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Intensive fertilization with nitrogen as a stressing factor in a spruce ecosystem I. Soil effects

Intensiv kvävegödsling som stressfaktor i ett granskogsekosystem I. Markreaktioner

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Abstract

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Soil studies were carried out before and after clear felling of an intensively fertilized young spruce plantation on old arable land. Particular attention was devoted to nitrogen mineralisation, nitrification, and leaching. Notable amounts of nitrate in the soil occurred before felling only on plots receiving high doses of ammonium nitrate, after clear felling also on some plots with no or low nitrogen supply. Marked quantities of nitrate nitrogen were observed in the deeper soil layers during the fertilizer experiment in plots with high fertilizer additions.

The soil reaction indicated an acidification as a result of fertilizer treatment.

In a pot experiment with soil from the field experiment the nitrate leaching by percolation was studied. Most of the leaching of nitrate nitrogen occurred in the first phase of the experiment. After the vegetation was established, the nitrate concentration in the percolating water rapidly decreased.

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Introduction (by C. O. Tamm)

The Hökaberg experiment, where the studies described in the present paper have been made, was started in 1957 with the objective of establishing and maintaining for a period of time different and, if possible, constant levels of nitrogen nutrition in a young stand of spruce. It was felt that the use of foliar analysis as a diagnostic tool in forest research required the establishment of standards for poor, good and excess nutrient supply in field experiments with adult trees, and not only with seedlings under greenhouse or nursery conditions. It was also felt that previous experiments with single applications of nutrients in the field had led to interpretation difficulties in the establishment of standard values for foliar levels because of the different time response for foliar levels and growth. At the same time it was considered of interest to study the behaviour of the forest ecosystem at optimum and supraoptimum levels of nitrogen. As the optimum with respect to nitrogen might be different according to the supply of other elements, a PK treatment was also included in the experiment.

Reports from the earlier stages of the experiment have been published previously (Tamm 1962, 1968). During the first four-year period only a nitrogen effect could be established, but in the following periods 1960—1963 and 1964—1966 a positive interaction was also observed between the nitrogen application and the PK treatment. No negative growth effect of the very high accumulated amounts of added nitrogen were observed at this stage although the highest nitrogen level was increased in 1963 in order to provoke such effects. There was very little difference in stem volume between the various levels of nitrogen and the stem volume in a plot depended not only on the fertilizer regime but also on the number and size of the trees within the plot at the start of the experiment. However, this latter influence could partly be corrected by analyses of covariance.

In the summer of 1969 some trees within the experiments showed signs of drought damage and other trees of insect damage (bark beetles). Much of the spruce forest east of the experiment had been removed shortly before 1969 and apparently the climatic conditions in 1968 and 1969 favoured the bark beetles and made them invade the experimental stand. No clear relation between either insect attacks or drought damage on the one hand and the experimental treatments on the other hand were observed, but it was found necessary to end the experiments because of these irregular damages and also because the plots were so small that the trees had outgrown the plots.

In order to get as much information as possible from the experiment, a biomass sampling was made at the conclusion of the experiment. The data from this biomass sampling have been briefly reported (Tamm 1971, 1973). At the same time samples for measuring annual radial growth were taken, which also have been briefly reported (Tamm 1972).

Soil samplings had already been started in 1967, as described in Tamm 1968, but were intensified at the conclusion of the experiment and the subsequent clear felling. The subject of the present paper, a first account of the final results from the Hökaberg experiment, concerns these soil samplings.

Further papers are planned, one describing the biomass, production, and nutrient accumulation in the stand, and another one describing the stem growth trends within the various treatments.

I. Soil effects (by B. Popović)

The soil investigations of the experimental area Hökaberg were started in 1967 with the intention of finding out to what extent the large amount of fertilizers supplied had changed the soil of the fertilized plots. The total quantity of fertilizers applied in the experiment during the period 1951—1969 is presented in Table 1 (expressed as kg per hectare of the nutrient elements).

Table 1. Fertilizer application in kilogram per hectare of element during the experiment 1957—1969, Hökaberg.

Treat-ment	Plot No	Period 1957—1967					Total (1957—1969)				
		N	P	K	Ca	Mg	N	P	K	Ca	Mg
N0	8 14	—	—	—	—	—	—	—	—	—	—
N0 PK	6 7	—	121	223	224	200	—	151	280	286	200
N1	1 15	525	—	—	138	—	625	—	—	158	—
N1 PK	5 12	525	121	223	382	200	625	151	280	444	200
N2	2 10	1150	—	—	446	—	1550	—	—	526	—
N2 PK	4 13	1150	121	223	690	200	1550	151	280	812	200
N4	3 16	3100	—	—	980	—	3900	—	—	1140	—
N4 PK	9 11	3100	121	223	1224	200	3900	151	280	1424	200

1 Methods

Field sampling procedure. Three different methods of sampling were used:

1) for the soil layer 0—20 cm 20 individual samples were collected in mathematical spacing to form one composite sample for each plot
2) Soil profiles 0—50 cm were sampled and samples for every 10 cm depth were taken separately in each profile and
3) Block samples approximately from the layer 0—20 cm were collected for the pot experiments, with a block of about 10 kg fresh soil from one pit for each pot.

Incubation experiments: The incubation experiments were performed in 300 ml Erlenmayer flasks (in duplicate) with 40 g of fresh soil material after adjustment of the moisture content to 60 per cent WHC (water holding capacity) and at the temperature 20° C, for periods of six and nine weeks. The flasks were supplied with a special plastic bag to decrease water loss (see Popović 1967, Tamm & Pettersson 1969).

Pot experiment: For the study of leaching of nutrient elements by percolation with water a pot experiment was performed with soil from differently fertilized plots. The soil material was put into Mitscherlich-vessels (see photo, p. 8) with a diameter of 20 cm under a glass roof and at outdoor temperature.

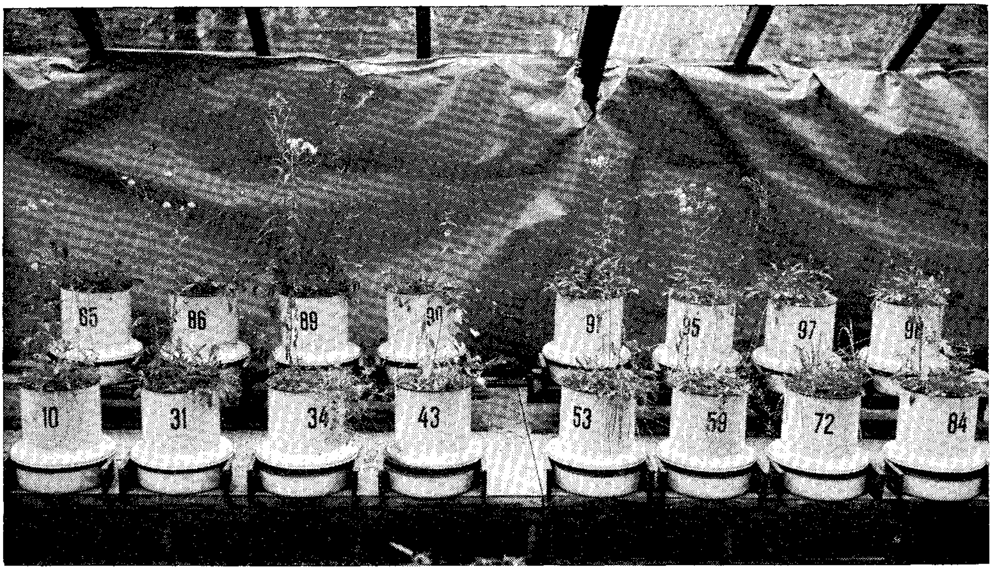
The experiment was started in October 1971 and ended in July 1973. Water corresponding to 25 mm precipitation was added every other week (except in winter), in 1973 only monthly (total 50 mm in 1971, 400 mm in 1972 and 100 mm in 1973). To compensate for the waterloss through evapo-transpiration water was added once weekly during the vegetation period. The percolating water was analysed immediately after sampling for ammonia and nitrate nitrogen, pH, conductivity and base cations (Ca, Mg, K, Na).

Analytical methods: For the NH_4-N and NO_3-N analyses fresh material was used, after having passed through a 2 mm mesh sieve. An extract was prepared for the determination of ammonia and nitrate nitrogen by shaking 40 g of fresh soil in 200 ml of 4 % $KAl(SO_4)_2$ solution. Before shaking the pH-value of the suspension was adjusted to about 6.5. In the first phase of the investigation the ammonia nitrogen was determined by Nessler after microdistillation (Popović 1971), but in the course of the investigation the Nessler reaction was exchanged for a direct determination in the extract of soil by the indophenol reaction (Fawcett & Scott 1960, Yerly 1970, Runge 1971). This reaction (Berthelot) proved to be about 10 times more sensitive than the Nessler reaction and the colour remains stable for 24 hours.

The nitrate nitrogen was determined by phenoldisulphonic acid. The total nitrogen content (Kjeldahl), loss on ignition (at 580° C) and pH-values in water suspension (1 : 3) were determined at each sampling.

