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Does nitrogen addition to raised bogs influence peat phosphorus pools?

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Abstract. Two *Sphagnum* moss species occupying hummock areas (*Sphagnum capillifolium*) and wetter hollows (*Sphagnum recurvum*) on a raised bog in north east Scotland were treated every two weeks with NH_4NO_3 solutions to supply 3g N m^{-2} yr^{-1}. Although *S. recurvum* moss contained a greater concentration of total P than *S. capillifolium* the amounts and N:P ratios were similar in both species. Larger amounts of total dissolved P (TDP) and molybdate reactive P (MRP) were extracted from beneath *S. recurvum* to 25 cm below the moss. Additions of N both increased and decreased the amounts of TDP at different times, and decreased MRP. The MRP fraction accounted for about 20 per cent of TDP and the difference was assumed to be in organic forms (DOP). Nitrogen addition had no effect on the amounts of DOP, but C:P ratios of this fraction changed with species, depth and N addition. Microbial P accounted for as much as 70 per cent of total P and showed seasonal variations, but no differences between the two moss species and N addition.

Introduction

The capacity of peat to retain atmospheric forms of nitrogen (N) has been related to the phosphorus (P) concentration of the peat and vegetation. Damman (1988) compared the P contents of a range of peatlands in North America and concluded that the variation in N retention could be ascribed to the variation in P contents between mires. Aerts et al. (1992) explained regional variations in N retention by peatlands in Sweden in terms of the P content and for N:P ratio of the vegetation > 14, P was considered to be deficient. The N:P ratio applied to a comparison of five raised bogs across Europe ranged between 9 and 58 and explained some of the variation in N retention by *Sphagnum magellanicum* (Williams et al. 1999).

Phosphorus content in peatland ecosystems is partly a function of the rate of supply and the upper horizons of raised bogs tend to have very low concentrations as atmospheric inputs are small (Gibson et al. 1995). The total P content of peat from raised bogs is particularly small compared to peatland

improved by fertilization (Brake et al. 1999). Total P concentrations decrease with depth in the peat profile (Brake et al. 1999) although the contents tend to increase because of increasing bulk density with increasing depth (Williams & Silcock 1997). The P in peaty soils is present mostly in organic forms (Williams 1994) and the microbial biomass can account for as much as 30% of the total P (Brake et al. 1999: Williams & Sparling 1984) compared with means of 3% of the organic P in mineral arable soils and 13.7% in grassland soils (Brookes et al. 1984). Concentrations of PO_4^{3-}, a biologically active pool of P, vary both spatially across wetland types and temporally with season (Kang & Freeman 1999). Highly organic soils are characterised by small P-sorption capacities and a low retention of inorganic PO_4^{3-} because of their low concentrations of P-binding elements, iron, aluminium and calcium (Cuttle 1983).

The work described here was carried out in parallel with a study of $^{15}NH_4{}^{15}NO_3$ retention by two *Sphagnum* species, *S. capillifolium* and *S. recurvum*, which colonise hummock and hollows, respectively (Williams et al. 1999). The objective was to test the hypothesis that differences in the retention of N by these two species, measured in a laboratory experiment (Silcock & Williams 1997), was a consequence of different P contents or concentrations. It was also postulated that P fractions such as microbial P and extractable forms of P would also vary temporally and spatially across the bog surface and with depth and be affected by N addition.

Materials and methods

Experimental site

The experimental site is a raised bog, the Moidach More (National Grid Reference NJ 030420) in the north-east of Scotland, located at an altitude of 275 m above sea level. The mean annual rainfall is approximately 800 mm and the mean annual temperature 8 °C. The average depth of the peat is 2.1 m and peat more than 0.5 m thick extends to 760 ha. The dominant vegetation comprised *Sphagnum* species such as *Sphagnum magellanicum* Brid., *S. papillosum* Lindb., *S. capillifolium* (Ehrh.) Hedw. and *S. recurvum var. mucronatum* (Russ.) Warnst., and *Erica tetralix* L. and *Trichophorum cespitosum* (L.) Hartm. *Calluna vulgaris* (L.) Hull occupied areas at the edge of the bog where there had been disturbance from peat cutting or burning. The experiment was carried out on carpets of *Sphagnum capillifolium* (Ehrh.) Hedw. and *S. recurvum var. mucronatum* (Russ.) Warnst. where relatively undecomposed moss litter extended to 20 cm depth (Williams et al. 1999).

