Crop Rotation and Residue Management Effects on Soil Carbon and Microbial Dynamics

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ABSTRACT

Understanding microbial dynamics is important in the development of new management strategies to reverse declining organic-matter content and fertility of agricultural soils. To determine the effects of crop rotation, crop residue management, and N fertilization, we measured changes in microbial biomass C and N and populations of several soil microbial groups in long-term (58-yr) plots under different winter wheat (*Triticum aestivum* L.) crop rotations. Wheat–fallow treatments included: wheat straw incorporated (5 Mg ha^{-1}), no N fertilization; wheat straw incorporated, 90 kg N ha^{-1}; wheat straw fall burned, no N fertilization; and wheat straw incorporated, 11 Mg barnyard manure ha^{-1}. Annual-crop treatments were: continuous wheat, straw incorporated, 90 kg N ha^{-1}; wheat–pea (*Pisum sativum* L.) rotation (25 yr), wheat and pea straw incorporated, 90 kg N ha^{-1} applied to wheat; and continuous grass pasture. Total soil and microbial biomass C and N contents were significantly greater in annual-crop than wheat–fallow rotations, except when manure was applied. Microbial biomass C in annual-crop and wheat–fallow rotations averaged 50 and 25%, respectively, of that in grass pasture. Residue management significantly influenced the level of microbial biomass C; for example, burning residues reduced microbial biomass to 57% of that in plots receiving barnyard manure. Microbial C represented 4.3, 2.8, and 2.2% and microbial N 5.3, 4.9, and 3.3% of total soil C and N under grass pasture, annual cropping, and wheat–fallow, respectively. Both microbial counts and microbial biomass were higher in early spring than other seasons. Annual cropping significantly reduced declines in soil organic matter and soil microbial biomass.

INCREASING PUBLIC CONCERN about environmental quality and the long-term productivity of agroecosystems has emphasized the need to develop and implement management strategies that maintain and protect soil and water resources. Both issues are related to maintaining the quantity of soil organic matter, which are strongly influenced by management (Janzen, 1987). Practices such as cultivation, crop rotation, residue management, and fertilization regulate soil microbial biomass, which mediates processes of residue decomposition, nutrient cycling, and organic-matter turnover (Biederbeck et al., 1984; McGill et al., 1986; Doran and Smith, 1987). Because microbial biomass and microbial activity are closely related to soil organic-matter content, they are positively influenced by organic amendments such as crop residues and animal manures. Soil microbial biomass C typically ranges from 100 to 600 mg kg^{-1} soil under cereals and can exceed 1500 mg kg^{-1} under native grassland or grass pasture (Adams and Laughlin, 1981; Ross et al., 1980; Schnürer et al., 1985; Anderson and Domsch, 1989).

Long-term field plots (1931–present) at the Columbia Basin Agricultural Research Center, Pendleton, OR, provide a unique resource to investigate long-term influences of crop rotation and crop residue management on soil productivity in the Pacific Northwest. These plots exhibit significant treatment-related differences in soil physical (Pikul and Allmaras, 1986), chemical (Douglas et al., 1984; Rasmussen and Rohde, 1989), and biological properties (Dick et al., 1988). Our objectives were to identify changes in microbial biomass C and N, specific microorganism populations, and soil C mineralization resulting from the different crop-management treatments.

MATERIALS AND METHODS

The plots established in 1931 are located in a semiarid climate typified by cool wet winters and hot dry summers. Annual precipitation averages 416 mm with 66% occurring from November through April. Long-term treatments include both WF and annual crop rotations on Walla Walla silt loam (coarse-silty, mixed mesic Typic Haploxeroll). The WF treatments, which were duplicated so that both cropped and fallow phases were represented every year,

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Abbreviations: WF, wheat–fallow; S − N, wheat straw incorporated with no added N; S + N, wheat straw incorporated + 90 kg N ha^{-1} as NH_4NO_3; FB, fall burning of wheat stuble with no added N; WW, continuous wheat with straw incorporated + 90 kg N ha^{-1} as NH_4NO_3 applied annually; WP, wheat-pea rotation with both straws incorporated + 90 kg N ha^{-1} as NH_4NO_3 applied to wheat; GP, grass pasture; MPN, most probable number.

