EFFECT OF CEREAL ROTATIONS ON SOIL pH, ORGANIC MATTER AND MICROBIAL PROPERTIES OF A BROWN LOAM

V.O. BIEDERBECK, C.A. CAMPBELL, R.P. ZENTNER and D.W. McANDREW

Research Station,
Research Branch, Agriculture Canada,
Swift Current, Saskatchewan. S9H 3X2

INTRODUCTION

On the Canadian Prairies and on the Northern Great Plains of the U.S.A., frequent summerfallowing has led to large losses of organic matter (Campbell et al. 1976) and has seriously impaired the physical and biological properties of the soils (Campbell and Souster 1982). The result has been a call by scientists for an increase in the use of N and P fertilizers and for a reduction in the frequency of mechanical tillage, a lengthening of crop rotations, and for the inclusion of N_2-fixing green manure crops in rotations (Campbell and Biederbeck 1980; Rennie 1982).

Recently, Rennie (1983) stressed the need to determine whether fertilizer N additions could increase soil organic matter and/or the N supplying power in prairie soils.

An ongoing crop rotation study initiated in 1967 at Swift Current, Saskatchewan provided a unique opportunity to assess the effects of various rotation lengths, cropping sequences and fertilizer treatments on the physical, chemical, and biological properties of the soil over a 17-yr period.

MATERIALS AND METHODS

Details of the design and method of this experiment have been published elsewhere (Campbell et al. 1983a, 1983b; Campbell et al. 1984); consequently, only a brief review is presented here together with some additional information required for an understanding of the procedures and parameters discussed.

In 1967, twelve crop rotations (Table 1) were established on 81, 0.04-ha, plots located on Wood Mountain loam, a Brown Chernozem in a three-replicate experiment. The land had previously been cropped in a fallow-wheat rotation since 1922. Average bulk density, pH and texture for the soil are shown in Table 2.

Fertilizer N, as ammonium nitrate (34-0-0), was broadcast and incorporated prior to spring cultivation; fertilizer P, as mono-ammonium phosphate (11-48-0), was placed with the seed. The fertilizers were applied in accordance with treatment specifications (Table 1) and the general recommendations of the Saskatchewan Soil Testing Laboratory.

Table 1. Crop rotations and treatments

Rotation number	Rotation† Sequence	Fertilizer Application
1	(Fallow)-wheat-wheat	P applied, no N applied
2	Fallow-wheat-(wheat)	N and P applied
3	Fallow-flax-(wheat)	N and P applied
4	Fallow-(fall rye)-wheat	N and P applied
5	Fallow-wheat-wheat	N applied, no P applied
6	(Oat hay)-(wheat)-wheat	N and P applied; oats cut for hay at soft dough stage
7	Flax-wheat-wheat	N and P applied
8	(Continuous wheat)	N and P applied
9‡	Continuous wheat	(Fallow if less than 60 cm of moist soil exists at seeding time) N and P applied
10‡	Continuous wheat	(Fallow if grassy weeds become a problem) N and P applied
11	Fallow-(wheat)	N and P applied
12	(Continuous wheat)	P applied, no N applied

† Special plots are indicated by brackets. These plot treatments were sampled for nutrients, soil moisture and plant growth at eight regular intervals during the growing season.

‡ Rotations 9 and 10 were cropped continuously during the first 12 yr because the criteria necessary for fallowing did not occur; these rotations were then changed to fallow-lentils.

Table 2. Average bulk density, pH and texture for test plot soils

Soil depth (cm)	Bulk density* ($g.cc^{-1}$)	$S\bar{x}$†	pH (soil paste)†	Texture
0-15	1.22	0.03	6.75	L-SiL
15-30	1.30	0.02	6.90	L-SiL
30-60	1.40	0.03	7.47	SiL-CL
60-90	1.58	0.03	7.93	CL
90-120	1.76	0.03	8.12	CL

* Sx = Standard error of mean bulk density

† All pH values differed significantly ($P < 0.05$) with depth; sample taken in 1982 in early August

‡ Measured by soil core method

Assessment of Seasonal pH Changes

During 1983, soil pH was measured, in dilute $CaCl_2$, on soil samples taken from the 0-2.5-, 2.5-7.5- and 7.5-15-cm depths, at regular intervals during April to mid-October. Soil moisture and NO_3-N were also measured on these samples.

