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Studies on nitrogen mobilisation in forest soils

Studier över kvävemobiliseringen i skogsjord

by

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ABSTRACT

Incubation experiments were performed on samples from various horizons of middle Swedish podzol profiles, stored under aerobic conditions at room temperature for up to two and a half years. More than one-third of the organic matter in the mor sample from a good site disappeared during two years' incubation at room temperature. Twenty-four to twenty-six per cent of its nitrogen content was simultaneously mineralised, the largest part as ammonia. The loss of organic matter was somewhat lower in samples from three poor sites (between 20 and 30 per cent) and the release of nitrogen was also lower (12 to 17 per cent). Both the breakdown and the release of nitrogen were generally lower in A_1 and A_2 samples and much lower in B horizon samples. Liming decreased nitrogen release in mor samples (often to nil) but increased release in B horizon samples. Liming also increased nitrate formation.

Introduction

Nitrogen availability has long been recognized as a major factor limiting forest growth, particularly in podzol sites with a mor humus layer (HESSELMAN 1917, 1926, 1937, ROMELL 1935). Interest has concentrated on the nitrogen in the humus layer (mor or mull), which indubitably supplies the largest part of the annual uptake by the vegetation, at the same time as most of the nitrogen in the litter fall is incorporated into the humus layer. It is very difficult to characterise the availability of the organic bound nitrogen in the various humus constituents by chemical means (WITTICH 1952, HANDLEY 1954, BREMNER 1965, KEENEY & BREMNER 1966 a and KONONOVA 1966), although some progress has been made recently (PERSSON 1968, KEENEY & BREMNER 1966 b). Therefore, most investigators have preferred to use incubation methods in the laboratory, in which soil samples are exposed to their own microflora and fauna (or sometimes to added organisms) for a certain period under favourable temperature and moisture conditions (e.g. HESSELMAN 1926, ZÖTTL 1960). Although it is admitted that the rate of formation of ammonia and nitrate in such experiments is different from that under field conditions, most early experimenters (and some more recent ones, too) overlooked that both the sampling itself and the pretreatment of the sample for the incubation experiment implied a treatment affecting the biological balance, often changing it drastically. This may result in a nitrogen mobilisation which would not take place *in situ*, unless the trees were removed or the soil worked. As ROMELL (1935) has emphasised, a piece of mor *in situ* is interwoven with fine roots and mycorrhizal hyphae. Sampling or even trenching brings about the death of this living material, supplying fresh substrate for decomposing organisms. The intensified breakdown of organic matter and the release of plant nutrients so provoked has been compared by ROMELL (1935) with a green manuring, and he has later (1957) called it the "assart effect" (cf. TAMM 1964).

Romell's criticism of earlier types of incubation experiment led him to try longer incubation periods, in order to measure the nitrogen released by the "assart effect" rather than the normal nitrogen turnover in the soil. His experiments could thus, in a way, be compared with what happens in the soil after clear felling. These experiments, arranged as time series, extended over periods of up to three years. The results have, however, only been published very briefly (MALMSTRÖM 1953, ROMELL 1967). A large fraction (up to one-third) of the mor nitrogen from very poor forests was released as ammonia and nitrate during his experiments. Liming promoted nitrification but reduced the total amount of mineralised nitrogen.

The present experiments are to be regarded as a continuation of Romell's experiments. The methods for the study of the nitrogen release are essentially the same. However, as both old (O. TAMM 1920) and new investigations (TAMM & HOLMEN 1967, TROEDSSON & TAMM, 1969) have shown that there is more organic matter (and nitrogen) in the mineral soil in many podzol profiles than in the A_0 horizon, A_1—A_2 and B horizon samples have also been included in the experiments. An attempt has been made to connect the laboratory investigations on organic matter breakdown with the conditions *in situ* by radiocarbon dating of B horizon samples (TAMM & HOLMEN 1967). Other analyses have also been performed both on the original samples and on those stored for a long period.

Sampling sites

Table 1 summarises some data concerning the sites and profiles from which the samples for the incubation experiments were collected. Some further information is to be found in Table 6 (see also references).

1. *Garpenberg.* State forest district Garpenberg, province of Dalarna. Altitude 196 m, just above the so-called highest shoreline (meaning that the site was never submerged after the last glaciation). Admixture of some basic rock material makes the soil parent material somewhat richer than would be expected from the underlying bedrock, which consists of weathering-resistant leptite. The soil profile type is a podzol, but a distinct A_2 horizon occurs only in patches, which makes the profile transitional towards brown podzolic (see Table 1).

Further details about this site may be found in other publications (TAMM & TROEDSSON 1957, dealing with water movement in the profile; TROEDSSON & TAMM, 1969, dealing with small-scale spatial variation in forest soil properties; TROEDSSON & LYFORD, in prep., with very detailed profile descriptions). Biomass in the stand and on a cleared area has been studied by NYKVIST (in prep.).

2. *Havtjärnheden.* State forest district of Älvdalen, province of Dalarna. Sandy till with a high stone content (fraction $<$ 2 mm ca 55 per cent of sample). The till consists mainly of material from a quartzitic sandstone and is extremely low in minerals releasing lime and other plant nutrients (MALMSTRÖM 1962, with a photo of a profile from the site, Fig. 34). Profile description, see Table 1. The vegetation is of a very poor type, with lichens dominating the ground layer and *Calluna vulgaris* (as low and slow-growing specimens) the field layer (Fig. 1).

3. *Haboskogen.* State forest district of Jönköping, province of Västergötland. Between Lake Vättern and the hill Hökensås (a northwesternly outpost of the central Southern Swedish uplands), extensive plains of outwash sand cover most of the ground. The sand is of glacifluvial origin, and the area is characterised by slightly undulating topography (with lakes and peatlands in the depressions) and a uniform cover of slow-growing pine-forest, sometimes with undergrowth of spruce. The site-class is better only where the tree roots reach moving ground-water, as in some of the gullies cut out by small streams flowing down to Lake Vättern. Both the ground vegetation and the soil pro-

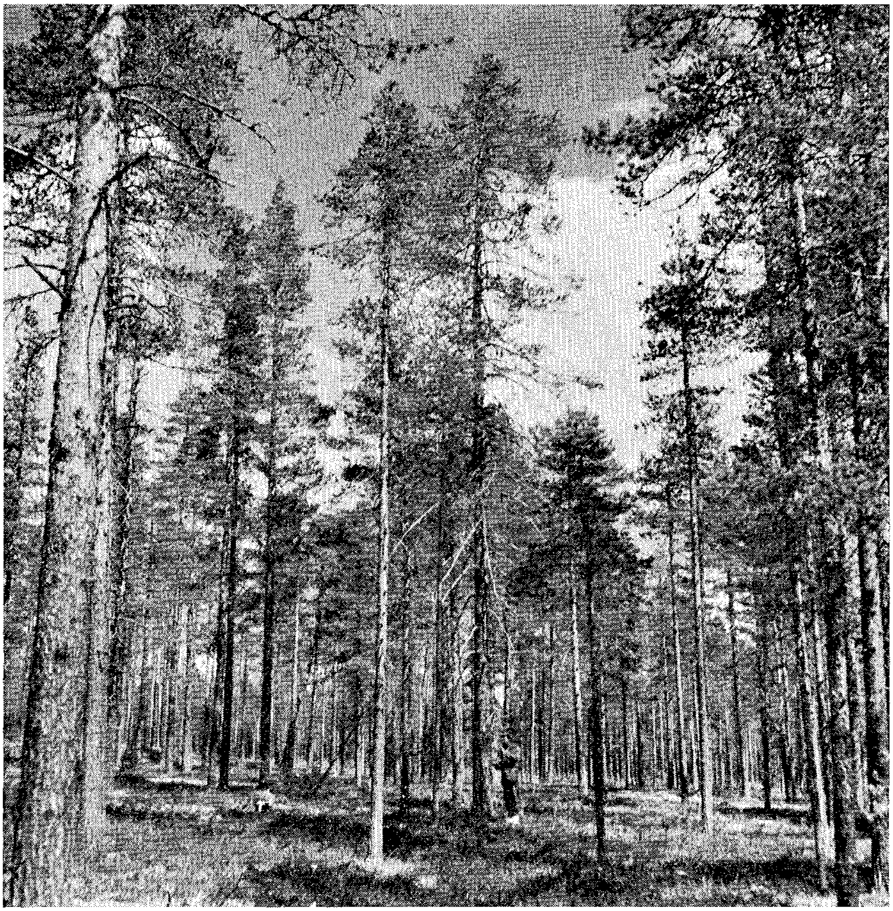

Fig. 1. The Havtjärnheden site

files are fairly uniform over large areas. The vegetation is poor in species and is, as a rule, dominated by one of the dwarf shrubs *Calluna vulgaris*, *Vaccinium vitis idaea* or *Vaccinium myrtillus* (with *Calluna* more common in open stands and *Vaccinium myrtillus* dominating in some of the denser middle-aged stands). The ground layer contains, in varying proportions, lichens (*Cladonia sylvestris* and *rangiferina*) and mosses (particularly *Pleurozium schreberi* but also *Dicranum* species and others). The soil profile is a podzol, usually with a rather deep A_2 horizon and a dark brown B_1 horizon (often a hardpan). Below the B_1 horizon there is a more normal accumulation horizon (B_2) and a gradual transition to the subsoil, which is rich in quartz and has a low content of valuable minerals, as at Havtjärnheden. The A_0 horizon is usually deeper than at Havtjärnheden and other "lichen-pine

Fig. 2. Haboskogen. "Radio-carbon site"

forests" in north Sweden, and often contains considerably more F-layer than H-layer.

