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An attempt to assess the optimum nitrogen level in Norway spruce under field conditions

Ett försök att fastställa det optimala kvävetillståndet i gran under fältförhållanden

by

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ABSTRACT

Two long-term field experiments are described, aiming at an assessment of the optimum internal level of nitrogen in spruce needles. The experiments were laid out in 1957 and 1958 in two young spruce plantations, one on an old field and one on forest land. Three or four nitrogen regimes, respectively, were maintained by annual application of ammonium nitrate fertiliser. Half the plots received also PK fertiliser. Both growth and nutrient levels in the stand were followed by measurements at close intervals. The nutrient studies concerned the percentages of nitrogen, phosphorus, potassium, calcium and magnesium in autumn samples of exposed current needles.

The nitrogen application increased growth in both experiments. At first both height and diameter growth were affected. Later, the main growth increase was in diameter and volume growth. Also PK application increased volume yield. Possible secondary effects of the fertiliser applications and the relationships between internal nutrient levels and growth are discussed in some detail. The value of long-term optimum nutrition experiments in the future study of forest nutrition is pointed out.

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1. Introduction

The term optimum nutrient supply is widely used in plant physiology and it is often found that the optimum with respect to one or another nutrient changes with the supply of other nutrients or with other environmental factors. Some of the reasons for this are obvious. Nutrient supply is usually measured as concentration in the substrate or amounts of nutrients supplied to the various treatments. An interaction is then possible both between the various nutrients themselves and between nutrients and other factors. In the first place this interaction may affect the concentration of available nutrients in the substrate and the uptake by the roots.

The introduction of foliar analysis as a method for assessing the internal nutrient levels of a plant offers a means of relating plant growth to the internal nutrient level instead of to the nutrient level in the substrate. Growth response curves based upon foliar levels have been presented for forest trees by several workers, beginning with Mitchell and Chandler in 1939. The values obtained can usually be fitted to a curve of the Mitscherlich-Baule type or to a simple parabola (Leyton 1958). Since the optimum type curves obtained in this way, being based upon internal nutrient levels, are free from some of the disturbing interactions described above, it would be interesting to investigate whether the optimum concentration levels found thus represent some characteristic property of the plant species in question, or whether they are subject to variation with changing environmental conditions. In their early work, Mitchell and Chandler seem to have taken it for granted that the optimum curves obtained in their experiments were characteristic for the various species. Leyton (1958), discussing in detail some of these problems, points out that the present evidence supports the concept of relatively constant optimum concentrations as characteristic for tree species, but hesitates to accept this conclusion unreservedly. However, most investigators working with foliar analysis need some kind of optimum concentration for the interpretation of their foliar values. It is therefore a rather unsatisfactory state of affairs that we do not know whether the optimum values commonly used have any deeper physiological basis, or whether they are just empirical pilot values valid only under the experimental conditions used.

The present author has earlier pointed out the difficulty of interpreting curves for growth response in relation to foliar concentrations obtained from field experiments (Tamm 1956, cf. also 1964 b, c). The main reason for this is that in a field experiment of the ordinary type, with one or a few applications of nutrients, the responses obtained for growth and foliar levels are not simultaneous. By choosing different pairs of points from the time curves for growth and for nutrient concentrations almost any type of relationship may be obtained.

The situation is not much better in solution culture experiments or pot experiments of the traditional type, as has been pointed out by INGESTAD (1962). In these experiments growth is usually determined as dry weight at harvest and the nutrient levels are measured at the same time, but the yield is the integrated result of growth over a long period when the nutrient concentrations in the leaves have, as a rule, been variable. In his latest work INGESTAD (1967) has shown a way out of this difficulty, by adapting the nutrient concentration in the solution to the uptake of the plant. In this way he has been able to maintain a constant and presumably optimum concentration of nutrients in the plant over an extended period of time. So far, however, his method can only be said to be strictly valid for plants growing in a controlled substrate and with a relatively constant growth rate during the period investigated.

However, it is quite obvious that an approach fundamentally similar to that used by INGESTAD (1967) must also be used in field experiments. Instead of working with a strongly variable nutrient concentration within the plants, we must maintain a more or less constant level in the foliage over a period of time, long enough to be able to measure a reliable growth response. The experiments to be described in this paper were planned in 1956 with this purpose in mind.

2. Description of sites and treatments

2.1. Experimental sites

It was thought that a suitable place for these experiments would be a young well-established spruce plantation suffering from growth check due to deficiency in nitrogen. A site of this type was available at Remningstorp Experimental Forest, province of Västergötland, South Sweden. When this site was first visited in 1954, a spruce (Picea abies Karst.) plantation (1947) on an old arable field was suffering from a pronounced deficiency in nitrogen, judging by the colour of the needles and by foliar analyses. However, before the experiment could be laid out, in early 1957, the young spruce had to a large extent recovered from visible nitrogen deficiency.

In the spring of 1957, 16 plots were laid out within the spruce plantation. A somewhat irregular topography and edge effects of other vegetation along the margins of the former field limited the size of the experiment. The 16 plots were considered relatively uniform with respect to the condition of the

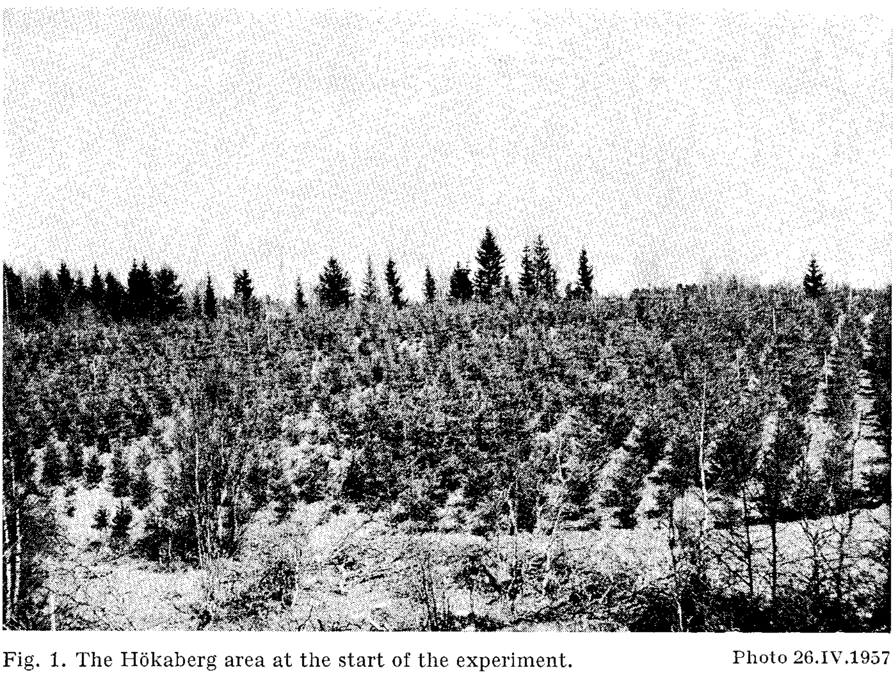

Fig. 1. The Hökaberg area at the start of the experiment. Photo 26.IV.1957

HÖKABERG

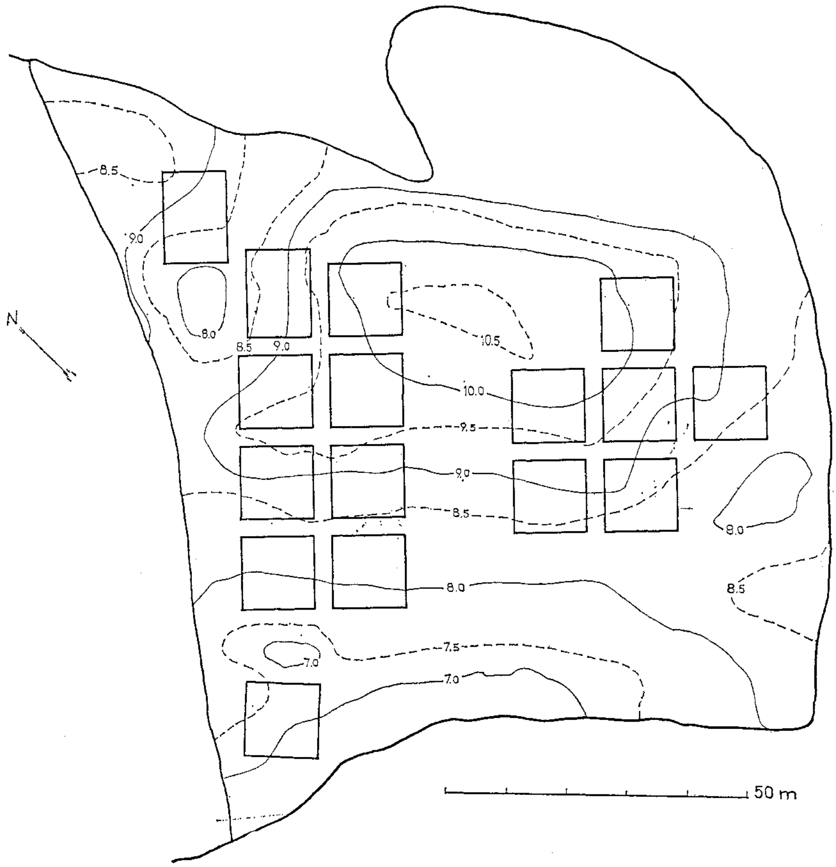

Fig. 2. Map of the Hökaberg experiment, with contour lines for every half metre.

spruce. However, later development has revealed minor heterogeneities. A few frost hollows in the field were avoided, as were also the steeper slopes. No detailed soil investigation was made at the start of the experiment, as the digging of pits might have disturbed the conditions within the plots. Samples of top soil from certain plots were studied later, as will be described below. A more detailed soil investigation is planned for the final revision. A soil profile from the control plot No. 8 is briefly described below.

0 —20 cm	A_p	Grey-brown loamy sand
20—30 cm	A/B	Transitional horizon
30—55 cm	B	Slightly loamy sand, moderately rust-coloured but gradually lighter downwards

Fig. 3. The Petersburg area. Photo 14.V.1959

55—65 cm C Slightly loamy yellowish sandy till.
(and farther down)

Stones occur in all horizons, as is usual in till. Roots occurred in the whole profile, most frequently in the A_p.

The area of Remningstorp is situated on the border between the Archaean rock (mainly gneiss) and a local occurrence of Cambrian, Ordovician and Silurian deposits. There is thus some admixture of Cambrian sandstones and shales and Ordovician and Silurian limestones and shales in the soil material although most of the material originates from the Archaean bedrock. The quarternary geology of this area is also rather complicated. At the end of the last glaciation some of the more important events were the warm "Alleröd" period and the following cold period ("younger Dryas"), when the ice stopped its retreat for a period of about 800 years and pushed forward over areas earlier released. This happened about 10,000 years ago in this area, resulting in the deposition of large amounts of soil material, both glacial till and glacifluvial material. Some of the deposits in the area have been identified with the great Fennoscandian terminal moraines, although they are considerably smaller than their equivalents in other areas, particularly the Finnish Salpausselkä ridges. The Remningstorp forest (and even more the area just south of it) is characterised by irregular ridges and depressions, and of a

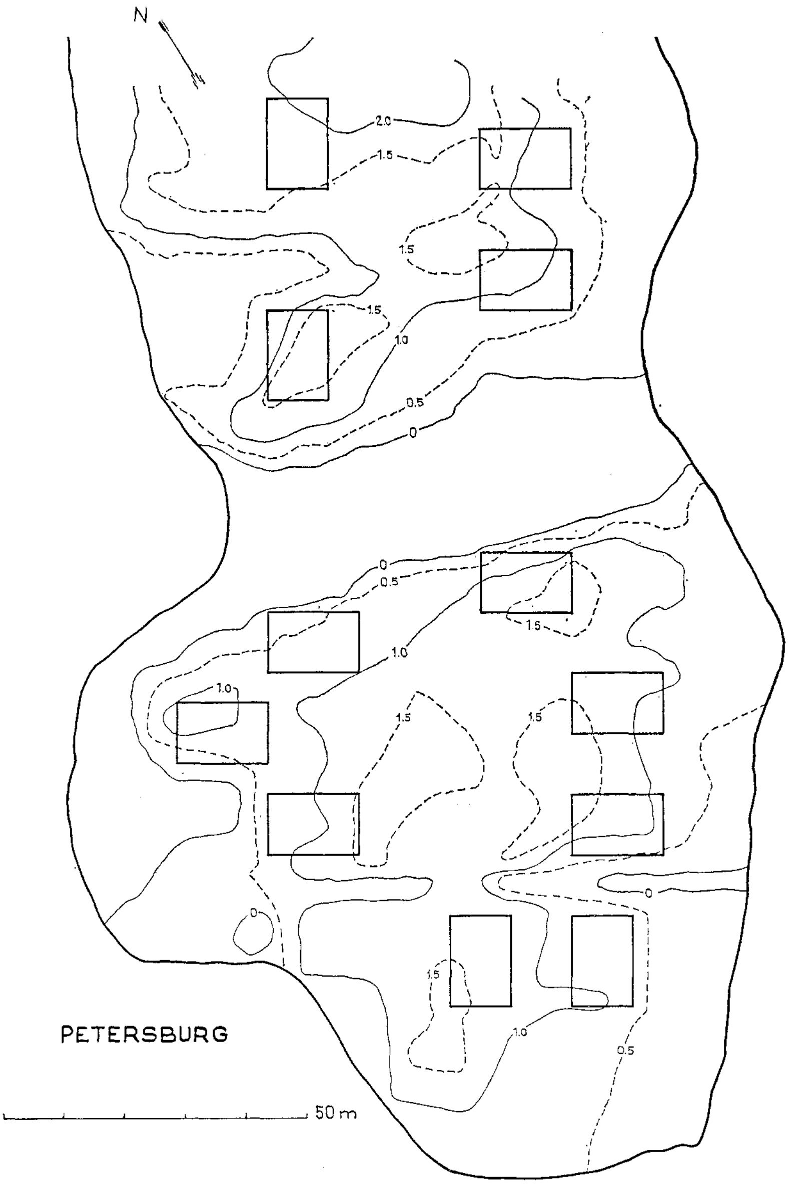

Fig. 4. Map of the Petersburg experiment, with contour lines for every half metre.

mixture of glacifluvial material with some till. The landforms and the alternation of different types of soil material have been ascribed to the melting *in situ* of part of the ice. Some authors believe that this "dead ice" was cut off when the ice dammed "Baltic Ice-Lake" found a new outlet north of

Billingen, an isolated plateau east of Remningstorp. For the present purpose we are not so concerned with the geological history, but it must be admitted that the heterogeneity of the soils makes much of the land unsuitable for such field experiments as require large uniform land areas.

After the experiment on the site now described, Hökaberg, was laid out, it was considered to be of interest to test some of the treatments on a forest site. There was an area available which had been clear-felled and planted at the same time as the Hökaberg area, which will be called Petersburg. Although both sites were planted at the same time and with similar spruce plants (2/2), early development was slower at Petersburg, due mainly to competing ground vegetation and frost action. In 1957, however, the spruce had just overcome the competition from the ground vegetation, although the individual growth variation was considerable. Twelve plots were laid out in this area, unfortunately without close examination of the soil. Later it was found that three of the four northern plots on the plan (Figure 4) had a distinct bleached horizon (A_2) in the soil profile, while the rest of the plots had a brown-podzolic soil. Plot No. 2 was transitional. Owing to this heterogeneity of the soil, which could only partly be made up for by rearranging the treatments and by choosing groups of trees outside the plots as additional controls, the Petersburg experiment can only be used as a side experiment, confirming or contradicting the results from the main experiment at Hökaberg. This possibility of confirmation is, however, important, since the number of plots at Hökaberg only admitted two duplicates of each treatment. A view of the experimental area at Petersburg is shown in Figure 3, where the appearance of the spruce clearly show the effects of frost in earlier years.

Apart from a high frequency of frost in topographic depressions there is nothing particular with the climate of Remningstorp. The meteorological station Skara (15 km SW. of Remningstorp, altitude 115 m against 130 m for Remningstorp) records an annual mean temperature of $+5°.5$ C and an annual precipitation of 582 mm for the period 1901—1930. The July mean temperature is 15°.6 C and the rainfall maximum is in August (84 mm).

