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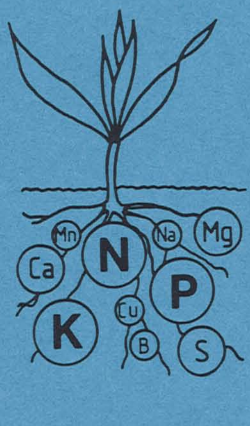
Long-term Effects of N Fertilizer on Crops and Soils

Långtidseffekter av kvävegödsling på gröda och mark

Lennart Mattsson



Dissertation

Institutionen för markvetenskap
Avd. för växtnäringslära

Swedish University of Agricultural Sciences
Dept. of Soil Sciences
Division of Soil Fertility

Rapport 170
Report

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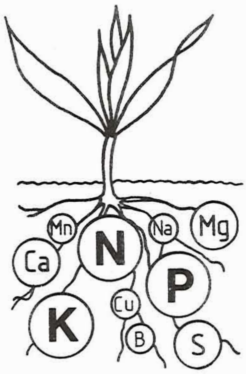

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Abstract

In four Swedish long-term field experiments, two started in 1969 and two in 1972, with applications of N, P and K, studies were made of yield responses, yield development and development of plant nutrient status of the soils with time, and plant nutrient balances. After-effects of N fertilization during 12-27 years were studied in a pot experiment. In a small plot experiment the effects on soil organic C with organic matter and N treatments were investigated. Attempts were made to determine the active, slow and passive soil organic matter fractions.

N responses were generally considerable. Compared with replenishment (supply=crop removal), P responses were also positive, except at one site. K responses were mostly insignificant compared with replenishment and sometimes even negative. Only at one site were there, on average, statistically significant interactions between N*P and N*K. No yield trends with time were observed either in the N treatments or in the PK treatments.

N balance calculations showed that approximately 60 kg ha^{-1} N was removed annually with the crop in zero N treatments. Net supply was of the same order of magnitude in the highest N treatments. 74-86 kg ha^{-1} N, annually applied balanced the crop N removal very well. Significant changes of soil N or soil C contents during the experimental period were not observed in the field experiments. Replenishment only caused decreasing values in the soils of easily soluble fractions of P and K.

In the pot experiment it was demonstrated that the after-effects of annual applications of 100 kg ha^{-1} N corresponded to an increased N-release of 0.3-9.5 kg ha^{-1} compared with zero N treatments. In the same experiment the relative size of the active-N fraction of the soil organic matter was determined using the differences in crop N uptake between treatments with the highest and lowest previous N application. The size ranged from 0.8-41.1%. In the small plot experiment, similar estimations for the active+slow fraction based on differences in soil C content ranged from 11-37%.

A few examples of fertilizer economics are discussed. Replenishment levels were the most profitable for P and K in the short view. In potatoes and sugar beets, however, higher levels were economically beneficial. Optimum levels of N usually increased with P application.

PREFACE

Since World War II, the development of Swedish agriculture has been fast and alterable. New management techniques, new varieties and advanced technical equipment have been introduced. The use of inorganic fertilizers has increased strongly.

In a perspective of many thousands of years during which farming has evolved, this rapid change has taken place within a few moments. From this point of view it is suitable to question the persistence of modern agricultural practices. Will high inputs of fertilizers increase soil fertility in the long run for later exploitation? Will large yields exhaust the soils? What will happen with the soil organic matter, its properties and the amount of it? Is it possible to maintain or increase it, or will it inevitably decline? Simply put: where are we going?

This thesis is a contribution to the understanding of these questions. It is a summary of the four following papers:

I Mattsson, L. 1987. Four Swedish long-term experiments with N, P and K. 1. Yield results. (Accepted for publication in Swedish Journal of agricultural Research).

II Mattsson, L. 1987. Four Swedish long-term experiments with N, P and K. 2. Soil data and plant nutrient balances. (Accepted for publication in Swedish Journal of agricultural Research).

III Persson, J & Mattsson, L. 1987. Soil C changes and size estimates of different organic C fractions in a Swedish long-term small plot experiment. (Submitted for publication in Swedish Journal of agricultural Research).

IV Mattsson, L. 1987. Four Swedish long-term experiments with N, P and K. 3. After-effects of N fertilization. (Submitted for publication in Swedish Journal of agricultural Research).

The papers are referred to by their Roman numerals.

CONTENTS

INTRODUCTION

The back-bone of this thesis is composed of results obtained in four Swedish long-term field experiments. Two of them were started in 1969 and they were later followed by two more in 1972. Already in the late 1950s, investigations were initiated in Sweden to examine the influence of rotations and long-term inorganic fertilizer use on crop production and soil fertility (Jansson, 1975). The experiments dealt with in the present investigation were initiated in order to extend and complement those started earlier. Although the term "long-term" is used in this context it must be realized that this is in a relative sense. Compared with some of the so-called classicals at Rothamsted, run since 1843 (Cooke, 1976) or the Askov experiments in Denmark, run since 1894 (Dam Kofoed & Nemming, 1976) or the experiment at Ås in Norway, run since 1938 (Uhlen, 1976), we have relatively juvenile material.

The aims of the investigations were:

- To demonstrate long-term effects of N, P and K on yields and on the plant nutrient status of the soils.
- To identify possible interactions on yield responses between N and PK fertilization.
- To demonstrate long-term effects of N application on soil organic matter.
- To estimate the sizes of different soil organic matter fractions.

SITE DESCRIPTION

A comprehensive description of the experimental sites was given by Mattsson (1979; I). Some notes on the sites are provided below. Meteorological data originate from the Swedish meteorological and hydrological institute. Temperature records were usually not available for the actual experimental field. In such cases an adjacent station was used instead and its name is given within parenthesis.

Röbäcksdalen and Offer, denoted Rb and Of, represent cultivated soils characteristic for the coastal areas and river valleys of north Sweden. Silty loams with pH(H_2O) 5.8 and 6.4 at Rb and Of, respectively, are the predominant soil type. The soil material originates from postglacial sediments and the mechanical composition changes insignificantly down to a depth of 1 m.

A large proportion of leys in the traditional crop rotation is characteristic for the region and is reflected in the soil C contents, which tend to be fairly high, 2.5-3.3% C. Annual mean precipitation amounts to 588 mm at Rb and 511 mm at Of of which 109 and 104 mm fall during April until June. Annual mean temperature is 3.1 ^{o}C at Rb and also 3.1 at Of (Lännäs). Both sites are situated north of the 63rd latitude with Rb the farthest north. The altitude is 10 m at Rb and 25 m at Of.

Stenstugu (St), is situated on the island of Gotland in the Baltic sea. The soil type is a calcareous clay loam with pH(H_2O) 7.7 and a rather uniform mechanical composition to a depth of 1 m. Geologically the area is a silurian till capped with glacial sediments (Karlsson & Håkansson, 1983). The cropping history is stamped with a varied crop rotation of leys, cereals and root crops. The soil C content is 1.7%. Annual mean precipitation is 561 mm of which 103 mm fall during April until June. Annual mean temperature is 7.2 °C (Visby airport) and the altitude is 45 m.

Lönstorp (Lt), on the west side of the province of Skåne in south Sweden represents cultivated glacial till deposits. The soil type is a silty loam, pH(H_2O) 7.4, with a uniform composition to a depth of 1 m. As at St, the cropping history is characterized by varied plant husbandry with leys and cereals as well as root crops. The soil C content is 1.7%. Annual mean precipitation is 507 mm of which 108 mm fall during April until June. Annual mean temperature is 8.0 °C (Lund) and the altitude 15 m.

To summarize, Rb and Of are representative for vast areas of cultivated coastal soils in north Sweden. St and Lt, on the contrary, are representative for soils with limited geographic extension. On the other hand, these soils are regarded as some of the most fertile cultivated soils in Sweden.

MATERIAL AND METHODS

Two complete crop rotations are reported. This means 14 years for Rb and Of and 10 years for St and Lt. Design, treatments and crop rotations are thoroughly described elsewhere (I). There were six different combinations of PK applications but there was no treatment completely without P and K. The lowest level was replenishment, i.e. supply equals crop removal. N applications varied with the crop grown. Average rates were 0, 37, 74, 129 and 217 kg ha^{-1} at Rb and Of and 0, 43, 86, 129 and 172 kg ha^{-1} at St and Lt. Manure was applied to all plots three times at Rb and four times at Of.

The rotations involved barley, three ley years, green rape, barley and potatoes at Rb and Of and barley, one ley year, oilseeds, winter wheat and sugar beets at St and Lt. To enable year by year comparisons, all the yields were transformed to and expressed as equivalents of barley grain with 15% moisture (I). The soils were analysed for easily soluble P (P-AL) and K (K-AL), total C and Kjeldahl N (II).

In a small plot experiment, initiated in 1956, with 15 different organic manure, crop residue and mineral fertilizer treatments, investigations were made of the soil organic matter changes (III). Five treatments were considered: continuous fallow, no N and straw additions, N but no straw, straw but no N and N+straw additions. The soil organic C and mineralized soil C on incubation were determined.

After-effects of previous N applications during 12-27 years were investigated in a pot experiment with soils from eight different long-term field experiments (IV). Besides Rb, Of, St and Lt, soils from four other experiments, two started in 1957 and two in 1963, were included. Amounts of 4.5-5.5 kg soil from the different N treatments in the field experiments were used and barley was grown twice without N application. The crop was harvested one week before ear emergence, weighed and analysed for Kjeldahl-N. The first harvest was assumed to level the soils as regards residual inorganic N and undecomposed organic material. Only data from the second harvest were used.

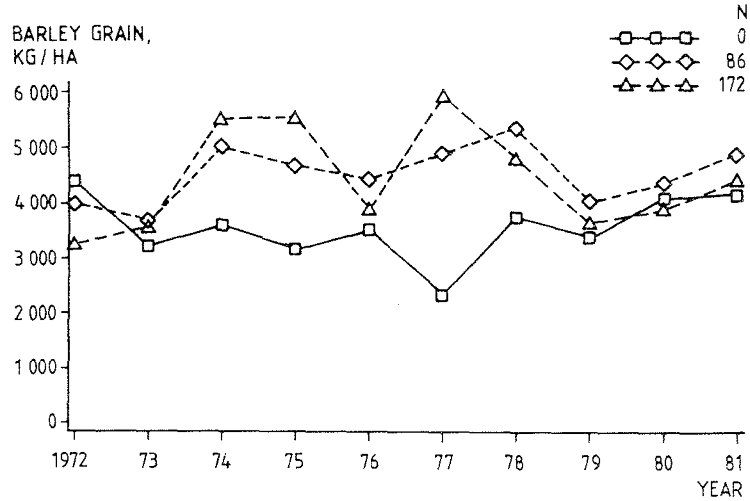

Fig. 1. Annual yields at different N levels at Lönstorp. PK1.

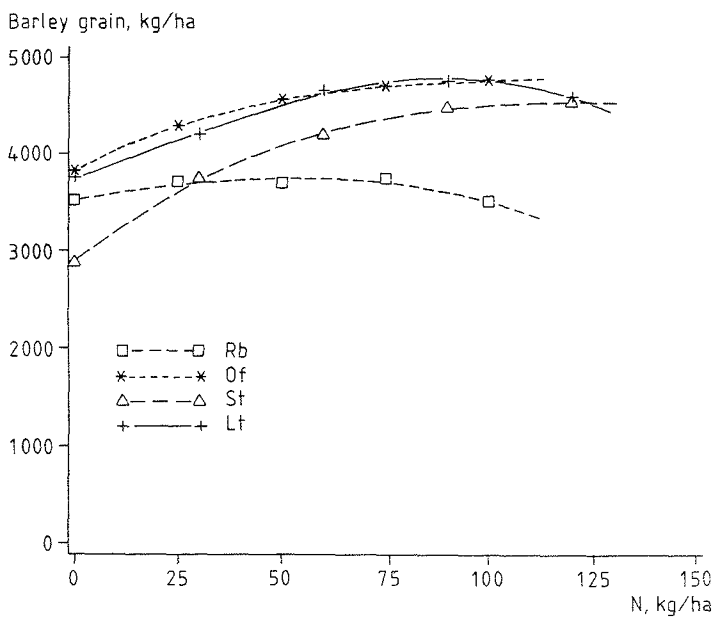

Fig. 2. Average N responses in barley. Means of six PK combinations. Rb=Röbäcksdalen, Of=Offer, St=Stenstugu, Lt=Lönstorp. Four years with barley at Rb and Of, two at St and Lt.

YIELD RESULTS

Nitrogen

The most striking aspect of the yield results was that the yields have remained almost constant despite both suboptimal and overoptimal rates of N fertilizer (Fig. 1). All four experimental sites demonstrated the same pattern in this respect. Repeated removal of N of the order of 60 kg ha^{-1} $year^{-1}$ without replenishment for 10 years or more in the N1 plots did not cause significant yield declines (I, II). Similarly, neither did a net supply of the same order of magnitude in the N5 plots cause increasing yield levels. N responses for individual crops, e.g. barley, were generally substantial (Fig. 2). This demonstrates that there was a shortage of N, which could be satisfied by adding N. Due to lodging at high N rates, N response in barley was low at Rb. In the other crops N responses were bigger.

Phosphorus and potassium

Positive P impacts, compared with the replenishment level, were observed at all sites except at St (I). At site Rb the impacts were large. The K impacts were generally small except at site Rb, where clear negative K impacts were observed. A reasonable explanation of the negative impacts as well as of the other inconsiderable K impacts cannot be given. Perhaps the level of replenishment simply was high enough to avoid crop production being limited. This level was approximately 125 kg ha^{-1} $year^{-1}$ including the manure. Regarding the K-AL values, this is higher than the level normally recommended (Hahlin & Eriksson, 1984). Considerable K impacts of 80 kg ha^{-1} upwards of that could not be expected.

PLANT NUTRIENT STATUS OF THE SOILS

Nitrogen and carbon

No significant changes with time concerning soil C and soil N contents were observed in samples from the field experiments (II). However, the small but positive N after-effect observed in the pot experiment (IV) indicated that a fraction of the fertilizer N not accounted for in the N balance nonetheless was not entirely lost from the root-zone. Some of it was incorporated into soil organic matter, although the differences were too small to be measured in field experiments with conventional sampling and analysis techniques.

In the small plot experiment, on the other hand, there were clearly detectable differences between the treatments in the soil C content (III). The lowest C content was found in the continuous fallow treatment, the highest in the treatment with straw+N additions. Straw alone or N alone caused intermediate effects.

Phosphorus and potassium

The experiments showed that replenishment only did not maintain the PK status of the soils when measured as easily soluble P and/or K. At site Rb, P-AL values declined 21% between 1969 and 1982. At Of, the decline was 18%. Between 1972 and 1981 P-AL values decreased 18 and 42% at St and Lt, respectively. The large decline at Lt depended partly on high initial P-AL values.

