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Nitrogen recovery in soil and needle biomass after fertilization of a Scots pine stand, and growth responses obtained

Återvinning av gödselkväve i mark och barrbiomassa hos ett tallbestånd, samt tillväxtreaktioner

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Abstract

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The distribution of fertilizer nitrogen in soil and needle biomass of an 120-year-old stand of Scots pine was studied over a period of six years. The nitrogen was applied as ammonium nitrate or urea and at rates of 150, 300 and 600 kg N per hectare. The soil investigations showed that, at the lowest nitrogen application rate, 21% of the ammonium nitrate and 49% of the urea nitrogen were immobilized in the soil in nonexchangeable form. For the corresponding treatments the losses by leaching were estimated to 30–40% and 0–10%, respectively.

The accumulation of fertilizer nitrogen in the needle biomass culminated during the third growing season. Relative to control, the total nitrogen accumulation for the lowest ammonium nitrate and urea application rates then amounted to 174 and 134% respectively. As regards volume growth, the ammonium nitrate was greatly superior to urea at the two lowest nitrogen application rates. The dose of 600 kg N per hectare proved to be over-optimal as far as the ammonium nitrate source of nitrogen was concerned.

Key words: Scots pine, nitrogen distribution, immobilization, leaching, ammonia volatilization, pH changes, ammonium nitrate, urea.

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Contents

1 Introduction

During the last twenty years the use of nitrogen fertilizers in practical forestry has attained significant proportions in Scandinavia, especially in Finland and Sweden. On the basis of research data, methods have been developed to evaluate the nitrogen status of the trees and to predict the responses of the stand to nitrogen application under various site conditions (see Rosvall, 1979).

The literature concerning the fate of applied nitrogen in forest ecosystems is still rather limited. According to the few data available from Sweden, the recovery of fertilizer nitrogen in the above-ground parts of the stand is generally low, being considerably less than that recorded for agricultural crops (Tamm, 1963, Popovic & Burgtorf, 1964, Björkman et al., 1967). On podsols a substantial proportion of the applied nitrogen is known to be immobilized in the soil profile (Nômmik & Popovic, 1971, Popovic & Nômmik, 1972). Upon application of urea, considerable ammonia loss to atmosphere may occur during warm and dry soil conditions (for references see Knowles, 1975). As regards leaching, relatively small losses of nitrogen via this mechanism have been recorded when moderate doses of urea are applied (Cole & Gessel, 1965, Overrein, 1972). After field application of ammonium nitrate, on the other hand, significant accumulation of mineral nitrogen, mainly nitrate in the ground water, has been reported (Tamm et al., 1974, Wiklander, 1977).

This paper reports results from a fertilizer experiment, designed to describe the distribution of applied fertilizer nitrogen in different components of a Scots pine ecosystem. The main effort has concerned the recovery and distribution pattern of fertilizer nitrogen in the soil profile during the experimental period. In addition, the uptake of fertilizer nitrogen by the stand was studied by intermittent sampling and analysis of the needle biomass. The data collected were compiled to present a partial balance sheet for the fertilizer nitrogen applied. The response of the stand to nitrogen application was quantified by estimating the volume increment relative to the control treatment.

2 Materials and Methods

2.1 Experimental design

The field trial was laid out in a randomized complete block design, with three replicates, including the treatments 150, 300 and 600 kg N per hectare as ammonium nitrate (AN) or urea, and the control treatment. Fertilizer materials were applied by hand as top dressing on July 16, 1974. The area of each plot was 30 × 30 m. The grouping of the plots into blocks was done mainly with consideration to homogeneity of the soil and field layer vegetation.

2.2 Site description

The experimental area was located in a basal, flat part of the Enköping esker, 15 km north of Heby, central Sweden (60°03′N, 16°52′E; 75 m a.s.l.). The soil is classified as an iron podzol, developed within sandy glacifluvial outwash, with a marked mor layer, 2–5 cm in thickness, and an A_2-horizon varying in thickness between 0 and 2 cm. Data on the soil properties (Table 1) indicate a poor (oligotrophic) soil with a C/N-ratio of the mor layer of 39. From data on textural composition it is apparent that the soil is dominated by the sand fraction (> 75 %) and that the clay fraction is less than 2 %.[1]

The stand consisted of an approximately 120-year-old Scots pine (*Pinus sylvestris* L.) population, with occasional young individuals of Norway spruce (Figure 1). The stand had a mean height of 18 m, a density of 580 stems per hectare and site index T16, according to the H100 system of the Royal College of Forestry. The average diameter at breast height was 25 cm, the basal area 28 m^2 ha^{-1},

[1] The nitrification capacity is extremely low both in the organic and mineral soil layers.

Figure 1. The stand of Scots pine at the experimental site at Kroksbo, Heby.

Table 1. Data on the soil profile. Mean figures for the experimental area before treatment.

Soil layer	Textural composition, %				pH (H_2O)	Carbon		Nitrogen		C/N
	Sand	Fine sand	Silt	Clay		%	ton ha^{-1}	%	kg ha^{-1}	
Litter					4.2	42.6	5.3	0.88	116	48
Humus					3.9	41.8	16.9	1.07	433	39
Mineral soil 0–5 cm	76	20	2	2	4.3	1.44	10.0	0.05	312	32
Mineral soil 5–15 cm	81	16	1	2	4.8	0.77	10.4	0.03	325	32
Mineral soil 15–25 cm	84	14	1	1	5.1	0.44	5.9	0.02	210	28

and the volume of the growing stock including bark 230 $m^3\ ha^{-1}$. The current growth was 4.4 $m^3\ ha^{-1}\ yr^{-1}$. The field layer vegetation was of dry-shrub type, with a bottom layer consisting mainly of *Cladonia* and *Cetraria* species.

Data on monthly mean temperature and precipitation for the period of July 1974 to May 1975 and the corresponding means for the period 1931–1960 are given in Figure 2 (Meteorological station, Sala).

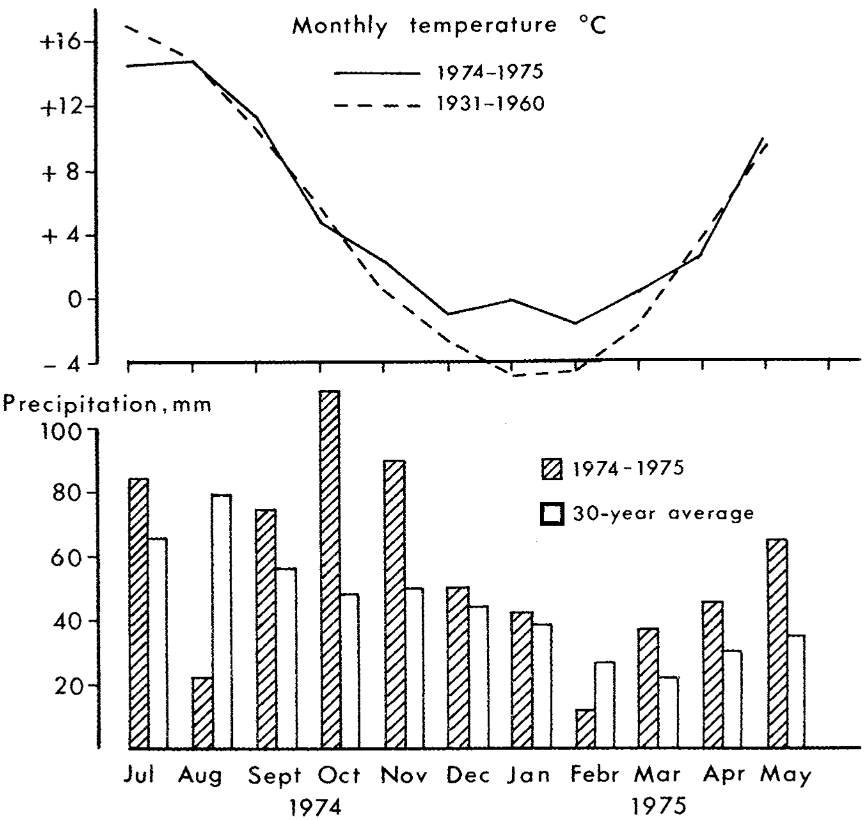


Figure 2. Mean monthly temperature and precipitation during the period of July 1974–May 1975, and corresponding average figures for the period of 1931–1960 (meteorological station, Sala).

2.3 Experimental techniques

2.3.1 *Soil sampling*

The sampling method used in this study is mainly based on the recommendations and instructions of Gjems et al. (1960), Troedsson & Tamm (1969) and Falck (1973).

Within every block, 25 subsamples were taken per plot, which were combined into one sample per soil layer. The sampling points were systematically distributed over the plot, following a quadratic formation of 6×6 m. The minimum distance to the boundary of the plot was 3 m. When sampling was repeated the bore holes were made within a distance of one metre from the first sampling point. Two types of soil auger were used as sampling tools. For sampling the litter, the humus and the uppermost 0–5 cm layer of mineral soil, the auger used had an 100 mm inner diameter and a curved sawlike cutter in the bottom of the bore cylinder. During sampling the auger was worked through the litter and humus layer, and the approximately 5 cm thick layer of mineral soil. The mineral soil sample included the transitory soil horizon (A_1), horizon of eluviation (A_2) and varying portions of the illuvial horizon (B). The litter sample included ground layer vegetation.

For sampling of mineral soil from deeper horizons, a core type of auger, with a diameter of 20 mm, was used. Two bore holes were made at each sampling point and the soil core was divided into 5–15 and 15–25 cm columns, respectively.

The soil sampling was partly carried out before the application of nitrogen (spring of 1974) and partly during the following phases of the observation period: (1) autumn, 1974; (2) spring, 1975; (3) spring, 1976 (the block II only); (4) spring, 1978.

2.3.2 *Preparation of soil samples for chemical analysis*

The pooled samples of soil, consisting of 25 subsamples per plot and soil layer, were subjected to oven-drying at 30°C. An exception was made for the litter and humus samples from the first sampling which were homogenized and analysed in a field-moist condition.

The samples of litter and humus were weighed after drying, ground to pass a 3 mm sieve, whereupon a representative sample of approximately 100 g by weight was taken out for analysis. This subsample was subjected to additional homogenizing by grinding to pass a 1 mm sieve. The collected litter and humus materials per 25 sampling points represented an area of 0.196 m^2 and included the roots occurring in the respective soil horizon.

The mineral soil from the 0–5 cm horizon was sieved to pass a 2 mm sieve and weighed. As regards the 5–15 and 15–25 cm soil layers, the weights per hectare and layer were obtained by calculating with a bulk density of 1.40. The sieved materials of mineral soil included the finest fraction of root biomass as it passed the 2 mm sieve.

2.3.3 *Sampling of needles*

During the experimental period the needles were sampled annually on each plot. Ten representative trees were selected and marked out for this purpose in each plot. On sampling, which occurred annually in January–February, two well-exposed branches were shot down from the uppermost part of the crown. The shoots of current and previous-year growth were separated by cutting. The needles were removed from the shoots and dried for 48 h at 70°C. After equilibration at room temperature and humidity, the needles were subjected to determination of 100-needle weight and then to grinding.

2.3.4 *Methods of chemical analysis*

Total nitrogen, N_{tot}, both in plant and soil materials, was determined according to the Kjeldahl digestion procedure, using Cu and Se as catalysts. Soil samples, which were collected in the autumn, 1974 and containing substantial amounts of nitrate nitrogen, were pretreated with Fe-powder to include nitrate in N_{tot} figures (Olsen, 1929).

Ammonium and nitrate nitrogen in the KCl extract of the soil was determined acidometrically after separation of NH_3 by destillation in the presence of MgO. Nitrate-N in the distillation residue was quantified by reduction with Devarda's alloy.

Non-extractable fertilizer nitrogen in the soil, N^x_{org}, mainly organic in nature, was obtained from data on total-N content per hectare per layer of the treated plot, and on C_{tot}/N_{tot} ratios of both the treated plot, C/N_{treat}, and the plots sampled prior to the fertilizer application, C/N_{ref} (mean figure per block):

$$N^x_{org} = N_{tot} \times \frac{C/N_{ref} - C/N_{treat}}{C/N_{ref}} - N^x_{min},$$

where

N^x_{org} = immobilized, non-extractable forms of fertilizer nitrogen, kg N per hectare per soil layer

N_{tot} = Kjeldahl-N (inclusive nitrate-N), kg N per hectare per soil layer

N^x_{min} = amounts of exchangeable ammonium and nitrate nitrogen originating from added fertilizer, kg N per hectare per soil layer (obtained as a difference between the fertilized and control treatment)

Organic carbon, C_{org}, was determined by a wet combustion technique according to Nômmik (1971 b).

pH in the soil was determined by glass electrode, using a soil-water suspension of 1:12.5 for litter and humus materials, and of 1:2.5 for mineral soil.