The base cation exchange capacity was determined in an extract prepared by shaking 2.5 g of airdry soil in 100 ml 0.5 N NH_4-acetate solution for 20 minutes. The extraction was repeated three or four times, so that the total volume of the solution was 300—400 ml (Andersson 1971).

Base cations (Ca, Mg, Na, K) in the percolating water from the pot experiment were analysed by atomic absorption spectrophotometry and in the same water samples ammonia and nitrate nitrogen were determined.



Scheme of the Hökaberg pot experiment, started in October 1971.

Vessel No	85	86	89	90	91	95	97	98	
Plot No	2		10		3		16		Upper series
Treatment	N2				N4				
Vessel No	8		14		53	59	72	84	
Plot No	10	31	34	43	1		15		Lower series
Treatment	N0				N1				

The stoniness was determined for all the plots of the experimental area by the rod testing method (Viro 1952). The correlation was studied between the rod penetration and the percentage fine soil fraction (<2 mm) for the layer 0—20 cm (Fig. 7). The values obtained were used to calculate the quantity of nitrogen and other elements in kg per hectare.

2 Results

2.1 Nitrogen mobilisation and nitrate formation in the soil of the experiment plots before clear felling

The first incubation experiment was made in the spring of 1967 (see Tamm 1968). In the spring of the following year ten plots were sampled from the experimental field in Hökaberg before that year's fertilization. The results of the incubation experiments with these samples are presented in Table 2 and show that the fertilizing affected nitrogen mobilisation qualitatively rather than quantitatively. After application of higher nitrogen fertilizer rates (treatments N2 and N4) a well-marked nitrification could be observed. With one exception, there was no nitrification in the control soil samples or in the N1 samples. This picture is in agreement with the results from the incubation experiment in 1967 (Tamm 1968).

The total amount of inorganic nitrogen was relatively weakly affected by fertilizer application. This is particularly obvious in Table 3, where the nitrogen is expressed in kg per hectare.

The nitrate nitrogen content in the profiles of treated and untreated plots can be followed from 1969 onward and some results of these observations are presented in Fig. 1. It should be kept in mind that each diagram represents one profile, in contrast to the sampling 0—20 cm described earlier, where each value stands for a composite sample from 20 sampling points. No marked change in the nitrate nitrogen content between control and N1-treated plots could be observed in 1969. On the N2-treated plots the nitrate nitrogen increased moderately with a slight tendency

Table 2. Loss on ignition, pH-values, amounts of Kjeldahl-nitrogen and inorganic nitrogen released in incubation test on top soil (0—20 cm), Hökaberg, sampling April 23, 1968.

Treatment	Plot No	Loss on igni. %	N-Kjel. % d.w.	pH in H_2O	$N_{inorg.}$ ppm/d.w. at start	6-weeks	9-weeks
N0	8	7.21	0.249	5.0	4 (1)*	85 (27)	29 (1)
	14	6.07	0.162	4.9	4 (1)	85 (3)	44 (1)
N1	1	7.18	0.196	4.6	7 (1)	99 (2)	61 (2)
	15	8.15	0.250	5.0	6 (1)	87 (3)	52 (1)
N2	2	8.25	0.256	5.0	13 (2)	105 (56)	55 (49)
	10	7.03	0.230	5.0	15 (3)	92 (52)	80 (71)
N4	3	6.35	0.209	4.8	14 (5)	71 (41)	44 (38)
	16	6.48	0.213	4.9	12 (4)	80 (43)	67 (60)
N2 PK	4	7.45	0.266	4.9	9 (2)	72 (36)	58 (48)
	13	6.22	0.185	4.8	8 (1)	60 (26)	71 (60)

* ( ) = nitrate nitrogen.

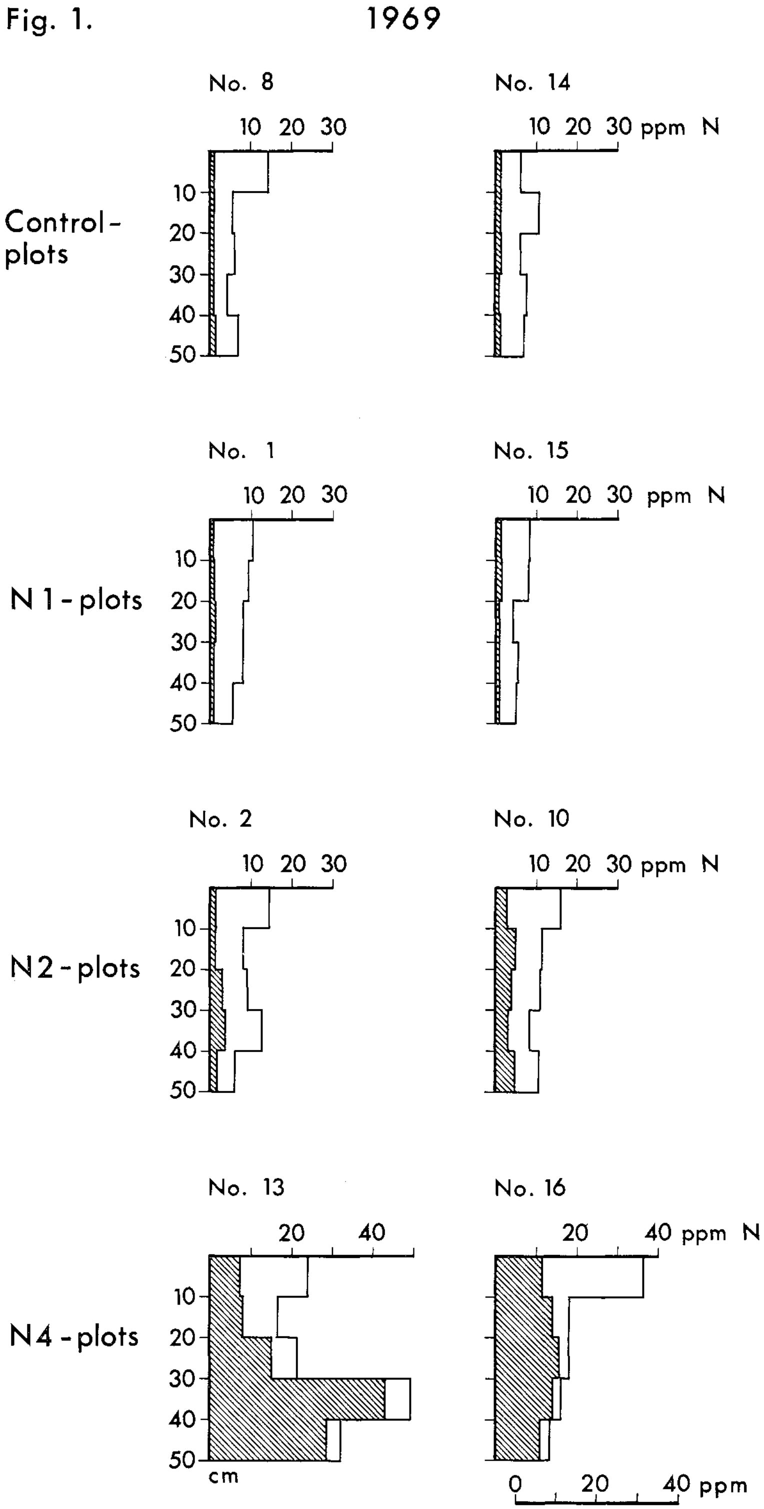


Figure 1 Distribution of nitrate and total inorganic nitrogen in the soil profile to 50 cm depth on differently fertilized plots, the Hökaberg experiment. Sampling in May 1969. Values in ppm/d.w. Hatched part of figure refers to nitrate nitrogen.

Table 3. Amount of Kjeldahl-nitrogen and inorganic nitrogen accumulated in incubation experiment calculated in kilogram per hectare for top soil (0—20 cm), Hökaberg sampling April 23, 1968.

Treatment	Plot No	Weight of < 2 mm fraction 10^3 kg/ha	N-Kjeld. kg/ha	$N_{inorg.}$ kg/ha		
				at start	6-weeks	9-weeks
N0	8	1512	3765	6 (2)	128 (41)	44 (1)
	14	1667	2700	8 (2)	141 (4)	73 (3)
N1	1	1320	2587	9 (1)	131 (2)	80 (2)
	15	1422	3555	8 (1)	124 (4)	74 (2)
N2	2	1398	3579	19 (2)	146 (78)	77 (69)
	10	1467	3374	22 (5)	135 (76)	117 (104)
N4	3	1594	3331	22 (7)	114 (65)	70 (60)
	16	1788	3808	21 (7)	144 (78)	120 (106)
N2 PK	4	1541	4099	14 (3)	111 (56)	89 (74)
	13	1806	3341	14 (2)	109 (47)	128 (108)

Dry weight calculated by formula $y = 764.9 + 40.83x$
y = dry weight in 10^3 kg/ha for soil layer 0—20 cm. (< 2 mm fraction).
x = Si (Stoniness index, Viro, 1952).

to higher content in the deeper layers of the soil profiles. The most intensive nitrogen fertilizing on the N4-treated plots showed a marked increase of nitrate content with the depth of the soil profile. For the same treatment we also note a clear increase of total inorganic nitrogen in the profile (Fig. 1). In the next year, 1970, the same plots were sampled again and in addition the remaining plots. The PK-fertilizers did not markedly change the situation, but a large variation within the same treatment could be observed (see Fig. 2a and 2b). An enrichment of nitrate nitrogen content in the deeper layers of the soil profiles is very obvious on the most heavily fertilized plots (N4 treatment, plot No 3 and No 9).