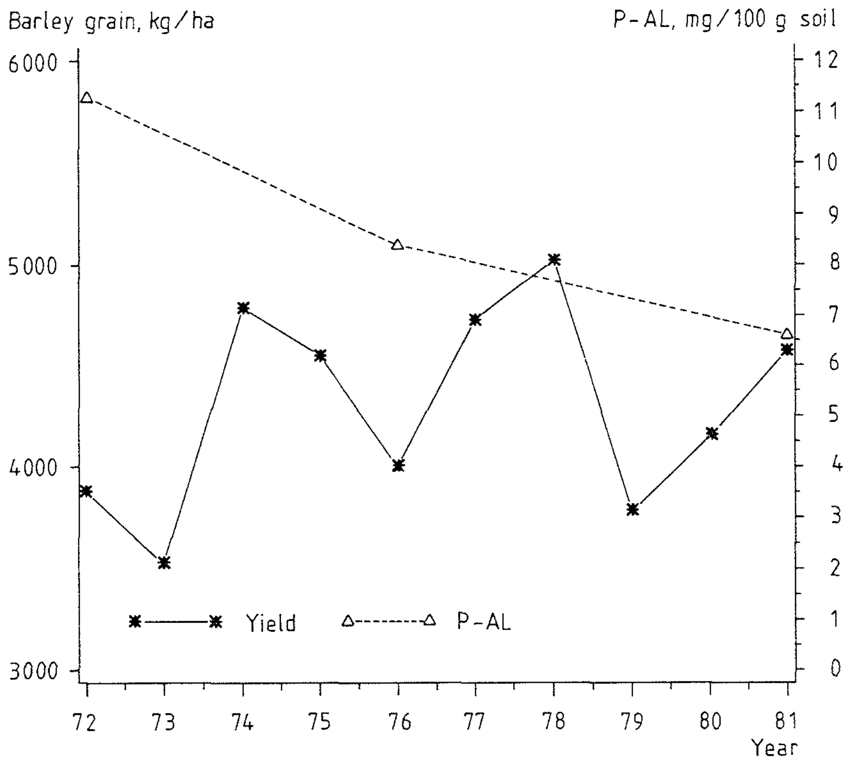

Fig. 3. Annual yields and easily soluble P (P-AL) in PK1. Yields are means of five N levels. Lönstorp.

However, the P decrease did not influence the yield levels negatively (Fig. 3). This applied to all the sites.

When P was supplied at surplus rates, P-AL increased markedly at all sites. The increase was most rapid during the first rotation (Fig. 4). As the exchangeable sites on the colloid-complex were occupied, the increase rate slowed down and equilibrium was achieved. Similar results were reported by Hahlin & Ericsson (1981). All the surplus P was not recovered in easily soluble form, however. Some of it was fixed. The lowest P fixation occurred at St and Lt the largest at Rb. P fixation correlated well with the soil pH (II).

Concerning K, the picture resembled that for P. At St and Lt K-AL values were almost halved within 10 years at the level of replenishment. At Rb and Of, the initial values of K-AL were lower than at St and Lt, resulting in less dramatic changes. When applied at surplus rates K-AL increased. Due to fixation, however, considerable amounts of K were not recovered in easily soluble form.

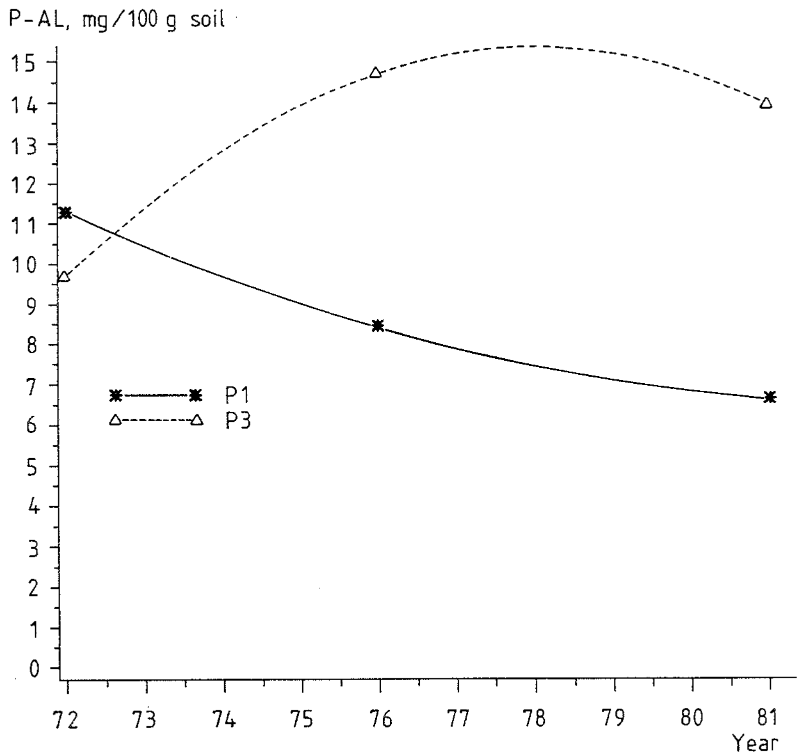

Fig. 4. Development of easily soluble P (P-AL) in P1=replenishment and P3=replenishment+40 kg ha^{-1}, P annually. Lönstorp.

SITE DIFFERENCES CONCERNING PK EFFECTS

There were considerable differences between the sites as regards both the yield impacts and impacts on the soil test values due to PK application.

On average P increased the yields significantly at Rb but not at St. When considering that P fixation was strongest at Rb and weakest at St, this seems plausible. The yield increase at Rb showed that P limited crop yields. The positive P effects also demonstrated that P fixation could be evaded by P application. Since there was no competition for P at St, the level of replenishment was sufficient and did not limit crop growth.

As already mentioned, K application resulted in no or only small yield increases. In the leys, sugar beets, green rape and potatoes, however, the K contents increased with increasing K applications. Accordingly, the removal of K with the crop also increased (Mattsson, 1985; II). Nevertheless substantial amounts of K were assumed to be fixed. This was most pronounced at Of, where nearly 90% was fixed when the removal with the crop was considered (II). The K fixation increased in the order Rb<St<Lt<Of. Clay content is

one factor governing K fixation (Nömmik, 1958). The higher the clay content, the more K is likely to be fixed. At Rb the clay content was 10% while it was considerably higher at the other sites.

AFTER-EFFECTS AND CYCLING OF N

Significance of earlier N application

The term after-effect is used here to denote the effect of N that at least once has entered the soil organic-N pool, either in the form of microbiomass-N or in the form of decomposed organic matter N. The after-effect ought to be distinguished from the residual effect, which also involves the N effects of inorganic fertilizer residues and undecomposed organic material (IV).

In the field experiments the after-effects could not be demonstrated explicitly. This had involved uniform N application on all plots, which was impossible. In the pot experiments, however, positive after-effects from earlier N applications were obtained (IV). Annual N application of 100 kg ha^{-1} increased the above-ground plant N uptake, by 0.01-0.38 mg 100^{-1} g soil compared to "zero N" soils. In a 0.20 m plough layer this is equivalent to 0.3-9.5 kg ha^{-1} N. Continuous application of 100 kg ha^{-1}, in this case for 12 years or more, may increase the N supply to a crop via mineralization by a maximum of 10 kg ha^{-1} compared to "zero N" plots for the same period.

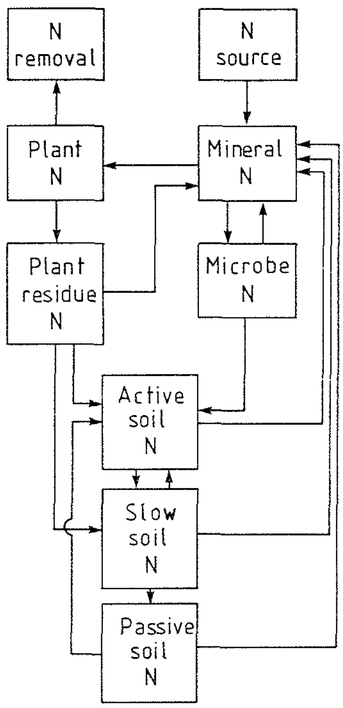

Fig. 5. Flow diagram for N (Modified after Parton et al. 1982).

Related to the net supply of N, which amounted to 1207 kg ha^{-1} including manure for site Rb in the N5 plots, it corresponds to 0.8%. This value may be assumed to be a measure of the net mineralization rate of the applied fertilizer N. The rate may seem low. Jansson (1963) reported values of 2.2 to 3.0%. In the present investigation all N that was not recovered in the crops was assumed to be incorporated into the soil organic matter N pool. This is an overestimation, because the soil N content did not change significantly with time (II). Leaching and denitrification are processes not accounted for. Considering this, the amount of fertilizer N that was really incorporated in organic matter should be reduced, thus increasing the net mineralization rate.

The concept used to understand the after-effects is summarized in Fig. 5. It is essentially the same conceptual model as the one proposed by Parton et al., (1982). Fertilizer N is used by the plants as well as by the microbes when they decompose N deficient organic material. The residue compounds formed in the decay process are partitioned in three fractions called active, slow and passive depending on the degree of availability for microbial decay. Their turn-over times were assumed to be 3, 30 and 1200 years (Parton et al., 1982).

It may be assumed that the incorporation of fertilizer N via plant residues and vigorous microbial activity into active- and slow-N fractions will be higher with high fertilizer applications than with low ones. The energy supply for the microbes is more favourable in the former case. As the supply of energy-rich fresh organic material decreases, as in the case with low N input, the significance of decomposition of previously decomposed material will increase. In the long-term view on zero N plots first the active and later the slow fraction will approach a new equilibrium characteristic for the climate, soil type, N supply and crops grown. In the pot experiment it was assumed that the active-N fraction was depleted in soils from the N1 plots. These plots were not treated with inorganic N for 12-27 years. The differences in N uptake between N5 and N1 plots in the pot experiment were then regarded a measure of the size of the active-N fraction.

The relative size ranged from 0.8-41.1% when all the eight soils were considered. Concerning the four experiments chiefly dealt with here, the range was 11.0-41.1%, the largest at St and the smallest at Lt. From this it may be concluded at St that the increased amounts of crop residues in N5 compared with N1 were transformed into a larger proportion of active organic matter than at Lt. The break-down of crop residues at Lt was more complete than at St, leaving only insignificant amounts of humus substances. On the other hand, this indicates considerable short-term effects, i.e. from one year to the next.

Since the presence of a crop always provides some decomposable material, depletion of the active- and slow-N fractions may take long time. In the small plot experiment (III), a continuous fallow treatment for 28 years was included. Assuming that the active and slow fractions were depleted in the fallow, the common size of the active+slow organic matter fractions in other treatments was estimated from the differences in soil C contents. Depending on N and organic matter application the size ranged from 11-37%. Incubation data with soils from the small plot experiment suggested that the turn-over rate of C from the passive organic matter fraction was faster than expected. Either the active and slow fractions were not depleted in the fallow treatment or the partitioning of the organic matter in three fractions was insufficient. A fourth fraction with a turn-over time somewhere between 30 and 1200 years was hypothetically proposed.

N sources for crop N uptake

A measure of the efficiency of the inorganic N applied may be calculated from the difference in N uptake by the crop between N3 and N1 in per cent of applied N (II). The following values were obtained: 21% at Rb, 30% at Of, 33% at St and 29% at Lt. The figures may seem low but are representative for this type of calculations (Jansson, 1986).

Combinations of results from the pot and field experiments may be used to estimate the contribution from different N-sources to the crop N supply (Table 1). A brief description of the various records in the table is given below.

N removed with crop. This is the amount of N removed with the crop. Values are means of 6 PK levels (II).

N in fertilizer. The differences of N yields between N5 and N1 are attributed to fertilizer N.

Symbiotic N-fixation. Values represent symbiotic N fixation in the leys. Each ley year is assumed to contribute 50 kg ha^{-1} in N1 but nothing in N5 (II).

Non symbiotic N-fixation. Values are based on Delwiche (1970). At the N5 level N fixation is assumed to be completely depressed.

Manure. Values are total N in manure and complete efficiency is assumed. In the short-term view this is an overestimation. A proportion of this N should more appropriately be attributed to active- and slow-N contributions instead. Losses e.g. due to ammoniavolatilization are not considered.

N in atmospheric fallout. Values are based on Rodhe (1982).

Active-N. Values are based on the estimations of the active-N proportions obtained in the pot experiment results (IV). Transformation to kg ha^{-1} was made assuming a bulk weight of 1.25 kg l^{-1} for the 0-20 cm layer. It was assumed that the amount of N supplied from mineralization originated from active-N fractions in proportion to the estimated size for this fraction in the pot experiment.

Slow-N. This is the difference when all other sources are subtracted from the crop N uptake. Contributions from the passive-N fraction are included here.

It follows from Table 1 that the active-N fraction contributed 5-20 kg ha^{-1} of the N removed with the crops, while the slow+passive-N fraction contributed 30-50 kg ha^{-1}. Expressed in per cent this is equal to 4-22 and 24-61%, respectively. The relative contribution from the slow+passive-N fraction tended to be less in N5 than in N1 at all sites. In absolute values, though, the opposite was the case except at site St.

Table 1. Contribution to crop N uptake from different N sources, kg ha^{-1} $year^{-1}$. N1 = zero or low N input level, N5 = high N input level

N source	Rb N1	Rb N5	Of N1	Of N5	St N1	St N5	Lt N1	Lt N5
N removed with crop	91	160	92	185	57	97	60	102
N in fertilizer	-	69	-	93	-	40	-	42
Symbiotic N-fixation	21	-	21	-	10	-	10	-
Non symbiotic N-fixation	5	-	5	-	5	-	5	-
Manure	29	29	29	29	-	-	-	-
N in atmospheric fallout	3	3	3	3	7	7	16	16
Active-N	-	20	-	7	-	21	-	5
Slow-N	33	39	34	53	35	29	29	39

The reliability of these calculations must of course be questioned. They are based on many uncertain assumptions, e.g., that the mineralization in N1 entirely originates from the slow+passive-N fraction and that the estimates of the active-N fractions are correct. Further, the short-term contribution of N originating from crop residues is not considered. In a similar investigation Jansson (1986) reported crop residues responsible for 5-14% of the N taken up and the N originating from stable humus contributed 27-77%. These figures may be compared with the active and slow+passive-N fractions in the present investigation.

PRACTICAL IMPLICATIONS

The present long-term experiments also provide a data base for assessing a proper fertilizer regime. In order to provide some examples, the crops ley II, barley and potatoes were examined at sites Rb and Of, and those of winter wheat and sugar beets at sites St and Lt. The examination was confined to the 2nd rotation only and the PK combinations chosen were PK1, PK3 and PK6. They may be considered as three different management systems concerning the input of P and K, respectively. PK1 is the low input system, PK3 high in P, low in K and PK6 the high input system. The reason to study the 2nd rotation only was that typical levels of fertility were assumed to have developed until then.