2.2. Treatments

A plan of the Hökaberg experiments is given in Figure 5 and one of the Petersburg experiments in Figure 6. The fertiliser applications are listed in Table 1. At Petersburg the plot size was 15×20 m for the fertiliser application over the whole period. The measuring plots were 10×15 m. At Hökaberg first 15×15 m plots were fertilised, while the "net" plots for measurement were 10×10 m. The risk of contamination from the more heavily fertilised plots was considered more serious than a decrease in effect on trees growing near

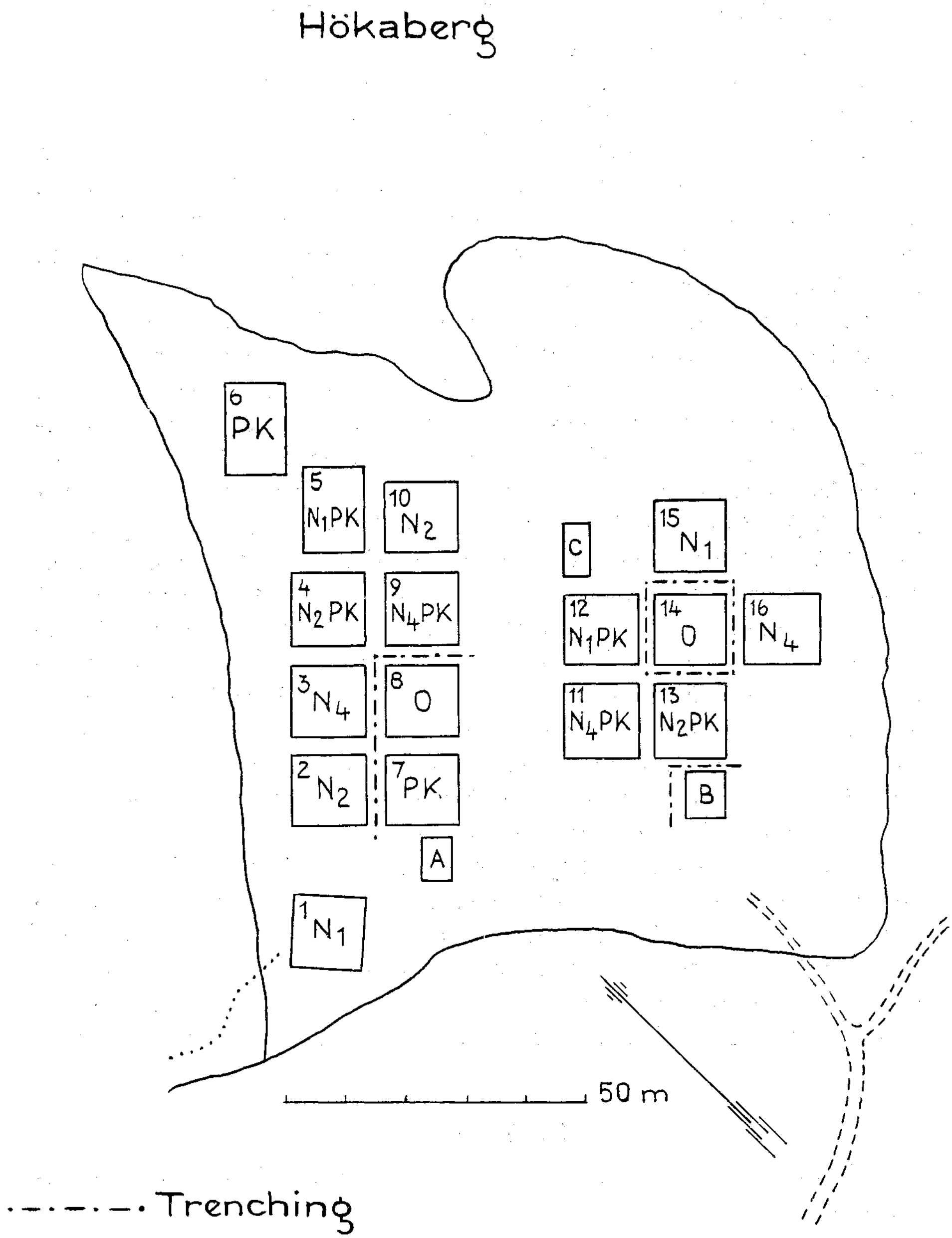

Fig. 5. Plan of the Hökaberg experiment. Plot size on map 12 by 12 m (except plots No. 5 and 6, which are 10 by 15 m), i.e. area fertilised 1960—1966, see text. Trenching done in May, 1964 by digging down steel plates to a depth of 50 cm.
The letters A, B, and C denote groups af additional control trees, see text.

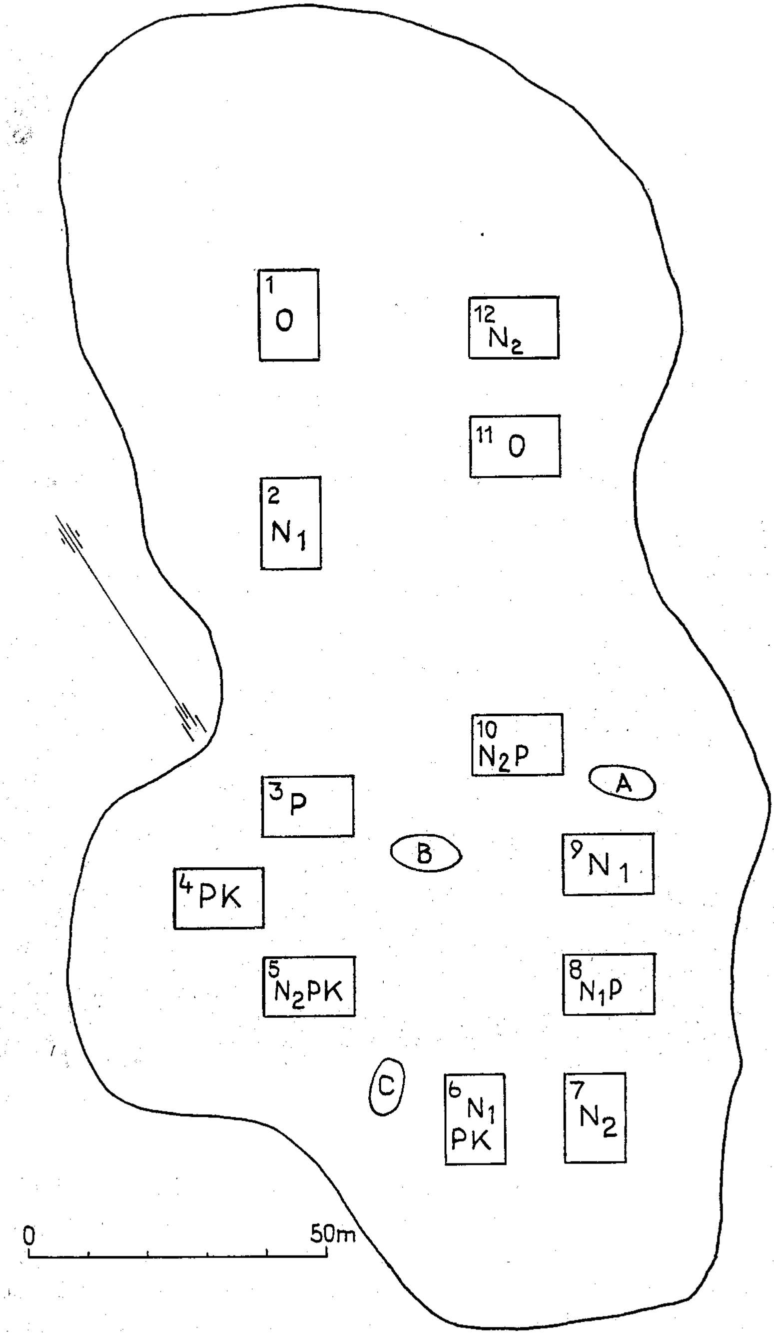

Fig. 6. Plan of the Petersburg experiment. Plot size on map 10 by 15 m, i.e. measured plots. The fertilised area was 15 by 20 m.
The letters A, B, and C denote groups of additional control trees, see text.

Fig. 7. Control plot (No. 8), remaining stand in 1961. Photo 26.V.1961

the border of the "net" plots, and therefore the area of the fertilised plots was decreased to 12×12 m from 1960 onwards; this means that only a belt one metre wide around the measured plots was fertilised. In the spring of 1964 steel plates were dug down to 50 cm depth in the border-lines between the plots which were not fertilised with nitrogen and those which were given heavy nitrogen applications. These plates were placed at the borders between the original 15×15 m plots (see Fig. 5).

The nitrogen fertiliser added was ammonium nitrate mixed with some dolomitic limestone ("kalkammonsalpeter"). The nitrogen content was 20.5 per cent in the first years and 26 per cent later. In agricultural use this fertiliser is considered to have a weak acidifying effect on the soil, but if a large part of the ammonium ions is taken up before oxidation to nitrate, the effect would be expected to be the opposite. Some data on soil acidity, etc., are given in Table 2. From 1963 on the treatment N_4 at Hökaberg was changed into N_8, 400 kg of nitrogen annually (the application divided into two, one in April and one in June, to avoid adverse salt effects).

At Petersburg the number of plots suitable for the experiment was even less than at Hökaberg, because of the greater irregularity in topography and sapling development (Fig. 3). The original plan was therefore to test some of the Hökaberg treatments without performing a more complete experiment. The high original nitrogen level made nitrogen effects less likely, while it was considered to be of some interest to try phosphorus and potassium separately, as both elements might affect frost hardiness. Therefore one block received phosphorus, one potassium, one both, and one neither of these elements. Each block comprised three plots with the nitrogen regimes N_0, N_1, and N_2, respectively. Further development very soon showed three things: that there was pronounced soil heterogeneity, that there were distinct nitrogen effects in colour (later in growth), and that the general level of potassium in the spruce needles was high. The treatments were then readjusted, so that later potassium additions were given to all phosphorus plots, but to no other plots (Table 1). It is believed that the potassium effects in the experiment, if any, have been negligible in comparison with the effects of nitrogen and phosphorus.

2.3. Plant nutrient concentrations in soil
(By B. Popović and C. O. Tamm)

As was said before, no complete soil investigation has been made in the experiment. It is, however, of considerable interest to find out whether the large amount of fertilisers supplied, nitrogen in particular, have changed the soil in the fertilised plots. Therefore, eight plots of the Hökaberg experiment were sampled in April 1967, just before that year's fertilisation. Two sets of samples were taken, both consisting of composite samples from each plot. One of the sets was reserved for nitrogen mobilisation experiments and kept moist until the start of these experiments. The other set of samples was air-dried and analysed by standard methods. Both mechanical composition and concentrations of plant nutrients were studied. In the case of the plant nutrients phosphorus, potassium, calcium, and magnesium, three different extraction methods were used: (1) "total", i.e. boiling with nitric and perchloric acid; (2) extraction with boiling two molar hydrochloric acid; and (3) extraction with ammonium lactate at pH 3.75.

The analytical results are given in Table 2, which shows a moderate variability between the various plots in most of the properties studied. In most cases there are no or very small differences which can be ascribed to the experimental treatments. There is a small but consistent increase in lactate-soluble phosphate on plots fertilised with PK. Lactate-soluble potassium its also higher on the PK plots but not on the N_2PK ones. It is worth noting that conductivity and pH are scarcely affected by the large amounts of fertiliser supplied during a ten-year period. The bottom line in Table 2 gives the amounts of nutrients per hectare, calculated on rather uncertain assumptions. These data are only intended to show the order of magnitude, to make possible a rough comparison with the amounts added, according to Table 1.

Table 3 presents the physical properties of the top soil on plot No. 8. It should be noted that the sampling in this case only concerns the uppermost 5 cm, which explains the high pore volume of the samples.

Table 4 shows first the loss on ignition and total nitrogen in the top soil from the same plots as the samples in Table 2. Then follows the ammonium and nitrate nitrogen values, both at the start of the experiment and after six and nine weeks incubation. The incubation method used agrees essentially with that of Zöttl (1960), with minor changes described by Popović (1967). The initial values are uniformly low, particularly in nitrate. After six, and still more after nine weeks, a considerable amount of ammonium nitrogen was released in the control and PK samples. The amount of ammonia found in the N_2 and N_2PK samples was higher at six than at nine weeks, which is explained by the nitrate nitrogen figures. Apparently, the nitrogen-fertilised plots have an intensely nitrifying soil, while almost no nitrification was observed in the control and PK samples. The total amount of nitrogen released as ammonia and nitrate is rather similar in all investigated samples, between 2.4 and 3.7 per cent of the total amount of nitrogen.

The information in Table 4 may be summarised as follows: top soil samples taken before the spring application of fertilisers, although with a crude sampling technique, have not revealed any consistent effect of the fertiliser treatments on loss on ignition, total nitrogen, level of ammonium nitrogen or nitrate nitrogen in the soil nor on the total amount of mineral nitrogen released during incubation experiments. Yet there has been a large and consistent difference between plots fertilised with nitrogen and those not fertilised with nitrogen, in respect of the form of nitrogen released. There was almost no nitrification in the samples from plots to which no nitrogen was given, while the main part of the released nitrogen on fertilised plots was in the form of nitrate.

3. Internal levels of nutrients in the spruce

3.1. Nutrient concentrations in exposed needles

3.1.1. Sampling

Both experiments have been followed by foliar analysis on current needles collected each autumn from a terminal shoot from the second whorl of at least ten trees within the "net" plots. Shoots facing south were preferred. The only exception from the autumn sampling concerned the 1956 needles from Hökaberg, which were collected in late March 1957. The needle samples were left to air-dry at room temperature until the needles fell off on touching. Earlier tests have shown that the respiratory activity in drying spruce needles is comparatively low and at that comparable samples can be obtained by this method. However, it is possible that some of the observed differences between different years may be caused by differences in drying conditions. The chemical analyses were performed by the routine methods used at the Department of Forest Ecology (Ingestad 1962, Holmen 1964).