included: wheat straw incorporated with no added N (abbreviated S − N; average 5 Mg [dry wt.] straw ha^{-1} applied biannually); wheat straw incorporated + 90 kg N ha^{-1} as NH_4NO_3 (abbreviated S + N; N applied biannually prior to seeding); wheat straw incorporated + barnyard manure (abbreviated S + M; average 11 Mg [dry wt.] manure ha^{-1} applied each fallow year); and fall burning of wheat stubble with no added N (abbreviated FB). The S + N treatment received 34 kg N ha^{-1} prior to 1967. Annual-crop rotations included: continuous wheat with straw incorporated + 90 kg N ha^{-1} as NH_4NO_3 applied annually (abbreviated WW; established 1931, no fertilizer applied prior to 1944); wheat–pea rotation with both straws incorporated + 90 kg N ha^{-1} as NH_4NO_3 applied to wheat (abbreviated WP; established 1963); and grass pasture (abbreviated GP; established 1931, grazed by cattle, fertilized with N occasionally, replanted with improved varieties to rejuvenate stand, and irrigated if necessary). The dominant grass species during this study was tall fescue (*Festuca arundinacea* Schreber), with lesser amounts of bulbus bluegrass (*Poa bulbosa* L.), green foxtail [*Seteria viridis* (L.) P. Beauv.], and yellow foxtail [*S. pumila* (Poiret) Roemer & Schultes].

Soil samples were collected 18 Sept. and 30 Nov. 1987, and 22 Feb. and 16 May 1988, from 0- to 10- and 10- to 20-cm depths with a 5-cm^2 soil coring tool. Both phases of the wheat–fallow and wheat of the wheat–pea rotations were sampled. Within each of four field replicates, three soil cores from each depth were combined. For cropped treatments, one core was collected within the planted row and combined with two from the interrow area. No September samples were taken for annual-crop treatments. All samples were sieved (2 mm) and stored no longer than 3 d at 4 °C before performing biological analyses.

Quadruplicate subsamples from each depth of each treatment were analyzed for total C with a Leco WR12 C analyzer [1], (Leco Corp., St. Joseph, MI) and for total N by Kjeldahl block digestion. Cold-water-soluble C was determined after shaking 5-g of air-dry soil in 25 mL of distilled water for 30 min. Extracts were centrifuged for 10 min at 13 340 *g*, passed through a washed Whatman no. 42 filter, and C measured by automated colorimetric analysis (Technicon Industrial Systems, 1976). Soil pH was determined on triplicate 10-g soil samples using a 1:2 soil/water ratio. Mineralizable soil C was determined by incubating 25 g of soil (November sampling) at 25 °C for 30 d, trapping evolved CO_2 in 1 *M* NaOH, and titrating with HCl (Anderson, 1982).

Microbial biomass C and N were estimated by the chloroform fumigation–incubation method of Jenkinson and Powlson (1976). Fumigated and nonfumigated samples (25 g dry wt.) were brought to a water potential of −0.033 MPa and incubated at 22 °C for 10 d. Microbial biomass C was calculated by dividing the CO_2 flush from the fumigated sample by $k_c = 0.41$ (Anderson and Domsch, 1978) where k_c is the proportion of microbial C released by fumigation that decomposes to CO_2 during incubation. Microbial biomass N was estimated as the difference in NH_4–N released by the fumigated and control samples using $k_N = 0.4$ (Carter and Rennie, 1982) where k_N is the proportion of microbial N released on fumigation that is mineralized during incubation. The amount of NH_4–N released from fumigated and control soil samples was determined by extraction with 2 *M* KCl followed by automated colorimetric analysis (Technicon Industrial Systems, 1976).