Exchangeable base cations were extracted from the soil samples with 1M NH_4Ac solution. The concentrations of K and Na in the extract were determined flame photometrically, and Mg and Ca by atomic absorption spectrometry.

Exchange acidity was determined by titrating 1M KCl extract of the soil to pH 7.0, using 0.02M KOH.

All of the analytical data presented refer to air-dry material.

2.3.5 *Methods of growth calculation*

In spring, 1974, when the trial was established, all trees on the control plots, within a circular area of 10 m radius with the point of intersection of the diagonals as centre, were numbered and their height measured. After 5 growing seasons in late August, 1978, the breast height diameter of all trees within such circular areas was measured on both control and treated plots. In the control plots the height of the previously numbered trees was remeasured and the height growth during the period calculated.

From each measured tree in all plots, an increment core was taken with an increment borer and the annual ring width was measured to an accuracy of 1/100 mm. The number of cores per plot varied between 13 and 24.

From the diameter measurements and the annual ring width measurements, the basal area growth of the different treated plots was calculated in both absolute and relative figures. The volume growth in m^3 ha^{-1} (m^3 = total volume over bark) of the control plots was calculated from the height growth, basal area growth (as shown in the annual ring width measurement) and special functions. The volume growth of the treated plots was then calculated in relationship to the plots' basal area growth, in comparison to that of the control plot and its volume growth, and corrected for differences in pretreatment basal area growth (Möller & Ryttersted, 1974).

3 Results and Discussion

3.1 Data on the distribution and recovery of fertilizer N in the soil profile and the effects of applied fertilizer N on selected soil properties

3.1.1 *Inorganic nitrogen*

The patterns of the distribution of inorganic N in the soil profile, including the four sampling dates, are illustrated in Figure 3 and Table 2. The quantity of inorganic nitrogen recorded in a soil layer in a treated plot, in excess of that in the control plot, has been considered in this report to originate from the added fertilizer. Even if not wholly objective, as no consideration is given to the effect of the fertilizer addition itself on the net mineralization of soil nitrogen, this approach using the difference method should be considered justified in the present context.

Even on the first sampling date, i.e. at the end of the first growing season, only frac-

Figure 3. Distribution and total amount of inorganic nitrogen in the soil profile in treated plots (reduced for the amounts in control plots).
Sampling: autumn, 1974 (○) and spring, 1975 (●).

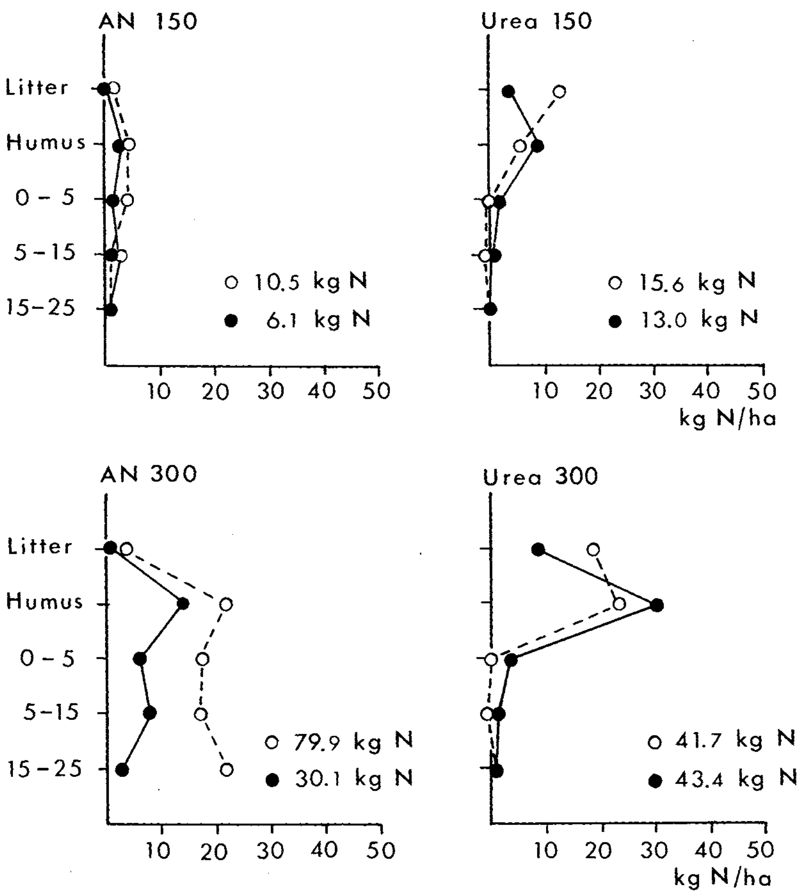


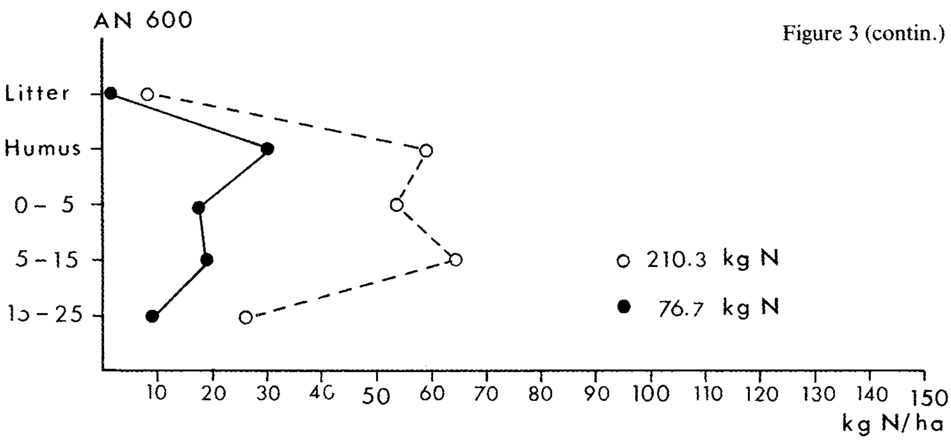
Table 2. Total amount of inorganic nitrogen recovered in the soil profile, kg N ha^{-1}. The figures in parentheses refer to nitrate.

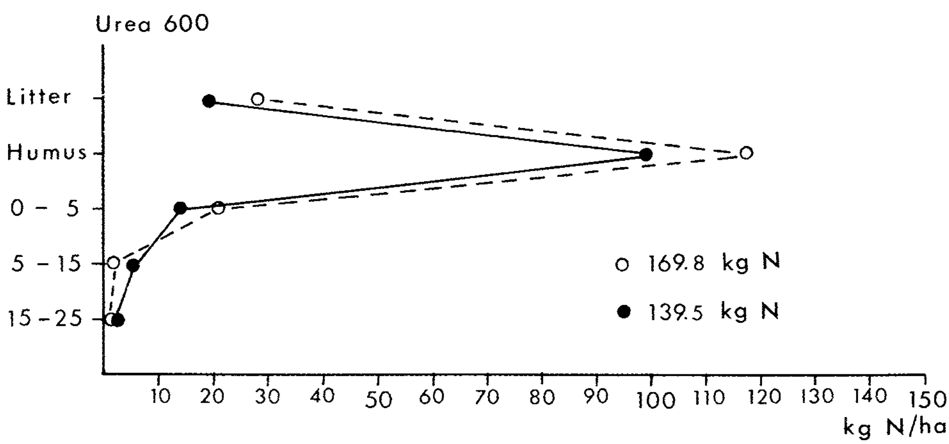
Treatment**	Sampling time			
	Autumn 1974	Spring 1975	Spring 1976*	Spring 1978
Control	27 (7)	8 (2)	1 (<1)	5 (<1)
AN 150	37 (8)	15 (3)	1 (<1)	6 (<1)
AN 300	105 (33)	39 (4)	4 (<1)	7 (<1)
AN 600	237 (77)	85 (7)	30 (1)	10 (<1)
Urea 150	44 (6)	21 (2)	1 (<1)	7 (<1)
Urea 300	68 (5)	52 (2)	6 (<1)	7 (<1)
Urea 600	196 (6)	147 (3)	38 (1)	9 (<1)
L.s.d. 5%	39 (17)	23 (2)		2 (<1)

* Block 2 only.
** July, 1974.

tional parts of the added fertilizer nitrogen were recovered in the soil profile in the form of exchangeable ammonium or nitrate. As to the lowest nitrogen application rate, 150 kg N per hectare, which is the nitrogen dose used in practice, the recovery for ammonium nitrate and urea source of nitrogen amounted to 7 and 10 per cent, respectively. At the higher application rates, recovery figures for extractable nitrogen increased, both absolutely and relatively. The above figures for the N300 dose were 27 and 14% and, for the

Figure 3 (contin.)





N600 dose, 35 and 28% for the ammonium nitrate and urea source of nitrogen, respectively.

In the ammonium nitrate treatments, the main part of the extractable nitrogen was recovered in the mineral soil layers, whereas in urea-treated plots a relatively high mineral nitrogen accumulation occurred in litter and humus horizons. In ammonium nitrate treatments approximately one-third of the recovered inorganic N consisted of nitrate, and the remainder of ammonium. The proportion of nitrate in the inorganic nitrogen pool increased with increasing profile depth (Figure 4). In urea-treated soils no measurable accumulation of nitrate occurred. The inorganic nitrogen distribution in the soil profile indicated that on ammonium nitrate-treated plots a considerable portion of the fertilizer nitrogen may have been leached out from the root zone as NH_4^+-ion.

The soil sampling, done in the spring of

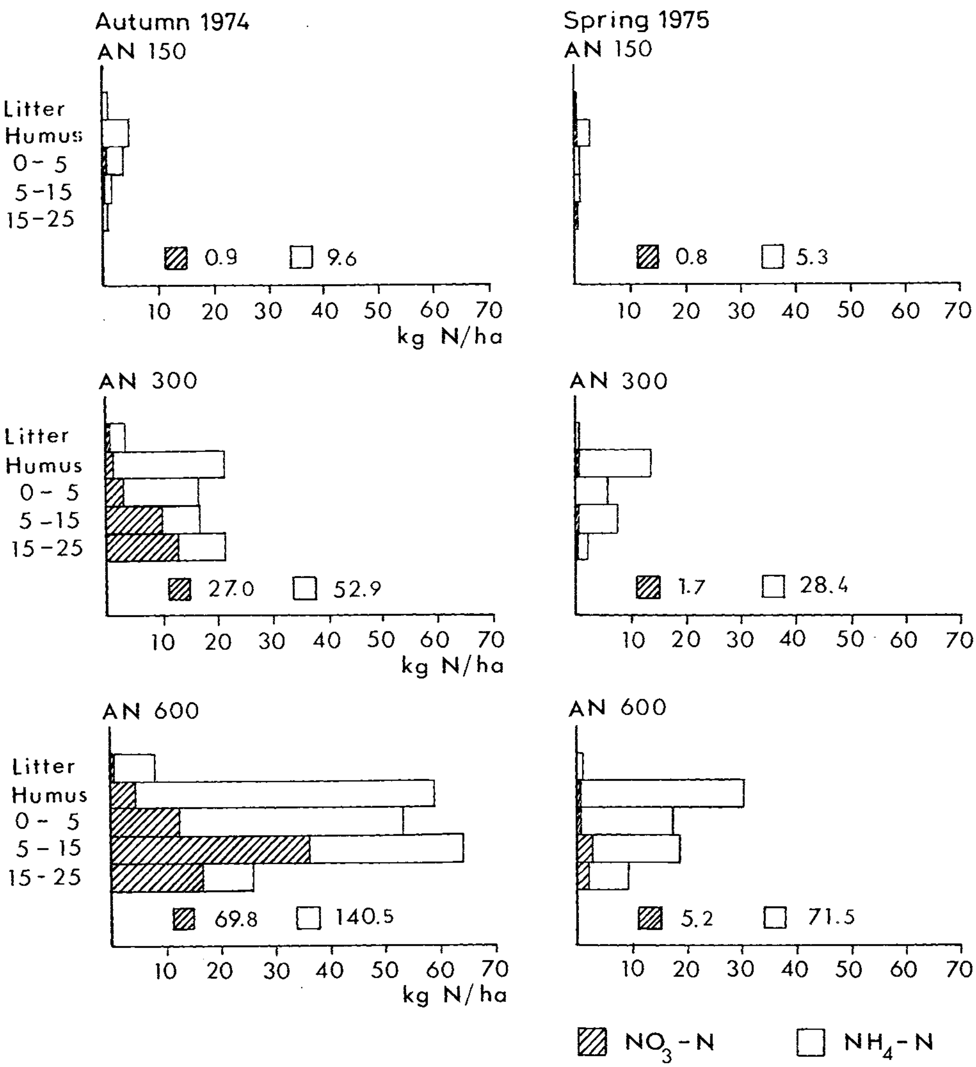


Figure 4. Distribution and recovery of ammonium and nitrate nitrogen in soil profiles of ammonium nitrate treated plots (reduced for the amounts in control plots).
Sampling: autumn, 1974 and spring, 1975.

