurs readily during precipitation (Tamm, 1951; Will, 1955; and Cassiday, 1966). Because of its mobility, K tends to concentrate in the active growing portion of the trees. New flushes, buds, and growing root tissue are generally higher in K concentration than older tissue (Madgwick, 1963; and White, 1964). Translocation within the plant from one tissue to another is commonly observed and at times of plentiful supply, K may be taken up in greater quantities than is needed by the plant, leading to the phenomenon of "luxury" consumption. Only when quantities of K reach a concentration causing salt injury will toxicity occur.

Interrelations of K and Other Nutrients

While K is closely related to Na, little evidence of substitution of Na for K in forest trees has been found. Only small responses

due to Na application has been observed in red pine (P.resinosa) in K deficient soils in New York (Madgwick, 1961). Potassium and Na uptake appear to be accomplished separately and evidence suggests that calcium (Ca) is required for the active uptake of K (Epstein, 1955) in addition to the physiological function relationships already noted for other nutrients.

Potassium as a Component of the Physical Environment

Mineralogical Sources of K

The average K content of the earth's crust is 2.4%, but the content in soil is variable and may range from only a few hundred parts per million (ppm) in quartzite sands to more than 24,000 ppm in soils containing large amounts of K-bearing minerals (Tisdale and Nelson, 1966).

The primary minerals most commonly associated with soil formation are K feldspar, $KAlSi_3O_8$; muscovite, $H_2KAl_3(SiO_4)_3$; and biotite, $(H,K)_2(Mg,Fe)_2Al_2(SiO_4)_3$ (Tisdale and Nelson, 1966). The feldspars are the most abundant of all minerals, making up approximately 57% of the earth's crust. The K feldspars contain an average of 14% K. The mica group of phyllosilicates (muscovite and biotite) are less abundant and make up 5.2% of the earth's crust and contain 8 to 10% K (Berry and Mason, 1959).

The relative availability of the K contained in these minerals follows the sequence: biotite > muscovite > feldspar. During soil weathering illite or hydrous mica which contains 3 to 5% K may form. Other clay minerals such as interstratified mica and montmorillonite may contain up to 0.5% K (Tisdale and Nelson, 1966).

While K in primary minerals is generally not available to plants, it has been shown to be somewhat water soluble in finely ground minerals. Carbonated water is effective in removing K from finely ground minerals (Rich, 1968), and mycorrhizal fungi have been shown to utilize K from minerals in association with forest tree roots (Harley and Wilson, 1959; Voigt, 1965).

Potassium may be fixed by certain clay minerals into relatively unavailable forms which allow the buildup of total K in the soil, while reducing the readily available K. This is beneficial in soils that are low in cation exchange capacity (CEC) and that contain small amount of K-bearing minerals (Volk, 1934; Vleck et al., 1974).

Potassium in Florida Forest Soils

Pine production in the southern Coastal Plain is predominantly in the flatwoods areas (Pritchett and Smith, 1974). Quartzite sands dominate the area, and often contain less than 5% silt plus clay and little or no detectable K-bearing primary minerals. The clay fractions of the surface horizons contain only small amounts of intergrade clay minerals, but increase slightly in amount with depth (Zelazny and Carlisle, 1971).

Leaching of K

Total quantities of K in flatwood soils range from 50 to 100 ppm with less than 25 ppm extractable with N NH_4OAc buffered at pH 4.8. The low CEC, low clay, and low organic matter contents would not appear to be conducive to retention of K in the flatwood soil. Nevertheless, greater than 50% of K applied as KCl at 90 kg/ha has been shown to be retained in surface soils undergoing leaching studies in soil columns after passage of 50 cm of water (Voss, R.L., unpublished). Under field

conditions the leaching losses of K due to prescribed burning and removal of forest cover appear to be relatively low (Wells, 1971; Gessel and Cole, 1965). Application of urea has also been shown to reduce the leaching of K in Leon soil supporting slash pine in pot experiments (Sarigumba, 1974).

Meteorological Inputs of K and Other Nutrients

The importance of nutrients in rainfall to nutrient cycling has been an item of conjecture for over a hundred years (Wetselaar and Hutton, 1963). Numerous early studies have had varied results, but it seems certain that both anion and cation concentrations are generally less than 1 ppm and contribute less than 1 to a few kg/ha/yr of nutrient to a system except in a few particular cases as summarized in Table 1 (Attiwill, 1966; Tamm, 1951; Nye, 1961; Miller, 1968; Duvigneaud and Denaeyer-De Smet, 1970; Cole et al., 1967; Wetselaar and Hutton, 1963).

Atmospheric inputs can be classified as wet deposition and dry deposition. Wet deposition includes condensation of rainfall around particulate matter and the interception of particles by raindrops. Dry deposition occurs as sedimentation of particulate matter through the atmosphere and by impaction of particulate matter upon obstacles in the path of the windflow. Sodium, Ca, Mg, P, and K exist in the atmosphere only in particulate form, originating from smoke, mineral dust, sea spray, and other aerosols (White and Turner, 1970). Dry deposition is difficult to assess, especially under forest cover, but attempts have been made to separate the foliar dust contribution from that leached from the tree crowns by using artificial entrapments of netting to

TABLE 1. A summary of some atmospheric nutrient inputs reported worldwide.

Location	Annual Rainfall	K	Na	Ca	Mg	P	Source
	cm	---------- Kg/ha/yr ----------					
Australia	97	2.0	16.8	2.7	5.4	tr.	(Attiwill, 1966)
England	171	2.8	-	6.7	6.1	.28	(Carlisle et al., 1967)
Ghana	165	17.8	-	12.9	11.5	.42	(Nye, 1961)
Hawaii	120	5.2	-	5.1	2.0	.2	(Voss, R. L. unpublished)
Ireland	-	1.6-11.7	-	-	-	-	(O'Carroll and McCarthy, 1973)
New Zealand	92	.3-.9	1.1	-	.2	-	(Wetselaar and Hutton, 1963)
New Zealand	-	5.0	54.0	7.0	10.0	.3	(Miller, 1968)
North Carolina	-	1.6	-	2.8	.7	.2	(Wells and Jergensen, 1973)
Oregon	-	6.1	-	8.1	10.4	1.5	(Tarrant et al., 1968)
Sweden	95	1.9	5.6	3.5	.91	.07	(Nihlajard, 1970)

simulate the foliage (Schlisinger and Reiner, 1974; Nihlajard, 1970) and special dust collectors (White and Turner, 1970; Woodwell and Whittaker, 1967). In general, contributions of nutrients from dry deposition are considerably smaller than from wet deposition and are usually collected along with the wet deposition in open rainfall collectors.

Response of Pine Trees to K Fertilization

Geographical Areas of K Deficiencies

Growth responses to fertilizer K in pine forests have been reported throughout the world (Leaf, 1967). In general, K deficiency occurs most often on acid sandy soils that are low in organic matter and low in CEC. Previously cropped lands, leached soils, and eroded soils may show K deficiency when planted to pine.

One of the most thoroughly studied areas of K deficient forest soils occurs in the glacial outwash soil areas of northern New York. Over 30 years of extensive research exists on these sandy soils where red pine (P. resinosa) and white pine (P. strobus) show marked responses to applied K. Early application of 224 kg/ha of KCl to 5- and 6-year-old trees corrected deficiency symptoms and increased the tissue K content from less than 0.34% to 0.74%. Response was still measurable after 16 years of growth (Heiberg and White, 1951).

In some of these soils the presence of a fine textured soil layer at depths of as great as 3 m enhanced growth by improving moisture relationships and preventing the leaching of K. Without additions of K, the foliage of trees growing in the soil area with the fine-textured layer had K concentrations of 0.35% while the foliage from trees growing in the areas without such a layer had K concentra-

tions of only 0.27% (White and Wood, 1958). Even those sandy soils shown to contain 2 to 3% total K have shown responses to K applications due to the relative unavailability of the K in the primary minerals (White and Leaf, 1964).

Similar coarse textured soils in Canada have also shown improved growth of pine with applications of up to 224 kg K/ha. Two years were required for a significant response in diameter increase and three years for height responses in 20-year-old red pine plantings (Gagnon, 1965).

In Denmark and throughout the Scandinavian countries, fertilizer applications of P and N appear to have significantly increased incidences of observable K deficiency symptoms (Holstener-Jørgensen, 1964).

Poorly drained silt loam soils in eastern Australia and fine sandy loams and loamy sands in western Australia have both been shown to be K deficient for radiata pine of all ages (Hall and Raupach, 1963; Raupach and Clarke, 1972). In Ireland, K deficiency is found on peat lands that have little or no primary K mineral sources and are far enough removed from the ocean that levels of K in the precipitation are insufficient to maintain K supplies for normal tree growth (O'Carrol and McCarthy, 1973).

In the coarse textured coastal plain soils of the southeastern United States K was not originally considered a limiting factor in pine production (Pritchett and Llewellyn, 1966; Walker, 1958). More recently, as additions of N and P were found to enhance growth on the less well drained soils, K responses in young slash pine and loblolly pine are being observed. Approximately 40% of a series of 36 experi-

ments with slash pine placed throughout the southeast have shown initial response to additions of 88 kg/ha of K when applied with N and P as compared to N and P applied alone (Pritchett and Smith, 1972), but these gains have not persisted as the trees attained sufficient size to more thoroughly exploit the site (Pritchett and Smith, 1974).

Deficiency Symptoms in Trees

Deficiency symptoms have been shown to occur quite rapidly when K concentrations drop below that necessary to maintain metabolic functions. Stunting, bluish-green discoloration of needles, chlorosis, and copper-colored discoloration of the terminal growth, with some necrosis, have been shown to be characteristics of K-deficient pitch pine (P. rigida), red pine, white pine, and shortleaf pine (P. echinata) grown in K-deficient solution cultures, with white pine showing general chlorosis and the rest only occasional chlorosis (Hobbs, 1944). Stunting and discoloration have also been recognized under field conditions in Scots pine (P. sylvestris) and radiata pine (P. radiata), with the previous years foliage yellowing as a result of the rapid translocation of K to the actively growing portion of the plant (Hall and Raupach, 1963), particularly during the early spring flush (Walker, 1956). Premature needle cast and short needles are often described as symptoms of K deficiency (Heiberg, Madgwick, and Leaf, 1964). Radiata pine grown on K-deficient sites in Australia show early spring symptoms of yellowing at the tips of the youngest needles immediately behind the current shoot in the lower laterals, giving a halo appearance to the shoot (Raupach and Hall, 1972). "U" shaped shoots have also been described (Raupach and Hall, 1972) as a K deficiency symptom in radiata pine in

Australia. Sulfur-induced K deficient slash pine grown on excessively drained soils in Florida also show a yellow halo appearance (Bengtson, G.W., personal communication).

Evaluation of Soil K Supplies

Soil testing has long been regarded as a rapid means of evaluating the nutrient supplying ability of a soil and much effort has gone into calibrating levels of K extracted by different test methods with a particular crop's ability to make use of that nutrient. Originally, total analysis served to give an approximation of the nutrient content of a soil, but with increased understanding of soil mineralogy this was abandoned in favor of various chemical extractants that could be calibrated to plant uptake.

Forest soils work has relied on test methods developed for agricultural crops and often the need for a soil test that takes into consideration the longer tenure of a forest crop on a given site is compromised in favor of the ease of adopting methods already developed.

One method of evaluating long term K supplying power for tree crops is boiling soil samples in $\underline{N}$ HNO_3 for 10 minutes. Good correlation with growth of red pine in the K-deficient outwash soils of New York has been reported (Hart, Leaf, and Statzback, 1969).

In the southeastern United States, methods developed by agricultural workers have been used extensively with varying degrees of success and in Florida the standard method for extracting P and cations is with $\underline{N}$ NH_4OAc buffered at pH 4.8. Levels of K found in soils by this method range from 3 to 50 ppm with values below 15 ppm for surface soils considered low in K for trees (Pritchett,W.L.,personal communication).

In general the use of soil test results alone for evaluation of K-deficient areas for pine has met with little success (Walker, 1956; Heiberg and Leaf, 1960).

Tissue K Concentration

Tissue analysis has proved to be somewhat more satisfactory than soil analysis in predicting areas of K response in pine (Leaf, 1973), although time of sampling, sample age, tissue type and crown position all affect the level of K found. In general, K concentrations decrease from the top of the crown to the bottom and decrease with the age of the tissue (White, 1954). Potassium concentration reaches a peak in the youngest tissue during the growing season and tends to be stable in the late fall and winter at a lower concentration than during the growing period. It would appear that late fall sampling of middle crown, current-year foliage is best for evaluating K status of pines (Wells and Metz, 1963; White, 1954). The incipient K deficiency level for this foliage appears to be 0.30 to 0.50% K for pine, with optimum levels of between 0.50 and 0.70% K (Ingestad, 1960; White and Wood, 1958; Heiberg and White, 1951; Stone and Leaf, 1967; Walter, 1956). In K deficient outwash soils of northern New York state red pine responded to K fertilization with 0.3% K concentration in the unfertilized tissue, and increased to 0.45% and above with K fertilization at rates of 220 kg/ha (Heiberg and White, 1951; Heiberg and Leaf, 1960). White pine increased to 0.4% K with fertilization. Scots pine (P. sylvestris) was found more demanding, with K deficient tissue of 0.3% K and sufficient tissue 0.7 - 1.6% K (Ingestad, 1960).

Severe deficiency symptoms in P. radiata in eastern Victoria,

Australia, were observed when the older needles in the lower whorl of the crown reached a level of 0.2% K. If lower than 0.35%, growth depression was detected (Raupach and Clarke, 1972). Application of 1000 kg KCl/ha gave optimum growth and increased the tissue K concentration to 0.6% K (Hall and Raupack, 1963; Raupack and Hall, 1972).

Slash and loblolly pine appear to require less K than the above species and slash pine is the least demanding of the two. Grown on Lakeland fine sand, both loblolly and slash pine seedlings approached a minimum value of 0.1% K with no K added in pot culture and a critical value of 0.2% K at application levels of 10 ppm K (Terman and Bengtson, 1973). On a Bladen clay loam, soil water level controlled at or near the surface of the soil gave foliar K levels of 0.58%. With 8-8-8 fertilizer applied at 1120 kg/ha, the K level increased to 1.2 - 1.5% K (Walker, 1962).

On flatwood soils, the foliar K levels of slash pine varied from 0.2 - 0.4% when N and P were added. Foliar K levels exceeded 0.4% when K was added at rates of 90 kg K/ha (Pritchett and Smith, 1974 ; Pritchett and Llewellyn,1966).

Extent of K Fertilization in Pine Production

Potassium fertilization is commercially practiced only in mid-western Europe, Japan, and Oceana at present with minor applications to correct specific deficient areas in New York, Canada, Australia, Scandinavia, and Ireland. In Japan, in 1970, only 70 to 80 thousand ha were fertilized with K at the time of establishment and another 20 to 30 thousand ha on established stands. Ten thousand ha in Oceana were

fertilized at time of establishment and 2 thousand ha on established stands. Midwestern Europe fertilized less than 30 thousand ha at establishment with 20 to 30 thousand ha of established stands fertilized with K in 1970 (Hagner, 1971). With the exception of these areas, it does not appear that any large increases in commercial use of K in forests will occur in the next few years.

Biomass and Nutrient Cycling in Forests with Reference to K

Biomass Production in Forests

It is important to know the amount, distribution, and functioning of tissue within a forest stand in order to evaluate the production and nutrient needs of the total plant community.

Recent studies of total biomass production throughout the world have been reviewed (Rodin and Bazilevich, 1967; Art and Marks, 1971). While values of over 400 t/ha of dry matter have been reported for mature forests in both temperate and tropical areas, values of between 100 and 200 t/ha are more commonly found for total tree, shrub, and herb above ground biomass. Great variability exists among reports of biomass production, but a number of studies have shown mature Pinus spp to reach a maximum biomass of approximately 200 t/ha when fully occupying a site (Art and Marks, 1971).

Loblolly and slash pine have been examined for total biomass as well as biomass distribution in the various components of the tree by total tree harvest in the southeastern United States. Biomass of young loblolly pine in a bottomland site in Mississippi increased by 10 t/ha during its fifth year of growth, increasing from 6 to 16 t/ha. Bark

percentage stayed relatively constant at 20%, with foliage decreasing from 40 to 33% and stem wood increasing from 39 to 47% (Nelson, Switzer, and Smith, 1968). At age 16 years, loblolly pine grown in South Carolina had accumulated a total above ground biomass of 156 t/ha with needles accounting for only 5% of the total, living branches 9%, dead branches 5.5%, stem bark 9.8% and stem wood 70%. Roots added 36 t/ha (23% of the above ground tree biomass) to the system (Wells and Jorgensen, 1973). Other studies in the southeast have shown agreement with these data, with needles accounting for 4 to 7% of the total above ground biomass, stem wood averaging 70%, stem bark ranging from 10 to 12%, and living branches averaging 10 to 11% of the total (Ralston, 1973; Metz and Wells, 1965).

Slash pine growing on sandy loams in North Carolina accumulated 31.7 t/ha of above ground biomass by age 8 years. Stem wood accounted for 38% of this total with stem bark, needles, live branches, and dead branches accounting for 12, 22.5, 21, and 5.7%, respectively (Nemeth, 1973). In Louisiana bottomland soils, 8-year-old slash pine had accumulated 50.7 t/ha on bedded sites as opposed to 34 to 37 t/ha on flat-disced or unprepared sites. Stem wood accounted for 40 to 43% of the total above ground biomass, with 16 to 17% bark, 16 to 22% branches, and 20 to 23% needles. Little effect due to bedding was found in the distribution of biomass, but the total biomass for the bedded site was significantly greater than the disced or unprepared sites due to the impact of an effective lowering of the water table during the winter by bedding (McKee and Shoulders, 1974). Twelve-year-old slash pine grown on imperfectly drained soil in Florida have shown

total above ground biomass production of 102 t/ha with 65% stem wood, 19% stem bark, 7.7% branches and 7.7% foliage. Another 27 t/ha was found in root biomass (Mead, 1971). Fertilized slash pine growing on a very poor drained Bladen soil in western Florida produced 190 t/ha above ground biomass during 14 years, with 68% stem wood, 6.9% needles, 12.2% branches, and 13% stem bark (Pritchett and Smith, 1974).

In studying whole tree harvest methods of slash pine, the total above ground biomass plus the roots in a 0.9 meter radius of soil about the base of the tree have been examined. About 13 to 19% of the total harvest was root material, 57 to 60% was bark-free stem to a 10 cm top, 10 to 15% was stem bark, 4 to 5.5% was the remaining stem with bark, 3 to 4% was branches, and 3.5 to 5% was needles (Koch, 1972).

Litter fall for slash pine was 1.4 t/ha for an 8-year-old stand in North Carolina (McKee and Shoulders, 1974). Total accumulation in the forest floor in Florida has been reported at 19.4 t/ha in 11-year-old slash pine (Mead, 1971) and 39.5 t/ha in fertilized 15-year-old slash pine (Pritchett and Smith, 1974).

Nutrient Cycling in Forests

The cycling of minerals is a phenomenon that is rather unique to forest nutrition studies as it is of minor importance in most agronomic crop production. Cycling occurs as a function of time, and while short term cycles may be important physiologically, it is the seasonal and annual fluctuations that appear to be most revealing in the study of tree nutrition.

Two basic nutrient cycles have been recognized in forest ecosystems; (1) biological cycle, composed of the circulation of nutrients

between the forest floor and the plant community, and (2) the geochemical cycle, concerned with input and output of mineral elements from the system under study (Duvigneaud and Denaeyer-De Smet, 1970). An additional cycle has been proposed recently to account for the internal biochemical transfer of nutrients wholly within the tree tissue (Switzer and Nelson, 1972).

The geochemical cycle includes atmospheric inputs, inputs via the soil from geologic weathering, and transport of minerals into the system through the ground water, both laterally and vertically. Losses to the geochemical cycle include harvest, fires, and transport out of the system through the ground water as leaching losses.

Rainfall inputs and the supplying ability of the soil have previously been discussed. In addition, the horizontal continuity of ground water in forest ecosystems well away from sources of nutrient input such as would occur in agricultural lands should provide a system where gains and losses are at or near steady state conditions. That is, ground water gains in nutrients are balanced by continuous losses. Fertilization, burning, and harvest may upset the balance and a period of time would then be necessary for a steady state situation to be reestablished (Ulrich, 1973; Wells, 1971; Stone, 1971).

The biological cycle includes nutrient uptake from the soil and forest floor, retention of nutrients within the tissue of the biomass, and the return of nutrients to the forest floor from the biomass by litterfall, throughfall, and stemflow. It also includes the ground flora as part of the system.

Studies in Mississippi showed that retention of nutrients in biomass followed the pattern of nutrient uptake, with Ca and Mg being

retained to the greatest degree in loblolly pine (Switzer and Nelson, 1972). Phosphorus and K were the most mobile in this system, being retained in lower amounts but showing greater mobility as active parts of the metabolic pool. The 20-year-old plantation showed 11% of the total annual requirement for K retained and the remainder recycled. A total of 40% of the Ca and 22% of the Mg was retained while the balance was recycled (Switzer and Nelson, 1972). The total content of K, Ca, Mg, and P within the tree biomass after 20 years was 98, 90, 24, and 19 kg/ha, respectively.

Sixteen-year-old loblolly pine in South Carolina was found to have a biomass containing 165, 187, 46, and 30 kg/ha of K, Ca, Mg, and P, respectively. The annual requirements at this age were 5.4 kg K/ha, 4.6 kg Ca/ha, 1.5 kg Mg/ha, and 0.9 kg P/ha (Wells and Jorgensen, 1973). Total above ground biomass nutrients in a 15-year-old fertilized slash pine plantation in West Florida was 137, 221, 52, and 24 kg/ha K, Ca, Mg, and P, respectively (Pritchett and Smith, 1974).

Annual returns of nutrients in litterfall were recorded for 16 to 20-year-old slash pine in Australia in which K was returned at 2.5 kg/ha, Ca at 16 kg/ha, Mg at 6.7 kg/ha, and P at 0.4 kg/ha (Dept. of Forestry, Queensland, 1971-72)[1]. Loblolly pine was found to return greater amounts of nutrients to the forest floor in an unthinned 16-year-old plantation than that reported for slash pine in North Carolina. Annual nutrient returns as litterfall were 13.9 kg K/ha, 26 kg Ca/ha, 6.2 kg Mg/ha, and 7.5 kg P/ha (Wells and Jorgensen, 1973).

Throughfall removal of nutrients from tree crowns was recognized

as early as 1814 by De Saussure. Nutrient removal as a percentage of element present follows the sequence K > Ca > N > P (Cassiday, 1966). Total annual removal of nutrients from radiata and loblolly crowns ranges from 6 - 20 kg K/ha, 2 - 20 kg Na/ha, 2 - 8 kg Mg/ha, and 0.1 - 1 kg P/ha (Attiwill, 1966; Will, 1968; Switzer and Nelson, 1972; Wells and Jorgensen, 1973).

Stemflow leaching, while causing only minor amounts of nutrient loss from the crown, may be beneficial to soil microflora at the base of the tree (Curlin, 1970).

Because K is such a mobile element, internal transfer within the biomass may contribute greatly to the K nutrient cycle. An estimate of up to 22% of the annual K requirement has been given for this portion of the nutrient cycle (Switzer and Nelson, 1972) but another estimate suggests that up to 50% of the K in the needles may be translocated into the other portions of the tree before abscission (Wells and Metz, 1963).

The ground flora plays an important role in the nutrient cycle in the early stages of stand development, but tends to lose its influence during crown closure. This may be as early as 7 - 10 years for loblolly and slash pine plantations, with the first few years of the stand development dominated by the ground cover (Switzer and Nelson, 1972). Large proportions of the total K of older forest ecosystems are sometimes found in the ground cover (Carlisle et al., 1967b; Armson, 1973). Some ground flora also seem to be predisposed to K accumulation. An example of this is the ubiquituous bracken fern (Pteridium aquilinum), a fire resistant inhabitant of woods and thickets (Cobb, 1963; Waters, 1903). Totals of 10 to 16 kg/ha of K have been found in bracken cover in oak forests in England. It contributed 18 - 31% of the annual K

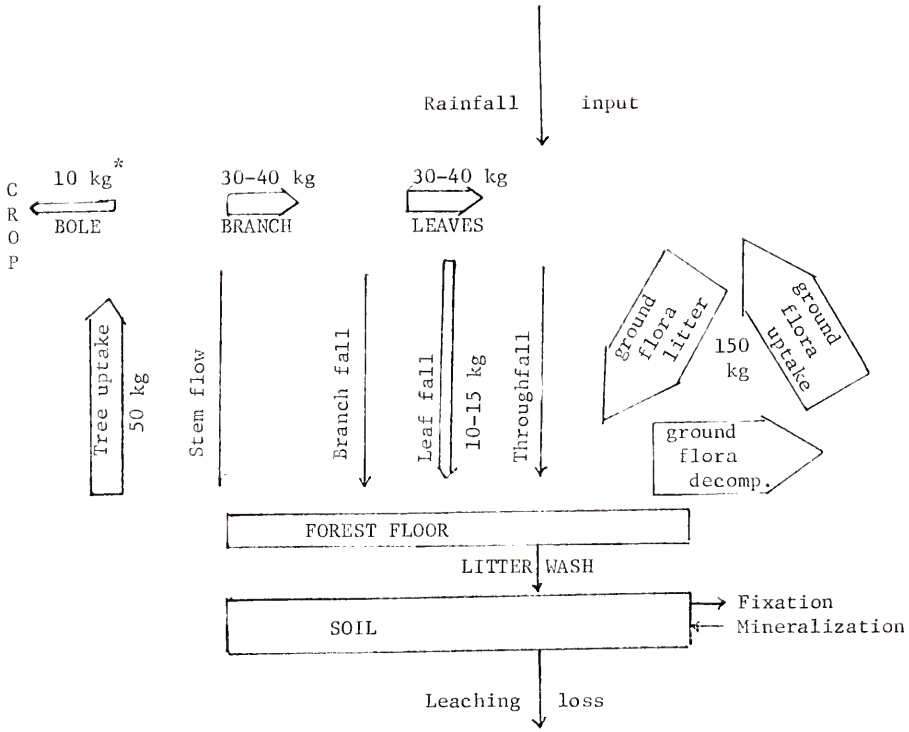
input into the soil (Carlisle et al., 1967b). In eastern Australia, K deficient areas of radiata pine failed to display deficiency symptoms or respond to K fertilizer applications in spots where bracken was present (Hall and Parnell, 1961).

Summary

Numerous methods of modeling the K cycle in forest ecosystems have been attempted and in general all have followed the concept of the biological and geochemical cycling systems previously described (Duvigneaud and Denaeyer-De Smet, 1970; Jordon et al., 1972). By examining the uptake and distribution of K in the system, inputs and outputs from the system, and ascertaining the adequacy of the system to sustain optimum growth, a logical outline of K flow can be charted as shown in Fig. 1 (Ovington, 1965). The addition of fertilizer as a single input into a natural system is shown in Fig. 2 in a systems model developed by Curlin (1970). Both show the interdependency of all the components of the biosystem in maintaining adequate nutrition.