Total numbers of culturable bacteria, fungi, and actinomycetes were determined by serial dilution and plating on selective media. Aerobic bacteria were counted on tryptic soy agar, fungi on potato dextrose agar amended with 0.1 mg mL^{-1} streptomycin sulfate, *Pseudomonas* spp. on modified King's B medium (Sands and Rovira, 1970), and actinomycetes on Porter's medium (Porter et al., 1960) after plates were incubated for 3 to 5 d at 22 °C. The MPN technique of Schmidt and Belser (1982) was modified using 96-well tissue culture plates to measure *Nitrosomonas* and *Nitrobacter* spp.

Analysis of variance was used to determine significant differences between the physical and biological parameters of each treatment. Data were analyzed using a randomized block split-plot design with four replicates.

Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the USDA.

Table 1. Organic-C amendments and chemical properties of the surface 20 cm of soil from long-term experimental treatments sampled in September 1987.

Treatment†	Added organic C‡	Total soil C	Total soil N	C/N	pH
	kg ha^{-1} yr^{-1}	g kg^{-1}			
Wheat–fallow					
SM	2410	15.2b	1.05c	14.5	6.7b
S + N	1590	11.2c	0.85d	13.0	5.6e
S − N	1110	12.0c	0.80d	15.0	6.1c
FB	380¶	10.5d	0.72e	14.3	6.1c
Annual crop					
WP	2290	15.5b	1.21b	12.8	5.8d
WW	2250	15.0b	1.27b	11.8	5.4f
GP	ND#	22.2a	2.00a	11.1	7.4a

† SM = straw incorporated + barnyard manure; S + N = straw incorporated, 90 kg N ha^{-1}; S − N = straw incorporated, 0 kg N ha^{-1}; FB = fall burn, 0 kg N ha^{-1}; WP = wheat–pea, WW = wheat–wheat, GP = grass pasture.
‡ Carbon content averaged 400 and 661 g C kg^{-1} wheat residue and manure, respectively.
§ Values in each column followed by the same letter are not significantly different at $P = 0.05$ by Duncan's multiple-range test.
¶ Assumes 67% of residue removed by burning.
# ND = Not determined.

RESULTS AND DISCUSSION

Soil chemical and biological properties of wheat–fallow, wheat–wheat, and wheat–pea rotations were

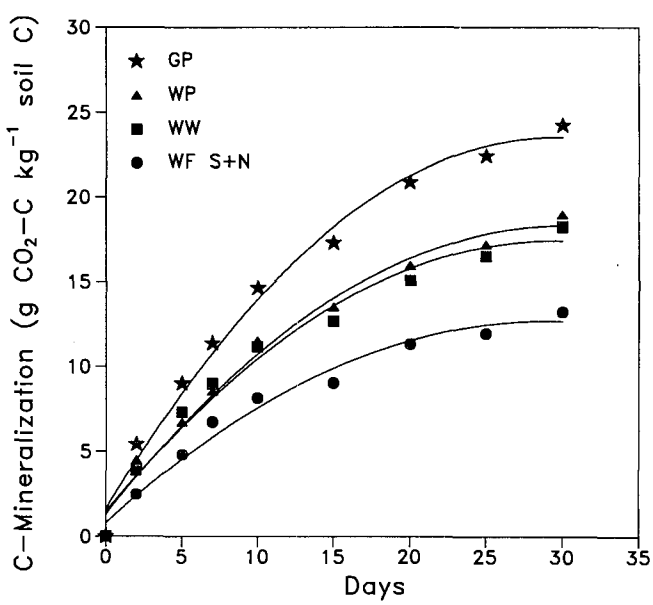

Fig. 1. Carbon mineralization of the 0- to 10-cm soil depth of the long-term grass pasture (GP), wheat–pea (WP), continuous wheat (WW), and wheat–fallow (WF, S + N) treatments.