Field experiment

Sphagnum capillifolium and *S. recurvum* were chosen for the experiment because they colonised contrasting sites, *S. capillifolium* is a hummock forming species whereas *S. recurvum* occupies hollows (Daniels & Eddy 1985). During June 1994, hollow pvc cylinders (length 30 cm, internal diam. 7.5 cm), were inserted into the moss carpet at 216 points (108 for each moss species) on the bog surface and vascular plants removed. The cylinder top was level with the surface of the moss carpet. The cores were set out in three replicate blocks (approx. 50 m^{-2}) for each species, where the moss species were concentrated. Using a randomising procedure, 36 cores (18 treated and 18 untreated) within each block were assigned harvest dates and treatments such that adjacent cores were not removed at the same time. At two week intervals, the controls received deionised water (200 cm^3). An equivalent volume containing 0.51 mg N $core^{-1}$ as NH_4NO_3 (equivalent to 115 mg N m^{-2} every 2 weeks or 3 g N m^{-2} yr^{-1}) was added to the N treated cores. The solutions were applied using a syringe modified to include 6 needle outlet ports to simulate the dropwise addition of rain. To avoid edge effects, solutions were applied evenly over a quadrat, 20 cm $\times$ 20 cm, that contained the core at its centre. Regular N additions were postponed if cores became waterlogged or iced-over during the winter and additional amounts added later when conditions allowed and this occurred in both moss species. Initially, 12 cores (3 replicates $\times$ 2 species $\times$ 2 treatments) were harvested monthly and then less frequently between October and March. On two occasions in December and March, cores were removed from the bog to an open area adjacent to the laboratory for treatment with NH_4NO_3 and subsequent incubation. The bottoms of these cores were covered with nylon mesh and the cylinders placed inside tall 1 dm^3 beakers with an artificial water table maintained at the surface of the core as it had been in the field, by the addition of deionised water. Solutions were added and the cores incubated in the open for two weeks prior to sampling. The cores in the field experiment were harvested on nine different occasions between July 1994 and August 1995, the date referring to the month of harvest.

The water-table depth was measured at two-week intervals at a central point in each of the three blocks for each of the two *Sphagnum* species. A bulked sample of rainwater was collected every two weeks at three locations at the field site adjacent to the cores.

Core analysis

The living moss in the surface 5 cm was removed from each core and the water extracted by suction through a sintered glass filter (pore size < 5 μm)

filtered through Millipore filters (0.45 μm). The extracted moss was weighed and freeze-dried.

Each peat core was removed from the pvc cylinder in the laboratory and sliced transversely into 5 cm sections for analysis. Some cores were incomplete after excavation, but in all cases the cores extended to 25 cm depth. Each section was weighed and stored at 4 °C prior to sub-sampling using a cork borer to remove 5 cm vertical sections.

Moisture contents of the peat were determined by drying weighed subsamples at 105 °C. Bulk density was expressed as the weight of dry matter per unit volume; ash contents were determined by heating overnight in an electric muffle at 500 °C. Acidity was measured as the pH of suspensions of peat in 0.01 M $CaCl_2$ at a sample:solution ratio of 1:5 (w/v).

Pore volume of the cores was calculated as the difference between the total volume and the volume of solids. The latter was calculated using an average value of 1.42 (se = 0.04) for the specific gravity of the peat solids which had been measured in ethanol (Segeberg 1955). The volume of water was calculated from the moisture content and the air volume obtained by difference and expressed as a percentage of pore volume.

Extractable P in the peat below 5 cm depth was obtained by shaking fresh samples (10 g) for 2 hr with 50 cm^3 0.5 M K_2SO_4 and filtering through glass fibre filters (Whatman GFA) under suction. The peat was washed with a further 50 cm^3 of extractant and after filtering again through Millipore filters (0.45 μm) extracts were made up to 100 cm^3.

Chemical analyses

Total P in the freeze dried moss and peat was measured after igniting samples at 500 °C overnight, taking up the ash in 0.1 M HCl and measuring PO_4^{3-} using the molybdenum blue method (Murphy & Riley 1962). Molybdate reactive P (MRP) in water and 0.5 M K_2SO_4 extracts was also measured using the molybdenum blue method (Murphy & Riley 1962). Total dissolved P (TDP) concentrations in the K_2SO_4 extracts of fumigated and fresh samples were measured as MRP after oxidation of extracts with alkaline potassium persulphate (Williams et al. 1995). The difference between TDP and MRP was considered to be organic P (DOP).