Table 2. Optimum levels of N, kg ha^{-1}, and corresponding yield levels, kg ha^{-1}. Based on observations from the 2nd rotation

Site	PK	Ley II, herbage N level	Ley II, herbage Yield	Barley, grain N level	Barley, grain Yield	Potato, tubers N level	Potato, tubers Yield
Rb	1	37	7208	59	3410	84	21984
	3	99	7839	33	3823	103	26347
	6	89	7954	47	3852	120	30660
Of	1	159	9107	47	3825	96	30520
	3	192	9574	49	4046	120	33156
	6	125	8468	57	3660	120	34360

Table 3. Optimum levels of N, kg ha^{-1} and corresponding yield levels, kg ha^{-1}. Based on observations from the 2nd rotation

Site	PK	Winter wheat, grain N level	Winter wheat, grain Yield	Sugar beet, roots N level	Sugar beet, roots Yield
St	1	122	7330	180	57700
	3	131	6880	169	53230
	6	78	6780	160	58220
Lt	1	43	5220	76	46630
	3	74	5370	180	54190
	6	73	5350	121	55280

Optimal levels of N for each crop were calculated according to a yield response function estimated for each PK level. The type of function was

$$y=a+bx+cx^2+dx^3$$

where y=yield, kg ha^{-1} and x=N, kg ha^{-1}. Optimum levels of N were defined as

$$dy/dx = P_g/P_p$$

where P_g= N price, Sw.kr. kg^{-1}. P_p= product price, Sw.kr. kg^{-1}. The prices used were barley=1.10, winter wheat=1.15, ley=1.25, potatoes=0.70 and sugar beets=0.31. For barley and winter wheat the prices relate to 15% moisture, for ley to D.M and for potato and sugar beets to fresh weight of tubers and roots, respectively. For N, P and K the prices assumed were 7.00, 14.00 and 5.50 Sw.kr. kg^{-1}, respectively. Quality differences due to fertilizer applications were not considered.

As can be seen from Tables 2-3, optimum levels of N often increased as the supply of P increased (PK1 and PK3). On the contrary, addition of extra K, PK6 compared with PK3, often caused decreasing optimum levels of N. With some exceptions the yields obtained at optimum levels of N increased as the optimum N increased.

When the the costs of P and K fertilizer were considered, the values shown in Table 4 were obtained. The net cash return in Sw.kr. ha^{-1} was the largest for PK1 with the exception of barley and potatoes at Rb, potatoes at Of and sugar beets at Lt. The large net returns of potatoes and sugar beets must not be over-emphazised, since the labour and machinery costs were not considered.

Table 4. Net cash return, Sw. kr. ha^{-1}, at optimum levels of N for different crops and PK combinations. Based on observations from the 2nd rotation

Site	Crop	PK combination 1	3	6
Rb	Ley II	7815	7610	7384
	Barley	2980	3056	2550
	Potato	14134	16495	18956
Of	Ley II	9351	9144	7791
	Barley	3394	3063	2142
	Potato	20020	21137	21554
St	Winter w.	7244	6102	5926
	Sugar b.	16018	14150	15320
Lt	Winter w.	5368	4758	4308
	Sugar b.	13273	14330	14642

With the approach used, only the direct fertilizer responses were considered. Concerning P and K fertilizing, one has to consider not only the yield responses but also the build-up of fertility in the soil. Differences in AL-values increased between treatments with heavy P and/or K applications and treatments with replenishment only. Although not observed in the present experiments, it could be argued that this should also be beneficial for the crop yields since a reserve of P and K is being built up in treatments with surplus applications. This reserve may be regarded as a resource, or literally speaking a bank account where the interest rate represented by the annual release of P and K may be exploited for crop growth. With this view, application of P and possibly also K may in part be considered as an investment for future revenues. Gunnarsson (1982) used this approach for evaluating the economics of P fertilizing in a 12-year experiment. He concluded that 25 kg ha^{-1} $year^{-1}$ was the optimum P rate.

CONCLUSIONS AND FINAL REMARKS

From data concerning long-term experiments and related investigations presented in this thesis the following conclusions may be drawn:

Completely excluded inorganic N application did not show dramatic yield reductions with time. Neither did surplus N application show increasing yields. The yields were influenced by N applications but the long-term influence on yield levels of a decade or two may be assumed to be small.

On soils not depleted with P and K, application of N may be decided independently of PK application.

Approximately one-third of applied P may be recovered as AL-soluble P. For K, the corresponding figure was 25% or less. Large amounts of both P and K were bound in forms not available to plants.

The after-effects of previous N applications, measured as above-ground plant N uptake, tended to be small. N mineralization increased from an average of 1.0 mg 100^{-1} g soil at zero or low to 1.3 mg 100^{-1} g soil at high previous N applications. In kg ha^{-1} this is equal to 25 and 33 kg, respectively.

Trying to estimate the size of active-N fractions of N fertilized soils gave values of 1-40% of the N taken up. Corresponding estimates for the active+slow-N fraction based on soil C instead gave values of 11-37%.

The active-N fraction contributed approximately 5-20% of the total plant N uptake. The slow+passive-N fraction was responsible for 25-60%.

Deeper understanding of the long-term effects of N fertilizer on crops and soils involves research focusing on the role of humus and humus formation in N cycling. Special attention should be paid to the young humus fractions. The significance of nearly all the plant growth factors may be of importance in this respect.

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SAMMANFATTNING

N-gödslingseffekt, skördeutveckling, och förändringar med tiden i markens växtnäringstillstånd och växtnäringsbalans undersöktes i fyra långliggande

fältförsök. Två av försöken startades 1969 och två 1972. Undersökningen omfattade 14 respektive 10 år. Efterverkan av 12-27 års N-gödsling undersöktes i ett kärlförsök och i ett ramförsök, anlagt 1956, studerades markens C-haltsförändringar vid tillförsel av organiskt material och N-gödsel. En ansats gjordes att bestämma storleken av tre olika fraktioner av markens organiska material. En aktiv fraktion med kort omsättningstid och främst påverkad av de senaste årens grödor och gödsling etc. En mellanfraktion med en omsättningstid på ca 30 år, huvudsakligen påverkad av växtföljd och driftsinriktning, och slutligen en passiv fraktion med mycket lång omsättningstid, cirka 1200 år, som inte mätbart påverkas av odlingsåtgärderna.

N-gödslingseffekterna var som regel stora i alla grödor. I jämförelse med ersättningsnivån (tillförsel=bortförsel) erhölls även positiva P-gödslingseffekter. K-gödsling, däremot gav små, inga eller negativa utslag. Möjligen berodde detta på att ersättningsnivån var förhållandevis hög. En viktig fråga är om N-gödslingseffekterna är beroende av PK-nivån? Sett över hela försöksperioden konstaterades statistiskt säkra belägg för detta i ett försök. Inga trender i skördarnas utveckling med tiden kunde konstateras vare sig vid låg eller hög N-nivå.

N-balansberäkningar visade att ungefär 60 kg ha^{-1} årligen bortfördes från ej N-gödslade rutor. Till rutor med den högsta N-gödslingen tillfördes ungefär lika mycket i överskott varje år. I genomsnitt balanserade en N-tillförsel på 74-86 kg ha^{-1} N-borförseln med skördeprodukterna. Påtagliga förändringar i markens N- och C-halt kunde inte påvisas i fältförsöken vare sig vid låg eller hög N-nivå. För P och K gällde att ersättningsnivåerna inte var tillräckliga för att motverka att de AL-lösliga fraktionerna av dessa ämnen i marken sjönk.

I kärlförsöket påvisades efterverkan av tidigare N-gödsling. I denna effekt inbegreps inte effekter av färsk organiskt material och oorganiska gödselmedelsrester. En årlig tillförsel av 100 kg ha^{-1} N gav en ökad N-frigörelse som motsvarade 0.3-9.5 kg ha^{-1} jämfört med ej N-gödslade rutor. Den stora variationen relaterades främst till skillnader i försöksjordarnas C-halter. Den aktiva fraktionens relativa storlek bestämd genom differensen i N-upptagning mellan den högsta och lägsta N-nivån varierade från 0.8-41.1%. I ramförsöket gjordes liknande beräkningar baserade på C-haltsdifferenser. Den gemensamma storleken för de två yngsta fraktionerna varierade från 11-37%.

Några exempel på gödslingsekonomi diskuteras. Ersättningsnivåerna av P och K var lönsammast utom i potatis och sockerbetor, där högre nivåer var ekonomiskt motiverade. I motsats till vad som konstaterades ovan för hela försöksperioden beträffande samspelseffekter mellan N och P, steg optimal N-giva vanligen med stigande P-gödsling.

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I

FOUR SWEDISH LONG-TERM EXPERIMENTS WITH N, P AND K
1. Yield results

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Abstract: Yield responses to N, P and K applications were investigated in four long-term field experiments. The pH(H_2O) of the soils ranged from 5.8-7.7 and their clay contents from 10-28%. Two crop rotations, five and seven years depending on location are reported.

In the control plots, P and K were applied to replenish crop removal of these nutrients. There were no zero P or zero K plots. Complementary dressings were 20 and 40 kg ha^{-1} $year^{-1}$ of P and 80 kg ha^{-1} $year^{-1}$ of K. N application varied with the crop and ranged from 0-80 kg ha^{-1} in barley undersown with ley and 0-320 kg ha^{-1} in some of the leys.

The largest N response was found in the leys. Oilseeds also responded strongly to N application. There were no evident trends with time of N response at any site. Plots with 10 to 14 years without application of inorganic N showed no yield decreases. Although not explicitly demonstrated, it could be assumed that N fixation by clover in the leys at all sites, and the animal manure applied regularly at two of the sites counteracted the expected yield decline.

At one site there were significant interactions on yields between N and P or N and K applications. N*P was slightly negative and N*K was slightly positive.

The general conclusion as regards yield response to N fertilization is that there is no interaction of practical importance between N and the other nutrients. The adjustment of N rates to different crops on soils, moderate to well supplied with P and K, can be made regardless of soil PK-status. The results have not shown what would happen on P and K deficient soils.

INTRODUCTION

When designing a correct fertilizer regime one has to consider various demands of the crops, the long- term productivity of the soils and environmental factors. There is also the question whether or not fertilizer interactions will take place. Long-term field experiments permits these questions to be studied as well as changes of the soil nutrient status with time.

Continuous cropping without replacement of nutrients will exhaust labile soil nutrient pools and lead to decreasing yields. It is questionable whether enrichment by fertilization may be assumed to act in the opposite direction, and lead to increasing yields. Time, crop rotation and original soil nutrient status will be influential. Examples of time trends in other long-term fertility studies are discussed below.

After 25 years of cropping without supply of N, P or K in Swedish soil fertility trials the yields had decreased to 50 % of the yields normally obtained for the area (Jansson, 1983). Recurrent application of manure counteracted this yield decrease. The decline was most rapid during the first four years without fertilizer application. No trends, however, were observed with time towards larger yields when NPK application was increased to a level 50% above normally recommended rates.

In continuous wheat cropping since 1843 in the U.K., wheat yields were largest during the period 1970-1978 even on control plots wihout N applications (Dyke et al., 1983). Average grain yields for the period 1970-1978 were 1650 kg ha^{-1}. Differences between these plots and plots with N rates of 144 kg ha^{-1} $year^{-1}$ were constant during the same period.

In Danish experiments since 1894, yields of not fertilized plots decreased during the first 5 to 10 years. Thereafter, the yields remained fairly constant (Dam Kofoed & Nemming, 1976).

In Norwegian experiments lasting for 25 to 50 years the yields of not fertilized plots were 50 to 80% of the yields on NPK-fertilized plots (Uhlen, 1976). The differences between fertilized and not fertilized plots remained constant over the years.

An important question concerning N fertilization is whether the N effects are dependent on the soil P and K status. Data dealing with this question are rare. In the Swedish soil fertility trials referred to above, a positive interaction between P and K was achieved in sugar-beets but not in barley, oilseeds or winter wheat.

The field experiments reported here were started with the purpose of contributing further data on this subject as well as providing information on yield developments occurring as a result of different fertilizer regimes. The present paper reports yield results from four long-term Swedish fertilizer experiments. A subsequent paper will deal with soil data and nutrient balances.

MATERIAL AND METHODS

Location

The experiments are conducted on experimental stations run by the Swedish University of Agricultural Sciences, Uppsala. The notations Rb, Of, St and Lt will be used to denote Röbäcksdalen, Offer, Stenstugu and Lönstorp respectively. A comprehensive description of the sites is given by Mattsson (1979). General site information is given in Table 1. Starting years were 1969 for Rb and Of, and 1972 for St and Lt. All four experiments are still running. The periods 1969-1982 at Rb and Of and 1972-1981 at St and Lt will be reported here.

Design

Three P levels, denoted P1, P2 and P3, combined with two K levels, denoted K1 and K2, were assigned on six main plots in a split-plot design with five N levels, denoted N1, N2, N3, N4 and N5, as sub-plots. The 30 treatment combinations were replicated twice, giving a total plot number of 60. Plot size was 90 m^2.

Table 1. Location, precipitation, and some soil properties of the experimental sites. Soil parameters refer to top soil and are means of six determinations

	Site			
	Rb	Of	St	Lt
Location				
longitude	20°14'E	17°46'E	18°27'E	13°6'E
latitude	63°48'N	63°9'N	57°35'N	55°40'N
Mean annual precipitation, mm	588	511	561	507
Clay content, %	10±0.5[a]	27±3.0[a]	28±1.4	22±0.6
Total carbon, %	3.3±0.2[b]	2.5±0.03	1.7±0.1	1.7±0.1
$pH_{(H_2O)}$	5.8±0.1	6.4±0.1	7.7±0.03	7.4±0.1
Easily soluble				
P(P-AL), mg/100 g soil	7.0±0.6	7.9±0.3	8.2±0.2	9.7±0.9
K(K-AL), "	7.3±0.2	10.0±0.6	19.9±0.4	13.3±0.9

[a] Average of two replicates. [b] Average of four replicates.

P and K applications were based on replenishment for crop removal of these nutrients in P1 and K1. In addition to replenishment, annual applications of 20 and 40 kg ha^{-1} P were given in P2 and P3, as were 80 kg ha^{-1} K in K2. Increased N application adjusted to the crop cultivated was employed. No fertilizer N was given in N1 while N3 corresponded to normal recommended rates. Mean fertilizer rates are given in Tables 2 and 3.

P was supplied as ´superphosphate´ (9% P) and K as ´potassium-chloride´ (48% K). N was supplied as ´ammonium-nitrate´ (34% N). Spring application was used except to autumn-sown crops, where P and K were applied before sowing.

Crop rotation

At Rb and Of the crop rotation was barley, ley I, ley II, ley III, green rape, barley and potatoes. At St and Lt the rotation was barley, ley I, oilseeds, winter wheat and sugar-beets.

The leys were harvested twice at Rb and Of but only once at St and Lt to enable the sowing of winter rape. If over-wintering of the rape failed it was replaced by white mustard. This occurred at both St and Lt during the winter of 1973/74 and at St in that of 1978/1979.

At Rb and Of farm animal manure was applied to all plots. Actual application times and amounts of manure are shown in Table 4.