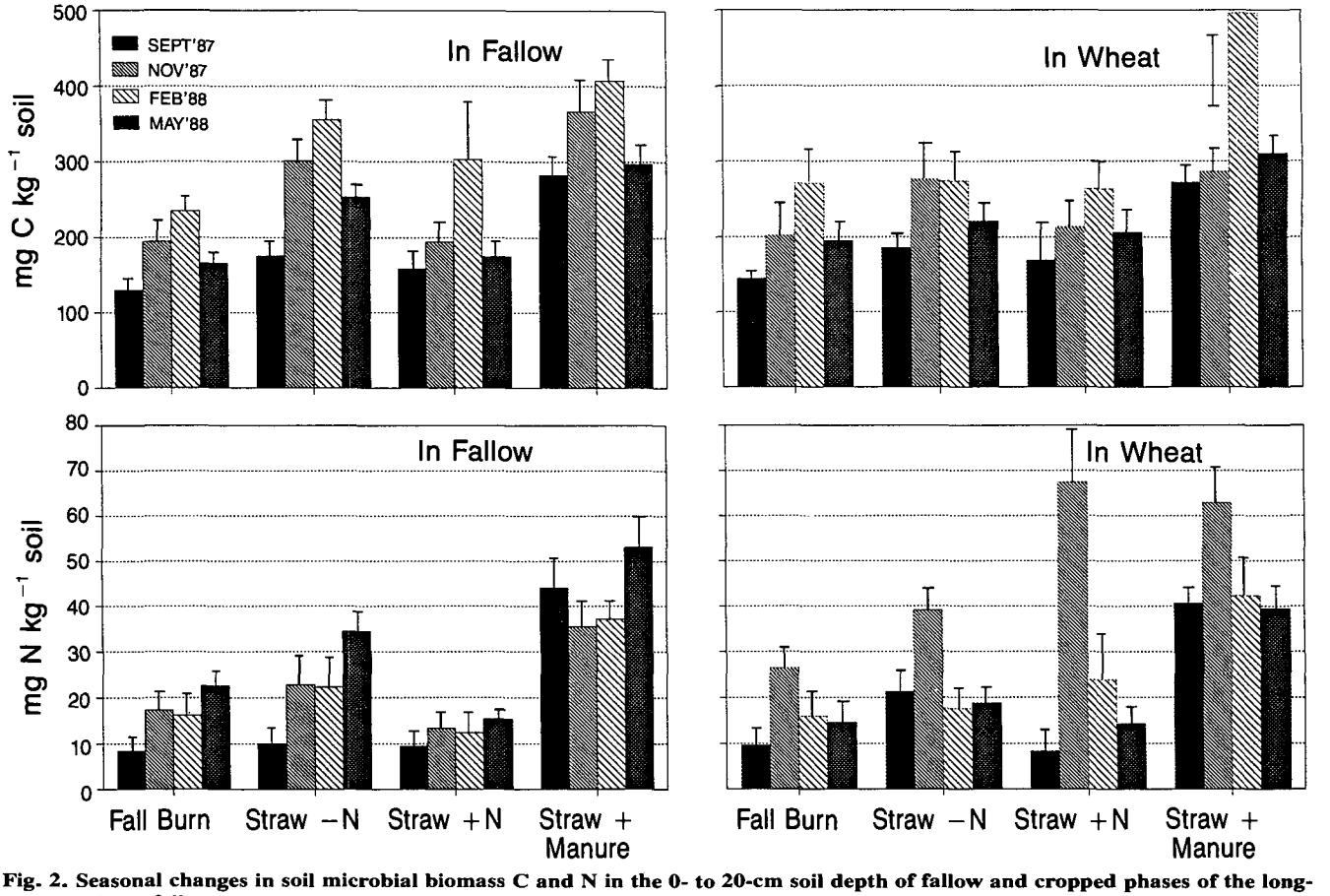

Fig. 2. Seasonal changes in soil microbial biomass C and N in the 0- to 20-cm soil depth of fallow and cropped phases of the long-term wheat–fallow treatments.