1975, showed that in ammonium nitrate-treated plots, a substantial part of the residual NH_4 and nearly all of the nitrate was removed from the soil profile during the first winter. In urea treatments only an insignificant change in the size of the inorganic nitrogen pool occurred during the winter.

The soil examination, which was carried out in the spring of 1976, embracing block 2 only, indicated no significant amounts of residual ammonium N in the soil profile of plots treated with 150 or 300 kg N per hectare. On plots treated with 600 kg N, both with ammonium nitrate and urea, the pool of exchangeable NH_4 exceeded that of the control plots with 20–30 kg N per hectare.

After an additional 2-year period, i.e. in the spring of 1978, the recovered amounts of exchangeable NH_4 in the soil profile corresponded to less than 1% of the fertilizer N initially added (cf. Morrison & Foster, 1977).

3.1.2 *Organic forms of nitrogen*

For the fertilizer nitrogen budget it is necessary to have an estimate of the amount of applied nitrogen that has been accumulated in the soil in non-exchangeable form. This nitrogen fraction may include both the chemically and microbically immobilized nitrogen as well as a part of the nitrogen accumulated in root biomass. Using ^{15}N techniques, it has been shown that the microbial immobilization may be significant in oligotrophic forest soils (Björkman et al., 1967, Nômmik & Popović, 1971, Overrein, 1972). The non-enzymatic immobilization, either in clay minerals or soil organic matter, may be considered negligible in the soil types in question.

An essential requirement for quantifying the changes in the total nitrogen pool of an individual soil profile is that the size of that pool has been estimated, with satisfactory accuracy, prior to the application of fertilizer materials. In the present case the first sampling of the soil was unfortunately carried out by untrained staff, resulting in an unacceptable divergence of total nitrogen figures when compared with those from later samplings. In this situation an alternative estimating technique was employed, which was based upon data on the size of Kjeldahl-N pool per hectare per soil layer of the treated plot, the C/N ratio for the soil layer in question, and the C/N ratio for the corresponding soil layer sampled prior to fertilizer treatment. In the latter case the arithmetic mean of 7 plots per block was used. Employing these data and the equation given in subsection 2.3.4, the amount of non-exchangeable fertilizer nitrogen, N^x_{org}, per hectare per layer was calculated.

The assessment of N^x_{org} according to the above principles gave statistically significant differences if the estimated figure exceeded 61 kg N per hectare per profile. This figure is nearly three times as high as that for assessment of inorganic nitrogen pool, N^x_{inorg}.

An analysis of the variation of both C/N and N_{tot} values, expressed in kg per hectare per soil layer, and embracing control plots from all three blocks and the four sampling dates, showed that the variation coefficient for N_{tot} was approximately three times as high as that for C/N ratios. For the litter layer the figures in question were 14.3 and 4.9%, and for the humus layer 11.0 and 3.2%, respectively.

The data on changes in C/N ratios and estimated amounts of immobilized fertilizer nitrogen in experimental soils, N^x_{org}, are given in Tables 3 and 4 and Figure 5. They refer to the sampling in spring, 1975, i.e. one year after the fertilizer application. The figures indicate that significantly higher amounts of fertilizer nitrogen were recovered in the soil in non-exchangeable forms after the urea treatments than after the ammonium nitrate treatments. The difference is especially marked at the lowest nitrogen application rate. In the latter case approximately half of the added urea N was retained by the soil in organically bound forms, mainly in the litter and humus layers. The analysis data from soil sampling in 1976 and 1978, even though less comprehensive, verify on the whole the immobilization pattern referred to above. It should be observed in this connection that the figures on N^x_{org} include indeterminate amounts of fertilizer N accumulated in the root biomass.

Preliminary data on N^x_{org} from this study, published elsewhere (Nômmik, 1977), give slightly higher figures than those reported here. They were based on another principle of calculating the C/N_{ref} values.

As a final assessment it should be stressed that without increasing the number of replicates or the sampling density per plot, the indirect difference method, used in this study to assess the quantitative changes in the organic nitrogen pool resulting from fertilizer treatment, would probably have been incapable of signifying the small changes in question in many soils developed on morainic mate-

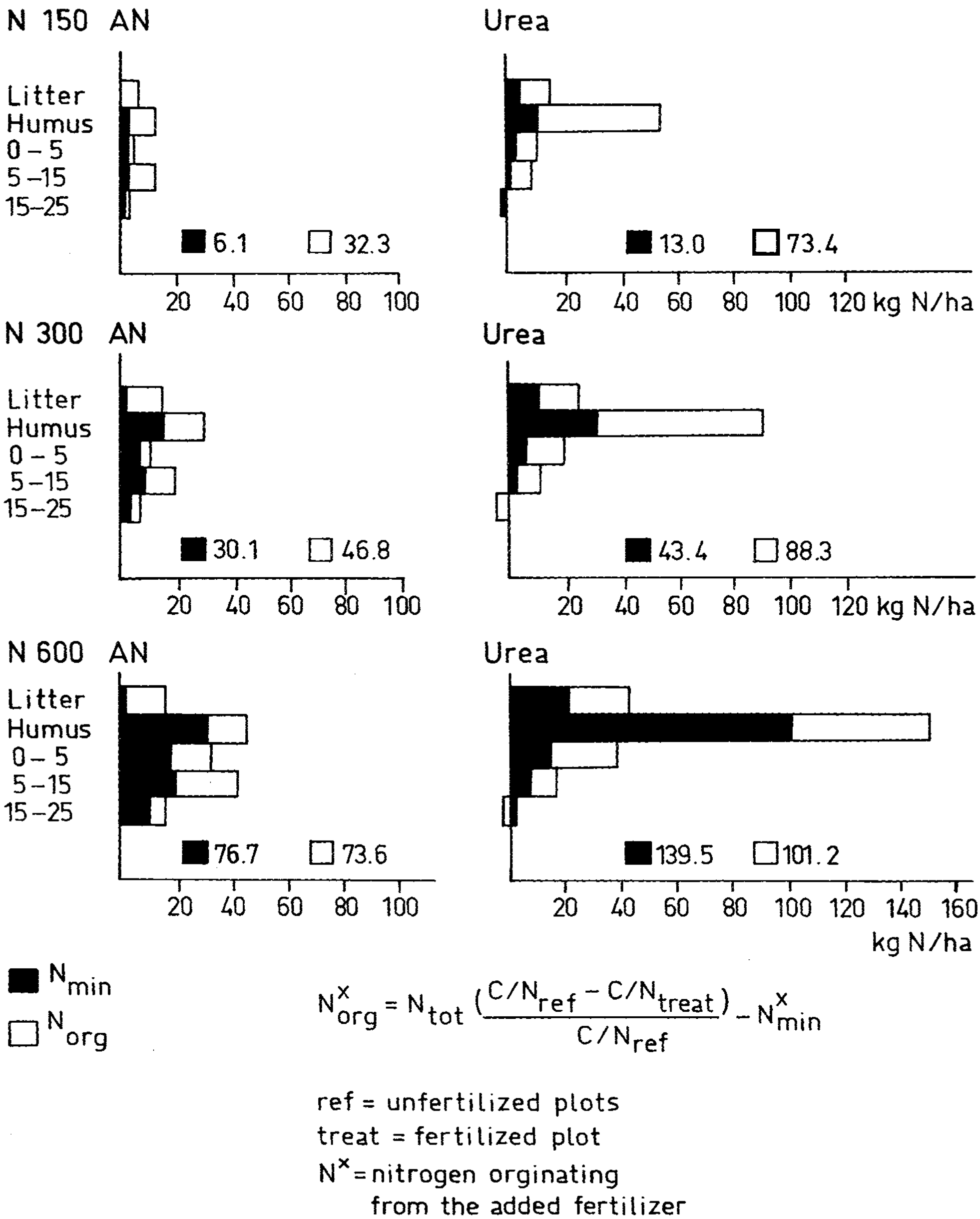


Figure 5. Amounts of fertilizer nitrogen recovered in the soil profile in inorganic (N_{min}) and non-extractable (N_{org}) forms.
AN = ammonium nitrate.
Sampling: spring, 1975.

Table 3. Changes in C/N ratios in the experimental soil following fertilizer treatment.
Refer to the sampling time, spring 1975.

Treatment	Litter	Humus	Mineral soil, cm		
			0–5	5–15	15–25
Control	48.5*	38.6*	32.8*	32.7*	29.4*
AN 150	45.6	37.4	32.8	32.0	28.6
AN 300	42.7	36.0	31.6	31.3	28.2
AN 600	42.1	34.6	29.3	29.6	27.3
Urea 150	41.3	33.9	32.0	32.1	28.8
Urea 300	40.1	31.6	31.0	32.1	30.0
Urea 600	33.5	28.0	28.7	31.8	29.3
L.s.d. 5%	4.5	2.4	4.6	3.2	2.2

* Reference figures used for calculation of N^x_{org}.

Table 4. Amounts of fertilizer nitrogen immobilized in the soil profile (N^x_{org}), kg N ha^{-1} $layer^{-1}$.
Refer to the sampling time, spring 1975.

Treatment	Litter	Humus	Mineral soil, cm			Total
			0–5	5–15	15–25	
AN 150	9	10	3	7	3	32
AN 300	15	15	5	9	4	47
AN 600	18	12	14	23	6	73
Urea 150	14	44	8	8	0	73
Urea 300	12	60	12	8	–4	88
Urea 600	23	48	24	9	–3	101
L.s.d. 5%	8	31	30	37	15	61

rials. In the present field trial the conditions were exceptionally favourable, as the soil material consisted of sedimentary sand, free of stones and blocks. A higher sensitivity in detecting and quantifying the changes in N_{org} pool would have been attained by using isotopically labelled nitrogen sources. However, this technique is costly and involves problems of interpretation (cf. Nômmik & Popović, 1971).

3.1.3 *Total recovery of fertilizer N in soil*

Data on the total recovery of fertilizer N in the soil profile, i.e. the sum of inorganic and organic forms of nitrogen, are given in Table 5 and Figure 5.

According to these figures, the recovery i markedly higher for urea than for ammoniu nitrate nitrogen. For the N150 applicatic rate the recovery for ammonium nitra treatment is 25% and for urea 57%. T corresponding figures for N300 and N6 application rates are 26 and 44%, and 25 a 40%, respectively. The recovery percent for urea nitrogen decreases with increas rate of application, whereas it remains changed for the ammonium nitrate sourc nitrogen.

3.1.4 *Losses by NH_3 volatilization*

By using microplots and the isotopic recc technique described by Nômmik (197

Table 5. Total recovery of fertilizer nitrogen in the soil profile to a depth of 25 cm, kg N ha^{-1}.
Sampling time: spring 1975.

Treatment	Inorganic N	Organic N*	Sum	% of added
AN 150	6	31	37	25
AN 300	31	47	78	26
AN 600	77	74	151	25
Urea 150	13	72	85	57
Urea 300	44	88	132	44
Urea 600	139	101	240	40
L.s.d. 5%	23	61	65	

* Refer to fertilizer N not recovered in KCl extraction.

restricted study was carried out to assess the ammonia loss that might have occurred on plots treated with 150 kg of urea N. The microplots were set out in an unutilized area within block 2. The treatment was carried out in 6 replicates and was started on the same day as the main trial. The soil investigation, which was performed after a 9-day period of exposure, showed a ^{15}N-recovery of 79%. As the amount of precipitation during this period was limited to 5 mm, the leaching could be excluded as a possible mechanism for removal of urea nitrogen from the soil. The size of the volatilization loss, amounting to 21% (S.D. 2.1%) is in agreement with previous measurements carried out under comparable soil, moisture and temperature conditions (Nômmik, 1973).

