Biol Fertil Soils (1997) 24:421–428

ORIGINAL PAPER

Z.L. He · J. Wu · A.G. O'Donnell · J.K. Syers

Seasonal responses in microbial biomass carbon, phosphorus and sulphur in soils under pasture

Received: 25 May 1996

Abstract The response of the soil microbial biomass to seasonal changes was investigated in the field under pastures. These studies showed that over a 9-month period, microbial biomass carbon, phosphorus and sulphur (biomass C, P, S), and their ratios (C:P, C:S, and P:S) responded differently to changes in soil moisture and to the input of fresh organic materials. From October to December (1993), when plant residues were largely incorporated into the soils, biomass C and S increased by 150–210%. Biomass P did not increase over this time, having decreased by 22–64% over the dry summer (July to September). There was no obvious correlation between biomass C, P, and S and air temperature. The largest amounts of biomass C and P (2100–2300 μg and 150–190 μg g^{-1} soil, respectively) were found in those soils receiving farmyard manure (FYM or FYM+NPK) and P fertilizer, whereas the use of ammonium sulphate decreased biomass C and P. The C:P, C:S, and P:S ratios of the biomass varied considerably (9–276:1; 50–149:1; and 0.3–14:1, respectively) with season and fertilizer regime. This reflected the potential for the biomass to release (when ratios were narrow) or to immobilize (wide ratios) P and S at different times of the year. Thus, seasonal responses in biomass C, P, and S are important in controlling the cycling of C, P, and S in pasture and ultimately in regulating plant availability of P and S. The uptake of P in the pasture was well correlated with the sum of P in the biomass and soil available pools. Thus, the simultaneous measurement of microbial biomass P and available P provide useful information on the potential plant availability of P.

Z.L. He[1] · J. Wu · A.G. O'Donnell · J.K. Syers (✉)
Department of Agricultural and Environmental Science,
University of Newcastle, Newcastle Upon Tyne, NE1 7RU, UK
Tel: (191)222-5677; Fax: (191)222-5677

Current address: [1] Department of Land Use and Applied Chemistry, Zhejiang Agricultural University, Hangzhou, Zhejiang, PR China

Key words Seasonal responses · Microbial biomass C · Microbial biomass P · Microbial biomass S · Nutrient cycling · Pasture

Introduction

The microbial biomass not only contains a labile pool of nutrients but also drives the cycling of organic matter and nutrients in soil (Jenkinson and Ladd 1981). McGill et al. (1986) proposed that seasonal changes in soil microbial biomass are directly involved in the turnover of organic matter and the cycling of nutrients in soil, thereby affecting their availability. Previous studies (Lynch and Panting 1982; Biederbeck et al. 1984; McGill et al. 1986; Bristow and Jarvis 1991; Kaiser and Heinemeyer 1993; Joergensen et al. 1994; Franzluebbers et al. 1994; Ross et al. 1995) have compared seasonal responses of microbial biomass C and N under different managements (soil and crop) or different temperature and moisture regimes and have provided valuable insights into the relationship between biomass C and N and the impacts of their seasonal dynamics on the cycling and availability of N in soil. However, data for other major plant nutrients such as P and S which, like N, are also subject to microbial transformations are limited, except for a few trials in New Zealand and India (Sorn-Srivichai et al. 1988; Ghani et al. 1990; Perrott et al. 1992; Srivastava 1992). Additional studies are therefore needed to improve our understanding of the role of the microbial biomass in controlling the availability of P and S in soil.

In the work reported here, the amounts of microbial biomass C, P, and S and available P and S in soils under pastures subject to different managements were measured over a 9-month period (March–December 1993), together with the dry matter, and the amounts of P and S in the harvested herbage. The objective was to extend our understanding of nutrient dynamics in soils by quantifying how the amounts and turnover of soil microbial biomass C, P, and S responded to changes in environmental factors such

Table 1 Plots selected and basic soil properties[a] in the Palace Leas Meadow Hay experiment

Plot No.	Treatments	Farmyard manure (t ha^{-1} year^{-1})	Mineral fertilizers[b] (kg ha^{-1} year^{-1})				pH	Organic C	Total P	Total S
			N	P	K	S		(%)		
1	FYM[c]+NPK	20	17	13	28	6	5.3	5.3	0.22	0.072
2	FYM[c]	20	0	0	0	0	5.4	5.3	0.19	0.066
6	Control	0	0	0	0	0	5.2	3.3	0.035	0.035
7	N	0	35	0	0	19	3.7	6.3	0.075	0.075
8	P	0	0	26	0	2	5.7	4.3	0.12	0.037
13	NPK	0	35	26	46	21	5.5	3.7	0.082	0.046

[a] Organic C and total S cited from Wu et al. (1994). Total P was determined by vanadophosphate color photometry following wet digestion (MAFF 1986), and pH determined in 0.5 *M* KCl at a water:soil ratio of 2:1
[b] Calculated from data provided by Pawson (1960)
[c] Farmyard manure

as temperature, moisture, plant growth, and fertilizer application and in doing so to assess the importance of the microbial biomass in regulating the plant availability of P and S in soil.