significantly altered by long-term management. Soil organic C and total N in the 0 to 20-cm depth were greater in annual-crop than wheat–fallow rotations, ranging from 10.5 and 0.72 g kg^{-1} in the fall-burned wheat–fallow, to 22.2 and 2.00 g kg^{-1} soil in the grass pasture, respectively (Table 1). Soil organic-C and total-N concentrations in the grass pasture are assumed to approximate C and N concentrations prior to cultivation (Rasmussen and Collins, 1991). Compared with 58 yr of grass pasture, cultivation reduced total soil C and N an average of 40 and 51%, respectively. Fallow in crop rotations accelerates the loss of soil organic C (Biederbeck et al., 1984), while annual cropping and animal-manure additions reduce C loss (Campbell, 1978). Compared with the wheat–fallow control plot (S − N), the additional organic C supplied by manure compensated for C loss due to fallow. The resulting organic-C level in the S + M plot was similar to that of the wheat–pea and wheat–wheat rotations, even though average annual C inputs were 11% higher. Annually cropped rotations (WW, WP) were not as intensively cultivated, suggesting they may require lower C inputs to maintain soil organic C.

Total soil N was similar between the S + N and S − N wheat–fallow treatments. Rasmussen et al. (1980) studied the N dynamics of these plots and found that the rate of decrease in soil N was similar among wheat–fallow treatments. They suggested that soil N change was dominated by the tillage practice and level of residue input, but not its N content. Because annually cropped plots received higher C and N additions and are less intensively cultivated than WF treatments, they maintain higher soil C and N.

Cultivation and N fertilization reduced soil pH from 7.4 in the grass pasture to a minimum of 5.4 in the continuous-wheat rotation. Long-term incorporation of animal manure slowed the reduction in pH, compared with the unfertilized control plot (S − N), whereas the use of NH_4 fertilizer accelerated the decrease in pH (S + N).

Figure 1 shows that the long-term crop rotation significantly influenced soil C-mineralization potential. Evolution of CO_2 during the initial 10 d of incubation averaged 8, 11, and 14 g CO_2–C kg^{-1} soil C for the wheat–fallow, annual crop (WW, WP), and grass pasture rotations, respectively. Soil CO_2 evolution rates in wheat–pea and wheat–wheat rotations were not significantly different at any incubation sampling date. Mineralizable C can provide an assessment of soil organic-matter changes induced by tillage or other management practices (Carter and Rennie, 1982: Campbell et al., 1989). Carbon lost as CO_2 during 30-d incubations total 1.3, 1.9, and 2.4% of the total C present in the wheat–fallow, annual-crop, and grass pasture soils, respectively. Although the soil samples were air dried prior to incubation, their CO_2 evolution rates should serve as an index of the amount of C respired by field soils following drying, rewetting, and subsequent disturbances due to cultivation. Typically, surface soils in the semiarid region of north-

