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Mineral nitrogen dynamics in poorly drained blanket peat

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Summary. Mineral-N dynamics have been measured over a period of 3 years in PK- and NPK-treated plots (4 m^2) laid out on an area of poorly drained, reseeded, blanket peat in the north of Scotland. Mineral-N, present in the peat almost entirely as NH_4^+, accumulated in winter, reaching 42 kg N ha^{-1} in the surface 10 cm in April before the application of 112.5 kg N ha^{-1} as NH_4NO_3 or urea. In situ incubation of peat cores isolated to prevent leaching, and with grass tops removed, confirmed that net mineralization occurred between November and April, with the greatest rate, 1.2 kg N ha^{-1} day^{-1}, recorded between March and April. During the period May to early June, immobilization of N predominated and rates of net immobilization ranged between 0.2 and 0.8 kg N ha^{-1} day^{-1}. This coincided with a poor uptake into herbage, less than 16% of soil mineral N and fertilizer NH_4NO_3 in June of the first 2 years. The largest counts (most probable number) of ammonifying bacteria in the surface 5 cm were recorded in July for aerobes (27.1×10^9 $litre^{-1}$) and August for anaerobes (7.1×10^9 $litre^{-1}$). N fertilizer increased these counts significantly ($P < 0.05$) to 56×10^9 aerobes and 13×10^9 anaerobes. During July and August, in 2 out of the 3 years, mineralization predominated over immobilization and mean net rates of up to 0.9 kg N ha^{-1} day^{-1} were recorded.

Key words: Peat – Reseed – Nitrogen mineralization – Ammonifiers – Nitrogen immobilization

Reseeded peatland has a lower potential for dry matter production than mineral soil (Newbould 1985), possibly because drainage on these highly organic soils is frequently unsatisfactory (Speirs 1982). Under wet conditions, root development and uptake of nutrients are likely to be impaired (Boggie 1968), enabling soil processes such as denitrification and immobilization to compete with plants for available N (Rangeley and Knowles 1988).

Applications of fertilizer N are frequently prescribed for upland soils to stimulate grass growth in spring (Jarret 1986). On upland soils, however, this early application of N appears to be used inefficiently by the sward (Frame et al. 1985). Losses of fertilizer N in runoff water, gaseous losses of N by denitrification of NO_3^- and volatilization of NH_3, and immobilization of N in the microbial biomass, may all contribute to the poor uptake. In grass clover swards, N losses are balanced in part by biological N fixation and atmospheric deposition of available forms of N (Roberts et al. 1984). Wheatley and Williams (1989) reported a high potential for NO_3^- reduction and N losses to the atmosphere in poorly drained reseeded blanket peat fertilized with NH_4NO_3 in spring. In this paper we describe the seasonal pattern of mineral-N concentrations obtained from measurements of net mineralization and immobilization of N in an area of blanket bog using an in situ incubation technique.

Materials and methods

Site and sampling. The experiment is located in an area of sloping blanket peat on Sletill Hill, Forsinard, Highland Region (National Grid Reference NC 924456), 200 m above sea level. The mean daily temperature at the nearest weather station 14 km away is 8 °C and the average rainfall is about 850 mm per year (Meteorological Office). The original vegetation on the virgin peat included *Trichophorum caespitosum* L. Hartm., *Eriophorum vaginatum* L., *Molinia caerulea* (L.) Moench and Sphagnum spp. In 1982, the vegetation was removed and redistributed using a screw-leveller and ground limestone was applied at 1 Mg ha^{-1}. The peat was reseeded with a mixture of timothy (*Phleum pratense* L.), ryegrass (*Lolium perenne* L.), rough- and smooth-stalked meadow grass (*Poa trivialis* L. and *Poa pratensis* L., respectively), and white clover (*Trifolium repens* L.). At the start of the experiment in spring 1985, the grass sward was composed mainly of smooth- and rough-stalked meadow grass, some white clover and pearlwort (*Sagina* L.).