Dissolved organic carbon (DOC) in extracts of the fresh peats was determined by oxidation using a soluble carbon analyser (OI Analytical Model 700,OI Corp., College Station, TX, U.S.A.).

Microbial P.

Microbial P was determined by the fumigation extraction (FE) method after fumigation for 18 h with chloroform vapour (Williams & Sparling 1984) followed by extraction with 0.5 M K_2SO_4. Microbial P was calculated from the flush of MRP extracted with 0.5 M K_2SO_4 using the recovery factor of 0.4 derived for soils by Brookes et al. (1984).

Statistical analysis

The results were expressed on an area (g or mg P m^{-2} for each 5 cm thick layer) basis for statistical analysis at each depth, measured from the surface of the moss. Comparisons of the two N treatments and two species over nine sampling times and at individual times were carried out at each depth by analysis of variance. For skewed distributions, values were transformed to the natural logarithm, but for clarity, untransformed means and standard errors of individual means are presented. A repeated measures technique, using values from all four depths to 25 cm, was also used to test for treatment effects throughout the peat cores (Kenward 1987). All statistical analyses were performed using the Genstat package (NAG, Oxford).

Results

The visual characteristics, and physical attributes such as bulk density, of the peat profiles in the surface 25 cm beneath the two *Sphagnum* species were similar (Williams et al. 1999). Water table level fell between June and August 1994 to 35 cm below the surface at both sites, rising again in September. From September until June the water table was at a significantly ($p < 0.001$) lower depth beneath *S. capillifolium* than *S. recurvum*, mean depth below the surface 4.7 cm compared with 2.2 cm. Mean air-filled porosity varied significantly ($p < 0.001$) with time in the surface 20 cm (Table 1). Below 20 cm depth, the overall mean value was 5% and showed no significant variation with time (not shown). In the 5–10 cm depth, air-filled porosity, averaged over time and N treatments, was significantly ($p < 0.05$) greater beneath *S. capillifolium* than *S. recurvum* (Table 1). The mean contents of ash ranged between 2.0 and 3.1% of dry matter at both sites from 5 to 25 cm depth. *S. recurvum* had a significantly ($p < 0.01$) higher pH (3.21–3.33) than *S. capillifolium* (3.08–3.15) (standard error of the means = 0.02, $n = 54$) at each of the four depths.

Table 1. Air filled porosity % of cores beneath *S. capillifolium* and *S. recurvum* at different depths. Values in parentheses are standard errors of difference between species means, n = 54

	S. capillifolium			*S. recurvum*		
	5–10 cm	10–15 cm	15–20 cm	5–10 cm	10–15 cm	15–20 cm
July	44.6	16.1	4.1	42.4	10.3	6.0
August	43.3	21.6	3.3	33.1	3.7	8.8
September	40.0	16.4	3.1	30.1	7.6	3.1
October	19.5	6.9	2.5	9.5	5.3	4.9
December	29.3	14.2	3.2	15.2	2.0	0.4
March	18.4	4.2	0.1	13.2	0.6	0.1
May	35.7	16.3	4.6	22.8	10.9	2.3
July	25.6	4.0	4.9	21.9	5.1	1.4
August	47.3	21.7	16.4	34.4	11.6	5.5
Mean	33.7	13.5	4.7	24.7 (2.7)	6.4 (2.5)	3.6 (1.2)

Total P and MRP in mosses

Concentrations of total P in the moss *S. recurvum* were almost twice as great as those in *S. capillifolium*, 648 mg P kg^{-1} compared with 354 mg P kg^{-1}, sampled during August 1994. Total N concentrations, averaged over all dates, were 6.6 and 11.6 mg g^{-1} dry mass (standard error of difference (SED) = 0.6, n = 54) for *S. capillifolium* and *S. recurvum*, respectively (Williams et al. 1999). Despite this large difference between the two moss species in the total P and total N concentrations, the mean N:P ratios, 16.6 ± 1.1 in *S. capillifolium* and 18.6 ± 1.5 in *S. recurvum* were similar. When total P concentrations in the mosses was expressed as g P m^{-2}, the mean values for *S. capillifolium* and *S. recurvum*, 0.42 and 0.45 g P m^{-2} (sed = 0.08, n = 6), respectively, were very similar.