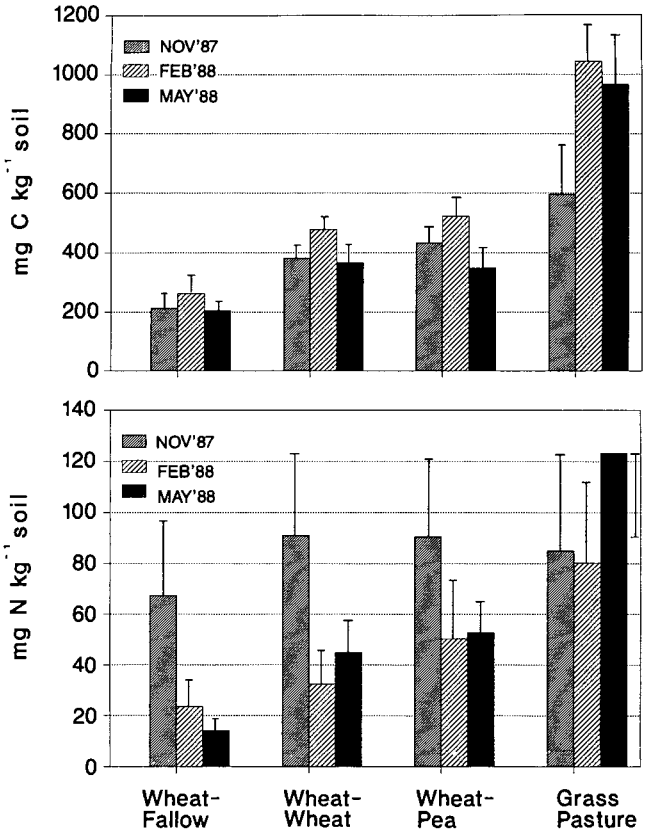

Fig. 3. Seasonal changes in soil microbial biomass C and N in the 0- to 20-cm soil depth of long-term wheat–fallow, continuous wheat, wheat–pea, and grass pasture rotations.

eastern Oregon dry to a water content of ≈40 to 50 g kg^{-1} soil during summer.

Lower C mineralization in the S + N treatment indicates a change in the quantity and possibly availability of organic C to the soil microflora. Soil organic C can be divided into active (labile) and resistant fractions (Van Veen and Paul, 1981). Generally, labile C consists of water-soluble C (simple sugars, organic acids, and proteins), the microbial biomass, and microbial products that are readily metabolized during the initial stages of incubation. Resistant fractions are composed of lignin-containing compounds or physically protected C. Carbon mineralized during the first 10 d of incubation was derived from the active components of soil organic matter and indicates variable accumulations of labile C resulting from different management practices and from the death of microbial biomass due to desiccation. Soluble-C concentrations prior to incubation were 75, 114, 135, and 231 mg C kg^{-1} soil for the S + N, WW, WP, and GP treatments, respectively. High concentrations of active C in the grass pasture account for rapid loss of soil C after tillage. Evolution of CO_2 for the 10- to 30-d period was similar to all cultivated treatments and averged 0.35 g CO_2–C kg^{-1} soil C d^{-1}, suggesting similar C availability to the active microbial biomass during this period. Results of this study agree with the findings of Schimel et al. (1985) and Janzen (1987) that crop rotations including fallow preferentially reduce the active fraction of soil organic matter because it is readily mineralized.

Crop-rotation and residue-management treatments also significantly influenced the size of microbial C and N pools (Fig. 2 and 3). Microbial biomass C varied seasonally among all rotations during the 1988 crop year, increasing from November to February, then decreasing by May to near November 1987 levels. Seasonal and rotational effects on biomass C in the cultivated treatments were combined for the 0- to 10- and 10- to 20-cm depth increments because there was no significant difference between depths. However, there was significantly more biomass C in the 0- to 10- than the 10- to 20-cm depth of the grass pasture on all sampling dates ($P < 0.05$; data not shown). Stubble burning reduced microbial biomass to 57% of that in the manured treatment, probably because the smaller amount of organic material returned to the soil (Table 1) limited the availability of mineralizable C to the microbial biomass. Our findings support those of Biederbeck et al. (1980), that soil organic-C loss increases and microbial biomass declines when residues are removed by burning.

Incorporation of barnyard manure produced higher microbial biomass than did the application of inorganic N fertilizer. Animal manure supplies additional mineralizable C and N that directly stimulates microbial activity and growth (McGill et al., 1986), but the effect of fertilizer N on microbial biomass was less straightforward. Generally, N fertilizer positively influences soil microbial biomass through increased crop production and greater return of organic C to the soil (Coote and Ramsey, 1983). Jenkinson and Powlson

Table 2. Microbial characteristics of soils at two depths under wheat–fallow and annual crop rotations and continuous grass pasture averaged across all sample dates.