3.1.5 *Effects on soil pH*

The microbial nitrogen transformations and nitrogen uptake by higher plants, as well as the ion exchange, are the main reactions responsible for the changes of pH and acid-base status of the soil observed to occur as a consequence of fertilizer nitrogen application. The question has been subjected to intensive studies within agroecosystems, although the documentation is less extensive for forest land.

The pH changes registered in the present field trial, covering an observation period of four years, are illustrated in Figure 6. Evidently, the most marked pH changes are caused by urea treatments. They are, however, normally of relatively short duration, and affect only the litter and humus layers. The initial rise in the pH, being a result of microbial hydrolysis of urea to ammonia, is gradually suppressed by ammonium uptake by plant roots and microbial cells, as well as through ammonia volatilization. The elevated pH values remain only as long as traces of added urea nitrogen are recoverable in the soil system in the form of exchangeable NH_4.

The initial effect of ammonium nitrate treatment is exactly the reverse. As a result of exchange reactions, the pH value decreases in the soil solution. This effect ebbs out as the excess salts are either consumed biologically or leached out from the soil system. The final result may have been affected by the NH_4/NO_3 ratio of the microbial and plant nitrogen uptake.

The results are thus in agreement with earlier observations, according to which the residual effects of the urea and ammonium nitrate sources of nitrogen on the soil pH may be considered to be negligible. This seems to apply to non-nitrifying forest soils of podsol type in general. As regards urea, a residual pH-increasing effect on this type of soil may be expected only when a substantial part of the ammonia, formed on hydrolysis, escapes the biological uptake and the chemical immobilization and is leached from the root zone as NH_4^+-ion.

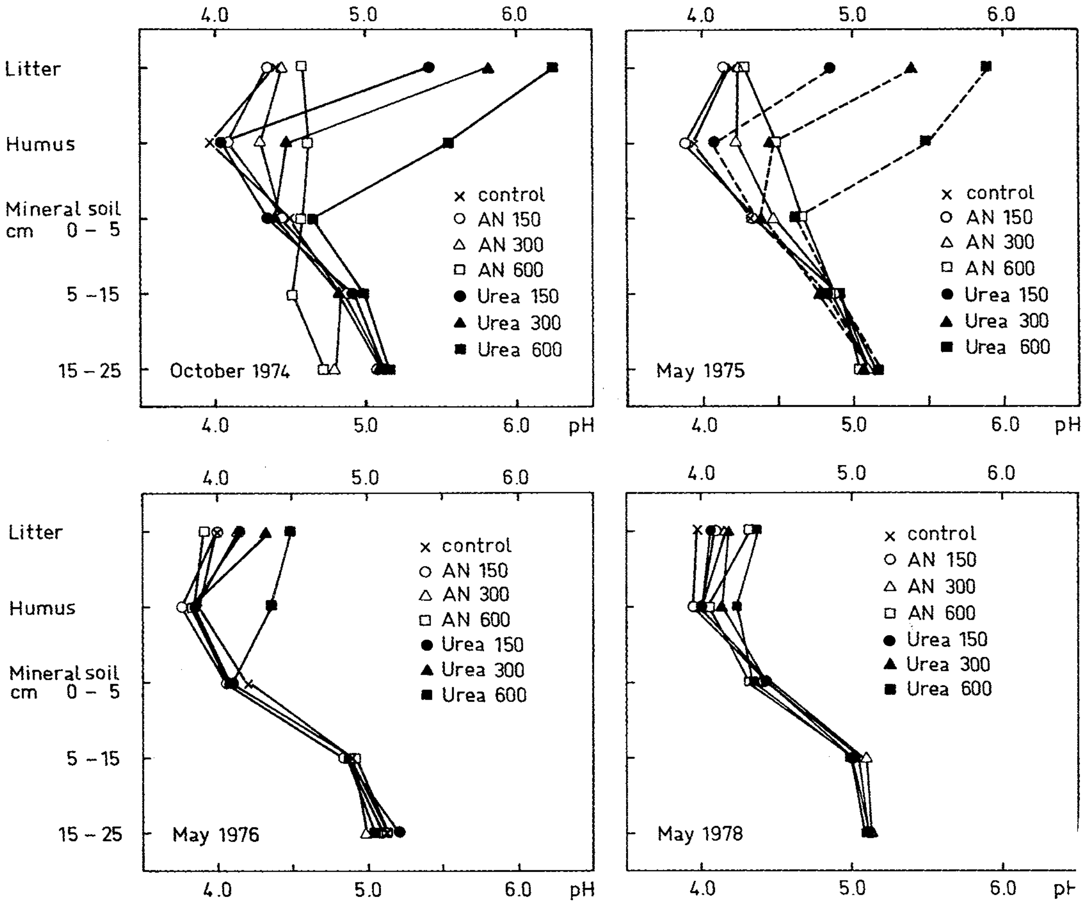


Figure 6. pH in the soil profile.
Mean figures for three replicates.

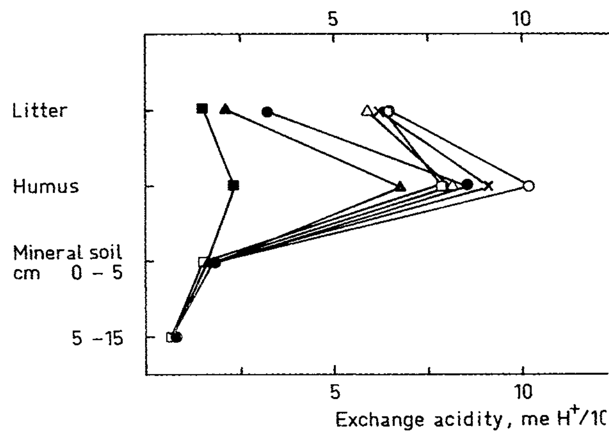


Figure 7.
Exchange acidity of
the soils.
For symbols see Figure 6.

3.1.6 *Effects on the soil content of exchangeable cations*

The soil samples collected in the spring of 1975 were subjected to examination to determine the influences of experimental treatments on the soil content of exchangeabl base cations and the exchange acidity. A regards the figures on exchange acidity th data in Figure 7 indicate a marked decreas with increasing urea application rate. In thi respect the effect of ammonium nitrate is insignificant.

Concerning the base cations, the ammonium nitrate treatmens resulted in a depletion of litter and humus layers on exchangeable K, Mg and Ca. The effect was statistically significant only for the content of K, amounting to 9.4 kg ha^{-1} in the humus layer and at the highest ammonium nitrate application rate (= 29% of the total pool of exchangeable K). For treatments with urea, the changes in the soil content of exchangeable base cations were small and within the margins of the experimental error.

3.1.7 *Effects on soil capacity to mineralize carbon and nitrogen*

Soil materials collected two years after the fertilizer application (spring 1976) and comprising block 2 only were examined to determine their capacity to net-mineralize nitrogen and carbon during aerobic incubation. The incubation technique used has been described by Nômmik (1971 a). Accumulation of inorganic nitrogen was measured after 8 and 16 weeks of incubation, whereas the measurement of CO_2 production was restricted to periods of 20 to 22 days and 54 to 56 days after initiation of the incubation.

As to the data in Table 6, there is a trend towards a decreasing *respiration rate* with increasing nitrogen application rate in the field. The effect is most marked for the humus material and applies to both ammonium nitrate and urea treatments.

These data are in accordance with the observations reported by Bååth et al. (1981), concerning the same experimental field, but referring to soil material collected as long as five years after the fertilizer application. The authors concluded that the fluorescein diacetate-active fungal biomass, as well as the total respiration rate, was significantly lower in plots treated with urea and ammonium nitrate than in control plots. The decrease in soil microbial activity and biomass was suggested to be a result of a change in plant root status and dynamics in the soil. According to the authors of the present paper the effects of the fertilizer nitrogen application on the resistance of soil organic colloids against microbial decomposition should not be overlooked in this connection.

In contrast to the above Swedish reports, an increased bacterial and fungal biomass and an increased respiration rate in forest humus as a result of urea treatment have been reported by other soil workers (Roberge & Knowles, 1967, Salonius. 1972).

Table 6. Respiration rate in soil materials from control and treated plots. The figures refer to amounts of CO_2 produced in aerobic incubation for 24 h at 20°C, expressed as % of C_{tot}. The soil sampled in the field in spring 1976, i.e. 2 years after the fertilizer application (block 2).

	Treatments						
	Control	AN 150	AN 300	AN 600	U 150	U 300	U 600
Observation period 20–22 days after the start of incubation							
Litter	3.23	3.36	3.30	2.75	3.26	2.76	2.66
Humus	1.31	1.08	0.92	0.85	1.44	1.00	1.06
Mineral soil, 0–5 cm	1.18	1.29	1.21	1.11	1.28	1.31	1.20
L.s.d. 5% = 0.41							
Observation period 54–56 days after the start of incubation							
Litter	1.55	1.66	1.61	1.36	1.56	1.24	1.29
Humus	0.89	0.76	0.65	0.51	0.77	0.58	0.55
Mineral soil, 0–5 cm	0.86	0.80	0.74	0.74	0.80	0.94	0.80
L.s.d. 5% = 0.22							

Table 7. Changes in the content of inorganic nitrogen in soil materials during aerobic incubation of 8 and 16 weeks, respectively (20°C). The figures refer to % of N_{tot}.
Field sampling of soil in spring 1976, i.e. two years after the fertilizer application (block 2).

Treatment	Litter		Humus		Mineral soil 0–5 cm	
	8	16	8	16	8	16
Control	0.0	0.1	0.9	2.2	1.0	2.9
AN 150	0.0	0.0	0.3	0.9	0.7	3.1
AN 300	0.0	0.0	0.4	2.0	1.3	5.0
AN 600	–0.5	–0.2	–0.3	–0.3	1.9	4.6
Urea 150	0.0	0.3	3.2	3.0	0.4	1.6
Urea 300	–0.5	–0.5	3.6	3.9	2.1	5.1
Urea 600	–4.1	–4.0	1.0	3.5	1.7	6.0
L.s.d. 5% = 2.4						

The net mineralization of soil *nitrogen* was shown to be effected by experimental treatment. In humus material the treatment with urea had improved the capacity to mobilize mineral nitrogen, whereas the reverse was the case for humus from ammonium nitrate treated plots. Organic material from the litter layer did not accumulate any mineral nitrogen. In the treatment with the highest dose of urea, the net mineralization was actually negative (Table 7).

The incubation was performed in only two replicates, which limits the reliability of the results obtained.

3.2 Accumulation of fertilizer nitrogen in the needle biomass

3.2.1 *Changes in needle weight*

The changes in needle weight, expressed in g per 100 needles and covering the whole observation period and all the experimental treatments, are given in Figure 8.

The weight of the needles of *current* growth generally increased with increasing nitrogen application rate (Figure 8 a). This applied both to ammonium nitrate and urea sources of nitrogen, and to all the observation years included in the study (no weight data for the first growing season). Furthermore, as a rule the 100-needle weights for the ammonium nitrate treatments were higher than those for corresponding urea treatments. From the 5th growing season this effect of the nitrogen source decreased markedly.

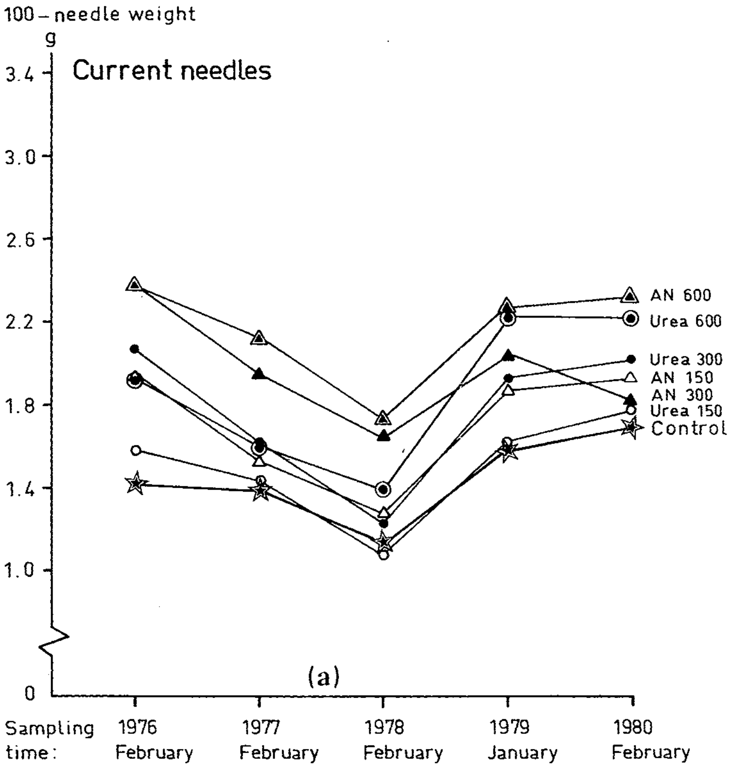
As regards the yearly variation in 100-needle weights there was a general observation that a marked weight minimum occurred during the fourth growing season (sampling in February, 1978).

