Long-term effects of lime application on ^{15}N availability to Sitka spruce seedlings growing in pots containing peat soils

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Summary

The long-term effects of liming a peat soil on nitrogen availability to 3-year-old *Picea sitchensis* seedlings were assessed in greenhouse experiments. Seedlings were planted in pots containing either unlimed or limed peat soils that had been limed 28 years earlier. The plants were harvested in October 1993, April 1994 and July 1994 with these dates representing 100, 160 and 263 days after planting respectively. Concentration of extractable NO_3^- in the limed peat was higher than in the unlimed peat. Liming also resulted in increases in extractable organic N and total extractable N in the peat. On all harvesting occasions, percentage ^{15}N utilization and total N were reduced in plants grown on the limed peat. Decreased concentrations of N in the fine-root fractions were apparent for plants grown on the limed peat at the October and July harvests only. During the growing season, the above-ground parts of the plant were the dominant sinks for nitrogen. The needles and fine roots were the major fractions for the utilization of ^{15}N particularly in April and July. The only effect of a limed peat on dry weight of plant fractions was a decrease in fine-root dry weight when plants were examined in October 1993. On all harvesting occasions, populations of mycorrhizae were decreased and roots were blackened for plants grown in the limed peat soil.

Introduction

The high acidity of deep, oligotrophic blanket peat is an undesirable characteristic as a medium for growing trees (Dickson, 1972). To restrict the negative effect of low pH on growth processes, liming is a common practice for acid forest soils. Limestone is often used to neutralize acidity, to reduce exchangeable Al and to increase available Ca in the soil (Kamprath and Foy, 1985). Application of lime also changes the properties of soils which, in turn, has effects on the availability of soil nutrients and nutrient uptake by plants growing on such soils (Marschner and Wilczynski, 1991).

Liming increases the breakdown rate of the soil organic matter and this is associated with increases in the activities and numbers of actinomycetes, bacteria, earthworms and fungal fruiting bodies (Adams *et al.*, 1978; Carey *et al.*, 1981). Immobilization, either of nitrogen in the forest floor or of added nitrogen, as a consequence of increased microbial activity has been reported (Adams and Cornforth, 1973; Carey *et al.*, 1981). Lime application, therefore, leads to a decrease in quantity of mineral nitrogen and to a greater proportion of mineral nitrogen recovered in peat soils as nitrate (Farrell, 1985). On the other hand, mycorrhizal associations may increase the ability of higher plants to compete for nitrogen (Dickson, 1989).

The storage of nitrogen and its internal supply is important for sustainable growth of evergreen trees (Miller *et al.*, 1979; Millard and Proe, 1992). The main objectives of this study were to investigate the long-term effects of liming on the ^{15}N dynamics of peat soils and ^{15}N utilization by 3-year-old *Picea sitchensis* seedlings growing in these peat soils. Data were also obtained for extractable mineral and organic nitrogen levels in the peat soils as well as total and percentage nitrogen, dry weight of plant fractions, characteristics of fine roots and populations of mycorrhizae for the experimental plants.

Materials and methods

Two types of peat, limed and unlimed, were collected on 8 July 1993 from the top 15 cm below the litter layer from two plots under 30-year-old *P. sitchensis* trees growing on deep unflushed blanket peat in Beaghs forest in Northern Ireland. One of the plots had been limed (22.5 t ha^{-1}) in 1965 and the second plot was unlimed.

These two plots are part of a designed experiment with the following history. Each plot measures 30 × 15 m. In September 1965, ground limestone at 0 (L_0), and 22.5 t ha^{-1} (L_1) and coarse rock phosphate at 750 kg ha^{-1} were applied 6 months prior to planting. In spring 1966, seedlings of Sitka spruce were planted. In 1970, muriate of potash (KCl) was applied at 225 kg ha^{-1} to the plots. Coarse rock phosphate was reapplied at 750 kg ha^{-1} in 1974. In spring 1976, KCl and urea were applied at 200 kg ha^{-1} and 500 kg ha^{-1}, respectively, to the plots. Urea at the standard rate of 350 kg ha^{-1} was reapplied to the plots prior to growth in 1985 and 1993. Full details of all treatments applied to the experimental site have been recorded by the Department of Agriculture for Northern Ireland.

