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FERTILIZER MOVEMENT IN A SLASH PINE ECOSYSTEM

I. UPTAKE OF N AND P AND N MOVEMENT IN THE SOIL*

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SUMMARY

The movement of N in an 11-year-old slash pine forest ecosystem was followed over two growing seasons by using N^{15}-labeled ammonium sulphate, applied in the spring at 0, 56, and 224 kg N/ha. The initial uptake of P^{32}, applied as concentrated superphosphate at 90 kg P/ha, and of labeled N from the highest application rate was followed in two trees for 71 days.

Dry weather following fertilizer application delayed uptake and both isotopes were first observed in the foliage 7 days after application. While uptake of P^{32} was at a steady rate between the third and tenth week, the uptake of N^{15} declined, due to reduced availability in the soil, after seven weeks. Concentrations of both isotopes were greater in the lower foliage than in the upper crown. The N^{15} levels were higher in currently developing foliage than in older foliage, while the reverse was true for P^{32}.

The maximum concentration of labeled-N occurred in the foliage at about 12 weeks. At this time the current foliage had derived 8.5 per cent of its N from the fertilizer in the low-N treatment and 27.5 per cent at the high-N treatment. However, N^{15} uptake into the developing foliage continued, at a reduced rate, until mid winter. In the second growing season, the foliage formed in the previous growing season decreased in total and labeled-N content due to translocation to newly developing tissue.

The N^{15} leached rapidly through the litter with only 9 per cent of the applied N, in the high-N treatment, occurring in the litter at the end of 6 weeks. In the first 12 weeks the amount of N^{15} in the litter and topsoil decreased rapidly (to 21 per cent in the high-N plots) but changed little thereafter. This decrease was related to uptake and probably to leaching.

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INTRODUCTION

In order to improve the use of fertilizer in forest ecosystems it is necessary to understand the fundamental processes involved in nutrient uptake and translocation under forest conditions. In this study, the movements of applied N and P in a pine forest ecosystem were investigated using labeled materials. The objectives were to study (a) the initial uptake patterns of N and P into the tree crowns, (b) the long-term movement of N into the trees; and (c) the movement of N from point of placement through the litter and soil.

A second paper in this series discusses the uptake of fertilizer N as related to the rate of application, and its distribution within the tree and other parts of the ecosystem, after two growing seasons.

MATERIALS AND METHODS

Experimental area

The study was in an 11-year-old slash pine (*Pinus elliottii* var. *elliottii* Engelm.) plantation of the University of Florida experimental forest near Gainesville, Florida. The stand was a typical high site-quality plantation established on formerly cultivated, moderately well-drained sand of the Tavares series. At the start of the experiment the trees averaged 12.1 m in height and 14.2 cm in diameter. The stand was unthinned and had a high stocking (1550 stems/ ha); this resulted in a light ground vegetation and well developed litter layer about 3–4 cm thick.

The soil, a member of the siliceous, hyperthemic, uncoated family of Typic Quartzipsamments [16] had an A_1 horizon 40–50 cm thick, which overlaid a white to light grey, occasionally mottled, A_2 of between 50 and 150 cm thickness. A dark indurated B_2h horizon sometimes occurred beneath the A_2. The topsoil had a very low silt plus clay content ($\leq 8.2\%$), was moderately acid (pH 5.0 to 5.3), and had a low cation exchange capacity (1.9 to 3.5 me/100 g). During the experiment the water table fluctuated between 0.5 and 2.3 m below the surface.

The climate of the region is subtropical, with almost half of the 1330 mm of rain falling between June and September. The mean temperature varies from about 15°C in January to 28°C in July.

Experimental design

An experiment with N^{15}- and P^{32}-labeled fertilizer was established in the spring (mid-May) using single tree plots. The plot area was 7.07 m^2 (1.5 m radius around each tree) and the experiment was a completely randomized design of four replications of 0, 56, and 224 kg N/ha. The N was applied as granular $(NH_4)_2SO_4$ (6–12 mesh) labeled with 2.388 atom percent N^{15}. A basal dressing of 90 kg P/ha as granular (6–9 mesh) concentrated superphosphate was applied to all plots and for two of the plots in the heaviest N treatment this was labeled with P^{32} (0.236 mc P^{32}/g P).