Materials and methods

Soils and sampling

The investigation was carried out with soils and herbage collected from the Palace Leas Meadow Hay Trial at Cockle Park Farm, Northumberland, UK. Soil at this site is a clay loam belonging to the Wigton Moor Series (Payton and Palmer 1990). The long-term hay meadow trial at Palace Leas was established in 1897 with plots subject to different fertilizer management since that time (Pawson 1960). Six plots were selected for this study; the management and basic soil properties are described in Table 1. Farmyard manure (FYM) and most NPK fertilizers were applied in early spring. Soil from the plots was sampled 3 weeks after the use of spring fertilizers and approximately 2 weeks from the start and end of the dry season, on 19 March, 22 July, and 2 October 1993, respectively. These dates, together with those chosen for 22 June and 9 December 1993, were considered to provide a good representation of the main seasonal changes in biomass and nutrient availability in the pasture.

For each time of sampling, ten cores were taken from the surface soil (0–15 cm) using an auger sampler (5 cm diameter) and pooled to provide one replicate sample. This was repeated twice more for each plot to give triplicate soil samples. Plant debris and roots were removed and the fresh soil sieved moist (<2 mm) and mixed thoroughly. To reduce interference from remaining living plant tissues, such as small pieces of roots, soil samples were stored at 4 °C in the dark for a maximum of 5 days. Biomass C, P, and S, and available P and S were measured in the moist soil and soil pH, organic C, total P, and total S analysed using air-dry samples.

Soil biomass C, P, S, and available P and S

Procedures for measuring biomass C and S were as described by Wu et al. (1990, 1994) and for biomass P as in Wu et al. (in press). Separate portions of fresh soil (25, 5, and 10 g on an oven-dried basis, for biomass C, P, and S measurements, respectively) were placed in a vacuum desiccator and exposed to alcohol-free $CHCl_3$ vapour at room temperature for 24 h (Jenkinson and Powlson 1976). Portions were then transferred to a clean desiccator and residual $CHCl_3$ removed by evacuation for 20 min. Fumigated portions, together with equivalent unfumigated portions, were extracted with 100 ml 0.5 *M* K_2SO_4, 20 ml 0.03 *M* NH_4F–0.025 *M* HCl, and 20 ml 0.01 *M* $CaCl_2$, respectively, for measuring biomass C, P, and S (Wu et al. 1990, 1994, in press). Prior to analysis, all extracts were filtered using Whatman No. 42 filter paper and stored at –18 °C to minimize any changes due to microbial activity.

Extracts of 0.5 *M* K_2SO_4 were analysed for organic C content in an automated carbon analyser (Dohrman DC 90, modified for UV oxidation) and biomass C was calculated as described by Wu et al. (1990). Extracts of 0.03 *M* NH_4F–0.025 *M* HCl were analysed for P by spectrophotometry (Wu et al., in press). Biomass P was calculated from the increase in extractable P in the fumigated soil over that in the control using a conversion factor (k_P) of 0.4 (Hedley and Stewart 1982). Extracts of 0.01 *M* $CaCl_2$ were analysed for total extractable S by ion chromatography following digestion with 30% H_2O_2 (Wu et al. 1994). Biomass S was calculated from the increase in total extractable S in the fumigated soil over that in the unfumigated soil using a conversion factor (k_S) of 0.31 (Wu et al. 1994). The values of available P and S were taken from the amounts of extractable P and S determined in the unfumigated soil as extracted in 0.03 *M* NH_4F–0.025 *M* HCl and 0.01 *M* $CaCl_2$, respectively.

Plant yield and P and S contents

Dry weight of harvested herbage was calculated from total fresh weight of two to three cuts and the dry matter content determined by drying samples for 2 h at 80 °C and an additional 48 h at 60 °C. Dry samples (three replicates) were ground to pass 1.0-mm mesh and digested with $HClO_4$ and HNO_3 (MAFF 1986). Saturated $MgCl_2$ solution was added to prevent the loss of P during digestion (Brookes and Powlson 1981). The contents of P and S were determined by vanadomolybdate spectrophotometry (MAFF 1986) and inductively coupled plasma spectrometry (ARL-Fisons 34000; Zhao et al. 1994), respectively.

Data analysis

Data were analysed using ANOVA and the means tested for significant differences using a *t*-test at 5% probability. Except for the deviation between replicates, which could be evaluated statistically, the major source of experimental error was likely to arise from variations in field sampling at different times and in the pre-treatment of samples (Patra et al. 1990). Under these circumstances, a coefficient of variation of 10–20% was considered acceptable, given the accuracy of the methods (Jenkinson 1988; Wu et al. 1994, in press). Therefore, differences of <20% of the measured values of microbial biomass C, P, and S were not regarded as significant. Similarly, it was considered that differences >20% were unlikely to be due to experimental error.