Changes in the weight of the *previous year's needles* are presented in Figure 8 b. They indicate a rather close relationship to the nitrogen application rates and even a covariation with the figures for current needles.

3.2.2 *Nitrogen content of needles*

The figures for total nitrogen contents ‹ current and previous year's needles, repr senting means for the three blocks, a illustrated graphically as a function of nitro; application rate (Figures 9 and 10) a length of the observation period (Figures and 12).

For *current needles,* which had been tiated in the first three growing seasons a nitrogen application, the nitrogen con figures are significantly higher for ammor nitrate than for urea treatments (Figur These differences in effect are smal' disappear entirely, for needles produce ring the following three growing season:



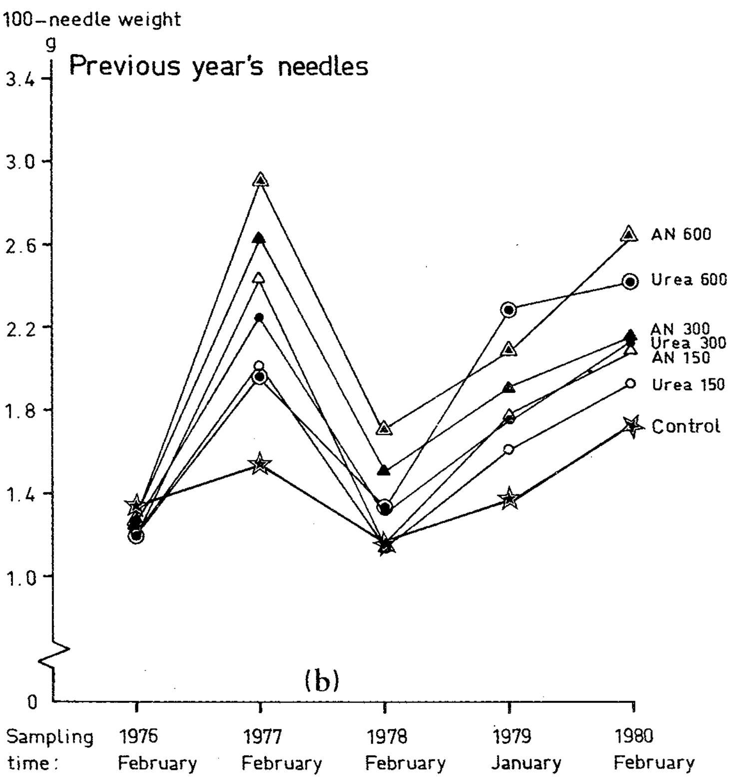


Figure 8.
100-needle weights of Scots pine.
a. Current needles
L.s.d. 5% = 0.40
b. Previous year's needles
(= one year old needles)
L.s.d. 5% = 0.37.

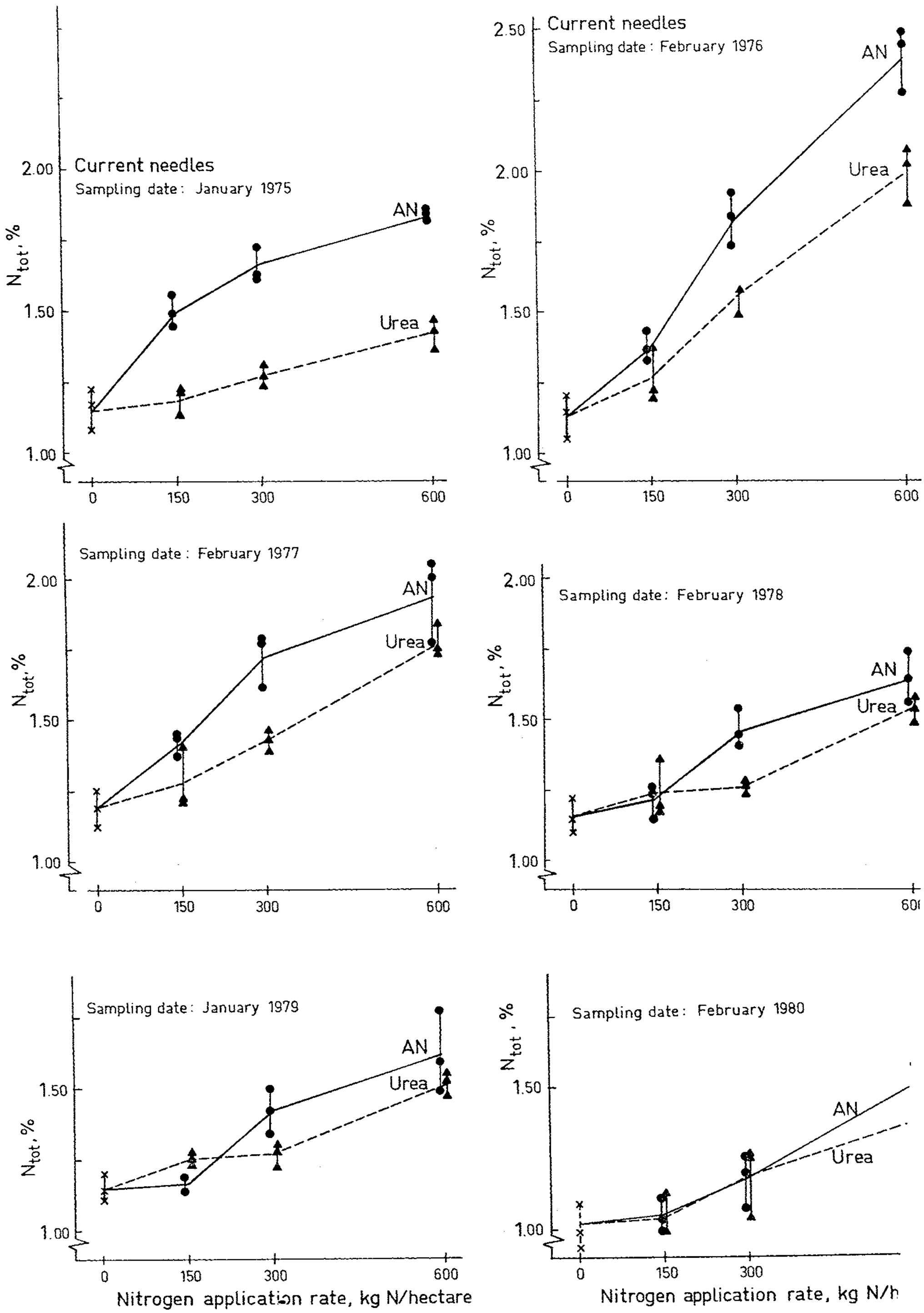
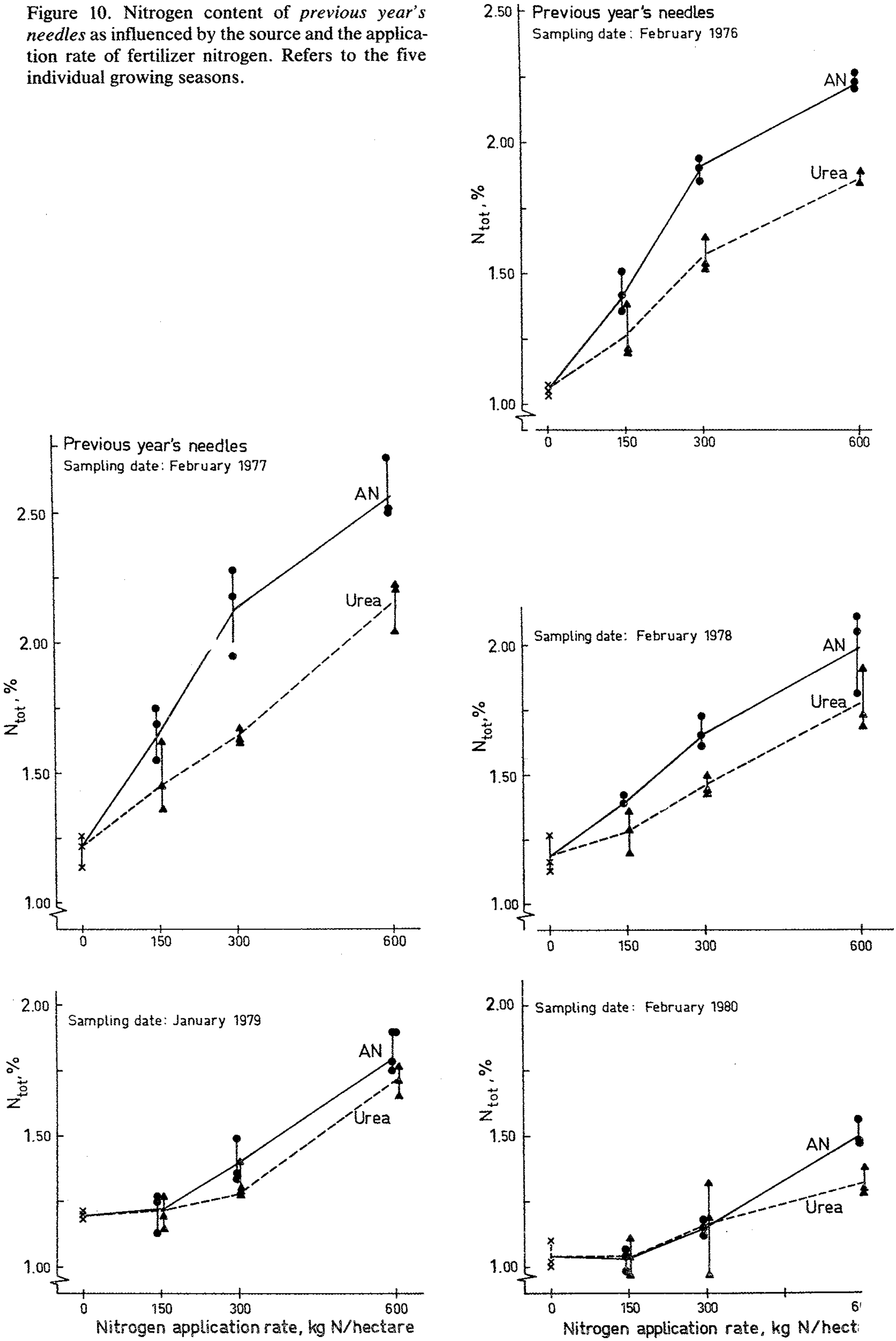


Figure 9. Nitrogen content of *current needles* as influenced by the source and the application rate fertilizer nitrogen. Refers to the six individual growing seasons.

Figure 10. Nitrogen content of *previous year's needles* as influenced by the source and the application rate of fertilizer nitrogen. Refers to the five individual growing seasons.