3.1.2. Hökaberg

Figure 8 shows the development of the nitrogen concentrations in spruce needles at Hökaberg. The plots within all treatments had uniformly low nitrogen content in 1956 and the first fertiliser application in the spring of 1957 led to a strong increase in nitrogen concentration, which, however, decreased again in 1958 in spite of the continued supply of nitrogen. The amount supplied in 1958 was, however, only half that given in 1957. In 1959 again, the application was increased to the same level as that given in 1957. But this time the increased application only provoked a small increase in nutrient concentration. The application in 1961 just maintained the difference in levels between the different treatments, but the application in 1962 cold not prevent a sharp drop in nitrogen concentration within all plots. Therefore, as was said before, the treatment N_4 was changed into N_8 (400 kg of nitrogen, given annually). This very high application given annually has maintained the nitrogen level in the foliage at a high and relatively constant nitrogen level. Unfortunately, the applications N_1 and N_2 were not changed and the curves for the nitrogen levels in those treatments appear to converge with those of the controls. The following diagrams Nos. 9, 10, 11 and 12 show the

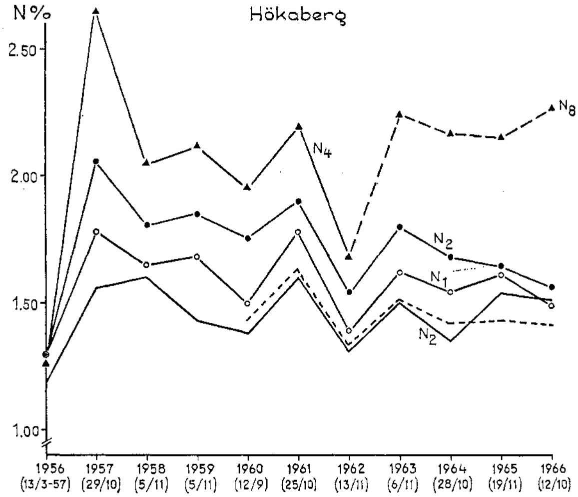

Fig. 8. Nitrogen

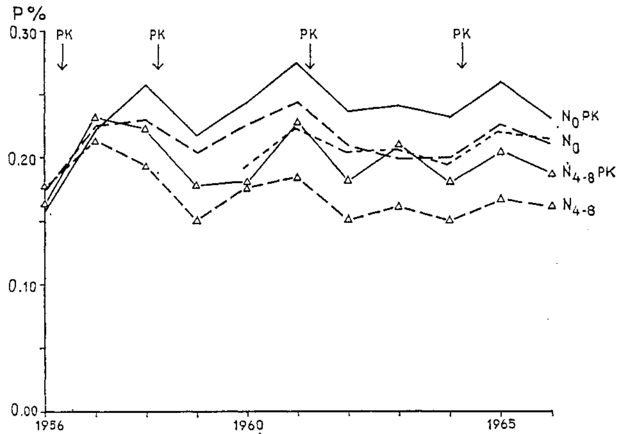

Fig. 9. Phosphorus

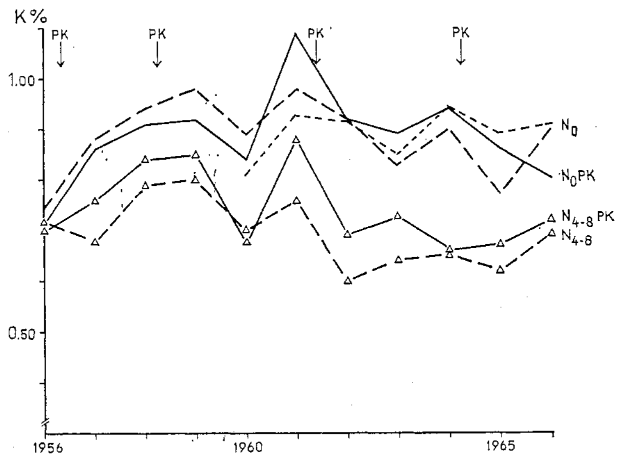

Fig. 10. Potassium

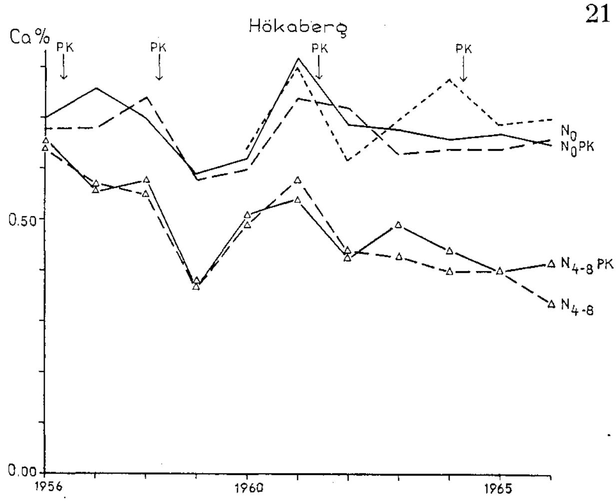

Fig. 11. Calcium

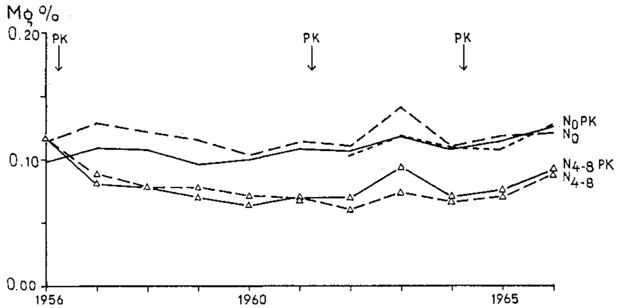

Fig. 12. Magnesium

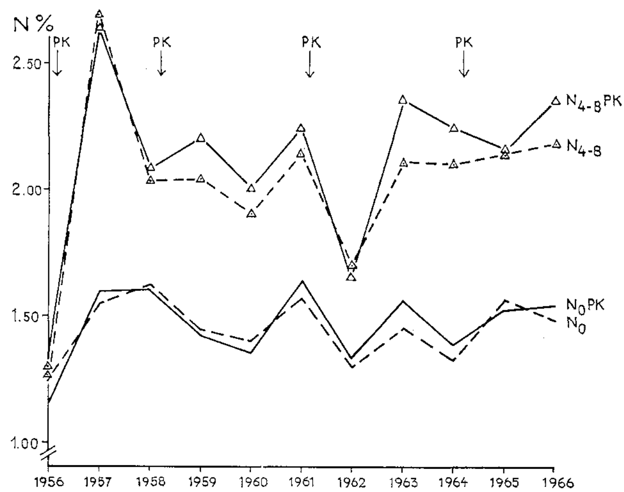

Fig. 13. Nitrogen

Fig. 8. to 13. Concentrations of various plant nutrients in exposed current needles at Hökaberg as a function of time and nutrient regime. The broken line starting in 1960 (1962 in Fig. 12) concerns the additional control trees. Sampling dates as noted in Fig. 8.

Fig. 14. View of the Petersburg experiment.

trends for phosphorus, potassium, calcium and magnesium. For the sake of simplicity, only curves for plots not fertilised with nitrogen and for those given the heaviest application are shown. The curves for the treatments N_{4-8} and N_0 show clearly the depressing influence of the addition of nitrogen on the levels of other elements, an effect which is only partly compensated for by addition of these elements (P, K and Ca). Magnesium was not added (except for small amounts contained in the ammonium-nitrate-limestone) and the foliar Mg levels are fairly low in the N_{4-8} treatment.

It is thus clear that the nitrogen application has affected the internal levels of other plant nutrients. It is now an important question whether the application of PK has also influenced the nitrogen levels. There is some evidence for such an influence, which may complicate the interpretation of the relationships between growth and plant nutrients. Figure 13 shows a slight tendency of plots fertilised with PK to show higher N contents than the plots not fertilised with PK. A more detailed examination of the data (see Table 5) shows that before the experiment (in 1956), there was a very small difference between +PK plots and —PK plots (on the average, 0.03 per cent nitrogen higher values on the —PK plots). For the years when PK was supplied in the spring, the autumn values show slightly higher levels on +PK plots. The difference is 0.03 per cent nitrogen in favour of the +PK plots, but this is not a statistically significant difference. For the six years when no PK was supplied, there is, however, an almost consistent difference in favour of the +PK plots, although the difference is relatively small (0.08 ± 0.02 per cent nitrogen).

3.1.3. Edge effects

In 1964 needle samples were collected in order to test the effect of the heaviest nitrogen application (400 kg N per hectare and year) on unfertilised spruce outside the borders of plots Nos. 9, 11 and 16 at Hökaberg. It was found that the spruce rows growing at the boundary of the fertilised area or just outside it showed lower nitrogen levels than the spruce within the measured plots (1.90 per cent as compared with 2.24). Needles from spruce growing approximately 1.2 and 2.4 m away contained 1.76 and 1.81 per cent nitrogen, respectively, while those from spruce growing more than 3.5 m away contained 1.48 to 1.52 per cent, without any visible relation to the distance from the plots. The averages for the N_0 and N_0PK plots varied from 1.32 to 1.42 in 1964. There is thus a clear fertiliser effect on spruce growing 2.4 m, or less, from a fertilised area, while the effect is small (or absent) on spruce growing 3.5 m or more away.

3.1.4. Petersburg

The diagrams Figures 15 to 18 show the various nutrient levels throughout the experimental period at the Petersburg plots. In this case, however, the data presented are averages for all plots given the element indicated. The possible interactions between nitrogen and the other nutrients are therefore not visible in the diagrams, but a detailed inspection of the data shows the same type of depressing effect of nitrogen on the levels of other elements (Table 6). However, the weak effect on the nitrogen level of the PK treatment, which could be demonstrated at Hökaberg in some years, is not visible at Petersburg, although it is not clear whether this is due to more irregular scatter of the data or to the absence of the phenomenon.

An interesting feature in the Petersburg diagram Fig. 15 is the high nitrogen level at the start of the experiment. At that time there were still some *Rubus idaeus, Chamaenerion angustifolium*, and other species, indicating high nutrient levels in the soil. At the same time the growth of the spruce was held back by competition from ground vegetation and by frost injuries. The

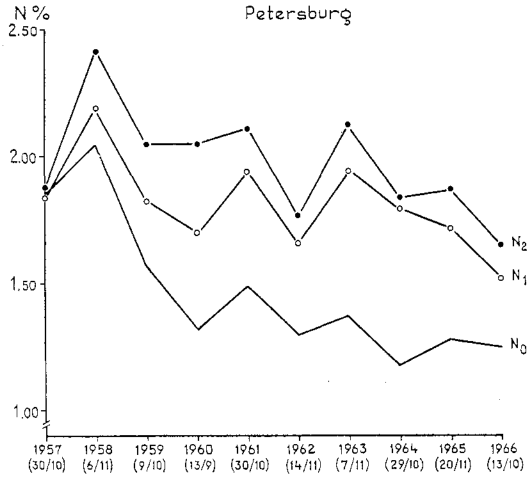

Fig. 15. Nitrogen (Separate curves for each nitrogen regime)

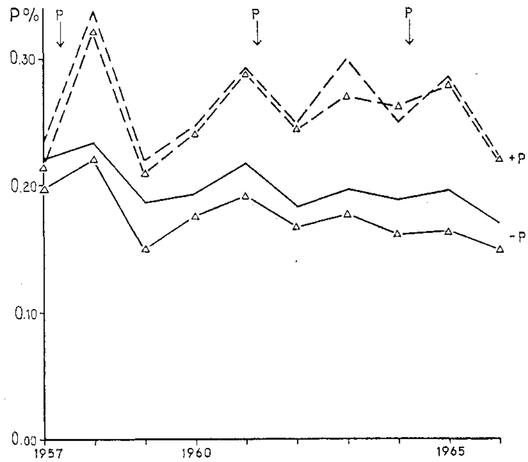

Fig. 16. Phosphorus
Solid lines: blocks without P (and K)
Broken lines: blocks with P (and K)

increasing growth of the spruce has, however, led to more normal nitrogen levels in the spruce foliage. Both P and K values must be considered rather high.

3.2. Nutrient concentrations in other parts of the trees

As was mentioned before, the spacing at Hökaberg was very dense (1.2×1.2 m) and in 1960 about 40 per cent of the trees were cut out. On this occasion a large number of sample trees was studied with respect to the dry weights and

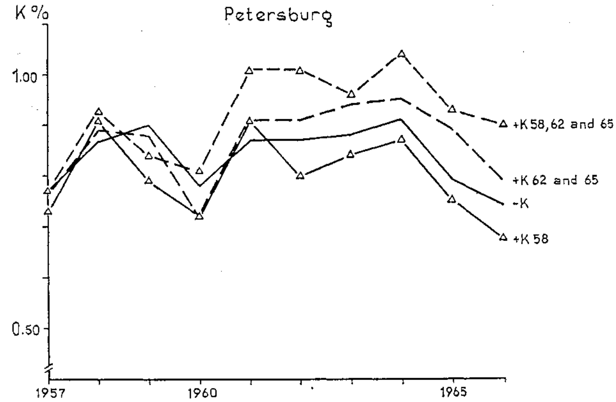

Fig. 17. Potassium
For explanations, see
Fig. 16.

Fig. 18. Calcium
For explanations, see
Fig. 16

Fig. 15 to 18. Concentrations of various plant nutrients in exposed current needles at Petersburg as a function of time and nutrient regime.
Sampling dates as noted in Fig. 15.

nutrient contents of the parts above ground. Needles (composite samples from the whole crowns), branches, bark and wood were analysed. The results from this investigation have been reported earlier (Tamm 1963, 1964 a) and here only the main results will be presented in Table 7, which in the first place shows that nitrogen concentrations increased in all parts of the trees after the nitrogen application. There seems to be a similar effect of the NPK treatments on the phosphorus levels, too.

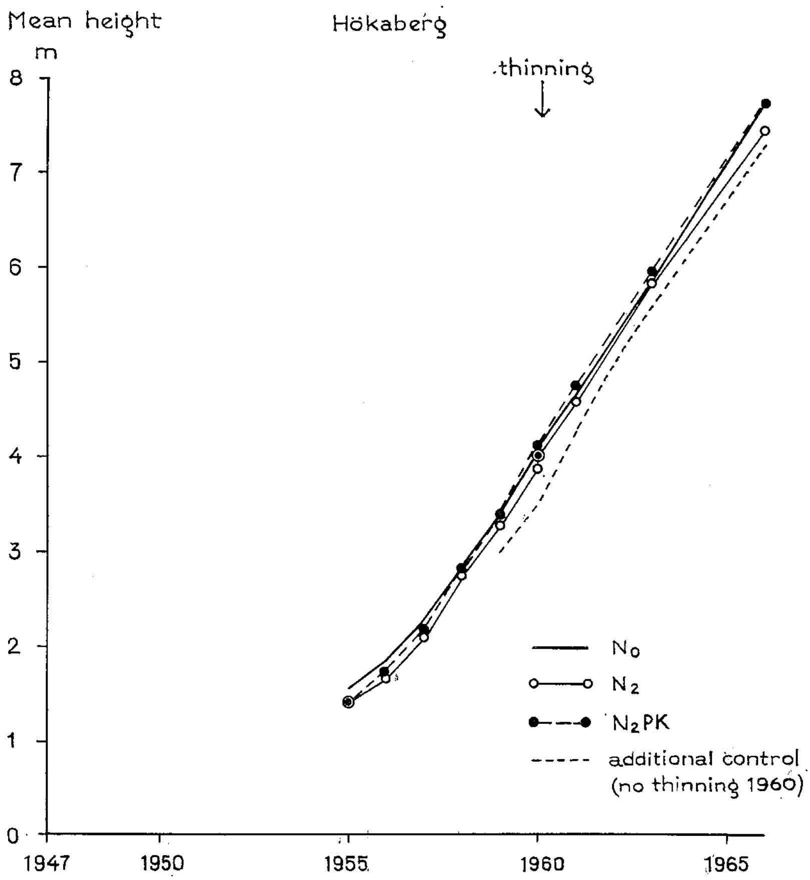

Fig. 19. Mean height development within some of the treatments of the Hökaberg experiment. The treatment called "thinning" was, strictly speaking, a cleaning (removal of smal trees without commercial value).

4. Growth measurements

4.1. Height and diameter growth

Growth measurements in the first years only comprised top shoot growth and in some cases needle weights. In 1960 also annual diameter growth for earlier years was measured on the felled trees.

Height and diameter growth increased in much the same way on the fertilised plots in the period 1956 to 1960 (Tamm 1964 a). The reaction in both height and diameter growth increased from slight in the first year to stronger in 1958. In 1959 there was a drought and the diameter and height growth were reduced on all plots. The reduction was slightly greater on the fertilised

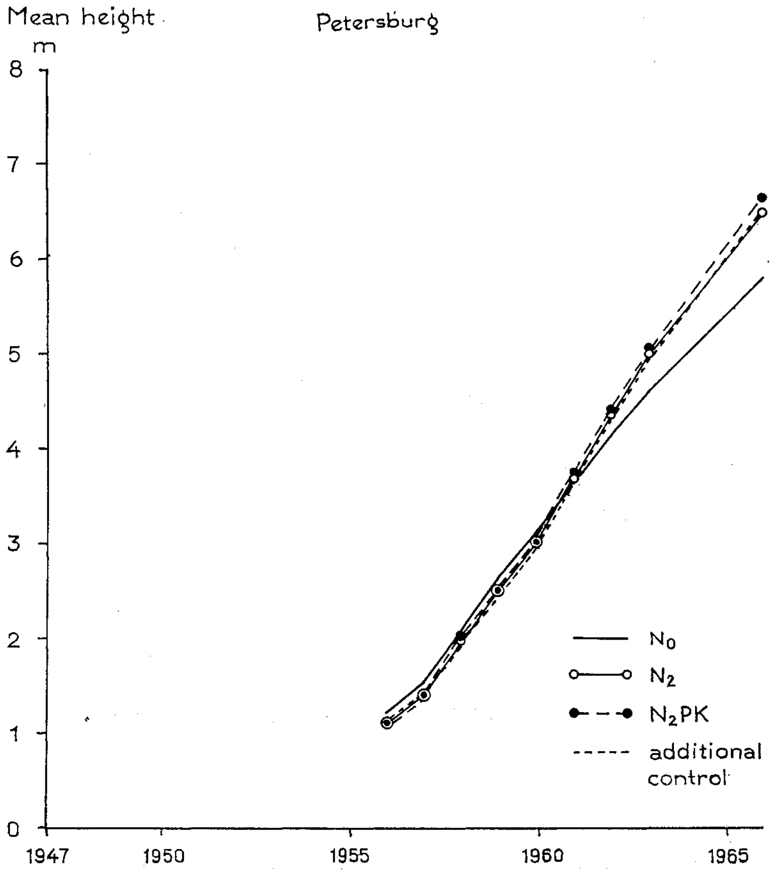

Fig. 20. Mean height development within some of the treatments of the Petersburg experiment.

plots than on the controls. In 1960 there was again an increase in height and diameter growth, although not to the same level as the 1958 values, see Tamm 1964 a.