Data related to the forest stand have been recorded by Kakei (1995). Concentration of phosphorus in needles of trees growing in the limed plots was high compared with the unlimed plots (L_0 = 1.45 and L_1 = 2.05 mg g^{-1} DW respectively). Concentration of N in needles of trees growing in the limed and unlimed plots was 9.75 and 11.15 mg g^{-1} DW respectively. There were no differences in tree growth between the limed and unlimed plots, while fine-root growth was increased by liming. The peat moisture in the limed and unlimed plots was 81.5 and 85.3 per cent, respectively, when the peat was removed from the plots. The peat pH was 5.38 and 3.55 in the limed and unlimed plots, respectively, when the peat was removed from the plots for use in experiments.

A sampling core was used to take peat samples. After removing the litter layer, plastic pots (1.75 l in volume) were filled with fresh peat containing about 140 g dry matter in each pot. To determine calcium content of limed and unlimed peats, 10 random fresh peat samples (each sample was 1 kg) from each type were dried (60°C for 72 h) and weighed. The dried samples were separately ground (Cyclotec, 1093 sample mill, mesh size = 2 mm) and then digested in 70 per cent HNO_3. After digestion, samples were analysed for concentration of calcium using an inductively coupled plasma–optical emission spectrometer (Perkin-Elmer) (ICP-OES). The mean concentrations of calcium in the limed and unlimed peats were 9.8 and 1.2 mg g^{-1} DW respectively.

Freshly dug, 3-year-old *P. sitchensis* seedlings (2 + 1) of Queen Charlotte Islands origin were transferred into pots, one plant per pot, on 9 July 1993 for the October experiment and on 29 October 1993 for both the April and July experiments. The average dry weight of a seedling was 10.11 g. In the nursery, the seedlings had received three fertilizer applications, each of 42.5 kg ha^{-1} of N, P_2O_5 and K_2O. Following potting, plants were placed outdoors at the Department of Agriculture, Newforge Lane, Belfast. The pH in each pot was measured by direct insertion of the electrode of a pH-meter (Whatman PHA 400) at the rooting zone just prior to each harvest. Mean pH was 3.48, 3.58 and 3.42 in the unlimed peat and

6.52, 5.18 and 5.45 in the limed peat at the October, April and July harvests respectively. One week before supplying ^{15}N, the plants were moved into a glasshouse (15–22°C).

Each pot received 139 mg of N as $(NH_4)_2SO_4$ labelled with ^{15}N at 5 atom per cent excess dissolved in 50 ml of distilled water. For the October experiment, the plants were supplied with labelled N on 11 October 1993 and harvested on 25 October 1993. For the April experiment, labelled N was added on 7 March 1994 and plants were harvested on 5 April 1994, while for the July experiment, labelled N was added on 22 June 1994 and plants were harvested on 22 July 1994. The plants were watered with distilled water twice a week while in the glasshouse. There were five replicates for the October experiment and 10 replicates for the April and July experiments.

At harvest, plant parts were dissected into leader (including its needles), needle (needles of whole plant except needles of leader), shoot (total branches without needles), stem (whole main stem), coarse root (> 5 mm in diameter), medium root (2–5 mm in diameter) and fine root (< 2 mm in diameter). Plant fractions and peat soils were oven-dried (60°C for 72 h), weighed and ground with a micro-mill (Glen Creston, DCFH 48 type, mesh size = 1 mm).

Concentrations of ^{15}N in plant fractions and peat samples were determined using a Carlo Erba NA 1500 Elemental analyser, linked to a VG Micromass 622 Stable Isotope Mass Spectrometer. A Roboprep CN Elemental Analyser was used to determine percentage nitrogen in the plant samples.

Percentage ^{15}N utilization by plant fractions and peat soils was calculated as:

$$\frac{\text{Atom per cent excess in sample}}{\text{Atom per cent excess in fertilizer}} \times \frac{\text{Yield of N (mg/pot)}}{\text{Rate of N applied (139 mg)}} \times 100$$

The atom per cent excess in the sample and fertilizer was corrected for the atom per cent ^{15}N in the sample and fertilizer using 0.367 atom per cent ^{15}N as natural abundance.

A 40 g subsample of the peat soil from each pot was treated with 200 ml of 2 mol/l KCl to extract NH_4^+-N and NO_3^--N. The extracts were centrifuged for 5 min and filtered. Concentrations of extractable NH_4^+-N and NO_3^--N were measured using a Flow Injection Analyser (Tecator Ltd). Extractable mineral N was the sum of extractable NH_4^+-N and NO_3^--N. Extractable organic N was calculated as total extractable N minus extractable mineral N.