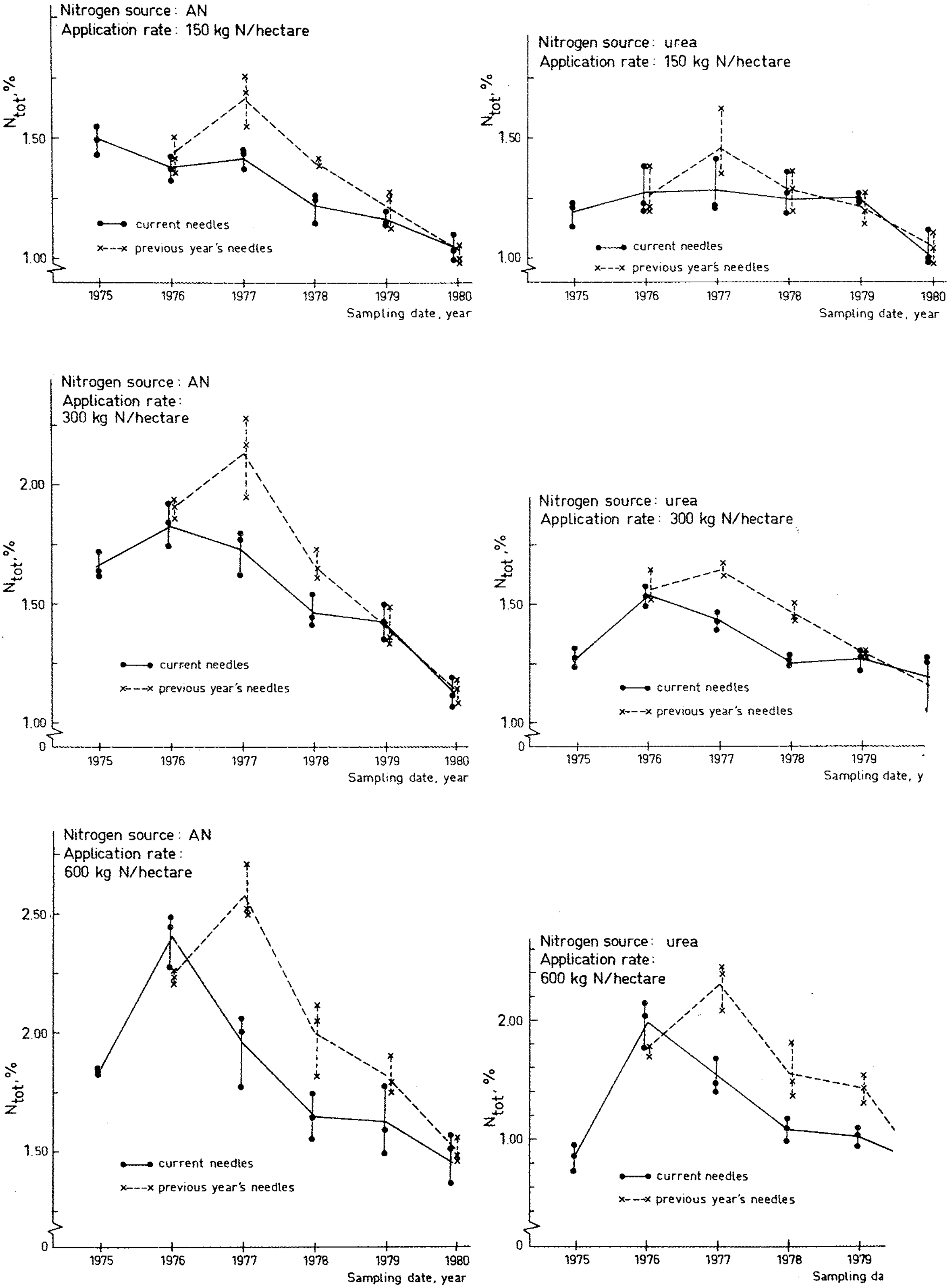


Figure 11. Nitrogen content of needles as influenced by the length of the observation period. Sampling period January–February.

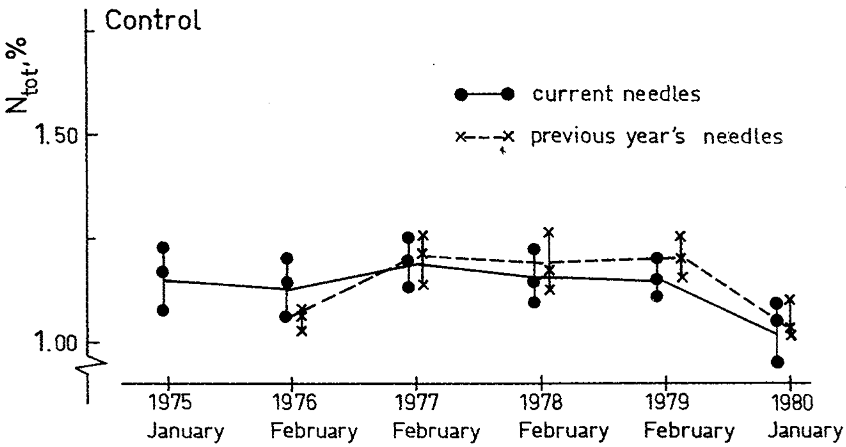


Figure 12. Nitrogen content of the needles in control plots.

The nitrogen content in current needles culminates during the second growing season, both for the ammonium nitrate and urea treatments (Figure 11). The N150 ammonium nitrate treatment, where the maximum in nitrogen content is already attained after the first growing season, is an exception. The nitrogen content figures for N600 treatment culminate at 2.40 and 1.99% for ammonium nitrate and urea, respectively. The corresponding figures for the N300 treatment are 1.83 and 1.55%. These figures are to be compared with 1.13%, representing the nitrogen content in the control treatment.

The changes in the nitrogen content of *previous year's needles,* as a function of fertilizer application rate, are shown in Figure 10. Again the ammonium nitrate here has resulted in higher nitrogen contents than have corresponding urea application rates. The highest nitrogen contents are attained after the third growing season, i.e. one year later than for the needle of current growth (Figure 11). A distinctive feature is that in all treatments after the 3rd growing period, the nitrogen contents of the needles of previous year's growth surpass those of the current growth (cf. Aronsson et al., 1977).

3.2.3 *Quantity of nitrogen per 100 needles*

The changes in the nitrogen content per 100 needles in relation to fertilizer treatment and the length of observation period are presented in Table 8. The corresponding figures, expressed as percentages of that for the control treatment, are shown in Figure 13. The variation pattern for needles of *current growth,* related to the length of the observation period, is similar to that of the nitrogen contents described above (Figure 9). Thus, the quantity of nitrogen per 100 needles culminated during the 2nd growing season. Likewise, the figures are generally lower for urea than for corresponding ammonium nitrate treated plots. For example, the figures for the second growing season and the N150 application rate, when related to control plots, are 167% for ammonium nitrate and only 125% for the corresponding urea treatment. For the N600 treatment the corresponding figures are 353 and 317%, respectively.

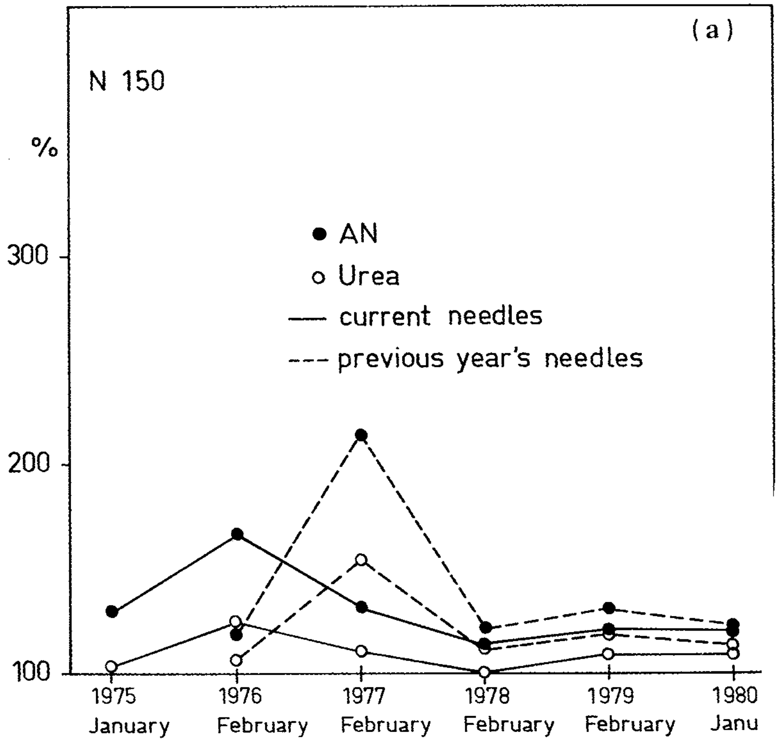
The amount of nitrogen per 100 needles of the *previous year's growth* culminates, as for the nitrogen percentages, during the 3rd growing season. For all of the nitrogen application rates and both of the nitrogen sources used, the figures for nitrogen content per 100 needles are higher for needles of previous year's growth than those for current growth. The only exception is for needles which were sampled after the second growing season (February 1976). As for needles of current growth, the nitrogen content per 100 needles of second year's tissue was higher

Table 8. Amounts of N_{tot} per 100 needles, mg. Arithmetical means of three replicates.
a = current needles
b = previous year's needles

Treatment	Needle age	Sampling date				
		February 1976	February 1977	February 1978	January 1979	February 1980
Control	a	16.1	16.5	13.5	18.3	17.2
	b	14.2	18.8	14.2	16.5	17.8
AN 150	a	27.0	21.8	15.9	22.1	20.5
	b	16.8	40.4	16.8	21.7	21.6
AN 300	a	43.8	33.8	24.4	28.9	21.4
	b	24.6	56.2	25.5	26.9	24.7
AN 600	a	57.0	41.1	28.8	36.9	38.9
	b	28.1	74.8	34.2	37.9	39.8
Urea 150	a	20.1	18.4	13.3	20.1	18.7
	b	15.2	28.4	15.6	19.7	20.2
Urea 300	a	32.1	24.1	16.0	24.8	24.2
	b	19.6	36.9	19.3	22.8	25.5
Urea 600	a	38.4	27.5	21.7	33.6	33.5
	b	22.2	42.3	24.1	39.4	33.2

L.s.d. 5% = 6.4

Figure 13 a–c. Amount of nitrogen per 100 needles, relative to control plot, during the six growing seasons following fertilizer application.
The figures for 1975 are obtained by calculation, using average weight data for needles of control plots.
Mean figures for three replicates.
L.s.d. 5%:
150 N = 31%
300 N = 49%
600 N = 73%



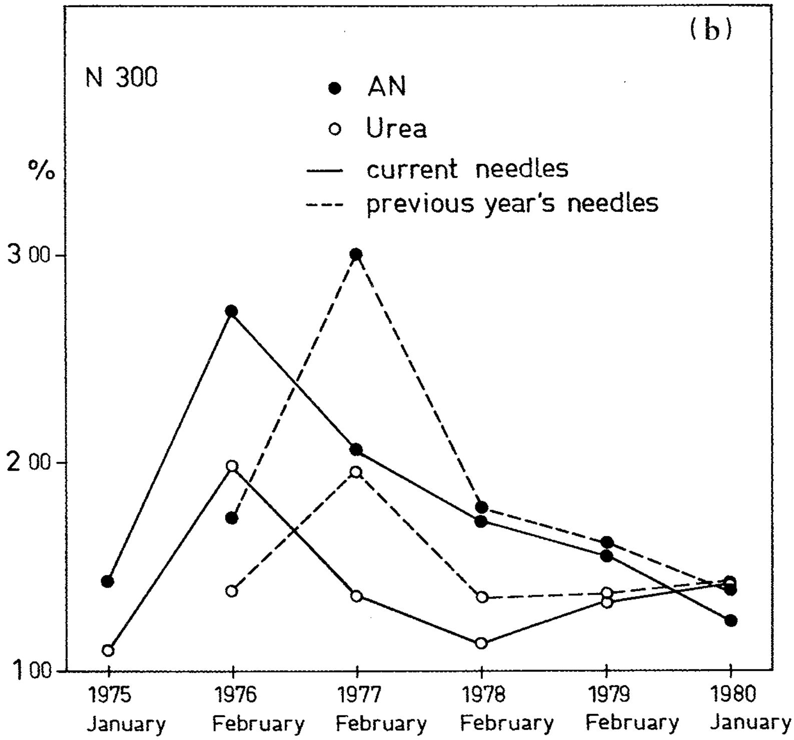


Figure 13 b.

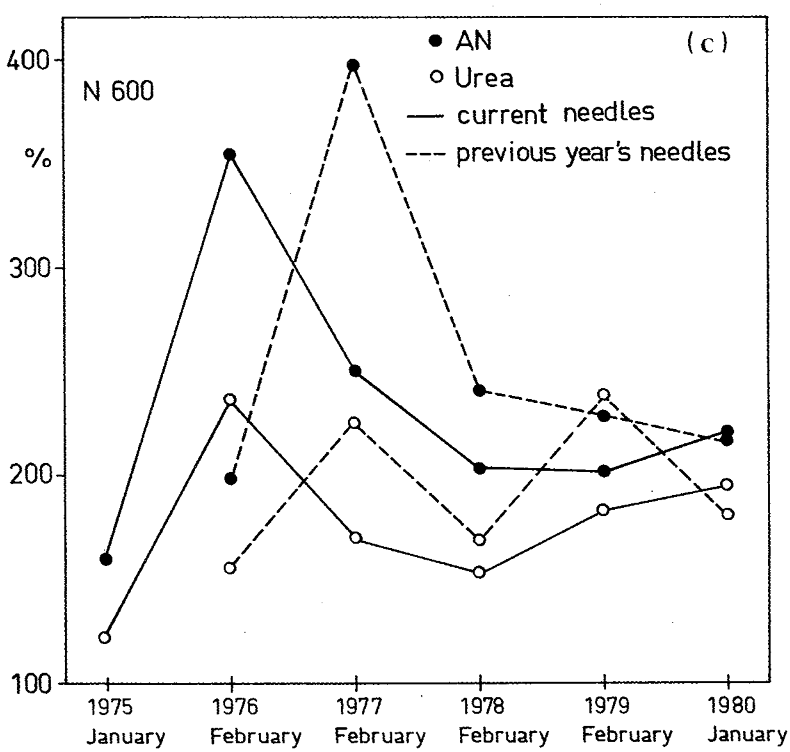


Figure 13 c.

after ammonium nitrate than after urea treatments. As regards the 3rd growing season, and relative to control plots, these figures of the N150 application rate for ammonium nitrate and urea are 215 and 155%, respectively. The corresponding figures for N600 treatment are 398 and 225%.