Twelve experimental plots, 2 m × 2 m, were laid out in an area fenced securely to exclude grazing animals, such as rabbits and deer, and divided into two sets of six. The same experimental treatments, PK and NPK,

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were applied randomly to each set, in three replicated blocks of two plots each. One of the sets was used for destructive sampling and the other was maintained intact for the measurement of herbage yields. In 1985 and 1986, all plots were supplied with 60 kg P ha^{-1} as granular superphosphate and 60 kg K ha^{-1} as KCl in two applications, the first in April and the second in June after the first cut. In 1987, the total annual application of P and K was increased to 120 kg ha^{-1} for each nutrient, applied in two equal dressings as before. On the NPK plots, in addition to P and K, 112.5 kg N ha^{-1} was applied as NH_4NO_3, in mid-April and again in June after the first harvest. In 1987, urea replaced NH_4NO_3 at the same rate of N application. At each application the fertilizer was broadcast by hand over the plots.

The plots were sampled at approximately monthly intervals between March and November.

Peat cores for immediate analysis and incubation were taken before the applications of N, P and K, except in April 1985 when the fertilizer was applied first. Sampling points in the plots were located with a system of random coordinates. Cores were removed from the surface 10 cm using a cylindrical polyvinylchloride tube (10 cm in diameter, 30 cm in length), reinforced at the top and fitted with a length of band-saw blade around the bottom edge. The cores, with grass tops removed, were transported to the laboratory in insulated boxes and stored at 2 °C until the analysis.

Net mineralization and immobilization of N in situ

On each sampling occasion, a duplicate set of six samples was taken, the grass tops removed and each core wrapped in polyethylene and returned to the peat. On the next sampling occasion these cores were removed to the laboratory for analysis and treated in the same way as the fresh cores.

Differences between the mineral-N content of cores at the end and that of fresh samples taken at the start of the incubation were used to calculate mean daily rates of net mineralization (increases) or net immobilization (decreases) for the period. In 1985, in situ incubation was started 3 weeks after the fertilizer application and, subsequently, core samples were taken and placed in position immediately before the plots were fertilized, in order avoid interference from other transformations of fertilizer N such as denitrification and volatilization. Consequently, the fertilized peat was sampled and incubated some 3–4 weeks after treatment. Values for net N mineralized during the first and second harvests were obtained from the net sum of the monthly values in each period.

Grass yield

Grass was cut from six undisturbed plots in June, August, and October, and the yield of oven-dry herbage was measured after drying the samples at 70 °C.

Physical and chemical analyses

The peat cores were cut into cylindrical sections corresponding to 0–5 and 5–10 cm in depth. Each section was weighed and the subsamples were dried at 70 °C to determine the moisture content. A specific gravity of 1.42 (SE 0.04), measured in ethanol (Segeberg 1955), was used to calculate the volume of solids in each core, the volume of water was calculated from the moisture content, and the pore and air volumes were obtained by difference.

Duplicate subsamples (10 g fresh weight) from each core of fresh and incubated peat were shaken with 50 ml 0.01 *M* $CaCl_2$ overnight and the suspension filtered through Whatman no. 42 paper and washed with a further 50 ml 0.01 *M* $CaCl_2$. Both filter and peat were then shaken for 2 h with 50 ml 1 *M* KCl and filtered. Ammonium concentrations were measured colorimetrically in $CaCl_2$ and KCl extracts (Crooke and Simpson 1971) and NO^{3-} was determined in $CaCl_2$ extracts only, after reduction to NO_2^- with copperized Cd (Henriksen and Selmer-Olsen 1970). Nitrite was not measured separately.

Total N in the peat and herbage was determined by digesting dry, milled samples (150 mg) with a 1:1 mixture of concentrated H_2SO_4 containing 0.1% (w:v) Se and 30% (v:v) H_2O_2 (Wall et al. 1975). Ammonium was measured in an acid digest using a colorimetric method (Crooke and Simpson 1971).

Acidity was determined by measuring pH potentiometrically in 0.01 *M* CaCl suspension of peat (5:1 solution:sample ratio).