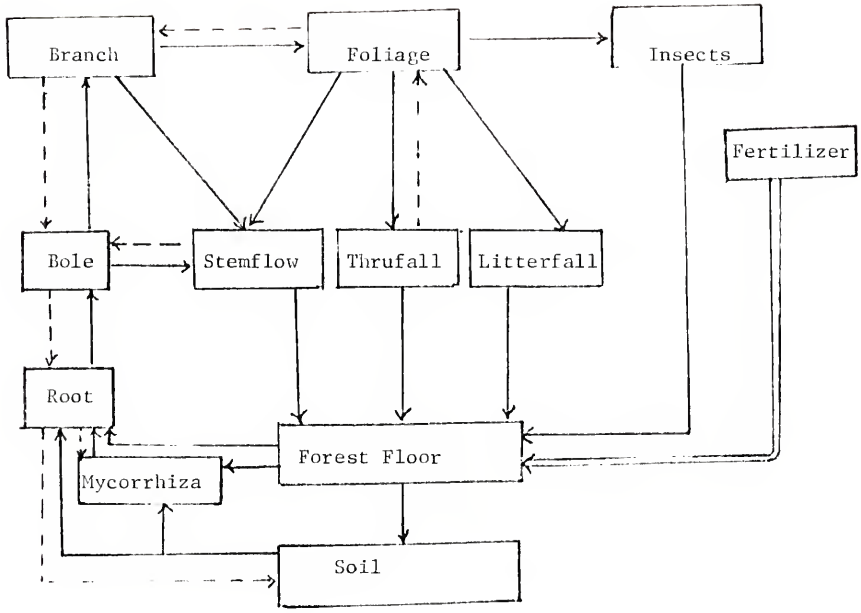
N O T E

[1]Annual report of Dept. of Forestry, 1971-1972. Queensland, Australia.



* Figures based on the K-cycle in 47-year-old trees, annual amounts/ha.

Fig. 1. Potassium cycle in Scots pine.



* Transfer from one compartment to another indicated by arrows.

Fig. 2. A systems model to mineral cycling.

MATERIALS AND METHODS

Experimental Site

Location and Description of Stand

The 13-year-old slash pine plantation used for the experiment was located in the Austin Cary Memorial Forest. The forest is owned and controlled by the University of Florida as a teaching and research laboratory and is situated approximately 15 km northeast of Gainesville on State Highway 24 in Alachua County, Florida.

Local history indicates that the area originally supported a longleaf pine (Pinus palustris) forest and may have undergone a period of naval stores production prior to acquisition by the University.

Trees were harvested in 1959 and prior to replanting the area was burned and bedded. The 1 - 0 slash pine seedlings originated from a single, open-pollinated seed source and were hand planted at a spacing of 1.5 x 3 m in December, 1960.

Measurements made in April, 1973 gave a site quality (age 25) of 65 for the stand (Barnes, 1955). The 13-year-old stand had a mean height of 11.1 m and mean diameter at breast height (dbh) of 12.3 cm. Stand density was 1660 trees/ha with diameter class distribution given on the following page.

Diameter class	%
6.25 cm	5
8.75 cm	8
11.25 cm	30
13.75 cm	34
16.25 cm	20
18.75 cm	3

Basal area of the stand was 20.0 m^2 with an estimated crown cover of 80 to 85%. A litter layer of only 1 to 2 cm was developed.

The ground cover consisted mainly of saw palmetto (Serenoa repens) and bracken fern (Pteridium aquilinum) with scattered wire grass (Aristida stricta) and blackberry (Rubus occidentalis).

Soil

The soil of the area was imperfectly drained and classified as a sandy, siliceous, hyperthermic family of Aeric Haplaquods. It had been mapped as a Leon very fine sand, but is now classified as a Myakka soil (Myakka is the hyperthermic taxadjunct of the Leon soil and occurs to the south of a line drawn between Perry and Jacksonville). The soil had a 1 to 2 cm thick organic layer (O1) over an inorganic dark colored surface horizon (A1) of 10 cm (Table 25). The A2 was between 45 and 75 cm thick and was light gray in color. The B2h horizon was irregular in depth and varied from a well developed spodic horizon to a weakly developed staining with no evidence of induration. The C horizon was light colored with occasional mottles and extended approximately 1.5 to 2 m where a D1 horizon of clay loam was uniformly present.

The surface soil was very fine sand with silt plus clay fractions of less than 5 percent. Acid conditions prevailed with low CEC, low organic matter, and low available nutrients (Table 25). The A2 was very low in organic matter and lower in CEC and available nutrients than

the surface horizon. The spodic horizon had greater organic matter than the surface horizon with CEC and available nutrients similar to the surface when it was present in a well developed state.

Climatic Data

Mean annual temperature for Alachua County is 21.1 C with average temperature for the months of December, January, and February falling below 15 C (U.S. Weather Bureau, 1970). May through September temperatures were between 25 to 30 C giving the area a broad sub-tropical to warm temperate classification. Mean annual soil temperature was 23 C and the mean annual rainfall was 133 cm. Rainfall was seasonal with nearly half falling during the summer months of June through September in severe, convection caused, thundershowers. The dry season extends from November to January with monthly averages of less than 7.5 cm with a second dry period often occuring from the last of April to mid-June.

The rainfall data from 1973 to 1974 from Austin Cary Memorial Forest are given in Fig. 3. The rain gauge was located approximately 2 km from the experimental site (Kaufman, C.M., personal communication).

Average depths to ground water measured in water table wells placed in the experiment are shown for selected dates in Fig. 1. Water table in the experimental area fluctuated from a low of 2 meters during the dry season to at or above the surface during the wet season.

Experimental Methods

Experimental Design

A randomized block design with three blocks of five treatments

each was established in the plantation. Blocking was done because of a suspected topographic and drainage gradient existing across the area. Each plot consisted of a 0.04 ha gross plot that received fertilization. A 0.02 ha net measurement plot consisting of 4 tree rows of 16.6 m length was used for measurements and sampling. The treatments applied were:

K0	No fertilizer
K0+	0 kg/ha K + 40 kg/ha N and 45 kg/ha P
K48+	48 kg/ha K + 40 kg/ha N and 45 kg/ha P
K96+	96 kg/ha K + 40 kg/ha N and 45 kg/ha P
K192+	192 kg/ha K + 40 kg/ha N and 45 kg/ha P

The K treatments were applied as granular fertilizer-grade KCl with the N and P supplied as fertilizer-grade diammonium phosphate (DAP) applied at a rate of 224 kg/ha. Application was with a hand carried cyclone-type spreader calibrated to deliver approximately 10 kg/ha. The fertilizer materials were then applied by applications in alternate directions across the gross plot until the fertilizer was expended. Fertilizer was applied May 2 and 3, 1973.

Sampling Methods

Sampling of foliage, stem flow, throughfall, rainfall, litter, soil water, ground water, and soil was carried out preceding and following fertilizer treatments. Intensive sampling was done over the first growing season with less rigorous sampling over the second growing season.

Foliage was collected from 8 to 10 trees in each plot for each sampling date in the 1973 growing season. Samples were clipped from the

south side, mid-crown position of randomly chosen trees, using pruning shears on an extension pole. Even distribution between first and second order branch sampling was attempted, taking care not to deplete the crown through continuous sampling. After sampling, the shoots were divided into old foliage (pre-1972 growth), current foliage (1972 growth), and flushes as they became large enough to sample (1973 growth). Buds and stems associated with the current and flush growth were also collected for analysis. Collection dates for 1973 were April 24, May 13, May 18, June 4, July 9, August 19, September 13, and November 14.

Stem flow was collected from a tree randomly selected from the 11.25 or 13.75 cm diameter class of each plot. The stem-flow collector consisted of an aluminum foil collar cemented to the tree stem with plastic roofing cement. It was placed 1 m above ground level and positioned to divert the stem flow to a funnel attached to the side of the tree with an aluminum nail. The funnel was attached to a plastic tube carrying the stem flow to a covered 36-liter plastic container.

Throughfall and rainfall were collected in one-liter containers placed on stakes 1 m above ground level. The area of the catchment was 105 cm^2 and it was fitted with a plastic disc that allowed rainfall to enter but minimized evaporation. Nylon netting covering the container prevented entry of litter, insects, and animals. One throughfall container was placed in each plot within 2 - 3 m of the stemflow catchment tree for the plot. Four open areas adjacent to the plantation served as locations for the rainfall catchment. Stemflow, throughfall, and rainfall collections were taken on the basis of rainfall amounts and frequency. During the first month collections were made after every rainfall. Thereafter, collections were made approximately monthly.

Litterfall was collected in 0.97 m^2 trays placed on the ground. They were constructed of 2.5 x 10 cm wooden frames with 0.3 cm^2 mesh galvanized hardware cloth bottoms. A tray was placed at a random position between rows within 5 m of the stemflow sample tree in each plot. The trays were put in place April 24, 1973 and collections were taken 5, 28, 60, 97, 133, 150, 163, 191, 282, and 582 days following fertilization.

Soil water and ground water collectors were placed in random locations between rows within 5 m of the stemflow sample tree and within 1 m of each other. Soil water was collected from 20 and 40 cm depths in each plot by means of 2.5 cm tubes fitted with porous ceramic cups. Water was extracted from the soil by evacuating the air from the tubes creating a negative pressure that allowed water to move from the soil, through the ceramic tip, into the tube. Sampling of the soil water was then accomplished by removing the water from the tube with gentle suction. Evacuation and sampling were accomplished using a hand vacuum pump fitted with a sample trap. Soil water was sampled 1 day prior to treatment and 15, 19, 25, 60, 101, and 133 days following fertilization.

Ground water wells were dug to 1.8 m with a 10 cm bucket auger. A plastic cylinder 15 cm diameter and 15 cm high was placed around the hole to prevent surface cave-in of the well. A 15 cm plastic pot was used as a cover for the well. Ground water depth measurements were taken for each plot by measuring depth to free water with the ground line as a reference. Sampling was done by suction similar to soil water sampling. Little caving occured during the duration of the experiment and was corrected by reaugering the well to remove the slumped soil. Ground water samples were taken 16 and 6 days before and 15, 25, 28, 60, 101, and 133

days following fertilizer application.

Soil samples were taken with a 2.5 cm diameter soil sampling tube from 10 to 12 random locations within each plot. Samples were taken from the 0 to 10 and 10 to 20-cm depths prior to the fertilizer application. Six days following the treatment 0 to 2.5 and 2.5 to 5-cm depths only were sampled. Nineteen days following treatment 0 to 2.5, 2.5 to 5, 5 to 7.5, 7.5 to 10, and 10 to 20-cm soil depths were sampled. At 25, 102, and 500 days following treatment, samples were collected from the same depths as the 19 day sampling with 20 to 40, and 40 to 60 cm depths taken as well.

Selected ground vegetation consisting of the above ground portions of bracken fern (Pteridium aquilinum) and saw palmetto (Serenoa repens) was harvested on August 13, 1973. Numerical methods were used to evaluate the saw palmetto by counting the total number of plants within the plots. Random samples of palmetto were taken for weight per plant determination and tissue analysis. Cover measurements were estimated for palmetto in the field by measuring per plant coverage. The bracken fern was sampled by harvesting the total number of fronds in random 1.5 x 3 m quadrants unoccupied by saw palmetto.

Laboratory Analysis

All tissue samples were transported to the laboratory immediately after harvest, dried to constant weight at 65 C, and ground to pass a 20 mesh sieve in a stainless steel Wiley Mill. Appropriate weights of tissue were dry ashed in a muffle furnace at 450 C to prevent K volatilization (Jackson, 1958), the ash taken up with 0.1 N HCl, filtered, and taken to volume for nutrient analysis. Potassium and Na

were determined by flame emission, Ca and Mg by atomic absorption spectrophotometry with lanthanum oxide added to suppress interferences (Perkin Elmer Corp., 1971), and P was determined by the ascorbic acid method (Watanabe and Olsen, 1965).

Water samples were analysed within 1 or 2 days of collection, using the methods described above for individual elemental analysis. Conductivity and pH were determined on selected samples using a Barnstead conductivity bridge and pH meter, respectively.

Soil samples were air dried, sieved to 20 mesh, and extracted with $\underline{N}$ NH_4OAc buffered at pH 4.8. A 10-g sample was extracted with 1:5 soil to extractant ratio in 90 ml Nalgene centrifuge tubes for 30 minutes in a reciprocating shaker. Following shaking, the suspension was centrifuged and an aliquot of the supernatant solution was taken for K, Na, Ca, Mg, and P analysis.

Soil pH was determined by pH meter in a 1:5 soil to water suspension and a 1:5 soil to $\underline{N}$ KCl suspension. Organic matter determination was by a modified Walkley-Black wet digestion method (Jackson, 1958) and particle size distribution by the hydrometer meter. Bulk density was determined by weighing soil cores. Available but non-exchangeable K was determined by boiling soil in $\underline{N}$ HNO_3 for 10 minutes at a ratio of 1:10 soil to acid.

Total analysis was done by digesting 100 mesh soil samples with HF in platinum crucibles (Jackson, 1958). The final HCl digest was analyzed for K, Na, Ca, and Mg.

Growth Data

Initial height and diameter measurements of each tree in all plots were taken in April of 1973 prior to height growth initiation for

the year. Final measurements were taken in October of 1974 after height growth for the season had terminated. Heights were determined by Häga hypsometer and dbh was determined by steel diameter tape. Total inner bark tree volumes were calculated using a volume formula modified for slash pine (CRIFF Progress Report, 1973-74)[1]:

$$\text{Vol in } m^3 = .000030(\text{dbh})^2(\text{ht}) + .00207$$

where dbh is in cm and height is in m.

Needle lengths for the first flush of 1973 were determined at the time of foliage sampling. Average needle lengths were taken from the mid-point of the flush from 8 to 10 trees. Crown cover was estimated from field observations.

Whole Tree Harvest

One tree from each plot in block I was felled for total above ground biomass analysis (Newbold, 1967). These trees were selected on the basis of random diameter class assignment stratified according to total diameter class distribution for each plot and a random selection of a single tree belonging to that class interval within the plot.

Total 1974 foliage, total 1973 and earlier foliage, total live branches, dead branches, stem wood, and stem bark were determined for each tree on a dry weight basis and compared with standard biomass formulae found in the literature (Mead, 1971; Nemeth, 1973; McKee and Shoulders, 1974). Nutrient concentration was determined on these tissues and compared with the foliage nutrient concentrations of the prior year as well as with published values for use in estimating nutrient content.

Volumes were determined on the felled stems according to Smalian's combined formula (Strickland, personal communication).

Statistical Treatment of Data

Standard methods of statistical analysis were used in the treatment of data (Steele and Torrie, 1960; Snedecor and Cochran, 1967) with the bulk of the analysis run with the IBM 360-165 computer using the Statistical Analysis System (Barr and Goodnight, 1972) of computation.

Details of the individual statistical analyses are given where appropriate.

N O T E

[1]CRIFF Progress Report (unpublished), 1973-1974. Soil Science Department, University of Florida, Gainesville, Florida. Volume formula modified from: Bailey, R.L., and J.L. Clutter, 1970. Volume tables for old-field loblolly pine plantations in the Georgia piedmont. Ga. Research Council Report 22.

RESULTS AND DISCUSSION

Precipitation Inputs into the System

While fertilizer applications may have a large, but relatively short-term impact on the slash pine ecosystem, the effect of inputs into the system from atmospheric sources is continuous. Both wet and dry depositions were collected with no attempt to separate the two in this experiment. During the first month, collections were taken after every rainfall. Subsequent samples were collected every month or when approximately one liter of rainfall had accumulated in the collector, whichever came first. Amounts of rainfall by collection date are recorded in Table 2. Rainfall was determined by measuring the volume collected, with each 100 ml collected equivalent to 0.95cm of rainfall.

During the first month of the experiment rain fell on six separate occasions for a total of 15 cm. This was followed by frequent short storms during June and into July (Fig. 3). A two-week rainless period in mid-July was followed by frequent rainfall through early August. Rainfall from then till the end of the year was relatively infrequent. A total of 85 cm of rainfall was collected at the experimental site during the 1973 experimental period. Rainfall records from a recording rain gauge located at another site in the Austin Cary Forest indicated 100 cm of rainfall for the same period of time.

Less rigorous sampling was done during 1974, with samples taken every two months. A total of 66 cm was collected during the 1974 sampling period from Jan. 1 to Sept. 24, 1974. The nearby recording rain

TABLE 2. Volumes and nutrient concentration of rainfall.

	1973 Collection date														
	4/27	5/9	5/13	5/18	5/25	5/28	5/31	6/29	7/9	7/30	8/9	8/30	9/17	10/17	12/21
	ml														
Volume/collector	70	64	171	20	286	600	349	1095	960	1075	1258	623	918	145	1295
	ppm														
K	0.31	0.42	0.01	0.50	0.01	0.39	0.08	0.14	0.05	0.06	0.00	0.10	0.15	0.43	0.20
Na	2.69	2.10	0.09	0.65	0.50	0.63	1.37	1.63	0.88	0.71	0.36	0.48	0.77	2.75	0.71
Ca	1.12	1.22	0.68	2.37	0.35	0.41	0.39	0.46	0.33	0.36	0.24	0.23	0.24	0.45	0.30
Mg	0.48	0.31	0.07	0.38	0.09	0.21	0.25	0.16	0.08	0.11	0.04	0.04	0.17	0.34	0.07
P	0.00	0.01	0.02	0.03	0.02	0.07	0.01	0.03	0.01	0.07	0.00	0.00	0.00	0.00	0.01

TABLE 2. (Continued)

	1974 Collection date					Weighted	Total
	2/25	4/2	5/16	7/11	9/24	average	rainfall
	ml						cm
Volume/collector	705	585	1065	2105	2500	-	107
	ppm						kg/ha
K	0.58	0.35	0.18	0.21	0.10	0.16	1.60
Na	1.71	0.76	0.26	0.57	0.17	0.74	7.23
Ca	1.08	0.56	0.77	0.66	0.33	0.46	4.55
Mg	0.20	0.22	0.26	0.15	0.04	0.13	1.30
P	0.00	0.11	0.03	0.00	0.01	0.02	.20

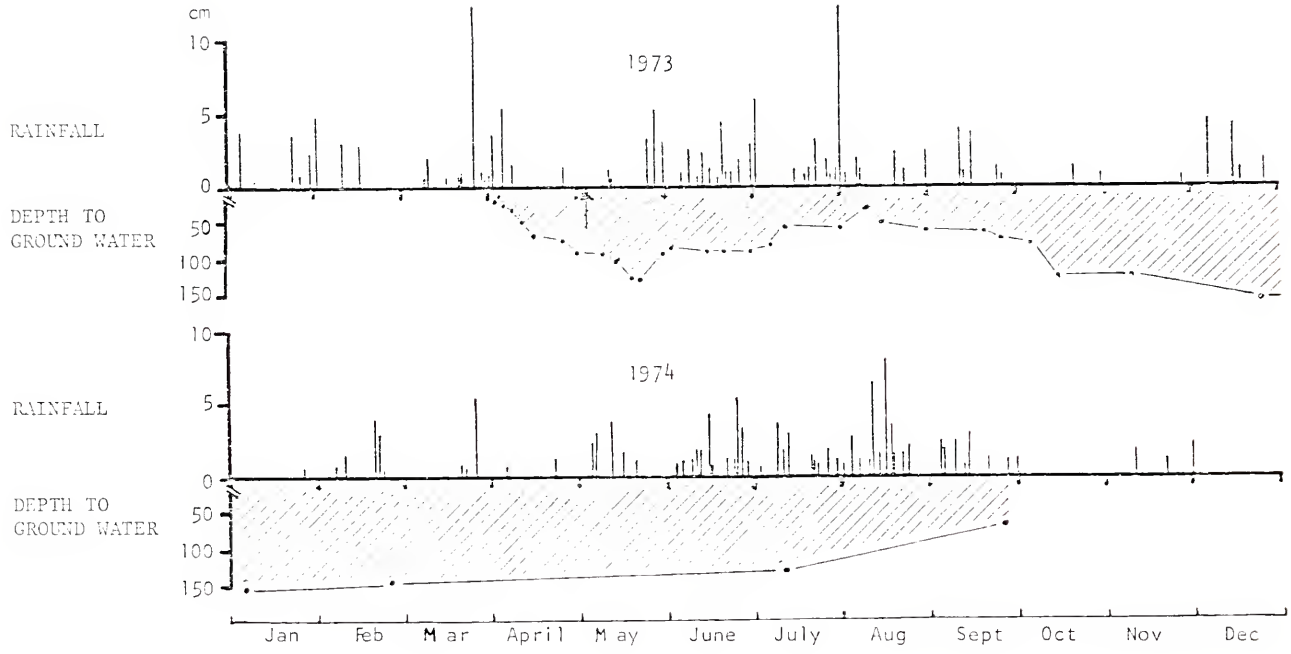


Fig. 3. Precipitation at Austin Cary Memorial Forest and ground water levels at selected dates.

gauge recorded 101 cm of rainfall for the period.

Rainfall nutrient concentrations for the 17-month duration averaged 0.16, 0.74, 0.46, 0.13, and 0.02 ppm, respectively, for K, Na, Ca, Mg, and P (Table 2). Annual contributions of these elements were 1.6, 7.2, 4.6, 1.3, and 0.2 kg/ha, respectively.

The total annual input of nutrients into the system agrees well with data reported in the southeastern United States (Wells, 1974) and other areas of the world (Table 1).

Growth Response in the Fertilized Plantation

Volume Increment Response to Treatment

No volume increment increases due to treatment were detected in the experiment (Table 3) over the 17-month experimental period. Total volume increased from an average of 0.0578 m^3/tree to 0.0681 m^3, with an average increment of 0.0091 m^3 per tree. The total stand volume at the beginning of the experiment was 96.8 m^3 compared to 111.3 at the conclusion, or an increase of only 14.5 m^3 for the 17 month period (Table 4). Neither basal area, height, dbh, nor calculated weight of foliage exhibited a response to K treatment. While this site was not identified as a K responsive site, it did have soil characteristics of low exchangeable K and low total K that suggested K might be a limiting factor for tree growth. Applications of 90 kg/ha to similar soils in the southeastern United States on poorly and very poorly drained sites have been shown to increase volumes by as much as 46% compared to the average volume of plots receiving N and P (Pritchett,W.L.,personal communications). In the northeastern United States it has been found that 2 to 3 years must elapse after treatment for significant increases in diameter and height

TABLE 3. Analysis of variance of volume increment response.

Source	df	ms	F
Treatment (A)	4	0.0278295	0.687 ns
Block (B)	2	0.1078477	2.663 ns
Error	491	0.0405017	

ns - indicates no significance.

TABLE 4. Mensuration data averages on plantation by treatment.

	April, 1973 Treatment					October, 1974 Treatment				
	K0	K0+	K48+	K96+	K192+	K0	K0+	K48+	K96+	K192+
Trees/ha	1613	1630	1662	1712	1580	1613	1630	1662	1712	1580
Tree height (m)	10.87	11.18	11.18	11.11	11.33	11.68	11.93	11.92	11.86	12.05
Height increment (m)	-	-	-	-	-	0.81	0.75	0.74	0.75	0.72
Dbh (cm)	12.45	12.47	12.40	12.24	12.75	12.88	12.98	12.90	12.70	13.26
Basal area (m^2)/tree	0.0126	0.0127	0.0128	0.0123	0.0134	0.0137	0.0138	0.0139	0.0133	0.0144
Basal area increment/tree (m^3)	-	-	-	-	-	0.0010	0.0011	0.0011	0.0011	0.0011
Foliage weight/tree (kg)[a]	-	-	-	-	-	3.035	3.059	3.147	2.938	3.263
Volume IB/tree (m^3)[b]	0.0569	0.0584	0.0601	0.0510	0.0626	0.0660	0.0677	0.0696	0.0653	0.0718
Volume IB increment/tree (m^3)	-	-	-	-	-	0.0091	0.0093	0.0095	0.0083	0.0092
Basal area (m^2)/ha	20.32	20.70	21.27	21.06	21.17	22.10	22.50	23.10	22.77	22.75
Volume IB (m^3)/ha	91.78	95.19	99.89	97.58	98.91	106.46	110.35	115.68	111.79	113.46

[a] Log foliage weight = .5325 + 2.6208 log dbh

[b] Volume IB = .000033 $(dbh)^2(ht)$ + .002069

to become apparent (Gagnon, 1965). Additional measurements must be taken at a later date to determine if this was the case in the present study.

Volume increments found were somewhat less than the 10 to 15 m^3/yr reported elsewhere for slash pine grown under similar conditions (Malac, 1968; Nemeth, 1973; and Barnes, 1955). The relatively small increment may be due in part to the failure of the final measurement to reflect the maximum diameter increase for the 1974 growing season, but must also reflect a poor site condition that is not related to K nutrition.

Needle Length

While needle length alone cannot define a nutrient response it was anticipated that the reported short length of needles due to K deficiency (Heiberg and White, 1951; Raupach and Clarke, 1972) might be corrected with K treatment.

Needle measurements taken throughout the 1973 growing season on the first flush, mid-crown growth showed no significant differences in needle length for the period during which elongation was taking place (Table 5). While no increase in needle length due to K fertilization occurred, an increase due to treatment with N and P, unrelated to K treatment was observed at the final measurement. Longer needle length has been observed in fertilized trees for up to 15 years following fertilization (Gooding, 1970).

Effect of Fertilization on K and Other Nutrient Contents in Tissue

K Concentration of Tissue as Influenced by Time and Fertilization

Foliage K concentrations are given in Table 27. The designation

TABLE 5. Variation of flush needle length with time (age) and treatment during the 1973 growing season. (9/14/73) represents date of maximum needle elongation)

Treatment	Date[a] 5/18/73	6/5/73	7/9/73	9/14/73
	cm			
K0	5.15 a	7.42 a	13.22 a	20.08 a
K0+	4.39 a	7.46 a	13.82 a	22.04 b
K48+	4.16 a	6.84 a	14.98 a	22.33 b
K96+	3.99 a	6.79 a	13.89 a	22.45 b
K192+	5.07 a	7.15 a	14.12 a	22.37 b
S(L)[b]	0.589	0.457	0.675	0.756

[a]Column entries followed by the same letter as a control do not differ significantly (P = 5%) from the control as determined by Dunnett's method of comparing several treatment means with a control (Dunnett, 1955).

[b]S(L) is the estimated standard error of a difference between two means = $\sqrt{2 \text{ error mean square}/N}$ where N = 24 observations per mean.

"old needles" represents those needles older than one year at the start of the experiment (those needles initiated during 1971). "Current needles" were the needles initiated during 1972. First and second flush needles and the bud and stem of those flushes were those initiated during the 1973 experimental period and were sampled as they became available.

Similar patterns of K concentrations were observed for all treatments in the various tissues examined (Fig. 4, 5, 6, 7, and 8) with the old and current needles showing a significant but relatively small variation in K concentration during the sampling period (Table 6). The flush samples all showed relatively large differences in K concentration associated with time of sampling and treatment.

Means of tissue concentration by treatment, regardless of sampling date, were compared by Dunnett's test for significant differences between treatment means and a control (Dunnett, 1955), and by linear regression (Table 7). Trees receiving no K had lower K concentration in old needles than those receiving the highest rate of K. Current needles of trees receiving no K had lower K concentrations than trees receiving K,with the highest rate of K application giving the highest K concentration in the current needles. The first and second flush needles and the first flush bud and stem tissue followed the same pattern of differences in K concentration as the current needles. In all tissue tested, the increase in K concentration was linearly related to increasing rates of K applied when adjustment for date of sampling was made. Multiple regression equations for the various tissue components are presented in Table 28.