From 1960 onwards the annual height growth measurements were discontinued, but both height and diameter of all trees within the net plots were measured in 1960, 1963, and 1966. Although the most important results from these measurements are the calculated tree and stand volumes, it is of some interest to study height and diameter growth separately.

Figure 19 shows the mean height development within some of the treatments in the Hökaberg experiment. (The heights in 1956 and 1966 can also be found in Table 8). There is a discontinuity in the curves in 1960 because of

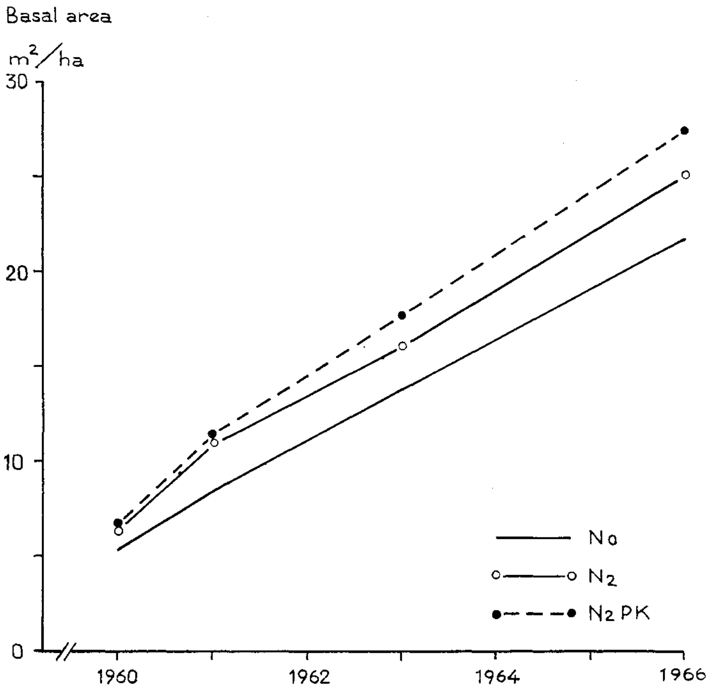

Fig. 21. Basal area development within some of the treatments of the Hökaberg experiment.

the cleaning. It is evident from the curves (and from Table 8) that the height development has been very similar within different parts of the Hökaberg experiment. Apart from the small effects in the first four-year period discussed above, there is hardly any evidence that the fertilisation has affected height growth. The additional control groups of trees, outside the experiment, which were left at the original 1.2×1.2 m spacing, started with a slightly lower mean height than the plots but showed almost the same height growth as those in the experiment.

For comparison we may look at Figure 20, which shows similar curves for some of the Petersburg treatments. In this case the height development of the N_0 plots is much slower than that of other treatments. As was said earlier, this can be ascribed to a difference in soil conditions with more podzolised soils within the part of the experimental area where both N_0 plots happened to be located. However, the curve for the additional controls, which are located in the part of the area with better soil conditions, shows a height development almost identical with that of the treatments N_2 and N_2PK. Considering

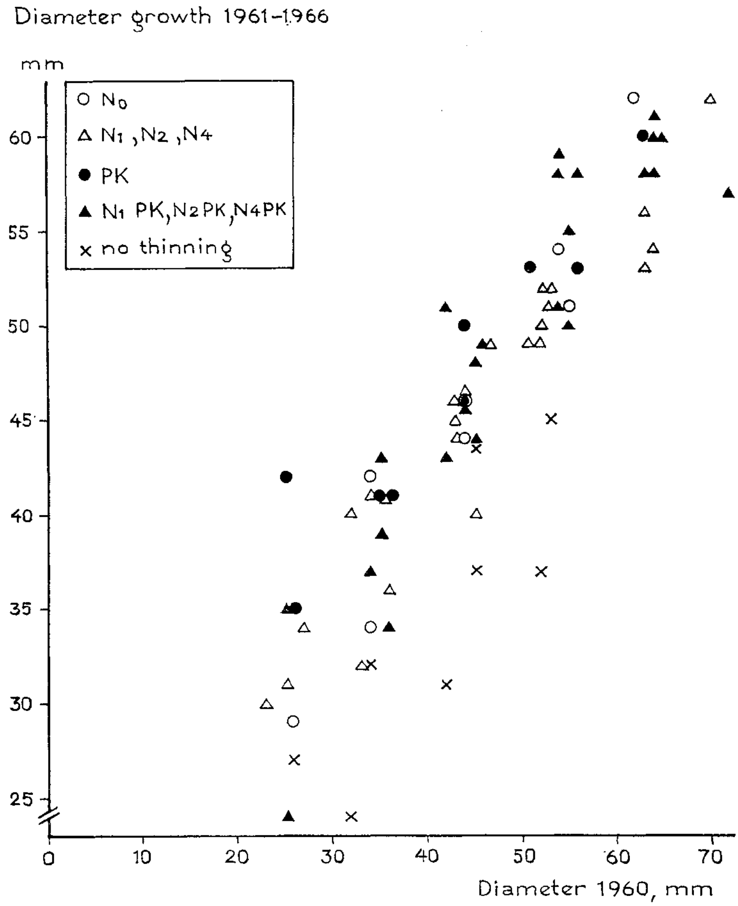

Fig. 22. Diameter growth 1961 to 1966 at Hökaberg as a function of the diameter in September 1960.

the similarity of height development within the various treatments of the Hökaberg experiment, this similarity at Petersburg may be taken as evidence that the additional controls can be used for comparison with the neighbouring plots (see also Table 9).

As height growth seems to be very little affected by the fertiliser treatments, any positive reaction for nitrogen or PK application would be expected to show up in diameter or basal area increase. Diameter was, however, not measured at the start of the experiment because many of the trees had not yet attained breast height at that time. More detailed studies of the diameter growth are to be carried out when the experiments are completed and when increment cores or stem sections can be measured. However, some information can be obtained from caliper measurements. Figure 21 shows the basal area development within some of the treatments at Hökaberg and again confirms the assumption that fertilisation has affected basal area growth much more than height growth in this stand. Fig. 22 shows the diameter growth for 1961—1966 as a function of the diameter in 1960. There is a slight tendency for NPK trees to grow better than trees without N or PK. The additional control trees (at their original dense spacing) have increased less in diameter than the rest.

4.2. Volume growth

Data for the standing volumes at Hökaberg and Petersburg at the first revision in 1960 to 1961 are presented in Table 10, together with the figures for current growth, computed for the two following revision periods. The Hökaberg data (in cubic metres over bark), corrected for differences in initial heights (see below), are as follows for the various N and PK regimes:

Hökaberg	Standing volume 1960	Annual volume growth 1961—1963	1964—1966
$N_0 + N_0PK$	22.1	12.5	15.2
$N_1 + N_1PK$	31.4	13.8	17.4
$N_2 + N_2PK$	31.9	14.6	18.1
$N_{4-8} + N_{4-8}PK$	32.5	14.4	17.2
—PK	28.9	12.6	16.2
+PK	30.1	14.0	17.8

There is a tendency to higher growth in plots fertilised with nitrogen, as also in plots fertilised with PK. The growth data from Hökaberg have been subjected to a detailed statistical treatment, summarised here in Tables 11 to 13. The first of these tables shows an analysis of variance for the volume data from 1960, as well as an analysis of covariance, where the average height of the spruces within each plot in 1956 has been used as concomitant measurement. The statistical treatment is very similar to that used by Huikari and Paarlahti (1968), analysing diameter growth on experimental plots. There is a highly significant regression of the standing volume in each plot on the height in 1956. The analysis of variance shows a highly significant effect of the nitrogen application, although there is no difference between the various nitrogen applications. There seems to be some interaction of the PK treatment with the nitrogen application and a significant difference between blocks, but of these two last relations only the block variation is confirmed by the analysis of covariance. The interaction PK×N seems to have been caused entirely by differences in original height between the plots in question. It is worth noting that the effect of the nitrogen application attains an even higher significance in the analyses of covariance, i.e., when the data have been corrected for differences in initial height.

The next table (Table 12) deals with the volume growth from 1961 to 1963 in the same experiment. We find here again a highly significant effect of the nitrogen application, while there is still no effect of the various levels. The interaction PK×N is significant in the analyses of variance and this time almost significant in the analysis of covariance ($P < 0.05$). The PK treatment does not show a significant effect but this may well be due to the design of the experiment, which leaves very few degrees of freedom for the correct comparison. A variance ratio formed from the mean square for "between PK and no PK" and the error (bracketed values in Table 12) shows a formal significance both in the analyses of variance and in that of covariance. However, one of the prerequisites for the validity of this comparison is that there shall be no significant "other block variation", which is certainly not true in the analysis of variance. For the last revision period the data are found in Table 13. The results of the analyses are very similar to those for the period before, although the significance for the interaction effects has increased.

Summing up the statistical analysis of the Hökaberg data, we may conclude that there is a clear positive effect of the nitrogen applications but that the volume growth within the three higher nitrogen levels is not statistically different, except that there is a possible difference in PK effect at various nitrogen levels during the last three-year period. There is no or little PK effect during the first four-year period, but later a PK effect appears, mainly as an interaction effect. An inspection of the growth data (Table 10) shows that the interaction consists in a positive effect of PK on nitrogen-fertilised plots, but no effect on plots without nitrogen. As was just mentioned, there may be a difference in the effect of PK on different levels of nitrogen application during the last three-year period.

The volume data (cubic metres over bark) from Table 10 for Petersburg can be summarised as follows for the various N and PK regimes:

Petersburg	Standing volume 1961	Annual volume growth 1963—1964	1964—1966
$N_0 + N_0PK$	12.4	7.4	9.2
$N_1 + N_1PK$	13.2	10.2	14.1
$N_2 + N_2PK$	15.7	10.6	14.2
—PK	14.0	8.7	11.4
+PK	13.6	10.2	13.4

The growth data above are not very well suited for a statistical analysis such as that just described for the Hökaberg values, because of the heterogeneity of the soil. It has already been stated that the control plots at Petersburg, together with some of the other plots, have soil conditions differing from the main part of the experiment. However, some information can be obtained from an analysis of the average stem volumes of trees between 140 and 200 cm in height at the start of the experiment in 1957. The analysis is presented in Table 14. In this case the data from one of the plots, No. 11, have been replaced by the value from the additional control trees, thus making the block comprising plots 7, 9 and 11 more uniform with regard to soil conditions. A corresponding analysis has also been carried out with the original data from plot 11. The results differ from those in Table 14 only by showing somewhat higher significance.

The result of the analysis of variance in Table 14 shows that at Petersburg there is almost significance for the nitrogen effect ($P < 0.05$) and no effect for other treatments or interactions, if the comparison is made correctly. However, the P value for the variance ratio for "between PK and no PK" over other block variation, is relatively small and the corresponding variance ratio with the error introduced instead of the other block variation is almost significant ($P < 0.05$). There is thus so far relatively weak evidence only for fertiliser effects at Petersburg, judging from the statistical analysis. The nitrogen effect is, however, corroborated by the general appearance of the fertilised plots. The possible PK effect is perhaps not so obvious, but here may be recalled the effects Brantseg (1967) found for phosphorus supply in young spruce forests on good sites. It is worth noting that in this case the positive effect (if any) shows up in N_0PK plots, too, and not only as an interaction effect after nitrogen fertilisation. But there is no indication of an immediate PK effect, as in the cases described by Brantseg.

Further discussion of the volume growth values from both Hökaberg and Petersburg follows in the next chapter.

4.3. Dry matter yield and total nutrient uptake

It should also be mentioned here that the measurements in 1960 have made it possible to calculate the dry matter and the total nutrient uptake above ground in the Hökaberg plots. These data have been presented earlier (Tamm 1963, 1964 a) and will not be discussed here. The main results are, however, presented in Table 15.

5. Relations between growth and nutrient levels

In earlier chapters we have confirmed that the application of nitrogen has established different nitrogen levels in the foliage of the various nitrogen regimes in both experiments. Since also growth data for various periods are available for each plot, as was discussed in the previous chapter, we may now study the relations between on the one hand growth, and on the other hand foliage levels of nitrogen and other nutrients. Before we make this study we must decide which periods should be used for both foliage concentrations and growth.

5.1. Hökaberg

At Hökaberg the foliage data cover the period from the start of the fertilisation in 1957 until 1966. Also volume growth data are available for the same period subdivided into three periods (1957 to 1960, 1961 to 1963 and 1964 to 1966). The data from Petersburg are very nearly the same, except that the experiment started one year later.

Some of the volume growth in both experiments was produced before the start of the experiment. The amount of volume actually produced is negligible, but we have found in the analyses of covariance that the volume growth produced later depended very much on the size of the spruce at the start of the experiment. However, this can be corrected for by using the average height in 1956 as concomitant measurement for the Hökaberg experiment. In the following we shall use volume data from Hökaberg which are corrected for the initial height differences, i.e. the volumes which according to the statistical evidence would have been most likely, if the plots had had identical average heights in 1956. These corrections are rather small and the use of the uncorrected data would only increase the scatter in the diagrams presented, but would not change the picture essentially.

The dependence of growth during a certain period on the growth already produced, which will be discussed in more detail in a later section, makes the value of comparisons over short periods doubtful. Most of the diagrams presented below are therefore diagrams illustrating the total yield (stem volume over bark) up to 1966 as a function of the nutrient concentration of the needles on the average for the whole period investigated. For the nitrogen regimes in the Hökaberg experiments, however, some diagrams have already been

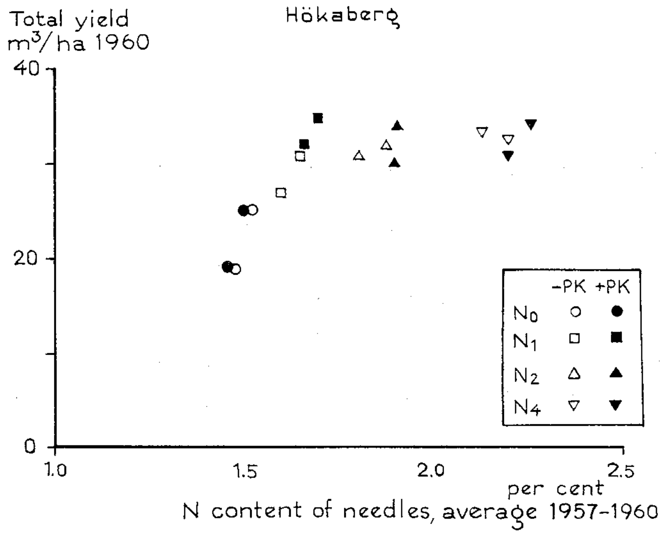

Fig. 23. Total stem volume in 1960 at Hökaberg plotted against average nitrogen concentration in exposed needles during the period 1957 to 1960.

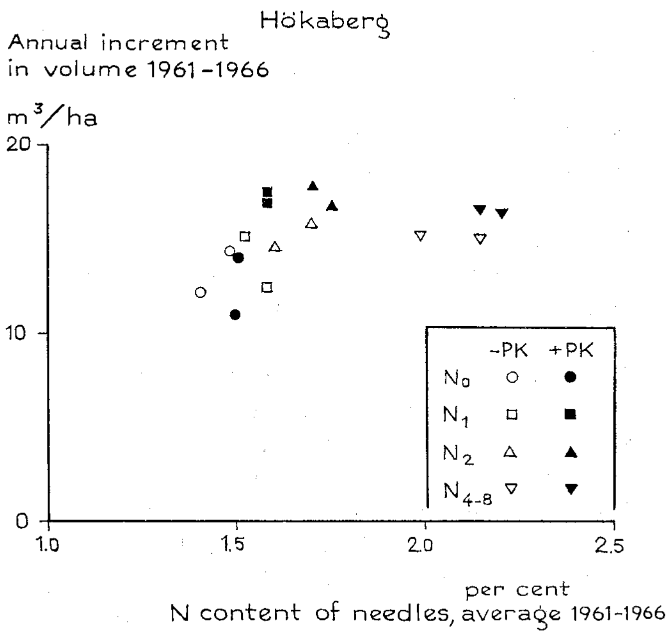

Fig. 24. Annual volume growth 1961 to 1966 at Hökaberg plotted against average nitrogen concentration in exposed needles during the same period.

presented covering the period 1957 to 1960 (TAMM 1964 a, 1965) and 1961 to 1963 (TAMM 1965); for purposes of comparison, the first of these diagrams is reproduced here (Fig. 23), together with a diagram showing the relation for the period after 1960 (Fig. 24). At the same time this last diagram illustrates the range of variation in annual volume growth within the experiment during that period, between 11 and 18 m^3 per hectare and annum.