2.2 Change of pH-values before and after clear felling

The high rates of fertilizer decreased the pH values notably thoughout the soil profile. This is especially clear from the sampling in 1970 (see Table 9). This acidification may be caused by the leaching of the base cations in connection with nitrate formation and transport through the soil profile. Judging from the data for the 1969 and 1970 soil profile investigation (Table 9), the N1 treatment has little or no effect on the pH.

After clear felling in December 1970 one set of plots (treatments PK, N1 PK and N2 PK) was investigated in the summer of 1971. The N2 PK plots were more acid than PK and N1 PK plots (Table 9).

2.3 Ammonium and nitrate nitrogen after clear felling

After clear felling in December 1970 systematical samplings of composite samples for the soil layer 0—20 cm from all plots of the Hökaberg experiment were carried out three times in 1971, twice in 1972 and once in 1973 (the last sampling in April 1973). The ammonia and nitrate nitrogen were analysed and the data are presented in the Table 4. The total amount of inorganic nitrogen (the sum of NH_4- and NO_3-N) showed no systematical variation between differently treated plots at the

Fig. 2a. 1970

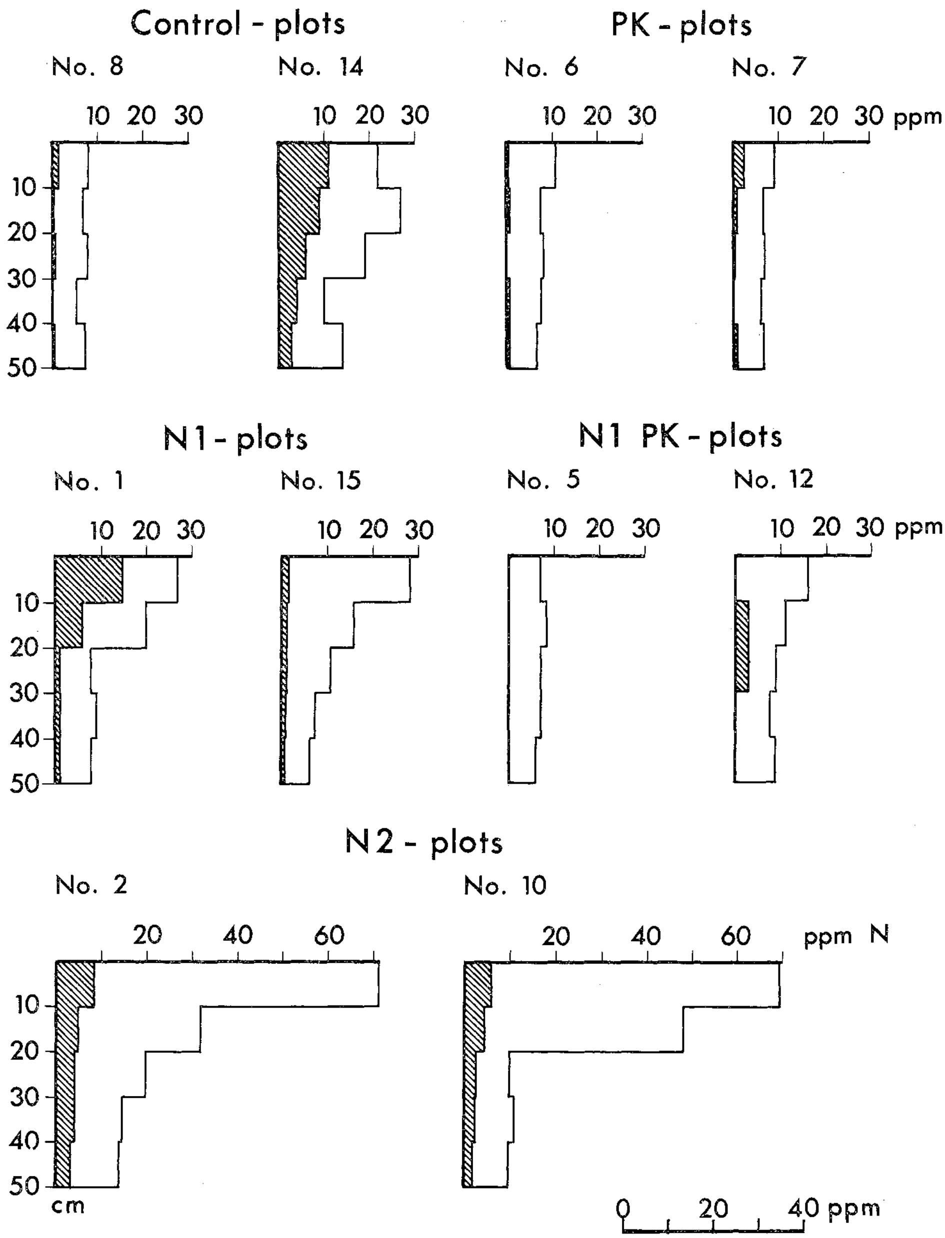


Figure 2a, 2b Distribution of nitrate and total inorganic nitrogen in soil profile to 50 cm depth on differently fertilized plots, the Hökaberg experiment. Sampling May 1970. Values in ppm/d.w. Hatched part of figure refers to nitrate nitrogen.

Fig. 2 b. 1970

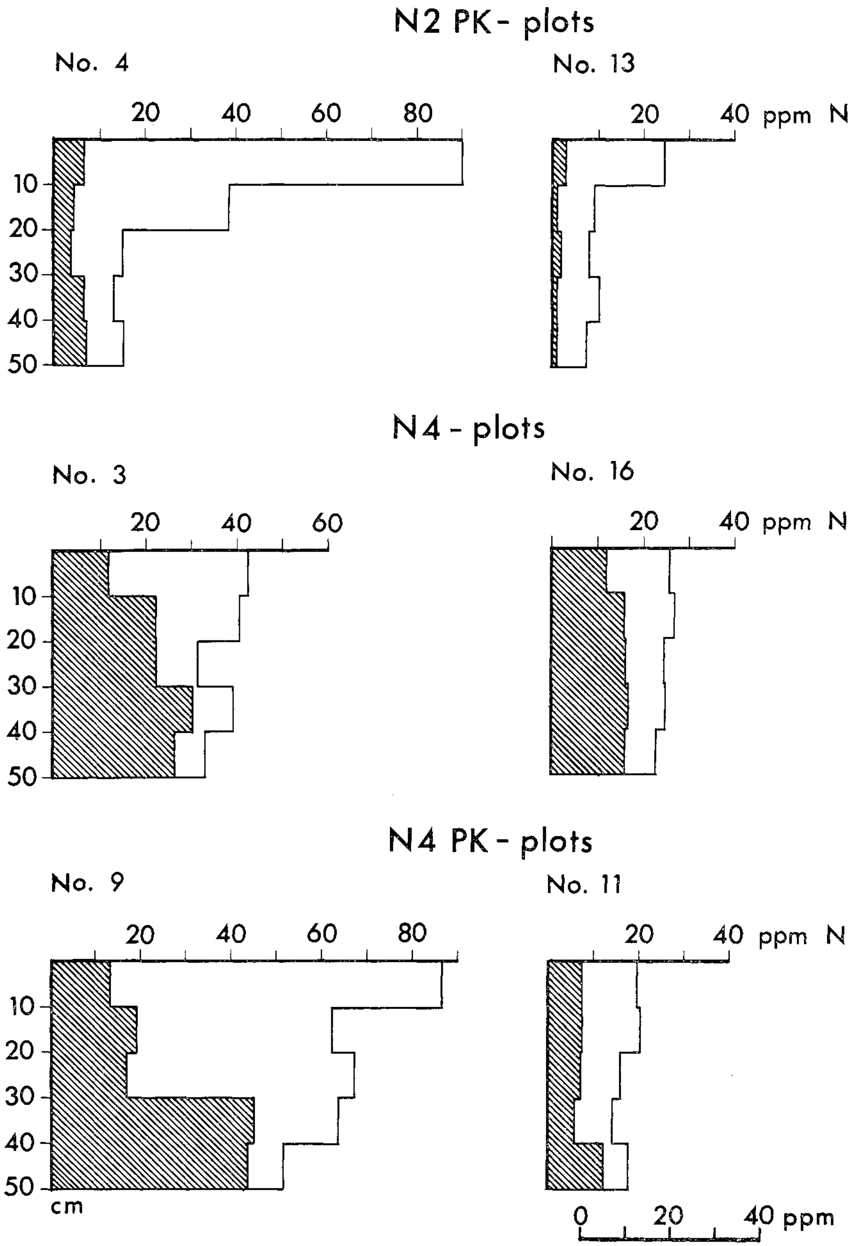

N2 PK- plots
No. 4
No. 13
N4 - plots
No. 3
No. 16
N4 PK - plots
No. 9
No. 11
20
40
60
80
ppm N
10
20
30
40
50
cm
0
40 ppm

Table 3a. The content of Kjeldahl-nitrogen as a percentage of dry weight at different sampling dates. The Hökaberg fertilizer experiment.