Initial uptake of N and P

Initial uptake of N and P was followed for 71 days in the two trees topdressed with P^{32}-labeled concentrated superphosphate and the highest rate of $(NH_4)_2SO_4$. Background isotope levels were determined on foliage samples collected before fertilizer application. Subsequent samples were taken from the terminal leaders and from first- and second-order branches in the upper and lower crown. On the first and alternate collections, samples were taken from each age of needles present; at other sampling dates only current-year needles were taken. A few fascicles were taken from all branches in the whorl, sampled so that defoliation was minimal on any one branch.

Two separate analyses of variances were calculated for each parameter [17]. The first used all three foliage ages (collected on six occasions) and the second was for current foliage only (collected on twelve occasions).

Long-term changes in the foliage

To study long-term changes in foliar N and N^{15} levels and contents, all 12 trees were sampled at 6-week intervals over two growing seasons, terminating in the second winter. Samples were taken from all second-order branches on marked whorls in the upper third of the crown. All ages of foliage present were sampled at each sampling time, but to reduce excessive defoliation samples were combined by fertilizer treatment. After drying at 60°C, twenty-five randomly selected fascicles were weighed.

The three foliage age groups (current and 1-year-old at the start of the experiment, and new foliage formed in the second growing season) were statistically analysed as separate groups [9 17].

Movement of N^{15} in the soil

Soil samples, to a depth of 50 cm by 10-cm increments, were collected 0, 6, 12, 30 and 84 weeks after fertilizer application. Except for the final sampling date the samples were combined by treatment before analysis. Litter samples were taken the same time as the soil samples, except that a litter sampling was also made at 3 weeks after treatment.

Soil bulk density was determined for each plot by 10-cm increments to a depth of 50 cm, using a double-cylinder, hammer-driven core sampler. Two litter samples of 1.0 m^2 area were collected from each plot at the end of the experiment and their dry weight determined.

Sample analysis

All foliage samples were dried at 60°C and ground in a Waring blender, and soil samples were air dried and sieved through a 2 mm screen. Total P in the foliage was determined by an ammonium molybdate/stannous chloride procedure [7] and total N in both soil and foliage by the salicylic acid modification of the Kjeldahl method [2].

The activity of P^{32} was determined by Cerenkov radiation [6]. A 0.5 g sample was ashed, dissolved in acid, transferred to polyethylene vials, brought up to a standard volume with water and counted for 30 minutes in a liquid scintillation counter.

The N^{15} atom percent was determined by mass spectrometer [3]. Results were corrected by comparison with standard N^{15} samples.

Rainfall

Five, 20-cm diameter, rain collectors were located under the trees during the first 10 weeks of the study. The precipitation was recorded each time foliage samples were collected.

RESULTS AND DISCUSSION

Initial uptake of N and P

The soil was very dry at the time the fertilizers were applied and hence the initial uptake of the labeled nutrients was apparently delayed. Labeled-N and -P were first detected, at levels just above background, 7 days after fertilizer application. Substantial uptake did not begin until after the fifteenth day (Fig. 1). A very light rain (2 mm) fell on the third day after treatment, but it did not completely wet the litter layer. However, on the seventh day 6 mm of rain fell and from the seventeenth day rain became more frequent (Table 1). The phosphate granules dissipated during the rainfall on the seventh day. Movement of soluble phosphate is rapid through litter [15] and uptake is also rapid when P reaches the feeding roots [5, 20]. The $(NH_4)_2SO_4$ granules dissolved within 24 hours, but because of the dry conditions the compound probably did not diffuse through the litter until the first rainfall.

The uptake of P^{32} appeared to increase at a constant rate between the third and tenth week (Fig. 1). Linear regressions calculated for each foliage age and crown level were all highly significant (R^2 from 0.72 to 0.97). In contrast, the uptake of N^{15} was not linear with time during this same period; there was a marked reduction in the rate of uptake after the seventh week (Fig. 1). This pattern of uptake was associated with the amount of fertilizer-N in the rooting zone. Very heavy rain (111 mm) was recorded in the eighth week and this probably led to the leaching of fertilizer-N from the topsoil (Table 1).