All three diagrams showing the relation between volume and nitrogen concentration in needles at Hökaberg, are optimum type diagrams. In the first one there is no evidence for a difference between the plots with and without PK. The diagram for the period 1961 to 1966, as well as that for total yield (Fig. 25), shows that for all nitrogen applications the +PK plots grow better than the – PK plots, while there is no difference between controls and PK plots without nitrogen. It is difficult to tell the exact position of the optimum, as the curves seem to have very broad maxima. The most likely position seems to be somewhere between 1.6 and 1.8 per cent N in the needles. The phenomenon mentioned earlier, namely that the +PK plots appear to show slightly higher nitrogen levels in the foliage than the – PK plots with the same nitrogen regime, can be seen in Figure 25, in which the +PK plots tend to be located more to the right in each nitrogen regime group than do the – PK plots.

The next diagram (Fig. 26) shows the relation between total yield at Hökaberg and the phosphorus concentration in the needles during the experimental period. We have to remember here that the P content of the needles has been affected by the nitrogen application. The highest P concentrations are found in the plots PK (without N) and the lowest in the heavily nitrogen fertilised plots without PK. However, if we look upon the nitrogen-fertilised plots only, we find a positive relation between the P content and the total yield, although the increase is not very great. The – N plots with and without PK form a separate group with lower yield at the same P content as the nitrogen-fertilised plots.

The diagrams illustrating the relation between total yield on the one hand and potassium or calcium concentrations in the needles on the other hand (Fig. 27 and 28) do not show any clear relations. In the case of magnesium concentrations, Fig. 29, there is a slight trend towards a negative relationship. The lowest yields are found with high magnesium concentrations and higher yields at somewhat lower concentrations.

5.2. Petersburg

Fig. 30 shows the relation between the standing volume at Petersburg in 1966 and the average nitrogen content of needles from 1958 to 1966. There appears to be a positive relation, although this correlation becomes much

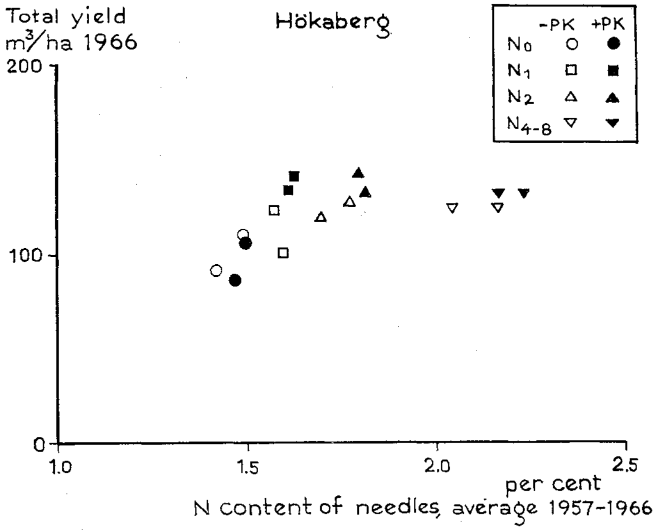

Fig. 25. Nitrogen

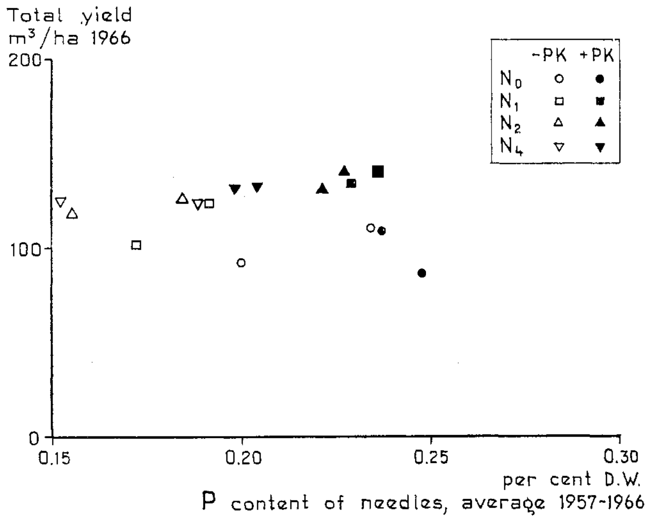

Fig. 26. Phosphorus

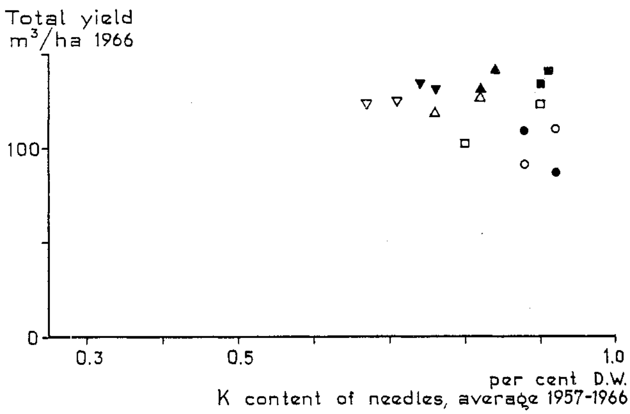

Fig. 27. Potassium

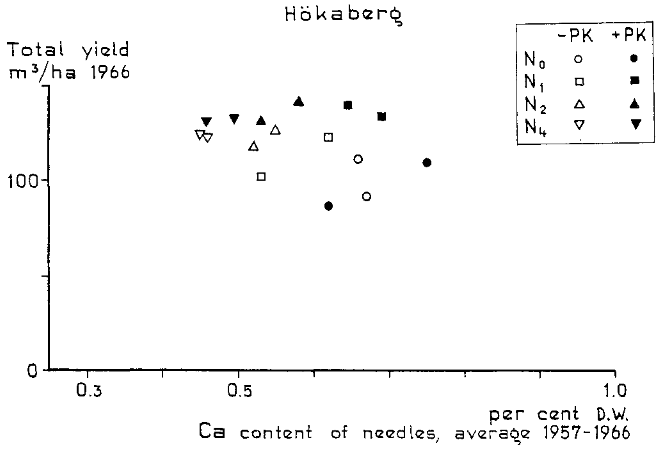

Fig. 28. Calcium

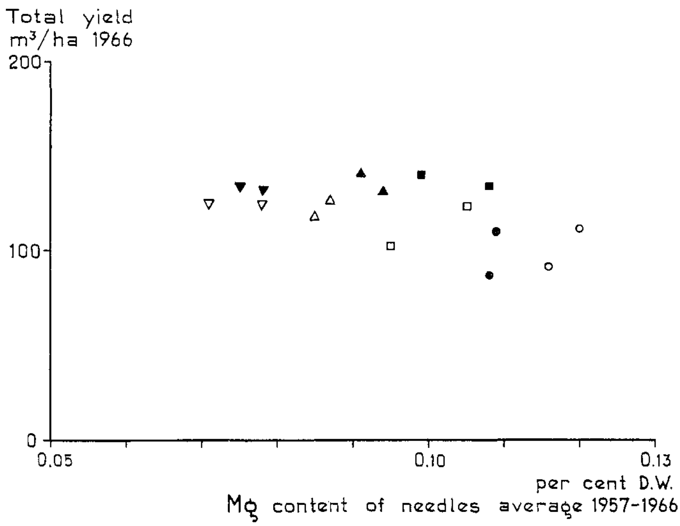

Fig. 29. Magnesium

Fig. 25 to 29. Total stem volume produced in 1966 at Hökaberg plotted against average concentrations of various plant nutrients in exposed needles during the period 1957 to 1966.

weaker if we eliminate the podzol plots which are marked separately in Figure 30. The transitional plot number 2 (treatment N_1) is not marked.

The next diagram (Fig. 31) deals with the yield in relation to the foliage phosphorus concentrations. The data give at first sight the impression of a typical optimum curve, but closer examination shows that it is only within the group of PK-fertilised plots that there is a clear (negative) relation between

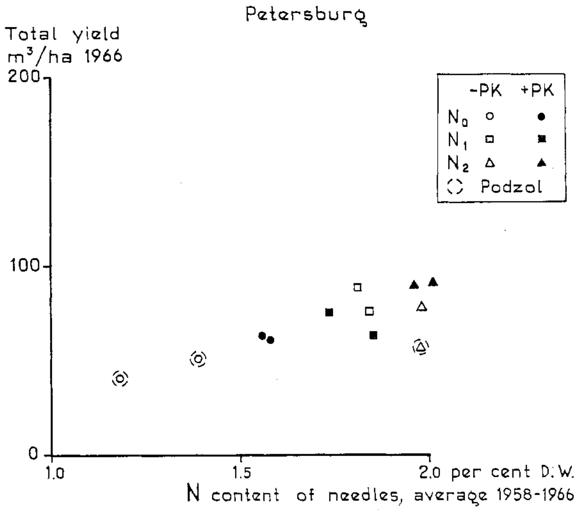

Fig. 30. Nitrogen

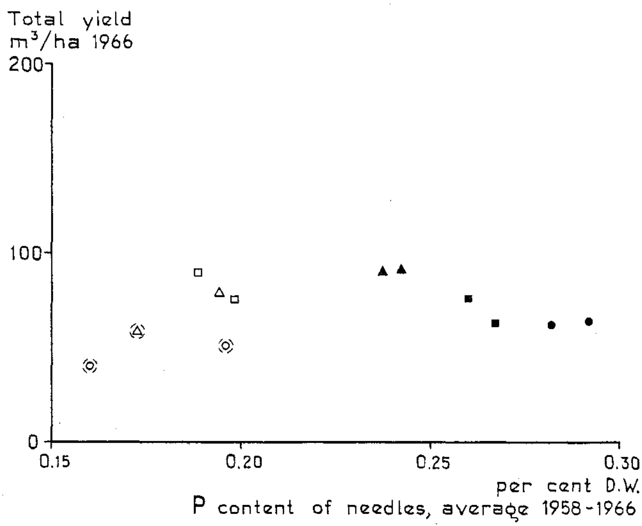

Fig. 31. Phosphorus

total yield and phosphorus concentration. The three podzol plots are low in both P concentration and growth.

The potassium diagram (Fig. 32) may contain a negative relation between total yield and potassium concentrations, at least if the podzol plots are kept separate from the rest. The potassium concentrations in the needles are fairly high (between 0.75 and 1.0 per cent dry weight). The calcium concen-

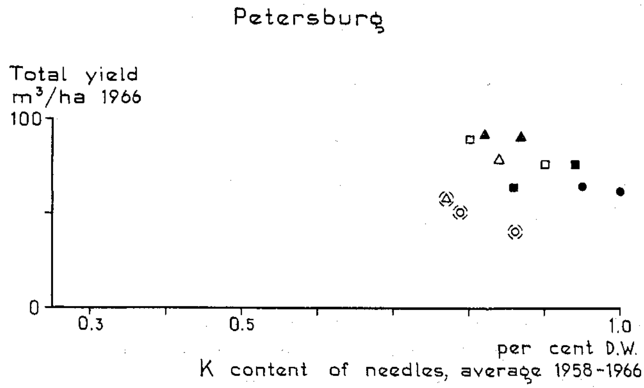

Fig. 32. Potassium

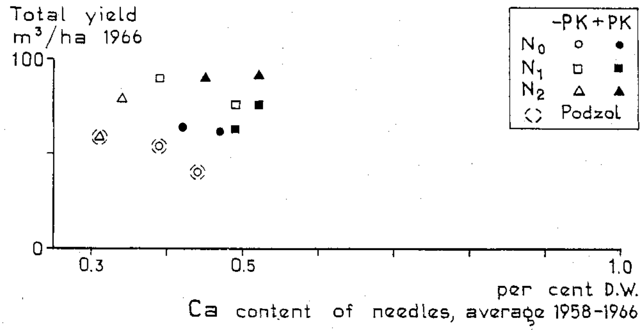

Fig. 33. Calcium

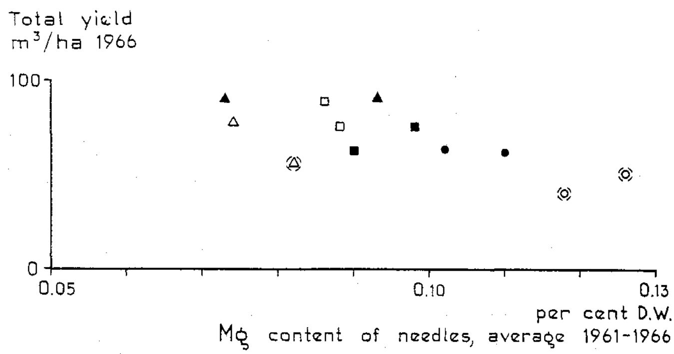

Fig. 34. Magnesium

Fig. 30 to 34. Total stem volume produced in 1966 at Petersburg plotted against average concentrations of various plant nutrients in exposed needles during the period 1958 to 1966 (1961 to 1966 in the case of magnesium, Fig. 34). The podzol plots (No. 1, 11, and 12) especially marked.

trations show no apparent relationship with the yield (Fig. 33). In the case of magnesium (Fig. 34), however, there is a tendency to negative correlation between total yield and magnesium concentrations, in the same way as in Figure 29 at Hökaberg. In this case magnesium data are available only for the latter part of the period (from 1961 onwards).

The value of the relations just described will be dealt with in more detail in the discussion section.

5.3. Statistical analyses of the individual growth variation and its re ation to needle nutrient concentration and other factors

A positive correlation between foliar nutrient levels and growth is often found in material from fertiliser experiments. It has been suggested that such correlations might be used to predict growth responses to fertilisation (Leyton 1958). If this assumption were true, a statistical analysis of the growth variation within unfertilised plots could be expected to give positive correlations with the levels of those nutrients which increased growth on that site. Apparently the experiments at Hökaberg and Petersburg are suitable places for testing this assumption.

The results from some earlier tests on the Hökaberg material have been reported earlier (Tamm 1964 a) and will be summarised briefly here.

The tests consisted in multiple regression calculations between various growth measures of 44 unfertilised trees at Hökaberg and the levels of nitrogen, phosphorus, potassium, calcium, and magnesium in the needles of the individual trees. The main results were that some significant but relatively weak correlations were obtained between growth and nutrient levels, but that the interrelations between various growth measures were so much stronger that a nutrient level did not attain any statistical significance as soon as some measure of earlier growth was introduced into the regression analysis.

A more detailed analysis was also made of the volume of the individual trees at Hökaberg in relation to average foliar nitrogen during a five-year period and to the trend in nitrogen within these individual trees. The average nitrogen level showed a significant positive correlation with the tree volumes, while the nitrogen trend showed a negative correlation ($P < 0.05$), see Table 16. The negative trend means that fast-growing trees tended to contain lower concentrations of nitrogen at the end of the period as compared with the concentration at the beginning of the period; and *vice-versa* for slow-growing trees. However, if the initial height of the trees, before fertilisation, was introduced into the multiple regression analysis, neither average nitrogen nor the nitrogen trend gave any significant contribution. A corresponding analysis was repeated on data available in 1966; there was still a positive sign for the regression coefficient for volume on nitrogen level and a negative sign for the coefficient for volume on nitrogen trend, but neither of these correlation was statistically significant (Table 16). The height at the start of the experiment still shows a highly significant correlation with the volume at the end of the period.

In the case of the Petersburg data available in 1966, there was no correlation between volume on the one hand and the average nitrogen concentration or the nitrogen trend on the other hand. The correlation between tree volume at the end of experiment and the initial tree height was here also highly significant, but the part of the total variation in tree volume in 1966 which is explained by differences in initial tree height is much less at Petersburg than at Hökaberg. Apparently tree height at Petersburg in 1957 was a relatively poor measure of potential growth. This is not surprising, since we know that the Petersburg spruce were held back in their early development by frost and competing ground vegetation.