Microbiological analysis

Numbers of ammonifying bacteria were estimated by the microdiluter modification (Darbyshire et al. 1974) of the most probable number technique, using a basal salts medium (Stanier 1947) containing 0.1% (w:v) peptone. Plates were incubated at 15 °C and numbers assessed by testing the wells for NH_4^+ using Nessler's reagent. Counts of anaerobic ammonifiers were carried out on cores transported to the laboratory anaerobically and processed and incubated inside an anaerobic cabinet (Don Whitley Scientific Ltd, Shibley, UK) cooled to 15 °C.

Statistical analysis

The statistical significance of differences between treatments in NH_4^+ contents of fresh and incubated samples was tested by analysis of variance (Ryan et al. 1985). Counts of ammonifying bacteria were transformed logarithmically and then subjected to an analysis of variance.

Results

At the start of the experiment, the peat in the surface 5 cm was less acid and contained more N, P, and K than that at 5–10 cm depth (Table 1). Throughout the 3-year sampling period there was little evidence of grass roots penetrating below 5 cm. On most sampling occasions, more than 80% of the pore volume in the surface 5 cm was filled with water. Below 5 cm the peat was close to saturation on most sampling occasions.

Mineral N in fresh peat

Mineral N in the fresh peat was present almost entirely as NH_4^+ even when sampling occurred 3–4 weeks after the fertilizer application. However, in April 1985, when peat was sampled immediately after applications of ammonium nitrate, NO_3^- was also detected. The annual seasonal pattern of NH_4^+ in the surface 10 cm was similar for each of the 3 years (Fig. 1). There was less variation be-

Table 1. Some physical and chemical characteristics of the peat at the start of the experiment

Depth (cm)	Pore volume (%)	Bulk density (g dm $litre^{-1}$)	pH ($CaCl_2$)	Total N (kg ha^{-1})	Total P (kg ha^{-1})	Total K (kg ha^{-1})
0–5	92.0	116.6	4.52	1197	68	32
5–10	90.7	134.8	3.91	1041	41	18
0–10				2238	109	50

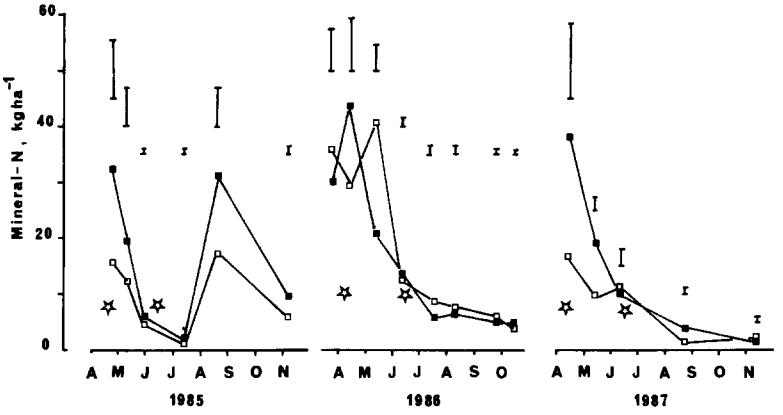

Fig. 1. Mean contents (kg N ha^{-1}) of mineral N in fresh peat from plots treated with PK (□) and NPK (■). *Bars* indicate SEM (2 df). ☆, application of NPK

tween sampling occasions in 5- to 10-cm depth than in the surface 0–5 cm (not shown). Differences between the PK and NPK treatments were seldom significant except in May 1986 when there was significantly ($P<0.05$) more NH_4^+ in the surface 5 cm of the PK- than the NPK-treated plots.

In situ incubation

Mineral N production and accumulation occurred entirely as NH_4^+. In spring, the NH_4^+ content of field-incubated cores (Fig. 2) was similar to that recorded in freshly sampled peat (Fig. 1). During 1985 and 1986, the net change during incubation was negative for most of April, May, and June (Fig. 2), and positive during July and August and from October through to April. In 1987, net immobilization occurred from April until the end of August. Adding fertilizer N did not appreciably change the seasonal patterns nor the rates of net mineralization and immobilization, probably because the peat treated with fertilizer N was not incubated until 3–4 weeks later.