Fine roots and mycorrhizae were examined under a stereo microscope (×60) to determine the effects of lime on them.

For each occasion, the effects of lime application on extractable NH_4^+-N, NO_3^--N and organic N and total extractable N in the peat were tested by analysis of variance. Significant differences between means were established using *t*-tests. For each plant fraction, effects of lime on percentage ^{15}N utilization by plant fractions and peat soils, and on the total N contents and percentage of N in plant fractions, were tested in the same manner.

Results

Peat samples were analysed to study the effects of lime application on concentrations of extractable NH_4^+-N and NO_3^--N for the April and July experiments only (Table 1). In April, the concentration of extractable NH_4^+-N in the unlimed peat was double that in the limed peat, while in July there were no significant differences in peat concentration of extractable NH_4^+-N between the limed and unlimed treatments. Concentration of extractable NO_3^--N in the limed peat was 135 and 23 times that in the unlimed peat in April and July respectively.

Extractable mineral N (mg g^{-1}) in the unlimed peat was 33 per cent greater than that in the limed peat in April (Table 1). In contrast, extractable organic N (mg g^{-1}) in the limed peat was 25 and 23 per cent greater than that in the unlimed peat in April and July respectively. Total extractable N (mg g^{-1}) in the limed peat was 22 and 23 per cent greater than that in the unlimed peat in April and July respectively (Table 1).

In the October experiment, the percentages of ^{15}N utilization by all plant fractions, with the exception of the medium-root fraction, were greater for plants on the unlimed peat compared with plants on the limed peat (Table 2). Lime application decreased total N in the leader,

Table 1: Long-term effects of lime application on concentrations of extractable NH_4^+-N, NO_3^--N, mineral N and organic N and total extractable N (mg g^{-1} DW) in peat soils used for the April and July experiments

Month/ lime level	Extractable NH_4^+-N	Extractable NO_3^--N	Extractable mineral N	Extractable organic N	Total extractable N
April					
L_0	1.07	0.002	1.072	14.23	15.30
L_1	0.54	0.269	0.809	17.78	18.59
SE	0.143**	0.073***	0.095**	0.251***	0.272***
July					
L_0	0.13	0.001	0.131	14.15	14.28
L_1	0.10	0.023	0.123	17.38	17.50
SE	0.059 NS	0.009***	0.027 NS	0.348***	0.157***

L_0 = unlimed peat; L_1 = limed peat; n = 10.
NS, not significant; **significant at P < 0.01; ***significant at P < 0.001.

Table 2: Effects of lime application on percentage ^{15}N utilization by plant fractions and peat soils and on total and percentage N in plant fractions in October 1993

	% Utilization ^{15}N			Total N (mg)			N%		
Plant fraction	L_0	L_1	SE	L_0	L_1	SE	L_0	L_1	SE
Leader	0.34	0.02	0.038***	10.5	6.4	2.22*	1.30	1.25	0.351 NS
Needles	2.97	0.24	0.473***	81.8	56.3	5.85**	1.25	1.17	0.222 NS
Shoots	1.48	0.20	0.151***	39.1	28.8	4.59*	0.88	0.88	0.155 NS
Stem	1.16	0.50	0.234**	30.8	36.6	11.24 NS	0.49	0.62	0.323 NS
Coarse roots	1.04	0.43	0.221**	12.9	9.2	5.55 NS	0.59	0.61	0.216 NS
Medium roots	0.48	0.44	0.166 NS	4.6	3.8	2.65 NS	0.79	0.56	0.447 NS
Fine roots	5.68	2.96	1.009**	40.7	24.8	8.78*	1.24	1.10	0.069*
Above-ground	5.95	0.96	1.334***	162.2	128.1	17.21*	0.90	0.88	0.123 NS
Below-ground	7.20	3.84	1.298**	58.2	37.8	9.32*	0.96	0.85	0.251 NS
Whole plant	13.15	4.80	1.705***	220.4	165.9	32.98*	0.91	0.88	0.173 NS
Peat	73.60	79.20	16.968 NS						
% ^{15}N recovered	86.75	84.00	23.369 NS						

L_0 = unlimed treatment; L_1 = limed treatment; n = 5.
NS, not significant; *significant at P < 0.05; **significant at P < 0.01; ***significant at P < 0.001.

needle, shoot and fine-root fractions. Total N in the above-ground parts, below-ground parts and whole plants was decreased with liming by 21.0, 35.1 and 24.7 per cent respectively. Lime application decreased the concentration of N in the fine-root fraction. Percentage ^{15}N utilization by plant fractions was low in the October experiment compared with the April and July experiments (cf. Tables 2, 3 and 4).