The application of N and P did not affect the K concentrations

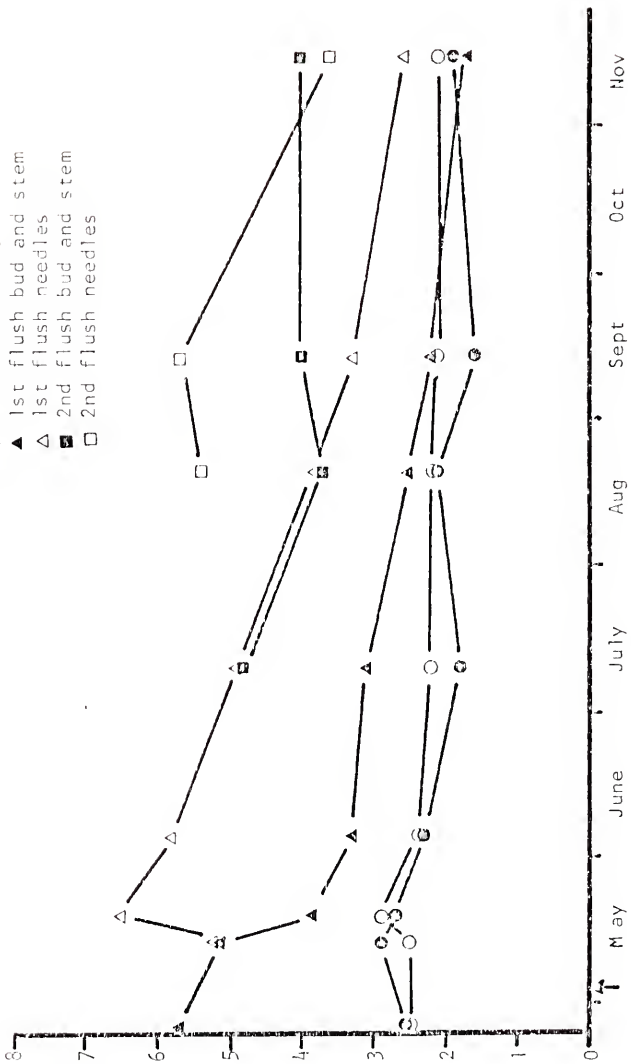


Fig. 4. Tissue K concentration with time in treatment K0.

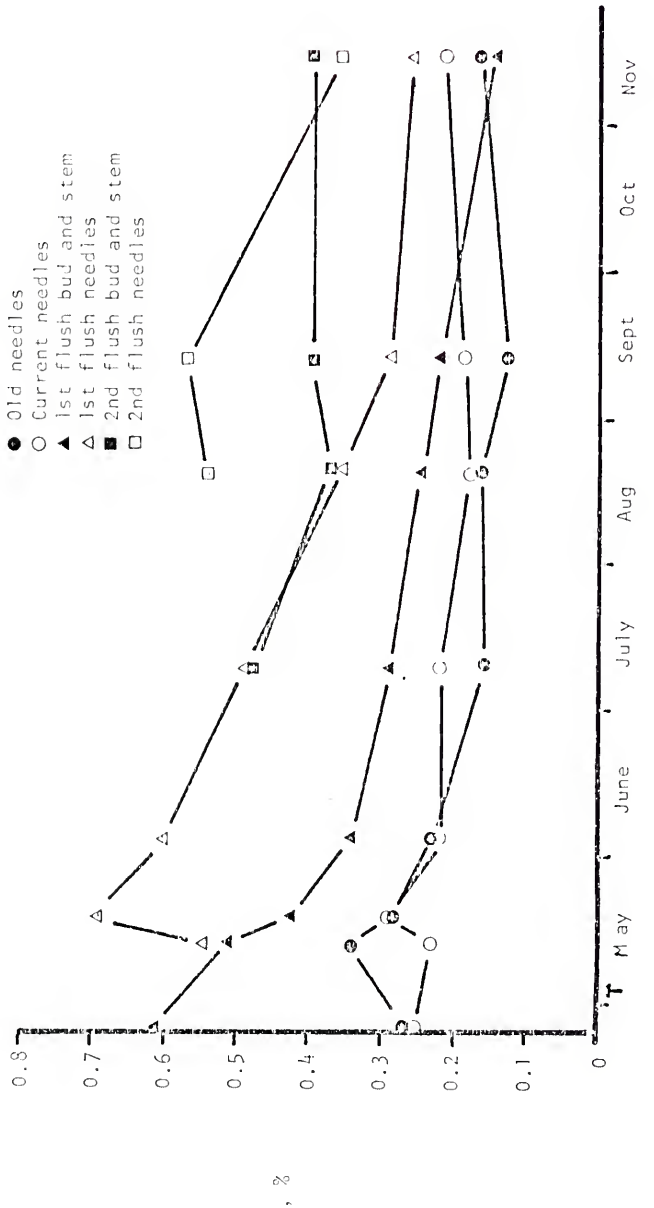


Fig. 5. Tissue K concentration with time in treatment K0+.

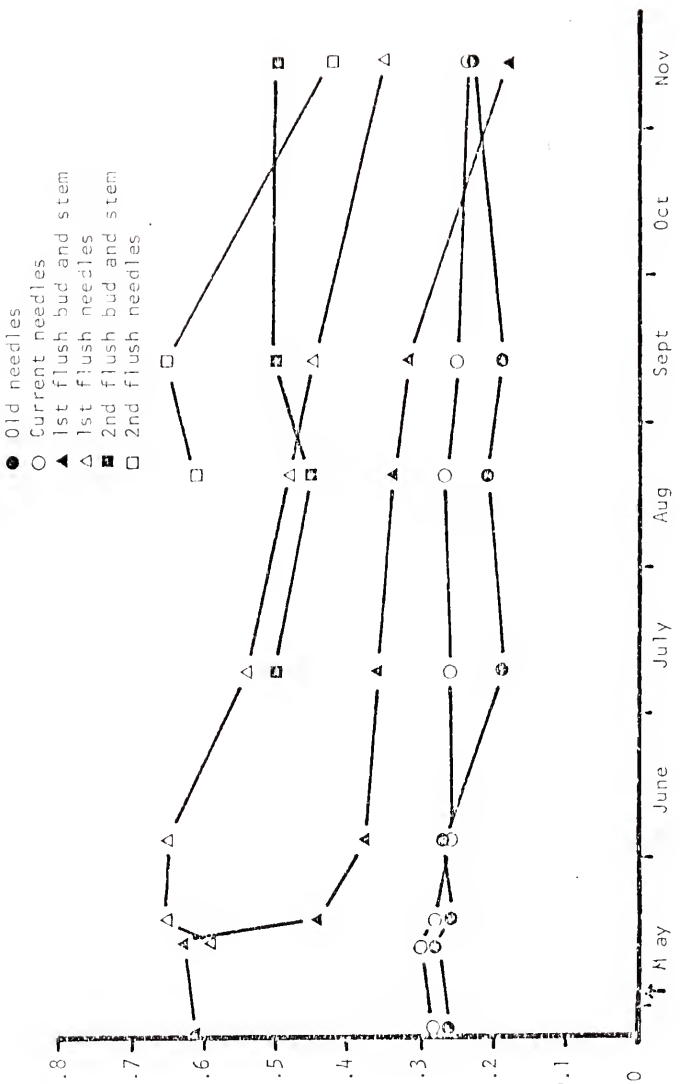


Fig. 6. Tissue K concentration with time in treatment K48+.

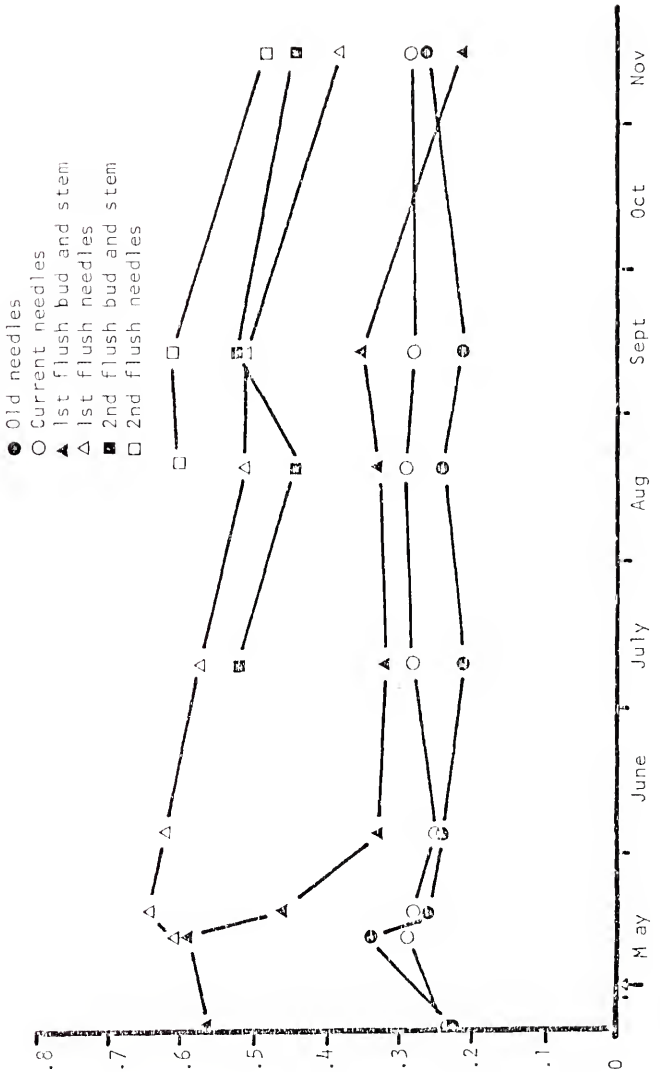


Fig. 7. Tissue K concentration with time in treatment K96+.

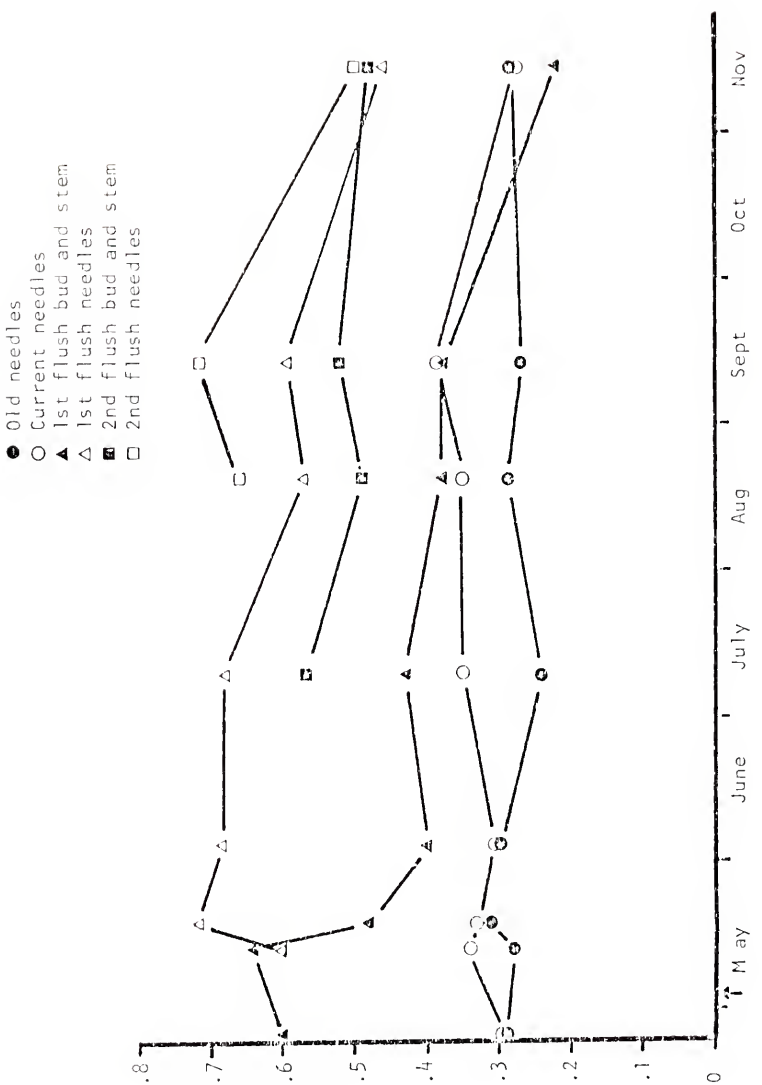


Fig. 8. Tissue K concentration with time in treatment K192+.

TABLE 6. Summary of tests of significance for K concentration of tissue by type of tissue, treatment, and date of sampling.

Type of tissue	Treatment (A)	Time (T)	AXT
Old needles	*	**	**
Current needles	**	**	**
1st flush needles	**	**	**
1st flush bud and stem	**	**	ns
2nd flush needles	**	**	ns
2nd flush bud and stem	**	**	ns

ns indicates no significance.

* indicates significance at P = 5%.

** indicates significance at P = 1%.

TABLE 7. Tissue K compared by Dunnett's test and linear regression.

Tissue component	Treatment[a]					S(L)[b]	N	r[c]
	K0	K0+	K48+	K96+	K192+			
	% K							
Old needles	0.22	0.22	0.24	0.25	0.28	0.016	24	0.424**
Current needles	0.24	0.23	0.27	0.27	0.33	0.014	24	0.703**
1st flush needles	0.46	0.45	0.53	0.55	0.62	0.021	21	0.432**
1st flush bud and stem	0.34	0.35	0.41	0.39	0.44	0.022	24	0.212*
2nd flush needles	0.49	0.47	0.56	0.56	0.63	0.013	9	0.449**
2nd flush bud and stem	0.42	0.39	0.49	0.48	0.51	0.016	12	0.523**

[a] K0 and K0+ do not differ significantly when compared with a Student's t-test.

[b] $S(L) = \sqrt{2 \text{ error mean square}/N}$, where N is the number of observations per mean.

[c] r = simple regression coefficient for treatment means receiving DAP.
ns indicates no significance
* indicates significance at P = 5%
** indicates significance at P = 1%

in any of the tissue studied.

Treatment means were also compared by date of sampling regardless of treatment (Table 8A). The early dates of sampling showed relatively little effect of treatment on K concentration. By 32 days after fertilizer application, only the highest K rate had increased the mean K concentration. Two months after treatment a linear response of K concentration with increasing rates of K application was found. The linear trend continued to be significant for the duration of the sampling period (Table 8A).

Mean K concentration of the various tissues on a given date, regardless of treatment, in old and current needles did not differ from one another until well into the growing season, at which time the mean concentration of the old needles was reduced from its early season level (Table 8B). The current tissue K concentration remained relatively constant throughout the growing season.

The first flush bud and stem was sampled prior to emergence of the needles, before fertilizer treatments. At two weeks following treatment, the needles and bud and stem from the first flush differed in K concentration from that of the first sampling. The K concentration in the buds and stems showed rapid reduction and the needles increased in K concentration and then decreased linearly. The second flush needles showed a similar pattern as the first flush but the bud and stem did not show a reduction of K concentration.

The pattern of K concentration over the sampling period indicated greater K concentrations in the first flush growth and less fluctuation in K concentration throughout the growing season than previously reported (Mead and Pritchett, 1974). The previous year's

TABLE 8. The effect of treatment and type of tissue on the mean K concentration for sampling dates.

A. The effect of treatment[a]

Sample date	Days after treatment	Treatment					S(L)	N	r
		KO	KO+	K48+	K96+	K192+			
		% K							
4/24	-10	0.36	0.37	0.38	0.34	0.40	0.019	9	0.032 ns
5/13	10	0.39	0.40	0.45	0.46	0.46	0.015	12	0.130 ns
5/18	15	0.40	0.42	0.41	0.41	0.46	0.032	12	0.094 ns
6/ 4	32	0.34	0.35	0.39	0.36	0.42	0.026	12	0.148 ns
7/ 9	67	0.34	0.32	0.37	0.38	0.45	0.017	15	0.300 *
8/19	108	0.33	0.32	0.39	0.40	0.45	0.017	18	0.274 *
9/13	133	0.32	0.29	0.39	0.41	0.48	0.020	18	0.389 **
11/14	195	0.27	0.24	0.32	0.34	0.37	0.012	18	0.395 **

B. The effect of tissue type[b]

Sample date	Days after treatment	Needles		1st flush		2nd flush		S(L)	N
		Old	Current	Needle	Bud and stem	Needle	Bud and stem		
		% K							
4/24	-10	0.26 a	0.26 a	-	0.59 b	-	-	0.009	15
5/13	10	0.30 a	0.28 a	0.57 b	0.57 b	-	-	0.014	15
5/18	15	0.28 a	0.29 a	0.67 b	0.44 c	-	-	0.015	15
6/ 4	32	0.25 a	0.25 a	0.62 b	0.36 c	-	-	0.011	15
7/ 9	67	0.19 a	0.26 b	0.55 c	0.34 d	-	0.50 e	0.012	15
8/19	108	0.22 a	0.26 b	0.45 c	0.31 d	0.59 e	0.42 f	0.012	15
9/13	133	0.19 a	0.26 b	0.44 c	0.30 d	0.62 e	0.46 f	0.012	15
11/14	195	0.22 a	0.25 a	0.33 b	0.19 c	0.41 d	0.43 d	0.015	15

[a]Treatment effect regardless of tissue types. Row means connected by the same line as the control (KO+) do not differ significantly from the control (P = 5%) as determined by Dunnett's test. See footnotes a, b, and c, Table 7. KO and KO+ do not differ when compared by Student's t test.

[b]Tissue type effect regardless of treatments. Means in rows followed by the same letter do not differ significantly from one another using Duncan's new multiple-range test (Duncan, 1955).

flush (or current needles) ranged from 0.20 to 0.30% K in the no and low K rate treatments and increased to a range of from 0.28 to 0.39% with the highest K application level. The lowest K concentrations generally occurred at the end of the season and even then differences due to K application rates existed.

With no K applied, the K concentration in slash pine in the study was considerably lower than many pines growing in known K deficient sites. The highest rate of K application in this experiment elevated the foliar K from the lower range of K concentration to a middle range for slash pine.

Na, Ca, Mg, and P Concentration of Tissue as Influenced by Time and Fertilization

Concentrations of Na, Ca, Mg, and P were little affected by fertilizer treatment during the sampling period with significant differences in concentrations only occurring among the various types of tissue. A summary of these effects is given by element in Table 9.

Average concentrations of Na in foliage were generally below 0.10% (Table 10) with the old needles having larger concentrations than the current or flush tissue (Table 29). Only traces of Na have been reported in slash pine foliage (Young, 1948).

Older tissue also accumulated higher concentrations of Ca early in the growing season (Table 10) and appeared to decrease in concentration as the flush bud and stem increased in Ca late in the growing season (Table 30). The first flush needles had somewhat higher Ca concentrations than the second flush needles and they both appeared to stay relatively constant during the season. Calcium concentrations were comparable to those previously reported for slash pine but did not show

TABLE 9. Summary of tests of significance for Na, Ca, Mg, and P concentrations of tissue by type of tissue and treatment effect.

	Treatment (A)	Tissue type (B)	AXB
Na concentration	ns	**	ns
Ca concentration	ns	**	ns
Mg concentration	ns	**	ns
P concentration	ns	**	ns

ns indicates no significance

* indicates significance at P = 5%.

** indicates significance at P = 1%.

TABLE 10. Average Na, Ca, Mg, and P concentrations in slash pine tissue.

Nutrient	Tissue component	Treatment				
		K0	K0+	K48+	K96+	K192+
		%				
Na	Old needles	0.09	0.09	0.09	0.11	0.10
	Current needles	0.05	0.05	0.05	0.05	0.05
	1st flush bud and stem	0.04	0.03	0.02	0.02	0.03
	1st flush needles	0.03	0.03	0.03	0.03	0.03
	2nd flush bud and stem	0.01	0.02	0.02	0.02	0.01
	2nd flush needles	0.02	0.02	0.02	0.02	0.02
Ca	Old needles	0.24	0.27	0.27	0.26	0.25
	Current needles	0.23	0.24	0.24	0.22	0.23
	1st flush bud and stem	0.10	0.12	0.13	0.12	0.12
	1st flush needles	0.19	0.19	0.20	0.19	0.19
	2nd flush bud and stem	0.06	0.07	0.09	0.08	0.09
	2nd flush needles	0.12	0.16	0.15	0.14	0.15
Mg	Old needles	0.09	0.10	0.10	0.10	0.09
	Current needles	0.12	0.12	0.12	0.12	0.12
	1st flush bud and stem	0.12	0.13	0.13	0.14	0.13
	1st flush needles	0.12	0.13	0.13	0.13	0.12
	2nd flush bud and stem	0.12	0.12	0.13	0.13	0.12
	2nd flush needles	0.14	0.14	0.16	0.15	0.15
P	Old needles	0.09	0.09	0.09	0.09	0.09
	Current needles	0.08	0.09	0.09	0.09	0.09
	1st flush bud and stem	0.11	0.12	0.11	0.11	0.11
	1st flush needles	0.08	0.08	0.10	0.09	0.09
	2nd flush bud and stem	0.10	0.08	0.10	0.10	0.11
	2nd flush needles	0.10	0.10	0.12	0.11	0.11

much increase in needle Ca concentrations among dates (Mead and Pritchett, 1974).

Little variation occurred in the Mg concentration with the exception of the lower concentrations in the old needles (Tables 10 and 31). Needle concentration of Mg has been found to vary dramatically with location with the concentration occasionally higher in the new flush than in the previous year's growth (current) and ranging from 0.07 to 0.14% in the needles with no consistent increasing or decreasing trend observable.

Phosphorus was also unaffected by treatment, even though DAP had been applied at 45 kg P/ha. Type of tissue was only a minor source of variation (Tables 10 and 32).

Phosphorus concentrations observed were consistent with reported values in tissue and showed little variation with time during the growing season or with type of tissue (Mead, 1971).

Leaching of Nutrients from the Trees

Throughfall Nutrient Concentrations

Concentration of K in the throughfall increased from 0.45 ppm with no K application to 0.67 ppm with 192 kg K/ha (Table 33). The annual contribution of K by the throughfall increased linearly from 3.7 to 5.7 kg/ha (Table 11) with a regression equation of kg K/ha = 3.53 + 0.011 kg K/ha applied. When the 1.6 kg K/ha/yr in rainfall was subtracted from this quantity a net of 2.1 kg K/ha was found to have been added as it passed through the tree crowns of the trees receiving no K and 4.1 kg K/ha in the trees receiving 192 kg K/ha. Whether this was leached from the foliage or dust is not readily known.

TABLE 11. Annual nutrient contents of throughfall.

Nutrient	Treatment[a]					S(L)[b]	N
	K0	K0+	K48+	K96+	K192+		
	kg/ha						
K	3.85	3.87	3.68	4.42	5.72	0.72	3
Na	8.02	7.80	7.46	8.38	9.53	0.80	3
Ca	8.49	6.60	4.88	6.51	7.26	1.15	3
Mg	2.44	2.59	1.85	2.27	2.78	0.51	3
P	0.10	0.10	0.12	0.15	0.10	0.14	3

[a] Row means connected by the same line as the control (K0+) do not differ significantly from the control (P = 5%) as determined by Dunnett's test. K0 and K0+ do not differ significantly when compared with a Student's t-test.

[b] See footnote b, Table 7.

Sodium concentrations in the throughfall were not much greater than the rainfall values and gave no evidence of fertilizer effect (Table 11). The average annual Na contribution in throughfall was 8.2 kg/ha compared to 7.2 kg/ha in rainfall. Values of Ca, Mg, and P in the throughfall showed no treatment effect (Tables 11 and 34). Quantities in the throughfall were 6.7 kg Ca/ha, 2.4 kg Mg/ha, and 0.11 kg P/ha annually. When the rainfall contribution was subtracted, the net throughfall contributions were 2.2 kg Ca/ha and 1.1 kg Mg/ha. Phosphorus in the throughfall was lower than the rainfall P content, 0.11 kg/ha and 0.20 kg/ha, respectively, giving a net uptake in the crown rather than a loss, suggesting direct foliar absorption of nutrients (Ovington, 1960).

In the southeastern United States, loblolly pine throughfall and stemflow were combined for annual contributions of 12.3 kg K/ha, 6.0 kg Ca/ha, 2.0 kg Mg/ha, and 0.5 kg P/ha (Wells and Jorgensen, 1974). Other than the higher K and P contribution, the loblolly pine values agreed with those found here for throughfall only. Radiata pine had larger amounts of K, Mg, and P, but smaller amounts of Ca than found in this study (Attiwill, 1966; Will, 1955; Will, 1968). Other studies have shown much greater nutrient concentrations in throughfall. Annual values as high as 35 kg K/ha, 35 kg Na/ha, 30 kg Ca/ha, 10 kg Mg/ha, and 0.5 to 1.0 kg P/ha have been reported (Madgwick and Ovington, 1959; O'Hare, 1967; Reiner, 1972; Tamm, 1951).

Stemflow Losses from Trees

Stemflow losses of nutrients were small with no apparent treatment effect (Table 12). Annual losses of 0.21 kg K/ha, 0.38 kg Na/ha,

TABLE 12. Annual nutrient loss from trees by stemflow.

Component	Treatment K0	K0+	K48+	K96+	K192+	Average	S(L)[a]	N
	liter/tree							
Stemflow collected	187	155	173	203	169	177	58	3
	cm							
Stemflow	3.0	2.5	2.8	3.3	2.5	2.8	0.92	3
	kg/ha							
K content	0.21	0.18	0.22	0.23	0.22	0.21	0.05	3
Na content	0.41	0.34	0.34	0.47	0.34	0.38	0.11	3
Ca content	0.42	0.41	0.49	0.47	0.42	0.44	0.08	3
Mg content	0.10	0.11	0.12	0.13	0.11	0.11	0.05	3
	ppm							
K concentration	0.67	0.72	0.76	0.68	0.81	0.73	-	-
Na concentration	1.36	1.37	1.38	1.36	1.25	1.35	-	-
Ca concentration	1.38	1.64	1.71	1.37	1.59	1.53	-	-
Mg concentration	0.40	0.42	0.43	0.38	0.42	0.42	-	-

[a]See footnote b Table 7.

0.44 kg Ca/ha, and 0.11 kg Mg/ha were found. Only traces of P could sometimes be found in the stemflow. These values represented less than 10% of the rainfall input. Nutrient contents of the stemflow in other studies were found to represent only 5% of the throughfall contribution (Wells and Jorgensen, 1973). While calculated on a per ha basis, stemflow may more directly affect the area immediately surrounding the tree with its higher nutrient content.