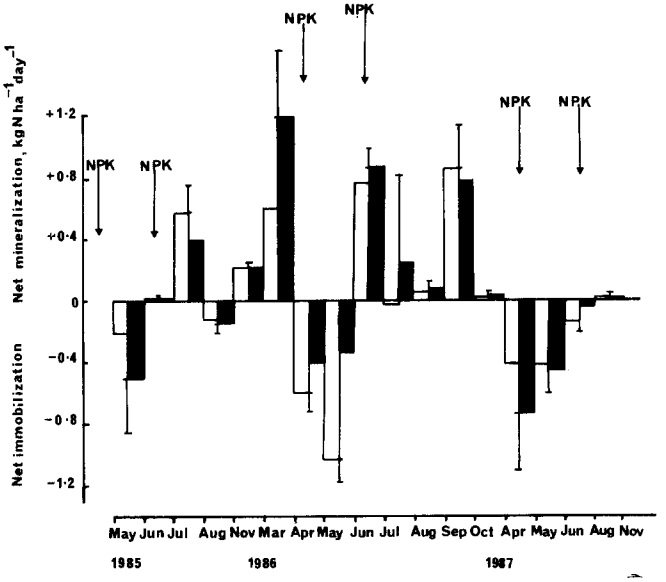

Fig. 2. Net changes in mineral N contents (kg ha^{-1} day^{-1}) of peat cores from 0 to 10 cm in depth incubated in situ in PK- (□) and NPK- (■) treated plots. *Bars* indicate SEM (2 df). ↓, NPK application

Table 2. Mineral N contents of the surface 10 cm of peat at the start and end of the first harvest of grass, April to June, net immobilized N during the harvest and herbage N

Year	Treatment	Mineral N (kg ha^{-1})		Immobilized N (kg ha^{-1})	Herbage N[b] (kg ha^{-1})	
		April[a]	June			
1985	PK	15.1	4.9	4.6	1.1	(19.6)
	NPK	121.7	5.9	11.4	7.3	(7.0)
	SE	0.50	0.18	24.19	1.31	
1986	PK	29.3	12.7	48.2	4.6	(>100)
	NPK	126.1	13.6	21.1	15.1	(16.5)
	SE	9.47	1.53	7.53	2.11	
1987	PK	17.0	11.3	18.6	10.6	(>100)
	NPK	140.1	10.3	29.6	28.3*	(28.2)
	SE	8.40	3.12	7.45	2.00	

SE, Standard error of the mean (n = 3)
*$P<0.05$ versus PK value
[a] NPK, soil mineral N + 112.5 kg fertilizer N
[b] Values in parentheses expressed as per cent of available N (April N – June N – Immobilized N)

N availability and herbage N

The N available for plant uptake was calculated for the first and second harvests of each year from the mineral-N contents before fertilizer application, the net immobilization or mineralization during the same period, the fertilizer N applied, and the residual mineral N at the end. For the first harvest between April and June, net immobilization predominated in each of the three years (Table 2), accounting for 30% of available N in 1985 and then for all of it in 1987. In 1986, the immobilized N greatly exceeded available N in the PK-treated plots. This anomaly was caused by a divergence in mineral-N contents between incubated cores and field samples. Mineral-N in fresh unincubated samples increased between April and May, but in the incubated cores it decreased over the same period. Fertilizer N had no significant effect on immobilization except that there was a progressive increase in the proportion of available N immobilized during the 3-year period in the NPK-treated plots.

Over the 3 years of the experiment the sward in the PK-treated plots developed an increasing proportion of white clover, and therefore an increase in biological N_2 fixation may have occurred. At the first harvest in 1985, the herbage N in these plots corresponded to 20% of the calculated available N and a marked increase to >100% in 1986 and 1987 probably reflects the greater proportion of N supplied by biological fixation. The NPK-treated plots did not contain clover, and during the 3-year period of the experiment herbage N accounted for 1–20% of the mineral N from soil and fertilizer. The increase in herbage N in the 3rd year coincided with the change from NH_4NO_3 to urea fertilizer applications.