Sampling date (year)	Treatment and plot number															
	N0		N0 PK		N1		N1 PK		N2		N2 PK		N4		N4 PK	
	8	14	6	7	1	15	5	12	2	10	4	13	3	16	9	11
1967	0.16	0.16	0.19	0.18	—	—	—	—	0.16	0.17	0.20	0.15	—	—	—	—
1968	0.25	0.16	—	—	0.20	0.25	—	—	0.26	0.23	0.27	0.18	0.21	0.21	—	—
1971																
June	0.15	0.13	0.19	0.18	0.17	0.18	0.19	0.15	0.16	0.16	0.18	0.13	0.17	0.14	0.18	0.15
July	0.16	0.13	0.17	0.15	0.18	0.17	0.19	0.14	0.15	0.17	0.17	0.14	0.15	0.15	0.16	0.15
Sept.	0.17	0.15	0.18	0.16	0.17	0.20	0.19	0.16	0.18	0.18	0.20	0.15	0.20	0.15	0.18	0.16
1972																
June	0.16	0.14	0.17	0.15	0.14	0.19	0.18	0.16	0.16	0.16	0.19	0.14	0.17	0.14	0.17	0.16
Oct.	0.14	0.14	0.18	0.15	0.17	0.19	0.18	0.16	0.18	0.17	0.18	0.14	0.18	0.14	0.17	0.16
1973																
April	0.17	0.14	0.17	0.14	0.16	0.18	0.18	0.16	0.17	0.17	0.18	0.14	0.18	0.13	0.18	0.16
Average	0.17	0.14	0.18	0.17	0.17	0.20	0.18	0.16	0.18	0.18	0.17	0.15	0.18	0.15	0.18	0.16

Fig. 3.

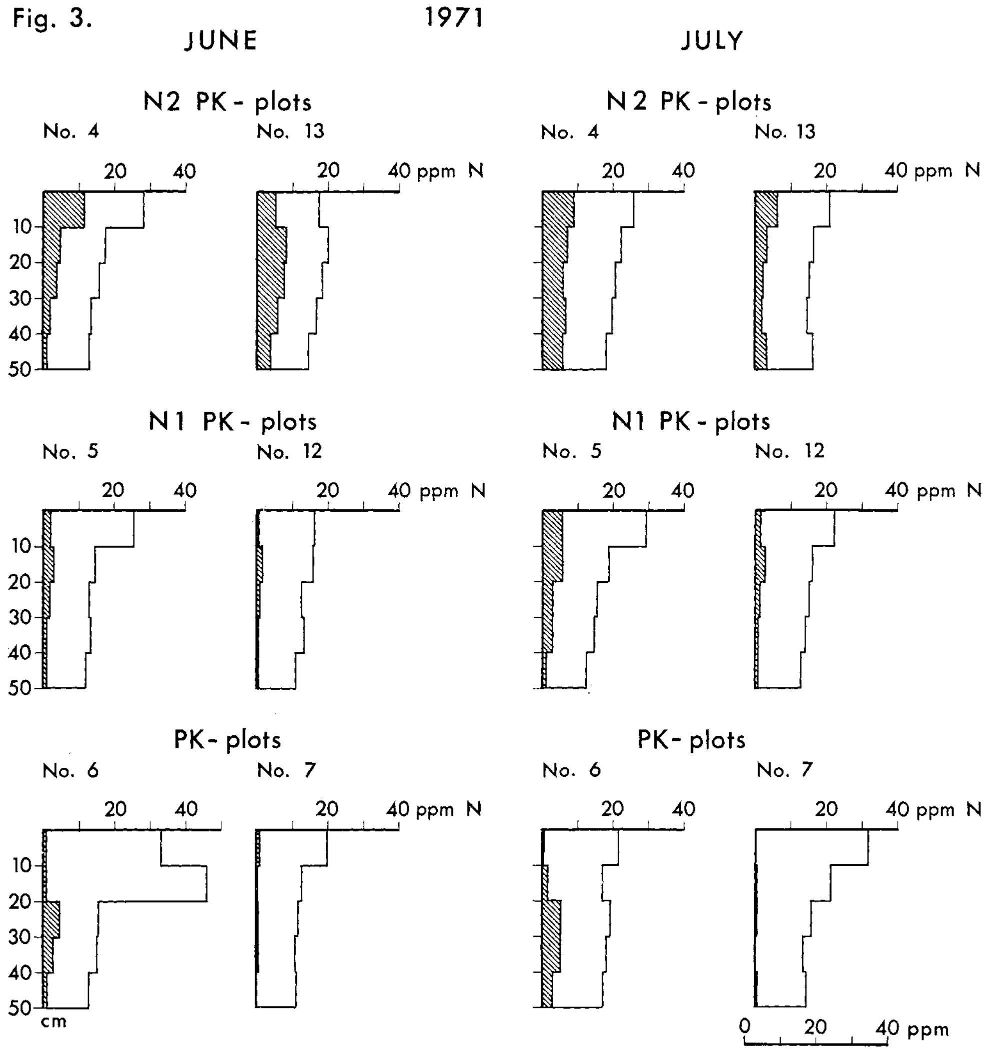


Figure 3 Distribution of nitrate and total inorganic nitrogen in soil profiles of some fertilized plots after clear felling, the Hökaberg experiment. Sampling June and July 1971. Values in ppm/d.w. Hatched part of figures refers to nitrate nitrogen.

Fig. 4 a.

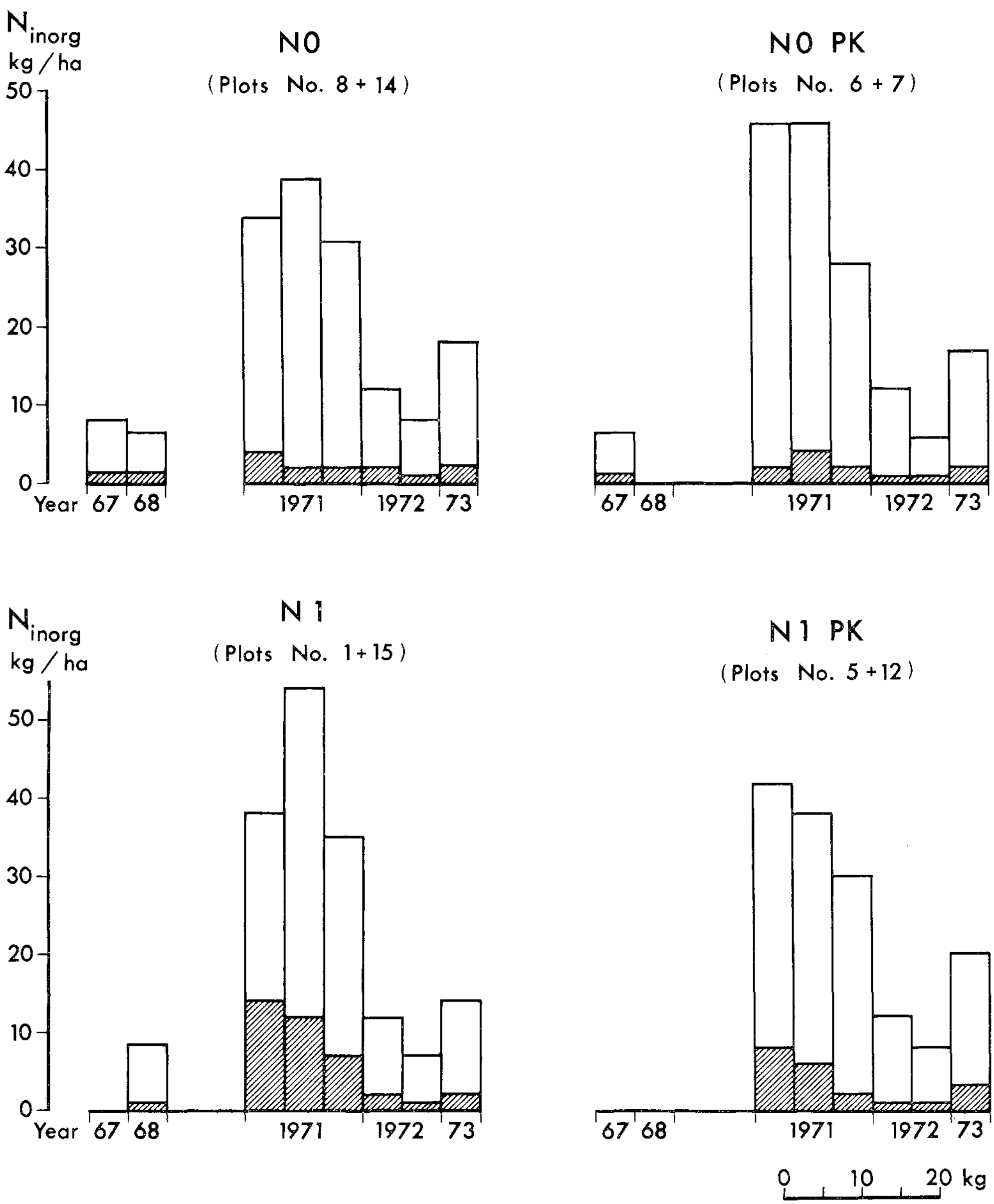


Figure 4a, 4b Amount of nitrate and total inorganic nitrogen in Kilogram per hectare for thetop soil (0—20 cm) of differently fertilized plots after clear felling, the Hökaberg experiment. Sampling 1967, 1968, 1971, 1972 and 1973. Hatched part of column refers to nitrate nitrogen.