Throughfall and Stemflow Quality and Quantity as Affected by Amounts of Rainfall

The origin of the nutrients in throughfall is open to question, although the water solubility of the nutrients in plant tissue is well documented (Cassiday, 1966). In an attempt to examine throughfall leaching more closely, regression analysis of throughfall nutrient concentration against quantity of throughfall for the various elements was performed (Table 13). The equations for K did not differ greatly with K treatment but did show a low negative linear relationship with quantity of throughfall. The nutrient concentration extrapolated to 0 volume indicated an initial throughfall concentration of 1 ppm K as compared to an overall average of only 0.5 ppm; suggesting that the initial rate of removal is greater than the overall rate of removal. Sodium behaved similarly, with an initial concentration 1.42 ppm as compared to a 1 ppm overall average. This was not the case with Ca and Mg, as both initial and overall average concentrations averaged 0.9 and 0.3 ppm, respectively. While dust accumulation on foliage may be a source of throughfall nutrients (Nihlajard, 1970; Schlisinger and Reiner , 1974) the leaching of nutrients from the live foliage cannot be discounted.

When rainfall and throughfall volumes were compared by regression

TABLE 13. Regression equations of throughfall volume on throughfall nutrient concentrations.

Element	Treatment	Regression equation	Correlation coefficient - r -
K	K0	ppm = 0.96 - 0.0005 (ml.volume)	- 0.345**
K	K0+	ppm = 1.12 - 0.0007 (ml.volume)	- 0.473**
K	K48+	ppm = 0.99 - 0.0005 (ml.volume)	- 0.363**
K	K96+	ppm = 1.03 - 0.0005 (ml.volume)	- 0.369**
K	K192+	ppm = 1.10 - 0.0005 (ml.volume)	- 0.312**
Na	All	ppm = 1.42 - 0.0005 (ml.volume)	- 0.443**
Ca	All	ppm = 0.88 - 0.0003 (ml.volume)	- 0.402**
Mg	All	ppm = 0.26 - 0.0001 (ml.volume)	- 0.507**

** significant at 1% level.

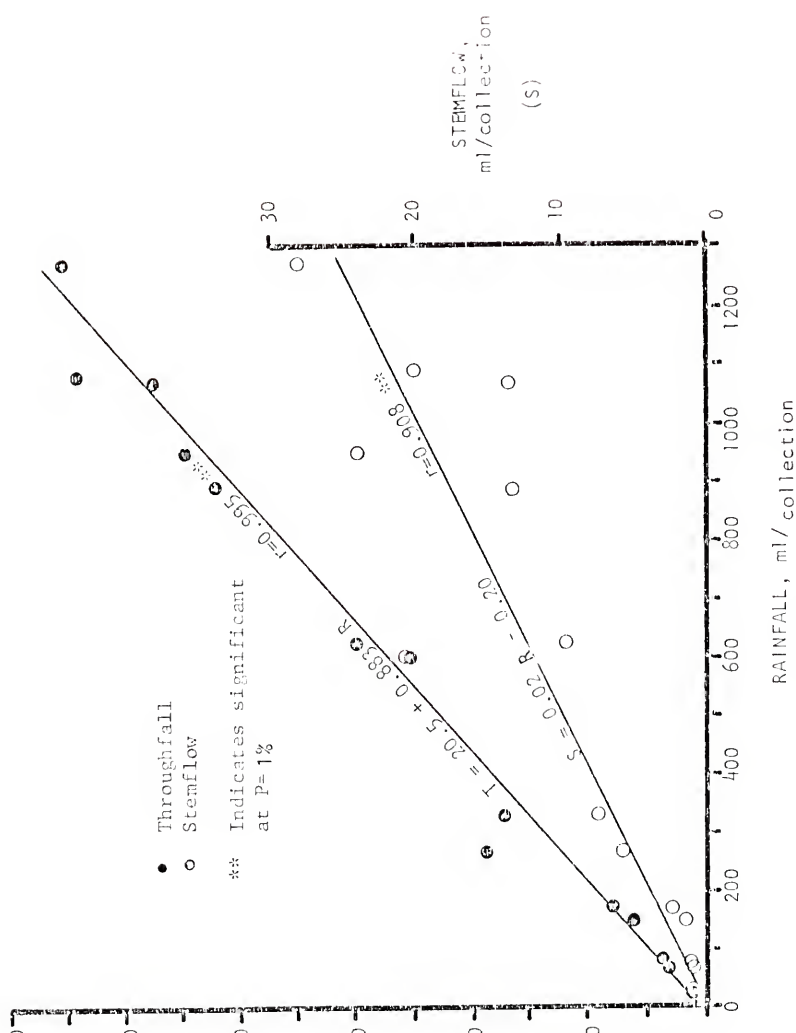


Fig. 9. Regression of throughfall and stemflow volumes on rainfall volume.

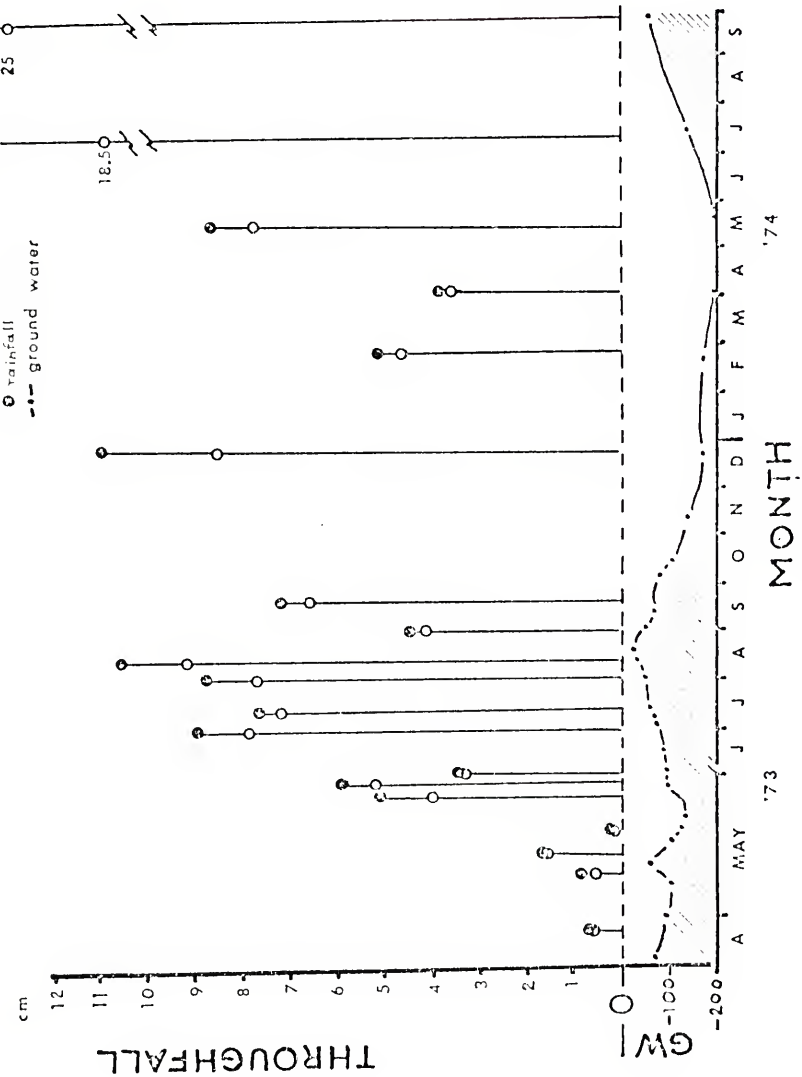


Fig. 10. Throughfall, rainfall, and groundwater level in the plantation.

(Fig. 9) a high correlation was found. Differences between rainfall and throughfall by collection are shown in Fig. 10. Stemflow was also compared to rainfall by regression (Fig. 9). On an annual basis, throughfall was 85% of the rainfall and stemflow was 3% of the rainfall on a total area basis. By difference, crown retention was found to account for 12% of rainfall.

Approximately 100 rainfall events occurred during the experimental period during which 151 cm of rain fell. Of this, 88% was accounted for by throughfall and stemflow. The remaining 12% or 18 cm of rainfall was divided between the individual rainfall events, giving approximately 0.18 cm of rainfall as a measure of crown retention.

While the plantation under study had not completed crown closure, the results of the stemflow and throughfall compared with results found elsewhere (Czarnowski and Olszewski, 1968; Nye, 1961; Stanhill, 1970; Smith, 1972; Voigt, 1960).

Litterfall

Estimates of Annual Litterfall

While needle fall occurred throughout the year, a large proportion was found in the winter (Table 35).

Litter weight averaged 3.8 t/ha/yr for the needle portion and 0.4 t/ha/yr (Table 36) for the "other" (branch, bark, cone and duff) portion (Table 37) and was not affected by fertilizer treatment. This compares with 3 to 5 t/ha/yr of needle production and 0.3 to 1.4 t/ha/yr branchfall found in loblolly pine (Wells, 1974) and 4 t/ha/yr for Caribbean pine (*P. caribaea*) (Bray and Gorham, 1964).

Effect of Fertilization on Litter Nutrient Concentration

No differences were found in nutrient concentration either in the needle litter or in the other litter (Table 14) with the exception of K treatment at 192 kg K/ha level. Annual nutrient returns to the forest floor through litterfall were 1.5 kg K/ha for the 0 K applied, increasing linearly with K applications to 3.5 kg K/ha for the highest K treatment. Other elements returned to the forest floor annually were 1.8 kg Na/ha, 12.1 kg Ca/ha, 3.5 kg Mg/ha, and 1.5 kg P/ha. Rainfall volumes did not affect the litter nutrient composition as determined by comparing the nutrient concentration at different dates with the amount of rainfall that occurred between litter collection dates.

The annual returns of litter fall were similar to those of a 21 m^2 basal area stand of thinned loblolly pine in the southeastern United States that had only 2.2 t/ha/yr total litter fall (Wells, 1974) indicating a lower concentration of nutrients in the slash pine litter in this study.

Residence Time of K and Other Nutrients in the Forest Floor

Samples taken below and adjacent to the 15 litter collection trays were examined to estimate the residence time of litter and nutrient losses over time. Because there was no weight response to treatment, the average litter and floor weights of all plots was used.

An average of 5.4 t/ha of needle fall occurred over the 17-month experimental period. Under the litter trays there had been a 17-month period of decomposition with no new additions, resulting in a residual of 5.9 t/ha of litter (Table 15A). The undisturbed forest floor was found to have an average of 12.2 t/ha as compared to only

TABLE 14. Annual nutrient content of litter from slash pine.

Nutrient	Litter component	Treatment[a] K0	K0+	K48+	K96+	K192+	S(L)	N	r
		kg/ha							
Weight	Needles	3805	3634	3748	3836	3996	532	3	0.226 ns
	Other	384	170	393	501	655	195	3	0.589 *
K	Needles	1.7	1.5	2.0	2.2	3.5	0.34	3	0.880 **
	Other	0.1	0.1	0.1	0.1	0.1	0.06	3	-
Na	Needles	1.7	1.7	1.6	1.9	2.0	0.29	3	-
	Other	0.0	0.0	0.1	0.1	0.1	0.05	3	-
Ca	Needles	11.9	11.9	12.7	11.9	12.1	1.29	3	-
	Other	1.0	0.4	1.3	1.6	1.8	0.75	3	-
Mg	Needles	3.5	3.4	3.2	3.7	3.7	0.97	3	-
	Other	0.1	0.1	0.1	0.3	0.1	0.20	3	-
P	Needles	1.2	1.7	1.6	1.6	1.5	0.30	3	-
	Other	0.0	0.0	0.0	0.1	0.1	0.09	3	-

[a]See footnotes a, b, and c Table 7. K0 and K0+ do not differ significantly when compared with a Student's t-test. Means connected by the same line as the control (K0+) do not differ significantly from the control (P = 5%) as determined by Dunnett's test.

TABLE 15. Quantities of litter, forest floor, and nutrient at conclusion of experiment.

A. Weight relations

Treatment	Litter Collector	Forest floor	
		Under collector	Adjacent to collector
	kg/ha/17 mo		
K0	5.4	6.5	12.0
K0+	5.1	5.6	11.4
K48+	5.3	6.9	13.0
K96+	5.4	5.2	11.9
K192+	5.7	5.1	12.5
Average	5.4	5.9	12.2
S(L)[a]	0.75	0.96	1.79

B. Nutrient relationships

Nutrient	Litter nutrient concentration	Forest floor nutrient concentration
	%	
K	0.057	0.046
Na	0.046	0.015
Ca	0.320	0.380
Mg	0.091	0.077
P	0.040	0.036

11.3 t/ha for litter fall collected plus the residual floor under the trays, although this difference was not significant.

When the nutrient concentration of the forest floor was compared to the average litter fall nutrient concentration, a 20% reduction of K and a 67% reduction of Na was found. Calcium, Mg, and P were found to increase 19%, decrease 15%, and decrease 10%, respectively, from the litter fall to the forest floor (Table 15B).

The forest floor measurements show results comparable to those of other areas of the southeastern United States of similar aged loblolly pine (Switzer and Nelson, 1972; Metz, Wells, and Kormanik, 1970). Accumulation of Ca with losses of Na, Mg, and P from the floor was expected due to the insolubility of Ca in the tissue and the solubility of the other nutrients. The small magnitude of the K loss may have significant implications in the ability of slash pine to maintain adequate growth with small amounts of soil K.

Nutrient Status of Soil and Soil Water Following Fertilization

Changes in Soil K with Depth and Time

Soil K concentration increased 6 to 22 times with increasing K treatment as early as 6 days following fertilization (Fig. 11, May 9, 1973). Only 0.6 cm of rainfall had occurred, but time was apparently sufficient to move fertilizer K to depths greater than 5 cm in the soils receiving 96 and 192 kg K/ha. Recoveries of K from soil were calculated by summing the extractable soil K for the profile depth, subtracting the extractable K found in the treatment receiving no K, and dividing the excess K by the application rate. At the first sampling after

treatment, recoveries of 108, 45, and 66% of applied K were found in plots receiving 48, 96, and 192 kg K/ha, respectively. In the 96 and 192 kg K/ha treatments, sampling depth appeared to be insufficient to recover larger amounts of applied K.

By the 19th day after sampling the influence of K application extended to a depth greater than 20 cm (Fig. 11, May 22, 1973) with less than 5 cm of rainfall since fertilization. Recoveries from soil were 59, 69, and 57% for treatments receiving 48, 96, and 192 kg K/ha, respectively. Deeper sampling of the soil on the 26th day after fertilization showed little added recovery of K but did show a redistribution of K down the soil profile (Fig. 11, May 29, 1973). Concentration of K in the 40-60 cm depth ranged from 1 to 7 ppm only (Table 26).

After 100 days, treatment effects were still present and 34, 25, and 29% of the applied K was found (Fig. 11, August 13, 1973).

By the conclusion of the experiment, 15, 13, and 7% of the 48, 96, and 192 kg K/ha added were recovered, respectively (Fig. 11, September 24, 1974).

A summary of the analysis of variance tests of significance for soil K and other nutrients during 1973 are given in Table 16.

Recoveries in the soil calculated only on the soil extractable basis indicated that K was not being removed rapidly from the soil by leaching as elevated K concentration front moving down the soil with time was not observed. Ground water K concentration did show increased K concentrations and may account for some loss. Plant uptake may account for some of the unrecoverable K in the soil (Bengtson and Voight, 1962; Riekert, 1971; Krause and Wilde, 1960), but insufficient sampling

TABLE 16. Summary of tests of significance for sampling time and nutrient concentration of soil by treatment and depth.

Date	Nutrient	Treatment (A)	Depth (D)	AXD
5/ 9/73	K	**	**	**
	Na	ns	**	ns
	Ca	ns	**	**
	Mg	ns	**	ns
	P	**	**	ns
5/22/73	K	**	**	**
	Na	ns	ns	ns
	Ca	ns	**	ns
	Mg	ns	**	ns
	P	**	**	ns
5/29/73	K	**	**	**
	Na	ns	ns	ns
	Ca	ns	**	ns
	Mg	ns	**	ns
	P	**	**	ns
8/13/73	K	**	**	**
	Na	ns	ns	ns
	Ca	ns	*	ns
	Mg	ns	**	ns
	P	**	ns	ns

ns not significant
* indicates significant at 5% level
** indicates significant at 1% level

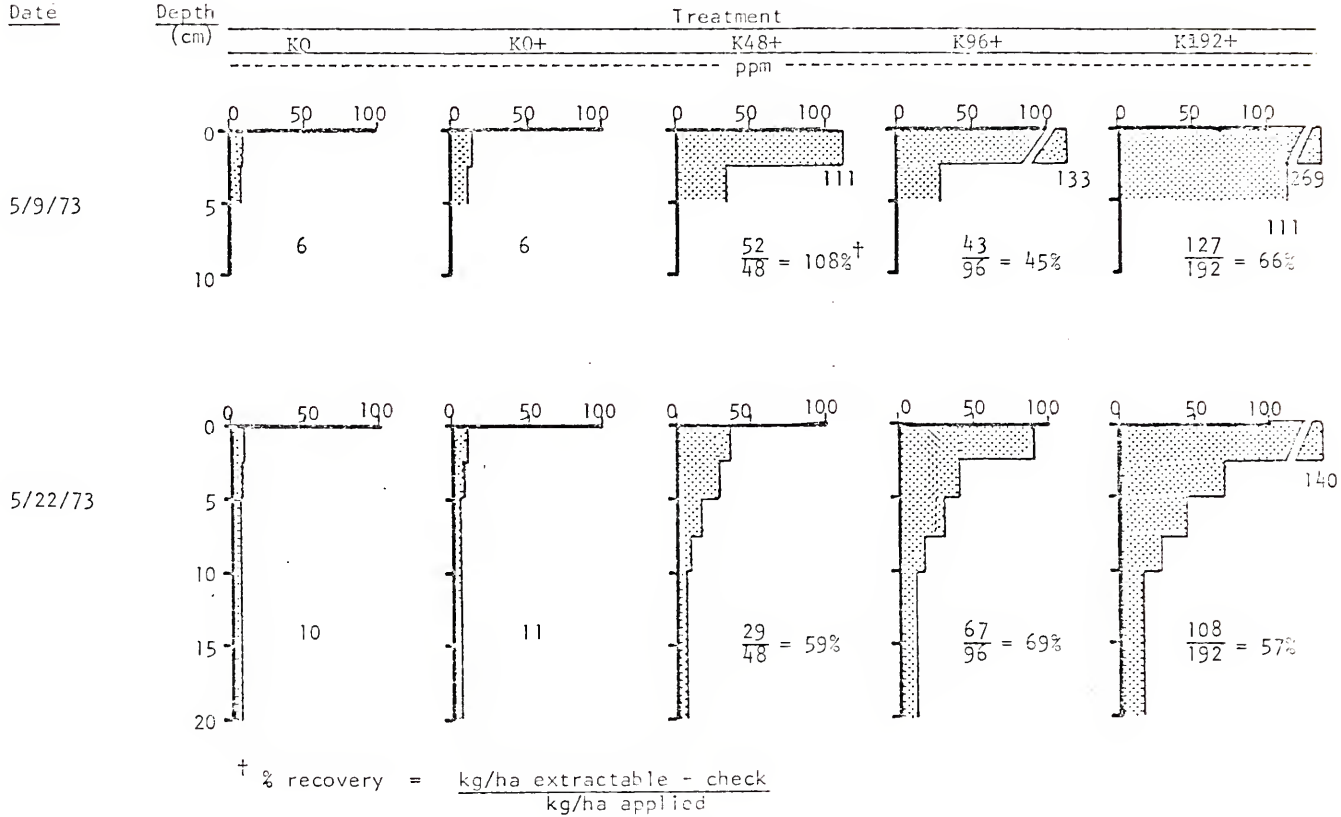


Fig. 11. Distribution of K in soil by treatment, time, and depth.

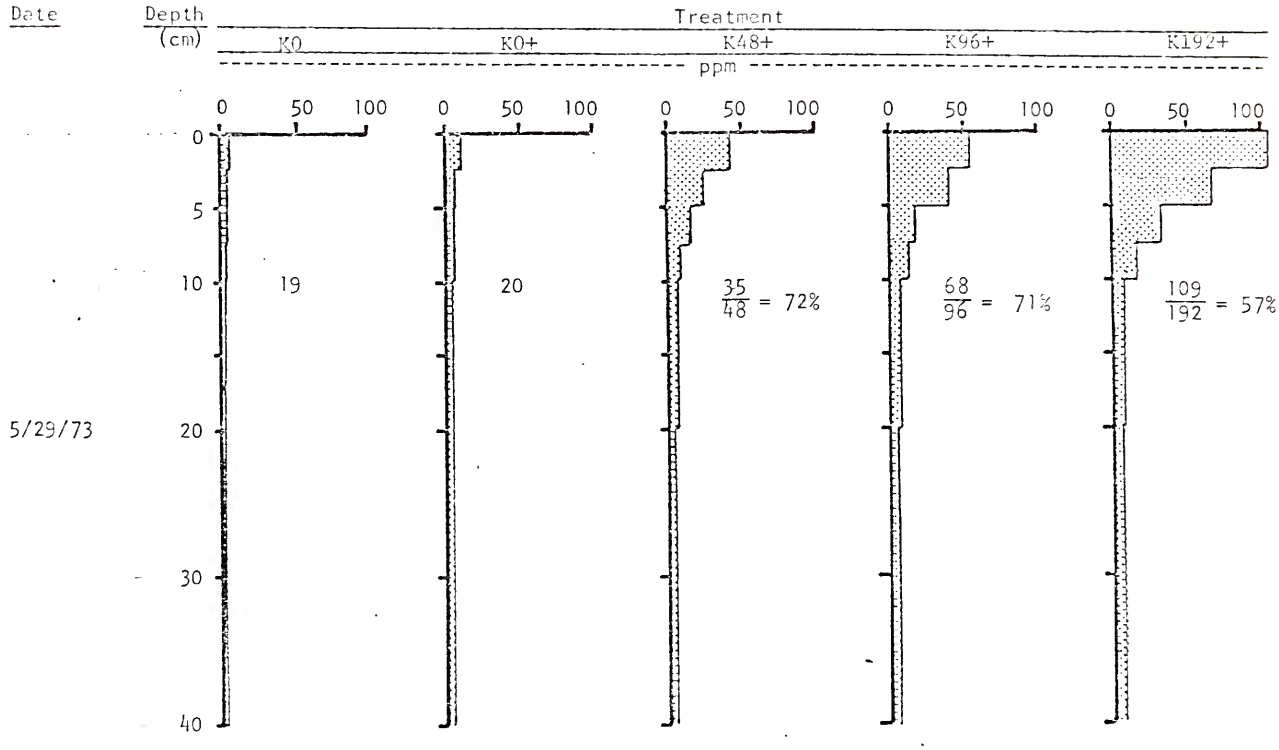


Fig. 11. Continued.

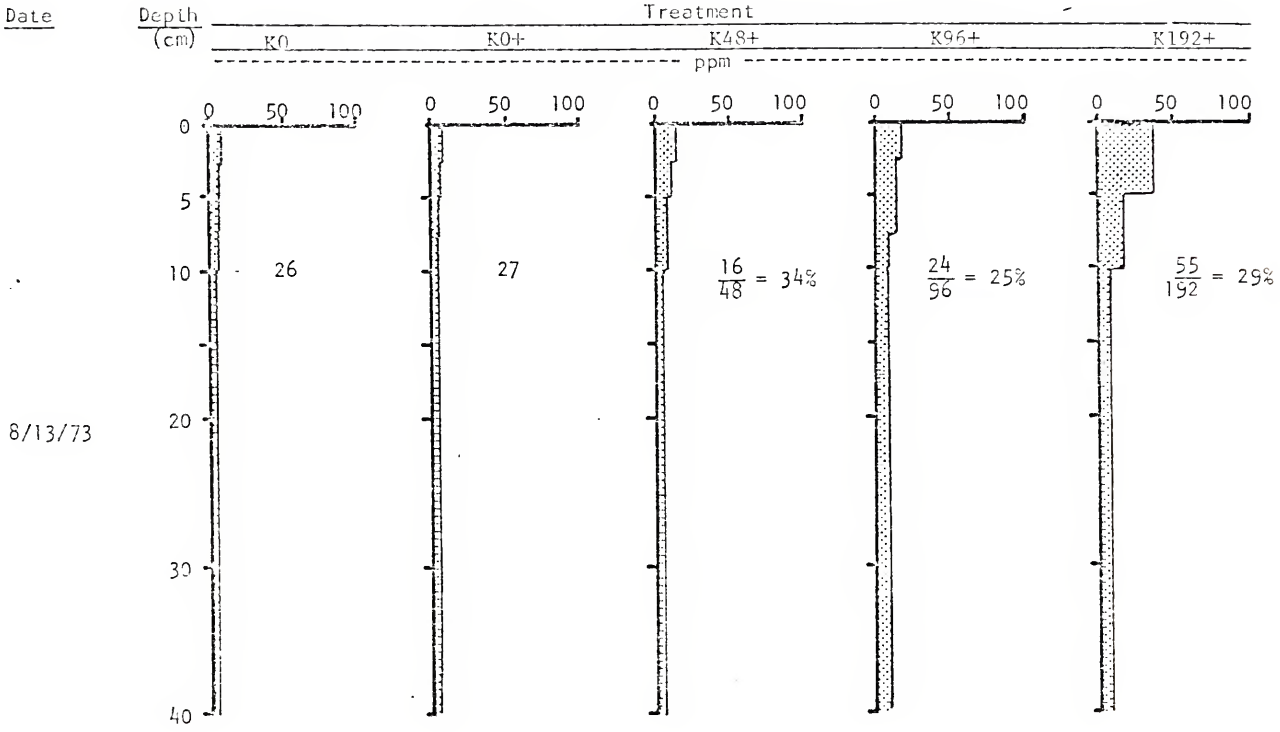


Fig. 11. Continued.

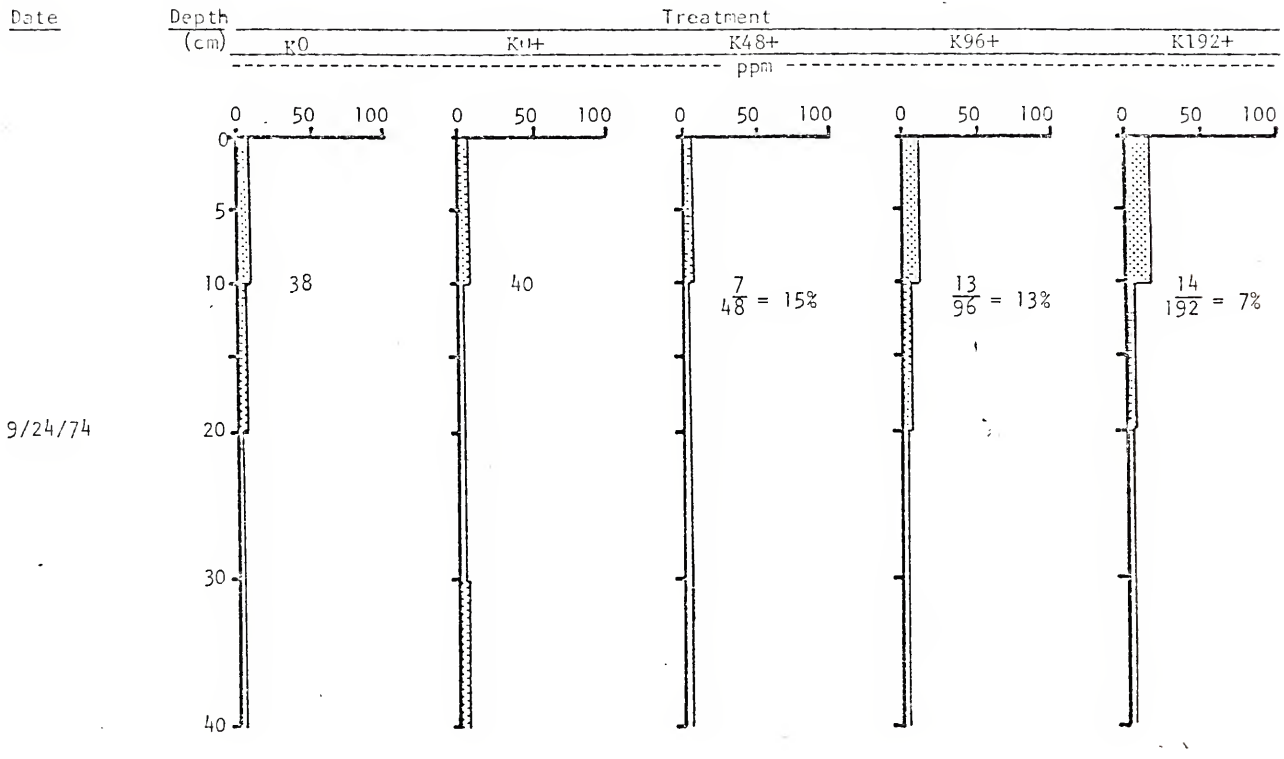


Fig. 11. Continued.

depth, fixation, and microbial uptake (Ewel et al., 1975) must also be considered.