Table 2. N-, P- and K- levels in kg.ha^{-1}

PK-combination

PK1.	Replenishment of P and K		
PK2.	" "	+ 20 P	
PK3.	" "	+ 40 P	
PK4.	" "		+ 80 K
PK5.	" "	+ 20 P	+ 80 K
PK6.	" "	+ 40 P	+ 80 K

N-levels

Crop	N1	N2	N3	N4	N5
Rb and Of					
Barley	0	30	60	90	120
" as cover crop	0	20	40	60	80
Ley	0	40	80	160	320
Green rape	0	60	120	180	240
Potatoes	0	30	60	90	120
Average	0	37	74	129	217
St and Lt					
Barley	0	30	60	90	120
Ley	0	50	100	150	200
Oilseeds	0	50	100	150	200
Winter wheat	0	40	80	120	160
Sugar-beets	0	45	90	135	180
Average	0	43	86	129	172

Table 3. Mean annual P and K rates, kg ha^{-1}. Average for two crop rotations. Manure not included

	Phosphorus			Potassium	
Site	1	2	3	1	2
Rb	10	30	50	93	173
Of	10	30	50	95	175
St	15	35	55	59	139
Lt	16	36	56	58	138

Table 4. Application of manure at Rb and Of

Site	Manure ton ha^{-1}	Year	Month	DM %	Content, % of DM P	K
Rb	40	73	05	[a]	[a]	[a]
"	30	77	10	10.9	1.3	5.0
"	40	79	10	8.6	0.8	5.7
Of	30	73	06	7.3	1.1	4.0
"	30	75	10	10.2	1.3	2.4
"	50	77	10	4.7	1.1	5.3
"	30	79	10	6.8	0.6	3.6

[a] Not analysed

Sampling and analyses

The yields of grain and oilseeds, potato tubers, sugar-beet roots, herbage from leys and green rape and straw from the cover crop preceding the leys were determined as averages for two replicates. Samples of each crop product representing both replicates were taken. All crop products sampled were analysed for contents of N, P and K. Sugar content of sugar-beets, oil content of oilseeds, etc., were also determined but will not be reported here.

Yield data presentation

The crops were grown sequentially. Thus there was only one crop per year and rotation, which is a draw-back when studing yield trends over the years. However, this draw-back can be coped with in several ways. One way is to calculate the economic value of all crop products and express the yields in Sw.kr. ha^{-1}. Another way is to express the yields in terms of nutrient removal, e.g. as N yields per ha, rather than dry matter production. A third way is to relate all yields to a common crop unit, e.g. cereal grain. None of the alternatives are perfect. The method chosen was to relate all harvest figures to the average barley yields of each site and express them as barley grain, kg ha^{-1} with 15% moisture. This method was considered to be the best when different crops were compared. It accounted for the relationships between the yields of different crops at the individual sites. Its weakness was its sensitivity to interactions between year and crop.

The following example illustrates the approach used. At site St the average barley grain yields were 2879, 3742, 4199, 4485 and 4536 kg ha^{-1} at the N1 to N5 levels, respectively, independent of PK levels.

Corresponding means of D.M. yields of ley I were 3150, 3465, 3810, 3900 and 3980 kg ha^{-1}. Then the factors used to express ley I yields as barley grain were derived from $2879*3150^{-1}=0.91$ at the N1 level, $3742*3465^{-1}=1.08$ at the N2 level etc. These factors were used to transform actual ley I yields at site St to barley grain. The same procedure was repeated for all crops at each site.

When observed yields are shown they are given in kg ha^{-1} with 15% moisture for cereal grain and oilseeds. Dry matter is used for herbage of leys and green rape, whereas fresh weight is used for sugar-beet roots and potato tubers.

Statistical applications

Yield data transformed to barley grain, kg ha^{-1}, were submitted to variance analysis (anova). The model chosen can be seen from Table 7. The years were considered as replicates and the error for main plots was estimated from the interaction year*P*K, while the error for sub-plots was estimated from the sum of the interactions year*N*P+year*N*K+year*N*P*K. With this approach possible yield trends with time due to the treatments could not be separated from the effect of the years.

To show the response of N and P or N and K, multiple linear regression was also performed. The model used was

$$y=a+bx+cx^2+dx^3+ez+fx*z$$

where y=barley grain, kg ha^{-1}
x=N, kg ha^{-1}
z=P or K, kg ha^{-1}
a, b, c, d, e, f=regression coefficients.

The corresponding response surfaces for site Of were plotted in 3-dimensional plots.

RESULTS

Average fertilizer responses

The barley yields of each experiment may be regarded as a measure of the average fertilizer responses and allow comparisons between the sites (Tables 5-6). The largest N responses were observed at St and the smallest at Rb. At the former site the N3 level increased the yield by 46% over N1 compared with only 5% at the latter site. Corresponding figures at Lt and Of were 23 and 20%, respectively. The low N response at Rb depends largely on yield depressions due to lodging in two of the four barley years.

N responses were highly significant at all sites (Table 7). P effects were significant and positive at Rb, Of and Lt. K effects were significant at Rb, St and Lt. There were significant interaction effects between N*year at all sites, between N*P and N*K at Of and a significant three-factor interaction N*P*K at Lt. The following interactions were also significant: P*K at St, P*year at St and Rb, and K*year at Rb.

Fertilizer responses in individual crops

The leys showed the largest N responses at Rb and Of, while oilseeds responded most strongly at St and Lt (Tables 5-6). The P3 level at Rb increased the tuber yield of potatoes by 23% and the grain yield of barley by 12% compared with the P1 level. K responses in individual crops were generally insignificant except at Rb.

Table 5. Average yields, kg ha^{-1}, of different crops at Röbäcksdalen and Offer

Crop	N-level	Site Rb	Site Of	P-level	Site Rb	Site Of	K-level	Site Rb	Site Of
Barley,	N1	3520	3810	P1	3420	4350	K1	3760	4430
grain	N3	3690	4560	P2	3630	4400	K2	3500	4420
	N5	3510	4760	P3	3840	4510			
$HSD_{0.05}$		544	780		361	518		246	353
Ley,	N1	5570	5800	P1	7340	7460	K1	7410	7540
D.M.	N3	7160	7410	P2	7250	7540	K2	7260	7530
	N5	9230	9380	P3	7430	7610			
$HSD_{0.05}$		775	934		515	621		351	423
Green	N1	3960	4630	P1	4890	5900	K1	4930	6110
rape	N3	5300	6290	P2	4960	6090	K2	4820	6040
	N5	4840	7180	P3	4760	6230			
$HSD_{0.05}$		1627	717		1076	474		731	322
Potato	N1	19130	20040	P1	19800	23960	K1	22230	24060
tubers	N3	22580	25350	P2	22060	25520	K2	21920	25810
	N5	23730	28420	P3	24360	25340			
$HSD_{0.05}$		1775	4404		1174	2912		797	1978

Table 6. Average yields, kg ha^{-1}, of different crops at Stenstugu and Lönnstorp

Crop	N-level	Site St	Site Lt	P-level	Site St	Site Lt	K-level	Site St	Site Lt
Barley,	N1	2880	3750	P1	3920	4300	K1	3930	4300
grain	N3	4200	4650	P2	3920	4330	K2	4000	4480
	N5	4540	4590	P3	4070	4530			
$HSD_{0.05}$		564	1295		373	857		253	582
Ley, D.M.	N1	3150	4390	P1	3840	4610	K1	3760	4690
	N3	3810	4580	P2	3560	4760	K2	3570	4770
	N5	3980	5190	P3	3590	4830			
$HSD_{0.05}$		591	1216		391	804		266	546
Oilseeds	N1	1310	1350	P1	1940	2050	K1	2090	2110
	N3	2060	2300	P2	2010	2130	K2	1950	2090
	N5	2590	2580	P3	2120	2110			
$HSD_{0.05}$		559	324		360	214		`251	145
Winter wheat,	N1	4320	3880	P1	5640	5100	K1	5770	5110
grain	N3	6000	4650	P2	5700	5260	K2	5610	5220
	N5	6440	5630	P3	5720	5130			
$HSD_{0.05}$		580	692		383	458		260	311
Sugar-beets,	N1	31510	30700	P1	43530	41920	K1	41300	42140
roots	N3	43370	46070	P2	40680	43120	K2	42170	43660
	N5	48910	49460	P3	41000	43670			
$HSD_{0.05}$		7424	5074		4910	3356		3334	2279

Yield response by year

Negative N response occurred at Rb in 1974, 1978, 1980 and 1982. The crops were barley, ley II, green rape and potatoes (Fig. 1). Yields were generally smaller during the first crop rotation compared with the second. Yield curves at Of presented an extremely jagged pattern (Fig. 2), with a small yield followed by a large one which is followed by a small one, etc. The largest N responses occurred in 1971 for ley II and in 1977 for ley I. Yield increases corresponding to more than 1000 kg ha^{-1} barley grain for level N3 compared with N1 were recorded in those years. N responses at St were large in 1977, 1978 and 1980 with barley, ley I and winter wheat, respectively (Fig. 3). At Lt, negative N effects occurred in 1972, while large positive N effects were recorded in 1977. In both years the crop was barley (Fig. 4).

Table 7. Analysis of variance for the yield data

	Rb		Of		St		Lt	
Source	df	F	df	F	df	F	df	F
Year	13	165.63***	13	149.96***	9	79.08***	9	79.78***
N	4	17.68***	4	295.36***	4	515.90***	4	176.07***
P	2	37.03***	2	8.64***	2	2.48	2	5.84*
K	1	34.33***	1	<1	1	5.75*	1	5.09*
N*year	52	7.95***	52	9.32***	36	10.60***	36	27.00***
P*year	26	13.48***	26	1.17	18	2.47*	18	2.14
K*year	13	6.80***	13	1.65	9	1.97	9	1.27
N*P	8	1.25	8	3.00**	8	1.70	8	<1
N*K	4	<1	4	4.92***	4	<1	4	2.26
P*K	2	<1	2	2.13	2	10.81***	2	2.72
N*P*K	8	1.27	8	<1	8	1.18	8	2.19*
Error [a]	26		26		18		18	
Error [b]	260		260		180		180	
Total	419		419		299		299	

[a] Source of error for main plot is P*K*year.

[b] Source of error for subplot is N*P*year + N*K*year + N*P*K*year.

Figures 1 to 4 show no clear trends with time at any site. Neither surplus N nor zero N treatments have influenced the yield levels markedly in any direction. A tendency towards increasing differences occurring between the N levels may be noted at St.

The correct adjustment of N fertilizer applications involves knowledge of interactions between impacts of N and other nutrients. The analysis of variance showed such interactions at Of (Table 7). These effects are shown in Figures 5 and 6. Concerning N*P the effect was negative. Increasing P application decreased the N response. However, the absolute yield increases of N applications were positive. For N*K, the higher the K rate, the better the N response.

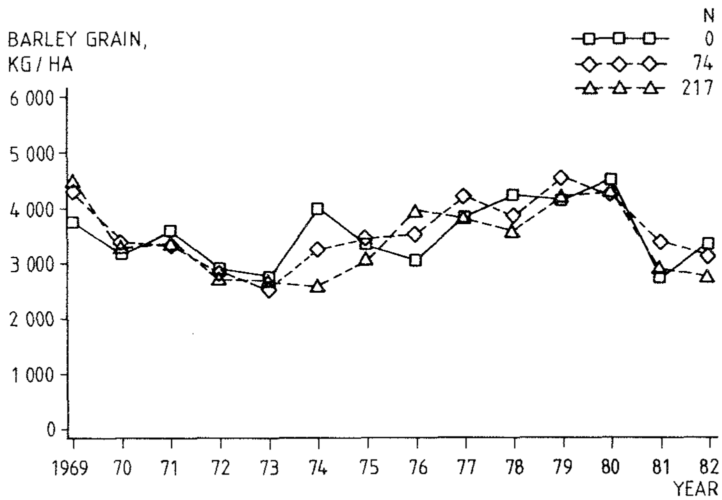

Fig. 1. Annual yields at different N levels at Röbäcksdalen. PK1.

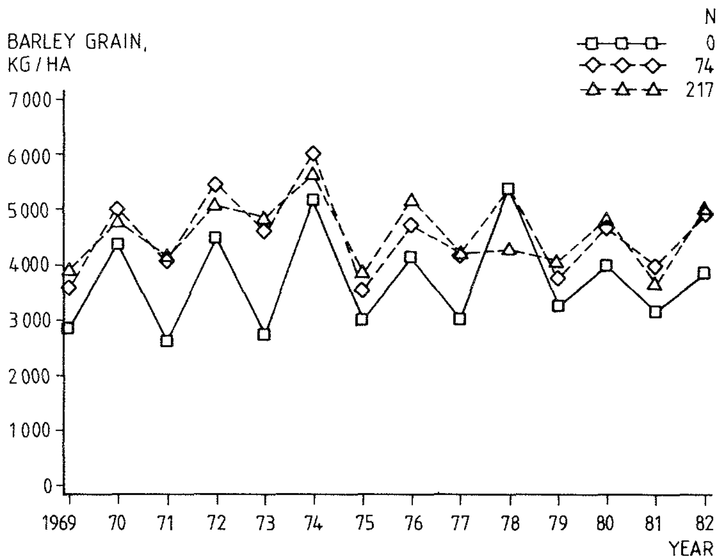

Fig. 2. Annual yields at different N levels at Offer. PK1.

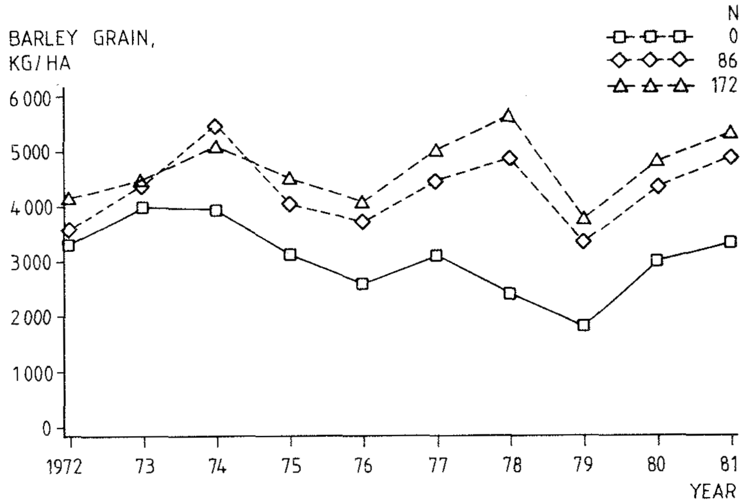

Fig. 3. Annual yields at different N levels at Stenstugu. PK1.

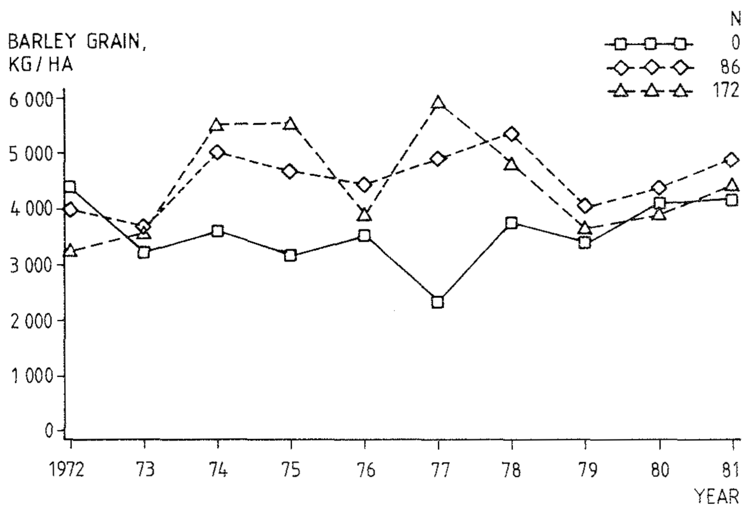

Fig. 4. Annual yields at different N levels at Lönstorp. PK1.