Soil Biological Properties

Soil from the 0- to 15-cm and 15- to 30-cm depths was sampled from all rotations after harvest in 1976 and 1981 and organic C and N determined by dry combustion and Kjeldahl methods, respectively. Samples taken at the start of the experiment were lost, consequently, the initial levels of organic N were estimated based on samples that had been taken in 1967 from a site within 50 m of the rotations; initial organic C estimates were not available.

All other biological properties were determined on soil taken from four selected rotations sampled on October 29, 1982. Three samples per replicate were taken (at random) from the 0- to 7.5-cm depth from plots that had been cropped in 1982. These samples were bulked to provide one sample per replicate. The soil was sieved (< 2 mm) and stored field moist at 0°C until used for the following analyses: potentially mineralizable N (Campbell et al. 1981), microbial respiration (Bartha and Pramer 1965), soil microbial biomass (Jenkinson and Powlson 1976), and numbers of aerobic heterotrophic bacteria and actinomycetes (Biederbeck and Campbell 1973) and yeasts. Yeasts were determined by inoculating serially diluted soil suspensions in quintuplate onto prepoured plates of rose bengal-streptomycin agar (RBSA) and, after 7 days at 20°C, counting only smooth colonies of distinctly nonfilamentous morphology. The k_C and k_N factors used to calculate biomass C and N were 0.41 (Anderson and Domsch 1978) and 0.40 (Carter and Rennie 1982), respectively.

In October, 1983, soils taken from seven selected rotation-years were analyzed for microbiological and biochemical characteristics. Preliminary results from some of these analyses are included in this paper.

RESULTS AND DISCUSSION

Physical Properties

As organic matter affects soil physical properties and the latter also influences microbial activities, it is relevant to consider some physical characteristics in the assessment of the effects of different rotations and fertilizer treatments on soil biological properties.

Bulk density measured 17 yr after initiation of this study showed no differences between treatments (data not shown), thus only the average bulk density for various soil depths are shown (Table 2).

With regard to seasonal pH changes, only the results for the two continuous wheat rotations (Rot. 8 and 12) are reported at this time (Fig. 1.). Each point on the graph is the mean of 3 replicates.

Since pH in the 0-2.5 cm depth was highly correlated with pH in the 2.5-7.5 cm (R^2=0.90) and to pH in the 7.5-15 cm depth (R^2=0.76) only data for the top 2.5 cm are shown.