MRP

From July to December 1994, MRP in waters extracted from the *S. recurvum* moss ranged between 3.7 and 23.0 mg P m^{-2} compared with 0.13 to 0.82 mg P m^{-2} for *S. capillifolium*. Averaged over the 5 months, this difference was significant ($p < 0.001$) and values did not change significantly with time and were unaffected by applications of N.

Total P in peat

At lower depths, between 5 and 20 cm, total P concentrations ranged between 171 and 822 mg P kg^{-1}, and no difference between the species was evident. Between 25 and 30 cm depth, peat beneath *S. recurvum* had a significantly ($p < 0.001$) greater total P concentration than that beneath *S. capillifolium*, 698 mg P kg^{-1} compared with 291 mg P kg^{-1} (SED = 38.6, $n = 6$). There was no impact of N on the total P concentration after two months of addition. The mean quantity of P in the underlying peat increased from 0.91 g P m^{-2} in the 5–10 cm depth to 2.23 g P m^{-2} at 25 to 30 cm. Differences between the two sites were not evident. A repeat analysis for total P in the peat in August 1995 again showed no differences between the contents of P in the two species and no effect of added N.

TDP in extracts of peat

The amounts of K_2SO_4-extracted TDP were significantly greater ($p < 0.001$) in *S. recurvum* than in *S. capillifolium* averaged over all dates at all depths to 25 cm. The quantities of extractable TDP also varied significantly ($p < 0.001$) with time at all depths to 25 cm. This variation was much greater in the higher values obtained with *S. recurvum* and the interaction was significant ($p < 0.01$) to 25 cm depth (Figure 1, 5–10 cm only). For *S. capillifolium*, values decreased from July through to October whereas beneath *S. recurvum*, TDP reached peak values in August.

In the 5–10 cm depth, addition of N both increased and decreased extractable TDP at different times. During July, TDP increased significantly ($p < 0.001$) after N addition. Effects of N were small beneath *S. capillifolium* and were greater beneath *S. recurvum*. In October 1994, N addition significantly ($p < 0.05$) decreased the TDP content and the interaction between N addition and the species was significant to 25 cm depth (Table 2).

MRP in extracts of peat

At each of the four depths, the average content of K_2SO_4 extractable MRP was significantly ($p < 0.001$) greater beneath *S. recurvum* than *S. capillifolium* by a factor of more than ten (Figure 2, 5–10 cm depth only). This difference between the species varied significantly ($p < 0.01$) with time between 5 and 15 cm depth, being greater during August 1994 than other sampling occasions. At all depths beneath *S. recurvum*, the greatest contents of MRP were obtained during August. This was not the case beneath *S. capillifolium* where temporal variation was smaller. At individual sampling times, N addition significantly ($p < 0.001$ and 0.05) decreased MRP in August and