The comparison of first- and second-order branches showed no significant difference in uptake. The single exception was that

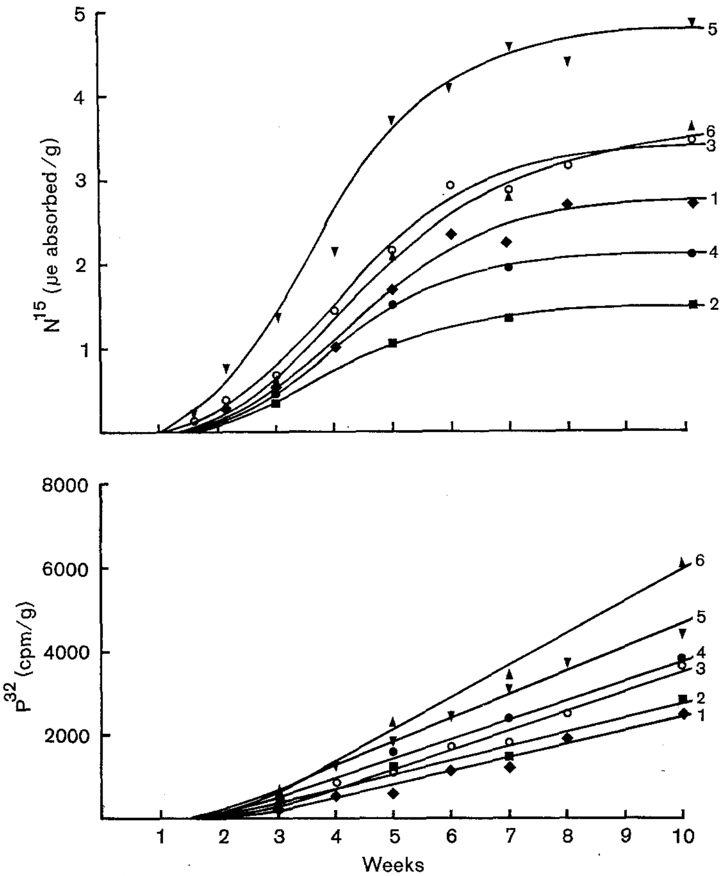

Fig. 1. The level of N^{15} and P^{32} in the foliage during the initial 10 weeks. *1* and *2* are current and 1-year-old foliage from the terminal leader; *3* and *4* are current and 1-year-old foliage from the upper crown; and *5* and *6* are current and 1-year-old foliage from the lower crown.

uptake, expressed as the N^{15} absorbed/g, was higher in the second-order branches of the lower crown than in first-order branches at this level (Table 2).

Both isotopes were found in higher concentrations in the lower crown than in the upper crown or terminal leader (Fig. 1 and Table 2). Thus, at the end of 10 weeks the current foliage had derived 19, 25, and 33 per cent of its N from the fertilizer in the terminal leader, upper crown, and lower crown branches respectively. The concentration of total N and P, as opposed to the isotope

TABLE 1

Rainfall reaching the forest floor during the initial 72 days after fertilizer application

Days after treatment	Rainfall mm
3	2
7	6
17, 18	19
20	3
25	8
28, 29, 30	29
31	9
40, 41, 42	8
49	3
50–56 * †	111
57–65 *	40
66–72 *	8

* Exact days of rainfall not known.

† Heaviest rainfall on day 51.

TABLE 2

Average concentration of N and P in the crown, and the levels of labeled N and P 71 days after the tagged fertilizer was applied

Part of crown	P %	N %	P^{32} cpm/g	N^{15} µe/g	% N from fertilizer
Terminal leader					
Current foliage	0.15	1.03	2494	2.72	18.6
1-year foliage	0.15	0.84	2797	1.50	12.6
Upper crown					
1st-order branch					
Current foliage	0.14	1.00	3553	3.40	24.6
1-year foliage	0.16	0.85	3871	2.13	16.7
2nd-order branch					
Current foliage	0.14	0.94	3887	3.52	25.2
Lower crown					
1st-order branch					
Current foliage	0.13	1.00	5061	4.64	31.1
1-year foliage	0.16	0.95	5742	2.89	20.3
2-year foliage	0.18	0.76	5871	2.44	20.2
2nd-order branch					
Current foliage	0.14	1.01	3886	5.06	32.9
1-year foliage	0.16	0.96	6577	3.34	21.1
2-year foliage	0.17	0.77	6599	1.62	22.9

levels, did not differ with sampling position (Table 2) indicating a uniform demand for these nutrients. The most satisfactory explanation for the high concentration of isotopes in the lower crown, on a per unit weight basis, appears to be that as the isotopes move up the crown they become further diluted with nutrients cycling internally within the tree. Studies with *Pinus taeda* suggest that there is movement of stored N and P from the wood and bark into the foliage in the spring [10]. The movement of nutrients out of older foliage before needle fall is also well documented [8 10 18].