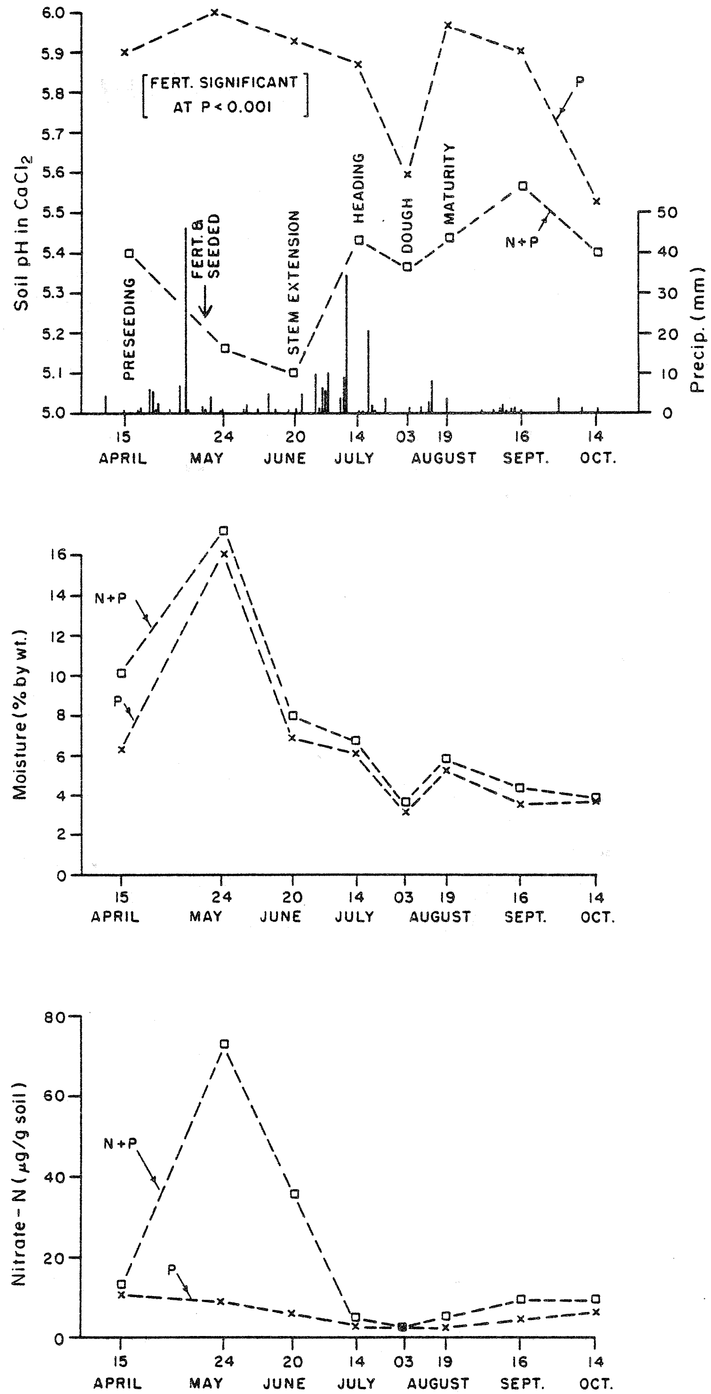

Fig. 1. Effect of growing season and fertilizer on soil pH (in $CaCl_2$) in continuous wheat rotations (1983)

Nitrogen fertilizer has been applied to Rot. 8 (N + P) at an average 35 kg N ha^{-1} yr^{-1} for the past 17 yr while Rot. 12 (P) has received very little N (about 5 kg N ha^{-1} yr^{-1}). It is apparent that the extra N applied to Rot. 8 has resulted in a decrease of about 0.5 pH units in the continuous wheat system. Although the effect of time was not significant in this comparison, it appears that pH changes in Rot. 8 (N + P) tended to be inversely related to NO_3-N (Fig. 1). For example, the increases in NO_3-N caused by fertilizer addition and net N mineralization during the period April 15-June 20 caused a drop in pH. In contrast, a sharp decrease in soil NO_3-N due to crop uptake between stem extension and heading increased soil pH sharply. The latter is due to the release of OH^- ions by plant roots when they take up NO_3^- ions (Franco and Munns 1982).

These results would seem to provide a warning that, although there are several desirable features which make continuous cropping a system to be recommended, we may in the long run, have to pay a price (e.g, by having to apply lime).

Soil Organic Matter

The original organic N level of the 0- to 15-cm depth in 1967 was about 0.18%. This level was similar to that observed in 1976 for the average fallow rotations, the oat (hay)-wheat-wheat rotation, and the continuous wheat rotation receiving only P fertilizer (Fig. 2). The N level in the continuous wheat rotation receiving N and P fertilizer annually had, by 1976, increased to 0.20% while N for flax-wheat-wheat and fallow-rye-wheat had also shown some increase (Fig. 2). By 1981 only the continuous type rotations receiving N and P fertilizer had significantly increased in organic N (Fig. 2, left); but there was a