6. Discussion

Some of the results presented in earlier sections do not need much further discussion to be accepted, for instance the positive effect of N and PK applications at Hökaberg. In other cases the results are fairly uncertain; in particular this is the case for some of the results from the Petersburg experiment which, as explained earlier, suffers from soil heterogeneity which obscures the treatment effects. However, more detailed discussion does not help us very much when the experiment is inaccurate. The various results from both experiments will be reviewed briefly in the summary, including results published earlier.

The discussion here will concentrate instead on two problems:
1) To what extent are the relationships found between growth and nutrient levels reliable and important for the interpretation of foliar analyses?
2) What conclusions can be drawn from the Hökaberg and Petersburg experiments regarding the design of future experiments for assessing optimum growth?

6.1. Growth-nutrient relationships

6.1.1. Nitrogen

Concerning the studies of volume growth as a function of foliage nitrogen levels, we must remember that we have established four different nitrogen levels, but failed to keep these levels quite constant. The most constant level has been the one with the highest nitrogen application, N_4 (later increased to N_8). During the ten-year period at Hökaberg, the nitrogen level (in autumn samples of exposed current needles) has been at, or just above, two per cent dry weight for eight years, while the initial year (1957) showed a higher value and 1962 a lower one. The controls without nitrogen have shown a nitrogen level in the foliage varying around 1.5 per cent and the two treatments N_1 and N_2 have shown intermediate values, although with a downward trend during most of the period. A more constant level within the "working range" of the growth/concentration curve would clearly have been desirable. However, considering the dominating influence of the nitrogen application on growth (as compared with the effect of other nutrients added), we may be satisfied with the conclusion that the differences in nitrogen levels between treatments are almost entirely direct effects of the nitrogen fertilisation and not indirect effects caused by other treatments. The effect found for PK application on nitrogen levels is much smaller than the differences due to the nitrogen dosages. Part of the nitrogen effect may be delayed by soil processes, since nitrification in incubated samples increased after N fertilisation, but the nitrogen will still come from added fertiliser.

There is thus no reason to suspect the increase in stem volume for the nitrogen levels corresponding to the treatments N_1 and N_2 to be anything but a direct causal relationship. (This is not the place to discuss the physiological background of this relationship). Things are not so clear-cut in the case of the downward trend at high nitrogen levels. First, the decrease is not large, and hardly well established statistically. Secondly, the rich supply of nitrogen has apparently depressed the uptake of other elements. This is not so serious for the interpretation in the case of phosphorus and potassium, where the fertilisation has counteracted this effect to some extent (in PK plots). Yet the magnesium concentrations are fairly low over the whole period in N_{4-8} plots. The same might be the case for some micro nutrient, although such deficiencies are unknown for forest trees growing on normal mineral soil in Sweden. It is thus not entirely excluded that a deficiency in some other nutrient might contribute to the lower growth at the highest nitrogen level.

A further possibility would be growth depressions due to high salt concentrations just after fertilisation. Later on the concentrations are fairly low, at least within N_2 plots according to the conductivity measurements (Table 2). There is no proof at all for the existence of such damage; rather, the N_4 treatment had the highest yield up to 1960, when the spruce was small and presumably more susceptible than later on.

The diagram from Petersburg, Figure 30, does not show a nitrogen optimum but this might well be due to the fact that there is no very high nitrogen level in the Petersburg experiment. The fact that the Petersburg data appear to show increasing growth with increasing nitrogen concentration even up to about two per cent dry weight in the foliage may be caused by the initially high nitrogen levels within this area. As was shown in Figure 15, there is a trend towards lower nitrogen levels throughout the experimental period at Petersburg. The nitrogen effects were rather small in the beginning when the general nitrogen level was high.

6.1.2. Phosphorus

Both the Hökaberg and the Petersburg diagrams might be interpreted as having an optimum at 0.20—0.24 per cent P, but it is hardly possible to draw any reliable conclusions. The reason for this is that not only growth but also phosphorus concentrations have been affected by the nitrogen applications even more than by the PK applications. Relationships between growth and phosphorus levels may therefore be indirect only.

6.1.3. Potassium, calcium, and magnesium

In the case of potassium and calcium very little can be said about optimum concentrations for these elements. There is no clear relation between growth and the concentrations of these elements, and the foliage levels of these elements have been affected by nitrogen application at least as much as in the case of phosphorus. The magnesium diagrams from Hökaberg and Petersburg are in fact more interesting, as they both show a tendency towards negative correlation between magnesium concentrations and growth. This trend is hardly statistically significant but provides a good example of the false relationships which may be inferred from a superficial examination of data on growth and foliage concentrations. There is no evidence that high magnesium concentrations, within the range studied, should be harmful for the spruce, but apparently the magnesium concentrations have been depressed in the fast-growing spruce on the fertilised plots. This is one of the pitfalls for the use of statistical correlations in foliar analysis.

6.1.4. Growth and foliar concentrations: some further complications

A somewhat similar phenomenon, related to the "dilution effect" of Lundegårdh, is probably responsible for the negative correlation between the growth of individual unfertilised trees at Hökaberg and the nitrogen trend in their foliage. Although fast-growing trees normally contained nitrogen concentrations in their needles higher than the average during the five-year period 1956 to 1960, they showed a tendency to lower this nitrogen level more than slow-growing trees. This is easy to explain, if we assume that growth is also limited by factors other than nitrogen supply, and that growth varied more than nitrogen uptake, but the phenomenon is certainly a difficulty in the accurate interpretation of diagnostic plant analyses.

In summary we may conclude that the experiment has given us some idea about the nitrogen optimum for spruce under the experimental conditions and that it has also given valuable information about some of the difficulties in the interpretation of foliar analyses. The great influence of tree vigour (often correlated with size) on foliage nutrient levels should always be kept in mind in the interpretation of leaf analyses, but it should also be remembered that size variation is a local phenomenon, while foliage concentration levels are more universally applicable—at least we hope so.

6.2. Future experimentation

These experiments may also be considered as model experiments and thereby help us to design new and better experiments in order to determine the optimum range of both nitrogen and other plant nutrients in tree stands. It has been shown that it is possible to maintain a relatively constant nitrogen level over a long period of time by annual control of the foliage concentrations. There is no reason why it should not be possible to establish controlled levels of other nutrients, too, on suitable sites. An important result is also that the heavy applications of fertiliser have apparently not seriously changed the chemical soil properties.

According to the opinion of the present author it would be highly desirable to establish within different countries and on different soils, optimum growth experiments with a range of nutrient applications, wide enough to establish rather well separated nutrient levels in the stand. It should then be attempted to maintain these levels over an extended period of time. In this way we would be able to elucidate many problems both regarding soil productivity and the interaction of various factors, as well as problems related to the use and interpretation of foliar analyses. Also the application of data from pot tests and nutrient solution cultures will be much easier, if we have data available from field experiments in which the nutrient conditions have been kept under control. Of course in field experiments it is not possible to achieve the same strict control as is, for instance, possible in solution culture experiments. In the field we have always to deal with a seasonal variation and with irregular weather conditions. Yet optimum growth experiments in the field constitute a line of research which may form a bridge between basic physiological work and the silvicultural fertiliser experiments, which usually are very much "applied" in character.

Summary

1. Two long-term fertiliser experiments, with annual applications of nitrogen at various levels were carried out in a young spruce plantation. Half the number of plots received PK additions at intervals.
2. Nitrogen effects on volume growth were observed in both experiments; they were most distinct in the "Hökaberg" experiment, which was laid out on former arable land. In the "Petersburg" experiment, on forest land, the soil heterogeneity might have obscured the fertiliser effects to some extent. The differences between the different nitrogen applications were not statistically different in any of the two experiments.
3. PK-effects on volume growth were not observed at first, but a statistically significant interaction between N and PK was established at Hökaberg at the revisions in 1963 and 1966. A tendency towards positive PK-effect could also be observed at Petersburg in 1966.
4. There was a small initial positive effect of nitrogen applications on the height growth of the spruces at Hökaberg, but later the height development was very similar within the various treatments. The fertiliser effects have shown up mainly in diameter (and volume) growth.
5. The foliar levels of N, P, K, Ca, and Mg were followed by annual sampling of all plots. The highest nitrogen application at Hökaberg (200 kg/ha of nitrogen, from 1963 on 400 kg/ha) maintained a foliar level at or slightly above two per cent of the needle dry weight in most years, while lower applications resulted in a sinking nitrogen trend. Phosphorus and potassium concentrations were increased by the PK treatment, but adversely affected by nitrogen application, as were also calcium and magnesium concentrations.
6. The application of nitrogen increased the nitrogen level of all investigated parts of the trees (wood, bark, branches and needles). A similar effect was observed of the NPK treatment on the phosphorus levels, while the levels of potassium and calcium varied more irregularly in wood, bark and branches.
7. Soil chemical properties were relatively little affected by the fertiliser applications at Hökaberg, but incubation experiments resulted in a release of ammonia from controls and PK-plots and a formation of nitrate (after an initial ammonia release) on N_2 and N_2PK plots.
8. A considerable part of the nitrogen applied in the first four years at

Hökaberg could be accounted for by analysis of the standing crop above ground (more than half the amount in the case of the lowest nitrogen application).

9. Plotting volume data against average foliar nitrogen concentrations yielded an optimum type curve at Hökaberg, with no further growth increase (rather, a decrease), when nitrogen concentrations exceeded 1.6—1.8 per cent dry weight. The corresponding Petersburg diagram showed a positive trend only, but no very high nitrogen applications were tried on this site.
10. Diagrams for volume data plotted against foliar concentrations of other nutrients showed none or more irregular trends, which in some cases could be explained as secondary effects of the nitrogen applications. The importance of these secondary effects in the interpretation of foliar analyses is pointed out.
11. Studies of the statistical correlations between growth and foliar concentrations of nutrients in individual trees have revealed some facts of importance for the use of foliar analysis as a diagnostic tool:
    a) Various growth parameters are almost invariably much more strongly correlated with each other than with nutrient concentrations. This is one of the reasons why such good correlations often obtain between growth and the amounts of nutrients per 1000 needles; the latter figure already contains a growth parameter, viz. the weight of 1000 needles.
    b) Although positive correlations are normally found between growth and the needle levels of growth-limiting nutrients, cases may be met with in which this correlation is negative, or at least where strong growth is associated with a negative trend in foliar levels.
12. Although there has been variation in foliar levels from year to year and therefore some inaccuracy in certain of the studied relationships between growth and nutrient levels, it is concluded that long-term experiments of this type would be of considerable help in the continued study of forest nutrition, forming a bridge between physiological laboratory experiments under strict control and field experiments of more traditional type.

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Sammanfattning

Ett försök att fastställa det optimala kvävetillståndet i gran under fältförhållanden

1. Två långtidsförsök med årlig tillförsel av kväve i olika doseringar till unga granplanteringar beskrivs. Halva antalet försöksytor erhöll dessutom vid vissa tillfällen gödsling med fosfor och kalium. Försöksytorna var belägna på Remningstorps försöksskog i Skaraborgs län, den ena (»Hökaberg») på tidigare åkermark, den andra (»Petersburg») på skogsmark. Bägge planteringarna hade gjorts 1947 med 4-årig gran. Hökaberg-försöket lades ut våren 1957 och Petersburg-försöket våren 1958.
2. I båda försöken observerades positiva kväveeffekter på volymtillväxten, tydligast i Hökaberg-försöket. I Petersburg-försöket försvåras tolkningen av resultaten av ojämnheter i marken. I intetdera av försöken observerades några säkra skillnader i effekt mellan olika kvävedoseringar.
3. Till en början kunde ingen effekt av PK-tillförseln iakttas på volymtillväxten, men vid de senare revisionerna av Hökaberg-försöket 1963 och 1966 förekom en statistiskt signifikant samspelseffekt mellan kväve och PK. Även på Petersburg kunde en tendens till positiv PK-effekt observeras 1966.
4. Höjdmätningar av granarna i Hökaberg-försöket visade att kvävetillförseln under de första åren hade en viss positiv effekt på höjdtillväxten, men senare har höjdutvecklingen varit mycket likartad inom alla försöksled. Gödslingseffekterna har således huvudsakligen kommit fram som diameter- och volymtillväxtökningar.
5. Växtnäringstillståndet i granbarren med avseende på kväve, fosfor, kalium, kalcium och magnesium har följts genom årlig provtagning av alla försöksparceller. Den högsta kvävedoseringen på Hökaberg, 400 kg N/ha från 1963, har vidmakthållit en nivå vid eller strax över 2 % kväve i granbarren under flertalet år, medan de lägre doseringarna resulterade i sjunkande kvävehalter under försöksperioden. Fosfor- och kaliumkoncentrationerna ökades genom PK-tillförseln men minskades genom kvävegödsling. Även kalcium- och magnesiumkoncentrationerna sänktes genom kvävegödsling.
6. Tillförseln av kväve ökade kvävehalten i alla studerade delar av trädet, ved, bark, grenar och barr. NPK-behandlingen hade en liknande effekt på fosfor-nivån medan kalium- och kalciuminnehållet varierade mera oregelbundet i ved, bark och grenar.
7. Markens kemiska egenskaper påverkades relativt litet av gödslingsåtgärderna men kvävemobiliseringsförsök resulterade i att prov från kvävegödslade parceller (med och utan PK) frigjorde nitratkväve i avsevärda mängder efter 6 och 9 veckors lagringstid, medan prov från ogödslade eller med enbart PK gödslade parceller endast bildade ammoniumkväve. Det var dock ingen klar skillnad mellan olika behandlingar i totalmängden frigjort kväve.

8. En avsevärd del, upp till mer än hälften, av det kväve som tillförts under de första fyra åren i Hökaberg-försöket, kunde återfinnas i beståndet vid revisionen 1960, då provträd togs ut så att deras näringsinnehåll ovan mark kunde beräknas.
9. När sambandet mellan totalvolym eller volymtillväxt och genomsnittlig kvävehalt under försöksperioden undersöktes erhölls en optimumkurva för Hökaberg, där tillväxten ökade vid låga kvävehalter men fr.o.m. värden mellan 1,6 och 1,8 % av torrvikten i exponerade barr höll sig konstant eller t.o.m. sjönk. I Petersburg-försöket erhölls ökande tillväxt med ökande kvävegiva men det är då att märka att någon verkligt stark kvävegödsling icke förekom i detta försök.
10. När motsvarande samband undersöktes för totalvolym eller volymtillväxter i relation till halterna av andra växtnäringsämnen i barren, erhölls mera oregelbundna samband, vilka i flera fall kunde förklaras som sekundäreffekter av kvävetillförseln. Sådana sekundäreffekter kan ibland vara ganska besvärliga för tolkningen av diagnostiska växtanalyser.
11. En serie beräkningar har gjorts av de statistiska sambanden mellan tillväxt och näringshalter i individuella träd, varvid flera ytterligare resultat av intresse för användningen av diagnostisk växtanalys har kommit fram:
    a) Olika mått på tillväxten är nästan alltid starkare korrelerade inbördes än med näringshalterna i barren. Detta är ett av de skäl varför man vanligen får så goda korrelationer mellan tillväxten och växtnäringsmängden, när denna mätes som innehåll per 1 000 barr. Denna senare siffra innehåller redan ett tillväxtmått, nämligen vikten av 1 000 barr.
    b) Trots att positiva korrelationer normalt uppträder mellan tillväxten och halterna av tillväxtbegränsande växtnäringsämnen i barren, kan fall uppkomma där denna korrelation är negativ eller åtminstone där en stark tillväxt är associerad med sjunkande halter i barren under en viss period.
12. Trots att det har varit en viss variation i barrnivåerna av kväve från år till år och följaktligen en viss brist på precision i några av de studerade relationerna mellan tillväxt och näringshalter, är det uppenbart att långtidsförsök av denna typ är av stort principiellt värde för fortsatta studier av skogens näringshushållning. Sådana försök kan överbrygga den klyfta som f. n. existerar mellan fysiologiska laboratorieförsök under noggrann kontroll och fältförsök av traditionell typ.

Tables

Table 1. Fertilizer applications in kilogram per hectare (of element). Nitrogen was given as ammonium nitrate limestone; phosphorus and potassium as superphosphate and potassium sulphate respectively, at start, and mixed PK-fertilizer (20—20) from 1959 on.