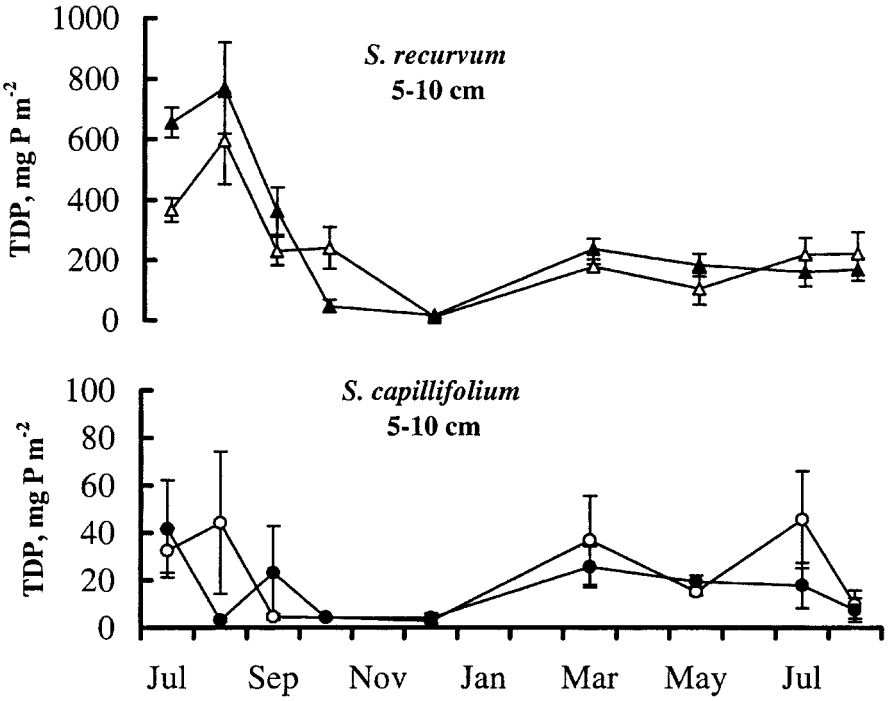

Figure 1. Contents of total dissolved P (TDP), mg P m^{-2}, in 0.5 M K_2SO_4 extracts of peat from beneath *S. capillifolium* and *S. recurvum* at 5–10 cm depth below the moss surface, ❍ – *S. capillifolium*, ● – *S. capillifolium* + N, Δ – *S. recurvum*, ▲ – *S. recurvum* + N. Error bars show the standard error of the individual means.

Table 2. Contents (mg m^{-2}) of extractable TDP in cores sampled October 1994 to 25 cm depth

Depth (cm)	*S. capillifolium*		*S. recurvum*		Significant differences
	Control	NH_4NO_3	Control	NH_4NO_3	
5–10	4	4	240	46	Sp**, N*, SpxN*
10–15	5	5	178	22	N*, SpxN*
15–20	5	5	143	6	Sp***, N***, SpxN***
20–25	5	6	86	15	Sp**, N*, SpxN*
Sum	19	20	647	89	Sp**, N***, SpxN***

Differences denoted by *, ** and *** significantly different at $p < 0.05$, 0.01 and 0.001, respectively. Sp = species, N = N treatment, interaction = Spx N.

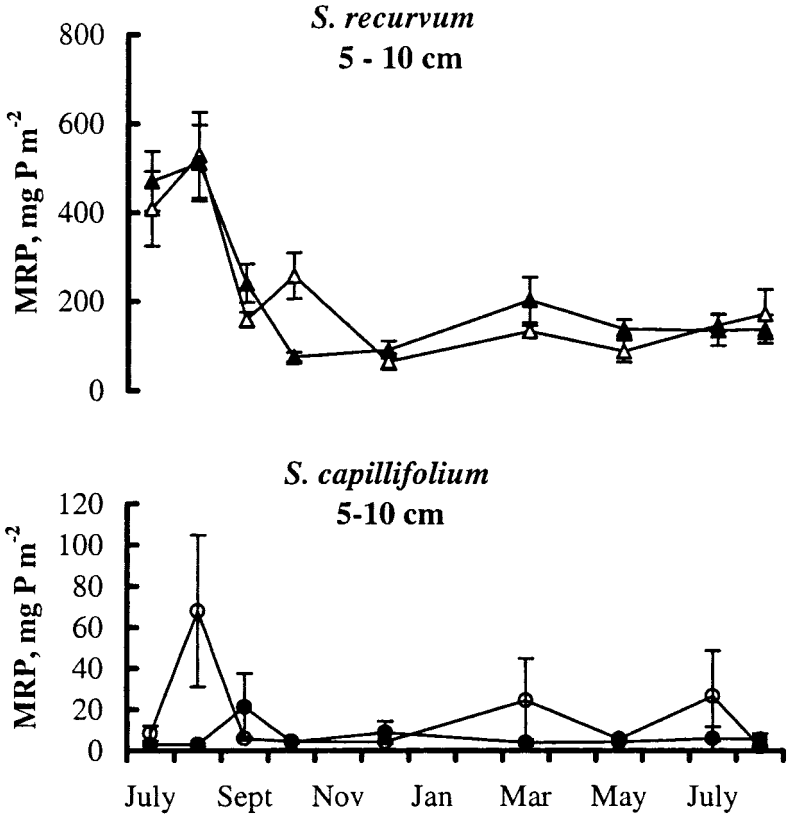

Figure 2. Contents of molybdate reactive P (MRP), mg P m^{-2}, in 0.5 M K_2SO_4 extracts of peat from beneath *S. capillifolium* and *S. recurvum* at 5–10 cm depth below the moss surface. ❍ – *S. capillifolium*, ● – *S. capillifolium* + N, Δ – *S. recurvum*, ▲ – *S. recurvum* + N. Error bars show the standard error of the individual means.