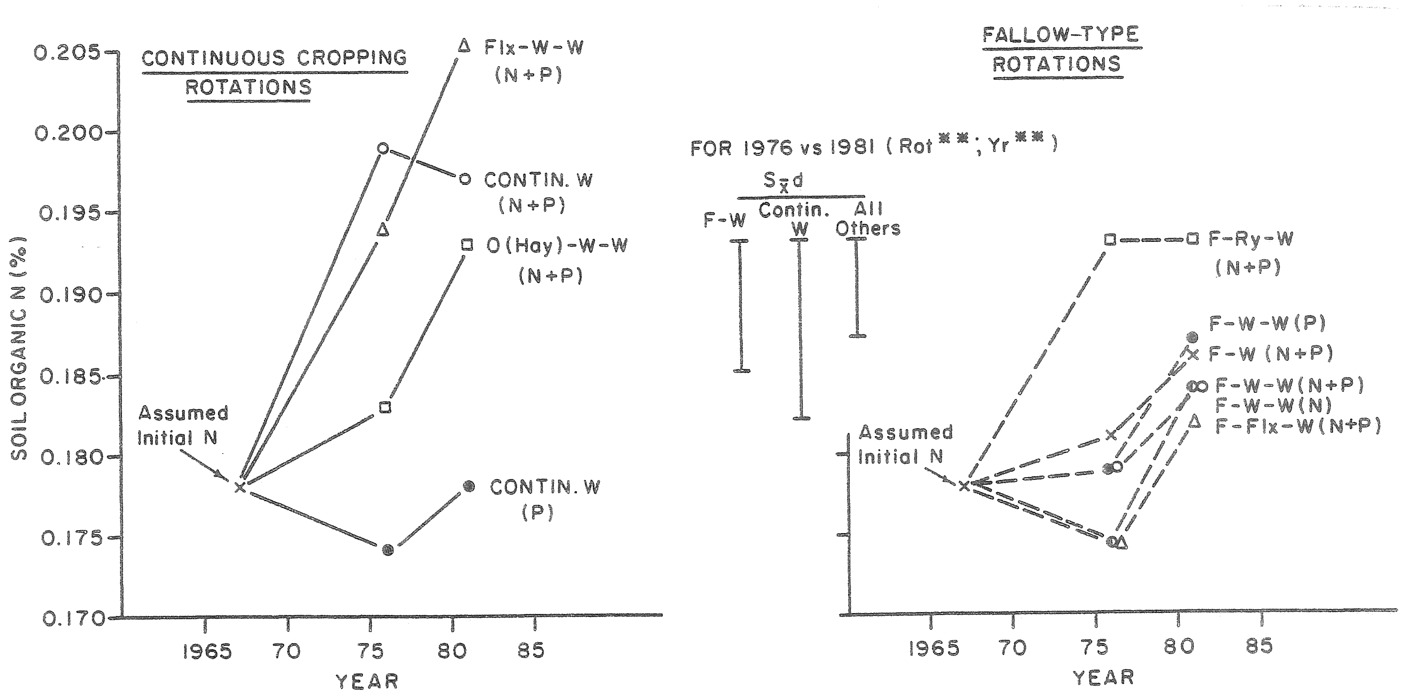

Fig. 2. Changes in soil organic N in 0- to 15-cm depth during 15 yr of cropping to various rotations

consistent tendency for most other rotations to increase also. Continuous wheat receiving only P fertilizer remained almost static and low (0.18%) while continuous wheat receiving N and P annually also remained static but relatively high (about 0.20%). The 0- to 15-cm depth of the virgin grassland for this soil has an N level of about 0.25 to 0.30% (Campbell and Souster 1982; Doughty et al. 1954).

The rotations showing the gradual buildup in organic N in the top 15 cm of soil were also the ones that made the most efficient use of NO_3-N located in the lower root zone, i.e., N that had usually been lost by leaching in the previous fallow-wheat system (Campbell et al. 1984). Similar N buildup has been reported in the U.S.A. by Bauer and Black (1981) for the Northern Great Plains and by Rasmussen and Rohde (1983) for Eastern Oregon.

A partial N balance showed that there was more N removed from each treatment plot as grain than N applied as fertilizer (Table 3). The "deficit" was much lower for continuous wheat receiving N and P than for continuous wheat receiving only P fertilizer and for the fallow rotations that only received N infrequently (Table 3). How then did the organic N in the 0- to 15-cm depth increase over the years? We believe that some of the N found in the plant was brought up by roots from deeper in the soil profile and that a portion of this N, plus residual fertilizer N, found its way into soil organic matter via decaying straw and roots. The majority of the cereal roots are located in the top 15 cm of soil (Campbell et al. 1977).