	Plot No.	1957			1958			1959			1960	1961	1962			1963	1964	1965			1966
		N	P	K	N	P	K	N	P	K	N	N	N	P	K	N	N	N	P	K	N
Hökaberg	1	50			25			50			50	50	50			50	50	50			50
	2	100			50			100			100	100	100			100	100	100			100
	3	200			100			200			200	200	200			400	400	400			400
	4	100	30	50	50			100	31	59	100	100	100	30	57	100	100	100	30	57	100
	5	50	30	50	25			50	31	59	50	50	50	30	57	50	50	50	30	57	50
	6		30	50					31	59				30	57				30	57	
	7		30	50					31	59				30	57				30	57	
	8		—						—		—	—		—		—	—		—		—
	9	200	30	50	100			200	31	59	200	200	200	30	57	400	400	400	30	57	400
	10	100			50			100			100	100	100			100	100	100			100
	11	200	30	50	100			200	31	59	200	200	200	30	57	400	400	400	30	57	400
	12	50	30	50	25			50	31	59	50	50	50	30	57	50	50	50	30	57	50
	13	100	30	50	50			100	31	59	100	100	100	30	57	100	100	100	30	57	100
	14		—						—		—	—		—		—	—		—		—
	15	50			25			50			50	50	50			50	50	50			50
	16	200			100			200			200	200	200			400	400	400			400
Petersburg	1	—					50														
	2	—			50		50	50			50	50	50			50	50	50			50
	3	—				30								30	57				30	57	
	4	—				30	50							30	57				30	57	
	5	—			100	30	50	100			100	100	100	30	57	100	100	100	30	57	100
	6	—			50	30	50	50			50	50	50	30	57	50	50	50	30	57	50
	7	—			100			100			100	100	100			100	100	100			100
	8	—			50	30		50			50	50	50	30	57	50	50	50	30	57	50
	9	—			50			50			50	50	50			50	50	50			50
	10	—			100	30		100			100	100	100	30	57	100	100	100	30	57	100
	11	—				—			—		—	—		—		—	—		—		—
	12	—			100		50	100			100	100	100			100	100	100			100

Table 2. Some analytical data for top soil (0—20 cm) of some plots within the Hökaberg experiment. Sampling April 18, 1967. Most chemical determinations according to standard methods approved by the Swedish Board of Agriculture. Per cent values refer to dry weight, mg/100 g to air dry weight, in both cases for material <2 mm. pH and conductivity with volume ratio soil : water 1 :1.

Plot No.	Treat-ment	Fraction of sample finer than			$D_{75\%}$	Texture index	Base mineral index	Conductivity $mho \cdot 10^{-6}$	pH	
		20 mm	2 mm	2μ	μ	(log $D_{75\%}$)		(20° C)	H_2O	KCl(1M)
8	O	96	74	8	68	1.8	8.4	113	5.0	3.9
14	O	96	78	8	60	1.8	8.9	135	5.0	4.0
6	PK	95	66	9	85	1.9	9.6	198	5.1	3.9
7	PK	98	75	8	55	1.7	12.3	108	4.9	3.9
2	N_2	95	68	7	70	1.8	8.9	120	5.1	4.0
10	N_2	98	64	7	120	2.1	11.2	118	5.1	4.0
4	N_2PK	99	75	8	46	1.7	12.2	108	4.9	3.9
13	N_2PK	95	78	7	72	1.8	9.1	129	4.8	3.9

Table 3. Physical properties of top soil (0—5 cm) of plot No. 8, Hökaberg (October 22, 1961) (average for 12 random samples taken out with an auger, diameter 69 mm; the data expressed as mm water multiplied by 12/13, as a thirteenth sample point fell on a stone.)

	At sampling	Free drainage over night	Suction			Wilting point	Avail-able water at sampling
			20 cm water	100 cm water	1/3 atm	(Helian-themum + Triticum)	
Waterholding capacity as mm water column	11.5	25.1	20.8	12.4	10.7	3.6	7.9

	Amount >2 mm per cent	Pore volume per cent of volume	Bulk density	Compact density
Other physical properties (Range within parantheses)	21.7 (7—68)	60.2 (51—65)	1.03 (0.90—1.27)	2.59 (2.57—2.61)

Table 2 (cont.). "Total" analysis means boiling with nitric and perchloric acid. Lactate soluble means P—AL, K—AL, etc. $D_{75\%}$ is the particle diameter which is exceeded by 75 per cent of the material (by weight). The lowest line in the table indicates the amounts in kg per hectare of elements, average for control plots, calculated on the assumption of one hectare having, to the depth 20 cm, $2 \cdot 10^6$ kg soil passing a 2 mm sieve.

Phosphorus			Potassium			Calcium			Magnesium		
Total %	Lactate-soluble mg/100 g	HCl-soluble mg/100g	Total %	Lactate-soluble mg/100 g	HCl-soluble mg/100g	Total %	Lactate-soluble mg/100 g	HCl-soluble mg/100 g	Total %	Lactate-soluble mg/100 g	HCl-soluble mg/100 g
0.061	1.1	33	0.103	5	50	0.29	31	120	0.23	5	140
0.055	0.2	30	0.096	6	42	0.16	29	110	0.17	4	120
0.075	2.4	31	0.197	12	76	0.25	57	170	0.28	5	180
0.057	1.9	34	0.107	11	50	0.19	32	110	0.18	4	100
0.056	0.2	36	0.141	5	70	0.26	47	170	0.26	5	190
0.063	1.0	35	0.162	5	60	0.27	55	160	0.24	6	170
0.069	1.7	33	0.105	6	44	0.32	42	150	0.23	4	140
0.059	2.3	31	0.073	6	32	0.15	34	90	0.12	3	80
1200	13	630	2000	110	920	4600	610	2400	4000	80	2600

Table 4. Loss on ignition and amounts of nitrogen, total and released as ammonia and nitrate in incubation tests on top soil (0—20 cm). Hökaberg experiment, sampling April 18, 1967.

Plot No.	Treatment	Loss on ignition %	N Kjeldahl %	NH_4-Nppm			NO_3-Nppm			NH_4-N+NO_3-N per cent of N Kjeldahl		
				start	6 weeks	9 weeks	start	6 weeks	9 weeks	start	6 weeks	9 weeks
8	O	4.61	0.161	5.2	47.0	47.3	1.1	1.0	1.4	0.34	2.57	2.60
14	O	5.29	0.161	3.1	42.0	45.5	0.9	0.9	1.1	0.23	2.40	2.60
6	PK	6.70	0.192	3.6	57.2	70.4	1.0	0.9	0.9	0.23	2.95	3.62
7	PK	5.89	0.178	3.3	43.6	47.6	0.8	0.7	1.2	0.23	2.41	2.65
2	N_2	5.81	0.158	4.4	36.8	12.4	0.9	26.5	63.3	0.26	3.07	3.68
10	N_2	5.48	0.169	4.3	40.1	16.4	0.9	13.8	40.3	0.27	2.79	2.94
4	N_2PK	6.14	0.200	4.4	33.3	10.9	0.9	17.6	42.0	0.24	2.35	2.44
13	N_2PK	4.70	0.152	3.5	28.2	10.5	0.8	27.8	53.7	0.23	3.00	3.43

Table 5. Concentrations of nutrients in exposed needles, Hökaberg 1956—1960. All values per cent dry weight. Each figure average for two duplicate plots. N4 changed to N8 from 1963 on.

Fertilisation N	PK	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966
						N						
—	—	1.24	1.54	1.62	1.44	1.40	1.57	1.29	1.45	1.32	1.56	1.48
—	+	1.14	1.59	1.60	1.42	1.35	1.64	1.33	1.56	1.38	1.52	1.54
N1	—	1.28	1.76	1.59	1.70	1.44	1.72	1.34	1.62	1.49	1.61	1.52
N1	+	1.32	1.79	1.71	1.66	1.56	1.79	1.43	1.62	1.58	1.61	1.46
N2	—	1.34	2.11	1.82	1.77	1.68	1.87	1.52	1.72	1.64	1.59	1.52
N2	+	1.23	2.02	1.84	1.94	1.83	1.94	1.56	1.87	1.72	1.68	1.60
N4	—	1.26	2.69	2.03	2.04	1.90	2.14	1.70	2.12	2.10	2.14	2.18
N4	+	1.30	2.64	2.08	2.21	2.01	2.24	1.66	2.36	2.24	2.16	2.36
						P						
—	—	0.174	0.225	0.230	0.204	0.226	0.244	0.209	0.199	0.200	0.226	0.210
—	+	0.157	0.222	0.258	0.218	0.244	0.276	0.237	0.241	0.232	0.260	0.228
N1	—	0.180	0.203	0.206	0.170	0.179	0.186	0.172	0.178	0.168	0.186	0.178
N1	+	0.174	0.236	0.250	0.218	0.231	0.260	0.206	0.224	0.217	0.253	0.230
N2	—	0.162	0.194	0.185	0.153	0.160	0.175	0.150	0.177	0.156	0.172	0.172
N2	+	0.171	0.232	0.244	0.204	0.220	0.240	0.212	0.223	0.214	0.226	0.224
N4	—	0.178	0.212	0.193	0.150	0.166	0.185	0.151	0.168	0.150	0.166	0.161
N4	+	0.164	0.233	0.223	0.178	0.180	0.228	0.182	0.210	0.180	0.204	0.186
						K						
—	—	0.74	0.88	0.94	0.98	0.89	0.98	0.92	0.83	0.90	0.77	0.90
—	+	0.71	0.86	0.91	0.92	0.84	1.09	0.92	0.89	0.94	0.86	0.82
N1	—	0.74	0.82	0.88	0.92	0.88	0.99	0.88	0.82	0.78	0.78	0.72
N1	+	0.75	0.90	0.96	1.04	0.79	1.02	0.87	0.88	0.88	0.85	0.83
N2	—	0.72	0.82	0.88	0.88	0.66	0.92	0.71	0.79	0.75	0.72	0.74
N2	+	0.72	0.87	0.95	0.95	0.75	0.88	0.74	0.82	0.83	0.72	0.78
N4	—	0.72	0.68	0.79	0.80	0.70	0.76	0.60	0.64	0.65	0.62	0.69
N4	+	0.70	0.76	0.84	0.85	0.68	0.88	0.69	0.73	0.66	0.67	0.72
						Ca						
—	—	0.68	0.68	0.74	0.58	0.60	0.74	0.72	0.63	0.64	0.64	0.66
—	+	0.70	0.76	0.70	0.59	0.62	0.82	0.69	0.68	0.66	0.67	0.66
N1	—	0.66	0.64	0.63	0.40	0.56	0.68	0.46	0.58	0.60	0.61	0.60
N1	+	0.70	0.68	0.68	0.62	0.56	0.74	0.68	0.66	0.68	0.68	0.70
N2	—	0.70	0.62	0.58	0.44	0.54	0.56	0.53	0.49	0.52	0.52	0.56
N2	+	0.65	0.58	0.63	0.51	0.56	0.66	0.55	0.50	0.50	0.54	0.53
N4	—	0.64	0.57	0.55	0.37	0.49	0.58	0.44	0.43	0.40	0.40	0.34
N4	+	0.66	0.56	0.58	0.38	0.51	0.54	0.43	0.49	0.44	0.40	0.42
						Mg						
—	—	0.118	0.114	0.107	0.117	0.104	0.114	0.111	0.141	0.110	0.118	0.121
—	+	0.099	0.113	0.110	0.118	0.100	0.108	0.106	0.118	0.108	0.114	0.125
N1	—	0.128	0.108	0.081	0.088	0.092	0.093	0.091	0.108	0.106	0.107	0.108
N1	+	0.109	0.115	0.092	0.082	0.098	0.091	0.090	0.109	0.096	0.100	0.121
N2	—	0.122	0.111	0.081	0.078	0.079	0.078	9.082	0.088	0.086	0.088	0.117
N2	+	0.108	0.110	0.094	0.079	0.082	0.085	0.083	0.109	0.089	0.094	0.116
N4	—	0.116	0.086	0.079	0.078	0.072	0.070	0.061	0.074	0.066	0.070	0.088
N4	+	0.096	0.103	0.081	0.070	0.064	0.068	0.070	0.095	0.071	0.076	0.091

Table 6. Concentrations of nutrients in exposed needles, Petersburg 1957—1966. All values per cent dry weight. Each figure average for two plots similarly treated (except for K addition in 1958, see Table 1).

Fertilisation N	PK	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966
							N				
—	—	1.74	1.94	1.38	1.17	1.22	1.10	1.13	1.10	1.23	1.24
—*	—	—	—	—	—	—	—	1.52	1.35	1.47	1.48
—	+	1.96	2.16	1.75	1.56	1.76	1.49	1.56	1.26	1.34	1.25
N1	—	1.82	2.15	1.92	1.72	2.00	1.65	1.96	1.82	1.70	1.52
N1	+	1.88	2.23	1.72	1.68	1.88	1.68	1.93	1.76	1.72	1.52
N2	—	1.80	2.52	2.07	2.03	2.14	1.77	2.12	1.82	1.80	1.57
N2	+	1.96	2.31	2.04	2.06	2.08	1.76	2.12	1.84	1.93	1.73
							P				
—	—	0.207	0.223	0.150	0.188	0.196	0.171	0.176	0.164	0.160	0.160
—*	—	—	—	—	—	—	—	0.206	0.199	0.203	0.188
—	+	0.230	0.350	0.235	0.271	0.301	0.280	0.299	0.271	0.317	0.260
N1	—	0.210	0.233	0.181	0.194	0.208	0.178	0.190	0.190	0.194	0.166
N1	+	0.220	0.318	0.212	0.248	0.294	0.244	0.304	0.279	0.272	0.212
N2	—	0.211	0.226	0.168	0.184	0.204	0.175	0.186	0.175	0.180	0.159
N2	+	0.224	0.330	0.214	0.244	0.291	0.247	0.284	0.256	0.282	0.221
							K				
—	—	0.78	0.93	0.84	0.81	0.96	0.88	0.84	0.84	0.68	0.66
—*	—	—	—	—	—	—	—	0.99	1.10	1.00	0.88
—	+	0.74	0.92	0.84	0.84	1.03	1.05	0.99	1.11	0.99	1.00
N1	—	0.74	0.88	0.88	0.76	0.90	0.83	0.88	0.94	0.82	0.74
N1	+	0.78	0.90	0.90	0.80	0.92	0.96	0.98	0.98	0.90	0.78
N2	—	0.75	0.85	0.80	0.69	0.80	0.80	0.86	0.89	0.82	0.72
N2	+	0.78	0.92	0.84	0.66	0.92	0.87	0.88	0.90	0.84	0.76
							Ca				
—	—	0.40	0.42	0.26	0.34	0.48	0.42	0.47	0.56	0.46	0.36
—*	—	—	—	—	—	—	—	0.54	0.57	0.53	0.51
—	+	0.48	0.52	0.31	0.44	0.56	0.45	0.44	0.47	0.46	0.36
N1	—	0.54	0.52	0.29	0.54	0.59	0.42	0.46	0.45	0.38	0.32
N1	+	0.53	0.57	0.27	0.54	0.66	0.49	0.53	0.59	0.48	0.40
N2	—	0.43	0.44	0.23	0.36	0.44	0.30	0.30	0.30	0.27	0.28
N2	+	0.50	0.58	0.29	0.50	0.65	0.43	0.56	0.48	0.46	0.40
							Mg				
—	—					0.116	0.103	0.142	0.130	0.122	0.122
—*	—					—	—	0.130	0.113	0.099	0.102
—	+					0.094	0.092	0.114	0.113	0.115	0.108
N1	—					0.080	0.078	0.102	0.082	0.090	0.093
N1	+					0.094	0.084	0.110	0.088	0.095	0.096
N2	—					0.068	0.072	0.094	0.073	0.077	0.084
N2	+					0.084	0.070	0.092	0.080	0.082	0.086

* additional control trees, see text

Table 7. Nutrient concentrations in wood, bark, branches and needles within eight plots of the Hökaberg experiment in September, 1960. All values as per cent dry weight. The analyses were made on composite samples from five trees from each plot.