September at the 5–10 cm depth (Figure 2). The effect of N varied significantly ($p < 0.01$) between the species on both occasions. In August, the effect was greater beneath *S. capillifolium* and in September it was greatest beneath *S. recurvum*.

Dissolved organic P

Beneath *S. recurvum* during July to September 1994 and March to August 1995 (Figure 1), MRP accounted for less than 20 per cent of TDP and the difference was assumed to be DOP. Averaged over all times, the quantity of DOP was significantly ($p < 0.05$ and 0.01) greater in *S. recurvum* than *S. capillifolium* at each of the four depths and in the total DOP to 25 cm depth (Figure 3). Values changed significantly ($p < 0.001$) with time and were

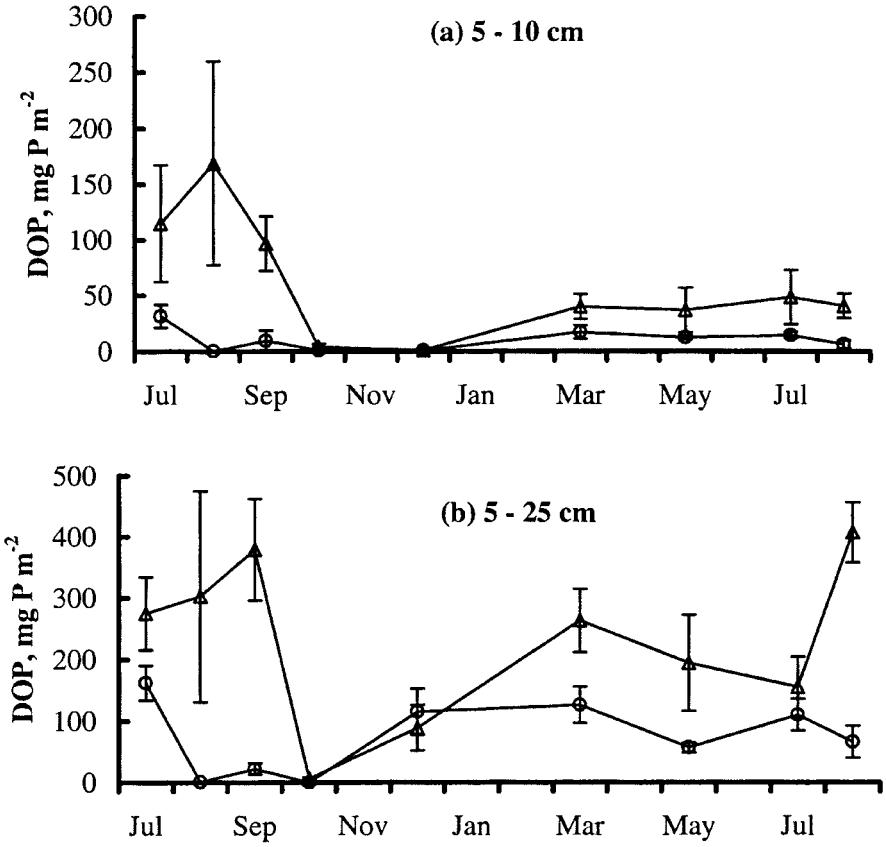

Figure 3. Contents of dissolved organic P (DOP), mg P m^{-2}, in 0.5 M K_2SO_4 extracts of peat from beneath ❍ – *S. capillifolium* and △ – *S. recurvum* at (a) 5–10 cm depth and (b) the total amount in the 5–25 cm depth. Error bars show the standard error of the individual means.

greater between July and October 1994 than on other occasions. Differences between the species were larger when values were high and this interaction was significant ($p < 0.001$) in the surface 20 cm depth. During the second growing season, values of DOP were smaller and differences beneath the two species were less. There was no evidence that the quantity of DOP was influenced by the addition of NH_4NO_3.

Neither species nor N addition had any significant effect on extractable DOC amounts, but calculated C:P ratios from the DOC and DOP values showed effects of both species and N treatments in the 5–10 and 10–15 cm depths (Table 3). Averaged over all sampling dates, C:P ratios were significantly lower in the peat beneath *S. recurvum* and in the cores receiving NH_4NO_3 at the two depths.