3.2.4 *Estimation of the amounts of fertilizer nitrogen accumulated in needle biomass*

For the fertilizer nitrogen budget, efforts were made to estimate the magnitude of nitrogen accumulation in the needle biomass. As no quantification of the size of the biomass was included in this study the figures presented below are rough estimates based on observations by other authors (Tamm, 1963, Bringmark, 1977) and on the following assumptions:

(1) The biomass of the current and the previous year's needles contained 20 kg N per hectare each.
(2) The needles of older growth are not included.
(3) The number of the current needles is not influenced by the experimental treatments (probably incorrect).

The figures so obtained are, of course, of restricted applicability and mainly for illustrating the fertilizer nitrogen accumulation relative to control plots and for making comparisons between the treatments (Table 9).

It is evident from the data presented that the accumulation of applied fertilizer nitrogen in needle biomass culminates during the 3rd growing season (sampling in February 1977). This applied to all nitrogen application rates and to both nitrogen sources. As regards ammonium nitrate treatments, the figures on fertilizer nitrogen recovery in the needle biomass declined drastically after the 3rd growing season. In urea-treated plots, on the other hand, these figures show no systematic decline during the three latest seasons of observation. The above finding illustrates the significance of the length of observation period on the figures extracted for quantifying the fertilizer nitrogen accumulation in the foliage.

According to this estimation, the percentage recovery of added nitrogen in needle biomass is only slightly influenced by the nitrogen application rate. On culmination, i.e. after the 3rd growing season, the figures vary between 15 and 20% for ammonium nitrate and 7 and 10% for urea.

Note should be made of the fact that for the N150 and N300 application rates the figures on fertilizer nitrogen accumulation in needle biomass indicate a culmination point as late as during the 3rd growing season, in spite of the fact that no measurable amounts of residual ammonium-N could be recovered in the soil in the beginning of the season. This

Table 9. Estimated amounts of fertilizer nitrogen accumulated in the needle biomass, kg N per hectare (for the bases of calculation see 3.2.4).

Treatment	Sampling date				
	February 1976	February 1977	February 1978	January 1979	February 1980
AN 150	18	29	10	10	8
AN 300	50	60	37	24	13
AN 600	72	91	53	46	50
Urea 150	7	12	3	6	4
Urea 300	18	21	11	15	17
Urea 600	39	38	27	45	36
L.s.d. 5% = 11					

indicates a redistribution of nitrogen within the tree, possibly from roots to needles.

3.3 Partial balance sheet for applied fertilizer nitrogen

A complete balance sheet for fertilizer nitrogen in a forest ecosystem may include the following items: quantities of nitrogen recovered in soil and in vegetation of bottom, field and tree layers, and quantities lost by leaching, denitrification and ammonia volatilization. Due to limitations in experimental techniques, up to now no field studies are reported from forest ecosystems, where all the above items have been quantified and thus included in the balance sheet.

Nor does the present investigation, the main objective of which was to obtain further information on fertilizer nitrogen transformations and recovery in the soil, afford data to provide a total budget for the applied fertilizer nitrogen. The quantification is limited to the uppermost 30–35 cm layer of the soil, and to the needle biomass. Beyond that, some measurements were made to quantify the NH_3 loss from the N150 treatment with urea.

In spite of incompleteness, the data produced have been collocated and presented for a partial nitrogen budget (Table 10). Soil data in this case refer to organically bound nitrogen, N^x_{org}, recovered in the soil in spring, 1975, i.e. one year after the application of fertilizers. Data on the needle biomass refer to measurements performed after the 3rd growing season. It is assumed that no measurable amounts of fertilizer nitrogen remained in the soil profile in inorganic forms at the end of the 3rd growing season. This is correct for the N150 and N300 treatments. In plots treated with N600, however, approximately 20–30 kg N/ha of fertilizer nitrogen was still present in the soil as exchangeable NH_4. The figures on fertilizer nitrogen recovery in this treatment have been underestimated, probably by 2–3%.

The figures in Table 10 show that, as regards the N150 treatment, the recovery of fertilizer N in the soil and the needle biomass amounted to 40 and 57%, respectively, depending on whether ammonium nitrate or urea was the nitrogen source. In plots treated with urea, the loss of nitrogen by NH_3 volatilization was estimated to 21%. According to this, the conclusion to be drawn is that of the nitrogen in urea treatment N150 approximately 70% was either inactivated in the soil or lost to the atmosphere during the first growing season.

For the N300 nitrogen level the total recovery is approximately as large for urea as for ammonium nitrate, amounting to 36%. The relatively low accumulation of urea nitrogen in needle biomass is compensated by a higher recovery in the N^x_{org}-pool of the soil. The recovery percentage is lowest for the N600 treatment and is approximately the same for urea and ammonium nitrate.

Table 10. Partial budget for fertilizer nitrogen. Refers to per cent of nitrogen added.
nd = not determined

	Ammonium nitrate			Urea		
	150	300	600	150	300	600
Soil*	21	16	12	49	29	17
litter	(6)	(5)	(3)	(9)	(4)	(4)
humus	(7)	(5)	(2)	(29)	(20)	(8)
mineral soil	(9)	(6)	(7)	(11)	(5)	(5)
Needle biomass**	19	20	15	8	7	6
Sum	40	36	27	57	36	23
Loss by NH_3 volatilization	nd	nd	nd	21	nd	nd

* Organically bound fertilizer N, recovered in spring, 1975.
** Amounts of fertilizer nitrogen in needle biomass after the third growing season.

Even though the recovery figures presented do not include the total biomass, they suggest a substantial loss of fertilizer nitrogen to ground water and/or the atmosphere. As to the gaseous loss by denitrification, according to the available information this is probably not very significant in the soil type in question (Pluth & Nômmik, 1981). Any such losses would have affected only the ammonium nitrate treated plots.

However, the leaching may have been an important source of nitrogen loss. According to rough estimations, the leaching loss for the N150 application rate may amount to 0–10% for urea and 30–40% for the ammonium nitrate source of nitrogen. The proportion of fertilizer nitrogen lost by leaching probably increases with increasing nitrogen application rate (cf. Miller et al., 1976). According to the distribution pattern for inorganic nitrogen in the soil profile, it seems likely that a considerable amount of leaching from the root zone occurred in the form of NH_4.

3.4 Volume growth of the stand during the observation period

The basal area growth, as an average for the three blocks, is given in Figures 14 and 15. Referring to Figure 14, a strong decrease in the basal area growth is indicated in control plots for the 1976 growing season. This decrease is probably a result of the unusually dry growing season, which might also have influenced the growth in 1977, and the growth response to fertilization. From Figure 15, which shows the basal area growth response in relative figures, it is apparent that the fertilization response for all treatments is at a maximum during the fifth growing season. Evidently, the fertilizer effect on basal area growth was not exhausted totally at the end of the first observation period of five years.

The volume growth response during the 5-year period, 1974–1978, is given in Table 11 and Figure 16. The results confirm the relationship found previously between growth increase and nitrogen application rate for the two nitrogen sources (Rosvall, 1979). The results also illustrate that the maximum

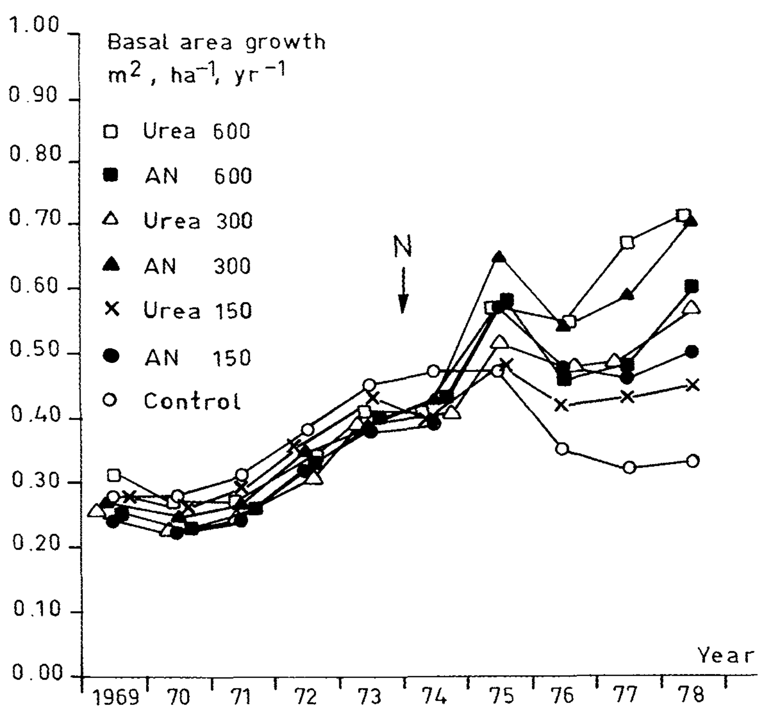


Figure 14. Basal area growth, $m^3 ha^{-1} yr^{-1}$. Average of three replications.

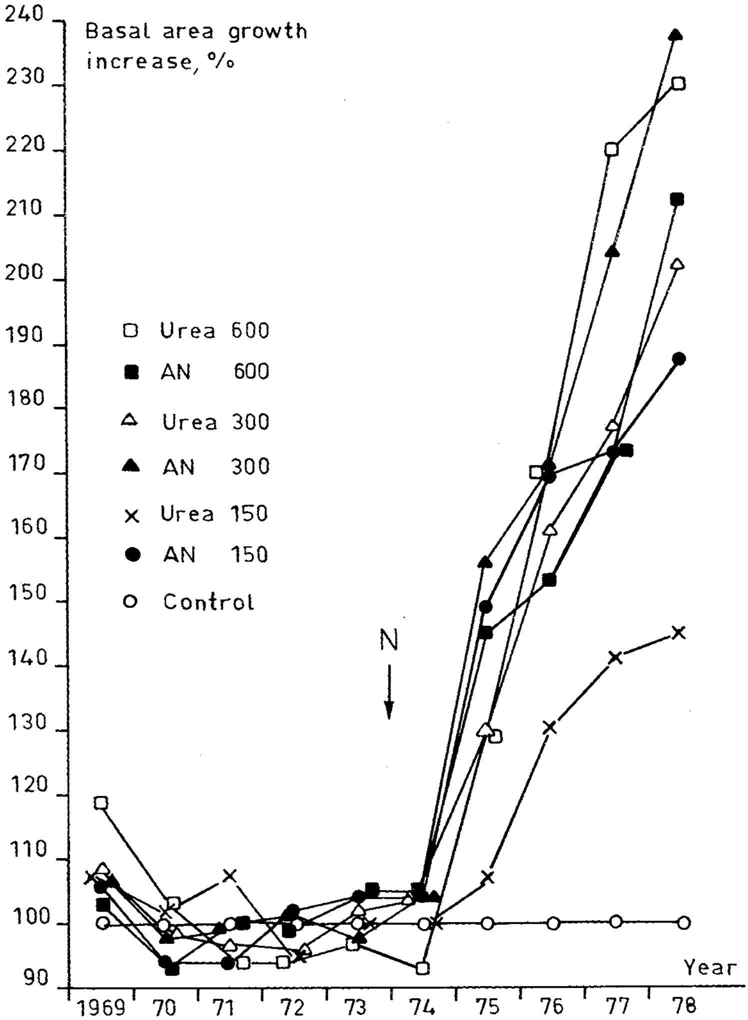


Figure 15. Basal area growth in the treated plots as percentage of that in control plots. Average of three replications.

growth response of 14.7 m^3 ha^{-1} $5yrs^{-1}$ was reached at an application rate of 300 kg N ha^{-1} when the nitrogen source was ammonium nitrate. Concerning urea, the maximum response still did not seem to have been reached at the N600 application rate.