A striking difference between the two isotopes was in their pattern of accumulation in different ages of foliage (Fig. 1 and Table 2). The highest levels of N^{15} were in the current foliage while those of P^{32} were found in the older foliage. A full explanation of these patterns of accumulation cannot be made on present information.

The high level of N^{15} was associated with foliage with high levels of total N. Nommik [11], who observed a similar pattern, suggested that it was best explained by consideration of the basic metabolism of leaves of varying ages. Young developing leaves require high amounts of N for protein synthesis, while older foliage requires little additional N because photosynthesis is their major function. However, the total N concentration was found to increase significantly in all ages of foliage. Thus over the initial 10 week period the current foliage rose from 0.85 to 1.01 per cent N, the 1-year-old foliage from 0.82 to 0.95 per cent and the 2-year-old foliage from 0.61 to 0.87 per cent N.

Similar high levels of P^{32} in the old foliage have been reported by Walker [20], though other workers have reported contrasting results [1 5 18]. One explanation may be that this is due to a dilution effect caused by the rapid growth of the current foliage. The foliage concentration of P is high for this species of pine and there are also indications of a dilution of total P in current needles. Total P levels in the current foliage dropped from 0.140 to 0.111 per cent over the 10 week period, while the 1-year-old foliage levels rose from 0.154 to 0.159 per cent and the 2-year-old foliage levels rose from 0.166 to 0.180 per cent.

Long-term changes in the foliage

The fertilizer application increased the concentration of N in the needles present on the trees at the time of application (Fig. 2). However, for both these foliage ages, the differences between treatments diminished during the winter as the N was translocated prior to needlefall. The N in the foliage initiated in the second growing season did not show significant response to treatment.

In contrast to total N concentration, the labeled-N (expressed as a percentage of N derived from the fertilizer) was markedly influenced by fertilization in all ages of foliage (Fig. 3). Furthermore, the differences among treatments did not diminish with time to the same extent as with total N concentrations. The highest level of N^{15} occurred about 12 weeks after the fertilizer was applied and at this time some 8.5 and 27.5 per cent of the N in the current needles of the low-N and high-N treatments had been derived from the fertilizer.

The effect of the fertilizer on total N content was a transitory one with the only significant effect of the treatment being observed in the current foliage at the start of the experiment (Fig. 4). In contrast, the needle content of labeled-N showed definite treatment effects for all classes of foliage (Fig. 3). The main effects of time and the

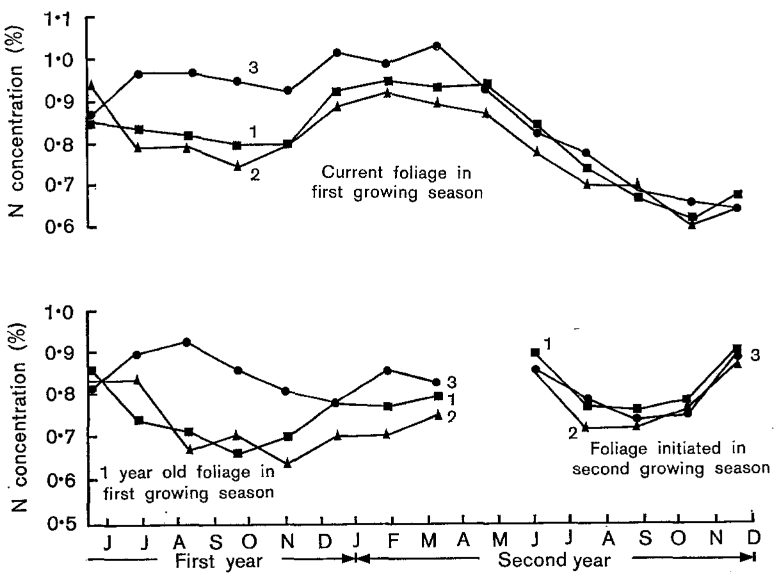

Fig. 2. The concentration of N in the foliage, *1*, *2* and *3* are the control, low- and high-N treatments, repectively.