Table 3. Mean C:P ratios, averaged over all sampling dates, calculated from the DOC and DOP contents of the K_2SO_4 extractable organic matter

Depth (cm)	*S. capillifolium*		*S. recurvum*		Significant differences
	Control	NH_4NO_3	Control	NH_4NO_3	
5–10	1028	574	265	382	Sp^{*}, N^{*}
10–15	941	543	592	202	Sp^{*}, N^{**}
15–20	382	708	148	293	Sp^{*}, N^{ns}
20–25	192	187	114	240	Sp^{ns}, N^{ns}

Differences denoted by **, * and ^{ns} are significant at $p < 0.01$, 0.05 and not significant, respectively.

Microbial P

Mean microbial P values averaged over both species and time, ranged from 716 mg P m^{-2} at 5–10 cm depth to 882 mg P m^{-2} at 20–25 cm depth. Values varied significantly ($p < 0.001$) with time and were smaller during October at each depth when they decreased 3–4 fold compared with the overall mean values. There were no significant differences in microbial P beneath the two moss species and there were no effects of NH_4NO_3 addition.

Discussion

The total P contents of the two *Sphagnum* species, 0.42–0.45 g P m^{-2}, were marginally greater than the 0.23 g P m^{-2} measured in a bryophyte community, but lower than the 0.89 obtained for phanerogram species on a fen peat in the Netherlands (Verhoeven et al. 1988). Although total P concentrations in the two *Sphagnum* mosses differed by almost a factor of two so did the concentrations of total N so that N:P ratios were similar at 16.6 and 18.6. Retention of ^{15}N from the $^{15}NH_4{}^{15}NO_3$ showed small differences between the species at different times, but the average retention was similar in *S. capillifolium* and *S. recurvum* (Williams et al. 1999). The total P contents of the upper 20 cm of peat were 6.7 and 7.3 g P m^{-2} beneath *S. capillifolium* and *S. recurvum*, respectively. In two raised bogs in Germany, the total P contents of the top 30 cm varied from 9.1 to 14.5 g P m^{-2}, and below 30 cm, values decreased sharply (Brake et al. 1999).

The greater content of extractable MRP in peat from the wetter hollows beneath *S. recurvum* compared to the drier *S. capillifolium* occurred throughout the upper 25 cm. The higher MRP contents were evident in the water associated with the living moss in the surface. The marginally

greater aeration beneath *S. capillifolium* could be expected to decrease MRP by increasing microbial activity, litter decomposition and immobilisation of MRP. Johnson and Damman (1991) measured slower rates of mass loss from *S. cuspidatum* litter in anoxic or intermittently anoxic layers than in the oxic zones of a raised bog. Furthermore, they also found that the rate of mass loss was species dependent. Similar intrinsic differences in litter quality beneath *S. capillifolium* and *S. recurvum* and the conditions in the underlying peat may have influenced P immobilisation and amounts of easily extractable TDP and MRP. However, the botanical origin of the litter beneath the two *Sphagnum* species was not established in this study. Walbridge (1991) reported that when microbial uptake of P in organic soils in pocosin ecosystems was inhibited, labelled $^{32}PO_4^{3-}$ remained in the inorganic pool. In both the raised bog at Moidach More and the pocosin wetlands, the inorganic ash content was of the order of 5% of dry peat or less, indicating that the potential for P sorption by minerals was low (Cuttle 1983). This would minimise the impact of changes in redox potential on MRP and increase the likelihood for MRP to accumulate (Verhoeven et al. 1988) and even leach down to lower depths.

Differences in air filled porosity beneath the two mosses, which could influence microbial P assimilation, were limited to the 5–10 cm depth whereas the greater amount of MRP beneath *S. recurvum* extended to 25 cm below the surface. The contents of MRP beneath *S. recurvum* were greatest during the summer months when the water table depth was greatest and also when temperatures were at their highest. Verhoeven et al. (1988) reported greater net P mineralization rates and greater extractable P concentrations in nutrient poor than in rich fens during June and July. They attributed the greater concentrations of MRP to lower pH and Ca concentrations reducing the potential for P sorption in the nutrient poor fen. Walbridge (1992), using anion exchange resins, showed that the supply of PO_4^{3-} in pocosin wetlands was greatest in June, July and August. Kang and Freeman (1999) compared phosphatase activity in three types of wetland soils, a bog, fen and swamp and found that activities were least in the waters of the acidic bog (pH 3.7–4.2) with *Sphagnum* mosses as the main vegetation. In general, the PO_4^{3-} concentrations in their bog waters were greater during June, July and August and showed a similar seasonal pattern as the amounts of extractable MRP at Moidach More. In our study, pH values were marginally lower beneath *S. capillifolium* than *S. recurvum* which could have resulted in a lower phosphatase activity.