The second harvests in 1985 and 1986 were marked by the occurrence of net N mineralization (Table 3), which was not significantly altered by the addition of fertilizer N. This net mineralization during the second harvest gave way in 1987 to net immobilization, which accounted for all of the mineral N in the PK-treated plots but only 4% of that in the NPK treatments. Again, the herbage N may have been derived mostly from biological N_2 fixation in the PK treatment in this 3rd year, whereas in 1985, with only a few clover plants present, herbage N was equivalent to 85% of that available (net N mineralization + June mineral N – August mineral N). In the NPK treatments, herbage N accounted for between 26 and 52% of the mineral N available and showed no trend during the 3-year period.

Ammonifying bacteria

The most probable number of aerobic ammonifying bacteria in the 5-cm layer ranged from 0.4 to 2.7×10^9 cells litre^{-1} fresh peat in the PK and NPK treatments, respectively, during April. The counts then increased steadily until July, when numbers in the NPK-treated plots (56×10^9 cells litre^{-1}) were significantly ($P<0.05$) greater than those (27.1×10^9 litre $^{-1}$) in the PK-fertilized peat. The counts diminished sharply in August without any further significant differences between treatments.

Numbers of anaerobic ammonifying bacteria were fairly constant between March and October in the range $2.8-50\times10^7$ cells litre $^{-1}$ in the PK treatment, except for August when the counts increased to 710×10^7 cells litre^{-1}. Fertilization with N significantly ($P<0.05$) increased the August value to 1300×10^{-7} litre^{-1} but no significant effects were detected on any other sampling occasion.

Discussion

In reseeded peat, rates of mineralization, immobilization and denitrification are greater than in the virgin unimproved blanket bog (Williams and Wheatley 1989). In the present experiment, counts of ammonifying bacteria, aerobic and anaerobic, were 10–100 times greater than the average values for an unimproved blanket bog peat (Williams and Wheatley 1988). Some of the differences are associated with liming (Klemmedtson et al. 1977), although the potential for denitrification and immobilization was intensified by the remains of the original bog vegetation being incorporated into the surface during the preparation for reseeding. Net immobilization and denitrification are both particularly important in peat between April and June (Wheatley and Williams 1989), with mineralization predominating in summer. This sequence of

Table 3. Mineral N contents of the surface 10 cm of peat at the start and end of the second harvest of grass, June to August, net amount of N mineralized during the harvest and herbage N

Year	Treatment	Mineral N (kg ha^{-1})		N mineralization (kg ha^{-1})	Herbage N[b] (kg ha^{-1})	
		June[a]	August			
1985	PK	4.9	17.6	28.5	13.4	(84.8)
	NPK	118.4	31.1	18.9	55.4	(52.2)
	SE	0.18	6.7	9.05	7.91	
1986	PK	12.7	7.7	26.4	11.8	(37.6)
	NPK	126.1	6.6	36.1	40.9	(26.3)
	Se	1.53	1.41	9.86	7.07	
1987	PK	11.3	1.2	−10.0	30.6	(>100)
	NPK	122.8	3.7	−4.6	56.2	(49.1)
	SE	3.12	1.12	5.87	2.78	

See footnotes to Table 2

[b] Values in parentheses expressed as percentage of available N (June N – August N + net N min)

nutrient mineralization, preceded by immobilization, which occurred in 2 out of 3 years, is characteristic of the phases observed during the decomposition of plant material (Melillo and Aber 1984). Furthermore, mean N immobilization in spring increased progressively during the 3-year period, with concomitantly increasing yields of dry matter and herbage N, which suggests that the process might have been driven by inputs of plant litter or root exudates.

In spring, net N immobilization in the NPK plots accounted for between 10 and 23% of the available N (soil mineral N and fertilizer N). These proportions are likely to be underestimates because the fertilized peat was not incubated until some 3 or 4 weeks after treatment. In contrast, NO_3^--N concentrations in peat treated with NH_4NO_3 or urea were negligible after this time, and changes in mineral N resulting from denitrification of NO_3^- were unlikely to have contributed to any overestimate of the measurement of immobilization. Disturbance to the core and removal of the grass to eliminate competition for available N could also have influenced mineralization rates. However, apart from one exception, similar trends in the mineral-N contents of fresh and incubated samples strongly suggested that any effects of disturbance were small.