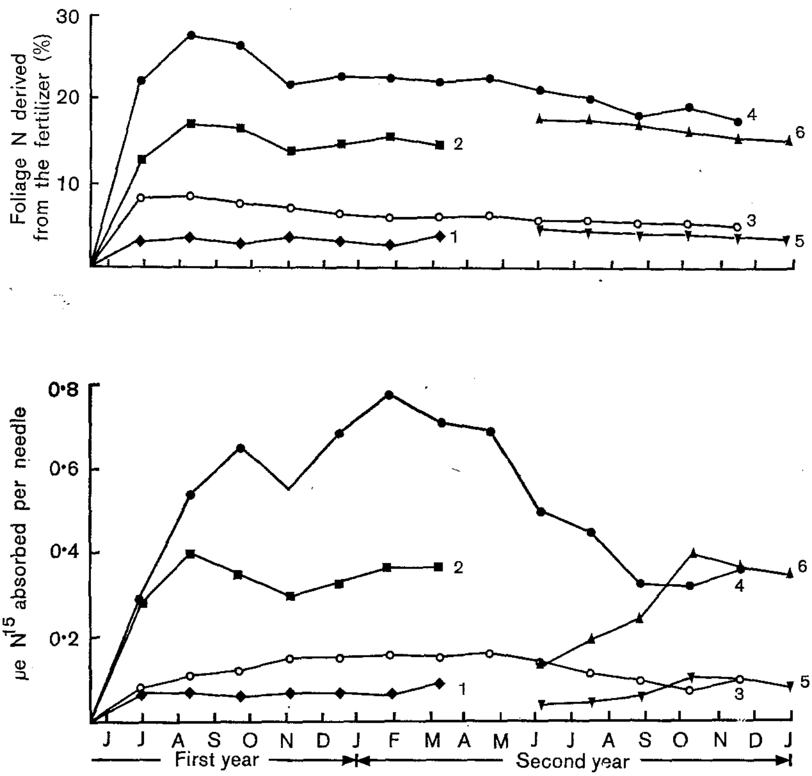

Fig. 3. The changes in N^{15} concentration and N^{15} content in the foliage. *1* and *2* are the low- and high-N treatments for the 1-year-old foliage in the first growing season; *3* and *4* are the low- and high-N treatments for the current foliage in the first growing season; *5* and *6* are the low- and high-N treatments for the current foliage in the second growing season, respectively.

interaction of time and treatment were also significant for current foliage formed in both growing seasons. Thus while seasonal patterns were similar, the changes were most marked in the high-N treatment. It is apparent that uptake of N from the fertilizer slowed after the 12th week, but did not cease and movement into current foliage continued into the winter.

It is interesting to note that the N^{15} content of the new foliage initiated in the second growing season eventually surpassed that in the previous year's needles, although the proportion of total N from the fertilizer was consistently lower in this new foliage (Fig. 3).

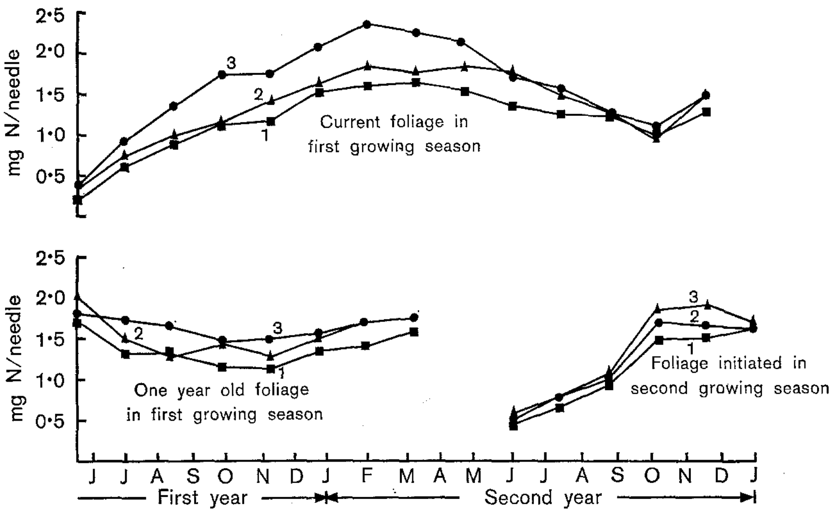

Fig. 4. The needle content of total N in the foliage. *1*, *2* and *3* are the control low- and high-N treatments, respectively.