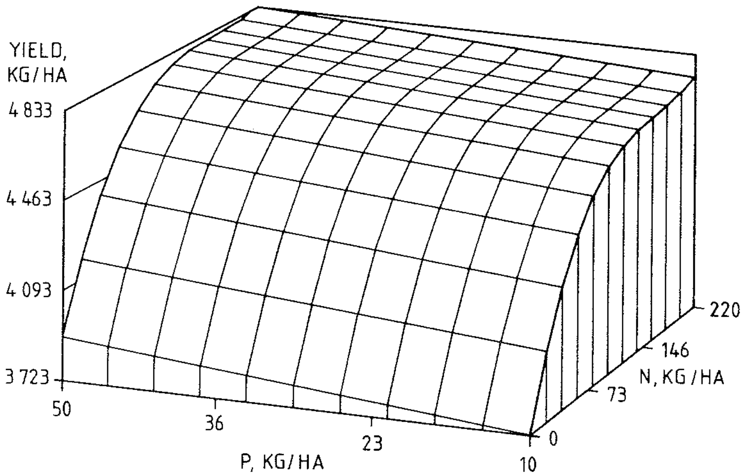

Fig. 5. N and P impacts on the yields at Offer independent of K level.
Response surface of the equation
$y=3680+16.06x-0.0922x^2+0.000181x^3+4.38z-0.0058x*z$,
$r^2=0.19^{***}$.

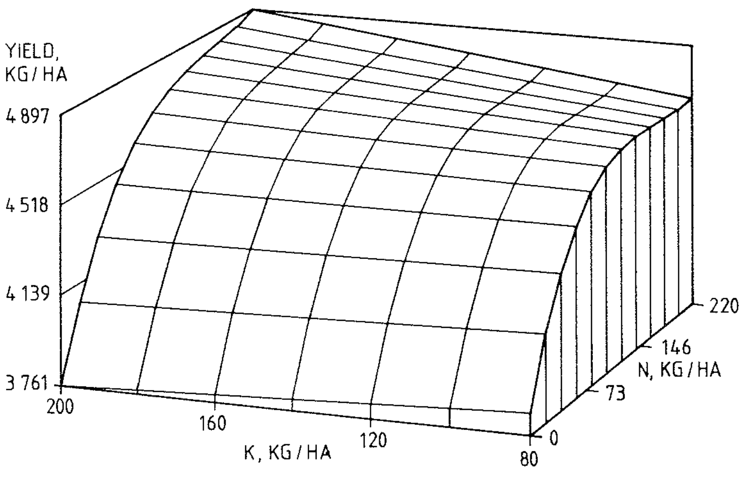

Fig. 6. N and K impacts on the yields at Offer independent of P level.
Response surface of the equation
$y=3915+14.27x-0.0922x^2+0.000181x^3-0.77z+0.0121x*z$,
$r^2=0.18^{***}$.

DISCUSSION

The assumption that N response is improved with increasing P and/or K application was not generally verified as far as the overall results are concerned. The explanation may depend on non-limiting soil PK-levels. Despite the fact that P and K status in the soil (not presented here) has decreased in PK1 since the experiments started, the values are still at a level where only small yield responses of P and K applications may be expected (Hahlin & Ericsson, 1981). It should be noticed that the F-values in the anova for N*P at St and N*K at Lt are not far from significance at the 5% level. This indicates that there are tendencies for interactions to occur. At present though, the conclusion is that N application on soils moderately or well supplied with P and K will be governed by other factors than the soil PK status. The question remains concerning N impacts on soils with low PK status. Such a status has not yet been achieved in the experiments.

Periods of 14 years at Rb and Of and 10 years at St and Lt with no inorganic N applications have not obviously influenced the yield trends with time. There was no evidence of increasing or decreasing yields either at high or at low N levels. In this sense the soil system has been resistant to changes.

In long-term experiments reported by Dam Kofoed & Nemming (1976) and Jansson (1983) the yields on plots which were not N fertilized decreased during the first 5-10 years but remained rather stabile thereafter. These experiments were started in 1894 and 1957, respectively. A similar yield decline was not observed in the zero-N plots of our experiments. It is possible that the organic N-pool was less and was depleted faster in these old experiments than in our experiments. The latter were started at a time when both yield levels were higher and crop residues were larger than in the late 1950s and especially at the end of the 19th century. Larger crop residues containing more N will maintain a humuspool capable of providing nitrogen for a longer period than can be done by small crop residues with low N contents. On N fertilized plots, however, the results agreed with both Dam Kofoed & Nemming (1976) , Jansson (1983) as well as Persson (1981) as regards yield development.

Since the leys contained clover, N-fixation must be taken into account. Average clover contents were 15% at Rb and Of and 25% at St and Lt. It was strongly influenced by the N level. N-fixation by clover grown alone can reach 180 kg ha^{-1} $year^{-1}$ (Nutman, 1976). Average calculations for Swedish leys indicate a gain of N by symbiotic N-fixation of approximately 50 kg ha^{-1} $year^{-1}$ (Falck, 1980). A total gain over two rotations of 300 kg ha^{-1} at Rb and Of (three ley years per rotation) and 100 kg ha^{-1} at St and Lt (one ley year per rotation) may be assumed.

The application of manure at Rb and Of has also counteracted the N depletion of the soils. The total N contribution from manure amounted to approximately 400 kg ha^{-1} at both sites, giving an average of 29 kg ha^{-1} $year^{-1}$ during the experimental period. Together with N gained from the N-fixation by clover, there was an average yearly N contribution of approximately 50 kg ha^{-1} to "zero N" plots. No doubt has this preserved the yield levels of these plots.

Dry and wet atmosheric N deposition must also be considered when N depletion and yield levels are discussed. The experiment at Lt is located close to a road with heavy traffic. It is possible that the nitrous oxides in the exhausts provided the experiment with N sufficient to counteract and disturb the expected yield development. This was also supported by the fact that despite identical rotations at St and Lt, there was a tendency for yields to decrease at the N1 level at the former site where the influence from traffic is less.

The manure applications may partly be accredited responsibility for the jagged shape of the curves for Of. The peaks in 1974, 1976, 1978 and 1980 all occurred in the year following the manure application. A similar pattern but not as evident, could be seen at Rb. Yield peaks in 1974, 1978 and 1980 at the N1 level all followed in the year after manure application.

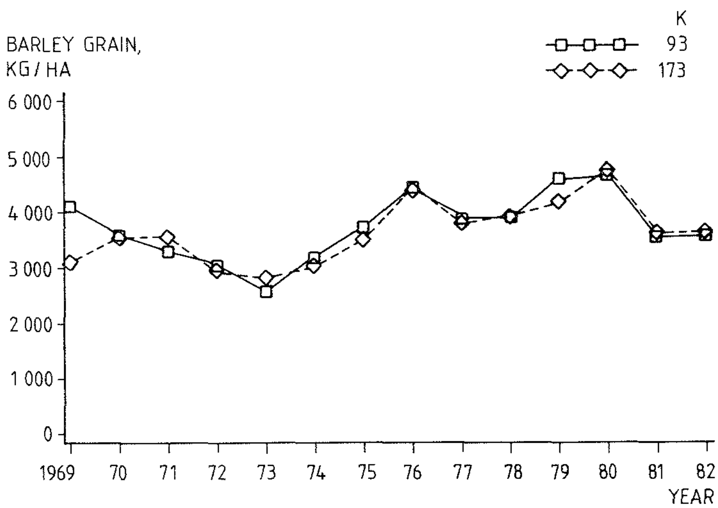

Fig. 7. Annual yields at different K levels at Röbäcksdalen. N level 3, independent of P level.

With some exceptions, K applications in addition to replenishment, did not give any yield response. It may therefore be concluded that fertilization at the K1 level did not usually limit crop yields.

Effects of surplus K were significant and negative at Rb. Negative effects may be expected if the K/Mg ratio of the soil is larger than 3 (Johansson & Hahlin, 1977). The ratio of K/Mg at the K2 level was 0.84 at Rb at the start of the experiment and 7.22 at the end of the 2nd rotation. This suggests that the K effects would change with time at Rb but, in fact, this has not been the case (Fig. 7). Reasonable explanations of the negative K effects cannot be found. Possibly, although this cannot be demonstrated, the K application at the K2 level was too high.

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II

FOUR SWEDISH LONG-TERM EXPERIMENTS WITH N, P AND K
2. Soil data and plant nutrient balances

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Abstract: In four long-term Swedish field experiments the impacts of combined applications of N, P and K on soil C, soil N and easily soluble P (P-AL) and K (K-AL) were investigated. The experiments were started in 1969 and 1972 and are still running. There are 6 different PK combinations combined with 5 N levels giving 30 plots in a split plot design. Clay contents of the soils were 10-28% with $pH_{(H_2O)}$ varying from 5.8 to 7.7.

Average application of fertilizer N varied from 0 to 217, of P from 10 to 56 and of K from 58 to 175 kg ha^{-1} $year^{-1}$. At two sites animal manure was applied regularly to the whole experimental field.

N balance calculations showed a net removal of 57-63 kg ha^{-1} $year^{-1}$ in zero N plots. In plots given the highest N rates, 61-86 kg ha^{-1} $year^{-1}$ were recorded as net surplus N. Soil N analyses showed neither a decrease nor an increase in plots with net removal of N or net surplus N. There were no definite trends with time as regards soil C content.

Related to the total soil N pool, the net loss of N in zero N plots corresponded to approximately 15%. Since this could not be verified in the soil N analyses, N fallout and positive N effects by the clover in the leys were considered to be of importance in maintaining the soil N reservoires. Moreover, the experimental periods, 10-14 years, were considered to be too short to allow measurements of the small changes of soil N and soil C that might have occurred.

Applications of surplus P resulted in increases of P-AL contents corresponding to 38-66 % of the added surplus P. The remaining part of the added P was supposed to be fixed. Of the added K, 1-25 % was recovered as K-AL, implying that 75-99 % of added K must have been fixed or lost by leaching. The amounts of P and K not accounted for in the top-soil were not found deeper in the soil profile, indicating that leaching was insignificant.

INTRODUCTION

Fertilizer N applied to a soil will partly be used by the crop and partly by soil microorganisms. Part of it will also be lost by leaching or denitrification. It does not matter whether the N is applied as organic or inorganic. If it is applied as organic N it first has to be mineralized before it can be used by the crop. Once the N has become inorganic the ammonium form is preferred by microbes to nitrate-N if both are present (Jansson et al., 1955; Jansson 1958). The higher the N level the larger the yields will be. Increasing the N level gives more abundant crop residues with higher N contents. The crop residues are primarily energetic material for soil microorganisms. Abundant supply of energy means increasing microbial activity and also increasing humus formation. Crop residues richer in N may also contribute to higher concentrations of N in humus substances than those formed from N deficient material (Lang & Sturm, 1983). Changes in humus formation and changes in the N content of the humus substances may be analysed as changes of soil C and N content.

Positive effects on soil C and soil N of N applications have been demonstrated (Jansson, 1975; Dam Kofoed & Nemming, 1976; Asmus & Görlitz, 1978; Körschens, 1978; Persson, 1980; Görlitz & Asmus, 1981; Kopytko et al., 1983). If manure was used the positive effects were mostly enhanced. Consequently, zero or low N application reduced crop production and probably also reduced the raw material available for humus formation.

In a series of four Swedish field experiments, mainly designed to investigate N responses at different P and K levels, impacts of fertilizer applications on soil N and soil C as well as on levels of easily soluble P and K in the soils were investigated. In this paper the impacts on soil N and soil C balances are reported together with the impacts on soil P and K dynamics of surplus P and K applications.

MATERIAL AND METHODS

Experimental design, treatments and yields are fully described by Mattsson (1987). The locations from north to south were Röbäcksdalen, Offer, Stenstugu and Lönstorp, denoted Rb, Of, St and Lt, respectively. A split plot design with two replicates of six combinations of P and K as main plots and with five different N levels as sub plots was employed. The clay contents of the soils were 10 % at Rb, 22 % at Lt, 27 % at Of and 28 % at St with $pH_{(H_2O)}$ levels of 5.8, 7.4, 6.4 and 7.7, respectively.

Sampling

Before the experiments started samples from each main plot were taken, the same procedure being used at all sites. Further samples were taken in 1972, 1975, 1979 and 1982 at Rb and Of and in 1976 and 1981 at St and Lt. Until 1976 one sample representing each treatment was taken, i.e., 30 samples per experiment. Thereafter, each PK combination was sampled separately, giving 6 different samples per experiment.

The sub-soils were sampled in 1972, 1975 and 1982 at Rb and Of and in 1976 and 1981 at St and Lt. The sampling depths varied but generally concerned the 40-60 cm layer. On some occasions the 20-50 and 20-40 cm layers were used instead.

Analyses

Easily soluble P and K, denoted P-AL and K-AL, respectively, were analysed according to Egnér et al. (1960). Soil C was analysed as total C by loss on ignition (Lantbruksstyrelsen, 1965). However, the 1969 samples from sites Rb and Of and the 1972 samples from sites St and Lt, were analysed for organic C using the method of Vestervall (1963). Total soil N was determined by the Kjeldahl method.

All crop products removed from the field were analysed for N, P and K. The nutrients removed with the crops together with the amounts applied were used to compute the nutrient balances.

Table 1. Soil N content, % of air dry soil. Means of 6 PK combinations. ( ) = number of observations

Site	Year	N-level N1	N3	N5
Rb	1972 (6)	0.24	0.24	0.24
	s.e.	0.01	0.01	0.01
	1982 (2)	0.22	0.23	0.22
	s.e.	0.01	0.01	0.0
Of	1972 (6)	0.27	0.28	0.28
	s.e.	0.0	0.0	0.03
	1982 (2)	0.27	0.27	0.28
	s.e.	0.0	0.01	0.0

RESULTS

Soil N balance

Analyses of soil N, given in per cent of dry soil, are listed in Table 1 for Rb and Of and in Table 2 for Lt and St. Determinations of soil N were not performed on the samples from 1969 at Rb and Of. It can be seen that 10 years of different N-regimes did not influence the soil N contents significantly. They varied with site, however, and increased in the order St<Lt<Rb<Of.

Soil N balances, calculated as differences between N applied and N removed show that net gain (+) and net loss (-) varied with N treatment and with site (Tables 3 and 4). At the N1 level the net loss over two rotations amounted to approximately 60 kg ha^{-1} $year^{-1}$. At the N3 level there were substantial differences between Rb and Of. At Rb the net loss was 3 kg ha^{-1} $year^{-1}$ whereas at Of the corresponding figure was 11 kg ha^{-1} . At St and Lt there was a small but positive net gain of N at the N3 level, with values of 0.5 and 1.7 kg ha^{-1} $year^{-1}$ respectively.