	Wheat–fallow†		Annual crop		Grass pasture	
	0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm
Biomass C (mg C kg^{-1})	266 (8.6)‡	255 (7.4)	421 (19.4)	423 (16.9)	1158 (110.2)	581 (39.0)
Biomass N§ (mg N kg^{-1})	28 (2.0)	24 (1.3)	79 (19.4)	41 (8.7)	128 (9.2)	64 (8.4)
Biomass C/N	9.5	10.5	5.3	10.3	9.1	9.1
Biomass C (% of soil C)	2.2	2.1	2.8	2.8	5.2	3.3
Biomass N (% of soil N)	3.3	2.8	6.4	3.3	6.4	4.1

† Average of fallow and crop phases.
‡ Standard error of the mean in parentheses.
§ Microbial N calculated using $k_N = 0.4$ (Carter and Rennie, 1982); k_N is the proportion of microbial N released upon fumigation that is mineralized during incubation.

(1976) and Sparling et al. (1983) also reported that fertilized soils maintained a microbial biomass greater than unfertilized soils. The opposite, however, was observed in our study. The S + N treatment supported a microbial biomass similar to the FB and S − N plots. It is likely that increasing soil acidity (pH = 5.6) coupled with a continuing fallow-induced decline in soil organic C contributed to the low microbial biomass in the S + N treatment. There was no analogous pH effect on the microbial biomass in annual cropping systems, possibly because it was offset by higher organic-C inputs.

Microbial biomass N in soil cropped in wheat followed a seasonal pattern similar to biomass C, but reached a maximum concentration in November rather than February (Fig. 2). In fallow soil, the maximum amount of N found in the biomass occurred in May following moldboard plowing of wheat stubble in April. Although their seasonal dynamics were different, the plots in fallow and cropped phases of the WF rotation had similar biomass N contents when averaged across seasons, i.e., average biomass N concentrations of FB, S − N, S + N, and SM plots were 16, 22, 12 and 42 mg N kg^{-1} in fallow soil and 17, 24, 28, and 46 mg N kg^{-1} in cropped soil, respectively.

Biomass N was significantly higher in the 0- to 10- than the 10- to 20-cm depth of the grass pasture and N-fertilized plots planted in wheat (data not shown). Fertilizer N was broadcast in September 1987 and incorporated into the surface 10 cm of soil using a rod-weeder prior to planting. In November, microbial biomass in the 0- to 10-cm depth of fertilized plots contained nearly three times as much N as the 10- to 20-cm increment (average of S + N, WW, and WP plots was 128 vs. 42 mg N kg^{-1} soil for the 0- to 10- and 10- to 20-cm depths, respectively). This increase indicated a substantial uptake of fertilizer N by the soil microflora. Although annually cropped (WW, WP) plots were not sampled in September, we suspect a similar uptake of fertilizer N. Carter and Rennie (1984) also found significant uptake of fertilizer N by microbial biomass in the 0- to 5-cm depth under both conventional and no-till management.

Table 2 shows biomass C and N concentrations averaged across all sampling dates. Annual-crop and wheat–fallow rotations supported an active microbial biomass 50 and 70% lower, respectively, than the grass pasture. Microbial biomass C of the 0- to 10- and 10- to 20-cm depths within cultivated treatments were similar, whereas the grass pasture had significantly more biomass C in the surface layer. Inversion tillage and subsequent mixing by rod-weeding apparently distributes organic materials uniformly within the surface 20 cm, thus accounting for the uniformity of microbial C. Patra et al. (1990) reported similar results for a grassland soil and for soils plowed to a depth of 23 cm at the Rothamsted Experiment Station. Microbial C represented 4.3, 2.8, and 2.2%, and microbial N 5.3, 4.9 and 3.3%, of the total soil C and N present in the grass pasture, annual-crop (WW, WP), and wheat–fallow rotations, respectively. Comparable values have been reported for other arable soils under similar management systems (Biederbeck et al., 1984; Campbell et al., 1989). Anderson and Domsch (1989) found that microbial biomass C averaged 2.3 and 2.9% of soil organic C for monocultures and continuous-crop rotations, respectively, with differences resulting from the type and amount of organic-C input.