Changes in Other Nutrients with Depth and Time

Concentrations of Na, Ca, and Mg varied with depth and time of sampling (Table 17), but were not influenced by treatment (Table 16). Phosphorous concentration in the surface 5 cm of soils receiving DAP was higher during the first month after fertilization than the soil that received no phosphorous (Table 26).

Soil Water and Ground Water Nutrient Concentration

Soil water nutrient concentrations show that K may move more rapidly into the soil via soil water than soil sampling would indicate, with relatively high concentrations being detected at 20 and 40 cm depths within 15 days after fertilization (Table 18). There was a linear response at the 20 cm depth but not at the 40 cm depth. No indication of K leaching into the ground water was detected until 60 days following fertilization when there appeared to be a linear increase of K in the ground water due to K application rates (Table 18).

Average K contents of the unfertilized treatments were similar to those found in tension lysimeter studies elsewhere in the Austin Cary forest on similar soils (CRIFF Progress Report, 1973-74), with a peak concentration in the spring of the year and a decline after the onset of the rainy season in June. Variation in concentration of cations in the ground water was high, with coefficients of variation often reaching 50% and variation of concentration of cations in the soil water often exceeding 100%.

TABLE 17. Average Na, Ca, Mg, and P concentrations in soil by sample date and depth.

Date	Depth (cm)	Na	Ca	Mg	P
		ppm			
4/27/73	0 - 5	9	75	11	1.8
	5 - 10	10	30	3	1.6
5/ 9/73	0 - 2.5	11	102	15	19.0
	2.5 - 5	9	72	10	8.9
5/22/73	0 - 2.5	4	64	10	7.7
	2.5 - 5	4	51	8	5.3
	5 - 7.5	4	45	6	3.9
	7.5 - 10	4	37	5	3.3
	10 - 20	4	23	2	2.9
5/29/73	0 - 2.5	6	85	13	4.1
	2.5 - 5	5	58	8	3.9
	5 - 7.5	5	56	7	3.7
	7.5 - 10	5	44	5	3.1
	10 - 20	3	34	3	2.8
	20 - 40	4	14	2	1.9
	40 - 60	4	11	2	1.8
8/13/73	0 - 2.5	8	86	12	2.3
	2.5 - 5	9	63	8	2.0
	5 - 7.5	8	52	7	1.9
	7.5 - 10	8	47	5	2.0
	10 - 20	5	25	4	1.8
	20 - 40	5	13	3	1.8
	40 - 60	5	9	2	2.0

TABLE 18. Soil water and groundwater nutrient concentrations.

Nutrient	Depth	Treatment	1973 Sampling date[a] 4/17	4/27	5/3	5/18	5/22	5/28	5/31	7/2	8/13	9/13	Ave.	r[b]
	cm		ppm											
K	20	K0	-	-	4.0	7.4	4.4	4.2	-	2.0	1.1	0.2	3.1	
		K0+	-	-	3.7	4.3	7.5	9.8	-	1.9	0.9	0.3	4.1	
		K48+	-	-	2.1	26.5	22.0	9.6	-	5.9	2.9	0.8	10.0	
		K96+	-	-	3.5	88.7	102.7	35.3	-	10.6	7.3	4.0	36.0	
		K192+	-	-	3.5	177.5	80.0	78.5	-	20.9	17.2	4.6	54.6	
													S(L)21.3 [a]	0.630**
	40	K0	-	-	1.6	2.7	9.9	3.5	-	1.4	1.0	0.4	2.9	
		K0+	-	-	3.1	9.2	14.8	7.0	-	3.0	1.3	0.5	5.6	
		K48+	-	-	0.9	13.7	23.9	19.4	-	2.5	1.5	0.7	8.9	
		K96+	-	-	4.3	172.0	73.6	41.0	-	9.9	4.1	1.7	43.8	
		K192+	-	-	2.3	46.3	37.1	18.0	-	6.9	10.4	4.6	17.9	
													S(L)12.5	0.200ns
	GW	K0	1.7	0.5	-	0.1	-	0.4	0.9	1.7	0.3	0.1	0.7	
		K0+	0.7	1.3	-	0.7	-	0.3	0.6	2.1	0.5	0.1	0.8	
		K48+	0.6	0.6	-	0.7	-	0.5	4.2	1.0	2.8	0.3	1.3	
		K96+	1.2	0.8	-	0.4	-	0.4	2.2	2.3	3.0	0.8	1.4	
		K192+	1.6	0.7	-	0.7	-	0.1	0.6	9.6	3.2	1.2	2.2	
													S(L) 1.6	0.490*
Na	20	K0	-	-	7.9	8.3	13.2	12.5	-	5.9	1.9	2.0	-	-
		K0+	-	-	7.5	9.1	21.5	9.7	-	5.5	2.5	2.2	-	-
		K48+	-	-	4.6	18.5	25.5	8.7	-	11.7	2.2	2.5	-	-
		K96+	-	-	8.6	20.8	24.8	11.4	-	8.0	4.0	2.7	-	-
		K192+	-	-	6.1	33.5	26.0	28.3	-	14.1	4.6	4.4	-	-

[a]See footnotes b and c, Table 7. N = 3 observations per mean.

[b]Regression using 21 observations (5/3-9/13/73) for soil water and 12 observations (5/31-9/13/73) for groundwater.

TABLE 18. Continued.

Nutrient	Depth	Treatment	1973 Sampling date 4/17	4/27	5/3	5/18	5/22	5/28	5/31	7/2	8/13	9/13	Ave.	r
	cm		ppm											
Na	40	K0	-	-	3.9	6.6	8.2	4.7	-	5.5	2.2	2.6	-	-
		K0+	-	-	5.2	16.0	22.7	17.3	-	5.3	1.5	3.0	-	-
		K48+	-	-	2.9	14.3	17.1	9.5	-	4.9	2.6	2.9	-	-
		K96+	-	-	6.9	30.0	22.4	23.8	-	5.8	3.6	3.5	-	-
		K192+	-	-	7.1	27.5	23.6	22.7	-	7.7	4.0	3.8	-	-
	GW	K0	2.6	2.5	-	1.5	-	1.5	2.7	2.6	1.3	2.3	-	-
		K0+	3.7	4.3	-	2.1	-	1.4	2.6	2.9	2.0	2.8	-	-
		K48+	3.0	2.4	-	3.1	-	1.9	3.9	3.3	1.7	2.8	-	-
		K96+	3.4	2.9	-	3.6	-	1.4	3.2	3.0	2.6	3.6	-	-
		K192+	3.2	4.4	-	6.3	-	1.3	2.2	6.4	3.4	3.3	-	-

Estimation of Water Use by the Plantation

Because of the role of K in the water relationships in trees it was hoped that a close examination of water table depths with treatment would reveal any differential water use in the plantation. Analysis of variance of water table depth with treatment was not significant.

While few water use values for slash pine have been reported, recent work in the Austin Cary Forest (CRIFF Progress Report 1973-74)' has shown a 40 cm difference in water table depth in Leon fine sand between an established stand and of 18- to 20-year-old slash and longleaf pine and a clear cut area in late spring when growth had stabilized. If an average bulk density of 1.4 g/cm^3 and a specific gravity for quartz sand of 2.65 (Berry and Mason, 1959) was assumed, each cm of ground water fluctuation would represent 0.47 cm of free water (% pore volume = 100 - [1.4 g/cm^3 ÷ 2.65 g/cm^3]).

A water use (transpiration) estimate was made by examining the rate at which the water table was lowered in the established stand as compared to the clear cut area in the previous work. During June 1974 the water table dropped 20 cm in 21 days in the clear cut area. In the established stand, the water was lowered by approximately 31 cm during the same time. This lowering of the water table depth by a difference of 0.52 cm/day or 0.24 cm of free water/day may approximate water use by the 18 to 20-year-old natural stand of slash and long-leaf pine during this period of active tree growth. While this transpiration rate would not be expected to continue throughout the year to give 88 cm/yr, this total may approximate the total evapotranspiration from forests of the area and compares to rates of 98 cm/yr (Hammond, L.C., personal communication) found in Florida and 60 cm/yr for temperate forests found by Stanhill (1970).

Rainfall Influences on Soil Water and Ground Water

The average ground water level in the experimental area over the duration of sampling as it relates to the amount and frequency of rainfall is shown in Fig. 1. While soil water was easily sampled with tube-type tension lysimeters in the early months of the experiment, the onset of the dry period in October 1973 caused a rapid lowering of the ground water level, increased soil water tension, and made it impossible to sample soil water for the duration of the experiment. Rainfall did not attain a sufficient frequency or quantity to raise the ground water level until June of 1974. Obviously, soil water and ground water are related to rainfall in a direct way and the depth to the free water table in the soil gives an indication of the water content of the soil and its tension.

Estimates of Leaching Loss

An estimate of the leaching loss was calculated from the difference between water use by the trees and the annual rainfall, using the ground water K concentration (Table 18). An average of 133 cm/yr of rainfall and 88 cm/yr water use by the trees resulted in a difference of 45 cm/yr leachate (4,500,000 kg/ha). In the check plots the ground water averaged 0.7 ppm K. In the plots receiving 192 K/ha the average was 2.2 ppm K. The difference of 1.5 ppm K concentration indicated loss of K through leaching. Concentrations of K as high as 10 ppm at one time (Table 18) also indicated substantial K loss from the 192 kg K/ha treatment, but dilution of the ground water by both vertical and lateral flow made estimates of the exact amount difficult. If dilution was disregarded, the 45 cm/yr water loss at 10 ppm K was equal to 45 kg K/yr.

Fertilizer Effects on Selective Ground Cover Plants

Biomass and Nutrient Content Changes in Saw Palmetto

Saw palmetto (Serenoa repens) is a major ground cover plant in

the experimental plantation. An average of 112 plants per plot was found by enumeration procedures (Newbould, 1967). Palmetto biomass ranged from 2107 to 3621 kg/ha with an average 2532 kg/ha (Table 25). Average surface area covered with palmetto was 28%.

A linear increase of K concentration with K application combined with biomass differences increased K from 9.2 kg/ha in the palmetto receiving no K to 24 kg K in those receiving K. The regression equation for concentration of K in palmetto was; ppm K = 5476 + 28.7 (kg K/ha applied). Sodium, Ca, and Mg concentration were found to decrease linearly with increasing K application.

Average contents of other nutrients in palmetto were 5 kg Na/ha, 5 kg Ca/ha, 4.3 kg Mg/ha, and 2.1 kg P/ha.

Biomass and Nutrient Content Changes in Bracken Fern

In areas not covered with palmetto, bracken fern (Pteridium aquilium) was a common ground cover plant that initiated new growth in early spring and dried back with the onset of the dry season in late September. Biomass ranged from 662 to 1176 kg/ha at mid-season with an average of 940 kg/ha over all treatments (Table 25).

Both K and P concentrations differed by treatment. Potassium concentration increased linearly with K application rate; ppm K = 14205 + 56.9 (kg K/ha applied). Fern receiving no K averaged 1.31% K, the low and middle rates averaged 1.95% K, and the high K rate averaged 2.46% K. The application of DAP increased the P concentration from 0.18 to 0.34%. Concentration of Na, Ca, and Mg were unaffected by treatment and averaged 0.03, 0.19, and 0.25%, respectively.

The K content of bracken fern averaged 11.7 kg/ha for the no K

TABLE 19. Ground cover biomass and nutrient concentrations.

		Braken fern (Pteridium aquilinum)									
	Biomass	Concentration					Content				
Treatment	kg/ha	K	Na	Ca	Mg	P	K	Na	Ca	Mg	P
		%					kg/ha				
K0	1095 a	1.38 a	0.03 a	0.20 a	0.26 a	0.18 a	15.2	0.3	2.2	2.9	2.0
K0+	662 a	1.24 a	0.02 a	0.20 a	0.28 a	0.28 b	8.1	0.2	1.3	1.8	1.8
K48+	863 a	1.95 b	0.03 a	0.19 a	0.25 a	0.33 b	17.0	0.2	1.6	2.1	2.9
K96+	1176 a	1.95 b	0.03 a	0.16 a	0.22 b	0.31 b	23.0	0.4	1.9	2.5	3.7
K192+	903 a	2.46 b	0.02 a	0.18 a	0.24 a	0.34 b	22.4	0.2	1.6	2.1	3.0
Mean	940	1.80	0.03	0.19	0.25	0.29	17.1	0.3	1.7	2.3	2.7
S(L)	382	0.18	0.004	0.03	0.016	0.02					
r^2	-	0.69**	0.04ns	0.05ns	0.25ns	0.29ns					
r	-	0.83	0.20	-0.22	-0.5[illegible]	0.54					

			Saw palmetto (Serenoa repens)									
	Biomass		Concentration					Content				
Treatment	kg/ha	% Cover	K	Na	Ca	Mg	P	K	Na	Ca	Mg	P
			%					kg/ha				
K0	2321 a	26 a	0.51 a	0.22 a	0.20 a	0.18 a	0.07 a	12.1	5.0	4.8	4.1	1.6
K0+	2107 a	24 a	0.42 a	0.25 a	0.23 a	0.20 a	0.07 a	9.2	5.3	4.8	4.3	1.6
K48+	3621 b	40 b	0.77 b	0.19 b	0.19 a	0.17 a	0.09 a	26.1	6.5	7.4	5.6	3.4
K96+	2156 a	24 a	0.94 b	0.19 b	0.18 a	0.17 a	0.09 a	22.3	4.0	3.8	3.7	2.2
K192+	2453 a	27 a	1.02 b	0.17 b	0.17 b	0.14 b	0.08 a	24.0	4.3	4.3	3.6	1.9
Mean	2532	28	0.73	0.20	0.19	0.17	0.08	18.7	5.0	5.0	4.3	2.1
S(L)	259	2.4	0.12	0.024	0.018	0.016	0.01	-	-	-	-	-
r^2	-	-	0.56**	0.55**	0.44**	0.46**	0.001ns					
r	-	-	0.75	-0.74	-0.66	-0.68	0.031					

Treatment means followed by the same letter as a control do not differ significantly by Dunnett's test. Control (K0+) and K0 followed by the same letter do not differ from one another at P = 5% when tested with the Student's t-test.

treatments, 20 kg/ha for the low and middle K treatments, and 22 kg/ha for the highest K application rate. Other nutrients were found in much lower quantities with averages of 0.3 kg Na/ha, 1.7 kg Ca/ha, 2.3 kg Mg/ha, and 2.7 kg P/ha.

Biomass and Nutrient Concentration in the Tree Component

Total Tree Harvest

Above ground biomass of a representative tree in each treatment of block I was taken in November, 1974 following the method outlined by Newbold (1967). Tree selection was by random selection from a stratified diameter class distribution to obtain a diameter class for samples in each plot (Madgwick, 1963; Burkhart and Strub, 1973). Within each plot a random tree of the specified diameter class was felled and sampled. Mensurational data for the five trees sampled are in Table 20. Tree height ranged from 10.6 to 14 m with dbh ranging from 10.7 to 15.8 cm. Basal area averaged 0.0134 m^2/tree and crown length averaged 35% of total height. Averages were calculated on the basis of the five trees harvested.

No root sampling was attempted in this experiment.

Biomass Distribution in the Above Ground Portion of the Trees

Total tree weights for the harvested trees ranged from 32 to 75 kg/tree with the stem and bark accounting for the largest portion of the weight (Table 20). An average of 84.2% of the total above ground tree weight was bark and stem. Dead branches averaged 2.7% of the total, live branches averaged 7.1%, and foliage averaged 6% of the

total tree weight. An average of 74% of the total foliage on the trees at time of harvest was 1974 foliage. Little or no foliage prior to 1973 origin was detected on the sample trees.

Inner and outer bark volume of the sample tree was calculated using Smalian's combined formula. Loss of bark in cutting sample discs invalidated actual bark measurements so bark volume was taken as the difference between the two calculated volumes. The volume of wood, times its specific gravity of 0.48 (Gooding, 1970), was used to determine the weight proportion of bark free stem in the sample trees. Bark weight could then be taken as the difference between the total stem weight and the calculated wood weight. Averages of 31 and 53% were found for the bark and wood portions of above ground biomass. While the bark may be overestimated, the bark thickness did not vary greatly from reported values for slash pine (Phillips and Schroeder, 1972).

When compared to the local volume formula used in the initial stand volume calculation, Smalian's inner bark formula correlated very highly with local volume (Fig. 11) but the local volume formula overestimated the inner bark volume on the sample trees by an average of 26%.

Nearly perfect agreement was found when the foliage formula of Mead (1971) was compared with the actual foliage of the sample trees (log foliage = 0.5325 + 2.6208 log dbh). The correlation coefficient was 0.999 (measured foliage = 0.5679 + 0.8076 calculated foliage). Treatment appeared to affect the retention of 1973 needles (Table 20). The 1973 needles accounted for 20% of the foliage in the no K treatments and 27-40% of the foliage in treatments receiving K in the unreplicated samples.

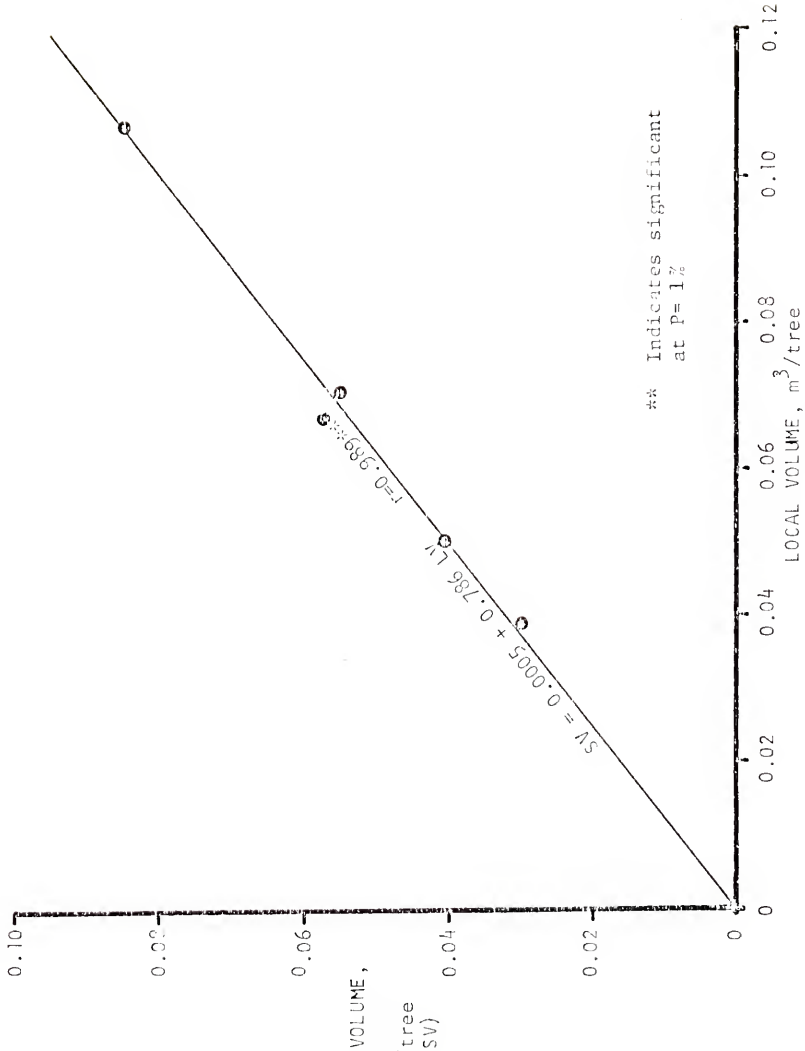


Fig. 12. Comparison of inner bark tree volumes by stem analysis and local volume formula.

TABLE 20. Biomass, biomass distribution, and mensuration date on harvested trees.

	Tree treatment number					
	K0	K0+	K48+	K96+	K192+	Average
	per tree					
Total weight (kg)	49.5	36.8	32.0	45.6	74.9	
Stem and bark weight (kg)	39.8	31.5	27.8	39.1	61.8	
(% of total)	(80.3)	(85.5)	(87.0)	(85.7)	(82.5)	(84.2)
Dead branches (kg)	1.79	0.72	0.38	1.17	3.02	
(% of total)	(3.6)	(2.0)	(1.2)	(2.6)	(4.0)	(2.7)
Live branches (kg)	4.80	2.61	1.86	2.43	5.71	
(% of total)	(9.7)	(7.1)	(5.8)	(5.3)	(7.6)	(7.1)
Foliage (kg)	3.13	2.13	1.94	2.92	4.39	
(% of total)	(6.3)	(5.5)	(6.1)	(6.4)	(5.0)	(6.0)
1973 foliage	0.65	0.45	0.53	1.13	1.43	
1974 foliage	2.48	1.58	1.41	1.79	2.96	
Calculated foliage (kg)[a]	3.18	1.93	1.69	3.02	4.68	
Height (m)	11.73	12.44	10.59	12.86	14.00	
DBH (cm)	13.59	11.23	10.69	13.33	15.75	
Basal area (m^2)	0.0145	0.0099	0.0089	0.0089	0.0195	
Crown length (m)	3.41	4.57	4.27	3.78	5.91	
Stem analysis volume IB (m^3)[b]	0.0574	0.0407	0.0297	0.0521	0.0846	
Stem analysis volume OB (m^3)[b]	0.0980	0.0744	0.0506	0.0982	0.1325	
Bark volume (m^3)	0.0406	0.0337	0.0209	0.0461	0.0478	
Local volume IB (m^3)[c]	0.0672	0.0498	0.0384	0.0708	0.1067	
Double bark thickness (cm) at 1.4 m	3.84	2.88	2.77	3.84	3.95	

a Log dry weight foliage = .5325 + 2.6208 log dbh.

b Smalians combined formula $V = .00007854\ h\ (d_o^2/2 + d_1^2 + d_2^2 + \ldots + d_{n-1}^2 + dn^2/2)$ where h is bolt length m, d_o is stump diameter in cm, d_1 ... are respective diameters of the tops of bolts 1 through n.

c. Volume IB = $.000030\ (dbh)^2(ht) + .002069$.

Stem wood of 8-year-old slash pine in Mississippi and in North Carolina has been shown to make up approximately 40% of the total above ground biomass with stem bark accounting from 12 - 16%, branches 20 - 21% and foliage 22 - 23% (Nemeth, 1973; McKee and Shoulders, 1974). Mead (1971) found 15% bark, 52% bole wood, 6% live branches, and 6% foliage in 13-year-old slash pine. In older trees the bole wood in slash pine was 57 - 60% of the total above ground biomass, branches were 3 - 4%, and needles were 3.5 - 5.0% of the total (Koch, 1972). Loblolly pine had larger proportions of stem wood and less bark, branches, and needles than slash pine at comparable ages (Metz and Wells, 1965; Wells and Jorgensen, 1973; Walker, 1973).

Radiata pine had biomass distribution similar to slash and loblolly pine (Orman and Will, 1960; Ovington et al., 1967). Root biomass for slash pine was 16 and 26% of the above ground biomass (White et al., 1971; Koch, 1972).

Comparison of Nutrient Contents in Various Parts of the Tree

Concentrations of nutrients by treatment for the various components of the harvested trees are presented in Table 21. From an examination of the unreplicated data it appeared that few differences due to treatment existed. Possible exceptions were found in the 1973 foliage, live branch, and bark K concentration in trees fertilized at 192 kg K/ha. Average biomass and nutrient contents for the plantation totaled 84.5 t/ha of above ground tree biomass containing 58 - 68 kg K/ha, 10.3 kg Na/ha, 120.3 kg Ca/ha, 27.2 kg Mg/ha, and 15.6 kg P/ha (Table 22). With the exception of Ca, these compared with 8-year-old slash pine grown on silt loam soil in Mississippi (McKee and Shoulders,1974) of

TABLE 21. Concentration of nutrients in biomass and forest floor.

	Tree (Treatment)	Foliage 1973	Foliage 1974	Live branches	Dead branches	Bark	Wood	Floor	Litter
% K	K0	0.26	0.33	0.12	0.02	0.03	0.06	0.04	0.04
	K0+	0.24	0.28	0.13	0.02	0.03	0.06	0.03	0.04
	K48+	0.27	0.31	0.12	0.03	0.03	0.06	0.05	0.05
	K96+	0.27	0.31	0.16	0.03	0.02	0.06	0.05	0.06
	K192+	0.35	0.36	0.20	0.02	0.04	0.06	0.06	0.09
% Na	K0	0.08	0.03	0.02	0.01	0.01	0.01	0.02	0.04
	K0+	0.05	0.02	0.02	0.01	0.01	0.01	0.01	0.04
	K48+	0.04	0.02	0.02	0.01	0.01	0.01	0.01	0.04
	K96+	0.09	0.03	0.02	0.01	0.01	0.01	0.01	0.05
	K192+	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.05
% Ca	K0	0.31	0.16	0.20	0.24	0.11	0.08	0.33	0.31
	K0+	0.38	0.17	0.35	0.29	0.18	0.07	0.39	0.33
	K48+	0.29	0.17	0.24	0.33	0.19	0.06	0.43	0.34
	K96+	0.31	0.18	0.30	0.31	0.27	0.09	0.36	0.31
	K192+	0.30	0.16	0.32	0.28	0.24	0.09	0.40	0.30
% Mg	K0	0.07	0.11	0.07	0.05	0.02	0.02	0.08	0.09
	K0+	0.13	0.11	0.07	0.04	0.02	0.02	0.08	0.09
	K48+	0.11	0.13	0.06	0.05	0.02	0.02	0.08	0.09
	K96+	0.10	0.12	0.10	0.05	0.02	0.03	0.08	0.09
	K192+	0.09	0.10	0.08	0.03	0.03	0.03	0.08	0.09
% P	K0	0.13	0.15	0.05	0.01	0.01	0.01	0.03	0.03
	K0+	0.15	0.09	0.03	0.02	0.01	0.01	0.04	0.05
	K48+	0.08	0.11	0.03	0.01	0.01	0.01	0.04	0.04
	K96+	0.12	0.13	0.05	0.02	0.02	0.01	0.04	0.04
	K192+	0.08	0.10	0.03	0.01	0.01	0.01	0.04	0.04

TABLE 22. Average tree biomass and nutrient content distribution in the plantation.