In the April experiment, lime decreased percentage ^{15}N utilization by all plant fractions with the exception of the medium-root fraction (Table 3). Likewise, the percentages ^{15}N utilization by above-ground parts, below-ground parts and whole plants were greater for plants on the unlimed peat compared with plants on the limed peat. Liming decreased total N in the needle, shoot and coarse-root fractions. Total N content in the above-ground parts of the unlimed plants was 30 per cent greater than that for limed plants. Lime application decreased the concentration of N in the shoot fraction. Percentage ^{15}N recovered

Table 3: Effects of lime application on percentage ^{15}N utilization by plant fractions and peat soils and on total and percentage N in plant fractions in April 1994

	% Utilization ^{15}N			Total N (mg)			N%		
Plant fraction	L_0	L_1	SE	L_0	L_1	SE	L_0	L_1	SE
Leader	3.52	2.37	0.396**	21.8	22.6	7.33 NS	1.95	2.00	0.882 NS
Needles	16.22	7.40	2.284***	119.7	89.1	11.19*	1.87	1.74	0.977 NS
Shoots	4.91	2.08	0.319***	47.1	31.9	6.66**	1.35	1.19	0.050*
Stem	1.99	0.90	0.122***	23.1	19.7	8.93 NS	0.70	0.65	0.323 NS
Coarse roots	0.39	0.20	0.033**	5.6	3.5	1.22*	0.64	0.48	0.203 NS
Medium roots	0.23	0.20	0.107 NS	2.8	3.1	1.61 NS	0.71	0.64	0.231 NS
Fine roots	7.35	5.25	0.449*	41.7	39.1	14.56 NS	1.66	1.52	0.372 NS
Above-ground	26.64	12.75	3.969***	211.7	163.3	19.88*	1.48	1.37	0.467 NS
Below-ground	7.97	5.65	1.018*	50.1	45.7	12.12 NS	1.33	1.21	0.308 NS
Whole plant	34.61	18.40	6.356***	261.8	209.0	16.55*	1.45	1.33	0.446 NS
Peat	60.20	59.4	23.995 NS						
% 15N recovered	94.81	77.80	8.349*						

L_0 = unlimed treatment; L_1 = limed treatment; $n = 10$.
NS, not significant;* significant at $P < 0.05$; **significant at $P < 0.01$; ***significant at $P < 0.001$.

Table 4: Effects of lime application on percentage ^{15}N utilization by plant fractions and peat soils and on total and percentage N in plant fractions in July 1994

	% Utilization ^{15}N			Total N (mg)			N%		
Plant fraction	L_0	L_1	SE	L_0	L_1	SE	L_0	L_1	SE
Leader	2.41	2.77	1.103 NS	10.7	13.4	5.54 NS	1.47	1.54	0.594 NS
Needles	25.16	21.86	0.243***	132.8	116.9	1.74**	1.55	1.54	0.577 NS
Shoots	9.36	7.77	0.091***	52.5	45.7	0.69**	0.96	0.95	0.463 NS
Stem	5.97	5.04	0.013***	32.6	28.7	9.93 NS	0.60	0.62	0.254 NS
Coarse roots	1.84	1.89	0.577 NS	10.6	10.6	3.89 NS	0.50	0.49	0.259 NS
Medium roots	0.81	0.92	0.358 NS	4.7	5.0	2.22 NS	0.57	0.65	0.227 NS
Fine roots	10.78	8.24	0.076***	49.7	41.8	6.34*	1.40	1.26	0.023**
Above-ground	42.90	37.44	0.123***	228.6	204.7	11.21*	1.13	1.14	0.338 NS
Below-ground	13.43	11.05	0.248**	65.0	57.4	20.25 NS	1.01	0.92	0.387 NS
Whole plant	56.33	48.49	0.100***	293.6	262.1	17.05*	1.10	1.09	0.299 NS
Peat	35.60	45.30	0.319**						
% 15N recovered	91.93	93.79	21.568 NS						

L_0 = unlimed treatment; L_1 = limed treatment; $n = 10$.
NS, not significant;* significant at $P < 0.05$; **significant at $P < 0.01$; ***significant at $P < 0.001$.

in the unlimed peat was higher than that in the limed peat.