Results and discussion

Seasonal changes in biomass C, P, and S and the effects of fertilizers

From March to October, soil microbial biomass C in the control plot (plot 6) and those receiving farmyard manure (FYM and FYM+NPK) remained relatively constant with variations (< 20%, see above) considered to be non-significant (Fig. 1 a). However, where mineral fertilizers (N, P, and NPK) were used, biomass C decreased significantly (23–34%) between either June and July, or July and October. These changes were consistent with the decline in soil water contents during the dry season (July–September; Fig. 2 a). It is interesting that biomass C in the soils from the control plot and those receiving FYM and FYM+NPK did not respond significantly to the moisture deficit over this period (Fig. 1 a). Although for the manured plots this may be due to better moisture retention, it may also suggest that the microbial populations in these soils (including the control soil) are better able to survive the effects of moisture deficit than the biomass in those treated with mineral fertilizers (N, P, and NPK). In support of this hypothesis, the control site contained the lowest amount of water over the dry season (17 ml 100 g^{-1}, Fig. 2 a) but showed no significant changes in biomass C. From October to December, biomass C in all plots increased by 150–210% (Fig. 1 a). These increases are most likely related to the incorporations of plant residues and dead roots, which provided substantial energy for the growth of the microbial biomass (Perrott et al. 1990). Over this period, water availability would no longer limit the growth of the microbial biomass (Fig. 2 a). It might be expected that as the fresh inputs were consumed, the microbial biomass maintained in the soil would decline in late winter and early spring. This is indicated by the fact that the amounts of biomass C in all plots measured in March were much less than those found in December (Fig. 1 a).

Seasonal responses in biomass P showed a different pattern from those seen for biomass C (Fig. 1 a, b). Between March and June, biomass P increased consistently in all plots, whereas it decreased markedly (22–64%) between July and October. These decreases mirrored the decline in soil water content (Fig. 2 a). Since moisture deficit had no significant effect on the size of the microbial biomass in the control, FYM, and FYM+NPK plots (as indicated by biomass C, Fig. 1 a), the decline in biomass P in these plots over this period demonstrates a marked loss of P from the biomass. Given that the microbial biomass is turning over but not decreasing in size, this loss might be explained by the limited diffusion of phosphate to microorganisms due to moisture deficit in the soil or by the replacement of one microbial community by another with a more limited capacity for immobilizing P. The former would be accelerated by the vigorous growth of plants, which would not only increase soil moisture deficit by evapotranspiration but compete with the microbial biomass for P, thereby decreasing P concentration in the soil solution. Under these circumstances, the turnover of the soil microbial biomass would lead to a lower biomass P level. This is supported by previous studies (Sparling et al. 1987; Perrott et al. 1990, 1992) and explains why the amounts of extractable P in all plots remained essentially constant or even increased (Fig. 3 a) in response to plant uptake and moisture deficit over the dry season (July to September); i.e. it was being supplied by microbial biomass turnover. When the moisture deficit was eliminated in October 1993, the decline in biomass P ceased in all plots (Fig. 1 b) although subsequent increases in microbial biomass P lagged markedly, compared with the rapid increases in biomass C (Fig. 1 a, b). Changes in biomass S in

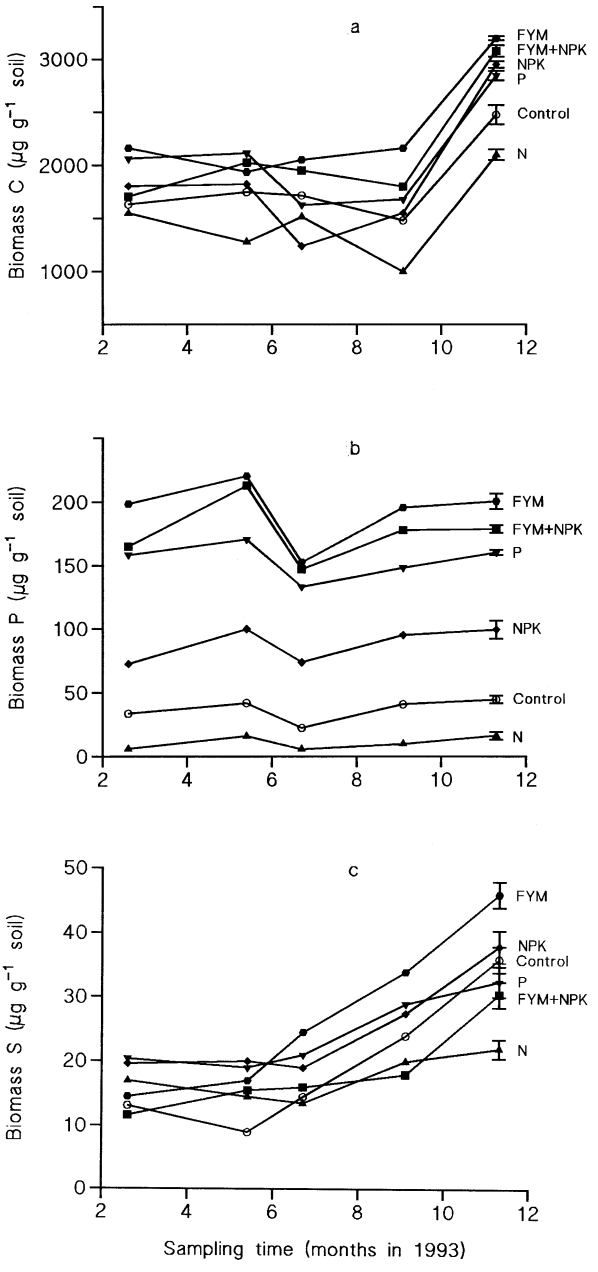

Fig. 1 a–c Changes in soil microbial biomass C (**a**), P (**b**), and S (**c**) in selected plots at the Palace Leas Meadow Hay experiment. *Error bars* show the standard deviations of the means averaged over the five sampling times