	Foliage		Branches		Stem		
	1973	1974	live	dead	bark	wood	Total
	t/ha						
Biomass	1.3	3.8	6.0	2.3	26.4	44.7	84.5
	kg/ha						
K (Treatment K0-K96+)	3.4	11.8	8.0	0.6	7.3	26.8	57.9
K (Treatment K192+)	4.6	13.7	12.0	0.6	10.6	26.8	68.3
Na	0.8	1.0	1.2	0.2	2.6	4.5	10.3
Ca	4.2	0.3	16.8	6.7	52.8	33.5	120.3
Mg	1.3	4.3	4.6	1.0	5.3	10.7	27.2
P	1.5	4.4	2.3	0.3	2.6	4.5	15.6

less biomass (34 - 50 t/ha), but higher proportion of bark and foliage. Sixteen-year-old loblolly pine in North Carolina had double the amount of biomass and P content found here and nearly three times the K and Mg contents. Calcium content was lower in loblolly pine (Wells and Jorgensen, 1973).

The Nutrient Cycle

The K Cycle in Slash Pine

The K cycle in the experimental plots was determined. Low levels of K were found in nearly every compartment of the system. Above ground portions of the standing tree biomass contained only 57.9 kg/ha of K in the treatment plots receiving no K fertilizer, giving an average concentration of less than 0.07% (Table 23). Roots were estimated to be 20% of the above ground portion of the tree biomass (Nemeth, 1972; Mead, 1971; Wells and Jorgensen, 1973) with an estimated K content of 0.11% (White, Pritchett, and Robertson, 1971). When roots were included in the system the K content of the trees biomass increased to 76.5 kg/ha (Fig. 12).

The fern and palmetto ground cover were only 3.4% as much biomass as the total tree, but held 29% as much K. The forest floor contained only 4.3 kg K/ha and included some material from ground cover flora.

Extractable K in the soil was found to be very low with only 39 kg K/ha in the surface 60 cm. This was 27% of the total K of the plant and soil extractable supply and only 6.5% of the total K in the soil.

Litterfall transferred 1.7 kg K/ha/yr from the crown of the trees to the forest floor while throughfall and stemflow removed 2.3

and 0.1 kg K/ha/yr, respectively, from the tree crowns.

The growing trees had a 10% net increase in biomass per year as estimated from stem volume increment and published estimates (Nemeth, 1973). This accounted for an annual uptake of 7.7 kg K/ha necessary for the 14th year of growth. Replenishing the K lost in the litterfall and the crown leaching required the uptake of an additional 4.2 kg K/ha/yr so that gross accumulation was approximately 11.9 kg K/ha/yr in the 14th year of growth.

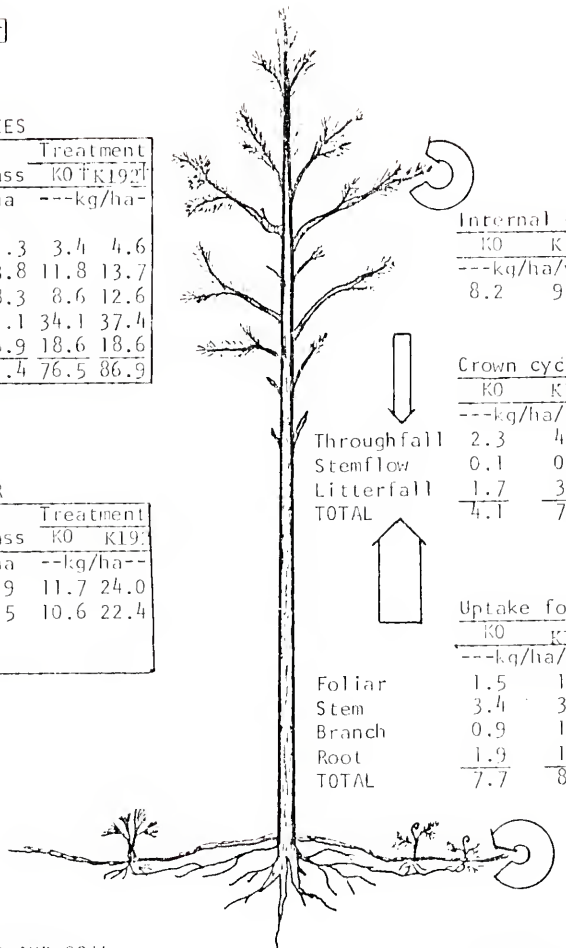
In the crown leachate, K would be readily available for return to the tree if ground cover competition was not too great. The litterfall needles, on the other hand, appeared to have returned the major proportion of readily available K to the tree before needle abscission (82%) and the remaining K was in a form that appeared to be only slowly available from the forest floor as evidenced by the similarity of K content in the litter and in the floor (Table 15).

Direct uptake of K from the forest floor by mycorrizal activity was not examined, but may result in a very efficient cycle that prevents loss of K by leaching from the forest floor (Ewel et al., 1975).

With these two losses from the tree system partially accounted for, it may be expected that only enough K for incremental growth would be necessary for continued biomass increases. If K input into the system was limited more than any other nutrient, the increase in biomass may be limited by the proportion of the net needs that can be supplied from other sources, including net decline of ground cover, soil sources, or a lowering of the concentration level of some part of the standing tree biomass by internal transfer.

TABLE 23. Biomass and nutrient contents during the 14th year of tree growth.

Component	Biomass	Treatment K0	Treatment K48-96	Treatment K192	Na	Ca	Mg	P
	- t/ha-				kg/ha			
Needles 1973	1.3	3.4	3.5	4.6	0.8	4.2	1.3	1.5
1974	3.8	11.8	11.8	13.7	1.0	6.3	4.3	4.4
Branches (Live)	6.0	8.0	8.4	12.0	1.0	16.8	4.6	2.3
(Dead)	2.3	0.6	0.7	0.6	0.2	6.7	1.0	0.3
Stem bark	26.4	7.3	7.3	10.6	2.6	52.8	5.3	2.6
Stem wood	44.7	26.8	26.8	26.8	4.5	33.5	10.7	4.5
Total above ground	84.5	57.9	58.5	68.3	10.3	120.3	27.2	15.6
Roots (estimated)	16.9	18.6	18.6	18.6	1.8	38.9	18.6	20.3
Tree total	101.4	76.5	77.1	86.9	12.1	159.2	45.8	35.9
Ground cover								
Palmetto	2.5	10.6	24.0	24.0	5.0	5.0	4.3	2.1
Fern	0.9	11.7	20.0	22.4	0.3	1.7	2.3	3.0
Total of palmetto and fern	3.4	22.3	44.0	46.4	5.3	6.7	6.6	5.1
Litter								
Needle	3.8	1.6	2.1	3.5	1.8	12.1	3.5	1.2
Other	0.4	0.1	0.1	0.1	0.1	5.0	0.1	tr
Total	4.2	1.7	2.2	3.6	1.9	17.1	3.6	1.2
Biomass total sampled	109.0	100.5	123.3	137.0	19.3	183.0	56.0	42.2
Forest floor	12.2	4.3	6.1	7.3	1.8	46.4	9.3	4.4
Soil (0-60 cm) Extractable		39.0	48.0	52.0	34.8	163.8	25.8	11.4
Total	121.2	143.8	177.4	196.3	55.9	393.2	91.1	58.0
Soil (0-60 cm) Total		600.0	609.0	613.0	-	2100.0	200.0	-



RAINFALL
1.6 kg/ha/yr

STANDING TREES

	Biomass	Treatment K0†	K192†
	t/ha	---kg/ha-	
Foliage			
1973	1.3	3.4	4.6
1974	3.8	11.8	13.7
Branches	8.3	8.6	12.6
Stem	71.1	34.1	37.4
Roots	16.9	18.6	18.6
TOTAL	101.4	76.5	86.9

Internal cycle

K0	K192
---kg/ha/yr---	
8.2	9.8

Crown cycle

	K0	K192
	---kg/ha/yr---	
Throughfall	2.3	4.1
Stemflow	0.1	0.2
Litterfall	1.7	3.6
TOTAL	4.1	7.9

GROUND COVER

	Biomass	Treatment K0	K192
	t/ha	--kg/ha--	
Fern	0.9	11.7	24.0
Palmetto	2.5	10.6	22.4

Uptake for increment

	K0	K192
	---kg/ha/yr---	
Foliar	1.5	1.8
Stem	3.4	3.7
Branch	0.9	1.3
Root	1.9	1.9
TOTAL	7.7	8.7

Ground cover

FOREST FLOOR AND SOIL

	Biomass	Treatment K0	K192
	t/ha	--kg/ha--	
Floor	12.2	4.3	7.3
Soil (ext)	-	39.0	52.0
Soil (tot)	-	600	600+

LEACHING LOSS

K0	K192
---kg/ha/yr-------	
3.0	10.0 _ 45 (min.)

†K0 & K192 indicate no and high K application rates, respectively.

Fig. 13. The K cycle in 13-year-old slash pine.

The Effect of Applied Fertilizer in the K Cycle

The application of K fertilizer at the two low rates had no effect on the biomass or K content of any of the tree components, but did increase the ground cover K content by 97%, the litterfall K content by 29%, the forest floor K content by 42%, and the extractable soil K content by 23%. Total K in the system increased by 33 kg K/ha or 23% over the no K treatment systems regardless of application rates in treatments receiving 48 and 96 kg K/ha.

While no biomass increase could be detected at the 192 kg K/ha application, nearly all components of the fertilized areas had higher K content than the no K treatment. Total tree K increased by 14% over the no K treatments. Ground cover K increased by 109%, litterfall K increased by 112%, the forest floor K increased by 70%, and the extractable soil K increased by 33% over the K content of those treatments receiving no K applications.

When the 1973 foliage was compared to the 1974 foliage on the basis of equal biomass, the 0 K treatments showed a net difference of 2.3 kg/ha/yr less K in the older needles (Fig. 12). This was equal to the net throughfall K leached from the crown and while undoubtably there was some leaching from the 1974 foliage, the net loss was at the expense of the older needles that had to translocate K in order to make up the 1974 needle deficit. When K was applied at the highest rate, the K concentration difference between the 1973 and 1974 needles was not found. While the net throughfall increased to 4.1 kg K/ha, this was apparently not at the expense of the net K content of the older needles and any deficits were made up from the increased supply of K available to the system from the addition of fertilizer.

Stemflow increased from 0.1 kg K/ha/yr to 0.2 kg K/ha/yr with the addition of the high rate of K.

The litterfall returned less K to the forest floor than would have been expected by an examination of the K content of the oldest needles still on the trees. Little evidence existed that loss of K was by the leaching of the old needles or the litter prior to collection. It may be assumed that resorption of K into other parts of the standing tree biomass by an internal cycle (Switzer and Nelson, 1972; Wells and Metz, 1963) did take place. With the addition of the high K rate, the litterfall K content increased from 1.7 to 3.5 kg/ha/yr and the internal cycle increased from 8.2 to 9.8 kg/ha/yr. The 1973 foliage had increased in K concentration from 0.26% in the no K treatments to 0.35% in the high K treatment and the litterfall increased from 0.06 to 0.09% K, respectively.

The 14% increase of K in the tree component of the system due to the high rate of K fertilization increased the annual increment of K from 7.7 to 8.7 kg/ha/yr.

Estimated leaching losses increased from 3 kg/ha in the unfertilized areas to 10 kg K/ha under the 192 kg K/ha application rates.

Cycle of Other Nutrients in the System

The tree biomass contained 12.1 kg Na/ha, 159.2 kg Ca/ha, 45.8 kg Mg/ha, and 35.9 kg P/ha at the conclusion of the experiment (Table 23). The ground cover contained nearly equal amounts of Na, Ca, Mg, and P with values of 5 to 7 kg/ha. Litterfall contributed 1.9 kg Na/ha/yr, 17.1 kg Ca/ha/yr, 3.6 kg Mg/ha/yr, and 1.2 kg P/ha/yr to the nutrient cycle. The forest floor contained 1.8, 46.4, 9.3, and 4.4

kg/ha of Na, Ca, Mg, and P, respectively, at the end of the experiment. Extractable Na, Ca, Mg, and P in the soil did not vary during the experiment and the soil contained 34.8 kg Na/ha, 163.8 kg Ca/ha, 25.8 kg Mg/ha, and 11.4 kg P/ha in the surface 60 cm of soil. Total soil nutrient contents were assumed to remain unchanged.

Net crown leaching by throughfall and stemflow accounted for 1.4 kg Na/ha/yr, 2.5 kg Ca/ha/yr, and 1.2 kg Mg/ha/yr. Phosphorous content in the crown leachate contained less P than rainfall and accounted for a net crown uptake of 0.1 kg/ha/yr. A comparison of 1973 and 1974 foliage indicated an increase of Na concentration with age but relatively stable concentration of Ca, Mg, and P as the needles aged.

On the basis of equal biomass, the leaf litterfall contained less Na, Mg, and P than the oldest needles still on the tree and may indicate internal transfer prior to abscission of up to 26% Na, 8% Mg, and 64%P that otherwise would have been in the litterfall. Calcium remained constant when equal biomass of needle litterfall and old needles was compared with a gain of Ca in the litterfall of 3% over expected.

Tree increment growth accounted for 1.2 kg Na/ha/yr,15.9 kg Ca/ha/yr, 4.6 kg Mg/ha/yr, and 3.6 kg P/ha/yr during the 14th year of growth.

While quantities of nutrients were found to be relatively low in the slash pine nutrient cycle when compared to loblolly pine in similar studies (Wells and Jorgensen, 1973; Switzer and Nelson, 1972), the ability of slash pine to internally adjust K and P contents over relatively short periods of time suggest a very efficient cycling of

limiting nutrients. This was dramatically shown by the 82 and 64% internal retention of K and P at needle cast.

The Recovery of Applied K in the Slash Pine Ecosystem

Recovery of applied K in the plantation system was determined at the end of the 17-month experimental period. Because of the short-term nature of the throughfall leaching and the combination of the litterfall into the forest floor, only the soil, tree net uptake, ground cover, and forest floor recoveries were calculated. Leaching loss was estimated from water use and K concentration data.

At the end of the experiment there were no differences in growth increment due to fertilizer application, but the 192 kg/ha rate of K had 13.6% more K in the tree biomass than the other treatments. This amounted to 7.7% of the applied K (Table 24). Ground cover K content increased approximately 100% and gave recoveries of 12.6% of the high K rate, 23% of the 96 kg K/ha rate and 45% of the 48 kg K/ha rate.

The forest floor increased in K concentration with increasing K rates without increasing in biomass. While K increased by 70% in the floor with the high K application rate, this amounted to only 1.6% of the applied fertilizer. At the lower K rates the recovery of applied K was 4 and 2% of applied K (treatments K 48 and K 96, respectively). Soil recoveries were low and amounted to 18.8, 9.3, and 6.8% for treatments receiving 48, 96, and 192 kg K/ha, respectively. Total K recovery in the fertilized plantation over 17 months was 68, 34, and 28 for the 48, 96, and 192 kg K/ha application rates.

Ground cover not sampled may have received some of the applied K, but the large amount of unrecovered K in the 96 and 192 kg K/ha

TABLE 24. Net recovery of K from applied fertilizer in the system.

Source	K Treatment			
	K0+	K48++	K96+	K192+
		%		
Tree increment	---	0.0	0.0	0.0
Tree accumulation	---	0.0	0.0	7.7
Ground cover accumulation	---	45.2	22.6	12.6
Forest floor	---	3.8	1.9	1.6
Soil (0-60 cm)	---	18.8	9.3	6.8
Total recovery	---	67.8	33.8	28.7
Leached (calculated) (minimum)		5.6	3.2	3.5-24.0

application rates suggest other mechanisms such as microbial uptake, root uptake, undetected leaching loss, and soil K fixation that were not evaluated in the experiment may be important.

Long-Term Implication of the K Cycle

It would appear from the data presented that unfertilized slash pine growing on flatwoods soils is gradually depleting the supply of soil K. Estimated leaching losses, while not large, are nevertheless greater than the rainfall input to the system and may contribute to this decline. A greater factor would be the periodic harvest of the trees. At age 25, assuming a yield of only 100 t/ha (Bennett, 1970) and the same K content, as much as 60 - 70 kg K/ha may be removed per harvest. With a total of only 600 kg K/ha in the soil it is possible to anticipate that within less than 10 rotations the K supply in the soil would be completely depleted. Whole tree harvest methods would greatly accelerate K removal by removing the total above ground portion of the trees.

At present there is no indication of the level that soil K may fall before K becomes limiting to tree growth, but it undoubtably will occur if K additions are not made. When fertilizer K is applied, the foliage increases in K concentration without a concurrent increase of concentration in the wood. Fern and palmetto ground cover increase as well, and serve as a reservoir of slowly available K, particularly refering to the annual nature of fern growth. While leaching loss does increase, this may be a temporary phenomenon that occurs until the K cycle can establish itself at a new equilibrium.

N O T E

'CRIFF Progress Report, 1973-1974 (unpublished). Soil Science Department, Gainesville, Florida.

SUMMARY AND CONCLUSIONS

The effect of applied K on the growth and K cycle in a 13-year-old slash pine plantation was examined. Potassium chloride was applied to 0.04 ha plots at rates equivalent to 0, 48, 96, and 192 kg K/ha. Diammonium phosphate (DAP) was applied to all plots at a rate of 224 kg/ha, except that there was a check which received no fertilizer. There were three replications of the treatments. Annual nutrient input into the system from rainfall was 1.6 kg K/ha, 7.2 kg Na/ha, 4.6 kg Ca/ha, 1.3 kg Mg/ha, and 0.2 kg P/ha.

No growth responses due to K fertilization were detected in the trees growing on the low-K status flatwood soil. However, an application of DAP increased first flush needle length 10% by the end of the first growing season after fertilization, but did not increase tree growth during this short period.

During the first growing season, K concentrations in various tissues of the trees were followed. Soil, litterfall, throughfall, stemflow, soil water, and ground water, were sampled and analyzed throughout the 17-month experimental period to determine the effect of K fertilization on the K cycle. Sodium, Ca, Mg, and P were also determined. At the conclusion of the experiment, five trees were harvested and nutrient contents determined.

Within 30 days following treatment, differences in K concentration due to K application were detected in the current and new flush

growth, with higher K concentrations found in the tissue of trees fertilized with the highest K rate. High concentrations of K were associated with the early flush growth of the stem and bud system as well as the newly emerged needles. Maximum K concentration in tissue was 0.72%, found in the first flush needles from trees receiving 192 kg K/ha. Concentrations of K below 0.20% were found in old needles and first flush stems of trees receiving no K.

No treatment effects were found for Na, Ca, Mg, and P concentration in any of the tree tissue.

Leaching losses from the trees were found by subtracting the rainfall contribution from the throughfall nutrient content. Approximately 2 kg K/ha/yr were leached from the crowns of trees receiving no K. An application of 192 kg K/ha increased this to 4 kg/ha/yr. Losses of Na, Ca, and Mg amounted to only 1, 2, and 1 kg/ha/yr, respectivaly. Phosphorous content was lower in the throughfall than in the rainfall. Stemflow losses were less than 10% of rainfall nutrient content. Of the total rainfall, only 88% reached the forest floor as throughfall and stemflow.

Litterfall annually contributed between 3 and 5 t/ha of biomass to the forest floor and contained 2 to 4 kg K/ha, 1.8 kg Na/ha, 12.1 kg Ca/ha, and 3.5 kg Mg/ha. Bracken fern and saw palmetto contributed large amounts of K to the system, increasing from 23 kg K/ha with no K fertilization to 46 kg K/ha with the 192 kg K/ha application.

The tree biomass and nutrient concentrations were determined by above ground harvest of trees. Root biomass and nutrient concentrations were estimated from published values for slash pine on similar

soils. Total tree biomass was 100 t/ha and contained 58 to 77 kg K.

Recovery of applied K in the soil after 17 months was between 7 and 19%. Tree uptake in the highest K application rate accounted for 8% of the applied K. Ground cover uptake accounted for 13 to 45% of applied K. Total recovery of applied K in the biomass ranged from 29 to 68%, with the highest rate of K resulting in the least recovery.

Application of K appeared to reduce the need for internal transfer of K from the 1973 needles to the 1974 needles but did not reduce the high amount of resorption of K by the trees prior to needle cast.

The following conclusions may be drawn from this study:

1. While growth response to applied K on slash pine plantations similar to the study plantation may not occur, or may require a longer time to respond than was involved in this study, increased K concentration did occur in the tree foliage.

2. High rates of K application were required to increase K concentrations in slash pine.

3. Saw palmetto and bracken fern responded to K fertilization by greatly increasing their K concentration. Their recovery of applied K was as great or greater than tree and soil retention combined.

4. Application of K had little or no effect on other nutrients in the ecosystem under study.

5. Losses of K from the system appeared to be well dispersed over time. While only 29% of the 192 kg K/ha application rate could be accounted for in the above ground portion of trees, groundcover, forest floor, and extractable soil K, as much as 24% of the K applied was calculated to be lost by leaching. Undetected leaching loss or other mechanisms of loss not evaluated in this study were also apparent.

APPENDIX

TABLE 25. Soil chemical and physical properties.

Soil type: Myakka fine sand, a sandy siliceous, hyperthermic Aeric Haplaquod.

Horizon	Depth (cm)	pH		Extractable					HNO_3 Ext.	Total					OM	Clay	Silt	Sand	BD	CEC
		H_2O	KCl	K	Na	Ca	Mg	P	K	K	Na	Ca	Mg	P						
				ppm					ppm	ppm					%					me/100 g
A1	0-10	4.3	3.7	7	10	53	2	2	9	115	250	290	15	60	2.0	0.8	1.6	95.6	1.5	2.3
A2	10-60	5.2	4.9	3	10	20	3	1	11	68	228	155	20	60	0.4	0.6	1.3	97.7	1.4	1.6
Bh	60-70	4.5	4.2	7	5	9	2	2	9	73	304	270	20	160	2.4	1.9	2.4	93.3	1.5	2.1
C	70+	4.3	4.1	7	5	10	3	1	9	71	245	180	20	-	0.1	0.4	1.3	98.2	1.4	1.4

TABLE 26 . Extractable soil nutrients by date, treatment and depth

Date	Treatment	Soil Depth (cm)	K	Na	Ca	Mg	P
			ppm				
4/19/73 (Pre-treatment)	K0	0 - 10	6	9	73	9	2
		10 - 20	3	10	26	3	1
	K0+	0 - 10	6	9	82	13	1
		10 - 20	4	10	45	7	2
	K48+	0 - 10	9	15	70	12	3
		10 - 20	3	10	36	3	1
	K96+	0 - 10	5	7	76	11	2
		10 - 20	3	10	31	4	2
	K192+	0 - 10	6	7	74	9	1
		10 - 20	3	11	26	3	2
5/ 9/73	K0	0 - 2.5	9	9	74	11	2
		2.5 - 5.0	7	8	52	7	6
	K0+	0 - 2.5	11	11	121	17	23
		2.5 - 5.0	7	9	81	10	8
	K48	0 - 2.5	133	14	112	16	26
		2.5 - 5.0	32	9	72	12	21
	K96+	0 - 2.5	111	11	97	15	20
		2.5 - 5.0	28	9	72	12	6
	K192+	0 - 2.5	269	13	106	15	24
		2.5 - 5.0	111	12	86	11	4
5/22/73	K0	0 - 2.5	6	3	54	10	1
		2.5 - 5.0	4	3	42	7	1
		5.0 - 7.5	3	3	30	5	1
		7.5 - 10.0	3	4	36	5	1
		10 - 20	3	3	17	1	2
	K0+	0 - 2.5	9	4	77	12	8
		2.5 - 5.0	6	3	54	9	7
		5.0 - 7.5	3	5	49	7	4
		7.5 - 10.0	2	4	34	4	4
		10 - 20	3	5	19	2	4

TABLE 26. (Continued)

Date	Treatment	Soil Depth (cm)	K	Na	Ca	Mg	P
			ppm				
5/22/73	K48+	0 - 2.5	35	4	56	8	9
		2.5 - 5.0	24	5	49	7	7
		5.0 - 7.5	16	4	47	6	6
		7.5 - 10	8	3	35	4	5
		10 - 20	7	2	29	2	3
	K96+	0 - 2.5	89	4	57	9	10
		2.5 - 5.0	40	5	51	8	6
		5.0 - 7.5	31	6	50	7	4
		7.5 - 10	16	3	38	6	3
		10 - 20	11	5	25	3	3
	K192+	0 - 2.5	140	6	77	11	11
		2.5 - 5.0	69	6	60	9	5
		5.0 - 7.5	44	5	51	7	4
		7.5 - 10	27	5	42	5	3
		10 - 20	15	6	26	2	2
5/29/73	K0	0 - 2.5	7	3	71	11	1
		2.5 - 5.0	6	3	52	7	1
		5.0 - 7.5	5	4	46	6	1
		7.5 - 10	4	6	42	4	1
		10 - 20	2	2	40	3	1
		20 - 40	2	3	14	1	1
		40 - 60	1	3	7	1	1
	K0+	0 - 2.5	11	7	101	16	4
		2.5 - 5.0	6	6	65	7	4
		5.0 - 7.5	5	7	67	7	5
		7.5 - 10	5	4	56	6	4
		10 - 20	2	4	63	4	3
		20 - 40	2	5	20	4	3
		40 - 60	2	3	18	4	3

TABLE 26. (Continued)

Date	Treatment	Soil Depth (cm)	K	Na	Ca	Mg	P
			ppm				
5/29/73	K48+	0 - 2.5	43	6	80	12	5
		2.5 - 5.0	24	7	56	8	5
		5.0 - 7.5	15	5	54	7	5
		7.5 - 10	9	5	45	5	4
		10 - 20	5	3	19	2	3
		20 - 40	3	3	9	1	2
		40 - 60	3	4	9	1	3
	K96+	0 - 2.5	53	7	82	10	7
		2.5 - 5.0	40	4	70	10	5
		5.0 - 7.5	17	6	59	10	3
		7.5 - 10	13	6	43	6	3
		10 - 20	7	4	33	6	4
		20 - 40	6	5	18	3	2
		40 - 60	6	7	16	3	1
	K192+	0 - 2.5	105	7	93	15	5
		2.5 - 5.0	67	4	45	7	5
		5.0 - 7.5	32	4	53	7	5
		7.5 - 10	16	4	36	5	3
		10 - 20	8	1	15	2	2
		20 - 40	8	2	8	1	1
		40 - 60	7	4	6	1	1
8/13/73	K0	0 - 2.5	8	7	91	14	2
		2.5 - 5.0	5	10	65	9	1
		5.0 - 7.5	5	8	50	7	1
		7.5 - 10	4	6	51	4	1
		10 - 20	3	3	28	3	2
		20 - 40	3	5	12	2	2
		40 - 60	2	6	9	2	1

TABLE 26. (Continued)