Table 3. Partial N balance for selected rotations during 15-yr period (1967-1981)

Rot. yr.	Rotation sequence	Fert.[+] treat.	Total N[‡] applied to rotation (kg.ha^{-1})	N uptake* in grain (kg.ha^{-1}.yr^{-1})	Difference** between N applied and N removed in grain
1-3	F-W-W	P	78	31.7	-319
2-3	F-W-W	N,P	251	37.0	-173
4-2	F-Rye-W	N,P	224	43.9	-181
8-1	Cont. W	N,P	477	33.5	-25
11-2	F-W	N,P	96	47.8	-286
12-1	Cont. W	P	78	29.2	-360

* Value only for rotation-yr underlined

[+] Ammonium nitrate and monoammonium phosphate

[‡] This value is the sum of N applied for all crop-years of the rotation (e.g., for rotation 1 it represents the sum of N applied to crops 1-2 and 1-3)

**N removed in grain from Rot. 1 each 3-yr cycle is assumed = grain-N of Rot. 11-2 + grain-N of Rot. 1-3, i.e., 79.5 kg.ha^{-1}.3 yr^{-1}. For 5 cycles (15 yr) total = 397. Difference = 78 - 397 = -319

As stated earlier, there were no estimates of the initial C levels available. Thus only changes during a recent 5-yr period are shown (Table 4). A few of the 3-yr rotations showed a decrease in % C. However, when pooled into groups of similar rotations, there was no significant change between 1976 and 1981 in % C of the 0- to 15-cm depth in either the fallow-containing rotations (avg. 1.74 - 1.77% C) nor in the well-fertilized continuous-type rotations (avg. 2.00 - 1.97 %C). By 1976, the well-fertilized continuous-type rotations had a 13.0% greater C content than the fallow rotations due to the extra residues returned to the soil and the protection from erosion afforded by the more prolonged soil cover. Where N had been withheld from the continuous wheat rotation, the C level was low and similar to that of the fallow rotations, perhaps due to low crop production (Campbell et al. 1983b). The 0- to 15-cm depth of the virgin grassland for this soil has a C level of about 2.50% (Campbell and Souster 1982).

C/N ratios tended to narrow between 1976-81 because C contents changed very little during this period, while there were marked increases in N level.

Table 4. Soil organic C and C/N ratios after 10 and 15 yr of cropping to various rotations

Rot. no.	Rotation description	Fert. treat.	% Org. C		C/N	
			1976	1981	1976	1981
1	F-W-W	P	1.79	1.75	10.00	9.35
2	F-W-W	N,P	1.76	1.61	9.85	8.77
3	F-Flx-W	N,P	1.75	1.73	10.14	9.45
4	F-Rye-W	N,P	1.90	1.82	9.84	9.40
5	F-W-W	N	1.69	1.73	9.71	9.35
6	O(hay)-W-W	N,P	1.88	1.87	10.26	9.64
7	Flx-W-W	N,P	2.08	1.96	10.73	9.56
8	Cont. W	N,P	1.84	2.07	9.24	10.57
11	F-W	N,P	1.76	1.82	9.68	9.82
12	Cont. W	P	1.70	1.71	9.76	9.60

For ANOVA done on yr 1976 and 1981 together:
$S\bar{x}$: (Org.C) for Rot. 11 = 0.10; Rot. 8 & 12 = 0.15; all others = 0.08;
$S\bar{x}$: (C/N) for Rot. 11 = 0.39; Rot. 8 & 12 = 0.55; all others = 0.32.

There were no changes in organic C or N in the 15- to 30-cm depth over the 16-yr study period (data not shown).

Microbial counts

The number of aerobic bacteria in the top 7.5 cm of soil was lowest in the fallow-wheat rotation, increased significantly with longer rotations, and was highest in the continuous wheat receiving only P (Table 5). In contrast, numbers of actinomycetes were small, decreased significantly from the fallow rotations to the continuous wheat rotations and were unaffected by N fertilization. Thus, the bacteria/actinomycete ratio in the 2-yr rotation was about one-third of the ratios in the continuous wheat rotations (Table 5), and poor N fertility also tended to widen the ratio. This trend indicates marked qualitative soil microbial changes in response to long-term differences in substrate availability.