Williams and Silcock (1997) reported that additions of 1 g N m^{-2} yr^{-1} as NH_4NO_3 to *S. magellanicum* increased extractable MRP in the underlying peat and argued that phosphatase activity released by the moss increased in response to increasing N supply under P deficient conditions. In the current

study, N addition stimulated extractable TDP at 5–10 and 10–15 cm depth, an effect that could be detected mainly during the summer months when the amounts of extractable P were greatest. During October, N addition decreased the amount of extractable TDP beneath *S. recurvum*, possibly because N addition was also stimulating P immobilisation by the microbial community. In the same cores, N addition sustained the microbial C and N at a time when values in the control cores were falling beneath both Sphagnum species (Williams & Silcock 2000). Microbial N values were smaller beneath *S. capillifolium* than *S. recurvum* and responded to added N to a greater extent under *S. capillifolium*, in contrast to the effect of N addition on TDP. However, microbial P measurements failed to show similar responses to added N as microbial C and N had done.

Mean total microbial P in the surface 25 cm of peat was 3.2 and 2.7 g m^{-2} beneath *S. capillifolium* and *S. recurvum*, respectively. These compare with values of 4.6 and 6.7 for the surface 30 cm of two raised bogs which had previously been drained (Brake et al. 1999). In pocosin wetlands, Walbridge (1991) obtained values ranging from 1 to 1.3 g P m^{-2} for the surface 15 cm. This microbial P represents a very high proportion of the total and a significant sink for P in the peat: values of 72% in the 5–10 cm beneath *S. capillifolium* and 53% at 20–25 cm depth compared to 57% and 46% beneath *S. recurvum*. Walbridge (1991) reported microbial P: total P values ranging between 37% and 56% in pocosin wetlands. Microbial P values in two drained raised bogs in Germany were greatest in the surface 3–6 cm, with values ranging from 345 to 409 mg kg^{-1}, equivalent to 44 and 70% of the total P (Brake et al. 1999). Microbial: total P decreased sharply with depth and values were 20% or less below 20 cm depth. There is a possibility that chloroform fumigation extracted P from non-microbial material such as living plant parts as the boundary between living and dead *Sphagnum* is poorly defined. However, the C:P ratios of the two mosses, assuming a total C concentration of 480 g C kg^{-1} dry moss, were 1354 for *S. capillifolium* and 741 for *S. recurvum*. Using biomass C values, measured using the substrate induced respiration method (Williams & Silcock 2000), mean ratios of microbial C: microbial P were marginally greater in the 5–10 cm depth, 28.5 and 34 beneath *S. capillifolium* and *S. recurvum*, respectively. Below 10 cm depth, all mean values varied between 23.6 and 26.8. Comparing these values with those for the living moss tissues indicates that any contribution of plant material to microbial P was very small. These values are greater than the C:P ratio of 16.7 for bacteria and 7–12 for fungi grown in cultures (Anderson & Domsch 1980). Hughes and Reynolds (1991) reported C:P ratios for microbial P of 22–36 for forest humus from clear-felled and pre-felled sites, respectively, and were similar to our own. However, in contrast to

the peat, microbial P contributed only 8% of the total organic P in the forest humus which had a mineral content of 49% of dry mass compared with 3% in the peat profiles.

The amounts of DOP fraction were different beneath the two *Sphagnum* species, but were unaffected by N addition. The seasonal changes in DOP and DON did not share the same pattern (Williams & Silcock 2000). Dissolved organic matter (DOM) in the extracts varied in its C:N ratio (Williams & Silcock 2000) and C:P ratios also indicated changes in the composition of the extractable (DOM) between the species, with depth and following N addition.

In conclusion, the addition of NH_4NO_3 which could both increase and decrease the amounts of extractable TDP in the wetter hollows of a raised bog peat had less of an impact on drier sites. The increase may have been the result of increasing phosphatase activity released by *Sphagnum* (Williams & Silcock 1997). On the other hand increased microbial immobilization of P may have caused the decrease in TDP. Organic P was an important component of the extractable TDP and its C:P ratio differed between the sites and decreased in response to N addition. Microbial biomass P was a significant pool of P at both sites, but showed little influence of N addition or *Sphagnum* species.

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