Date	Treatment	Soil Depth (cm)	K	Na	Ca	Mg	P
			ppm				
8/13/73	K0+	0 - 2.5	7	8	99	14	3
		2.5 - 5.0	6	7	71	9	3
		5.0 - 7.5	5	9	50	8	2
		7.5 - 10	4	9	54	7	3
		10 - 20	4	7	27	4	2
		20 - 40	2	4	14	3	4
		40 - 60	3	5	15	2	5
	K48+	0 - 2.5	14	9	74	11	2
		2.5 - 5.0	10	11	55	7	2
		5.0 - 7.5	7	8	47	5	2
		7.5 - 10	7	9	30	5	2
		10 - 20	5	8	20	5	1
		20 - 40	4	7	10	2	1
		40 - 60	4	6			
	K96+	0 - 2.5	16	9	86	13	3
		2.5 - 5.0	13	7	53	7	3
		5.0 - 7.5	12	9	63	7	3
		7.5 - 10	7	9	56	4	2
		10 - 20	6	6	30	4	2
		20 - 40	5	5	14	3	2
		40 - 60	4	4	8	2	2
	K192+	0 - 2.5	34	8	79	11	2
		2.5 - 5.0	33	8	72	9	2
		5.0 - 7.5	16	7	51	5	1
		7.5 - 10	15	7	46	4	2
		10 - 20	8	4	20	3	2
		20 - 40	8	6	13	2	1
		40 - 60	5	4	5	2	1

TABLE 26. (Continued)

Date	Treatment	Soil Depth (cm)	K	Na
			----- ppm ------	
9/24/74 (Final)	K0	0 - 10	8	2
		10 - 20	5	2
		20 - 40	2	1
		40 - 60	1	1
		60 - 80	2	1
		80 -100	1	1
	K0+	0 - 10	6	2
		10 - 20	2	1
		20 - 40	2	1
		40 - 60	6	2
		60 - 80	9	1
		80 -100	4	1
	K48+	0 - 10	6	2
		10 - 20	2	2
		20 - 40	2	1
		40 - 60	1	1
		60 - 80	6	1
		80 -100	3	1
	K96+	10 - 20	4	2
		20 - 40	1	1
		40 - 60	2	1
		60 - 80	4	1
		80 -100	6	1
	K192+	0 - 10	15	2
		10 - 20	4	1
		20 - 40	3	1
		40 - 60	3	1
		60 - 80	2	1
		80 - 100	1	1
	K96+	0 - 10	7	2

TABLE 27. Average concentration of K in foliage

Sample	Treatment	1973 collection date							
		4/24	5/13	5/18	6/4	7/9	8/19	9/13	11/14
		%							
Old Needles	K0	0.25	0.29	0.27	0.23	0.18	0.21	0.16	0.19
	K0+	0.27	0.34	0.28	0.23	0.16	0.16	0.13	0.17
	K48+	0.26	0.28	0.26	0.27	0.19	0.21	0.19	0.23
	K96+	0.23	0.34	0.26	0.24	0.21	0.24	0.21	0.26
	K192+	0.29	0.28	0.31	0.30	0.24	0.29	0.27	0.29
Current Needles	K0	0.25	0.25	0.29	0.24	0.22	0.21	0.21	0.21
	K0+	0.25	0.23	0.29	0.22	0.22	0.18	0.19	0.22
	K48+	0.28	0.30	0.28	0.26	0.26	0.27	0.25	0.24
	K96+	0.23	0.29	0.28	0.25	0.28	0.29	0.28	0.28
	K192+	0.29	0.34	0.33	0.30	0.35	0.35	0.39	0.28
1st Flush Needles	K0		0.51	0.65	0.58	0.49	0.38	0.33	0.26
	K0+		0.54	0.69	0.60	0.47	0.36	0.29	0.23
	K48+		0.59	0.65	0.65	0.54	0.48	0.45	0.35
	K96+		0.61	0.64	0.62	0.57	0.51	0.51	0.38
	K192+		0.60	0.72	0.68	0.68	0.57	0.60	0.46
1st Flush Bud and Stem	K0	0.57	0.52	0.38	0.33	0.31	0.25	0.22	0.17
	K0+	0.61	0.51	0.42	0.34	0.29	0.25	0.22	0.15
	K48+	0.61	0.63	0.44	0.38	0.36	0.34	0.32	0.18
	K96+	0.56	0.59	0.46	0.33	0.32	0.33	0.35	0.21
	K192+	0.60	0.64	0.48	0.40	0.43	0.38	0.38	0.22
2nd Flush Needles	K0						0.54	0.57	0.36
	K0+						0.55	0.55	0.30
	K48+						0.61	0.65	0.42
	K96+						0.60	0.61	0.48
	K192+						0.66	0.72	0.50
2nd Flush Bud and Stem	K0					0.48	0.38	0.40	0.40
	K0+					0.47	0.38	0.36	0.34
	K48+					0.50	0.45	0.50	0.50
	K96+					0.52	0.44	0.52	0.44
	K192+					0.55	0.47	0.52	0.48

TABLE 28. Multiple regression equations for % K in various tissue components.

Tissue component	Regression equation[a]	N[b]	R^2[c]
Old needles	ppm K = 2390 + 3.44X_1 - 3.28X_2	96	0.324**
Current needles	ppm K = 2355 + 5.10X_1 - 0.80X_2	96	0.505**
1st flush needles	ppm K = 5957 + 7.89X_1 - 15.60X_2	84	0.774**
1st flush bud and stem	ppm K = 4833 + 4.20X_1 - 17.54X_2	96	0.738**
2nd flush needles	ppm K = 8247 + 7.49X_1 - 22.91X_2	36	0.704**
2nd flush bud and stem	ppm K = 4783 + 5.17X_1 - 4.53X_2	48	0.363**

[a] X_1 = kg K/ha applied and
X_2 = days after treatment.

[b] N = number of observations compared.

[c] * = indicates significance at P = 5%.
** = indicates significance at P = 1%.

TABLE 29. Average concentration of Na in foliage.

Sample	Treatment	Date 4/29	5/13	5/18	6/4	7/9	8/19	9/13	11/14
		% Na							
Old Needles	K0	0.08	0.11	0.10	0.07	0.11	0.09	0.08	0.11
	K0+	0.10	0.09	0.11	0.07	0.11	0.09	0.09	0.10
	K48+	0.10	0.09	0.09	0.07	0.12	0.08	0.07	0.11
	K96+	0.12	0.10	0.12	0.10	0.13	0.10	0.10	0.11
	K192+	0.09	0.09	0.11	0.06	0.11	0.09	0.09	0.12
Current Flush Needles	K0	0.04	0.05	0.05	0.03	0.06	0.05	0.06	0.07
	K0+	0.06	0.05	0.06	0.03	0.05	0.07	0.06	0.08
	K48+	0.06	0.04	0.04	0.03	0.06	0.06	0.05	0.07
	K96+	0.06	0.04	0.05	0.04	0.07	0.06	0.05	0.06
	K192+	0.04	0.04	0.05	0.03	0.06	0.07	0.04	0.07
1st Flush Needles	K0		0.02	0.03	0.01	0.03	0.03	0.01	0.03
	K0+		0.02	0.03	0.01	0.03	0.03	0.03	0.04
	K48+		0.02	0.03	0.01	0.03	0.03	0.01	0.04
	K96+		0.02	0.02	0.01	0.03	0.03	0.01	0.04
	K192+		0.02	0.03	0.01	0.04	0.04	0.01	0.04
1st Flush Bud and Stem	K0	0.03	0.04	0.03	0.01	0.05	0.03	0.04	0.04
	K0+	0.03	0.04	0.03	0.01	0.04	0.03	0.04	0.03
	K48+	0.03	0.04	0.03	0.01	0.04	0.03	0.04	0.03
	K96+	0.03	0.03	0.03	0.01	0.04	0.03	0.05	0.03
	K192+	0.02	0.03	0.02	0.01	0.04	0.03	0.04	0.03
2nd Flush Needles	K0						0.01	0.01	0.01
	K0+						0.01	0.02	0.03
	K48+						0.02	0.02	0.01
	K96+						0.02	0.01	0.02
	K192+						0.02	0.01	0.01
2nd Flush Bud and Stem	K0					0.01	0.02	0.01	0.03
	K0+					0.01	0.02	0.02	0.04
	K48+					0.01	0.02	0.01	0.03
	K96+					0.01	0.02	0.01	0.03
	K192+					0.01	0.02	0.01	0.03

TABLE 30. Average concentration of Ca in foliage.

Sample	Treatment	Date							
		4/24	5/13	5/18	6/4	7/9	8/19	9/13	11/14
		% Ca							
Old Needles	K0	0.28	0.27	0.30	0.30	0.17	0.24	0.24	0.13
	K0+	0.29	0.31	0.34	0.32	0.22	0.27	0.24	0.16
	K48+	0.28	0.34	0.36	0.30	0.18	0.26	0.29	0.17
	K96+	0.29	0.33	0.32	0.29	0.18	0.26	0.27	0.15
	K192+	0.26	0.28	0.32	0.32	0.17	0.24	0.28	0.16
Current Needles	K0	0.19	0.26	0.25	0.24	0.28	0.24	0.21	0.15
	K0+	0.19	0.24	0.26	0.28	0.25	0.25	0.24	0.17
	K48+	0.23	0.23	0.28	0.26	0.29	0.25	0.21	0.16
	K96+	0.19	0.21	0.24	0.25	0.25	0.25	0.24	0.15
	K192+	0.18	0.20	0.28	0.24	0.24	0.26	0.24	0.16
1st Flush Needles	K0		0.12	0.09	0.12	0.09	0.12	0.12	0.09
	K0+		0.09	0.16	0.15	0.11	0.13	0.12	0.10
	K48+		0.09	0.11	0.15	0.14	0.15	0.14	0.12
	K96+		0.07	0.11	0.15	0.12	0.15	0.14	0.11
	K192+		0.06	0.12	0.18	0.13	0.15	0.12	0.09
1st Flush Bud and Stem	K0	0.09	0.21	0.14	0.09	0.21	0.17	0.21	0.38
	K0+	0.09	0.13	0.14	0.10	0.20	0.18	0.24	0.40
	K48+	0.12	0.18	0.15	0.09	0.26	0.20	0.26	0.33
	K96+	0.10	0.17	0.14	0.09	0.19	0.18	0.25	0.37
	K192+	0.09	0.11	0.14	0.19	0.23	0.19	0.25	0.30
2nd Flush	K0						0.07	0.06	0.06
	K0+						0.05	0.08	0.08
	K48+						0.07	0.11	0.08
	K96+						0.06	0.08	0.09
	K192+						0.10	0.10	0.06
2nd Flush Bud and Stem	K0					0.05	0.11	0.10	0.22
	K0+					0.04	0.10	0.11	0.37
	K48+					0.06	0.15	0.14	0.25
	K96+					0.05	0.11	0.12	0.26
	K192+					0.06	0.14	0.13	0.28

TABLE 31. Average concentration of Mg in foliage.

Sample	Treatment	Date							
		4/24	5/13	5/18	6/4	7/9	8/19	9/13	11/14
		% Mg							
Old Needles	K0	0.10	0.09	0.10	0.10	0.07	0.07	0.07	0.08
	K0+	0.12	0.11	0.13	0.11	0.08	0.09	0.09	0.09
	K48+	0.10	0.12	0.12	0.11	0.08	0.07	0.09	0.07
	K96+	0.11	0.14	0.13	0.11	0.09	0.08	0.09	0.08
	K192+	0.09	0.11	0.12	0.11	0.09	0.08	0.07	0.08
Current Needles	K0	0.12	0.14	0.14	0.12	0.11	0.11	0.09	0.09
	K0+	0.13	0.14	0.16	0.13	0.12	0.12	0.10	0.09
	K48+	0.13	0.13	0.16	0.12	0.12	0.11	0.10	0.08
	K96+	0.13	0.14	0.16	0.13	0.11	0.13	0.11	0.08
	K192+	0.12	0.13	0.17	0.13	0.12	0.11	0.09	0.09
1st Flush Needles	K0		0.13	0.13	0.14	0.10	0.14	0.12	0.11
	K0+		0.13	0.16	0.15	0.10	0.14	0.13	0.11
	K48+		0.11	0.14	0.15	0.12	0.14	0.12	0.11
	K96+		0.14	0.15	0.16	0.11	0.16	0.13	0.12
	K192+		0.13	0.15	0.16	0.12	0.14	0.11	0.09
1st Flush Bud and Stem	K0	0.13	0.15	0.16	0.09	0.13	0.10	0.09	0.13
	K0+	0.13	0.16	0.16	0.09	0.14	0.10	0.11	0.13
	K48+	0.15	0.17	0.16	0.09	0.14	0.10	0.10	0.11
	K96+	0.14	0.15	0.16	0.09	0.13	0.10	0.12	0.13
	K192+	0.12	0.17	0.16	0.09	0.13	0.09	0.10	0.11
2nd Flush Needles	K0						0.14	0.12	0.10
	K0+						0.13	0.13	0.10
	K48+						0.15	0.15	0.10
	K96+						0.14	0.13	0.12
	K192+						0.15	0.13	0.09
2nd Flush Bud and Stem	K0					0.12	0.13	0.13	0.19
	K0+					0.11	0.12	0.13	0.19
	K48+					0.12	0.17	0.14	0.21
	K96+					0.12	0.12	0.14	0.20
	K192+					0.12	0.13	0.13	0.20

TABLE 32. Average concentration of P in foliage.

Sample	Treatment	Date							
		4/24	5/13	5/18	6/4	7/9	8/19	9/13	11/14
		% P							
Old Needles	K0	0.08	0.08	0.08	0.09	0.07	0.06	0.07	0.06
	K0+	0.08	0.09	0.09	0.10	0.10	0.10	0.10	0.09
	K48+	0.08	0.09	0.08	0.09	0.08	0.11	0.10	0.09
	K96+	0.08	0.10	0.10	0.10	0.08	0.11	0.10	0.09
	K192+	0.08	0.09	0.08	0.08	0.08	0.08	0.09	0.07
Current Needles	K0	0.07	0.09	0.08	0.09	0.08	0.08	0.07	0.07
	K0+	0.08	0.09	0.09	0.10	0.09	0.10	0.09	0.09
	K48+	0.08	0.08	0.09	0.10	0.08	0.10	0.09	0.09
	K96+	0.08	0.09	0.09	0.10	0.08	0.10	0.10	0.09
	K192+	0.08	0.09	0.08	0.09	0.08	0.09	0.10	0.08
1st Flush	K0		0.13	0.13	0.12	0.10	0.09	0.09	0.08
	K0+		0.13	0.14	0.13	0.11	0.11	0.10	0.09
	K48+		0.13	0.13	0.13	0.11	0.11	0.10	0.09
	K96+		0.14	0.14	0.12	0.11	0.11	0.10	0.08
	K192+		0.13	0.14	0.13	0.11	0.10	0.09	0.08
1st Flush Bud and Stem	K0	0.14	0.11	0.09	0.07	0.08	0.06	0.06	0.06
	K0+	0.14	0.11	0.09	0.09	0.08	0.06	0.06	0.06
	K48+	0.14	0.13	0.10	0.08	0.09	0.08	0.07	0.07
	K96+	0.14	0.11	0.10	0.08	0.08	0.08	0.07	0.06
	K192+	0.14	0.12	0.10	0.09	0.09	0.07	0.08	0.06
2nd Flush Needles	K0						0.12	0.09	0.08
	K0+						0.13	0.11	0.09
	K48+						0.15	0.11	0.10
	K96+						0.13	0.10	0.08
	K192+						0.13	0.11	0.09
2nd Flush Bud and Stem	K0					0.10	0.09	0.09	0.11
	K0+					0.11	0.10	0.10	0.10
	K48+					0.11	0.11	0.11	0.13
	K96+					0.11	0.10	0.11	0.11
	K192+					0.11	0.09	0.12	0.11

TABLE 33. Volume of throughfall and K and Na concentrations.

	Treatment	1973 Collection dates														
		4/27	5/9	5/13	5/18	5/25	5/28	5/31	6/29	7/9	7/30	8/9	8/30	9/17	10/27	12/21
		ml/collection														
Volume	K0	70	62	165	24	405	493	326	589	863	953	1130	637	863	128	1153
	K0+	67	52	173	23	395	495	323	953	883	937	1163	603	806	113	1020
	K48+	68	61	153	22	322	505	325	993	882	930	1040	573	860	121	1067
	K96+	61	50	162	24	323	552	323	967	925	953	1097	580	846	133	1183
	K192+	75	58	162	23	358	503	321	987	953	986	1137	597	827	117	953
		ppm														
K	K0	1.10	1.60	0.18	1.15	0.13	0.27	0.15	0.37	0.23	0.27	0.08	0.30	0.27	2.20	1.00
	K0+	1.37	2.07	0.32	1.72	0.58	0.20	0.23	0.45	0.28	0.33	0.07	0.30	0.23	1.73	0.70
	K48+	1.03	2.17	0.28	1.42	0.13	0.20	0.13	0.31	0.35	0.30	0.12	0.40	0.30	1.56	0.93
	K96+	1.41	2.33	0.37	0.77	0.27	0.15	0.27	0.50	0.32	0.40	0.15	0.53	0.53	2.13	0.97
	K192+	1.17	2.17	0.30	0.93	0.22	0.20	0.17	0.60	0.37	0.48	0.25	0.83	0.57	2.43	1.43
Na	K0	5.83	4.63	0.23	0.74	0.12	0.17	1.43	1.80	1.20	1.00	0.35	0.60	1.95	2.62	1.06
	K0+	6.99	5.63	0.43	1.44	0.23	0.08	1.38	0.88	1.12	1.40	0.37	0.55	2.25	3.82	1.55
	K48+	6.13	4.03	0.47	0.98	0.10	0.12	1.38	1.15	0.82	1.15	0.43	0.83	1.72	3.17	1.22
	K96+	7.14	4.93	0.38	0.35	0.30	0.05	1.45	1.23	1.12	1.25	0.30	0.92	2.23	3.13	1.10
	K192+	6.34	5.03	0.43	0.85	0.18	0.07	1.35	1.80	1.07	1.18	0.88	0.67	1.92	3.65	1.56

TABLE 33. (Continued)

	Treatment	1974 Collection date 2/25	4/2	5/16	7/11	9/24	Average	cm/yr
		ml						
Volume	K0	717	540	966	1583	1275	-	
	K0+	507	533	933	1833	1110	-	
	K48+	647	510	963	2150	1175	-	90
	K96+	657	570	1030	1825	2540	-	
	K192+	733	580	950	1667	1180	-	
		ppm						kg/ha/yr
K	K0	1.10	0.29	0.84	0.41	0.45	.46	3.85
	K0+	1.05	0.44	0.52	0.62	0.36	.45	3.87
	K48+	1.20	0.29	0.91	0.64	0.76	.49	3.68
	K96+	1.10	0.37	0.50	0.65	0.43	.53	4.42
	K192+	1.30	0.62	0.70	0.60	0.81	.67	5.72
Na	K0	2.03	0.88	0.45	0.40	0.30	.95	8.02
	K0+	2.07	0.91	0.48	0.47	0.25	.90	7.80
	K48+	2.37	0.82	0.43	0.67	0.34	.99	7.46
	K96+	1.98	0.85	0.37	0.57	0.37	1.00	8.38
	K192+	2.33	1.00	0.48	0.55	0.31	1.11	9.53

TABLE 34. Throughfall volumes and Ca, Mg, and P concentrations

	Treatment	1973 Sampling 4/27	5/28	6/29	7/30	8/30	9/17	10/17	12/21	1974 Sampling 2/25	4/2	5/16	7/11	9/24	Average	Total cm. rainfall/yr
		ml/collection														
Volume	K0	70	1149	1313	1816	1767	863	128	1153	717	540	966	1583	1275	-	
	K0+	67	1138	1276	1820	1800	806	113	1020	507	533	933	1833	1110	-	
	K48+	68	1063	1318	1812	1613	860	121	1067	647	510	963	2150	1175	-	83
	K96+	61	1111	1290	1878	1677	846	133	1183	657	570	1030	1825	2540	-	
	K192+	75	1104	1308	1939	1734	827	117	953	733	580	950	1667	1180	-	
		ppm														kg/ha/yr
Ca	K0	2.05	0.61	2.03	0.92	0.60	0.44	0.77	0.67	1.37	1.12	2.58	0.48	0.72	1.01	8.49
	K0+	2.17	0.60	1.26	0.71	0.53	0.47	0.68	0.95	1.50	1.03	0.99	0.57	0.57	.76	6.60
	K48+	1.93	0.55	0.58	0.57	0.57	0.38	0.77	0.64	1.07	0.88	1.12	0.69	0.71	.65	4.88
	K96+	2.53	0.54	1.16	0.77	0.65	0.54	0.65	0.71	1.50	0.63	0.92	0.58	0.52	.78	6.51
	K192+	2.84	0.55	1.54	0.88	0.50	0.40	0.88	0.85	1.53	0.91	0.82	0.70	0.47	.84	7.26
Mg	K0	1.11	0.20	0.32	0.23	0.13	0.24	0.61	0.36	0.35	0.39	0.75	0.19	0.17	.29	2.44
	K0+	1.38	0.20	0.35	0.24	0.20	0.29	0.97	0.29	0.50	0.50	0.51	0.24	0.17	.30	2.59
	K48+	1.25	0.19	0.26	0.17	0.13	0.19	0.58	0.30	0.34	0.31	0.50	0.26	0.16	.25	1.85
	K96+	1.52	0.23	0.33	0.21	0.17	0.25	0.62	0.34	0.40	0.34	0.36	0.21	0.14	.27	2.27
	K192+	1.42	0.20	0.47	0.26	0.19	0.25	0.78	0.45	0.48	0.41	0.47	0.21	0.25	.32	2.78
P	K0	0.05	0.02	0.04	0.01	0.01	0.03	0.00	0.00	0.02	0.02	0.00	0.00	0.01	.01	.10
	K0+	0.09	0.02	0.03	0.01	0.00	0.02	0.01	0.00	0.01	0.04	0.00	0.00	0.01	.01	.10
	K48+	0.05	0.02	0.02	0.02	0.03	0.02	0.00	0.00	0.02	0.00	0.01	0.01	0.02	.02	.12
	K96+	0.07	0.03	0.02	0.03	0.04	0.00	0.00	0.01	0.04	0.01	0.00	0.01	0.01	.02	.15
	K192+	0.04	0.02	0.03	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.01	.01	.10

TABLE 35. Needle litter weights and nutrient concentrations.

	Treatment	1973 Sampling date 5/8	5/31	7/2	8/9	9/13	10/3	10/17	11/14	1974 2/11	10/1	kg/ha/yr
		g/tray										
Litter weights	K0	59.4	165.3	292.4	396.5	459.7	201.0	309.4	647.2	1431.0	1562.6	3805
	K0+	44.4	158.0	166.0	318.1	470.5	169.8	300.4	682.7	1531.3	1420.2	3634
	K48+	22.9	141.7	311.1	341.7	419.1	195.8	285.1	646.2	1590.7	1486.1	3748
	K96+	15.3	209.0	236.8	391.0	457.9	190.6	322.6	694.5	1379.6	1666.7	3836
	K192+	12.8	143.3	297.6	443.8	455.6	197.9	369.8	844.5	1537.9	1489.6	3996
		%										
K	K0	0.11	0.06	0.06	0.07	0.04	0.05	0.04	0.04	0.04	0.04	1.7
	K0+	0.10	0.05	0.07	0.07	0.03	0.03	0.04	0.04	0.04	0.04	1.5
	K48+	0.12	0.06	0.07	0.08	0.05	0.05	0.05	0.05	0.05	0.05	2.0
	K96+	0.05	0.04	0.06	0.10	0.06	0.06	0.07	0.06	0.05	0.05	2.2
	K192+	0.14	0.07	0.09	0.13	0.07	0.07	0.10	0.09	0.09	0.07	3.5
Na	K0	0.07	0.05	0.04	0.02	0.04	0.05	0.07	0.09	0.06	0.02	1.7
	K0+	0.07	0.05	0.04	0.02	0.04	0.06	0.07	0.08	0.06	0.02	1.7
	K48+	0.07	0.05	0.04	0.03	0.03	0.05	0.06	0.07	0.05	0.02	1.6
	K96+	0.10	0.07	0.05	0.02	0.05	0.08	0.08	0.09	0.07	0.02	1.9
	K192+	0.08	0.05	0.05	0.03	0.04	0.05	0.07	0.09	0.06	0.02	2.0
Ca	K0	0.42	0.40	0.17	0.25	0.33	0.33	0.35	0.30	0.27	0.38	11.9
	K0+	0.42	0.37	0.17	0.27	0.34	0.34	0.36	0.29	0.29	0.39	11.9
	K48+	0.37	0.45	0.19	0.29	0.38	0.38	0.42	0.29	0.30	0.42	12.7
	K96+	0.34	0.39	0.18	0.26	0.33	0.35	0.34	0.26	0.26	0.36	11.9
	K192+	0.24	0.36	0.17	0.28	0.35	0.35	0.35	0.29	0.26	0.36	12.1

TABLE 35. (Continued)

	Treatment	1973 Sampling date								1974		kg/ha/yr
		5/8	5/31	7/2	8/9	9/13	10/3	10/17	11/14	2/11	10/1	
		%										
Mg	K0	0.15	0.11	0.07	0.08	0.09	0.09	0.10	0.08	0.09	0.10	3.5
	K0+	0.17	0.11	0.08	0.09	0.09	0.10	0.11	0.08	0.09	0.10	3.4
	K48+	0.12	0.11	0.08	0.07	0.08	0.08	0.09	0.08	0.08	0.10	3.2
	K96+	0.13	0.11	0.08	0.08	0.09	0.09	0.11	0.09	0.09	0.11	3.7
	K192+	0.13	0.14	0.08	0.08	0.09	0.04	0.11	0.08	0.08	0.11	3.7
P	K0	0.04	0.04	0.03	0.03	0.03	0.04	0.03	0.03	0.03	0.03	1.2
	K0+	0.05	0.05	0.04	0.05	0.05	0.04	0.06	0.06	0.05	0.03	1.7
	K48+	0.05	0.04	0.04	0.04	0.05	0.05	0.06	0.05	0.05	0.03	1.6
	K96+	0.04	0.04	0.04	0.04	0.05	0.04	0.05	0.05	0.04	0.03	1.6
	K192+	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	1.5

TABLE 36. Other litter weights and nutrient concentrations.