Yeasts are unicellular organisms that reproduce by budding or fission, thus the yeast population was considered to represent one small, but metabolically active, component of the large fungal flora of surface soils. The number of yeasts was greater under well-fertilized continuous wheat than in the fallow rotations (Table 5). The population level under continuous wheat receiving only P was as low as that in the 2-yr and the 3-yr rotations.

Table 5. Effect of crop rotation and N fertilizer on microbial counts, biomass, respiration and N-supplying power in the 0- to 7.5-cm depth after 16 yr

Parameter Measured[a]	Rotation & Fertilizer Treatment 11-2 F-W N,P	2-3 F-W-W N,P	8-1 Cont.W N,P	12-1 Cont.W P	$S\bar{x}d$	LSD[b]
Microbial Counts						
org.g^{-1} soil						
Bacteria ($x10^6$)	82	135	156	201	10	23
Actinomycetes ($x10^6$)	34	37	24	26	2	5
Bact./Actin. ratio	2.4	3.7	6.5	7.8	0.4	0.9
Yeasts ($x10^4$)	11	12	24	15	5	12
Microbial Biomass						
Carbon ($\mu g.g^{-1}$)	216	271	260	428	44	108
Biomass C as % of soil C	1.1	1.6	1.2	2.4	0.3	0.8
Nitrogen ($\mu g.g^{-1}$)	62	78	65	86	14	35
Biomass N as % of soil N	3.1	4.1	2.9	4.4	0.7	1.7
C/N ratio	3.4	3.5	4.1	5.1	0.8	2.0
Respiration, cumulative						
CO_2-C ($\mu g.g^{-1}$), 10 days at 20°C	92	99	138	111	14	24
N-Supplying Power						
Potentially mineralizable N,						
N_o ($\mu g.g^{-1}$), 18 wk at 35°C	159	197	230	185	15	37
N_o as % of soil N	7.9	10.4	10.2	9.4	ND	ND
Min. rate constant, k (wk^{-1})	0.161	0.121	0.141	0.137	0.017	0.041
Mineralization rate, ($\mu g.g^{-1}.wk^{-1}$)	26	24	32	25	ND	ND

[a] For the soil segment sampled μg CorN.g^{-1} soil x 0.833 is equivalent to kg CorN.ha^{-1} based on an average bulk density of 1.11 g.cc^{-1}.
[b] Least significant differences (P = 0.05).

Microbial Biomass

Biomass C in the four rotations generally reflected the pattern observed for bacterial numbers although only continuous wheat receiving only P had significantly more biomass than the other rotations (Table 5). The size of the biomass in these soils was similar to that reported by Carter and Rennie (1982) for conventionally tilled Dark Brown soils in Saskatchewan. Biomass C accounted for 1.1% of the soil organic C in the fallow-wheat and 2.4% in continuous wheat receiving only P.

Biomass N followed a trend similar to C, being lowest in fallow-wheat and highest in continuous wheat receiving only P, but the differences between rotations were not significant (Table 5). The amounts of biomass N accounted for 2.9 to 4.4% of soil N and were similar to values reported by Carter and Rennie (1982) for some Dark Brown soils. The proportion of soil N contained in the biomass was two to three times greater than the proportion of soil C present as biomass. The biomass C/N ratio was narrowest in fallow-wheat and widest in continuous wheat receiving only P. The 50% increase in biomass C/N ratios across the four rotations is indicative of a qualitative microbial shift toward a more fungally (i.e., high C/N cytoplasm) dominated system.

The greater microbial numbers and biomass obtained in the continuous-type rotations compared to the fallow roations was expected due to the difference in carbonaceous residues returned to the soil (Campbell and Biederbeck 1982). But, the much higher microbial numbers and mass present in the continuous wheat receiving only P compared to the well-fertilized continuous wheat (Table 5) was surprising.