Two sites were studied within this area. The samples for incubation experiments were collected close to Experiment No. 876, a fertiliser experiment started in 1955 and showing a very strong response to nitrogen, but not to minerals, in the pine stand (Tamm & Carbonnier 1961, Fig. 11). Soil analyses had earlier been carried out on samples from this site (Table 6). The samples for radiocarbon dating were, however, collected in another part of the same state forest. In fact, two samples were used which had been collected in 1934 by O. Tamm during his pedological studies of the sandy soils in this region (O. Tamm 1937). These samples were preferred to more recent ones as there was no risk of contamination with C14 from nuclear explosions when using old samples. Tables 1 and 6 show some soil data from a profile, which must be very close to that sampled by O. TAMM in 1934, and Fig. 2 a view of the site and the profile (see also Fig. 1 in O. TAMM & C. O. TAMM 1963 and O. TAMM 1937, Fig. 5).

4. *Korpfjäll.* Province of Värmland. Slightly sloping ground on the "saddle" of a ridge. The site sampled had a residual stand of slow-growing spruce, while the surroundings had been clear-felled. The soil profile was an iron podzol with a distinct but variable light grey A_2 horizon. Some mottling was already visible at a depth of 35 to 40 cm, indicating somewhat impeded drainage (as also witnessed by the *Sphagnum* patches). The sampling took place in late autumn in rainy weather and advancing dusk, which made it necessary to simplify sampling and profile descriptions. Therefore the A_0 and B horizons alone were sampled, and amounts per unit area could be calculated for A_0 only (based on auger samples collected at the same time as the main sample).

Methods

The laboratory methods used in this investigation were to a large extent worked out by one of us (A. P.) in collaboration with L.-G. Romell for his above-mentioned investigations into the breakdown of humus layer samples (1967, Fig. 2). The use of mineral soil samples together with mor samples made necessary certain modifications of the methods, which have not been published in full. Therefore a description will be given here of the principles used.

Sampling

Soil samples are to be considered as living systems, particularly in connection with certain analytical procedures, e.g. determination of ammonification and nitrification. As the preparation of samples for incubation experiments involves rather complex treatment (field sampling, sifting, adjustment of water content, preliminary analytical determinations, etc.) before the experiments can be started, it was considered best to collect the samples in late autumn, when the soils had a high natural water content, and when only small chemical and micro-biological changes were to be expected during the interval between sampling and the start of the experiment, provided that storage and most of the treatments took place at the normal low outdoor temperature.

Soil samples are best collected as "monoliths" (Gjems *et al.* 1960), with all horizons sampled. This was usually done in the present sampling, despite the fact that the experiments were carried out with material from certain horizons only. If the sampling is intended to be representative for a certain area, a relatively large number of subsamples must be taken, scattered over the area (Gjems *et al.*, l.c., Troedsson & Tamm, 1969). This was not done in the present case, therefore the samples should only be considered as representing the small (but fairly typical) spot sampled. In some of the sites, however, a comparison can be made with a representative sampling, carried out on another occasion (data for Garpenberg and Haboskogen, Expt. 876, in Table 6).

For the sampling a quadrat (¼—4 m^2) was marked out. Then living vegetation (field layer) was cut with a pair of scissors and collected. The next sampling unit was the litter layer; usually living mosses and lichens were not separated from their litter in this sampling. From the A horizon it was attempted to sample both the A_0 horizon (the mor layer) and the upper part of the mineral soil with some organic content (A_1 and A_2). All the sites studied in this investigation have podzol profiles, although some investigators may prefer to call the Garpenberg profile transitional to brown podzolic. In some cases the boundary between A_0 and A_1 was very irregular, which necessitated sampling of the transition layer as a separate unit. The A_2 horizon was sampled separately in the profiles at Havtjärnheden and Haboskogen, where the grey colour of the horizon suggested a relatively large content of organic matter. At Garpenberg the A_2 horizon was very irregular and discontinuous; at Korpfjäll the A_2 was well developed but light in colour. A_2 was not sampled on both of these sites. The B horizon was sampled on all sites, and the samples comprised the upper part of the horizon (B_1, or B_1 + part of B_2, if B_1 was very shallow). Samples from deeper layers were collected for analysis, but were not used in the incubation experiments.

Laboratory pretreatment of samples

The samples were stored outdoors and transported to the laboratory within two or three days after sampling. At the laboratory they were kept outdoors until they could be treated. The first treatment consisted in sieving on a screen with a 14 mm mesh, to remove stones and coarse roots. The sample passing this screen was then passed through a finer sieve, of 3 mm mesh, in some cases after an intermediate screening on a 5 mm sieve. The sieving was relatively hard work and a stiff brush was used to help the finer parts of the samples to pass the sieve. The portion passing the 3 mm screen was then used for further studies. Its water content had to be adjusted to a suitable level (see Table 2), viz. about 60 per cent of the water content after free drainage overnight. Samples drier than this value were moistened with distilled water. Very wet samples were placed on a bed of absorbent cellulose wadding until sufficient water had been sucked away by capillary action. (In later experiments a domestic laundry centrifuge was used, with the sample in a canvas bag). The samples were always used in the moist state for the experiments, while aliquots of the samples were air-dried and oven-dried for chemical analysis.

The sieve residues were weighed, fresh and dry. In the case of the A_0 horizon, they consisted mostly of roots and other organic material. In the case of mineral horizons, a minor part was also roots, while most of the residues consisted of stone and gravel. Table 6 gives some information on the amount and character of residues in the various samples. Some of the residues were lost by accident and could not be analysed.

Incubation experiments

The incubation experiments were performed in one-litre Erlenmeyer flasks, filled with a layer of sample material two to two and a half cm deep

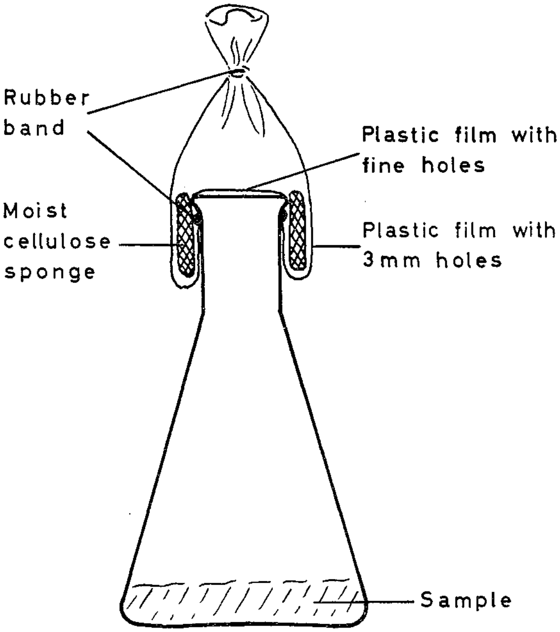

Fig. 3. Incubation flask with arrangement permitting aeration but minimising water losses from sample

(2.5—3 cm for B horizon samples). The neck of the flask was covered with a thin polyethylene bag with some fine holes to allow air to enter. In the plastic bag were stored pieces of cellulose sponge moistened with water, containing a little copper sulphate, see Fig. 3. This arrangement was intended to permit the access of air to the samples while minimising water loss. The cellulose sponges were regularly remoistened but the samples had only to be watered at long intervals (every other or every third month). Water was then added to bring them up to the original weight, without allowance for breakdown of the samples, except in A_0 samples where the dry weight determinations from the preceding sampling were used as a guide in order to maintain the original moisture conditions. Flasks were taken out for analysis at intervals, as indicated in Table 3. In the first series (Garpenberg and Havtjärnheden) usually the whole content of the flask was extracted with a potassium chloride solution and aliquots were taken out after centrifuging. In later series (Haboskogen and Korpfjäll), only one-half of the flask contents was extracted, while the rest was used for other analytical determinations (Table 5). The same procedure was applied to Garpenberg and Havtjärnheden flasks incubated for two or two and a half years. In many samples (mineral horizon samples in particular) it proved difficult to distil over the ammonia quantitatively in a few minutes, as was the case in the controls, when the extracts had been made alkaline with magnesium oxide as in the ordinary Devarda procedure. Much better results were obtained if the extracts were first almost neutralised with potassium hydroxide and then made alkaline by the addition of magnesium oxide.