Fig. 4 b.

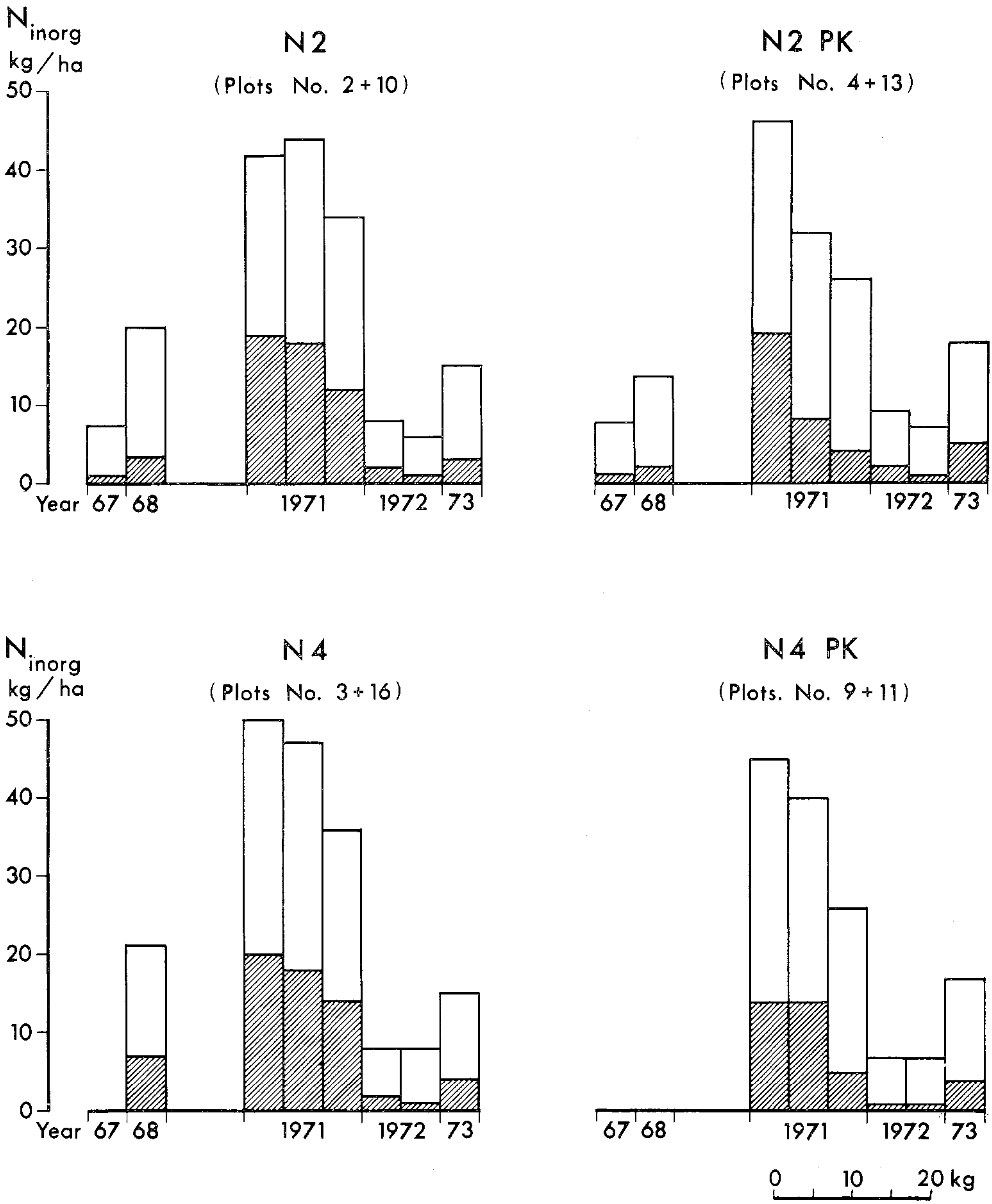

N inorg
kg / ha
N 2
(Plots No. 2 + 10)
N 2 PK
(Plots No. 4 + 13)
N 4
(Plots No. 3 + 16)
N 4 PK
(Plots. No. 9 + 11)
50
40
30
20
10
0
Year 67 68 1971 1972 73
0 10 20 kg

Table 4. Amount of ammonia and nitrate nitrogen in the soil 0—20 cm after clear felling in December 1970, Hökaberg. Sampling; summer 1971, 1972 and spring 1973. Values in ppm N/d.w.

Treatment	1971			1972		1973
	10.6	28.7	28.9	9.6	3.10	27.4
N0	21.2 (2.2)	24.5 (1.5)	19.5 (1.5)	7.3 (0.8)	21.0 (0.4)	11.1 (1.3)
N0 PK	29.2 (1.0)	29.1 (2.2)	17.8 (0.6)	7.7 (0.5)	19.5 (0.5)	11.1 (1.0)
N1	27.4 (10.0)	39.1 (8.6)	25.3 (5.1)	9.1 (1.0)	23.6 (0.6)	10.3 (1.6)
N1 PK	26.4 (5.2)	23.3 (3.8)	18.5 (1.7)	8.0 (0.7)	23.4 (0.7)	12.6 (1.8)
N2	29.9 (13.0)	31.4 (12.2)	23.7 (8.4)	5.9 (1.4)	18.4 (0.7)	10.6 (2.1)
N2 PK	27.1 (11.3)	19.3 (4.2)	15.6 (2.1)	6.4 (1.4)	19.2 (0.5)	10.4 (2.8)
N4	30.1 (11.7)	27.9 (10.7)	21.3 (7.9)	4.9 (1.0)	19.6 (0.7)	9.0 (2.1)
N4 PK	29.6 (8.5)	26.1 (9.0)	17.7 (3.4)	4.7 (0.8)	18.7 (0.7)	10.9 (2.9)

same sampling date, but nitrate nitrogen increased with the rate of fertilizer application. At the beginning of the investigation (the first year after clear felling) little or no grass and herb vegetation was established. This may explain the relatively high content of inorganic nitrogen in the soil. The second year after clear felling a rich vegetation appeared and this resulted in a low content of inorganic nitrogen, particularly of nitrate (sampling on the 10th of June 1972). On the last sampling date (the 27th of April 1973) the content of inorganic nitrogen and nitrate-N increased slightly. This can be explained by the sampling date being so early in the season (before maximum root activity).

During the vegetation period 1971 (the first one after the clear felling) soil samples were collected from profiles down to 50 cm depth on the PK-, N1 PK and N2 PK treated plots on two different dates (June 10, and July 28). The total inorganic nitrogen content (expressed as ppm N_{min} D.W.) varied little between different treatments and sampling dates (see Fig. 3). The nitrate nitrogen content was small in most of the tested profiles. A tendency toward higher values in the N2 PK plots could be observed (Fig. 3).

Table 5. pH-values of soil samples (0—20 cm) from the clear felled area, Hökaberg. Sampling; summer 1971, 1972 and spring 1973.

Treatment	1971			1972		1973
	10.6	28.7	28.9	9.6	3.10	27.4
N0	4.9	5.0	4.8	5.2	4.7	5.2
N0 PK	4.9	5.0	4.8	5.2	4.7	5.1
N1	4.8	4.9	4.8	5.2	4.8	5.2
N1 PK	4.8	5.0	4.8	5.3	4.7	5.2
N2	4.5	4.7	4.6	5.2	4.8	5.0
N2 PK	4.4	4.7	4.6	4.9	4.7	4.9
N4	4.2	4.4	4.4	4.8	4.4	4.6
N4 PK	4.2	4.4	4.4	4.8	4.3	4.7

Table 6. Base cations, hydrogen ions and the cation exchange capacity, in kilogram equivalents (kg e/ha) per hectare. Average of three sampling dates (June, July and September 1971).