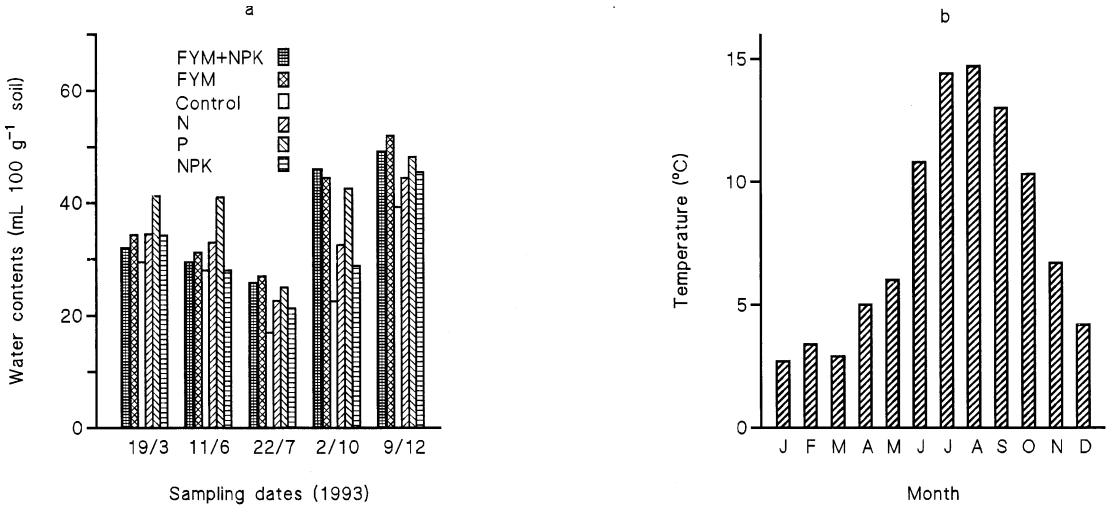

Fig. 2 a, b Soil water contents (**a**) and daily mean temperature (**b**) at the field site (1993)

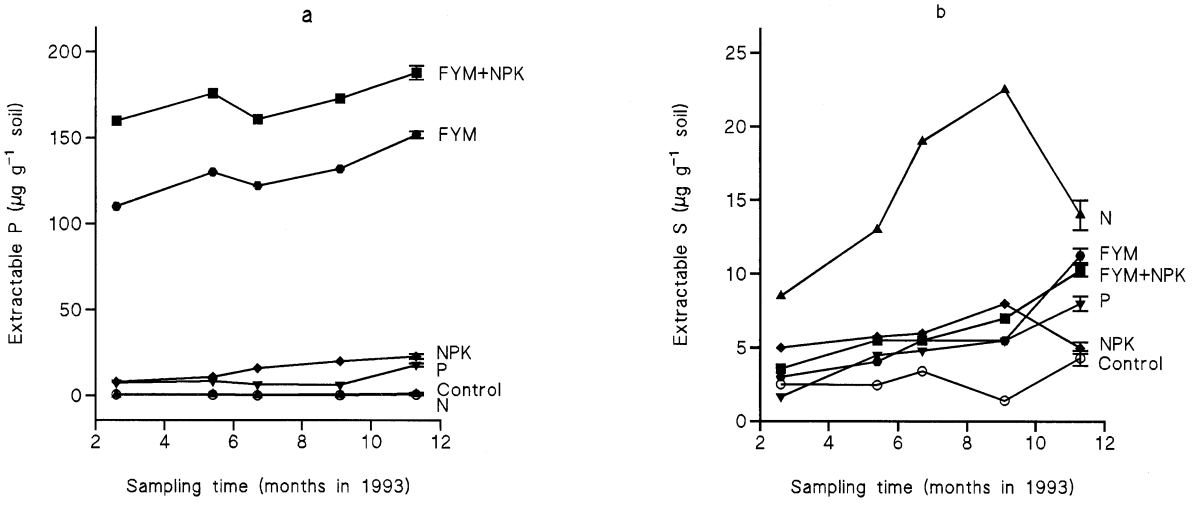

Fig. 3 a, b Changes in available P (**a**) and S (**b**) in the selected plots at the Palace Leas Meadow Hay experiment. *Error bars* are as in Fig. 1

the earlier phase of the trial period (March–July) were insignificant, except for an increase in the plot receiving FYM+NPK and a decrease in the control plot (Fig. 1 c). Unlike the significant effect on biomass C and P, moisture deficit during the dry season had little measurable effect on biomass S. Throughout the latter phase of the trial, biomass S increased consistently in all plots (Fig. 1 c). This might be due to increases in both the size of the soil microbial biomass and the availability of S over this period (September–December; Figs. 1 a, 3 b). As with biomass C, it is likely that biomass S in all plots would decline in spring, due to the turnover of the biomass, coupled with leaching losses of S during a wet winter. The pattern of seasonal changes in biomass S seen here compared well with those obtained for New Zealand pasture by Ghani et al. (1990).