Microbial Respiration

Microbial activity as measured by CO_2 evolution was greatest in the continuous wheat receiving adequate N and P and lowest in the fallow rotations (Table 5). The well-fertilized continuous wheat had a 24% higher respiration rate than the continuous wheat receiving only P.

N-Supplying Power

The potentially mineralizable N (N_o) was also greatest in the well-fertilized continuous wheat and lowest in the fallow-wheat rotation (Table 5). On the average, this labile N fraction of soil organic matter accounted for 9.5% of the total N in the top 7.5 cm of these soils, i.e., slightly higher than for the 0-15 cm depth (Campbell and Souster 1982). There was no significant difference between mineralization rate constants, which averaged 0.14 wk^{-1}, although k for the fallow-wheat rotation tended to be higher than for the other rotations (Table 5). The mineralization rate (N_o x k) at 35°C and near optimum moisture was highest for well-fertilized continuous wheat and varied little between the other three rotations.

The evidence suggests that the larger biomass associated with the N-starved continuous wheat rotation might be much less active than the biomass in the well-fertilized continuous wheat treatment. This was confirmed by the respiration and N-supplying power results and by our selective enumeration of yeasts. Perhaps the shortage of N, compared to C, in the continuous wheat receiving only P, has resulted in a popula-

Table 6. Effect of crop rotation and fertilization on microbial counts and biomass in the 0- to 7.5-cm depth after 17 yr

Parameter measured	Rotation and fertilizer treatment						
	11-1 F-W N,P	11-2 F-W N,P	2-3 F-W-W N,P	1-3 F-W-W P	5-3 F-W-W N	8-1 Cont.W N,P	12-1 Cont.W P
	mean ± S.E.M.*						
Microbial counts (organisms/g soil)							
Total Bacteria ($X 10^6$)	66±3	80±9	100±5	129±3	115±4	85±3	106±5
Denitrifiers ($X 10^3$)	6.5±0.8	3.0±1.1	12.6±0.5	1.0±0.4	15.8±1.2	12.6±2.9	2.0±0.9
Microbial Biomass							
Carbon, g/soil	211±17	265±17	289±28	337±22	313±40	296±18	390±29

* S.E.M. = standard error of the mean.

tion that has a high proportion of its organisms as resting structures such as dormant cells, encapsulated cells, cysts and spores. Such structures are usually higher in C and lower in N concentration than are metabolically active forms.

The marked differences in soil microbial properties observed between the four rotations (Table 5) sampled in 1982 were confirmed by the microbial counts and biomass estimates obtained when the same four rotations plus three more were sampled again in 1983 (Table 6). Bacterial numbers and microbial biomass were lowest in the fallowed soil of the fallow-wheat rotation and generally increased with rotation length. However, among similar rotations microbial numbers and biomass were always greater in rotations receiving only P than in those receiving N and P fertilizer. This type of soil microbial repression due to N-fertilization has also been observed recently by Söderström et al. (1983) in studies with Swedish forest soils.

N-fertilization, at the rates used in our rotation study, seems to cause a strong and lasting stimulation of the denitrifier population near the soil surface. In rotations receiving N fertilizer, numbers of denitrifiers were severalfold greater than in similar rotations without N amendment (Table 6). There were also more denitrifiers in the fallowed than in the cropped soil of the 2-yr rotation.

CONCLUSIONS

Our results confirmed that frequent summerfallowing has seriously impaired the biological properties of our soils. However, not only can the trend in organic matter decline be reversed, but the physical and biological quality of the soil can also be improved by a combination of extending the rotation length (cropping annually), applying N and P fertilizers at rates normally recommended by the Soil Test Laboratory, and by using a stubble mulch tillage technique. Thus, even with present day agronomic technology, it appears that we can reverse the current disastrous trend in soil fertility. Furthermore, the recently publicized predictions that grain production in the Brown soil zone will peak around the year 2000 and then begin "an agonizing decline" due to rapid soil degradation (Hamm and Cameron 1983) seem unfounded and premature. One word of caution seems warranted with regard to soil pH. It appears that soil pH could be reduced by long-term use of N fertilizers and this may result in added expenditure for lime in the long run.

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