A large amount of the N required for the current flush in the second growing season was apparently derived by redistribution (internal nutrient cycling). In the second growing season the 1-year-old foliage (*e.g.* foliage formed in the season the fertilizer was applied) decreased in total N and N^{15} content. These losses, between January and September, were 0.57, 0.90, and 1.24 mg N per needle for the control, low-, and high-N treatments, respectively. In this same period, the new needles accumulated an average of 1.69 mg of N. The amount of N^{15} lost by the old flush was 0.09 and 0.45 μe per needle for the low- and high-N treatments, respectively. The figures illustrate not only the importance of nutrient transfer, but also suggest that the fertilizer N, which initially went into partially formed needles, was incorporated into more easily mobilized compounds in the needles.

Movement of N^{15} in the soil

The amount of labeled-N in the litter decreased rapidly, with almost all of the leaching taking place in the first three weeks (Fig. 5). In this period a total of 30 mm of rain reached the forest floor. Between the third and sixth week a further 54 mm of rain was recorded and the fertilizer-N in the litter of the high-N treatment

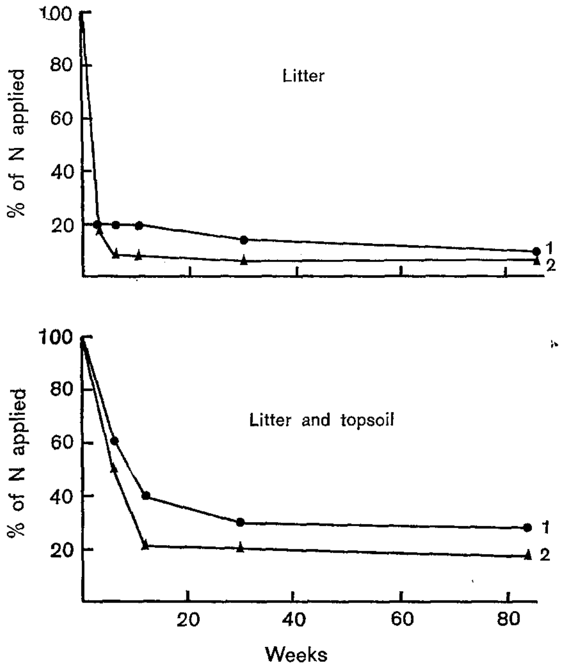

Fig. 5. The depletion of fertilizer-N in the litter and litter plus topsoil over two growing seasons. *1* and *2* are the low- and high-N treatments, respectively.

decreased from 20 to 9 per cent of that applied. In terms of absolute amounts of fertilizer-N held in the litter the retention at 6 weeks was equal to 3.8 and 6.8 me/100 g of litter, for the 56 and 224 kg N/ha treatments, respectively. Thus, the amount of labeled-N held in the litter was not in proportion to the rates applied. The rapid leaching of NH_4-N through the litter agrees with a study under Douglas-fir [4] and the retention pattern for the two rates of fertilizer-N and the longer-term stability of labeled-N levels with findings that the NH_4-ion is initially held on cation exchange sites of the organic matter and that it later undergoes biochemical reactions to become partly non-exchangeable [12 14].

The movement of labeled-N down the soil profile and changes with time are illustrated in Fig. 5 and 6. At any one time, the greatest amount of labeled-N was held in the top 10 cm of soil. The average CEC of the soil was 3.8, 2.8, 2.5, and 1.9 me/100 g soil for the 0–10, 10–20, 20–30, and 30–50 cm depths. The analysis of variance on the individual plot samples collected at the end of the second growing season indicated that labeled-N was significantly higher in the high-N treatment. The effect of greater retention in the upper part of the profile was also reflected in the significant soil depth and treatment x soil depth effects. In contrast, the total N concentration in the soil at the end of the second growing season was not significantly influenced by treatment. Total N decreased from 0.041 per cent in the 0–10 cm zone to 0.019 per cent at the 40–50 cm depth.

There was a rapid depletion of labeled-N from the litter + soil in the first 12 weeks, followed by stable conditions thereafter (Fig. 6). The period of rapid decline is associated with probable leaching and gaseous losses [19], as well as uptake by the trees. Overrein [13] has reported that during the 12 weeks of his lysimeter study about 20 per cent of the ammonium chloride (applied at 25 g N/m^2) leached through a podzolic soil with a higher CEC and clay content than the soil used in this study. Periods of intense rainfall occurred in July, August, and September following the fertilizer application. The heavy rain in the eighth week of the study (mid-July) has already been commented on (Table 1).