	Treatment	1973 Sampling								1974		
		5/8	5/31	7/2	8/9	9/13	10/3	10/17	11/14	2/11	10/1	kg/ha/yr
		gm/tray										
Other litter weights	K0	-	-	194.8	490.6	-	-	-	-	-	315.6	384
	K0+	-	-	-	102.1	-	-	42.7	-	232.3	114.6	170
	K48+	-	-	522.9	-	-	-	105.2	172.4	-	232.6	393
	K96+	-	-	119.8	83.3	-	-	-	-	-	586.8	501
	K192+	-	-	178.7	622.9	-	-	-	471.9	270.3	395.8	655
		%										
K	K0	-	-	0.01	0.01	-	-	-	-	-	0.02	0.1
	K0+	-	-	-	0.02	-	-	0.02	-	0.03	0.02	0.1
	K48+	-	-	0.02	-	-	-	0.02	0.01	-	0.03	0.1
	K96+	-	-	0.01	0.03	-	-	-	-	-	0.03	0.1
	K192+	-	-	0.01	0.02	-	-	-	-	0.02	0.0]	0.1
Na	K0	-	-	0.01	0.01	-	-	-	-	-	0.01	0.0
	K0+	-	-	-	0.01	-	-	0.01	-	0.01	0.01	0.0
	K48+	-	-	0.01	-	-	-	0.01	0.03	-	0.01	0.1
	K96+	-	-	0.01	0.01	-	-	-	-	-	0.01	0.1
	K192+	-	-	0.01	0.01	-	-	-	0.03	0.01	0.01	0.1
Ca	K0	-	-	0.27	0.14	-	-	-	-	-	0.24	1.0
	K0+	-	-	-	0.30	-	-	0.50	-	0.15	0.29	0.4
	K48+	-	-	0.31	-	-	-	0.43	0.29	-	0.33	1.3
	K96+	-	-	0.22	0.28	-	-	-	-	-	0.31	1.6
	K192+	-	-	0.30	0.21	-	-	-	0.33	0.24	0.28	1.8

TABLE 36. (Continued)

	Treatment	1973 Sampling								1974		Kg/ha/yr
		5/8	5/31	7/2	8/9	9/13	10/3	10/17	11/14	2/11	10/1	
		%										
Mg	K0	-	-	0.03	0.02	-	-	-	-	-	0.05	.1
	K0+	-	-	-	0.04	-	-	0.04	-	0.05	0.04	.1
	K48+	-	-	0.03	-	-	-	0.03	0.02	-	0.05	.1
	K96+	-	-	0.02	0.05	-	-	-	-	-	0.05	.3
	K192+	-	-	0.03	0.03	-	-	-	0.04	0.04	0.03	.1
P	K0	-	-	0.01	0.01	-	-	-	-	-	0.01	0.0
	K0+	-	-	-	0.01	-	-	0.02	-	0.01	0.02	0.0
	K48+	-	-	0.01	-	-	-	0.02	0.02	-	0.01	0.0
	K96+	-	-	0.01	0.01	-	-	-	-	-	0.02	0.1
	K192+	-	-	0.01	0.01	-	-	-	0.02	0.01	0.01	0.0

LITERATURE CITED

Armson, K.A. 1965. Seasonal patterns of nutrient absorption by forest trees. p.65-75 In C.A. Youngberg (ed.) Forest-soil relationships. Oregon State Univ. Press, Corvallis.

Armson, K.A. 1973. Soil and plant analysis techniques as a diagnostic criteria. p. 55-66 In A.L. Leaf (ed.) Forest fertility symposium proc. USDA Forest Serv. Gen. Tech. Rep. NE 3.

Art, H.W., and P.L. Marks. 1971. A summary table of biomass and net annual primary production in forest ecosystem of the world. p. 3-35 In H.E. Young (ed.) Forest biomass studies. Orono, Maine.

Attiwill, P.M. 1966. Chemical composition of rainwater in relation to cycling of nutrients in mature Eucalyptus forests. Plant Soil 24:390-406.

Attiwill, P.M. 1972. On the cycling of elements in mature Eucalyptus obliqua forest. p. 39-46 In R. Boardman (ed.) The Australian forest-tree nutrition conference. Forest and Timber Bureau, Canberra.

Bailey, R.L., and J.K. Clutter. 1970. Volume tables for old-field loblolly pine plantations in the Georgia piedmont. Ga. Forest Res. Coun. Report 22.

Barnes, R.L. 1955. Growth and yield of slash pine plantations in Florida. Univ. Fla. School of Forestry Res. Rept. 3.

Barnes, R.L., and C.W. Ralson. 1955. Soil factors related to growth and yield of slash pine plantations. Univ. Fla. Agr. Expt. Sta. Tech. Bul. 559.

Barr, H., and J.H. Goodnight. 1972. A users guide to the statistical analysis systems. North Carolina State Univ., Inst. Statist., Raleigh.

Baule, H., and C. Fricker. 1970. The fertilizer treatment of forest trees. BLV Verlagsgesellschaft, Munchen.

Bengtson, C.W., and G.K. Voight. 1962. A greenhouse study of relationships between nutrient movement and conversion in a sandy soil and the nutrition of slash pine seedlings. Soil Sci. Soc. Amer. Proc. 26:609-612.

Bennet, F.A. 1970. Yields and stand structural patterns for old-field plantations of slash pine. USDA Forest Serv. Res. Paper SE-60.

Berry, L.G., and B. Mason. 1959. Mineralogy. W.H. Freeman and Co., San Francisco.

Bjorkmann, E. 1967. Manuring and resistance to disease. p. 328.331. In A colloquium on forest fertilization. Int. Potash Inst., Jyväskylä, Finland.

Bray, J.R., and E. Gorham. 1964. Litter production in forest of the world. Adv. Ecol. Res. 2:102-157.

Brüning, D., D. Trillmich, and E. Uckel. 1967. 35 years of fertilization trials with K - Mg on pines in the Templin area. p. 240-249. In A colloquium on forest fertilization. Int. Potash Inst., Jyväskylä, Finland.

Burkhart, H.T., and M.R. Strub. 1973. Dry weight yield estimates for loblolly pine. In IUFRO, Biomass studies 5401:29-41.

Carlisle, A., A.H.F. Brown, and E.J. White. 1967a. The nutrient content of rainfall and its role in the forest nutrient cycle. In IUFRO, Proc. of XIV Congress, Munich II:145-158.

Carlisle, A., A.H.F. Brown, and E.J. White. 1967b. The nutrient cycle of tree stem-flow and ground flora, litter, and leaching in a sissle oak woodland. J. Ecol. 55:615-627.

Cassiday, N.G. 1966. A natural method for recording and comparing concentrations of plant constituents that are water soluble, with particular reference to Cl and K. Plant Soil. 25:372-384.

Cobb, B. 1963. A field guide to the fern. Houghton Mifflin Co., Boston.

Cole, D.W., and S.P. Gessel. 1965. Movements of elements through a forest soil as influenced by tree removal and fertilizer additions. p. 95-104. In C.A. Youngberg (ed.) Forest soil relationships in North America. Oregon State Univ. Press, Corvallis.

Cole, D.W., S.P. Gessel, and S.F. Dice. 1967. Distribution and cycling of N, P, K, and Ca in second-growth Douglas-fir ecosystem. p. 197-232, In H.E. Young (ed.) Primary productivity and mineral cycling in natural ecosystems. Univ. of Maine, Orono.

Crow, T.R. 1971. Estimation of biomass in an even-aged stand. p. 35-48. In H.E. Young (ed.) Forest biomass studies. Univ. of Maine, Orono.

Curlin, J.W. 1970. Nutrient cycling as a factor in site productivity and forest fertilization. p. 313-325. In C.T. Youngberg (ed.) Tree growth and forest soils. Oregon State Univ.Press, Corvallis.

Czarnowski, M.S., and J.L. Olszewski. 1968. Rainfall interception by forest canopy. Oikos 19:345-350.

Duncan, D.B. 1955. Multiple range and multiple F tests. Biometrics. 11:1-42.

Dunnett, C.W. 1955. A multiple comparison procedure for comparing several treatments with a control. J. Amer. Statist. Assoc. 50:1096-1121.

Duvigneaud, P., and S. Denaeyer-De Smet. 1970. Biological cycling of minerals in temperate deciduous forest. p. 199-225. In D.E. Reichle (ed.). Analysis of temperate forest ecosystem. Springer-Verlag., N.Y.

Epstein, E. 1955. Passive permeation and active transport of ions in roots. Plant Physiol. 30:529-535.

Ewel, K.C., J.F. Gamble, and A.E. Lugo. 1975. Aspects of mineral nutrients cycling in a southern mixed hardwoods forest in north-central Florida. (In press).

Formes, R.H., J.V. Berglund, and A.L. Leaf. 1970. A comparison of the growth and nutrition of Picea abies (L) Kurst and Pinus resinosa on a K deficient site subjected to K fertilization. Plant soil 33:345-360.

Gagnon, J.D. 1965. Effect of Mg and K fertilization on a 20-year-old red pine plantation. Forest Chron. 41:290-294.

Gauch, H.G. 1972. Inorganic plant nutrition. Dowden, Hutchinson and Ross Inc., Straudsburg, Pa.

Gessel, S.P., and D.W. Cole. 1965. Influence of removal of forest cover on movement of water and associated elements through soil. J. Amer. Water Works Assoc. 57:13011310.

Gooding, J.W. 1970. Effect of fertilization on crown, stem, and wood properties of slash pine (Pinus elliottii var. elliottii Engelm.). MSF Thesis. Univ. of Florida.

Hagner, S. 1971. The present standard of practical forest fertilization in different parts of the world. p. 184-207. In Proc. of Div. 3, 15th IUFRO Congress, Gainesville, Florida.

Hall, J.J., and M. Raupach. 1963. Foliar analysis and growth in Pinus radiata showing K deficiency in eastern Victoria. Appita 17:76-84.

Hall, J.J., and H.M. Parnell. 1961. K deficiency in Pinus radiata in eastern Victoria. Aust. For. 25:111-115.

Harley J.L., and J.M. Wilson. 1959. Absorption of K by beech mycorrhiza. New Phytol. 58:281-298.

Hart, J.B., Jr., A.L. Leaf, and S.J. Statzback. 1969. Variation in K availability to trees within an outwash soil. Soil Sci. Soc. Amer. Proc. 33:950-954.

Heiberg, S.O., and A.L. Leaf. 1960. Potassium fertilization of coniferous plantations in New York. Proc. of 7th Int. Cong. of Soil Sci. (Madison, Wis.) 3:376-383.

Heiberg, S.O., and A.L. Leaf. 1961. Effect of forest debris and mineral fertilizers on the amelioration of sandy soils. Proc. 13th IUFRO Congress, Vienna.

Heiberg, S.O., H.A.I. Magwick, and A.L. Leaf. 1964. Some long-time effects of fertilization on red pine plantations. Forest Sci. 10:17-23.

Heiberg, S.O., and D.P. White. 1951. K deficiency of reforested pine and spruce stands in northern New York state. Soil Sci. Soc. Amer. Proc. 15:361-376.

Hobbs, C.H. 1944. Studies on mineral deficiencies in pine. Plant Physiol. 19:590-602.

Holstener-Jørgensen, H. 1964. K and Mg deficiency symptoms in fertilizer experiments in Norway spruce plantations in Jutland (in Danish). Saertryk af Det Ferstlige Forsogsvaesen i Danmark. 29:1-23.

Hoover, M.D., D.F. Olson Jr., and G.E. Greene. 1953. Soil moisture under a young loblolly pine plantation. Soil Sci. Soc. Amer. Proc. 17:147-150.

Hughes, R.H., and J.E. Jackson. 1962. Fertilization of young slash pine in cultivated plantation. SE Forest Expt. Sta. Paper 148.

Ingestad, T. 1960. Studies on the nutrition of forest tree seedlings. Physiol. Planta. 13:513-533.

Jackson, M.L. 1958. Soil Chemical Analysis. Prentice Hall Inc. Englewood Cliffs, N.J.

Jordon, C.F., J.R. Kline, and D.J. Sasscer. 1972. Relative stability of mineral cycles in forest ecosystems. Amer. Naturalist 106: 237-253.

Jorgensen, M.F., and A.L. Leaf. 1965. Soil moisture-fertility interactions related to growth and nutrient uptake of red pine. Soil Sci. Soc. Amer. Proc. 29:294-299.

Koch, P. 1972. Utilization of the southern pines. USDA Agr. Handbook 420.

Leaf, A.L. 1967. K, Mg, and S deficiencies in forest trees. p. 88-122. In Forest fertilization - theory and practice. TVA, Nat. Fert. Develop. Cen., Muscle Shoals, Ala.

Leaf, A.L. 1973. Plant analysis as an aid in fertilizing forests. In Soil testing and plant analysis. Amer. Soc. Agron.,Madison, Wis.

Leaf, A.L., R.E. Leonard, and J.V. Bergland. 1971. Root distribution of a plantation-grown red pine in an outwash soil. Ecol. 52: 153-158.

Leaf, A.L., R.E. Leonard, J.V. Bergland, A.R. Eschner, P.H. Cochran, J. B. Hart Jr., G.M. Marion, and R.A. Cunningham. 1970. Growth and development of Pinus resinosa plantations subjected to irrigation-fertilization treatments. p. 97-118. In C.B. Davey (ed.) Tree growth and forest soils. Oregon State Univ. Press, Corvallis.

Likens, G.E., and F.H. Bormann. 1972. Nutrient cycling in ecosystems. p. 25-67. In J.A. Wiens (ed.) Ecosystem structure and function. Oregon State Univ. Press, Corvallis.

Likens, G.E., F.H. Bormann, N.M. Johnson, and R.S. Pierce. 1967. Calcium, magnesium, potassium and sodium budgets for a small forested ecosystem. Ecol. 48:772-785.

McKee, N.H. Jr., and E. Shoulders. 1974. Slash pine biomass response to site preparation and soil properties. Soil Sci. Soc. Amer. Proc. 38:144-148.

Madgwick, H.A.I. 1963. Nutritional Research: Some problems of the total tree approach. Soil Sci. Soc. Amer. Proc. 27:598-600.

Malac, B.F. 1968. Research in forest fertilization at Union Camp. p. 204-208. In Forest fertilization - theory and practice. TVA, Nat. Fert. Develop. Cen., Muscle Shoals, Ala.

Marion, G.M., J.V. Berglund, and A.L. Leaf. 1968. Morphological and chemical analysis of red pine buds: Their relationships to tree growth on a K deficient to nondeficient site continuum. Plant Soil 28:313-324.

May, J.T., H.H. Johnson, and A.R. Gilmore. 1962. Chemical composition of southern pine seedlings. GA. Forest Res. Coun. Res. Paper 10.

Mead, D.J. 1971. Movement of added nitrogen and phosphorus in a pine forest ecosystem. Ph.D. Thesis. Univ. Fla.

Mead, D.J., and W.L. Pritchett. 1974. Variation of N, P, K, Ca, Mg, Mn, Zn, and Al in slash pine foliage. Comm. Soil Sci. and Plant Anal. 5:291-301.

Malkonen, E. 1973. Effect of complete tree utilization on the nutrient reserves of forest soils. p. 379-386. In IUFRO biomass studies, Univ. of Maine Press, Orono.

Metz, L.J., and C.G. Wells. 1965. Weight and nutrient content of the above-ground parts of some loblolly pines. USDA Forest Serv. Res. Paper SE-17.

Metz, L.J., C.G. Wells, and P.P. Kormanik. 1970. Comparing the forest floor and surface soil beneath four pine species. USDA Forest Serv. Res. Paper SE-55.

Miller, R.B. 1968. Flows and cycle of macro- and micro-elements in a forest soil and its environment. Proc. 9th Int. Cong. of Soil Sci. (Adelaide, Aus.) 4:323-331.

Miller, W.F. 1966. Annual changes in foliar N, P, and K levels of loblolly pine with site and weather factors. Plant Soil 24: 369-378.

Mustanoja, K.J., and A.L. Leaf. 1965. Forest fertilization research, 1957 - 1964. Bot. Rev. 31:151-246.

Nelson, L.E., G.L. Switzer, and W.H. Smith. 1968. Dry matter and nutrient accumulation in young loblolly pine (Pinus taeda L.) p. 261-273. In C.F. Youngberg. Tree growth and forest soils. Oregon State Univ. Press, Corvallis.

Nemeth, J.C. 1973. Dry matter production in young loblolly (Pinus taeda L.) and slash pine (Pinus elliottii Engelm) plantations. Ecol. Monogr. 43:21-41.

Newbould, P.S. 1967. Methods for estimating the primary production of forests. IBS, Oxford.

Nihlajard, B. 1970. Precipitation, its chemical composition and effect on soil water in a beech and a spruce forest in southern Sweden. Oikos 21:208-217.

Nye, P.H. 1961. Organic matter and nutrient cycles under moist tropical forest. Plant Soil 13:333-346.

O'Carroll, N., and R. McCarthy. 1973. K supplied by precipitation and its possible role in forest nutrition. Irish Forest. 30: 89-93.

O'Hare, P.J. 1967. The leaching of nutrients by rainwater from forest trees. p. 122-130. In Proc. of fifth colloquium of forest fertilization. Int. Potash Inst., Berne.

Orman, H.R., and G.M. Will. 1960. Nutrient content of P. radiata. N.Z. Sci. 3:510-522.

Ovington, J.D. 1960. The nutrient cycle and its modification through silviculture practices. Proc. of Fifth World Forest Congress 1:533-538.

Ovington, J.D. 1972. Woodlands. English Univ. Press Ltd. London.

Ovington, D.J., W.G. Forrest, and J.S. Armstrong. 1967. Tree biomass estimation. p. 4-31. In H.E. Young (ed.) Symposium on primary productivity and mineral cycling in natural ecosystems. Ecol. Soc. Amer., Univ. of Maine Press, Orono.

Phullips, D.R., and J.G. Schroeder. 1972. Some physical characteristics of bark from plantation-grown slash and loblolly pine. Forest Prod. J. 22:30-33.

Pritchett, W.L. 1969. Slash pine growth during the seven to ten years after fertilizing young plantations. Soil Crop Sci. Soc. Fla. Proc. 29:34-44.

Pritchett, W.L. 1972. The effect of N and P fertilizers on the growth and composition of loblolly and slash pine seedlings in pots. Soil Crop Sci. Soc. Fla. Proc. 33:161-165.

Pritchett, W.L., and J.L. Gray. 1974. Is forest fertilization feasable? Forest Farmer 33:6-7.

Pritchett, W.L., and W.H. Smith. 1969. Sources of nutrients and their reactions in forest soils. Soil Crop Sci. Fla. Proc. 29:149-158.

Pritchett, W.L., and W.H. Smith. 1972. Fertilizer responses in young pine plantations. Soil Sci. Soc. Amer. Proc. 36:660-663.

Pritchett, W.L., and W.H. Smith. 1974. Management of wet savanna forest soils for pine production. Fla. Agr. Exp. Sta. Bul. 762.

Pritchett, W.L., and W.R. Llewellyn. 1966. Response of slash pine (Pinus elliottii Engelm.var. elliottii) to P in sandy soils. Soil Sci. Soc. Amer. Proc. 30:509-512.

Ralston, C.W. 1973. Annual production in a loblolly pine plantation. p. 106-130. In IUFRO biomass studies. Univ. of Maine Press, Orono.

Ralston, C.W., and A.B. Prince. 1963. Accumulation of dry matter and nutrients by pine and hardwood forests in the lower piedmont of North Carolina. p. 77-94. In C.T. Youngberg (ed.) Forest - Soil relations in North America. Oregon State Univ. Press, Corvallis.

Raupach, M., and M.J. Hall. 1972. Foliar levels of K in relation to K deficiency symptoms in radiata pine. Aust. Forest. 36:204-213.

Raupach, M., and A.R.P. Clarke. 1972. Deficiency symptoms, fertilizer response, and foliar levels of K in Pinus radiata. p. 136-143. In M. Boardman (ed.) The Australian forest tree nutrition conference. Forest and Timber Bureau, Canberra.

Reiner, W.A. 1972. Nutrient content of canopy throughfall in three Minnesota forests. Oikos 23:14-22.

Remezov, N.P., and P.S. Pogrebnyak. 1969. Forest Soil Science Trans. from Russian by Israel Prog. Sci. Trans.

Rennie, P.J. 1966. A forest sampling procedure for nutrient uptake studies. Comm. Forest. Rev. 45:119-128.

Rich, C.I. 1968. Minerology of Soil K. In Role of K in agriculture. Amer. Soc. of Agron., Madison.

Riekert, H. 1971. The mobility of P, K, and Ca in forest soils. Soil Sci. Soc. Amer. Proc. 35:35-356.

Rodin, L.E., and N.I. Bazilevich. 1967. Production and mineral cycling in terrestrial vegetation. Oliver and Boyd, London.

Rosendahl, R.O. 1942. The effect of mycorrhizal and nonmycorrhizal fungi on the availability of difficultly soluble K and P minerals. Soil Sci. Soc. Amer. Proc. 7:477-479.

Sarigumba, T.I. 1974. Movement and transformations of Urea-N in three forest soils of the southern coastal plain. Ph.D. Thesis. Univ. of Florida.

Schlisinger, W.H., and W.A. Reiner. 1974. Deposition of water and cations on artificial foliar collectors in fir krummholz of New England mountain. Ecol. 55:378-386.

Smith, M.K. 1972. Throughfall, stemflow, and interception in pine and eucalyptus forests. Aust. Forest. 36:190-197.

Snedecor, G.W., and W.G. Cochran. 1967. Statistical methods. Iowa State Univ. Press, Ames.

Stanhill, G. 1970. The water flux in temperate forests: Precipitation and evaporation. p. 242-256. In D.E. Reichle (ed.) Analysis of temperate forest ecosystems. Springer-Verlag, New York.

Steele, R.G.D., and J.H. Torrie. 1960. Principles and procedures of statistics. McGraw Hill, New York.

Stone, E.L. 1971. Effect of prescribed burning on long term production of coastal plain soils. p. 115-129. In Prescribed burning symposium proceedings. USDA Forest Serv., Charleston, S.C.

Sucoff, E.I. 1962. K, Mg, and Ca requirement of Virginia pine. USDA Forest Serv., NE Forest Exp. Sta. Paper 169.

Switzer, G.L., and L.E. Nelson. 1972. Nutrient accumulation and cycling in loblolly plantation ecosystems: The first twenty years. Soil Sci. Soc. Amer. Proc. 36:143-147.

Tamm, C.O. 1951. Removal of plant nutrients from tree crowns by rain. Physiol. Planta. 4:184-188.

Tarrant, R.F., K.C. Lu, W.B. Bollen, and C.S. Chen. 1968. Nutrient cycling by throughfall and stemflow precipitation in three coastal Oregon forest types. USDA Forest Serv. Res. Paper PNW 54.

Terman, G.S., and G.W. Bengtson. 1973. Yield - nutrient concentration relationships in slash and loblolly pine seedlings. Soil Sci. Soc. Amer. Proc. 37:445-450.

Tisdale, S.L., and W.L. Nelson. 1966. Soil fertility and fertilizers, 3rd edition. MacMillian Co., New York.

Ulrich, B. 1973. The nutrient cycle in forest ecosystems as influenced by fertilization. Int. Symp. on Forest Fertilization. FAO/IUFRO, Paris (In press).

Vleck, P.L.G., Th.J.M. Blom, J. Beek, and W.L. Lindsay. 1974. Determination of the solubility product of various iron hydroxides and jarosite by the chelation method. Soil Sci. Soc. Amer. Proc. 38:429-432.

Voigt, G.K. 1960. Distribution of rainfall under forest stands. Forest Sci. 6:2-10.

Voigt, G.K. 1965. Biological mobilization of K from primary minerals. p. 33-46. In C.T. Youngberg (ed.) Forest soil relations in North America. Oregon State Univ. Press, Corvallis.

Volk, N.J. 1934. The fixation of K in difficultly available form in soils. Soil Sci. 37:267-287.

Walker, L.C. 1956. Foliage symptoms as indicators of K deficient soils. Forest Sci. 2:113-120.

Walker, L.C. 1962. The effects of water and fertilizer on loblolly and slash pine seedlings. Soil Sci. Soc. Amer. Proc. 26:197-200.

Walker, L.D. 1958. Fertilizing southern pines. p. 15-23. In First California Forest Soils and Forest Fertilization Conf. Proc., Davis.

Watanabe, F.S., and S.R. Olsen. 1965. Tests of an ascorbic acid method for determining P in water and $NaHCo_3$ extracts from soils. Soil Sci. Soc. Amer. Proc. 29:677-678.

Waters, C.E. 1903. Ferns. Henry Holt and Co., New York.

Weetman, G.F., and S.B. Hill. 1973. General environment and biological concerns in relation to forest fertilization. p. 19-35. In Forest Fertilization Symposium Proceedings. USDA Forest Serv. Gen. Tech. Report NE 3.

Wells, C.G. 1971. Effects of prescribed burning on soil chemical and nutrient availability. p. 86-99. In Prescribed burning symposium proceedings. USDA Forest Serv., Charleston, S.C.

Wells, C.G., and J.R. Jorgensen. 1973. Nutrient cycling in loblolly pine plantations. Forest Soils Conference, Quebec, P.Q. (In press).

Wells, C.G., and L.J. Metz. 1963. Variation of nutrient content of loblolly pine needles with season, age, soil, and position in the crown. Soil Sci. Soc. Amer. Proc. 27:90-93.

Wetselaar, R., and J.T. Hutton. 1963. Ionic composition of rainfall at Katherine, North Territory and its part in the cycling of plant nutrients. Aust. Agr. Res. 14:319-329.

White, D.P. 1954. Variation in the N, P, and K contents of pine needles with season, crown position and sample treatment. Soil Sci. Soc. Amer. Proc. 18:326-330.

White, D.P., and A.L. Leaf. 1964. Soil and tissue K related to tree growth. Soil Sci. 98:395-402.

White, E.H., W.L. Pritchett, and W.K. Robertson. 1971. Slash pine root biomass and nutrient concentration. p. 165-176. In H.E. Young (ed.) Forest biomass studies. Univ. of Maine , Orono.

White, E.J., and F. Turner. 1970. A method of estimation income in nutrients in a catch of airborne particles by a woodland canopy. J. Ecol. 7:441-461.

Will, G.M. 1955. Removal of mineral nutrients from tree crowns by rain. Nature 176:1180.

Will, G.M. 1957. Variations in the mineral content of radiata pine needles with age and position in tree corwn. N.Z. Sci. Tech. 38:699-706.

Will, G.M. 1968. The uptake, cycling and removal of mineral nutrients by crops of Pinus radiata. Proc. N.Z. Ecol. Res. 15:20-24.

Woodwell, G.M., and P.H. Whittaker. 1967. Primary productivity and the cation budget of the Brookhaven forest. In H.E. Young (ed.) Symposium on primary productivity and mineral cycling in natural ecosystems. Univ. of Maine, Orono.

Young, H.E. 1947. The response of loblolly pine and slash pine to phosphate manures. Queensland J. Agr. Sci. 5:97-105.

Young, H.E., and P.M. Carpenter. 1967. Weight, nutrient element,and productivity studies of seedlings and saplings of eight tree species in natural ecosystems. Maine Agr. Exp. Sta. Tech. Bul. 28, Orono.

Zelazny, L.W., and V.W. Carlisle. 1971. Mineralogy of Florida aeric haplaquods. Soil Crop Sci. Soc. of Fla. Proc. 31:161-165.

BIOGRAPHICAL SKETCH

Roylyn L. Voss was born on April 5, 1939, in Ingham County, Michigan. He graduated with a Bachelor of Science with honor in Agriculture from Michigan State University on June 11, 1961. From 1961 to 1970 he was employed by the University of Hawaii in sequence as research assistant, extension specialist in soil management, and as research associate. During that time he completed the requirements for the degree of Master of Science in Agronomy and Soil Science, receiving it on May 31, 1970. In September, 1970, he entered the Graduate School of the University of Florida to work on his Doctor of Philosophy degree in Forest Soils, which he received in June, 1975.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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