The data reported here show clearly that the responses of microbial biomass C, P and S to seasonal changes are complicated and influenced not only by the growth of the microorganisms but by the different chemical characteristics of C, P, and S. This is seen in the different seasonal responses in biomass C, P, and S under pasture, which make it inadvisable to use measurements of biomass C to predict (possibly through modelling) the effects of microbial biomass turnover on the plant availability of P and S.

From the data presented in Fig. 1, it can be seen that changes in biomass C, P, and S showed little relationship to temperature over the observed range (daily average of 3–15 °C; Fig. 2 b). This is in agreement with previous studies (Wardle and Parkinson 1990; Joergensen et al. 1994). McGill et al. (1986) have suggested that temperature affects only the activity, and not the size, of the soil microbial biomass.

The amounts of biomass C and P, averaged over the trial period, differed significantly with fertilizer regime (Table 2); this is consistent with previous studies (Lynch and Panting 1982; Anderson and Domsch 1989). The largest increases in biomass C and P were seen in plots treat-

Table 2 Annual average amounts of biomass C, P, and S, and available P and S contents in surface soil (0–15 cm) in the selected plots of the Palace Leas Meadow Hay experiment[a]

Plot No.[b]	Biomass C		Biomass P		Available P		Biomass S		Available S	
	μg g^{-1} soil	kg ha^{-1}	μg g^{-1} soil	kg ha^{-1}	μg g^{-1} soil	kg ha^{-1}	μg g^{-1} soil	kg ha^{-1}	μg g^{-1} soil	kg ha^{-1}
1	2104	3160	178	267	172	257	18	27	6.3	9.5
2	2283	3420	193	290	129	193	27	41	5.7	8.6
6	1826	2740	37	56	0.4	0.7	19	29	2.8	4.2
7	1504	2250	11	17	0.7	1.0	17	26	15.5	23.2
8	2070	3100	154	231	10.6	16	24	36	5.1	7.7
13	1877	2710	88	132	15.5	23	25	37	6.9	10.3
$LSD_{P=0.05}$	144	216	23	34	6.3	9.5	7.0	10.5	1.5	2.3

[a] Values are the mean of the five sampling times
[b] For treatments see Table 1

ed with FYM and FYM+NPK. This is not too surprising, given that farmyard manure not only provides the necessary energy and nutrients to support an increase in microbial biomass, but also improves soil aeration and water retention. However, there were marked differences between the responses of biomass C and P to farmyard manures (Table 2). Compared with the values measured in the control plot and that treated with NPK, the amounts of biomass P in plots receiving FYM and FYM+NPK increased by 200–520%. This is in contrast to much smaller increases (12–25%) in biomass C in these plots. In addition to the large increases in biomass P (200–520%), using farmyard manure is particularly effective at increasing both total P and available P in these soils (Tables 1, 2).

The effects of mineral fertilizers on biomass C and P were dependent upon the fertilizer composition. In the plot receiving only P fertilizer, the amounts of biomass C and P accounted for 90–98% and 80–87%, respectively, of the microbial biomass C and P measured in the plots receiving FYM and FYM+NPK. In contrast, the amount of available P in those plots receiving mineral P fertilizer accounted for only a small proportion (6–8%) of the available P in the manured plots. In the plot treated with ammonium sulphate (N) only, the amounts of both biomass C and P decreased significantly. This was most likely due to the effect of strong acidity (pH 3.7) in this soil, due to the continuous use of ammonium sulphate without liming.

The data presented in Table 2 show no consistent trend in the effects of fertilizers on biomass S. The measurement of biomass S was less reproducible (greater standard deviation) than the measurement of biomass C and P, making differences between treatments less significant. It is interesting, however, that the lowest value of biomass-S (17 μg g^{-1} soil) was found in the plot receiving ammonium sulphate fertilizers (plot 7). This suggests that the amount of S immobilized by the microbial biomass is more dependent on the size of the biomass and soil conditions such as pH than on the S supply since here biomass C and pH were lowest whilst available S was highest (Table 2).

Ratios of C, P, and S in soil microbial biomass

The ratio of C:P, C:S, and P:S in the soil microbial biomass can be used to indicate the likely impact of the microbial biomass on the availability of P and S in soil. With narrow C:P and C:S ratios, the biomass in enriched in P and S and in turn has a high potential to release these nutrients by mineralization or turnover. Where the C:P and C:S ratios are wide, the tendency is for the biomass to immobilize more available P and S from soil. Previous studies have proposed that C:P ratio of the soil microbial biomass is generally in the range 10–35:1, whereas the C:S ratio is between 50 and 100:1 (Brookes et al. 1985; Chapman 1987; Sarathchandra et al. 1984; Srivastava 1992; Wu et al. 1994). Under the pasture investigated in this study, these ratios varied from 9 to 276:1 and 50 to 200:1, respectively, according to the sampling time and management regime (Table 3).