The possible leaching of N from these soils has important implications in the selection of fertilizer sources, and time and rate of application. The use of slowly available sources of N would appear to have advantages. Greater uptake might also be achieved by applying the fertilizer in the autumn, immediately before the winter dry period.

CONCLUSIONS

A 10-week study of P^{32} and N^{15} uptake from labeled concentrated superphosphate and ammonium sulphate fertilizers showed that:

(1) Both isotopes accumulated in higher concentrations in tissue of the lower part of the crown than in the upper crown.

(2) There was little difference in total or labeled-N and -P levels among foliage samples from different orders of branches within a crown level.

(3) The highest levels of labeled-N were in the current foliage, but the highest levels of labeled-P were recorded in the older foliage.

(4) Uptake of P^{32} was approximately linear between the third and tenth weeks, indicating a more or less constant availability.

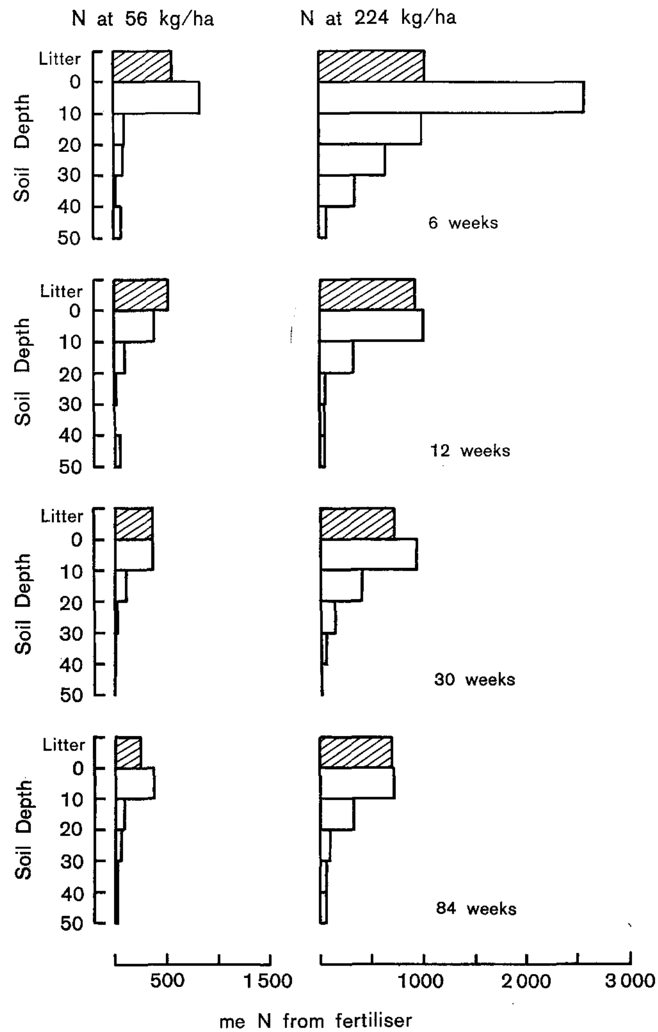

Fig. 6. The changes in fertilizer-N in the litter and soil with time.

In contrast, the uptake of fertilizer-N showed a marked reduction in the seventh week, associated with a drop in the amount of labeled-N in the rooting zone.

The longer-term changes in labeled- and total-N in the foliage, litter, and soil were followed over the two growing seasons. The conclusions were:

(1) The N concentration in the needles was influenced by the fertilizer only during the first growing season.

(2) The concentration of labeled-N in the foliage reached a maximum at about 12 weeks at which time some 8.5 and 27.5 per cent of the N in the current foliage of the 56 and 224 kg/ha treatments, respectively, had come from the fertilizer.

(3) Before the 1-year-old needles were shed at the end of the second growing season a portion of the N was translocated to the new flush.

(4) The fertilizer-N was leached rapidly through the litter when the rain occurred. At the end of 3 weeks only 20 and 17 per cent of the applied N remained in the litter for the low- and high-N treatments, respectively.