Most of the incubation series were carried out both with natural samples and with samples mixed with calcium carbonate. In the first series (Garpenberg) the A_0 sample was treated with an amount of calcium carbonate, which increased the pH from 4.0 to 6.3 at the start of the experiment. This amount, however, was later found to be too small to maintain a considerable difference in pH between the two series. At the end of the experiment, after two years, the pH was still 4.0 in the untreated samples (after a temporary increase earlier in the incubation) and 4.2 in the limed ones (Table 3). In the A_1 and B horizon samples, the difference was larger after two years. The amount of calcium carbonate was increased in the A_0 samples in the later series, Haboskogen and Korpfjäll.

A certain amount of the Garpenberg material was stored in a deep freeze for a whole year. A second series on the Garpenberg material was then run on this material parallel with the series Havtjärnheden. Similar replications were also planned for the other series but the low temperature storage was interrupted for a period by mistake before this could be done.

Results and discussion

The experimental results are presented in Table 3 and in the diagrams, Fig. 4 to 10. Some additional information is also to be found in Table 4 and 5.

Garpenberg

Figure 4 shows that at Garpenberg up to 24 per cent of the nitrogen content of the A_0 sample was released as ammonia and nitrate nitrogen after one and a half to two years. This is in good agreement with Romell's earlier results (ROMELL 1967). The rate of nitrogen release in the mor layer is relatively slow during the first weeks, then increases, and after one year again decreases. The A_1 samples behave very similarly to the A_0 sample except that the final release is only about 18 per cent of the original nitrogen content. The B horizon samples show considerably less nitrogen mobilisation, about five per cent at the end of the experiment. It should be mentioned here that the B curve in Figure 4 concerns the deep-frozen samples, because the B horizon values in the first series are considered less reliable, owing to analytical difficulties. The two-year value in this series, however, which was obtained with the improved alkalinisation technique, as described in a previous section, agreed well with the corresponding value in Fig. 4.

It seems quite clear that the addition of lime to A_0 and A_1 samples initially increases nitrogen release but later retards it. The final nitrogen mobilisation is thus less in the limed samples than in the untreated samples. This is in good agreement with Romell's results (unpublished material, cf. also VIRO 1963). Nömmik found similar inhibition of the nitrogen release in samples from the same site. He was also able to establish a relationship between the change in pH and the decrease in ammonia formation in A_0 samples (NÖMMIK 1968). KAILA and SOINI (1957) also reported variable effects of lime in soil incubation experiments, in this case with peat soils. In the B horizon samples it appears that liming increased nitrogen mobilisation. Nömmik (personal communication) has obtained similar results. An inspection of the data in Table 3 shows that most of the released nitrogen in the un-limed samples is in the form of ammonium ions, although there is a tendency towards nitrate accumulation at the end of the experimental series in the A_0 and B horizon samples. In the limed series most of the nitrogen released is in the form of nitrate, with few exceptions, viz.: A_1 horizon samples, where one of the incubation flasks analysed after one, one and a half, and two years contained

Fig. 4

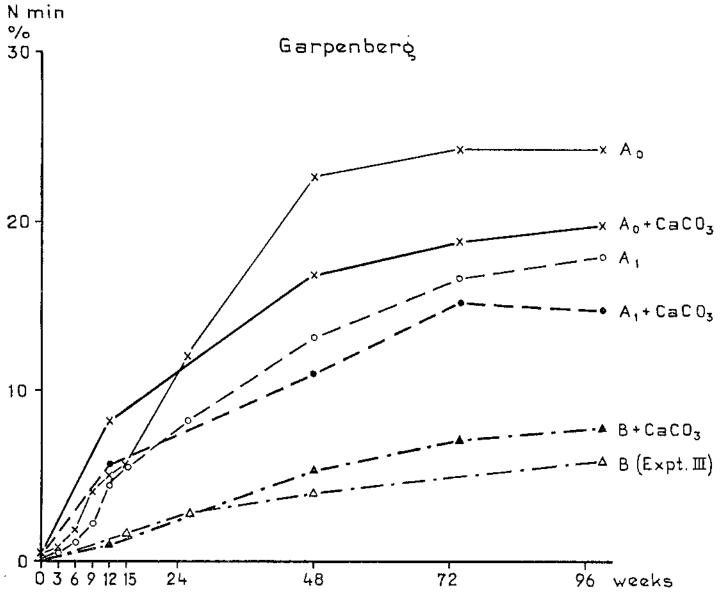
N min
%
30
20
10
0
Garpenberg
A₀
A₀+CaCO₃
A₁
A₁+CaCO₃
B+CaCO₃
B (Expt. III)
0 3 6 9 12 15 24 48 72 96 weeks

Fig. 5

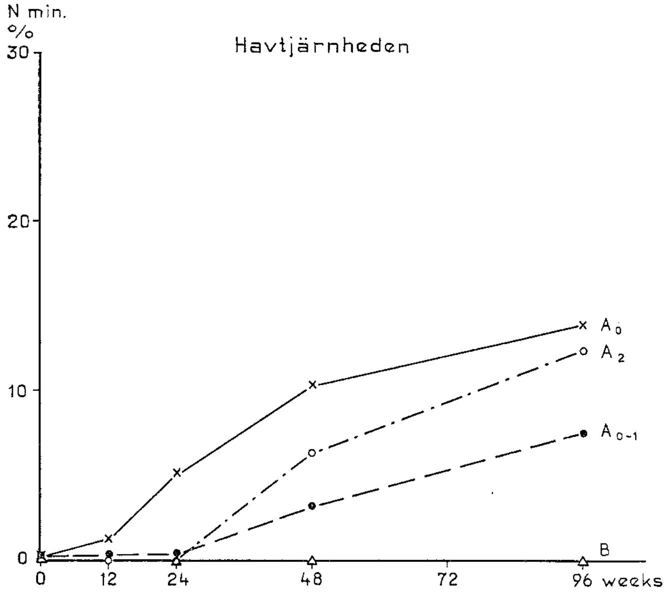
N min.
%
30
20
10
0
Havtjärnheden
A₀
A₂
A₀₋₁
B
0 12 24 48 72 96 weeks

Fig. 6

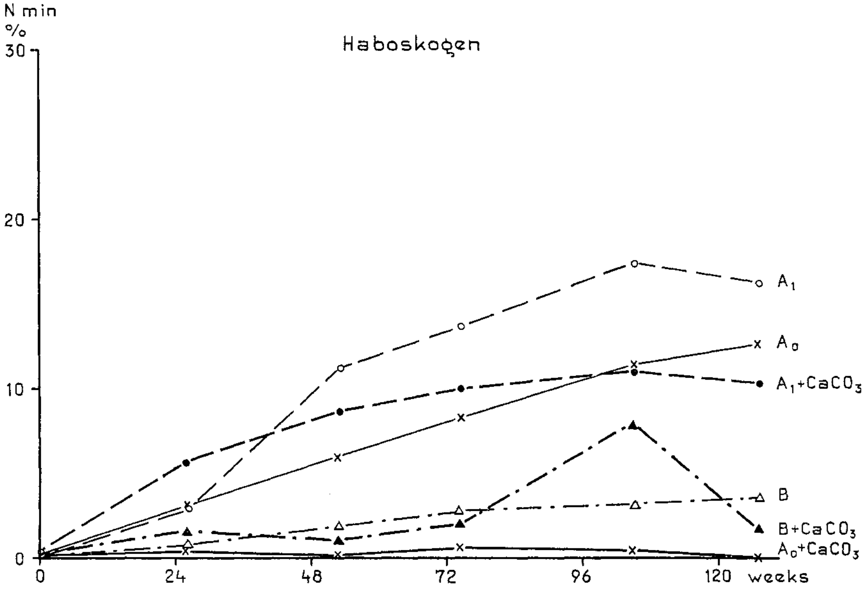

Fig. 7

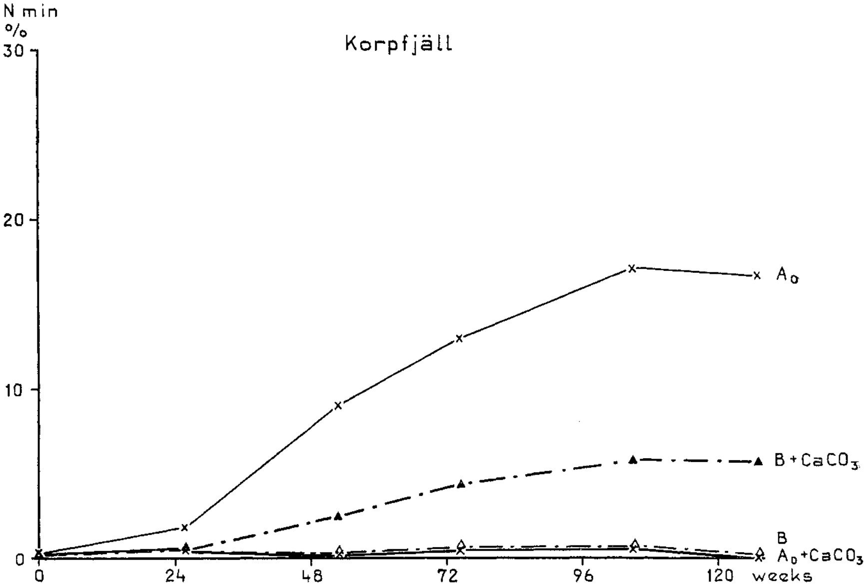

Fig. 4—7. Sum of ammonia nitrogen and nitrate nitrogen in the flasks after various periods of incubation. All values expressed as percentage of total initial nitrogen content of sample. Values from Table 3

mostly ammonia nitrogen, whereas the other duplicate contained mainly nitrate. In this particular series there are also large pH differences between the duplicates; the reasons for these differences are not known. It may, however, be mentioned that particularly in the limed samples there was for a period considerable earthworm activity during incubation.