Treat-ment	Base cations in kilogram equivalents per hectare					Hydrogen H · kg e/ha	Exchange capacity "T" kg e/ha	Degree of base saturation, per cent S/T:100
	Ca	Mg	Na	K	total "S"			
N0	29.2	4.9	1.2	2.0	37.3	166.2	203.6	18.32
N0 PK	38.9	6.3	1.0	3.0	49.2	171.3	220.7	22.29
N1	35.6	7.0	1.2	4.0	47.0	161.1	208.3	22.95
N1 PK	41.3	7.0	1.1	2.6	52.0	180.9	233.1	22.31
N2	35.6	5.8	1.0	2.0	44.4	165.8	210.1	21.13
N2 PK	22.6	3.9	1.2	2.4	30.0	198.6	228.6	13.12
N4	16.6	5.0	1.1	1.7	24.5	197.1	221.7	11.05
N4 PK	18.0	5.2	1.1	2.0	26.3	193.1	219.3	11.99

Fig. 5

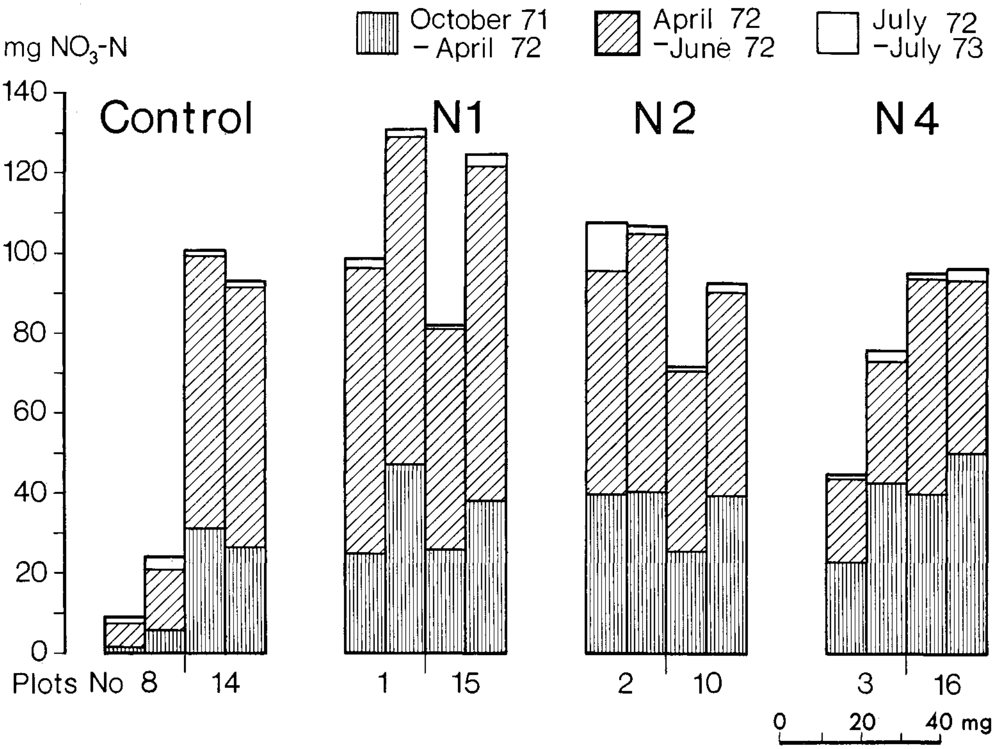


Figure 5 Amount of nitrate nitrogen (mg per pot) in percolate from the pot experiment, Hökaberg. October 1971 to July 1973.

Table 7. Nitrogen balance account for the percolation experiment with soil from the Hökaberg plots in Mitscherlich vessels, October 1971—July 1973.

Treat-ment	Plot No	Kjeld.-N in soil mg/vessel		Nitrate-N in soil mg/vessel		N-uptake by vegetation mg/vessel	Change in N-content of vessel+ vegetation mg/vessel	N accounted for in percolation water
		at start	change during expt.	at start	change			
N0	8	7491	— 87	95	— 81	296	+128	9
	8	6792	0	17	0	371	+371	22
	14	7528	—363	54	— 50	352	— 61	101
	14	7797	—146	90	— 86	275	+ 43	92
Average		7402	—149	64	— 54	324	+120	56
N1	1	8635	+411	36	— 28	292	+675	99
	1	9748	—785	30	— 22	304	—503	131
	15	6633	—119	35	— 27	290	+144	82
	15	9505	—704	73	— 67	317	—454	124
Average		8630	—299	44	— 36	301	—138	109
N2	2	7650	+412	83	— 75	274	+611	108
	2	6626	+530	106	—100	389	+819	107
	10	9124	—285	107	— 93	966	+588	72
	10	9163	+727	101	— 95	366	+998	93
Average		8141	+346	99	— 91	506	+754	95
N4	3	9174	—985	41	— 33	368	—650	45
	3	8019	—790	48	— 42	322	—510	75
	16	6892	— 90	84	— 70	364	+204	95
	16	8690	—250	99	— 95	338	— 7	95
Average		8194	—529	68	— 60	348	—241	78
Average all treatment		8092	—158	69	— 60	368	+150	84
Stand. deviat. per vessel		990	502	29	29	164	507	34

Figures 4a and 4b summarise all available data on the quantity of inorganic nitrogen in the layer 0—20 cm from the representative samplings before and after clear felling. They show the very clear effect of stand removal on the nitrogen mobilisation and the occurrence of nitrification in the soil. It is also evident that this effect is of short duration. Already in the second year after clear felling (when the grass and herb vegetation was well established), the inorganic nitrogen levels returned to the same level as before the clear felling. Data are lacking from some of the plots for the period before 1970, but the results from the profile sampling (Figs. 1 and 2) may be used to fill in the gaps, at least in a qualitative way.

The acidity was measured for the same sampling dates and experimental plots. Some low pH-values can be observed on plots treated with higher fertilizer rates (N2 and N4) in 1971 but later this tendency becomes weaker and in 1972 and 1973 a

Table 7a. Dry weight of vegetation in g per vessel and its nitrogen content (percentage of d.w.) above and below ground. Pot experiment, Hökaberg.

Treatment	Plot No	Dry weight g/vessel			Nitrogen content per cent d.w.	
		above g.	below g.	Sum	above g.	below g.
N0	8	14.0	13.8	27.8	1.11	1.02
	8	13.3	17.1	30.4	1.24	1.20
	14	7.6	20.9	28.5	1.32	0.73
	14	7.6	16.1	23.7	1.22	1.14
N1	1	7.5	16.1	23.6	1.40	1.16
	1	9.6	13.9	23.5	1.21	1.35
	15	9.6	18.2	27.8	1.18	0.97
	15	7.9	12.8	20.7	1.74	1.40
N2	2	6.6	11.1	17.7	1.76	1.42
	2	12.6	21.3	33.9	0.95	1.26
	10	8.9	44.3	53.2	1.62	1.86
	10	9.7	16.3	26.0	1.62	1.28
N4	3	8.2	21.3	29.5	1.20	1.26
	3	9.1	15.0	24.1	1.34	1.48
	16	8.2	19.7	27.9	1.12	1.38
	16	6.5	19.8	26.3	1.06	1.36

lower pH-value was observed only on the plot treated with N4 (see Table 5).

Since it had become evident that higher rates of fertilizer decreased pH, it was of interest to see whether loss of base cations could be observed. One series of soil samples for the layer 0—20 cm, collected on three dates during the summer 1971, was analysed for base cations and hydrogen. The results are presented in Table 6, calculated in kilogram equivalents per hectare. There is a clear tendency toward lower base saturation after application of high rates of fertilizer (N4).

2.4 Losses of nitrogen by leaching in pot experiments

In the first autumn after clear felling (in September 1971) soil samples were collected from eight plots (treatments N0, N1, N2, N4) to start a pot experiment with irrigation and collection of the percolating water (detail see chapter 1).

The percolating water, which was analysed immediately after sampling, showed a very low concentration of ammonia (traces), and the nitrate nitrogen varied a great deal. High nitrate concentrations could be observed in the first phase (October 1971) of the experiment and in the spring of the following year (1972) before the grass and herb vegetation had been established. Later the concentration decreased rapidly and stayed low until the end of the experiment (Fig. 5). The difference between treated and control plots is not very evident, but we have to take into account the great variation between individual vessels and plots (No 8 and No 14 in particular, see Fig. 5). This is largely a consequence of the sampling method, relatively undisturbed monoliths, one for each vessel.

An attempt was made to make a balance-account for this experiment and some data are presented in Table 7. The great variation of Kjeldahl-nitrogen quantity per vessel should be noted. The high nitrate content at the beginning of the experiment does not correspond to a high nitrate nitrogen content in the percolate in

Table 8. The conductivity and pH-values of the percolating water (average 1972—1973. Base cations and nitrate anions in milligram equivalent per litre in the percolating water (accumulated for all the percolates from April 1972 till July 1973). The Hökaberg pot experiment.

Treatment	Plots No	Conductivity mho. 10^{-6} 20° C	pH	mg eq/litre					
				Ca	Mg	Na	K	Sum	NO_3
N0	8	46	6.2	2.24	0.64	0.70	0.23	3.81	0.58
	8	65	6.2	2.08	0.72	0.56	0.83	4.19	1.41
	14	105	5.9	4.48	1.98	0.74	1.03	8.23	6.95
	14	107	5.8	5.12	1.40	0.68	0.83	8.03	5.81
N1	1	109	5.6	6.26	2.10	0.77	0.23	9.36	6.73
	1	121	5.6	6.44	2.92	0.92	0.28	10.56	8.14
	15	91	5.7	4.34	2.62	0.74	0.35	8.05	5.47
	15	123	5.5	6.18	2.18	0.61	1.17	10.16	7.99
N2	2	106	5.5	4.18	2.26	0.53	0.53	7.28	6.01
	2	106	5.5	5.58	2.20	0.64	0.36	8.78	5.78
	10	83	5.3	5.26	1.80	0.47	0.51	8.04	4.81
	10	90	5.4	5.70	1.88	0.51	0.54	8.63	5.67
N4	3	66	5.3	3.22	2.82	0.45	0.23	6.72	2.93
	3	63	5.1	3.00	1.78	0.53	0.22	5.53	4.61
	16	102	4.9	4.30	2.58	0.58	0.20	7.66	4.86
	16	89	5.0	3.66	2.34	0.54	0.21	6.75	4.39

all cases (for example plot No 8), but low nitrate contents in the percolating water were noticeable in all the vessels at the end of the experiment (see Fig. 5).