Seasonal variability in the C:P, C:S, and P:S ratios of the biomass reflected the seasonal responses seen in biomass C, P, and S (Fig. 1, Table 3). Between March and June, the C:P ratios of the biomass in all plots decreased, although the extent of these decreases was small in plots treated with FYM, FYM+NPK, and P. These results suggest that over this period, P is immobilized due to an increase in microbial activity during the warmer spring (Fig. 1b). As shown by the data for July, the C:P ratio of the biomass in the control and those plots treated with FYM, FYM+NPK, and N increased during the dry season (July–September). The ratio then declined in October. In contrast, in plots receiving P and NPK, the ratio changed little throughout the dry season, due to the decrease in soil water content, which affected not only the availability of P but also the size of the microbial biomass (Fig. 1a, b). Over the remaining period, the C:P ratios of the biomass increased consistently in all plots (Table 3). These data show clearly that the P content of the microbial biomass varied significantly throughout the growing season.

Throughout the trial period, the C:S ratio of the microbial biomass decreased in all plots except that treated with N (Table 3). Similar tends were also found in the P:S ratio of the biomass. This supports our previous hypothesis that

Table 3 C:P, C:S, and P:S ratios of soil microbial biomass in the selected plots of the Palace Leas Meadow Hay experiment

Plot No.[a]	C:P ratios					C:S ratios					P:S ratios				
	March	June	July	Oct.	Dec.	March	June	July	Oct.	Dec.	March	June	July	Oct.	Dec.
1	11:1	9:1	13:1	10:1	17:1	147:1	135:1	122:1	97:1	99:1	14:1	15:1	9:1	10:1	6:1
2	11:1	9:1	13:1	11:1	16:1	149:1	114:1	82:1	64:1	68:1	14:1	13:1	6:1	6:1	4:1
6	48:1	43:1	76:1	37:1	55:1	125:1	200:1	114:1	63:1	69:1	2.6:1	5:1	1.5:1	1.7:1	1.2:1
7	276:1	79:1	263:1	100:1	128:1	96:1	88:1	112:1	50:1	95:1	0.3:1	1.1:1	0.4:1	0.5:1	0.7:1
8	16:1	12:1	12:1	11:1	16:1	127:1	111:1	78:1	59:1	89:1	8:1	9:1	6:1	5:1	5:1
13	25:1	18:1	17:1	16:1	30:1	90:1	94:1	65:1	54:1	80:1	4:1	5:1	4:1	4:1	2.6:1

[a] For treatments see Table 1

Table 4 Dry weights, amounts and contents of P and S of herbage harvested from the selected plots of the Palace Leas Meadow Hay experiment

Plot No.[a]	Yields (dry matter) (t ha^{-1})	P in the herbage		S in the herbage	
		(%)	(kg ha^{-1})	(%)	(kg ha^{-1})
1	3.61	0.31	9.6	0.19	6.0
2	4.06	0.31	10.9	0.22	7.8
6	1.13	0.21	2.1	0.18	1.8
7	1.30	0.22	2.4	0.25	2.8
8	2.54	0.33	7.2	0.22	4.8
13	2.17	0.31	5.9	0.22	4.1

[a] For treatments see Table 1

the ability of the soil microbial biomass to supply P and S differs. The decrease in the C:S and P:S ratios indicated the high S status of the microbial biomass over the trial period. However, it is likely that with the turnover of the biomass the following spring this S would be released.

Different fertilizer regimes have resulted in marked differences in the C:P, C:S and P:S ratios of the microbial biomass (Table 3). In the plot treated with NPK, the C:P and C:S ratios of the biomass (16–30:1 and 54–90:1) fell in the middle of the ranges reported previously (10–35:1 and 50–100:1). In the plots receiving FYM, FYM+NPK, and P, the C:P ratio of the biomass (9–17:1) was lower, indicating that the microbial biomass in these plots was significantly enriched in P. Between March and June, the C:S ratios of the biomass in the plots receiving FYM, FYM+NPK, and P were relatively wide (>100:1). This suggests that, at this time, S availability in the soil was relatively low, although it was unlikely that the soil would become S deficient. In the control plot and that treated with N, the microbial biomass had a wide C:P ratio (37–76:1 and 79–276:1, respectively) but a narrow P:S ratio (1.2–5:1 and 0.3–1.1:1, respectively). These data indicate that the P status of the microbial biomass was extremely poor, which, together with the very low available P (<1 μg g^{-1}, Table 2), is likely to have resulted in P deficiency in these soils.