It should be noted that deep-freezing apparently prevented nitrification of the ammonia released in A_0 and A_1 samples. The total amount of nitrogen released was, however, practically the same in the deep-frozen samples as in the first series. A confirmation of this observation would be desirable in the future.

The breakdown of organic matter runs parallel with the nitrogen mineralisation (Table 3, see also Fig. 9); in fact the loss of carbon appears to be somewhat greater than the loss of nitrogen in most cases. There is thus a relative enrichment of the samples in nitrogen. It should be noted that the addition of lime hampers the breakdown of organic matter.

Havtjärnheden

Figure 5 presents the results from the very poor site Havtjärnheden. The shape of the A_0 curve is similar to that for Garpenberg, although the total breakdown after two years amounts to 14 per cent of the total nitrogen in the A_0 instead of 24 per cent. The humus in the transitional layer between A_0 and A_1 is apparently fairly resistent to breakdown, even more so than the A_2 humus, which releases almost as much of its nitrogen content as does the A_0 horizon. The existence of a lag period before nitrogen release starts is very clear in this experiment. The data in Table 3 on organic matter breakdown, however, show that there is already a considerable breakdown after twelve weeks, although very little nitrogen was released on this occasion. No measurable amount of ammonia or nitrogen was found in any of the incubation flasks containing B horizon sample. There was a slight loss of carbon after two years even in the B horizon samples, and the carbon dating (Table 6, see also Tamm and Holmen 1967) suggests a turnover of organic matter in the B horizon too. The most probable explanation of the lack of ammonia or nitrate release is that any nitrogen released in this sample is fixed again in living or dead organic matter.

Haboskogen

Figure 6 presents the results from the Haboskogen samples. In this case the release of nitrogen from unlimed samples was larger in the A_1 horizon than in the A_0 horizon. Liming decreased nitrogen mobilisation in the A_0 horizon to almost nil, while organic matter breakdown was increased (Fig. 9 and 10). Liming the A_1 samples had the same effect as at Garpenberg, first an initial increase, later a decrease in nitrogen release. The nitrogen released in the limed samples was in the form of nitrate. The B horizon samples from Haboskogen showed a small but measurable release of nitrogen, part of which appeared as nitrate. In this case the limed series shows rather irregular results. No safe conclusions can be drawn from this series. The carbon determinations on the unlimed B horizon samples show a moderate breakdown of organic matter.

Korpfjäll

Figure 7 presents the results from Korpfjäll. The A_0 curve is rather similar to that of the other sites with an initial lag period and a final release of about 17 per cent of the total nitrogen content. With lime, however, the nitrogen release decreases to almost nil. No A_1 or A_2 samples are available from this site, but the B horizon samples show no or very little nitrogen release over the whole experimental period except after liming. There was, however, a loss of carbon also in the unlimed B horizon samples from Korpfjäll.

The data for the A_0 horizon concerning the release of nitrogen, are again presented in Figure 8 for the four sites. Figure 9 presents the loss in combustible substance for the same samples. A comparison of these two diagrams confirms what has already been stated, viz. that there are considerable differences between on the one hand the good site Garpenberg, and on the other hand the three poor sites, concerning both the release of nitrogen and the breakdown of organic matter. There seems to be a good parallel between these two processes in the A_0 horizon in all four samples, but the loss of combustible substance is always higher than the release of nitrogen. There is thus a relative increase in the nitrogen content of all four samples during incubation.

Figure 10 shows the course of the loss of combustible substance in the limed samples. Calcium carbonate decreased the rate of decomposition in the Garpenberg sample, while the Korpfjäll sample appeared to be relatively little affected. Liming increased the decomposition somewhat in the Haboskogen A_0 sample. It must be remembered that the lime addition was considerably larger in the Haboskogen and Korpfjäll samples than in the Garpenberg series.

It remains to discuss the results of the incubation experiments in relation to the radiocarbon datings, made on samples from the three sites Garpenberg, Havtjärnheden and Haboskogen. The radiocarbon datings have been published earlier (TAMM and HOLMEN 1967) but the data are also presented in Table 6. As was briefly discussed in the earlier paper, there is an apparent

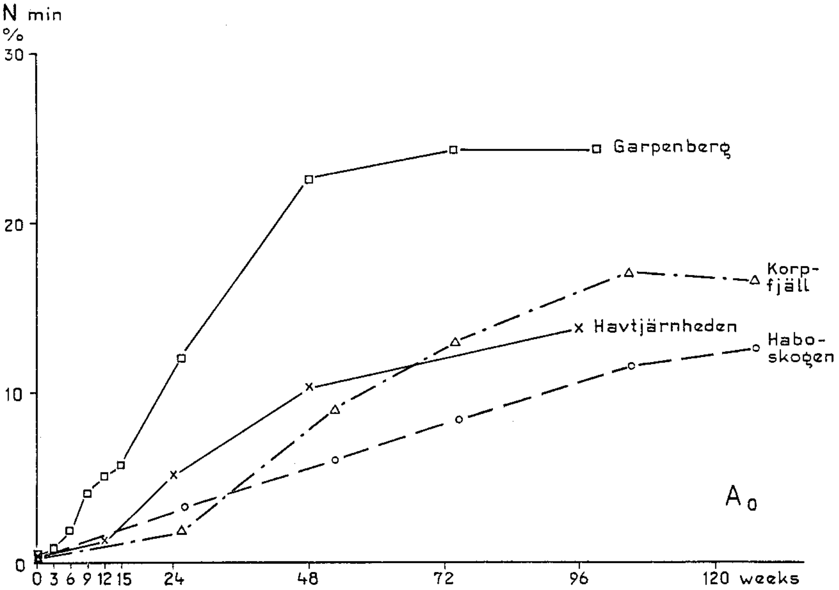

Fig. 8. Comparison of the release of nitrogen in A_0 samples from the four sites.

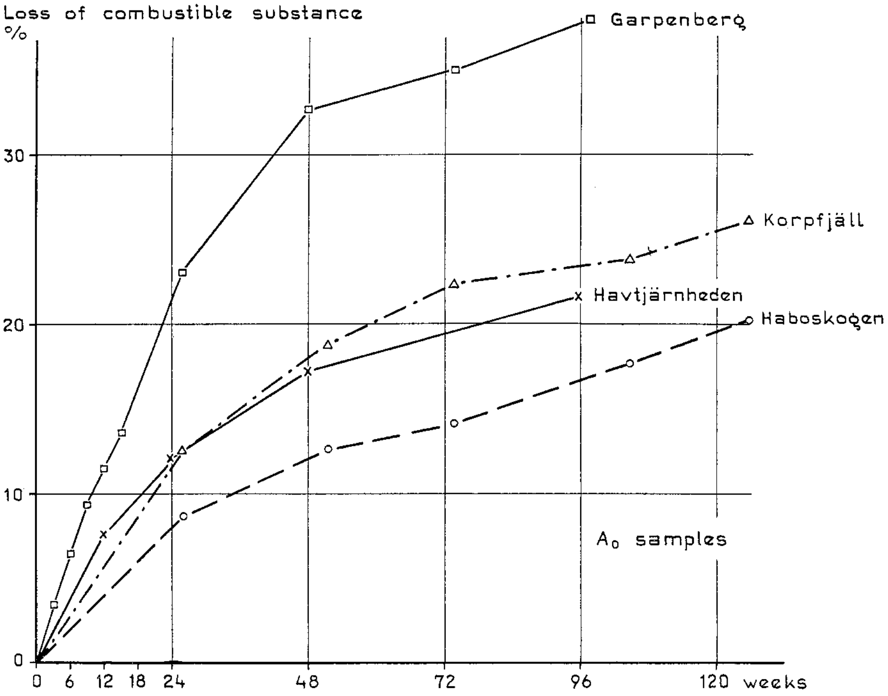

Fig. 9. Comparison of the losses of organic matter (measured as loss on ignition) during incubation of A_0 samples from the four sites studied.