For the lowest nitrogen application rate (N150), ammonium nitrate gave 2.12 times as high a volume growth increase as urea. This is an unusually high superiority for ammonium nitrate, but the result corresponds rather well with data on nitrogen accumulation in foliage. Likewise the results are in relatively good agreement with the expected growth increase, calculated from the predictive equations for estimating the fertilization response, worked out at the Institute for Forest Improvement (Rosvall, 1979). The response of the lowest application rate of urea is the only exception. The obtained growth increase, regarding the N150 application rate was 10.4 and 4.9 m^3 ha^{-1} $5yrs^{-1}$ for the two nitrogen sources, respectively.

At the rate of 300 kg N ha^{-1}, ammonium nitrate gave a growth increase of 14.7 and urea 10.3 m^3 ha^{-1} $5yrs^{-1}$, indicating a 43% superiority for ammonium nitrate, which is a normal figure. The N600 application rate

Table 11. Volume growth increase 1974–1978, m^3 ha^{-1} $5yrs^{-1}$.
m^3 = stemwood including bark

Block number	Treatment					
	AN 150	AN 300	AN 600	U 150	U 300	U 600
1	8.5	12.9	9.7	4.3	12.5	12.3
2	14.3	17.5	14.9	6.5	10.2	15.1
3	8.4	13.7	8.3	3.9	8.3	12.5
Average	10.4	14.7	11.0	4.9	10.3	13.3
S.D.	3.4	2.5	3.5	1.4	2.1	1.6

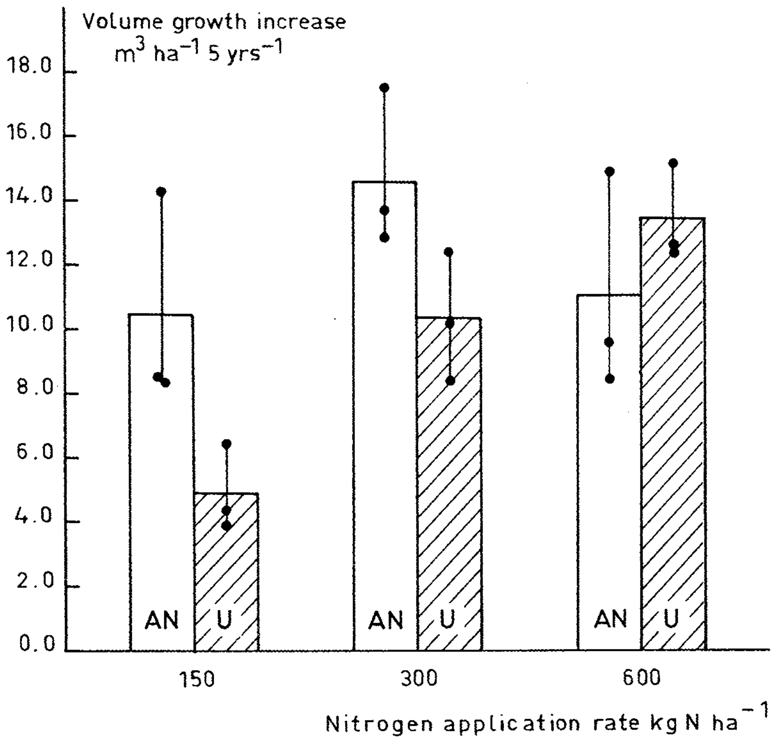


Figure 16. Volume growth increase in m^3ha^{-1} (stem volume including bark), 1974–1978. Average of three replications. The dots represent single observations.

proved to be over-optimal when the nitrogen was applied as ammonium nitrate, but not as urea.

The figures on volume growth increase were generally positively correlated with the increase in needle weight, the nitrogen content in the needles and the quantity of nitrogen per 100 needles. The number of observations was too limited, however, to justify a statistical analysis.

4 Summary

A field trial was conducted to study the distribution and recovery of fertilizer nitrogen in the soil profile and the needle biomass in a 120-year-old stand of Scots pine (*Pinus sylvestris* L.). The soil is characterized as a well-drained, sandy glacifluvial sediment. The effects of nitrogen were tested at four application rates (0, 150, 300 and 600 kg per hectare), using ammonium nitrate and urea as nitrogen sources. The observation period was limited to six growing seasons following the fertilizer application.

The soil investigation, which was carried out in the autumn of 1974, i.e. after the first growing season, indicated that of the 150 kg of nitrogen applied only 7 to 10% could be recovered in the soil profile in inorganic forms, depending on whether ammonium nitrate or urea was the nitrogen source. The recovery percentage increased with increasing nitrogen dose. In treatments using ammonium nitrate, approximately one-third of the recovered inorganic nitrogen consisted of nitrate, and two-thirds of ammonium. The proportion of nitrate in the inorganic nitrogen pool increased with increasing profile depth. In urea treatments, no measurable accumulation of nitrate occurred.

From data on the inorganic nitrogen content of the soil profile in the following spring (1975), it was concluded that during the winter the soil profiles of the ammonium nitrate-treated plots were totally drained of nitrate, and even the content of exchangeable ammonium was markedly decreased. The size of ammonium pool on urea-treated plots was only slightly affected during the winter season. After two growing seasons no excessive amounts of inorganic nitrogen were recovered in the soil profile in plots treated with 150 or 300 kg N ha^{-1}. This applied both to the ammonium nitrate and the urea sources of nitrogen.

Data on the size of the total and inorganic nitrogen pools in the treated plots, and the C/N ratios in both treated and reference plots, were used to calculate the quantities of fertilizer nitrogen which had been immobilized in the soil (including part of the nitrogen accumulated in roots). The figures for the N150 application rate and the 25 cm mineral soil depth amounted to 21 and 49% for the ammonium nitrate and urea sources of nitrogen, respectively.

Parallel to soil investigations, the study included yearly sampling of the needles of Scots pine to quantify the amounts of fertilizer nitrogen accumulated in the needle biomass. It was shown that the accumulation culminated after the 3rd growing season when the nitrogen contents for N150 treatment, relative to the control, amounted to 174 and 134% for the ammonium nitrate and urea nitrogen treatments, respectively. After six growing seasons, a substantial proportion of the fertilizer nitrogen, initially absorbed by the trees, still remained in the crowns.

A partial budget for fertilizer nitrogen indicated that, for the N150 application rate, the recovery in soil (as non-extractable nitrogen) and in needle biomass totalled between 40 and 57%, depending on whether ammonium nitrate or urea was the nitrogen source. The recovery percentages tended to decline with increasing nitrogen application rate. When one takes into account the ammonia lost by volatilization, which was estimated to 21% in the N150 urea treatment, approximately 70% of the applied nitrogen in this treatment was inactivated, or lost by volatilization during the first growing season.

No direct observations were made on nitrogen loss by leaching and denitrification. When excluding the denitrification, and calculating by the method of differences, the leaching loss in the N150 treatment could be

assessed to 0–10% for urea and 30–40% for ammonium nitrate. The proportion of leaching loss in the fertilizer nitrogen budget was assumed to increase with increasing nitrogen application rate.

The volume of the stand increased with an increase in the nitrogen application rate up to 600 kg N ha^{-1} for urea, but only up to 300 kg N for ammonium nitrate. The dose of 600 kg N ha^{-1} as ammonium nitrate proved to be above the optimum for volume growth.

Ammonium nitrate was superior to urea at the two lowest nitrogen application rates. At the nitrogen application rate of N150 the volume growth increase for ammonium nitrate and urea during the 5-year period was 10.4 and 4.9 m^3 ha^{-1} of stemwood including bark, respectively.

For both nitrogen sources and all application rates, the basal area growth increase reached its maximum during the fifth, i.e. the last year of observation.

Acknowledgements

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Sammanfattning

I en fältundersökning belyses frågan om handelsgödselkvävets återvinning och fördelning både i markprofilen och i trädbeståndets barrbiomassa under en observationstid av sex vegetationsperioder. Forskningsobjektet utgjordes av ett avverkningsmoget tallbestånd på sedimentmark, beläget 15 km N om Heby, Västmanland. Försöket omfattade sju försöksled (kontroll samt tre nivåer av ammoniumnitrat resp. urea) och utfördes med tre samparceller. Kvävet tillfördes som engångsgiva på sommaren 1974 och i mängder motsvarande 0, 150, 300 och 600 kg N ha^{-1}.

Av den markundersökning, som utfördes på hösten efter den första vegetationsperioden, framgick att av den lägsta kvävegivan återfanns i den undersökta delen av markprofilen endast 7 resp. 10% i oorganisk form, då ammoniumnitrat resp. urea utgjorde kvävekällan. Den procentuella återvinningen ökade med stigande kvävegiva. På parceller behandlade med ammoniumnitrat utgjorde nitratkväve ca 1/3 och ammoniumkväve 2/3 av den oorganiska kvävepoolen. Nitratets andel ökade med stigande profildjup. På ureabehandlade ytor uppmättes ingen ansamling av nitratkväve. Markanalyser utförda på våren, ett år efter gödselns applicering, visade att markprofilen på parceller gödslade med ammoniumnitrat helt tömts på nitrat, och att även ammoniumpoolen hade avsevärt minskat i storlek. På ureabehandlade parceller blev ammoniumpoolen och dess fördelning i markprofilen i stort sett opåverkad. Efter ytterligare ett år uppvisade markprofilen inga överskottshalter av utbytbart ammonium, varken på parceller behandlade med 150 eller 300 kg N ha^{-1}, vilket gällde båda gödselmedlen.

Med ledning av uppgifter på innehållet av oorganiskt kväve och totalkväve på behandlad parcell, och på C/N-kvoten i både behandlad parcell och kontrollparcell, beräknades mängden tillfört gödselkväve som hade immobiliserats i marken i organiskt bunden form (inklusive ansamlingen i rotbiomassan). Vid tillförsel av 150 kg N ha^{-1} blev ifrågavarande värden 21% för ammoniumnitrat och 40% för urea.

Förna- och humuslagrets innehåll av utbytbart K minskade med stigande ammoniumnitrattillförsel. Även mikrobaktiviteten i humuslagret, mätt som CO_2-produktion per tidsenhet, visade trenden att avta med stigande kvävegödslingsintensitet.

Parallellt med markundersökningar utfördes årliga mätningar av gödselkvävets ansamling i barrbiomassan. Man konstaterade bl.a., att ansamlingen kulminerade under den tredje vegetationsperioden, då den på kvävenivån 150 kg N ha^{-1} uppnådde värdet 174% för ammoniumnitrat och 134% för urea (kontroll = 100). Efter den sjätte vegetations perioden var en signifikant del av det gödsel kväve, som initiellt upptagits av träder fortfarande registrerbar i kronorna.

Enligt en partiell budget, som baserades ı gödselkväveansamlingen i markens organis substans och i barrbiomassan, uppskattad återvinningen för den lägsta kvävegivan 40 resp. 58%, beroende på om ammoniu nitrat eller urea utgjorde kvävekällan. Å vinningsprocenten avtog med stigande kv giva.

Om man tog hänsyn till kväveförlu genom ammoniakavgång, som vid den l ureagivan uppmättes till 21%, betydde att omkring 70% av det tillförda ureakv ett tidigt stadium inaktiverades eller tap ur ekosystemet genom markprocessern träffande förlusterna från ekosystemet g denitrifikation och utlakning saknades (mätdata. Enligt en grov uppskattning utlakningsförlusten vara av storleksor 30–40% för ammoniumnitrat och 0–1

urea. Utlakningens andel i handelsgödselkvävets budget ansågs stiga med stigande kvävegiva.

Vad beträffar ökningen av volymtillväxten var ammoniumnitrat överlägset urea vid de två lägsta kvävegivorna. Vid behandling med 150 kg N ha^{-1} var tillväxtökningen för den första 5-årsperioden 10.4 m^3sk ha^{-1} för ammoniumnitrat och 4.9 m^3sk ha^{-1} för urea. Motsvarande siffror för 300 kg N var 14.7 resp. 10.3 m^3sk ha^{-1}. Den högsta kvävegivan (600 kg N ha^{-1}) var överoptimal för ammoniumnitratet, med tillväxtökningen sjunkande till 11.0 m^3sk, medan för ureans vidkommande registrerades en fortsatt ökning till 13.3 m^3sk.