The change in nitrogen content of vessel+vegetation is not statistically significant and therefore no conclusion can be made drawn regarding on possible nitrogen fixation and denitrification.

2.5 Losses of cations by leaching in pot experiments

The loss of base cations by percolation (Table 8) increases somewhat in the vessels with soil from treated plots, but does not directly correspond to the rate of fertilizing. Treatment N4 showed lower values in some cases than the untreated soil. Here the relatively large variation between two control plots must be pointed out. This limits the value of this comparison.

The pH-values of the percolating water decrease with increase of the rate of fertilizer, but the differences are moderate (Table 8). The relative conductivity (see also Table 8) showed an irregular variation so it is not easy to get a clear picture of this. The calculation of base cations and nitrate anions in the form of milligram equivalent, also given in Table 8, showed that most of the negative nitrate ions are counterbalanced by Ca ions, but magnesium ions are also significant.

3 Discussion

One can not expect the root uptake to be sufficient to take care of the large fertilizer quantities used on this site (up to 3900 kg N/ha during 13 years, see Table 1). Only a limited part of this quantity could be accounted for in the stand (Tamm 1971). An important part of the nitrogen applied has disappeared from the system in different ways (volatilisation, denitrification or leaching).

The addition of a great quantity of nitrogen fertilizers can influence the microorganism populations in the soil. This could be observed in the results of the incubation experiment presented in Table 2 where an application of higher rates of nitrogen fertilizer resulted in an intensive nitrification in this acid forest soil, which was not found in the control or at a low rate of nitrogen fertilizer (N1 level). The nitrifying soil samples also showed a higher acidity (lower pH-values) than the non-nitrifying soil samples. It is known that the nitrifying bacteria prefer a more neutral reaction or the alcaline side of the neutral point (Nömmik 1968). There are other microorganisms, e.g. some fungi, which may nitrify ammonia, especially if this is accumulated in higher quantities. It has been observed earlier that nitrogen fertilizing also increased the soil nitrification even at lower pH-values than in this case. Some nitrification even occurred on control plots (Popović 1967). Liming has often been used as a melioration treatment and affects the soil nitrification positively, especially in soils with a more favourable nitrogen supply, judging from the results of field and laboratory experiments (Popović 1973, Tamm & Pettersson 1969).

The occurrence of an intensive nitrification on the treated plots seems to be of a long duration, and could be observed in this case also after the end of the fertilizing period and the subsequent clear felling (cf. Fig. 4a och 4b).

In contrast to the quantity of the nitrate nitrogen the total inorganic nitrogen (the sum of ammonia and nitrate nitrogen) did not change markedly during the fertilizing, judging from the results of the nitrogen analysis (Table 2 and 4).

The quantity of Kjeldahl nitrogen in the soil of differently fertilized plots changed very slightly with the large quantity of nitrogen applied (see Table 3 and 3a, Fig. 6) and the variation between the various treatments remained at 10—15 per cent. All this is in contrast with the nitrogen content in the needles from treated plots, which increased markedly with a higher nitrogen level (especially N4 treatment), as did also litter nitrogen (see Tamm 1971).

After the clear felling, at least in the first phase as long as the grass vegetation had not been established, the risk for loss of nitrogen from the system was considerably increased by heavy fertilization, judging from the results of this investigation (Fig. 3). A tendency toward higher nitrate content at a higher rate of fertilizer was observed.

A very illustrative picture of the trends of nitrate and total inorganic nitrogen content is given in the Figs. 4a and 4b, which relate to nitrogen concentration in the layer 0—20 cm. First the great difference between the nitrogen content in the soil under the spruce stand and the first year after clear felling must be noted. After one year the concentration of inorganic nitrogen decreased to the same level as before the clear felling. The establishment of grass vegetation a short time after clear felling in the year 1972 explained this situation, because the plant root uptake

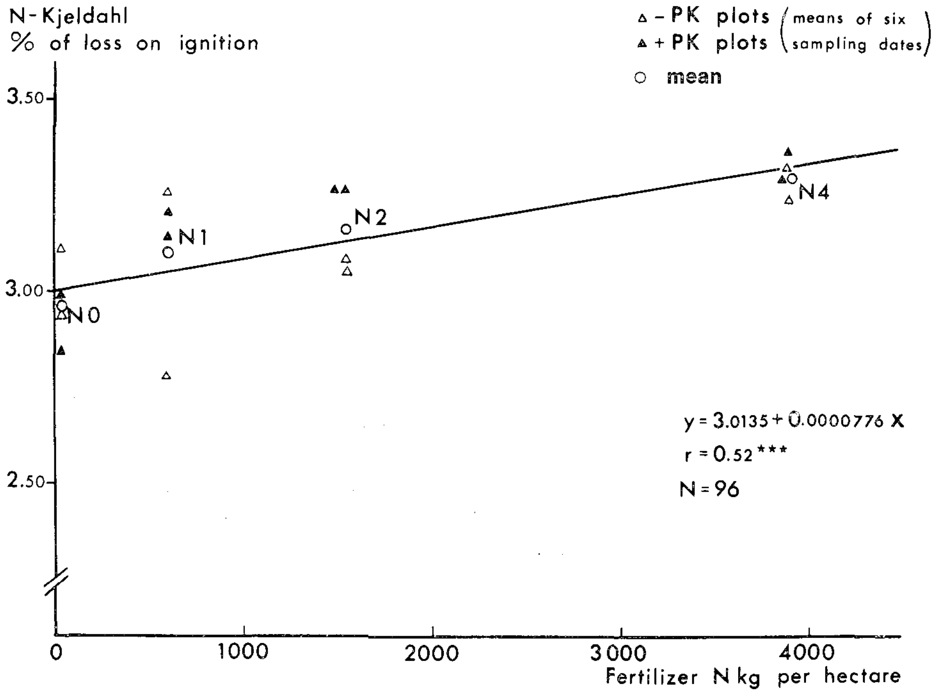


Figure 6 Relation between Kjeldahl-nitrogen as a percentage of loss on ignition and supplied fertilizer nitrogen during the experiment. Soil sampling (layer 0—20 cm) in June, July and September 1971, June and October 1972, April 1973.

takes care of much of the inorganic nitrogen content in the soil.

It should be observed from the results of the soil investigation (soil profile) in 1969 and 1970 that the nitrate concentration increased in the deeper soil layers on fertilized plots especially with a higher rate of N-fertilizer (N2- and N4-treatment). Some leaching of nitrate nitrogen could be expected. As is to observe from results of analysis of the percolating water (Fig. 5) of the pot experiment (see text p. 21), a rather high concentration of nitrate nitrogen is found in the first phase of the pot experiment (autumn 1971—spring 1972 until June). Besides the absence of vegetation and uptake by roots in this phase of the experiment, it is possible that the disturbance of the soil leads to an increase of microbiological activity, including mineralisation and nitrification in the soil (Vömel 1970).

Because of the great variation between the two control plots it is very difficult to estimate the influence of previous fertilizing on the nitrate content in the percolating water, but a slight tendency toward decrease of the nitrate concentration in the percolating water with higher rate of fertilization could be observed. If this is so it may be explained by the mobilisation of native soil nitrogen. Vömel (1970) showed by similar lysimeter experiments and the use of labelling with the ^{15}N isotope, that the nitrogen leached into the subsoil layers is derived mainly from "native" soil nitrogen, not from added fertilizer nitrogen. Mineralisation of residual fertilizer nitrogen in the soil should be rather low (Vömel 1970). It is not possible to get an exact explanation of this phenomenon in our experiment.

When the grass and herb vegetation had grown up (mainly from seeds present in the soil) the nitrate content in the percolating water decreased (as did the contents of other nutrient elements, see Fig.

Table 9. pH-values in the soil profile (0—50 cm depth) within differently fertilized plots, the Hökaberg experiment. Samplings 1969, 1970 and 1971.