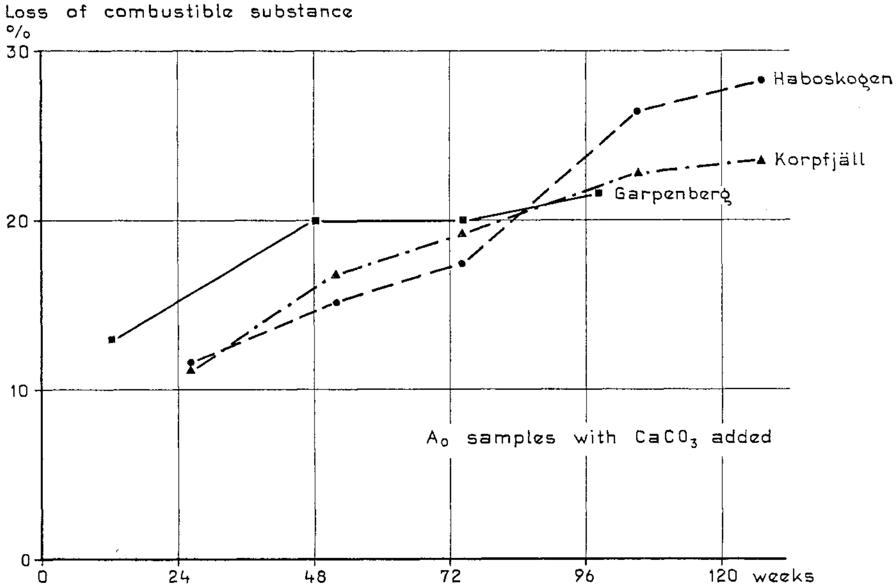

Fig. 10. Comparison of the loss of organic matter (measured as loss on ignition) in limed A_0 samples from the three sites Garpenberg, Haboskogen, and Korpfjäll.

contradiction in the relatively low radiocarbon age of the organic matter in the B horizon, in all three profiles studied, and the lack of measurable release of nitrogen in incubation experiments with the Havtjärnheden sample (as also in the Korpfjäll B horizon). However, some breakdown of organic matter was observed in these samples, too. The loss of carbon was very low in the Havtjärnheden B horizon, but the Haboskogen sample did not differ much from that from Garpenberg (Table 5).

It seems very probable that a continuous breakdown of organic matter does occur in B horizons of podzol profiles, as suggested in the previous paper. At the same time there is, of course, a deposition of new material in the same horizon. The nitrogen once deposited in the B horizon seems to be held back tenaciously, presumably as a result of uptake by soil microorganisms, as was discussed in the earlier paper. Tree roots, particularly those with mycorrhiza, may well compete with the microorganisms for this nitrogen.

In a forest ecosystem with normal circulation of nutrients between tree stand and soil, only a very small fraction of the tree uptake of nitrogen originates from the B horizon. Conditions may be different if the normal circulation is interrupted, for instance, after one or more forest fires.

The present results have also a bearing on other forest nutrition problems. Hesselman discussed the positive effect of soil working on nitrogen mobilisation and also the effect of minerals on nitrate formation in the forest soil. Hesselman and his contemporaries studied mostly the conditions in the humus layer. Similar effects exist also for mineral soil horizons. In Holland VAN GOOR (1952) has shown that deep soil working favoured oak regeneration but decreased the site quality in the long run. Very often soil working has been combined with liming, as in the German practice of "Vollumbruch". The effect of this treatment is certainly complex, involving for instance effects on the soil moisture regime, but the effect of liming on the breakdown of B horizon humus, observed in the present experiments, may well contribute to the favourable effects of "Vollumbruch" with liming on podzol sites.

Concluding remarks

There are great difficulties involved in the assessment of the amounts of nitrogen in a form available for higher plants. The main reasons for this are to be found in the dynamics of nitrogen turn-over in the soil. Ammonium and nitrate nitrogen usually occur in small quantities only, the actual amounts depending on the accidental and rapidly changing balance between what is being released by break-down of organic matter and what is taken up by organisms, roots in particular. Direct measurements of ammonium and nitrate production can be made in the field or in laboratory experiments, if root uptake is eliminated. The results obtained may in some cases agree well with other estimates (e.g. from the annual uptake of nitrogen by a crop). In other cases there is reason to believe that nitrogen mobilisation in incubation flasks, or even in trenched plots in the field, differs strongly from that in an undisturbed site. Apart from the well recognised change in temperature and moisture in the incubation flask, there is a change in the microbiological balance due to sampling and the other treatments. Even cutting off roots may have such effects (Romell's assart effect). Particularly samples from poor sites with mor humus often show long periods of ripening (several weeks or months) before notable amounts of ammonia are released in incubation experiments. The activity of the micro-organisms surviving sampling does not result in an immediate release of ammonia; very probably a population of ammonifying micro-organisms builds up successively.

The experiments described in this paper do not attempt to measure nitrogen mobilisation under natural conditions, not even after corrections for the change in physical environment. Instead they try to compare the extent to which various soil horizons take part in the nitrogen and carbon cycles. Two to 38 per cent of the organic matter disappeared during the experimental period (with 0 to 24 per cent of the nitrogen released), the lowest figures concerning B horizon samples from poor sites, the highest ones A_0 samples from a good site. As no information was obtained from this type of experiment regarding the turn-over time for the 98 to 62 per cent of the organic matter not decomposed, a radiocarbon dating was made on soil humus from three of the sites studied. The radiocarbon ages obtained were fairly low (330—470 years for B horizon samples), which confirms the view that the bulk of the soil organic matter takes part in a continuous deposition—decomposition process.

The present results confirm the common belief that the A horizon, and the mor layer in particular, is of paramount importance for forest nitrogen nutrition on podzol sites. The small amounts of ammonia and nitrate nitrogen released in the B horizon are but a small contribution to the annual supply. However, limited as these quantities may be, they are probably not without importance for the stability of forest sites against catastrophes (e.g. fire) and for the site quality.

It seems likely that nitrogen mobilisation in mineral soil horizons can be stimulated by treatments such as soil working and ditching (of poorly drained sites). Liming (in combination with soil working) also increases nitrogen mobilisation in the B horizon, although the effect is the opposite in mor. It is at present hardly economically feasible to carry out the treatments described on ordinary podzol sites in order to improve nitrogen nutrition, even if such an effect may be a desirable by-product of soil working or draining operations carried out for other purposes.

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Sammanfattning

Studier över kvävemobiliseringen i skogsjord

Trots att kvävets tillgänglighet i marken synes vara en avgörande faktor för skogsproduktionen, har vi mycket begränsade möjligheter att karakterisera skogsmarken med avseende på denna viktiga egenskap. Den vid ett bestämt tillfälle i marken förefintliga och analyserbara mängden av växttillgängligt kväve, alltså ammoniak och nitrat, är i regel mycket liten och växlar starkt från gång till gång, alltefter variationer i nedbrytningsorganismernas aktivitet och rötternas och mykorrhiza-svamparnas upptagningsförmåga. Många forskare har därför gjort lagringsförsök, varvid man dock i regel inskränkt sig till humuslagret, eftersom humuslagrets kväve vanligen är den viktigaste kvävekällan för vegetationen. Man kan härvid skilja på två typer av undersökningar, dels kortfristiga, sådana som utförts av Hesselman och Zöttl, där man siktar till att få ett mått på provens kväveleveransförmåga, som anses stå i någorlunda proportion till kväveleveransförmågan under naturliga betingelser. Den andra typen av undersökningar är mera långfristiga försök. Sådana har särskilt utförts av Romell, som bedömer det som utsiktslöst att försöka uppskatta kväveleveransförmågan *in situ* med lagringsförsök, eftersom proven förändras redan i och med provtagningen. Romell menar i stället att man med långvariga lagringsförsök kan få en uppfattning om den kväveleveransförmåga ett humuslager har vid kraftiga rubbningar i ekosystemet, exempelvis kalhuggning eller bränning.

Föreliggande undersökning ansluter sig närmast till Romells tankegångar och har utförts med i stort sett samma metodik som hans försök. Den skiljer sig emellertid från Romells försök genom att även andra markhorisonter än humuslagret tagits med i undersökningarna. Det är nämligen väl känt att större delen av ekosystemets kväveförråd i normala svenska skogar med podsolprofil vanligen finns i mineraljorden. Såväl humuslagrets som beståndets kväveförråd är lägre.

Försöken har sträckt sig över perioder om 2—2 1/2 år och har utförts som tidsserier med undersökning av ammoniak- och nitratinnehållet i vissa kolvar vid bestämda tidpunkter. Provtagningslokalerna har varit fyra, 1. äldre granbestånd av god bonitet vid Garpenberg, 2. tallbonitet av mycket låg bonitet på Havtjärnheden, Älvdalens västra revir, 3. tallskog av låg bonitet på kronoparken Haboskogen nära Vättern, Västergötland, 4. restbestånd av gran i en sluttning med något ofullkomlig dränering i ett höjdläge i Värmland, Korpfjäll. Proven från Garpenberg, Haboskogen och Korpfjäll har undersökts såväl med som utan tillsats av kalciumkarbonat till lagringskolvarna. Lagringen har skett i Erlenmeyer-kolvar med lufttillträde samt med en fuktighet i närheten av den s. k. fältkapaciteten.