The mean microbial C/N ratio of wheat–fallow treatments for all sampling dates was 10, but individual treatments varied from 5 to 21, sometimes exceeding the C/N ratio of the bulk soil. Such high C/N ratios are unreasonable and indicate that the use of a single conversion factor (k_n) is inappropriate. Dalal and Mayer (1987) also reported that microbial C/N ratios sometimes approach those of bulk soil and suggested that these ratios represent a stabilized microbial biomass that remains following mineralization of labile biomass components during incubation. Plots amended with N fertilizer or manure maintained C/N ratios ranging from 5 to 8; these narrower ratios result from the additional input of N and may indicate a shift in microbial population dominance. Wheatley et al. (1990) and others have suggested that the decline in microbial C/N ratio can be accounted for by a shift from fungal to bacterial populations.

Seasonal dynamics of soil microbial populations mirrored the changes in microbial biomass C (Table 3). Although there were significant differences among individual treatments, the data have been grouped to simplify their presentation. Cumulative counts of total bacteria, *Pseudomonas*, and fungi increased an average of 54-fold from November 1987 to February 1988, then declined drastically in May, whereas soil actinomycete populations remained relatively stable for the same period. Cropped soils supported significantly higher microbial populations than fallow, indicating a strong rhizosphere effect promoted by the presence of

Table 3. Seasonal changes in soil microbial populations as influenced by long-term management treatments.

	Wheat–fallow rotation						Annual crop rotations					
	In fallow			In wheat			WP + WW†			Grass pasture		
Sample date:	Nov.	Feb.	May	Nov.	Feb.	May	Nov.	Feb.	May	Nov.	Feb.	May
	organisms g^{-1} dry soil											
Total bacteria (× 10^6)	1.2a‡	32.6b	0.9a	1.4a	75.6c	1.3a	2.6a	83.1c	1.8a	1.9a	70.8c	7.8b
Pseudomonas (× 10^4)	0.4a	0.9a	0.2a	1.4a	7.5b	1.8a	0.7a	4.3b	1.1a	3.9b	50.1c	4.2b
Fungi (× 10^4)	0.4a	8.5b	1.1[1]	0.4a	10.9b	1.1a	2.6a	21.5c	9.2b	0.2a	7.8b	0.6a
Actinomycetes (× 10^4)	0.7a	0.8a	0.9a	1.1a	0.7a	1.2a	2.0a	1.8a	2.1a	2.6a	1.8a	1.6a
Nitrosomonas (× 10^4)	ND§	4.6a	2.8a	ND	1.0a	7.2b	ND	30.0c	ND	ND	96.0d	ND
Nitrobacter (× 10^4)	ND	0.9a	0.9a	ND	2.5a	1.0a	ND	4.0a	0.5a	ND	14.0b	2.3a

† WP = Wheat–pea rotation; WW = wheat–wheat rotation.
‡ In-row means followed by different letters are significantly different at $P = 0.05$ by Duncans' multiple-range test.
§ ND = Not determined.

roots. As expected, *Pseudomonas* populations were greatest in the grass pasture, because of the characteristic dominance of this genus in the rhizosphere of fibrous root systems (Alexander, 1977). Although populations of *Nitrosomonas* and *Nitrobacter* were not determined on all sample dates, the data are consistent with the assumption of seasonal dynamics similar to other microbial groups.

Reductions in soil organic matter as a result of crop-rotation and residue-management treatments resulted in similar decreases in the size and activity of the soil microbial biomass. Microbial populations attained different levels of stability as a result of the quantity and quality of resources provided through cultural practices. Soil microbial biomass C and N, C-mineralizaiton potential, and microbial populations were significantly lower in WF rotations than in annual cropping. Soil organic C ranged from 22.2 in the GP to 10.5 g kg^{-1} in the FB treatment for a 58-yr period, averaging 202 mg C kg^{-1} yr^{-1}. At the end of this period, average microbial biomass in the FB treatment was 210 mg C kg^{-1} soil. Assuming 50% metabolic efficiency, turnover of the soil microbial biomass would be ≈2.1 yr, similar to that reported in the literature for wheat–fallow (Schnürer et al., 1985) and continuous wheat (Jenkinson et al., 1980).

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