At the N5 level, considerable positive net gains of N were obtained. Of and Rb differed from each other. A net gain of 86 kg ha^{-1} $year^{-1}$ at Rb corresponded to 61 kg ha^{-1} $year^{-1}$ at Of. At St and Lt the values were 75 and 70 kg ha^{-1} $year^{-1}$, respectively.

Soil C content was not significantly influenced by N application. On the other hand, significant changes with time were observed (Table 5). A clear decline in soil C was noted at Rb. At Of, St and Lt the soil C contents increased from the first to the second sampling.

Table 2. Soil N content, % of air dry soil. Means of 6 PK combinations. ( ) = number of observations

Site	Year	N-level N1	N3	N5
St	1972 (6)		-0.18-	
	s.e.		0.01	
	1981 (2)	0.18	0.17	0.18
	s.e.	0.01	0.02	0.01
Lt	1972 (6)		-0.20-	
	s.e.		0.01	
	1981 (2)	0.19	0.19	0.20
	s.e.	0.0	0.0	0.01

Table 3. N balance sheet, kg ha^{-1}. Total of 14 years

Site	N-level N1	N2	N3	N4	N5
Rb					
Applied					
Mineral fert.	0	520	1040	1800	3040
Animal manure	403	403	403	403	403
Total	403	923	1443	2203	3443
Removed[a]	1273	1668	1491	1794	2236
Balance	-870	-745	-48	409	1207
Per Year	-62.1	-53.2	-3.4	29.2	86.2
Of					
Applied					
Mineral fert.	0	520	1040	1800	3040
Animal manure	408	408	408	408	408
Total	408	928	1448	2208	3448
Removed[a]	1292	1429	1607	1981	2596
Balance	-884	-501	-159	227	852
Per Year	-63.1	-35.8	-11.4	16.2	60.9

[a] Means of 6 PK-combinations

Soil P and K dynamics

The experimental design involved surplus applications of P amounting to 20 or 40 kg ha^{-1} $year^{-1}$ and surplus K amounting to 80 kg ha^{-1} $year^{-1}$ in addition to replenishment. Over two rotations this implies a surplus P application of 280 kg ha^{-1} in P2 and 560 kg ha^{-1} in P3 at Rb and Of (14 years) and 200 and 400 kg ha^{-1} at St and Lt (10 years).

P-AL values of the soils increased with P application (Tables 6 and 7). Values in P1 showed a negative trend, in P2 they remained constant, while in P3 a positive trend with time was observed. At Rb, the K-AL values in K2 increased with time but did not change at Of (Table 6.). The K-AL values, in both K1 and K2, decreased with time at St and Lt (Table 7). Replenishment only (P1), did not maintain the P-AL values. Although not as clearly shown, there was a similar tendency for K-AL values in the replenishment treatments with K (K1). These results, both for P and K, are in agreement with Jansson (1983).

Table 4. N balance sheet, kg ha^{-1}. Total of 10 years

Site	N-level N1	N2	N3	N4	N5
St					
Applied					
Mineral fert.	0	430	860	1290	1720
Removed[a]	572	714	855	1027	972
Balance	-572	-284	5	263	748
Per year	-57.2	-28.4	0.5	26.3	74.8
Lt					
Applied					
Mineral fert.	0	430	860	1290	1720
Removed[a]	597	706	843	945	1017
Balance	-597	-276	17	345	703
Per Year	-59.7	-27.6	1.7	34.5	70.3

[a] Means of 6 PK-combinations

Table 5. Soil carbon content, % of air dry soil, different years. Means of 6 PK combinations at the same site

Year	Site Rb	Of	Year	Site St	Lt
1969	3.33[a]	2.48	1972	1.67	1.72
1975	3.20	2.85	1976	1.82	1.85
1982	2.90	2.87	1981	1.63	1.83
$HSD_{0.05}$	[b]	0.10		0.15	0.12

[a]Mean of four replicates. [b]Not determined.

Table 6. Easily soluble P (P-AL) and K (K-AL), mg 100^{-1} g^{-1} $soil^{-1}$, at Rb and Of. Means of two and three observations each year at the same site for P-AL and K-AL, respectively

Treat-ment	Rb 1969	-72	-75	-79	-82	HSD[a]	Of 1969	-72	-75	-79	-82	HSD[a]
	P-AL											
P1	7.90	5.51	5.91	4.45	4.35	1.52	8.00	5.96	6.65	7.05	6.60	6.01
P2	5.30	6.86	8.67	7.80	7.95	2.43	8.40	7.52	8.89	10.45	9.80	8.52
P3	7.90	8.98	10.37	11.35	11.55	3.99	7.30	8.80	11.14	14.45	15.10	2.57
	K-AL											
K1	7.3	6.4	12.5	7.3	9.4	3.5	11.2	11.5	10.7	9.7	9.0	2.1
K2	7.2	11.5	21.9	19.5	20.7	4.6	8.8	10.0	10.2	10.0	9.5	1.3

[a]$HSD_{0.05}$ is for comparison between years

Table 7. Easily soluble P (P-AL) and K (K-AL), mg 100^{-1} g^{-1} $soil^{-1}$, at St and Lt. Means of two and three observations each year at the same site for P-AL and K-AL, respectively

Treatment	St 1972	-76	-81	HSD[a]	Lt 1972	-76	-81	HSD[a]
	P-AL							
P1	8.30	7.61	6.80	3.19	11.30	8.35	6.55	6.61
P2	8.50	9.90	9.30	1.75	8.00	10.51	8.75	5.31
P3	7.90	11.27	14.20	4.28	9.70	14.65	13.90	4.12
	K-AL							
K1	20.0	15.2	10.8	4.0	14.2	9.8	7.8	5.2
K2	19.8	17.5	13.7	4.3	12.5	12.7	9.2	1.1

[a]$HSD_{0.05}$ is for comparison between years

No increases of either P-AL or K-AL due to P or K applications were observed in the sub-soils (Table 8). On the contrary, there were some indications of decreasing values.

Table 8. Easily soluble P (P-AL) and K (K-AL) in the subsoils, mg 100^{-1} g^{-1} $soil^{-1}$. Means of two and three observations each year at the same site for P-AL and K-AL, respectively

			P-AL			K-AL	
		Layer	P-level			K-level	
Site	Year	cm	P1	P2	P3	K1	K2
Rb	72	20-50	2.6	2.3	2.6	4.2	4.7
	75	20-50	3.1	3.3	3.5	5.9	7.2
	82	40-60	2.0	2.0	2.0	2.8	3.6
	$HSD_{0.05}$		1.0	1.9	1.7	1.0	1.4
Of	72	20-50	4.0	4.4	5.2	9.9	7.9
	75	20-40	4.5	5.6	6.4	8.3	7.5
	82	40-60	7.1	8.1	8.1	8.2	6.0
	$HSD_{0.05}$		2.3	4.5	3.6	1.9	0.7
St	76	40-60	2.1	2.1	1.9	9.8	10.8
	81	20-40	4.7	5.4	5.0	9.6	10.3
	$HSD_{0.05}$		0.6	0.8	0.8	4.5	5.0
Lt	76	40-60	3.7	2.8	3.9	8.3	8.5
	81	40-60	3.3	2.6	3.2	6.7	6.2
	$HSD_{0.05}$		1.8	2.1	3.2	2.4	1.6

DISCUSSION

First, it must be stated that there is a considerable inaccuracy concerning sampling and determination of soil C, N, P and K. This has to be stressed when discussing the relevance of the results. The N1 plots lost 60-63 kg ha^{-1} $year^{-1}$ during 10-14 years. Despite this, the soil analyses have not indicated declining soil N contents. On the one hand, these results are in accordance with those reported by Jansson (1975) and by Jenkinsson (1977), but on the other, they disagree with those of Fiedler et al. (1964), where the soil N content decreased during a 10-year experiment without N application.

At St and Lt, the soils lost 600 kg ha^{-1} over a 10-year period in the N1 plots. The total N pool at St was 4500 kg ha^{-1} in the 0-20 cm layer in 1969. A loss of 600 kg means a 13 % reduction of this pool. The yield curves over the years show that this has not been deleterious to the yields (Mattsson, 1987). N may have been provided by other sources. N sources not accounted for in the balance sheets are N fallout, symbiotic and non-symbiotic N fixation and N supply from ground water.

There are various estimates of N fallout. Rodhe (1982) reports 7-16 kg ha^{-1} $year^{-1}$. The fallout in Sweden decreases from south-west to north-east.

At St 7 kg ha^{-1} $year^{-1}$ may be assumed. N fallout at Lt, which is located in the southwestern parts of the country, may be 16 kg ha^{-1}.

Non-symbiotic N-fixation may account for 5 kg ha^{-1} $year^{-1}$ (Delwiche, 1970). Symbiotic N-fixation at St and Lt is estimated to 50 kg ha^{-1} $rotation^{-1}$ (Mattsson, 1987). Together, this points at additional N corresponding to 220-310 kg ha^{-1}. If we take this into account, a net loss of 290-380 kg ha^{-1} will be recorded instead of 600 kg in the N1 plots. Looking at these analysis figures it is apparent that there was no decrease in the soil N. 300 kg ha^{-1} of N is equivalent to a change in soil N content of 0.01 percentage points. Sampling and measurements of soil N cannot be performed with such precision.

The same discussion also applies to Rb and Of, even though N fallout may be assumed to be less than at St and Lt, say 3 kg ha^{-1} $year^{-1}$ N. Three ley years per rotation will incorporate 300 kg ha^{-1} during two rotations (Mattsson, 1987). A yearly loss of N of 30 kg ha^{-1} instead of 62 kg ha^{-1} is obtained.

An analogous discussion concerning the N5 plots can be made. N contributions via fixation may be excluded as non-symbiotic and symbiotic fixations are depressed when N applications increase. The positive N balances given in Tables 3 and 4 may thus be considered to show the actual situation. Nontheless, we found no evidence in figures of soil N contents to verify that accumulation of N takes place in the soils due to the positive N balance. Similar results are also reported by Jansson (1975) and by Jenkinsson (1977).

According to the N balance sheets, the differences in soil N between N1 and N5 were 1300-2000 kg ha^{-1}. This implies a difference between N1 and N5 of 0.05-0.08 percentage points. No such differences were observed, however. Regardless of N1 or N5 the soil N contents were the same. We must conclude that considerable amounts of surplus N are not accounted for and are probably lost by leaching and/or denitrification. These processes are accelerated when soils are supplied with N (Firestone, 1982;Legg & Meisinger, 1982).

The differences in P-AL between P1 and P3 at the end of the experimental period ranged from 7.2 to 8.5 mg 100^{-1} g soil, the smallest at Rb and the largest at Of. For the 0-20 cm of the top-soil this is equivalent to 180-213 kg ha^{-1} P, which should be compared with the 560 kg ha^{-1} applied as surplus P at Rb and Of. We can conclude that a considerable proportion of applied surplus P was bound in forms unavailable to plants. The proportions withdrawn in that way were 62 % at Of and 68 % at Rb. The corresponding value was 54 % at both St and Lt. Ranking the sites with respect to their P fixation, they increased in the order St=Lt<Of<Rb. The soil pH of the sites decreased in the same order.

Concerning K, a similar discussion may apply. Only small amounts of applied surplus K were accounted for in the analyses. A large proportion was not recovered as AL-soluble K. The part not accounted for ranged from 75-99 % of applied K and increased in the order Rb<St<Lt<Of. The unaccounted-for K may have leached or may have been fixed. Since no increases of K-AL values were observed in the sub-soils, leaching may be excluded. The clay content plays a role concerning K fixation. Site Rb, with the smallest amounts of unaccounted-for K, also had the lowest clay content. The clay contents of the other sites did not vary significantly. If all the surplus K supplied but not recovered was fixed, it would correspond to approximately 1100 kg ha^{-1} at Of. According to Brady (1974), 1-10 % of the total soil K

may be in a fixed form. This implies that the top-soil at Of contains 10 to 100 tonnes ha^{-1}, K. This is a reasonable range since Brady (1974) states approximately 34 tonnes ha^{-1} to be a normal value for soils in humid areas.

Application of surplus P and K will also increase the removal of these nutrients with the crop. This has been calculated for Rb and Of (Mattsson, 1985). If it is considered, the proportions of unaccounted-for P and K will decrease. At Rb e.g., the unaccounted-for P will fall from 68 to 60 % and the unaccounted-for K at Of from 99 to 87 %. Similar calculations at St and Lt have not been performed.

At Rb, the soil C contents decreased during the experimental period. At Of, however, they increased slightly instead. The C contents were higher at Rb than at Of at the beginning of the experiments but the high content may be difficult to maintain unless the land is permanently cropped as ley or is supplied with large quantities of organic matter (Persson, 1981). At Of, 25 % more animal manure was applied than at Rb. It is possible that this is the reason why the soil C contents at the two sites have approached each other.

The increase in soil C contents observed at St and Lt may be an illusion and might be attributed to the change in the method for C determination between 1972 and 1976. Both soils contain $CaCO_3$. Determination of organic C does not include carbonate-C, which is the case in total C determinations. The latter method was used from 1976 and later.

In these experiments we have been able to verify neither soil N depletion nor soil N accumulation. Experimental periods which were too short and lacking accuracy in measurements of soil C and soil N were the most probable explanations. In two of the present experiments, manure was also applied. This will also enhance the variability. Becker, cited by Körschens (1978), reported variations of soil C from 0.72-1.05 % C within an area of only 600 m^2. Changes caused by different treatments take a long time to develop. Experimental periods of at least 10 years are necessary (Körschens, 1978). Moreover, field experiments are inaccurate tools in this context. Pot experiments with soils of different N status established in the field experiments may provide further information.

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III

SOIL C CHANGES AND SIZE ESTIMATES OF DIFFERENT ORGANIC C FRACTIONS IN A SWEDISH LONG-TERM SMALL PLOT EXPERIMENT

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Abstract: The development of soil organic C and the sizes of different organic C fractions were estimated from data obtained in a 28 years old, Swedish small plot experiment. Treatments with crop residues and mineral fertilizer N were investigated. A treatment with continuous fallow was also included.

In the fallow the soil organic C declined from 1.48% to 1.13% during the experimental period. Annual cropping without N addition counteracted the C decline. Addition of straw and supply of N (80 kg ha^{-1} $year^{-1}$) increased the C content to 1.79% after 28 years.

Based on the C content in the fallow treatment, the size of the active+slow C fraction was estimated to range between 11-37%. This correlated well with simulated values for the experiment. The size of the active+slow fraction determined from mineralization data indicated that there may be a further C fraction with a turn-over time somewhere between 30 and 1200 years. The relevance of this is discussed.

INTRODUCTION

A long-term small plot experiment, located at the Swedish University of Agricultural Sciences in Uppsala and initiated in 1956, was used to estimate soil organic C fractions. The experiment included 15 different organic manure, crop residue and mineral fertilizer treatments. Yields and details of the experiment are reported by Nilsson (1980), Persson (1980) and Persson (1981).