Försöksresultaten återges i tabell 3 samt i figurerna 4—10. I humusprovet från Garpenberg försvann genom nedbrytning mer än 1/3 av det organiska

materialet varvid 1/4 av kväveinnehållet överfördes till ammonium- och nitratjoner, huvudsakligen ammoniumjoner. Förlusten av organisk substans var något lägre i humusproven från de sämre lokalerna, mellan 20 och 30 % och kvävemobiliseringen var också lägre, 12—17 %. Såväl nedbrytningen som kvävefrigörelsen var oftast lägre i A_1 och A_2-prov än i humuslagret. Ännu lägre var nedbrytning och kvävemobilisering i B-horisont-proven. I provet från Havtjärnheden, Älvdalen, kunde över huvud taget ingen mätbar kvävemobilisering fastställas i B-horisonten även om uppenbarligen en viss förlust av organiskt material ägde rum. Kalkning minskade kvävemobiliseringen i humuslagerproven ända till noll men föreföll att kunna öka mobiliseringen i B-horisonten. En klar effekt av kalkningen var också en ökning av nitratbildningen på bekostnad av den först bildade ammoniaken.

Försöksresultaten diskuteras bl. a. i relation till de C-14-dateringar av organiskt material som skett på markprov från lokalerna Garpenberg, Havtjärnheden och Haboskogen (Tamm & Holmen 1967). En viss omsättning av det organiska materialet i B-horisonten äger tydligen rum och detta tillsammans med den svaga kvävemobilisering som i vissa prov kunnat påvisas, gör det sannolikt att B-horisont-humusen och dess kväveförråd på lång sikt har en viss betydelse för det skogliga ekosystemet. Bl. a. kan man tänka sig att små årliga tillskott av kväve genom nedbrytning av rostjordens humus kan betyda en del för återställandet av ett gott skogstillstånd, exempelvis efter hårda skogsbränder. Möjligheterna att med artificiella medel öka kväveutbudet från rostjordens humus ter sig ganska små i vårt land. Åtgärder med verkan i denna riktning förekommer dock på andra håll, exempelvis i Tyskland, där man ibland kalkar och djupplöjer skogsmark i samband med föryngringsåtgärder. Det bör också observeras att åtgärder sådana som dikning av försumpad fastmark eller s.k. radikal markberedning även kan öka kväveutbudet från mineraljorden.

Tables

Table 1. Schematic description of sampled sites and profiles

Site	Garpenberg	Havtjärnheden	Haboskogen, Expt. 876	Haboskogen, radiocarbon dated site	Korpfjäll
Lat. N.	60°16′	61°21′	57°59′	57°59′	60°25′
Long. E.	16°13′	13°29′	14°03′	14°00′	13°29′
Altitude, m.	196	500	240	240	440
Annual mean temperature (calculated according to Ångström, 1938)	4.1°C	1.5°C	5.7°C	5.7°C	2.8°C
Annual mean precipitation (read from map, Atlas över Sverige, 1962)	600 mm	650—700 mm	600 mm	600 mm	700 mm
Topography	Flat	Flat	Flat	Flat	Gentle eastward slope
Soil parent material	Till, sandy-silty	Till, very stony	Deep outwash sand	Deep outwash sand	Till, sandy to fine sandy
$d_{75}\%$*, μ	14	200	200	200	12
Tree stand	Dense stand of mature spruce with some pine	Open stand of mature pine	70 year-old pine	Middle-aged pine with spruce undergrowth	Residual spruce stand
Site class (estimated average yield)	6 m³ per hectare	1.5 m³ per hectare	3 m³ per hectare	Similar to Expt. 876	Not determined, fairly low
Dominating vegetation					
Field layer	Deschampsia flexuosa with low degree of cover. Occasional herbs	Calluna vulgaris, some Vaccinium myrtillus and V. vitis idaea	Vaccinium vitis idaea, Calluna vulgaris	Vaccinium vitis idaea, some Calluna vulgaris	Vaccinium myrtillus, some V. vitis idaea
Ground layer	Hylocomium splendens with Pleurozium Schreberi	Cladonia rangiferina and sylvatica, some Pleurozium Schreberi and Dicranum scoparium	Cladonia rangiferina and Cl. sylvatica, Dicranum rugosum	Pleurozium Schreberi, Dicranum rugosum, some Cladonia rang. and Cl. sylv.	Pleurozium Schreberi, Hylocomium splendens, Dicranum scoparium. In patches Sphagnum sp.

Soil horizons (depths in cm)					
A_{00} (litter, "standing dead moss")	3	2	5	5	5
A_0	7	2—4	6	6 Some charcoal, small lumps of mineral soil	5 Some charcoal
A_1	1—2	0—2	12 Irregular pattern of dark gray and light gray sand	14 Similar to Expt. 876. Lower part slightly reddish Below A_2 1—2 cm A_3, dark with high organic content	1—3 Some charcoal
A_2	0—4	8 14, gray brown, lighter downwards			8—17 Light gray
B_1	29—35, light brown	1— 5, dark brown hardpan	7 Very irregular. Light brown patches in darker sand	1.5—3 cm dark brown hardpan	3—7 Dark brown
B_2 or B/C		5—10, rust-coloured, lighter downwards	10 Transitional to subsoil. Patchy as B_1	5—10 cm rust-coloured, cemented, in patches lighter and more friable	ca. 16 Light brown with dark spots
Characteristics of C horizon	Subsoil changes abruptly from slightly rust-coloured to gray, very compact at 60 cm depth	C horizon from about 18 cm below surface of A_1. The till contains small lenses of sediment (fine sand)	Subsoil medium sand, light gray to slightly reddish	Subsoil reddish medium sand underlain by somewhat finer material; boundary at oblique angle with ground surface	From 35 cm downward transition to slightly mottled C horizon
Base mineral index	8.2	2.1	1.0	1.2	9.1 (B horizon)
Date of sample collection	21.11.1958	20.10.1959	21.10.1961	—	27.10.1961

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* Diameter of the soil particle at the lower quartile of the size distribution (75 per cent of the material coarser, 25 per cent finer)

Table 2. Water content of samples under different conditions. Percentages of dry weight.

Site	Horizon	"Water capacity"		Water content at				Water content at start of experiments
		Empirical pilot value	Free drainage	Suction 20 cm H_2O	Suction 100 cm H_2O	Suction 1/3 atm	Wilting point	
Garpenberg	A_0	250	n.d.	n.d.	n.d.	n.d.	n.d.	148
Havtjärnheden	A_0	340	n.d.	n.d.	n.d.	n.d.	n.d.	201
Haboskogen	A_0	280	570	290	240	230	n.d.	233
Korpfjäll	A_0	290	650	310	260	240	n.d.	232
Garpenberg	A_1	90	n.d.	n.d.	n.d.	n.d.	n.d.	55
Havtjärnheden	A_0—A_1	85	n.d.	n.d.	n.d.	n.d.	n.d.	43
''	A_2	70	n.d.	n.d.	n.d.	n.d.	n.d.	22
Haboskogen	A_1	26	46	30	22	13	n.d.	18
Garpenberg	B	40	n.d.	n.d.	n.d.	n.d.	n.d.	31
Havtjärnheden	B	100	n.d.	n.d.	n.d.	n.d.	n.d.	31
Haboskogen	B	30	40	38	17	12	6	13
Korpfjäll	B	80	130	84	66	58	34	69

Table 3, see p. 34—37.

Table 4, see p. 38—39.

Table 5. Loss of carbon after two years' incubation

Sample	Carbon content at start per cent dry weight	Loss of carbon after 2 years incubation per cent of initial value
Havtjärnheden A_2	2.1	15
Haboskogen A_1	2.0	11
Garpenberg B	2.3	8
Havtjärnheden B	4.4	2
Haboskogen B	1.3	6
Korpfjäll B	5.5	4

Table 6. Quantitative data on sampled profiles and samples used for incubation experiments. (Most profile data from separate samplings)

1 Site	2 Horizon	3 Area sampled dm^2	4 Total dry weight of horizon g/dm^2	5 Fraction of horizon used in experiment per cent	6 Character of unused fraction (= sieve residue)	7 Estimated loss on ignition kg per hectare	8 Estimated amount of nitrogen kg per hectare	9 Radiocarbon age years	10 Horizon
Garpenberg	Moss layer and litter (A_{00})	400	14.5	—	—	—	—	—	A_{00}
	A_0	400	56.2	57	Organic	67 000	1 150	low	A_0
	A_1	400	142.5	86	Largely organic	34 000	650	low	A_1
	A_1/B	—	—	—	—				A_1/B
	B	—	690	73	Stones and gravel; some roots	106 000	2330	370 ± 100	B
Havtjärnheden	Vegetation and litter (A_{00})	16	17.4	—	—	17 400	150	—	A_{00}
	A_0	100	24.9	68	Organic	24 000	290	—	A_0
	A_0/A_1	100	32.4	73	Largely organic	17 000	270	140 ± 80	A_0/A_1
	A_2	100	n.d.	(70)	Stones and gravel; very few roots			230 ± 85	A_2
	B	—	n.d.	(60)	As A_2	28 000	420	400 ± 80	B
Haboskogen (Expt. 876)	A_0	7.7*	56.0	71	Loss on ign. higher, N % lower than in main fraction	52 000	740	—	A_0
	A_1/A_2	—	—	97	Loss on ign. 20 %; N % 0.16	25 000	530	—	A_1/A_2
	B	—	—	97	Stones and gravel; some roots	37 000	520	—	B
(Radiocarbon dated site)	Vegetation (field layer)	25	0.8	—		770	7	—	—
	Moss and litter layer (A_{00})	25	10.3	—	—	9 850	80	—	A_{00}
	A_0	4.8*	121	—	—	42 400	n.d.	—	A_0
	A_1/A_2	—	1 905	—	—	31 600	n.d.	—	A_1/A_2
	B	—	1 213	—	—	33 500	n.d.	330 ± 65	B_1
	B_2	—	2 340	—	—	7 500	n.d.	465 ± 65	B_2
	C (down to 50 cm)	—	1 548	—	—	3 600	n.d.	—	C
Korpfjäll	A_0	4.0*	64	78	Loss on ign. higher, N % lower than in main fraction	46 800	450	—	A_0
	B	—	—	68	Stones and gravel; some roots	n.d.	n.d.	—	B