Treatment

	N_0		N_1		N_2		N_4	
	—PK	+PK	—PK	+PK	—PK	+PK	—PK	+PK
				N				
Wood	0.128	0.104	0.124	0.137	0.132	0.153	0.141	0.148
Bark	0.80	0.69	0.80	0.85	0.85	1.00	0.81	0.94
Branches	0.54	0.51	0.64	0.64	0.58	0.68	0.62	0.74
Needles	1.24	1.16	1.28	1.40	1.60	1.65	2.00	2.10
				P				
Wood	0.023	0.017	0.022	0.026	0.019	0.024	0.020	0.024
Bark	0.098	0.094	0.086	0.115	0.087	0.115	0.073	0.096
Branches	0.084	0.080	0.079	0.106	0.065	0.082	0.062	0.083
Needles	0.177	0.184	0.122	0.171	0.120	0.166	0.110	0.144
				K				
Wood	0.142	0.119	0.130	0.126	0.101	0.124	0.124	0.110
Bark	0.51	0.46	0.42	0.47	0.34	0.45	0.35	0.38
Branches	0.38	0.31	0.37	0.38	0.30	0.29	0.25	0.34
Needles	0.68	0.72	0.57	0.64	0.60	0.57	0.42	0.45
				Ca				
Wood	0.073	0.060	0.063	0.069	0.066	0.071	0.066	0.064
Bark	0.71	0.78	0.72	0.82	0.85	0.74	0.68	0.64
Branches	0.44	0.52	0.48	0.50	0.45	0.50	0.46	0.44
Needles	1.24	1.40	1.00	1.27	1.20	1.12	1.11	1.12

Table 8. Tree heights and stem volumes in the Hökaberg experiment. The data are arithmetic mean values. Number of stems before cleaning in 1960, with numbers after cleaning within parentheses.

Block			Nitrogen regime N_0	N_1	N_2	N_{4-8}	average
I	Plot No.	a	8	1	2	3	
—PK	Number of stems	b	47 (29)	66 (36)	68 (39)	65 (39)	
	Mean height 1956 m	c	1.82	1.56	1.47	1.56	
	» » 1966 m	d	7.50	6.80	6.90	6.40	
	» volume o.b. dm³ 1960	e	4.94	3.50	4.02	4.24	
	» » » » 1963	f	15.77	11.65	12.92	13.72	
	» » » » 1966	g	30.54	22.65	25.17	25.93	
	» basal area cm² 1966	h	67.55	56.00	59.51	63.85	
IV		a	14	15	10	16	—PK
—PK		b	65 (36)	62 (36)	54 (31)	66 (38)	62 (36)
		c	1.91	1.61	1.87	1.74	1.69
		d	7.90	7.40	8.00	7.50	7.30
		e	5.11	5.24	7.04	5.45	4.94
		f	16.04	16.56	21.73	16.36	15.59
		g	31.01	30.67	39.32	29.78	29.38
		h	66.61	68.97	87.58	66.89	67.12
II		a	6	5	4	9	
+PK		b	62 (35)	63 (36)	66 (38)	55 (31)	
		c	1.56	1.74	1.64	1.70	
		d	7.60	7.70	7.80	8.10	
		e	3.70	5.64	5.44	7.23	
		f	12.34	18.13	17.73	22.79	
		g	26.28	34.55	33.27	40.03	
		h	59.40	74.50	73.39	81.80	
III		a	7	12	13	11	+PK
+PK		b	50 (28)	55 (34)	56 (33)	37 (34)	58 (34)
		c	1.70	1.88	1.79	1.75	1.72
		d	7.60	8.00	7.70	7.60	7.76
		e	4.49	6.58	5.43	5.47	5.50
		f	14.54	21.13	19.11	18.77	18.07
		g	28.86	38.27	36.02	34.59	33.98
		h	63.86	84.85	82.27	79.65	74.96
I+IV+II+III			average N_0	N_1	N_2	N_{4-8}	Entire experiment
		b	56 (32)	62 (36)	61 (35)	61 (36)	60 (35)
		c	1.75	1.70	1.69	1.69	1.70
		d	7.65	7.48	7.60	7.40	7.53
		e	4.56	5.24	5.48	5.60	5.17
		f	14.67	16.87	17.87	17.91	16.83
		g	29.17	31.54	33.44	32.58	31.68
		h	64.36	71.08	75.69	73.05	71.04

Table 9. Tree heights and stem volumes in the Petersburg experiment. The data are arithmetic mean values.

Block			Nitrogen regime N_0	N_1	N_2	
I	Plot No.	a	11	9	7	(additional
—PK	Total number of trees	b	61	58	54	control)
	Mean height 1966 m	c	5.45	5.90	6.05	
	Mean volume 1963	d	6.20	8.58	10.33	
	o.b. dm³ 1966	e	12.56	19.65	21.73	
	Trees 140—200 cm 1957	f	24	15	15	20
	Mean height 1957, m	g	1.66	1.60	1.66	1.68
	» » 1966, m	h	6.50	7.04	6.89	6.50
	Mean volume o.b. dm³ 1961	i	5.27	5.82	7.86	
	Mean volume o.b. dm³ 1963	k	10.59	15.43	17.45	10.22
	Mean volume o.b. dm³ 1966	l	20.40	32.98	33.24	22.62
		a	1	2	12	—PK average
III		b	62	62	62	60
—PK		c	5.00	6.28	4.99	5.61
		d	5.50	11.07	6.01	7.95
		e	9.86	21.68	14.04	16.59
		f	23	25	6	18
		g	1.65	1.62	1.62	1.64
		h	5.56	6.78	6.75	6.60
		i	4.00	6.27	7.05	6.04
		k	7.06	13.60	15.12	13.21
		l	12.56	26.57	32.49	26.37
		a	3	8	10	
II		b	51	39	66	
+PK		c	5.99	5.86	6.10	
		d	9.21	9.59	9.82	
		e	18.97	24.35	21.09	
		f	15	9	8	
		g	1.61	1.55	1.55	
		h	7.01	7.21	6.90	
		i	6.45	6.36	6,61	
		k	14.21	17.21	14.31	
		l	28.15	41.55	29.82	
		a	4	6	5	+PK average
IV		b	57	54	62	55
+PK		c	5.79	5.90	6.27	5.98
		d	7.68	8.52	10.77	9.26
		e	16.12	21.09	21.99	20.60
		f	10	13	15	12
		g	1.62	1.58	1.62	1.59
		h	6.79	6.85	7.05	6.97
		i	5.98	6.12	7.02	6.42
		k	14.80	15.53	16.41	15.41
		l	29.89	35.23	34.27	33.15

		average N_0	N_1	N_2	Entire experiment
I+II+III+IV	b	58	53	60	57
	c	5.56	5.98	5.85	5.80
	d	7.15	9.44	9.37	8.61
	e	14.38	21.69	19.71	18.59
	f	18	16	11	15
	g	1.64	1.59	1.61	1.61
	h	6.49	6.97	6.90	6.78
	i	5.43	6.14	7.14	6.23
	k	11.66	15.44	15.82	14.31
	l	22.75	34.08	32.46	29.76

Table 10. Standing volume at first revision and annual volume growth at Hökaberg and Petersburg. (Values within parenthesis corrected for initial differences in mean height).

HÖKABERG

Treatment	Plot No.	Volume 1960 m^3 o.b.	Annual growth m^3 o.b. 1961—1963	1964—1966
N_0	8	22.5 (19.2)	10.5 (10.2)	14.3 (14.1)
	14	30.7 (24.9)	13.1 (11.8)	18.0 (16.8
PK	6	21.2 (25.1)	10.0 (10.9)	16.3 (17.0)
	7	19.3 (19.2)	9.4 (9.0)	13.4 (13.1)
N_1	1	23.4 (27.3)	9.8 (10.8)	13.2 (14.1)
	15	28.4 (31.2)	13.6 (13.7)	16.9 (17.0)
N_1PK	5	33.2 (32.1)	15.0 (14.6)	19.7 (19.3)
	12	37.3 (35.0)	16.4 (16.1)	19.4 (19.0)
N_2	2	24.6 (31.0)	11.9 (12.9)	15.6 (16.5)
	10	36.7 (32.0)	15.2 (14.4)	18.2 (17.4)
N_2PK	4	32.7 (34.3)	15.6 (15.8)	19.7 (19.9)
	13	32.8 (30.3)	15.0 (15.1)	18.6 (18.6)
N_{4-8}	3	29.0 (32.9)	12.3 (13.5)	15.9 (16.9)
	16	33.6 (32.4)	13.8 (13.4)	17.0 (16.6)
N_{4-8}8K	9	34.2 (34.1)	16.1 (15.4)	18.1 (17.5)
	11	32.1 (30.7)	15.1 (15.2)	17.9 (18.0)

PETERSBURG

Treatment	Plot No.	Volume 1961 m^3 o.b.	Annual growth m^3 o.b. 1962—1963	1964—1966
N_0	11	12.1	6.4	8.7
	1	12.7	5.0	6.2
PK	3	13.5	8.9	10.9
	4	11.3	9.0	10.8
N_1	9	11.9	10.6	14.3
	2	21.4	12.2	14.3
N_1PK	8	8.6	8.1	12.8
	6	11.0	9.8	15.0
N_2	7	15.8	10.7	13.8
	12	9.8	7.5	11.0
N_2PK	10	18.4	12.4	16.3
	5	18.7	12.9	15.5

Table 11. Mean squares and variance ratios from statistical analysis of volume 1960 of spruce ("Hökaberg" experiment). Analysis of covariance with average height in 1956 as independent variable. For variance ratios within parenthesis, see text. One, two, or three asterisks denote the significance levels 5, 1, and 0.1 per cent.

Source of variation	Analysis of variance				Analysis of covariance			
	Degrees of free-dom	Sum of squares	Mean square	Variance ratio	Degrees of free-dom	Sum of squares	Mean square	Variance ratio
Between blocks	3	123.26			2	37.38		
Between PK and no PK	1	12.25	12.25	0.22(2.38)	1	3.25	3.25	0.10(0.98)
Other block variation	2	111.01	55.50	10.80*	1	34.13	34.13	9.72*
Between N levels	3	199.00			3	268.69		
Between N_0 and $N_1+N_2+N_4$	1	193.60	193.60	37.66***	1	261.88	261.88	74.67***
Between N applications	2	5.40	2.70	0.53	2	6.81	3.40	0.97
Interaction	3	122.70			3	9.87		
Interaction PK×N	1	86.40	86.40	16.81**	1	0.83	0.83	0.24
Interaction PK×N appl.	2	36.30	18.15	3.53	2	9.04	4.52	1.29
Error	6	30.84	5.14		5	17.54	3.51	
	15	475.80			13	333.48		

Table 12. Mean squares and variance ratios from statistical analysis of volume growth 1961—63 of spruce ("Hökaberg") experiment. See also legend to Table 11.

Source of variation	Analysis of variance				Analysis of covariance			
	Degrees of free dom	Sum of squares	Mean square	Variance ratio	Degrees of free-dom	Sum of squares	Mean square	Variance ratio
Between blocks	3	230.46			2	58.88		
Between PK and no PK	1	87.89	87.89	1.23(16.8**)	1	55.32	55.32	15.5(9.58)
Other block variation	2	142.57	71.28	(13.6**)	1	3.56	3.56	0.62
Between N levels	3	320.91			3	408.17		
Between N_0 and $N_1+N_2+N_4$	1	310.59	310.59	59.4***	1	396.10	396.10	68.5***
Between N applications	2	10.32	5.16	0.99	2	12.07	6.04	1.05
Interaction	3	184.36			3	79.41		
Interaction PK×N	1	159.50	159.50	30.5**	1	57.04	57.04	9.89*
Interaction PK×N appl.	2	24.86	12.43	2.38	2	22.37	11.18	1.93
Error	6	31.36	5.23		5	28.87	5.77	
Total variation	15	767.09			13	575.33		

Table 13. Mean squares and variance ratios from statistical analysis of volume growth 1964—66 of spruce ("Hökaberg" experiment). See also legend to Table 11.

Source of variation	Analysis of variance				Analysis of covariance			
	Degrees of free-dom	Sum of squares	Mean square	Variance ratio	Degrees of free-dom	Sum of squares	Mean square	Variance ratio
Between blocks	3	271.64			2	108.56		
Between PK and no PK	1	110.25	110.25	1.37(15.91**)	1	74.50	74.50	2.19(24.92**)
Other block variation	2	161.39	80.70	11.65**	1	34.06	34.06	11.39*
Between N levels	3	123.86			3	153.29		
Between N_0 and $N_1+N_2+N_3$.	1	109.81	109.81	15.85**	1	137.05	137.05	45.84**
Between N applications	2	14.05	7.03	1.01	2	16.24	8.12	2.72
Interaction	3	154.40			3	146.45		
Interaction PK × N	1	111.63	111.63	16.11**	1	81.07	81.07	27.11**
Interaction PK × N appl.	2	42.77	21.39	3.09	2	65.38	32.69	10.93*
Error	6	41.56	6.93		5	14.93	2.99	
	15	591.46			13	423.23		

Table 14. Analysis of variance of average volumes (in dm³) in 1966 of spruces within the experiment "Petersburg". Only trees between 140 and 200 cm at start.

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio
Between blocks	3	172.62		
Between PK and no PK . .	1	133.20	133.20	6.76 (8.40*)
Other block variation	2	39.42	19.71	1.24
Between N levels	2	270.03		
Between N_0 and N_1+N_3 . .	1	264.74	264.74	16.70*
Between N applications . . .	1	5.30	5.30	0.33
Interaction	2	72.34		
Interaction PK × N	1	27.83	27.83	1.76
Interaction PK × N appl. . .	1	44.51	44.51	2.81
Error	4	63.39	15.85	
Total variation	11	578.38		

Table 15. Dry weight of stand and amounts of nutrients taken up at Hökaberg. Sampling in September, 1960. Dry weight figures given both as computed from measured stem volumes and dry weight factors determined individually (for 8 plots) and as estimated from stem volumes adjusted for initial height differences and the mean dry weight factors for the whole experiment. The amounts of nutrients are based upon the latter set of dry weights, but can also be computed from the first sets of dry weights and the concentrations given in Table 7.

	Measured stem volumes, m^3 o.b. per hectare							
	N_0		N_1		N_2		N_4	
	—PK	+PK	—PK	+PK	—PK	+PK	—PK	+PK
	30.7	21.2	23.4	37.3	36.7	32.8	29.0	32.1
	Dry weight, kg per hectare							
Wood	10740	7040	8100	12160	13180	10730	10270	10180
Bark	1900	1570	1640	2320	2640	1950	2410	2080
Branches	9240	7460	8280	12120	11960	10070	10760	11460
Needles	10440	8800	9940	14100	14570	11710	12350	13000
Sum	32320	24870	27960	40700	42350	34460	35790	36720
	Conversion factors for dry weight from stem volume							
Wood	0.339							
Bark	0.068							
Branches	0.337							
Needles	0.393							
	Stem volumes, adjusted for initial height differences, m^3 o.b. per hectare							
	24.9	25.1	27.3	35.0	32.0	30.3	32.9	30.7
	Dry weight of stand above ground, estimated from adjusted volumes, kg per hectare							
	28300	28500	31000	39800	36400	34500	37400	34900
	Amounts of nitrogen in stand above ground, kg per hectare							
	161	198	243	297	305	281	388	385
	180		270		293		387	
	Amounts of phosphorus in stand above ground, kg per hectare							
	24	31	28	40	24	29	30	32
	28		34		27		31	
	Amounts of potassium in stand above ground, kg per hectare							
	106	123	126	154	127	109	121	113
	115		140		118		117	
	Amounts of calcium in stand above ground, kg per hectare							
	161	205	183	258	236	193	237	211
	183		220		214		224	

Table 16. Variation in volume around mean value or regression line among individual unfertilised spruce. One, two, or three asterisks denote the significance levels 5, 1, and 0.1 per cent for the influence of the the variable indicated.

Source of variation	Hökaberg 1956—1960 Mean square	Hökaberg 1956 —1966 Mean square	Petersburg 1957—1966 Mean square
Total variation in volume at end of period indicated	6.85	245.3	53.5
Linear regression on			
average foliar N (X_{23})	5.94 (pos.)**	228.1 (pos.)	52.9 (pos.)
foliar N trend (X_{24})	6.29 (neg.)*	254.4 (neg.)	54.8 (pos.)
X_{23} and X_{24}	5.67	209.5	
height at start (X_{20})	0.96 (pos.)***	33.6 (pos.)***	34.7 (pos.)***
X_{20} and X_{23}	0.98	32.7	
	44 trees average volume 5.5 dm³	26 trees average volume 31.4 dm³	34 trees average volume 18.2 dm³