Soil layer	N0		N0 PK		N1		N1 PK		N2		N2 PK		N4		N4 PK	
	8	14	6	7	1	15	5	12	2	10	4	13	3	16	9	11
								1969 (May)								
0—10 cm	4.6	4.9			4.8	4.9			4.4	4.1			4.6	4.5		
11—20 cm	4.9	4.7			4.9	5.0			4.7	5.0			4.2	4.3		
21—30 cm	5.1	4.8			5.0	5.0			5.1	5.6			4.3	4.4		
31—40 cm	5.3	4.8			5.1	5.3			5.0	5.3			4.4	4.4		
41—50 cm	5.4	5.1			5.5	5.3			5.3	5.6			4.6	4.4		
								1970 (May)								
0—10 cm	4.9	4.6	4.6	4.6	4.4	4.8	4.2	4.8	4.4	4.7	5.3	4.3	4.2	4.3	4.1	4.0
11—20 cm	5.0	5.0	4.7	5.0	4.7	5.0	4.7	4.8	5.2	4.5	5.0	4.8	4.0	4.1	4.5	4.0
21—30 cm	4.8	4.9	4.6	5.0	4.3	4.7	4.5	4.6	5.1	5.1	4.8	4.8	4.2	4.4	4.7	4.3
31—40 cm	5.1	4.9	4.9	5.0	4.9	4.9	4.3	5.1	5.3	4.9	5.0	4.9	4.0	4.1	4.7	4.7
41—50 cm	5.0	4.8	4.1	5.1	4.9	4.9	5.3	5.3	4.7	5.0	4.9	4.7	4.6	4.1	4.6	4.7
								1971 (July)								
0—10 cm			5.1	5.0			4.9	5.2			4.6	4.5				
11—20 cm			5.2	5.1			5.1	5.1			4.6	4.5				
21—30 cm			5.3	5.2			5.3	5.2			4.9	4.7				
31—40 cm			5.2	5.2			5.3	5.3			5.1	4.8				
41—50 cm			5.3	5.2			5.4	5.2			5.3	4.9				

5). The same development was observed in the field, where the soil sampling was carried out during the three years (1971—1973). If the nitrate nitrogen quantity leached by percolating water is expressed as kg N per hectare, the amount varied between 20 and 40 kg N per hectare except in the control plot No 8 with very low values (2.9 resp. 7.2 kg N per hectare) and one pot from the N4 treatment (14.4 kg N per hectare). Wiklander (1971) found values of up to 24 kg nitrate nitrogen per hectare and year (at the depth of 0.7 and 1.0 m) in the drainage water from fertilized arable soil in Sweden under field conditions. In our case nothing is known of the possibility of nitrate retention in the deeper soil layers (under 20 cm). Most of the nitrogen (up to 90 per cent) was leached in the first phase of the pot experiment. Considering that the source of nitrogen was of both forms (ammonia and nitrate) in the applied fertilizer, the leaching of nitrate nitrogen in a relatively short time after application is to be expected. This was shown by Overrein (1971) in a long-term experiment in Norway. In a small lysimeter experiment in Germany quantities of nitrogen per hectare corresponding to 18—47 kg were leached through a 26 cm soil layer (Vömel 1971).

Acidification of the soil as a result of nitrogen fertilization could be observed during this fertilizing experiment (Table 9) and persisted for some time after the clear felling (for the three years the soil was investigated). This was also observed in the pot experiment, where the pH-values of the percolating water showed the same tendency.

The increased concentration of nitrate nitrogen in deeper layers of the treated plots during the fertilizer experiment and the intensive nitrification in the top soil for the period after the clear felling are apparently consequences of the applied fertilizer treatment. The nitrification followed by downward transportation of nitrate ions and accompanying cations also lead to soil acidification and lowered base saturation.

The observed effects were most marked at the high levels of nitrogen (N2 and N4), where the total amounts given far exceed practical forest fertilization. At the level N1 (corresponding to 3—4 repeated fertilizations with the rates used at present in Sweden) the effects were relatively small.

Even at the high N levels, the ecosystem soon regained its ability to retain inorganic nitrogen, which had been temporarily decreased by the clear felling.

4 Summary

A field experiment aiming at optimal fertilizer supply to a young spruce plantation on old arable land was used to study the soil changes, especially nitrogen mineralisation, nitrification and leaching.

As a result of very intensive nitrogen fertilizer application (ammonium nitrate) nitrification occurred in the soil. This was not recorded on a large scale on the control plots before clear felling.

Considerable quantities of nitrate nitrogen were observed in the deeper soil layers during the fertilizer experiment in the plots treated with high rates of fertilizer.

The soil reaction indicated an acidification as a result of the fertilizer treatment, particularly at higher doses. The pH depression remained for some time after the end of the fertilizer experiment and subsequent clear felling, at least during the investigation period (1971—1973). The acid soil reaction did not prevent nitrification (which lowered the pH further).

The nitrogen mineralisation (ammonia+ nitrate) in the soil did not change markedly as a result of fertilizer application. Very high rates of nitrogen fertilizer application caused a marked reduction of base saturation in the soil.

In a pot experiment, performed with soil from the field experiment, the greatest part of nitrate nitrogen was leached by percolation in the first phase, as long as grass and herb vegetation was not established. When the vegetation grew up the nitrate concentration in the percolating water decreased rapidly. The exchangeable base cations followed the nitrate in a similar way.

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6 Sammanfattning

Intensiv kvävegödsling som stressfaktor i ett granskogsekosystem

I. Markreaktioner

För undersökning av markförändringar, särskilt med avseende på kvävemineralisering, nitrifikation och utlakning har utnyttjats ett fältförsök med intensiv kvävetillförsel, ett s.k. optimeringsförsök i en ung granplantering anlagd på tidigare åkermark. De tillförda gödselmängderna varierade mellan 625 och 3 900 kg kväve per hektar, alltså långt över vad som f.n. används vid praktisk skogsgödsling.

Som resultat av intensiv kvävegödsling (i form av ammonium-nitrat) kunde nitrifikation observeras i marken, men inte på kontrollytorna före kalhuggningen, december 1970. Större mängder av nitratkväve har under försökstiden konstaterats i djupare markskikt på de ytor, som gödslades med högre kvävegivor, vilket tyder på en pågående utlakning av nitrat.

Markreaktionen visar en försurningseffekt av gödslingen, särskilt vid högre givor. Denna försurning (omkring en halv pH-enhet) stannar kvar också en tid efter gödslingens slut och följande kalhuggning, åtminstone för undersökningsperioden (1971—1973). Den sura markreaktionen förhindrade inte nitrifikation, vilken är en orsak, sannolikt den viktigaste, till pH-sänkningen.

Kvävegödsling har inte kvantitativt påverkat kvävemineraliseringen, men kvalitativt har en väsentlig förändring åstadkommits genom att kvävegödsling har gett nitrifikation. Samtidigt har mycket stark kvävegödsling orsakat en minskning av markens basmättnad.

Ett kärlförsök har gjorts med jord från olika behandlingar inom fältförsöket, insamlad efter kalhuggningen för att studera hur bevattning och perkolering påverkade bl.a. nitratutlakningen. Den största mängden nitrat utlakades under försökets första fas, innan gräs- och örtvegetation hade etablerat sig i kärlen. Sedan hyggesvegetationen blivit riklig minskade nitratkoncentrationen i perkoleringsvattnet kraftigt i samtliga kärl. Det utlakade nitratet åtföljdes av katjoner ur markens förråd av utbytbara baskationer (Ca, Mg, K, Na).

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8 Appendix
Soil physical properties

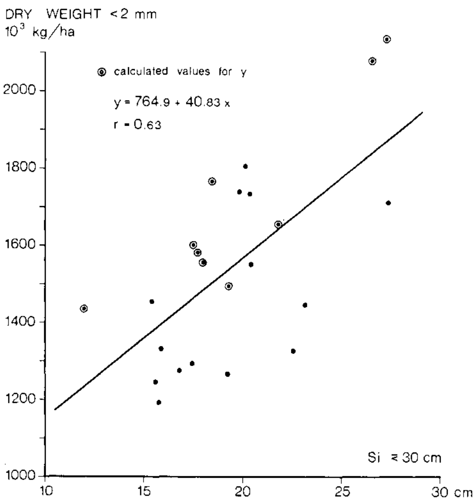

Figure 7 The fine soil fraction (<2 mm) related to stoniness index (determined according to Viro, 1952).
Note. The "calculated values" for the soil fraction <2 mm were calculated through regression analysis from the weight of the fraction <6 mm, since the weight of the finer subfractions were lost by accident.

Table 10. The analytical data for the soil (top soil 0—20 cm and two profiles) of some plots from the Hökaberg fertilizer experiment. Sampling April 23, 1968.

Treatment	Plot No	Soil layer cm	Fraction of sample (soil under 2 mm)					D 75 %	Texture index log D 75 %	Base mineral index
			2—0.6	0.6—0.2	0.2—0.02	0.02—0.002	0.002			
N0	8	0—20	10	33	38	11	8	40	1.6	10.5
	14	0—20	15	38	29	10	8	48	1.7	8.6
N1	1	0—20	18	33	27	14	8	40	1.6	10.2
	15	0—20	15	36	27	14	8	42	1.6	10.8
N2	2	0—20	16	30	32	14	8	42	1.6	11.7
	10	0—20	18	30	32	12	8	38	1.6	11.7
N2 PK	4	0—20	10	32	37	13	8	34	1.5	12.4
	13	0—20	11	40	32	9	8	48	1.7	—
N4	3	0—20	9	34	36	12	9	30	1.5	11.5
	16	0—20	15	38	29	10	8	64	1.8	8.5
N0	14	0—10	16	39	26	9	10	56	1.8	8.1
		11—20	18	39	25	10	8	56	1.8	7.0
		21—30	22	44	18	8	8	85	1.9	9.0
		31—50	22	44	15	12	7	48	1.7	9.4
N4	16	0—10	14	37	32	10	7	56	1.8	9.5
		11—20	18	35	30	10	7	60	1.8	7.9
		21—30	19	40	27	8	6	75	1.9	7.9
		31—50	19	48	23	4	6	110	2.0	10.7