* Area of 10—20 auger samples; area of sample for incubation experiments not determined

Table 3. Initial weights, ammonia and nitrogen relea

Site	Horizon	Values at start				$CaCO_3$ added g/flask	N mineralised,		
		Fresh weight g/flask	Dry weight g/flask	Loss on ignition g/flask	Total nitrogen mg/flask		at start	12 weeks	½ year
Garpenberg	A_0	140	56.5	26.0	519	—	0.6 *0.0* 0.2 *0.0* pH 4.0	4.6 *0.1* 5.5 *0.5* pH 4.4	11.9 *0.0* 12.1 *0.1* pH 4.8
”	A_0 $CaCO_3$	140	56.5	26.0	519	0.9	0.6 *0.0* 0.2 *0.0* pH 6.3[3]	7.8 *0.3* 8.6 *0.1* pH 6.2	— —
”	A_0 “deep-frozen”	140	55.9	26.0	519	—	1.1 *0.0* pH 4.3	—	11.2 *0.0* pH 4.6
Havtjärnheden	A_0	90	29.9	24.8	306.7	—	0.2 *0.0* 0.2 *0.0* pH 3.4	0.9 *0.0* 1.0 *0.0* pH 3.5	5.0 *0.0* pH 3.8
Haboskogen	A_0	100	30.0	26.5	342	—	0.2 *0.0* 0.0 *0.0* pH 3.0	— —	3.2 *0.0* 2.9 *0.0* pH 3.1
”	A_0 $CaCO_3$	100	30.0	26.5	342	2.0	0.6 *0.0* 0.2 *0.0* pH n.d.	— — —	0.4 *0.0* 0.4 *0.0* pH 6.7
Korpfjäll	A_0	100	30.1	24.6	300	—	0.2 *0.1* 0.2 *0.2* pH 3.0	— —	1.8 *0.0* 1.7 *0.0* pH 3.3
”	A_0 $CaCO_3$	100	30.1	24.6	300	1.8	0.2 *0.1* 0.2 *0.2* pH n.d.	— —	0.4 *0.0* 0.3 *0.0* pH 7.0
Garpenberg	A_1	200	129	21.3	453	—	0.1 *0.1* 0.2 *0.2* pH 3.9	4.5 *0.0* 4.7 *0.1* pH 4.1	8.3 *0.0* 8.1 *0.0* pH 4.3
”	A_1 $CaCO_3$	200	129	21.3	453	1.2	0.1 *0.1* 0.2 *0.2* pH 6.3[3]	5.5 *0.0* 5.7 *0.2* pH 6.1	— —
”	A_1 “deep-frozen”	200	128	21.3	453	—	0.7 *0.0* 0.8 *0.0* pH 3.9	—	8.0 *0.0* pH 4.3
Havtjärnheden	A_1 (with some AO included)	156	109	20.3	245	—	0.2 0.2 n.d. pH 3.2	0.3 0.3 n.d. pH 3.1	0.3 n.d. pH 3.2
”	A_2	270	221	8.9	117	—	0.4 0.4 n.d. pH 3.4	0.0 0.0 n.d. pH 3.2	0.0 n.d. pH 3.4
Haboskogen	A_1	200	170	6.2	107	—	0.6 *0.2* 0.4 *0.1* pH 3.2	— —	3.4 2.1 n.d. pH 3.6

loss of organic matter in incubation experiments

t of total. Italics nitrate N				Organic matter breakdown[4] after					
r									
year	1½ year	2 years	2½ year	12 weeks	½ year	1 year	1½ year	2 years	2½ years
8 *0.5* 4 *4.0* H 4.9	24.6 *8.2* 24.0 *8.0* pH 4.1	23.9 *9.0* 24.7 *8.7* pH 4.0	— —	11.5	24.5 21.5	32.8 32.6	35.2 34.9	38.5 37.5	— —
8 *17.4* 0 *15.7* H 4.4	20.0 *15.9* 17.5 *17.5* pH 4.4	19.8 *19.2* 19.8 *19.1* pH 4.2	— —	12.5 13.1	— —	18.2 21.2	20.2 19.5	21.4 21.5	— —
9 *0.4* H 5.1	—	26.5 *0.8* pH 4.5	—	—	17.4	28.2	—	36.5	—
3 *0.1* H 4.1	—	13.8 *0.0* pH 4.0	—	7.6 7.7	12.1	17.3	—	21.6	—
0 *0.2* 8 *0.0* H 3.3	8.3 *0.4* 8.3 *0.6* pH 3.2	11.4 *0.1* 11.3 *0.0* pH 3.4	11.8 *0.0* 13.2 *0.0* pH 3.2	— —	9.0 8.3	12.5 12.8	14.8 13.4	16.6 18.5	19.5 21.0
2 *0.1* 2 *0.0* H 6.7	0.6 *0.5* 0.5 *0.5* pH 6.5	0.4 *0.4* 0.5 *0.5* pH 6.4	0.0 *0.0* 0.0 *0.0* pH 6.1	—	11.3 11.3	14.3 15.7	16.9 17.6	28.0 25.0	29.6 26.7
9 *0.0* 0 *0.0* H 3.6	13.5 *0.6* 12.6 *0.1* pH 3.6	17.3 *0.8* 17.2 *0.8* pH 3.7	16.7 *0.4* pH 3.6	— —	12.7 12.5	19.2 18.5	22.3 22.4	22.4 25.2	26.2
3 *0.0* 3 *0.1* H 6.8	0.5 *0.5* 0.5 *0.5* pH 6.6	0.6 *0.5* 0.7 *0.6* pH 6.6	0.0 *0.0* 0.0 *0.0* pH 6.5	— —	10.8 11.9	16.3 16.9	15.0 22.9	22.4 22.8	24.1 22.9
3 *0.1* 4 *0.1* H 4.5	16.7 *0.0* 16.7 *0.1* pH 4.6	18.6 *0.0* 17.3 *0.0* pH 4.6	— —	5.1 4.7	7.1 8.4	14.1 13.5	19.0 18.0	22.4 22.4	— —
4 *0.1* 7 *7.5* H 6.0 4.7	14.2 *0.5* 16.3 *11.0* pH 6.1 4.9	15.0 *5.0* 14.7 *13.7* pH 5.2 4.6	— —	5.8 7.1	— —	13.7 11.8	16.5 14.3	17.5 14.5	— —
0.2 H 4.4	—	18.8 *0.1* pH 4.8	—	—	7.0	12.9	—	17.0	—
0.1 H 3.6	—	7.5 *0.3* pH 3.5	—	3.4 3.8	7.6	12.5	—	23.7 *24*	—
0.0 H 3.7	— —	12.4 *0.0* pH 4.0	—	n.d.	n.d.	n.d.	—	*15*	—
0.0 *1.1* H 4.0	13.6 *0.8* 13.6 *0.8* pH 3.9	17.5 *1.5* 17.3 *1.1* pH 4.2	16.0 *0.3* 16.3 *0.1* pH 4.2	—	*2*	*9*	*9*	*11*	*20*

Table 3. (cont.)