MATERIAL AND METHODS

Soil samples were taken at the beginning of the experiment and after 12, 19, 20, 22, 24, 26 and 28 years. The samples were analysed for organic C. Five treatments were chosen to calculate the regression of soil organic C content on year according to the model

$$y = a + b*\ln x$$

where y = organic C, % of air dry soil
x = year (1, 2, ...28)
a, b = regression coefficients

The treatments chosen were:
A. Continuous fallow.
B. Annual cropping, crop residues removed, no N.
C. Annual cropping, crop residues removed, 80 kg ha^{-1} $year^{-1}$, N.
F. Annual cropping, straw added, no N.
G. Annual cropping, straw added, 80 kg ha^{-1} $year^{-1}$, N.

On soil samples taken in 1983 the C mineralization was determined by incubation. 20 g soil were supplied with water corresponding to 30 % of WHC and incubated for 135 days. The carbon dioxide evolved was determined according to a method described by Bjarnason (1987). The sum of mineralized C was determined and plotted against the soil organic C.

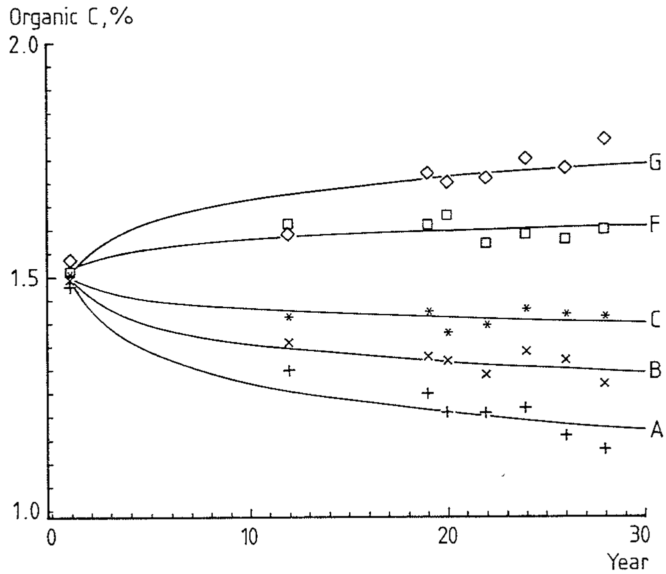

Fig. 1. Soil organic C, % of air dry soil as a function of time. A. Continuous fallow. B. Annual cropping, no N. C. Annual cropping, 80 kg ha^{-1} $year^{-1}$, N. F. Annual cropping, straw added, no N. G. Annual cropping, straw added, 80 kg ha^{-1} $year^{-1}$, N.

RESULTS

After 28 years the soil organic C contents in each treatment had approached steady state (Fig. 1). The estimated regression equations gave a sufficiently good description of the development of the C content. The coefficients of the equations are shown in Table 1. In the fallow treatment, the C content decline was the strongest. When a crop was grown (treatment B), the C decline was counteracted and addition of straw even increased the C content slightly. N supply in addition to straw increased the content significantly. All changes observed tended to be fast in the beginning of the experimental period.

A close relationship between mineralized C and soil organic C content was observed (Fig. 2). The data were fitted to a straight line with the regression equation

$$y=-2.92 + 8.75x$$

where y=mineralized C, mg 20^{-1} g soil and x=organic C, % of air dry soil. The coefficient of determination, r^2, was 0.83 and the number of observations was 48. Earlier observations in the present experiment have indicated that the behaviour of the organic C supplied in peat and sewage sludge differ from the other treatments. Probably the C in the peat is not biologically equilibrated with the native soil C, due to high C/N ratios. Detrimental effects of heavy metals may be the reason why sewage sludge behaves differently. The observations for these treatments were excluded from the analysis.

Table 1. Coefficients obtained for the regression y = a + b ln x, where y = soil organic C, %, and x = year (1,2...28)

Treatment	a	b	t	r^2
A	1,493	-0,094	-8,11***	0,92
B	1,493	-0,058	-7,71***	0,91
C	1,496	-0,028	-4,40**	0,76
F	1,519	0,026	3,05*	0,61
G	1,508	0,068	4,45**	0,77

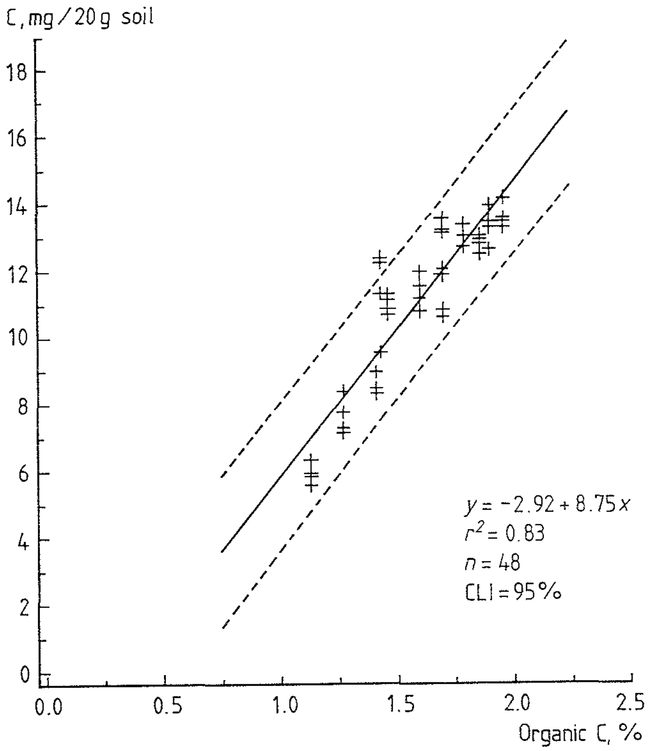

Fig. 2. Mineralized C, mg 20^{-1} g soil, as a function of soil organic C.

DISCUSSION

Supply of organic material was positive for the humus balance. Supply of N alone counteracted the soil C decline but could not prevent it. N in addition to straw resulted in the most positive effects, causing marked increases of the C content. One reason for the increased soil C contents in treatments supplied with N is that more raw material is available due to increased crop residues and a large root mass compared with treatments without N. The results also indicated that the formation of new humus substances was more effective when the N supply was sufficient than when there was a shortage of N.

To provide a better understanding of the problem, soil organic matter has often been discussed in terms of different fractions. A common way of fractionation is to isolate fractions as humic acids, fulvic acids and humine. This method give concrete fractions, the size of which can be determined. However the extractant agents may cause changes in the chemical structure of the humus substances. This is a disadvantage when studying their chemistry. Further, it is difficult to isolate biologically homogenous fractions (Persson, 1968).

An alternative way to characterize soil organic matter is to discuss it in terms of fractions with different turn-over times. This is relevant from a biological point of view and with regard to energy flow and nutrient cycling. Modelling is a useful tool in estimating the size of the fractions. Parton et al., (1982) proposed a model in which the soil organic matter was separated into three fractions: An active, a slow and a passive fraction with turn-over times of 3, 30 and 1200 years, respectively.

The results of our experiment can be discussed in relation to the fractions mentioned. Assume that the passive fraction has not changed significantly during the experimental period in any treatment. Also assume that the active and slow fractions are depleted in the fallow treatment. If these assumptions are correct the soil C content in the fallow treatment is a measure of the passive fraction. Based on this, the size of the active+slow fraction can be calculated as the difference in soil C contents between a given treatment and the fallow. This calculation will, however, underestimate the size because the active and slow fractions were not entirely depleted in the fallow treatment. The soil C content in this treatment is still decreasing, indicating the existence of a microflora. This has also been confirmed by Schnürer (1985). Data from the mineralization experiment indicated the same thing.

The size of the active+slow fraction may also be calculated using the mineralization data. The close relationship between mineralized C and soil C content has already been pointed out. From the regression equation given in Figure 2 the soil C content giving zero mineralization can be derived. It was equal to 0.33% corresponding to 8250 kg ha^{-1}, C. Assuming that this amount represented the passive C fraction in all treatments, the active+slow fraction was calculated. The two different estimates of the active+slow fraction are shown in Table 2. Values derived from the validation of the model proposed by Parton et al., (1982) are also listed. The agreement between simulated values and values based on soil C contents only was good. The size of the active+slow fraction determined from mineralization data became considerably larger than the other two.

The disagreement may be explained in different ways. According to Jansson (1963) the biological half-life of soil organic N can be calculated from the equation

$$t_{1/2}=0.693\ k^{-1}$$

where k is the average removal coefficient. Based on the incubation experiment, the C mineralization in the fallow treatment was 5.92 mg 20^{-1} g soil, corresponding to 740 kg ha^{-1}, C. The total C amount in this treatment was 28250 kg ha^{-1}. From this a k-value of 740/28250=0.0262 was derived. We assumed that the C entirely originated from the passive-C fraction. With a turn-over time of 1200 years for this fraction, equal to a half-life of 832 years, the expected k-value ought to have been 0.000833. The k-value obtained in the calculations above was approximately 30 times larger, indicating that the assumed passive-C fraction was not as passive as had been assumed. Another fraction with a turn-over time somewhere between 30 and 1000 years may be considered. If this is correct the passive fraction as determined from the incubation data should increase, thereby decreasing the difference compared with the determinations based on the C content only. It is also well-known that soil preparation will influence the soil organic matter, making some of it more available for decomposition. It may be proposed that this is more favourable in a soil poor in decomposable material i.e., as in the fallow treatment, than in a soil rich in decomposable organic material.

Table 2. Total organic C, ton ha^{-1}, and amounts of C in the active + slow organic matter fraction calculated in three ways. I: Based on soil C content only. II: Based on mineralization data. III: Simulated values according to Parton et al., (1982)

Treat-ment	Organic C, ton ha^{-1}	Method I ton ha^{-1}	%	II ton ha^{-1}	%	III ton ha^{-1}	%
A	28.3	-	-	20.0	71	1.5	5
B	31.8	3.5	11	23.5	74	3.0	9
C	35.3	7.0	20	27.0	77	7.8	22
F	40.0	11.8	30	31.8	80	12.2	31
G	44.8	16.5	37	36.5	81	16.0	36

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IV

FOUR SWEDISH LONG-TERM EXPERIMENTS WITH N, P AND K
3. After-effects of N-fertilization

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Abstract: The after-effects of previous N applications on soil N mineralization were investigated. The impacts of annual N rates ranging from 0 to 160 kg ha^{-1} during 12 to 27 years without animal manure and between 35 and 245 kg ha^{-1} at the two sites where manure was applied regularly were investigated. Rates of manure corresponded to 35 kg ha^{-1} $year^{-1}$, N.

Barley was grown in 6 l Mitscherlich pots without N fertilization and all above-ground parts were harvested approximately one week before ear emergence. To allow for inhomogeneity, differences in easily decomposable fresh organic matter and impacts from residual inorganic N, barley was grown and harvested twice. Reported data concern the second harvest. Yields of dry matter and Kjeldahl N were determined in each pot.

There were statistically significant positive after-effects on dry matter yields at three sites, where the yield increases were of the order of 42-92 % for the highest previous N rates compared with the lowest ones. When the previous N treatment had been high there was generally more N harvested per pot than with zero or low N applications. Significant differences were obtained at three sites.

Estimations of the N mineralization capacity gave values in the interval 0.66 to 1.57 mg 100^{-1} g soil at zero or low previous N applications and 0.77 to 2.37 mg 100^{-1} g soil at high previous N applications. The N mineralization differences between high and low previous N applications were considered to be a measure of the size of the active-N pool. Its size was estimated to 0.8-41.1 % of total N mineralized.

There were significant relationships between mineralized N, previous N application and soil C content. The interaction effect between soil C content and previous N application on N mineralization was negligible.

INTRODUCTION

Abundant N supply not only increases the yields but also favours the production of easily decomposable crop residues. As they are the source of energy for soil microbial activity, the conditions for increased microbial growth are enhanced. If the energy substrate is N deficient, the biological activity is favoured when inorganic N is applied. This will also promote the formation of humus substances, a process which is supposed to be more effective when the supply of N is favourable than when there is a shortage of N (Persson, 1981). Whether this leads to humus substances containing more N, or whether the immobilized N merely is more available to decomposition is an open question. The net mineralization of the humus substances formed, however, may contribute to the N supply of the subsequent crops (Cooke, 1976).

The N that is incorporated in the humus substances, constituting the soil organic matter, is not equally available to microbial attack. A generally adopted view on soil organic matter is that it is composed of fractions with varying affinities to decomposition. Different numbers of fractions have been suggested ranging from an active and a passive (Jansson, 1958) to five different fractions (Jenkinson & Rayner, 1977). No fraction is completely resistant to decay but the half-life range within wide limits. For the five compartments proposed by Jenkinson & Rayner (1977), the half-life of decomposable plant material was calculated to be 0.165 years, while the fraction called chemically stabilized organic matter was estimated to be 1980 years. Obviously these large differences in decomposition rates will influence the contributions to the inorganic-N pool from different humus fractions. Paul & Juma (1981) used simulation techniques to show that the stabilized-N fraction with a half-life of 27 years contributed 40 % of the mineral-N pool. Other contributors were biomass-N, active-N and metabolite-N. Janssen (1984) estimated that 57-81 % of the total mineralized N came from the fraction he called young soil organic matter. The highest value relates to a farming system including applications of both inorganic N and animal manure, the lowest value relates to a system with inorganic N only. The supply of fertilizer together with the prevailing farming system determined the size of the different humus fractions.

Our hypothesis in this investigation was that different N-regimes in long-term experiments have promoted the establishment of characteristic levels of readily decomposable humus substances positively related to the N supply. When these levels are compared concerning their N mineralization, the relative size of the active-N pool may be estimated. The scope of this investigation was to validate this hypothesis and to estimate the size of the active-N pool.

MATERIAL AND METHODS

Soils from four different field experiments named Röbäcksdalen, Offer, Stenstugu and Lönstorp and denoted Rb, Of, St and Lt, respectively were used. Rb and Of were started in 1969, St and Lt in 1972 (Mattsson, 1987 a,b). In order to widen the investigation two experiments, Fors (Fo) and Kungsängen (Kn), started in 1963 (Nilsson, 1986) and two experiments, Ekebo (Ek) and Örja (Or), started in 1957 (Jansson, 1975), were also included.

The soils were representative for different N regimes (Table 1). Animal manure had been applied at Rb and Of. At Fo, Kn, Ek and Or, plots to which no manure had been applied were used. The 0-20 cm soil layers of different N treatments were sampled. After preparation, 4.5-5.5 kg soil, depending on the bulk weight of the soils, were filled in 6 l Mitscherlich pots. Three pots from each N treatment were prepared. Each pot was weighed and the soil moisture content determined. General soil data at the onset of the experiments are summarized in Table 2. Easily soluble P, K and Mg, denoted P-AL, K-AL and Mg-AL, respectively, were determined according to Egnér et al., (1960). Soil C was determined with a dry combustion method at 1300 ^{o}C on a Ströhlein equipment.