With regard to the July experiment, lime decreased the percentage ^{15}N utilization in needles, shoots, stem, fine roots, above-ground parts, below-ground parts and whole plants (Table 4). Percentage ^{15}N utilization by the limed peat was 27 per cent greater than that by the unlimed peat. Total N in the needles, shoots, fine roots, above-ground parts and whole plants was decreased by liming. The application of lime had a significant effect only on the concentration of N in the fine roots decreasing it from 1.4 to 1.26 per cent.

Table 5 shows the effect of lime on the dry weight of various plant fractions. Growing plants on the limed peat had no effect on the dry weight of plant fractions except for the fine-root fraction in October. The dry weight of this fraction was lower with lime than without lime.

The plants grown on the limed peat had blackened roots and many of their root tips were killed compared with plants grown on the unlimed peat. The mycorrhizal populations were lower in the limed peat than those in the unlimed peat.

Discussion

Ammonium (NH_4^+) and nitrate (NO_3^-) are the major inorganic nitrogen ions in the soil. The concentration of these ions in the root zone is controlled by the rate of mineralization and nitrification. Nitrogen mineralization is the biologically mediated release of organically bound nitrogen and its conversion into $NH_4^+$and NO_3^-. Net mineralization will occur only when the nitrogen released by decomposition exceeds that required by the microflora (Carlyle, 1986). This occurs when the substrate C:N ratio decreases to that of microbial biomass; thus the C:N ratio at which mineralization begins can be associated with site and other factors (Berg and Ekbohm, 1983). In high C:N litter, essentially all nitrogen is immobilized by microorganisms and is not available to higher plants (Dickson, 1989). The high concentration of extractable NO_3-N in the limed peat observed in this study might have been derived from increased nitrification due to higher populations and activities of microorganisms under less acid conditions (Adams and Cornforth, 1973; Carey *et al*. 1981).

Concentration of extractable organic N in the limed peat was high in both the April and July experiments compared with the unlimed peat. This might be due to immobilization of peat nitrogen in microorganisms, whose populations increased as a result of liming. There were no differences in concentration of peat extractable NH_4^+-N between the limed and unlimed peat for the July experiment. This could be because the difference in percentage N utilized by the plants grown with or without limed peat was low in July compared with that in April. In addition, concentration of extractable NO_3-N in the limed peat in April was 11.7 times greater than that in July, suggesting a higher rate of nitrification in April. Percentages of ^{15}N utilized by whole plants grown in limed and unlimed peats in July were 1.6 and 2.6 times, respectively, higher than those utilized by these plants in April. This could be due to the generally higher concentration of extractable NH_4^+-N in the peat soils in April compared with July.

It is clear that an increased concentration of NO_3^- in the peat soil is one of the long-term effects of liming. What proportion of this is the direct result of nitrification was not determined in

Table 5: Effects of lime application on plant dry weight (g) in October, April and July

Plant fraction	October 1993			April 1994			July 1994		
	L_0	L_1	SE	L_0	L_1	SE	L_0	L_1	SE
Leader	0.81	0.51	0.469 NS	1.12	1.13	0.320 NS	0.73	0.87	0.332 NS
Needles	6.54	4.81	2.765 NS	6.40	5.12	2.221 NS	8.57	7.59	3.453 NS
Shoots	4.44	3.27	2.899 NS	3.49	2.68	1.399 NS	5.47	4.81	2.810 NS
Stem	6.29	5.90	3.031 NS	3.30	3.03	1.457 NS	5.43	4.63	2.743 NS
Coarse roots	2.19	1.51	0.927 NS	0.87	0.73	0.338 NS	2.11	2.16	1.101 NS
Medium roots	0.58	0.67	0.311 NS	0.39	0.49	0.241 NS	0.83	0.77	0.388 NS
Fine roots	3.28	2.25	0.522*	2.51	2.57	0.602 NS	3.55	3.32	1.134 NS
Above-ground	18.8	14.49	7.951 NS	14.31	11.96	5.210 NS	20.20	17.90	7.771 NS
Below-ground	6.05	4.43	3.733 NS	3.77	3.79	1.027 NS	6.49	6.25	2.297 NS
Whole plant	24.3	18.92	9.405 NS	18.08	15.75	6.353 NS	26.69	24.15	9.978 NS

L_0 = unlimed treatment; L_1 = limed treatment; *n* = 5 in October and *n* = 10 in April and July.
NS, not significant; *significant at $P < 0.05$.