Site	Horizon	Values at start				CaCo$_3$ added g/flask	N mineralised,		
		Fresh weight g/flask	Dry weight g/flask	Loss on ignition g/flask	Total nitrogen mg/flask		at start	12 weeks	½ yea
Habo-skogen	A$_1$ CaCO$_3$	200	170	6.2	107	1.0	0.6 *0.2* 0.4 *0.1* pH n.d.	—	5.1 6.1 n.d. pH 7.3
Garpenberg	B	250	191	9.9	214	—	0.1 *0.1* 0.1 *0.1* pH 4.5	(0.6 *0.0* 0.8 *0.0*)[1] pH 4.4	(1.3 *0.* 1.2 *0.* pH 4.0
”	B CaCO$_3$	250	191	9.9	214	0.8	0.1 *0.1* 0.1 *0.1* pH 6.5	1.1 *0.5* 1.1 *0.3* pH 6.4	—
”	B “deep-frozen”	250	191	9.9	214	—	0.1 *0.1* 0.1 *0.1* pH 4.6	—	2.8 *0.* pH 4.5
Havtjärn-heden	B	260	198	21.8	299	—	0.1 0.1 pH 4.7	0.0 0.0 pH 4.6	0.0 pH 4.7
Habo-skogen	B	250	222	7.6	102	—	0.3 *0.0* 0.4 *0.0* pH 4.6	—	1.1 n. 0.5 n. pH 4.5
”	B CaCO$_3$	250	222	7.6	102	0.7	0.3 *0.0* 0.4 *0.0* pH 6.7[3]	—	1.4 n. 1.8 n. pH 6.9
Korpfjäll	B	250	148	18.4	272	—	0.1 *0.0* 0.0 *0.0* pH 5.1	—	0.4 n. 0.4 n. pH 5.1
”	B CaCO$_3$	250	148	18.4	272	0.9	0.1 *0.0* 0.0 *0.0* pH 6.5[3]	—	0.4 n. 0.4 n. pH 6.6 6.3

1) Garpenberg B horizon samples 12 weeks—1½ year probably somewhat too low (analytical difficulties)

2) stored 1—2 months more than two years (kept in a defect freezing box)

3) calculated from titration curve

4) loss of combustible material in per cent of that originally present. Italics stand for loss of carbon in per ce that originally present

t of total. Italics nitrate N				Organic matter breakdown[4] after					
er									
1 year	1½ year	2 years	2½ years	12 weeks	½ year	1 year	1½ year	2 years	2½ years
.4 *7.3* .7 *8.5* H 7.5	10.1 *10.1* 10.0 *9.4* pH 7.5	11.2 *10.8* 11.0 *10.7* pH 7.5	10.3 *10.3* 10.3 *10.3* pH 7.3	—	n.d.	n.d.	n.d.	n.d.	*(10)*
.9 *0.9*[1] .2 *0.6*) H 3.9	(2.2 *0.8*)[1] (1.3 *0.1*) pH 3.9	5.4 *3.9* 5.5 *3.9* pH 3.9	—	n.d.	n.d.	n.d.	n.d.	*8*	—
.3 *0.2* .4 *0.2* H 5.8	7.3 *7.3* 7.2 *7.2* pH 5.8	7.8 *7.6* 7.9 *7.7* pH 5.9	—	n.d.	—	n.d.	n.d.	*13*[2]	—
.0 *1.7* H 4.2	—	5.9 *2.9* pH 4.0	—	—	n.d.	n.d.	—	n.d.	—
.0 H 4.8	—	0.0 pH 4.8		n.d.	n.d.	n.d.	—	*2*	—
.9 *1.9* .9 *1.7* H 4.6	3.1 *1.5* 2.4 *0.8* pH 4.5	3.4 *1.6* 3.1 *1.8* pH 4.2	3.6 *3.6* (0.3 *0.3*) pH 4.1	—	*2*	aberrant value	*6*	*6*	*11*
.8 n.d. .2 n.d. H 6.8	2.0 *1.6* 2.4 *2.2* pH 6.7	8.5 *8.3* 7.6 *7.2* pH 6.7	2.2 *2.2* 1.2 *1.2* pH 6.6	—	n.d.	n.d.	n.d.	n.d.	6
4 *0.2* 2 *0.1* H 5.0	0.6 *0.4* 0.6 *0.4* pH 5.0	0.9 *0.8* 0.5 *0.5* pH 5.0	0.1 *0.1* 0.1 *0.1* pH 4.8	—	*2*	*2.5*	*4*	*4*	*11*
5 *2.1* 5 *2.5* H 6.0	4.4 *4.4* 4.5 *4.5* pH 5.8	5.8 *5.7* 5.7 *5.6* pH 5.9	5.2 *5.2* 6.2 *6.2* pH 5.8	—	n.d.	n.d.	n.d.	n.d.	*9*

Table 4. Analytical data for samples at start and end of incubation experiments. Va

Site	Horizon	Duration of experiment years	Addition of $CaCO_3$ g/flask	Sample dry weight g/flask		Loss on ignition per cent		N_{total} per cent		P_{total} per cent	
				start	end	start	end	start	end	start	en
Garpenberg	A_0	2	—	56.5	46.5	46.0	34.6	0.919	1.03	0.065	0.0
Garpenberg	A_0	2	0.93	56.5	51.5	46.0*	39.6	n.d.	0.922	n.d.	n.
Havtjärnheden	A_0	2	—	29.9	24.9	82.2	78.2	1.03	1.26	0.083	0.0
Haboskogen	A_0	2½	—	30.0	24.7	87.9	85.6	1.14	1.36	0.067	0.0
Haboskogen	A_0	2½	2.0	30.0	24.4	85.5*	77.9	n.d.	n.d.	n.d.	n.
Korpfjäll	A_0	2½	—	30.1	24.3	81.6	77.3	0.996	n.d.	0.073	n.
Korpfjäll	A_0	2½	1.8	30.1	26.1	79.4*	72.8	n.d.	1.17	n.d.	0.0
Garpenberg	A_1	2	—	128.8	123.5	16.5	12.6	0.352	0.346	0.036	n.
Garpenberg	A_1	2	1.2	128.8	126.3	16.8 *	13.7	n.d.	0.363	n.d.	n.
Havtjärnheden	A_0—A_1	2	—	109.4	108.0	18.3	14.5	0.224	n.d.	0.030	n.
Havtjärnheden	A_2	2	—	221.2	220.0	4.1	3.1	0.053	0.060	0.010	n.
Haboskogen	A_1	2½	—	169.8	169.1	3.7	3.1	0.063	0.057	0.009	0.0
Haboskogen	A_1	2½	1.0	169.8	170.3	3.9*	3.5	n.d.	0.052	n.d.	0.0
Garpenberg	B	2	—	191.2	189.9	5.2	5.0	0.112	0.116	0.030	n.
Garpenberg	B	2	0.8	191.2	191.8	5.3*	5.1	n.d.	0.116	n.d.	n.
Havtjärnheden	B	2	—	198.0	196.8	10.4	10.0	0.151	0.163	0.139	n.
Haboskogen	B	2½	—	222.0	220.9	3.2	3.0	0.046	0.044	0.072	0.0
Haboskogen	B	2½	0.7	222.0	221.5	3.3*	3.2	n.d.	0.044	n.d.	0.0
Korpfjäll	B	2½	—	147.8	146.8	12.9	12.6	0.184	(0.187)	0.047	0.0
Korpfjäll	B	—	0.9	147.8	(149.1)	13.1*	13.1	n.d.	0.178	n.d.	0.0

*calculated on the assumption that 56 per cent of the added calcium carbonate remains with the ashes
**calculated

hin parantheses less reliable, due to variation between duplicates, extremely low values, etc.

P-$_{\mathrm{Al}}$ mg/100 g		P-$_{\mathrm{HCl}}$ mg/100 g		K$_{\mathrm{total}}$ per cent		K-$_{\mathrm{Al}}$ mg/100 g		K-$_{\mathrm{HCl}}$ mg/100 g		Ca$_{\mathrm{total}}$ per cent	
art	end	start	end	start	end	start	end	start	end	start	end
8	16	32	43	0.08	0.10	40	50	55	60	0.50	0.62
.d.	6	n.d.	38	n.d.	n.d.	n.d.	38	n.d.	62	n.d.	n.d.
5	28	36	51	0.12	0.12	75	41	66	75	0.21	0.24
5	20	30	44	0.06	0.09	52	56	61	62	0.20	0.24
.d.	5	n.d.	29	n.d.	n.d.	n.d.	62	n.d.	76	n.d.	n.d.
5	10	28	50	0.09	n.d.	65	75	76	90	0.18	n.d.
.d.	11	n.d.	32	n.d.	0.10	n.d.	68	n.d.	75	2.42**	3.03
3	2	16	16	0.07	n.d.	9	13	30	29	0.37	n.d.
.d.	2	n.d.	16	n.d.	n.d.	n.d.	10	n.d.	22	n.d.	n.d.
5	n.d.	11	n.d.	0.11	n.d.	21	n.d.	29	n.d.	0.03	n.d.
2	1	6	6	0.10	n.d.	5	5	16	18	0.01	n.d.
0.3	0.6	2	3	0.02	0.02	2	1	9	9	(0.01)	0.01
.d.	0.7	n.d.	6	n.d.	0.01	n.d.	0.6	n.d.	8	0.24**	0.26
.4	0.1	19	16	0.08	n.d.	2	1	27	30	0.42	n.d.
.d.	0.1	n.d.	16	n.d.	n.d.	n.d.	1	n.d.	25	n.d.	n.d.
2	0.6	110	104	0.10	n.d.	4	5	10	12	0.04	n.d.
2	1	60	59	0.03	0.02	1	0.6	6	8	0.02	0.02
.d.	2	n.d.	64	n.d.	0.02	n.d.	0.6	n.d.	8	0.15**	(0.16)
.1	0.1	27	28	0.05	0.05	5	2	13	12	0.18	0.19
.d.	0.2	n.d.	26	n.d.	0.05	n.d.	2	n.d.	12	0.42**	(0.37)