(5) Labeled-N leached down the soil profile. The total amount of fertilizer-N in the litter and topsoil was stable after 12 weeks, with 39 and 21 per cent of the applied N present in the low-N and high-N treatments, respectively.

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REFERENCES

1 Biddulph, O., The translocation of minerals in plants. *In*: Mineral nutrition of plants. Ed. E. Truog. Univ. of Wisconsin Press, Madison, Wisc. 469–482 (1951).

2 Bremner, J. M., Total nitrogen. *In*: Methods of Soil Analysis. Ed. C. A. Black. Agronomy **9**. Amer. Soc. of Agr., Madison, Wisc. 1149–1178 (1965).

3 Bremner, J. M., Isotope-ratio analysis of nitrogen – 15 tracer investigations. *In*: Methods of Soil Analysis. Ed. C. A. Black. Agronomy **9**. Amer. Soc. of Agr., Madison, Wisc. 1256–1286 (1965).

4 Cole, D. W. and Gessel, S. P., Movement of elements through a forest soil as influenced by tree removal and fertilizer additions. *In*: Forest-Soil Relationships in North America. Ed. C. T. Youngberg. Oregon State Univ. Press, Corvallis, Oregon. 96–104 (1965).

5 Farrar, J. L., Distribution of radiophosphorus in red pine seedlings. Can. Dept. Resources and Development Silv. Leafl. No. **78**, 4 pp. (1953).

6 Haberer, K. Von, Measurement of beta activities in aqueous samples utilizing Cerenkov radiation. Parchard Tech. Bull. **16,** 14 pp. (1966).
7 Jackson, M. L., Soil Chemical Analysis. Prentice Hall, Englewood Cliffs, N.J. 498 pp. (1958).
8 Lowry, G. L. and Avard, P. M., Nutrient content of black spruce and jack pine needles: III. Seasonal variations and recommended sampling procedures. Pulp Paper Research Inst. Can. Woodl. Paper **10,** 54 pp. (1969).
9 Mead, D. J., Movement of added nitrogen and phosphorus in a pine forest ecosystem. Ph.D. Dissertation, Univ. of Florida (1971).
10 Nelson, L. E., Switzer, G. L. and Smith, W. H., Dry matter and nutrient accumulation in young loblolly pine (*Pinus taeda* L.). *In*: Tree Growth and Forest Soils. Ed. C. T. Youngberg and C. B. Davey. Oregon State Univ. Press, Corvallis, Oregon. 261–273 (1970).
11 Nommik, H., The uptake and translocation of fertilizer N^{15} in young trees of Scots pine and Norway spruce. Studia Forest Seucia **35,** 18 pp. (1966).
12 Overrein, L. N., Immobilization and mineralization of tracer N in forest raw humus. I. Effect of temperature on the interchange of nitrogen after addition of urea-, ammonium-, and nitrate-N^{15}. Plant and Soil **27,** 1–19 (1967).
13 Overrein, L. N., Lysimeter studies on tracer nitrogen in forest soil: 2. Comparative losses of nitrogen through leaching and volatilization after the addition of urea-, ammonium-, and nitrate-N^{15}. Soil Sci. **107,** 149–159 (1969).
14 Overrein, L. N., Tracer studies on nitrogen immobilization/mineralization relationships in forest raw humus. Plant and Soil **32,** 478–500 (1970).
15 Riekerk, H. and Gessel, S. P., Mineral cycling in a Douglas-fir forest stand. Health Phys. **11,** 1363–1369 (1965).
16 Soil Survey Staff, Placement of series, southern region. USDA Soil Conservation Service Publ., 43 pp. (1970).
17 Steel, R. G. D. and Torrie, J. H., Principles and Procedures of Statistics. McGraw-Hill Book Company, Inc., New York. 481 pp. (1960).
18 Tamm, C. O., Studies on forest nutrition: 1. Seasonal variation in the nutrient content of conifer needles. Meddr. Skogsforsv. Inst., Stockl. **45,** 1–34 (1955).
19 Volk, G. M., Gaseous loss and mobility as factors in nitrogen efficiency. Soil and Crop Sci. Soc. Florida Proc. **21,** 261–268 (1961).
20 Walker, L. C., Isotope tracer methods in tree nutrition. *In*: First North American Forest Soils Conference. Ed. Agr. Exp. Sta. Mich. State Univ., East Lansing, Mich. 25–30 (1958).