this study. However, higher extractable NO_3^- levels could have had an important effect on reduction of nitrogen uptake by roots of plants grown on the limed peat. The current result is in agreement with results reported for Norway spruce by Persson (1988) and for *Larix kaempferi* trees by Arnold and Van Diest (1991). Nitrogen can be taken up by mycorrhizae associated with fine roots (Liljelund and Nihlgård, 1988). They are able to absorb ammonical nitrogen and pass it on in some form to their host (Brady, 1984). Bigg (1982), in his study on *P. sitchensis* seedlings, observed that *P. sitchensis* seedlings infected with *Lactarius rufus* mycorrhizal fungi had root systems that were 66 per cent heavier and 38 per cent longer than those of uninoculated seedlings. He also found that this species of mycorrhizae grew well when ammonium was supplied, but was completely unable to utilize nitrate. Thus, any enhancement of nitrification as a result of liming could lower populations of mycorrhizae and N uptake by them. In addition, the direct mineralization and cycling of nitrogen by mycorrhizae are important for increasing the availability of nitrogen in the soil (Vogt *et al.*, 1982).

In the current study, the decrease in nitrogen uptake by plants grown on limed peat compared with those grown on unlimed peat could also be due to decreasing fine-root length and number of root tips as a result of growing plants under limed conditions for a short time (Kakei, 1995). A positive correlation between nutrient uptake and fine-root length would be expected since root length is important for resource acquisition. Lehto (1994) also found that liming decreased numbers of short root tips of *Picea abies*. The latter author concluded that lime directly and adversely affected the mycorrhizal populations. Root tips are important sites for nutrient uptake (Mengel and Kirkby, 1982). Hence, any changes in the number of functional root tips will affect the uptake of nutrient minerals including N.

For the October experiment, percentage ^{15}N utilization by the below-ground parts was higher than that for the above-ground parts, particularly in the case of the plants grown on limed peat. The average percentage ^{15}N utilization by the below-ground parts was 1.6 times greater than that by the above-ground parts for the limed and unlimed treatments taken together. This might be due to continued root growth (cf. Van Den Driessche, 1987) with the result that a proportion of ^{15}N was stored directly in the root system (Millard and Proe, 1992). The present results are in agreement with results reported by Millard and Proe (1993) for *P. sitchensis* plants. Among the plant fractions, fine roots and needles utilized the highest percentages of ^{15}N. In *P. sitchensis*, the main storage site for N is the needles of the current year, but roots can also store N (Millard and Proe, 1993).

For April and July, the average percentages ^{15}N utilized by the above-ground parts were 2.9 and 3.3 times higher, respectively, than those utilized by the below-ground parts when data for limed and unlimed treatments were combined. On average, the above-ground parts contained 3.9 and 3.5 times more total N than that did the below-ground parts for April and July respectively. Millard and Proe (1992) found that *P. sitchensis* could remobilize N from roots to support the growth of new foliage in spring. The percentage ^{15}N utilization and the total N contents were highest in the fine-root, needle and shoot fractions, which might be due to the high demands of these fractions for N and translocation of N from old to young tissues for reuse (Miller, 1986). The leader, needles and fine roots contained the highest concentrations of N in all three experiments. This was probably due to the capacity of these fractions to store N during the autumn and winter (Millard and Proe, 1992) as well as to the high activity of these fractions during the spring and summer growing season (Hulm and Killham, 1990).

In the current study, growth of plants on a limed peat soil did not affect the dry weight of plant fractions except in the case of fine roots in October. Negative effects of liming on fine-root growth when plants are grown under limed conditions for a short time have also been reported by Murach (1988) and Kakei (1995).

Conclusions

Liming of a peat soil led 28 years later to a higher concentration of extractable NO_3^- some of which might have derived from nitrification. Extractable organic N and total extractable N in the peat soil were also increased by liming. Percentage ^{15}N utilization and total N were decreased in 3-year-old

Sitka spruce plants that were grown in pots containing the limed peat. The needles and fine roots of plants growing in pots containing peat soils were the main organs for the utilization and storage of nitrogen. During the growing season, the above-ground parts were the major regions utilizing ^{15}N while in the fall ^{15}N utilization by plants was lower and the roots were the dominant sink for nitrogen particularly in the case of plants grown on the limed peat. The decrease in ^{15}N utilization by the Sitka spruce plants grown on the limed peat might be caused by a reduction in mycorrhizal populations associated with fine roots in combination with a high transformation rate of peat nitrogen from NH_4^+-N to NO_3^--N.

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