Soil microbial biomass as a reservoir of available nutrients

In the soils investigated here, soil microbial biomass C, shown as the mean of five sampling times, ranged between 1500 and 2280 μg g^{-1} (Table 2). Assuming it contained 47% C (Jenkinson and Ladd 1981), this is equivalent to 4.8–7.3 t ha^{-1} total dry biota assuming a soil bulk density of 1 g cm^{-3}. The amounts of P and S held in the biomass were substantial, with an average of 11–193 μg P and 17–27 μg S g^{-1} soil. This is equivalent to 17–290 kg P and 26–41 kg S ha^{-1} in the 0- to 15-cm layer. These values are considerably greater than those found for available P and S except in those plots receiving FYM and FYM+NPK, where there was a marked accumulation of P, and in the plot receiving ammonium sulphate, where the availability of S increased. Jenkinson and Parry (1989) proposed that in the United Kingdom the turnover time of soil microbial biomass was about 1.5 years: equivalent to an annual turnover rate of 0.67. Based on this rate, P and S cycled through the microbial pool are estimated for these plots to be 11–190 kg P and 17–27 kg S ha^{-1} per annum. These values were several times greater than the amounts of P and S recovered in the harvested herbage (2–11 kg P and 1.8–6 kg S ha^{-1}, Table 4). Thus, the data show that the soil microbial biomass represents a substantial reserve of P and S in pasture. This is in agreement with the hypotheses proposed by Perrott and Sarathchandra (1989) and Srivastava and Singh (1991).

The result of this work indicated that the role of the microbial biomass in controlling the availability of P and S was different between plots. From the data presented in Tables 1, 2, and 4, it is seen that in plots receiving FYM, FYM+NPK, P and NPK, the availability of P was more than sufficient for plant demand, with the microbial biomass serving as a reservoir preventing P from being fixed in soil or incorporated into the soil organic matter. It is expected that the microbial biomass has an important role in improving the efficiency of P fertilizer applied to the plots receiving P and NPK where available P (11–25.5 μg g^{-1} soil) accounted for only a small proportion (6–18%) of that held in the microbial biomass. In the control plot and that receiving N, the availability of P was extremely low (<1 μg g^{-1} soil) and was possibly insufficient for plant demand (2.1–2.4 kg P ha^{-1} in harvested herbage, excluding P in the roots and remaining tops; Table 4). However, the amounts of available P were shown to increase slightly

over the trial period (Fig. 3 a). These measurements demonstrate that in those plots P supply to the pasture was primarily dependent upon the turnover of biomass P and the microbially mediated mineralization of organic P.

Herbage yield was positively correlated with the levels of biomass C and P present in soil (Tables 2, 4). This is in agreement with Insam et al. (1991), who showed a good correlation between crop yield and the amount of soil biomass C. Low herbage yields in the control plot and that treated with N appeared together with low P contents (0.2%) and were likely the result of limited P availability. The amount of P in the herbage was more closely related to biomass P (averaged over the sampling period) than to available P present in the soil ($r = 0.91$ and 0.70, respectively, $d = 5$). However, the most significant correlation was found between the amount of P in the herbage and the sum of biomass P and available P ($r = 0.99$). Due to small variations in S content, the amounts of S in the herbage were determined largely by the yields (Table 4). Thus, any correlation between the content and amount of S in the herbage and biomass S and available S was not apparent.

In conclusion, soil microbial biomass C, P, and S varied throughout the year according to different patterns. As expected, biomass C was closely related to the inputs of fresh organic materials, such as plant residues, whilst biomass P appeared to be more sensitive to soil moisture deficit. Fertilization had a marked effect on biomass P and S, with the microbial biomass serving as both a reservoir and a major driving force in regulating the plant availability of P and S. The contents of P and S in the pasture were closely related to the C:P and C:S ratios of the soil microbial biomass. These ratios should provide useful information with which to assess the levels of C, P, and S in the microbial biomass and their potential impacts on nutrient availability to plants.

Acknowledgements The Chinese Committee of Education, the British Council, and the C Alma Baker Trust, Huntingdon, UK, provided financial support for Dr. He, and the Biotechnology and Biological Sciences Research Council provided financial support for Dr. Wu.

References

Anderson TH, Domsch KH (1989) Ratios of microbial biomass to total organic carbon in arable soils. Soil Biol Biochem 21:471–479

Biederbeck VO, Campbell CA, Zentner RP (1984) Effect of crop rotation and fertilization on some biological properties of a loam in southwestern Saskatchewan. Can J Soil Sci 64:355–367

Bristow AW, Jarvis SC (1991) Effects of grazing and nitrogen fertilizers on the soil microbial biomass under permanent pasture. J Sci Food Agric 54:9–21

Brookes PC, Powlson DS (1981) Preventing phosphorus losses during perchloric acid digestion of sodium bicarbonate soil extracts. J Sci Food Agric 32:671–674

Brookes PC, Powlson DS, Jenkinson DS (1985) Phosphorus in the soil microbial biomass. Soil Biol Biochem 16:169–175

Chapman SJ (1987) Microbial sulphur in some Scottish soils. Soil Biol Biochem 19:301–305

Franzluebbers AJ, Hons FN, Zuberer (1994) Seasonal changes in soil microbial biomass and mineralizable C and N in wheat management systems. Soil Biol Biochem 26:1469–1475

Ghani A, McLaren RG, Swift RS (1990) Seasonal fluctuation of sulphate and soil microbial biomass-S in the surface of a Wakanui soil. N Z J Agric Res 33:467–472