All pots were fertilized with 90 mg pot^{-1}, P and 450 mg pot^{-1}, K. Barley, cv. Ida, was grown until approximately one week before ear emergence (Zadoks 44). After harvest a new barley crop was sown. The preparations for this crop were similar to the first one. All above-ground parts of the crop were harvested, dried at 55 ^{o}C weighed and analysed for Kjeldahl-N. Differences between the previous N applications concerning residual inorganic N and easily decomposable crop residues were assumed to be levelled by growing the first barley crop. All the yield data presented in this paper refer to harvest no. 2.

Table 1. N application data for the experimental soils. Totals represent N applied to the field until 1984

Site	N-treatment N1	N2	N3	N4	N5
Rb; N, kg ha^{-1} $year^{-1}$	35.1	71.8	108.5	161.1	245.8
Total, 15 years	527	1077	1627	2417	3687
Of; N, kg ha^{-1} $year^{-1}$	33.9	70.6	107.3	156.9	244.6
Total, 15 years	509	1059	1609	2399	3669
St+Lt; N, kg ha^{-1} $year^{-1}$	0	40.0	80.0	120.0	160.0
Total, 12 years	0	480	960	1440	1920
Kn+Fo; N, kg ha^{-1} $year^{-1}$	0	25.2	50.5	75.7	
Total, 21 years	0	530	1060	1590	
Or+Ek; N, kg ha^{-1} $year^{-1}$	0	49.3	98.5	147.8	
Total, 27 years	0	1330	2660	3990	

Table 2. General soil data. Values for P, K and Mg in mg 100^{-1} g soil

Parameter	Site Rb	Of	St	Lt	Fo	Kn	Ek	Or
pH	6.3	7.1	7.2	7.3	7.0	6.3	6.8	7.2
P-AL	14.3	15.0	13.7	15.3	15.9	11.4	9.1	8.8
K-AL	29.6	11.9	16.6	11.2	11.8	18.1	22.0	14.0
Mg-AL	3.6	29.9	9.2	11.5	14.9	47.0	5.9	9.7
Clay, %	10	27	28	22	25[a]	60[a]	13	15

[a] Estimated values

RESULTS

Dry matter yields

Impacts of earlier N treatments, or more appropriately the after-effects of earlier N treatments, varied considerably between sites. The largest dry matter yields were found at Rb (Table 3). The Rb pots produced 4.5-6.5 g pot^{-1} while the Or pots only produced 2.1-2.8 g pot^{-1}. Statistically significant and positive differences between N5 and N1 were found at St, Lt and Ek. At Rb a significant negative effect was found.

Table 3. Above-ground dry matter yields, g pot^{-1}, on soils with previously differentiated N applications.No N applied to the pot experiment

N treatment	Site Rb	Of	St	Lt	Fo	Kn	Ek	Or
N1	6.5	3.8	2.5	2.4	3.8	1.6	2.6	2.1
N2	4.5	4.3	3.2	3.3	4.1	2.4	1.8	2.2
N3	5.1	3.3	3.0	3.4	3.6	3.3	2.1	2.5
N4	6.2	4.0	3.8	4.1	3.5	2.7	3.7	2.8
N5	4.7	4.5	4.8	3.5				
$HSD_{0.05}$	1.5	1.9	1.4	1.0	1.7	2.1	0.5	1.1

N yields

As with the dry matter yields, the largest N yields occurred at Rb (Table 4). N treatments N1 and N5 differed significantly at Rb, St and Lt. At the other sites there were usually indications of positive impacts of earlier N applications, although not at significant levels. At Rb and Ek, there were substantial drops in the N yields between N1 and N2, and at Fo there were indications of overall negative effects of earlier N applications.

Table 4. Above-ground N yields, mg pot^{-1}, on soils with previously differentiated N applications. No N applied to the pot experiment

N treatment	Site Rb	Of	St	Lt	Fo	Kn	Ek	Or
N1	73.6	42.9	30.5	37.2	44.3	22.0	56.9	31.7
N2	49.8	46.7	39.2	44.1	40.7	30.3	39.3	37.6
N3	59.1	39.2	32.3	41.2	35.4	33.8	46.7	36.2
N4	81.9	45.1	41.9	48.4	38.0	30.7	55.0	43.4
N5	89.3	48.9	53.9	40.1				
$HSD_{0.05}$	18.2	19.3	16.4	8.2	16.9	17.9	21.9	20.6

Content of C and Kjeldahl N in the soil

Impacts of earlier N applications on soil C content were small at most sites (Table 5). Reported values are means of two determinations usually diverging less than 0.01 percentage points. At Kn, Fo and Or, an increase with increasing N application was noticed. The highest C values were found at Rb and the lowest at Or. Averages at these sites were 3.05 % and 1.04 %, respectively.

Table 5. Soil C content, % of air dry sample, in soils with previously differentiated N applications

N treatment	Site							
	Rb	Of	St	Lt	Fo	Kn	Ek	Or
N1	3.18	2.88	1.65	1.80	1.72	2.05	2.30	0.96
N2	2.70	2.74	1.51	1.88	2.11	2.16	2.28	1.01
N3	3.19	2.97	1.70	1.93	1.95	2.15	2.23	1.05
N4	2.95	2.77	1.52	1.81	2.20	2.24	2.50	1.15
N5	3.21	2.85	1.54	1.81				

As with C, the N impacts on total N in the soil were small. They are not reported here. Differences between sites were larger than between N treatments. The highest values, 0.26 % on average, were found at Of, while the lowest, 0.11 % on average, were found at Or (Table 7).

After-effects of earlier N applications

The term after-effect is used in this context to denote the effects of earlier N applications, that can be ascribed to long-term changes of the soil organic matter. With this definition there is a difference compared with the term residual effect also involving the effects of inorganic fertilizer residues and undecomposed organic material.

The data in Table 4 may be regarded as a measure of the N mineralization in each soil expressed in mg 100^{-1} g soil. In this case, the N content of the roots is neglected. Using the data in Table 4 the regression of N mineralization on earlier N applications was estimated. The model used was

$$y=a+bx$$

where y=N yield, mg 100^{-1} g soil
x=Average N application, kg ha^{-1} $year^{-1}$ (x=0-245).

Estimates of the intercept, a, and the regression coefficient, b, are given in Table 6. Values of b indicate a positive relationship between mineralization and earlier N applications. However, b was significantly different from zero at two sites only.

From the regression equations, estimated values for mineralized N in N1 and N5 treatments, (N4 at Fo, Kn, Ek, Or) can be computed (Table 7). N mineralization was 0.66-1.57 mg 100^{-1} g soil in N1 whereas it was 0.77-2.37 mg 100^{-1} g soil in N4 or N5.

The data obtained suggested a relationship between the soil N mineralization on the one hand and both soil C content and earlier N applications on the other. Therefore a multiple linear regression of the N yields on both

Table 6. Regression coefficients in the model $y = a+bx$ where, y = N yield, mg 100^{-1} g soil, x= N application, kg ha^{-1} $year^{-1}$

Site	a	b	t	r^2
Rb	1.44	0.0038	3.09[a]	0.42
Of	1.09	0.0007	1.09	0.08
St	0.66	0.0029	3.83[a]	0.53
Lt	0.89	0.0007	1.48	0.14
Fo	0.93	-0.0021	-1.53	0.19
Kn	0.70	0.0034	1.73	0.23
Ek	1.20	0.0001	0.07	0.01
Or	0.74	0.0016	1.85	0.25

[a] Significant at the 99% level

Table 7. Average C and N contents of experimental soils, estimated N mineralization, mg 100^{-1} g soil, at the lowest and highest N treatment and relative size of active-N pool

	Average		N-mineralization, mg 100^{-1} g soil			Diff.
Site	C, %	N, %	N1	N5(N4)	Diff.	% of N5(N4)
Rb	3.05	0.23	1.57	2.37	0.80	33.8
Of	2.84	0.26	1.11	1.26	0.15	11.9
St	1.58	0.16	0.66	1.12	0.46	41.1
Lt	1.85	0.19	0.89	1.00	0.11	11.0
Fo[a]	2.00	0.15	0.93	0.77	-0.16	-
Kn[a]	2.15	0.22	0.70	0.96	0.26	27.1
Ek[a]	2.32	0.18	1.20	1.21	0.01	0.8
Or[a]	1.04	0.11	0.74	0.98	0.24	24.5

[a] Treatment N4 instead of N5

Table 8. Cropped N, % of total soil N, on soils with previously differentiated N applications

N treatment	Site Rb	Of	St	Lt	Fo	Kn	Ek	Or
N1	0.84	0.43	0.40	0.47	0.61	0.27	0.83	0.65
N5(N4)	1.00	0.50	0.83	0.46	0.53	0.42	0.73	0.85

these parameters was performed. The regression model was

$$y=a+bz+bz^2+dx+ez*x$$

where y=mineralized N, mg 100^{-1} g soil
x=average N application, kg ha^{-1} $year^{-1}$ (x=0-245)
z=soil C, % (z=0.96-3.21)

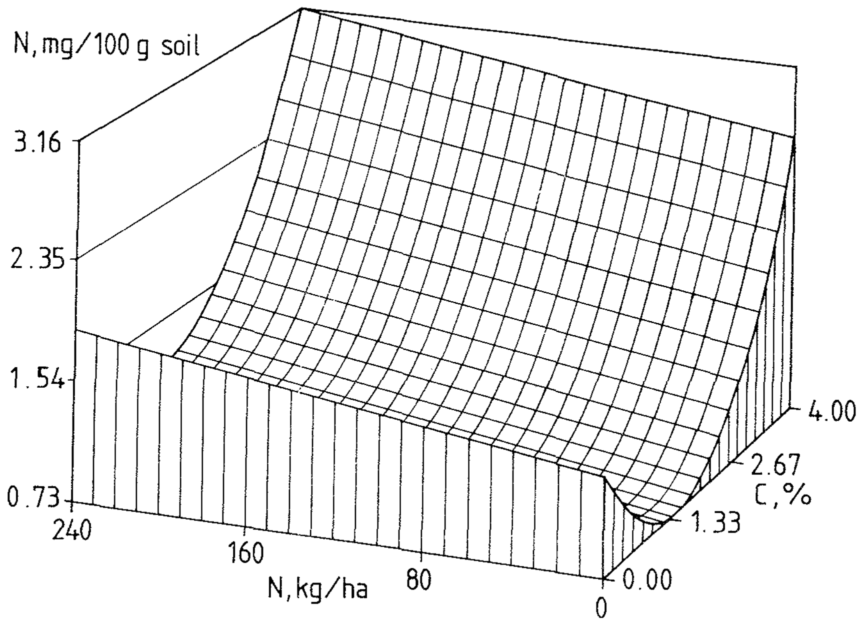

Fig. 1. Impacts of soil C content (z) and previous N applications (x) on N mineralization (y). Response surface of the equation $y=1.398-0.905z+0.304z^2+0.002x+ 0.004\ 10^{-2}zx$, defined for x=0-245 and z=0.96-3.21.

The coefficients obtained were a=1.398, b=-0.905, c=0.304, d=0.002 and e=0.004 10^{-2}. The number of observations was 96. Site Fo was omitted. The coefficient of determination was 0.624^{***} and the corresponding response surface was plotted in Figure 1. It is demonstrated in the figure that N mineralization depends on both earlier N applications and on soil C content but the interaction between these parameters was insignificant.

Estimating the size of the active-N pool

With some exceptions, harvested N expressed as a percentage of the total soil N per pot increased with earlier N applications (Table 8). In other words, the proportion of decomposable N increased, indicating that easily decomposable humus substances may have accumulated. The N in these substances may be regarded as active-N. Assuming that the difference in N mineralization between N1 and N5 (N4) was proportional to the size of the active-N pool, it was possible to estimate its relative size. These calculations produced values ranging from 0.8 % at Ek to 41.1 % of the total mineralized N at St. At Fo the difference N4-N1 was negative (Table 7).

DISCUSSION

The scope of the investigaion was to estimate after-effects of earlier N applications and the size of the active-N pool. The soils used represented various N-regimes, the extremes were without any fertilizer N application during 27 years, on the one hand, and average yearly application of 245 kg ha^{-1}, on the other.

It was demonstrated that after-effects of earlier N applications exist. These after-effects can be regarded as mineralization effects and not as impacts of inorganic fertilizer residues. However, the effects were small and could not be explained with soil C changes. The soil C content was only insignificantly influenced by earlier N application. This is not unique, but has also been observed in English long-term experiments (Jenkinson & Johnston, 1977), as well as in other Swedish experiments (Jansson, 1986). In a small plot field experiment, however, Persson & Mattsson (1987) reported considerable increases in soil organic C with N application.

In the present experiments it was demonstrated that the average soil C content of each site significantly influenced the mineralization capacity. Thus, it may be concluded that the mineralization capacity of the sites was chiefly determined by the cropping and management history preceding the experiment and to a lesser extent by the experimental treatments. The high soil C contents demonstrated at Rb and Of were a consequence of the ley-dominated crop rotations, common in North Sweden. In addition, the application of manure at these sites also influenced the soil C content. Manure have generally proved to be positive in maintaining and even increasing the soil C content (Cooke, 1976; Uhlen, 1976; Kofoed & Nemming, 1976; v. Dijk, 1981; Persson, 1981)

In our experiment we assumed the difference in N mineralization between high N treatments and zero or low N treatments to be proportional to the accumulation of humus substances containing active-N compounds. These assumptions produced estimates of the size of the active-N pool ranging from 0.8 to 41.1 % of the total N mineralized. The pool increased in the order Ek<Lt<Of<Or<Kn<Rb<St. The estimates were based on the assumption that the net mineralization of N in N1 entirely originated from old stable humus substances. This is not entirely correct since the crop annually contributed some easily decomposable organic material as crop residues and roots. In addition, manure was applied at the sites Rb and Of. The observed values of the active-N pool must therefore be considered as minimum values. They may be compared with corresponding estimates in a small plot field experiment reported by Persson & Mattsson (1987). They based the calculations upon the soil C content in a treatment with continuous fallow for 28 years without additions of C or N. Depending on the treatment, the size of the active-N pool in this experiment ranged from 11-37%. Other estimates of the active-N pool are 10-15 % (Jansson, 1958), 50 % (Jenkinsson & Rayner, 1977), 63 % (Paul & Juma, 1981), and 51-81 % (Janssen, 1984).

In the calculations it was assumed that the differences of the energy levels between pots from the same site were not influenced by crop residues from the first crop grown, but only depended on earlier N applications. Otherwise, temporary changes in microbial activity could give unreliable results. The calculations were also based on the assumption that the inorganic-N pool was equal in all pots from the same site when crop no. 2 was sown.

The first assumption was not completely met. Yield differences in harvest no. 1 also indicated different amounts of root residues in pots with high earlier N supply compared with zero or low N pots. The largest difference occurred at Rb, the smallest at Or. At St the difference between N5 and N1 in harvest no. 1 was negative. At Rb this indicates a temporary increase of organic matter favouring N immobilization with an underestimation of the active-N pool of perhaps 10-20 % as a result.

The second assumption above was chiefly met, except at Kn. Complementary investigations at that site, indicated differences in the inorganic-N pool when crop no. 2 was sown. These differences might have resulted in an overestimation of the active-N pool of the order 10 %.

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