It is not clear what proportions of immobilization occur in the microbial biomass, in soil organic matter, or in grass roots remaining in the cores after removal of the grass. Ledgard et al. (1989) reported that 53% of ^{15}N applied to grassclover swards was detected in the roots, 20% in the tops, and less than 10% in the microbial biomass at the first harvest. In contrast, Bristow et al. (1987) reported that more than 30% of 90 kg N ha^{-1} applied as NH_4NO_3 during April was rapidly immobilized in the microbial biomass within 2 days and that this proportion declined over the growing season to around 1%. In the incubated cores in the present study, assimilation by roots was considered of minor importance after removal of the grass. Thus, the microbial biomass and the soil organic matter are the most likely sites of immobilization. Measurements of microbial N in the surface 10 cm of peat were equivalent to approximately 200 kg N ha^{-1} and there was no significant difference between the PK and NPK treatments at the end of the growing season (Williams and Wheatley 1989). Similar values, ranging from 170 to 225 kg N ha^{-1}, have been reported for a pasture soil in New Zealand (Sarathchandra et al. 1988), which suggests that a microbial biomass fluctuating in size and N content could accommodate a significant proportion of the applied N.

The predominance of immobilization over mineralization in the spring may have been a result of low temperatures inhibiting the activities of ammonifying bacteria and of secondary decomposers such as enchytraeid worms and protozoa. These organisms, by grazing fungal and bacterial biomass and secreting available forms of N, accelerate nutrient turnover (Clarholm 1985). When low spring temperatures limit these activities, the N immobilizing component of the microbial biomass appears to become more active than the mineralization processes. Concomitant increases in net mineralization and counts of ammonifiers in the summer are consistent with the higher temperatures stimulating both gross and net rates of mineralization. A sharp fall in net N mineralization in July 1986 coincided with a period of dry weather, resulting in markedly lower moisture contents in the peat (Wheatley and Williams 1989), but this had no corresponding effect on most probable number counts of either aerobic or anaerobic ammonifying bacteria. Rates of net N mineralization reached 0.9 kg N ha^{-1} day^{-1} during the summer months of 1985 and 1986, and were similar to values of 0.6 and 1.4 kg N ha^{-1} day^{-1} measured in clay and loamy soils, respectively (Phillips et al. 1988). Barraclough (1988) reported rates of 2.1 kg N ha^{-1} day^{-1} for gross mineralization and 0.95 kg N ha^{-1} day^{-1} for simultaneous immobilization in grassland soils.

Accumulations of mineral N at the end of winter have been reported previously in grassland soils (Williams 1969) and in podzolic soils (Gupta and Rorison 1975). These have been attributed to partial death of the soil microbial biomass by freezing and thawing (Harmsen and van Schreven 1955) or to net mineralization during autumn when plant uptake is minimal and soil temperatures favourable to microbial activity (Davy and Taylor 1974). In agricultural soils in Canada, up to 48 kg N ha^{-1} accumulated over winter in the upper 60 cm of the soil profile (Malhi and Nyborg 1986) compared with 41 kg N ha^{-1} in the surface 10 cm of the peat at the present site. Low concentrations of NH_4^+ in the peat during November, when soil temperatures had fallen below 5 °C, rule out the combination of low N uptake and active net N mineralization as a reason for the accumulation of NH_4^+.

In conclusion, N immobilization predominated over mineralization in spring, and the ensuing competition for mineral N is likely to have been an important factor in the poor uptake of N into herbage at the first harvest. The annual patterns of immobilization followed by mineralization are consistent with phases of decomposition of plant material and immobilization of N into the microbial biomass. Clearly, the origin of organic substrates and the remineralization of immobilized N are important factors in the N dynamics of this peat.

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