Hedley MJ, Stewart JWB (1982) Method to measure microbial biomass phosphorus in soils. Soil Biol Biochem 14:377–385

Insam H, Mitchell CC, Dormaar JF (1991) Relationship of soil microbial biomass and activity with fertilization practice and crop yield of three Ultisols. Soil Biol Biochem 23:459–46

Jenkinson DS (1988) The determination of microbial biomass carbon and nitrogen in soil. In: Wilson JR (ed) Advances in nitrogen cycling in agricultural ecosystem. CAB International, Wallingford, pp 368–386

Jenkinson DS, Ladd JN (1981) Microbial biomass in soil: measurement and turnover. Soil Biochem 5:415–471

Jenkinson DS, Parry LN (1989) The nitrogen cycle in the Broadbalk wheat experiment, a model for the turnover of nitrogen through the soil microbial biomass. Soil Biol Biochem 21:535–541

Jenkinson DS, Powlson DS (1976) The effect of biocidal treatments on metabolism in soil: V. A method for measuring biomass. Soil Biol Biochem 8:209–213

Joergensen RG, Meyer B, Mueller T (1994) Time-course of the soil microbial biomass under wheat: A one year field study. Soil Biol Biochem 26:987–994

Kaiser EA, Heinemeyer O (1993) Seasonal variations of soil microbial biomass carbon within the plough layer. Soil Biol Biochem 24:1649–1655

Lynch JM, Panting LM (1982) Effects of season, cultivation and nitrogen fertilizer on the size of the soil microbial biomass. J Sci Food Agric 33:249–252

Ministry of Agriculture Fisheries and Food (1986) The analysis of agricultural materials, 3rd edn. MAFF/ADAS RB 427. MAFF, London

McGill WB, Cannon KR, Robertson JA, Cook FD (1986) Dynamics of soil microbial biomass and water-soluble organic C in Breton L after 50 years of cropping to two rotations. Can J Soil Sci 66:1–19

Patra DD, Brookes PC, Coleman K, Jenkinson DS (1990) Seasonal changes of soil microbial biomass in an arable and a grassland soil which have been under uniform management for many years. Soil Biol Biochem 22:739–742

Pawson HC (1960) Cockle Park Farm. Oxford University Press, London

Payton RW, Palmer RC (1990) Soils of the Alnwick and Rothbury District. Mem Soil Survey, Silsoe, UK

Perrott KW, Sarathchandra SU (1989) Phosphorus in the microbial biomass of New Zealand soils under established pasture. N Z J Agric Res 32:409–413

Perrott KW, Sarathchandra SU, Waller JE (1990) Seasonal storage and release of phosphorus and potassium by organic matter and the microbial biomass in a high-producing pastoral soil. Aust J Soil Res 28:593–608

Perrott KW, Sarathchandra SU, Dow BW (1992) Seasonal and fertilizer effects on the organic cycle and microbial biomass in a hill country soil under pasture. Aust J Soil Res 30:383–394

Ross DJ, Speir TW, Kettles HA, Mackay AD (1995) Soil microbial biomass, C and N mineralization and enzyme activities in a hill pasture: influence of season and slow-release P and S fertilizer. Soil Biol Biochem 27:1431–1443

Sarathchandra SU, Perrott KW, Upsell MP (1984) Microbiological and biochemical characteristics of a range of New Zealand soils under established pasture. Soil Biol Biochem 16:177–183

Sorn-Srivichai P, Syers JK, Tillman RW, Cornforth IS (1988) An evaluation of water extraction as soil-testing procedure for phosphorus II. Factors affecting the amounts of water-extractable phosphorus in field soils. Fert Res 15:225–236

Sparling GP, Milne JDG, Vincent KW (1987) Effect of soil moisture regime on the microbial contribution to Olsen phosphorus values. N Z J Agric Res 30:79–84

Srivastava SC (1992) Microbial C, N and P in dry tropical soils: Seasonal changes and influence of soil moisture. Soil Biol Biochem 24:711–714

Srivastava SC, Singh JS (1991) Microbial C, N and P in dry tropical soils: effects of alternate land-use and nutrient flux. Soil Biol Biochem 23:117–124

Wardle DA, Parkinson D (1990) Interactions between microclimatic variables and the soil microbial biomass. Biol Fertil Soils 9:273–280

Wu J, Joergensen RG, Pommerning B, Chaussod R, Brookes PC (1990) Measurement of soil microbial biomass by fumigation-extraction – an automated procedure. Soil Biol Biochem 22:1167–1169

Wu J, O'Donnell AG, He ZL, Syers JK (1994) Fumigation-extraction method for the measurement of soil microbial biomass-S. Soil Biol Biochem 26:117–125

Wu J, He ZL, O'Donnell AG, Syers JK (in press) Measurement of microbial biomass phosphorus in acid soils. Soil Sci Soc Am J

Zhao F, McGrath SP, Crossland AR (1994) Comparison of three wet digestion methods for the determination of plant sulphur by ICP-AES. Comm Soil Sci Plant Anal 25:407–418