CHAPTER 9

The role of fertilizer nutrients in rebuilding soil organic matter

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ABSTRACT

The rebuilding of soil organic matter is a continual process which involves the physical breakdown, biochemical transformation and biophysical stabilization of organic material. The growth and death of organisms results in the uptake (immobilization) and release (mineralization) of macro- and micronutrients and in formation of new soil organic matter. The objective of this chapter is to examine the role of fertilizer nutrients in rebuilding soil organic matter in soils of the Canadian prairies.

Results from field experiments using ^{14}C and ^{15}N tracers have shown that: (1) the below ground input of organic matter could be a function of specific cultivar and the throughput of C through the roots contributed more to building soil organic matter than the standing root mass; (2) fertilizer N is rapidly transformed into shoot N, root N, microbial N, and non-microbial organic N. The recovery of fertilizer N in microbial biomass is 1 to 3% after one field season but the recovery of fertilizer N in non-microbial organic N ranges from 14 to 21%. The partitioning of fertilizer N occurs quickly and contributes to the formation of new soil organic matter.

Changes in the soil organic matter content and quality over a 50 year period at the Breton plots confirmed that fertilizer nutrients and/or manure together with cropping practices may significantly increase total organic matter and the quality of that organic matter. The average soil organic matter content on the five-year rotation was approximately 20% higher than for the two-year rotation. Fertilizer including N, P, K, and S significantly increased the soil organic matter, a reflection of much greater root masses etc. However organic matter was consistently highest on the manure treatments.

Trends similar to those noted above for the Breton plots were obtained from long term rotations at Swift Current and Lethbridge. Potentially mineralizable N was increased by approximately one-third. In general, P positively impacted on soil organic matter only where yield responses were significant. In contrast, N and P fertilizer had inconsistent and only minimal effects on soil organic matter on a deep Black soil at Melfort.

The results of these several long term rotational studies across the prairies shows that fertilizer nutrients, in particular N, play an indispensable and key role in the sustainability of soil organic matter.

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INTRODUCTION

Soil organic matter is composed of fresh and partially decomposed plant material, microbial and faunal biomass, products of biomass and humus. Decomposition involves physical breakdown, biochemical transformation and biophysical stabilization of organic material. Heterotrophic organisms in soil utilize carbon (C) in the organic material for metabolism. Subsequent decomposition of these organisms and their products results in the formation of complex, heterogeneous humic materials (Juma and McGill, 1986). The growth and death of organisms also results in the uptake (immobilization) and release (mineralization) of macro- and micronutrients. Therefore, there is direct interaction between the C added to soil through above-ground and below-ground crop residues and the addition of fertilizers, especially nitrogen (N). The objective of this chapter is to examine the role of fertilizer nutrients in maintaining or rebuilding soil organic matter.

CARBON INPUT INTO SOIL

Crop residues, roots, and root-released materials are sources of C for soil organisms. A portion of C is utilized for production of biomass while the rest is used for maintenance and energy production. Crop residue management has generally focused on manipulation of straw in the fall or in the spring. However, straw management does not reveal an accurate picture of C inputs to soil because root C input is ignored. Although the standing root mass at harvest may be only 10% of shoot mass, a quantity equal to about 3 to 4-fold of maximum standing root mass C is released into the soil over the growing season in the form of root material, exudates, and other soluble products (Sauerbeck and Johnen, 1977). Thus, up to 33% of total C fixed by photosynthesis is used to build and maintain the root system.

Van Veen et al. (1991) summarized previous work and reported that 60 to 90% of the total C assimilated by arable crops was stabilized in different pools of the crop-soil system and 10 to 40% of that was released from the roots into the soil. Estimations of annual input of C into soil by a growing crop ranged from 900 to 3000 kg ha^{-1}. Large variations exist with plant species, cultivars and development stages, and environmental conditions (Van Veen et al., 1991). Some estimates of above- and below-ground dry matter inputs, and C and N additions for different crops in western Canada have been presented by Campbell et. al. (1991a).

The significance of root inputs to maintain soil organic matter contents has not been studied to the same extent as above-ground inputs. Campbell et al. (1991b) found no significant differences in soil organic matter content in wheat-wheat-fallow rotation over a period of 30 years amongst treatments where the straw was left on the surface or baled off. They suggested that root inputs may be more important than straw inputs in maintaining the amount of organic matter present in soil. Also, the continuous root input over the growing season is responsible for the activity of microorganisms and fauna which in turn affect nutrient cycling (Juma and McGill, 1986).

Recent work of Xu and Juma (1992) using barley cultivars (Abee, Bonanza, Harrington and Samson) grown in a Black Chernozem showed that shoot and root mass of Abee was significantly greater than that of Samson, indicating that the below ground input of organic matter could be a function of a specific cultivar (Fig. 1). However, the amount of standing root C represents only a part of C translocated below-ground. The C released from roots enters the soluble C pool which is utilized by microorganisms for growth, respiration and production of metabolites. Cultivars which release more of the C translocated to the roots may be responsible for partial stabilization of added C in soil organic matter (Fig. 2).

In an experiment using ^{14}C pulse-labeling techniques on two barley cultivars (Abee and Samson), Xu and Juma (1993) found that ^{14}C distribution in soil was 1-2% in water soluble organic C, 8-9% in microbial C and about 90% was in the soil organic matter including very fine roots which could not be removed from soil. However, the major portion of soil ^{14}C can be described as the C stabilized in the soil. There was a significant

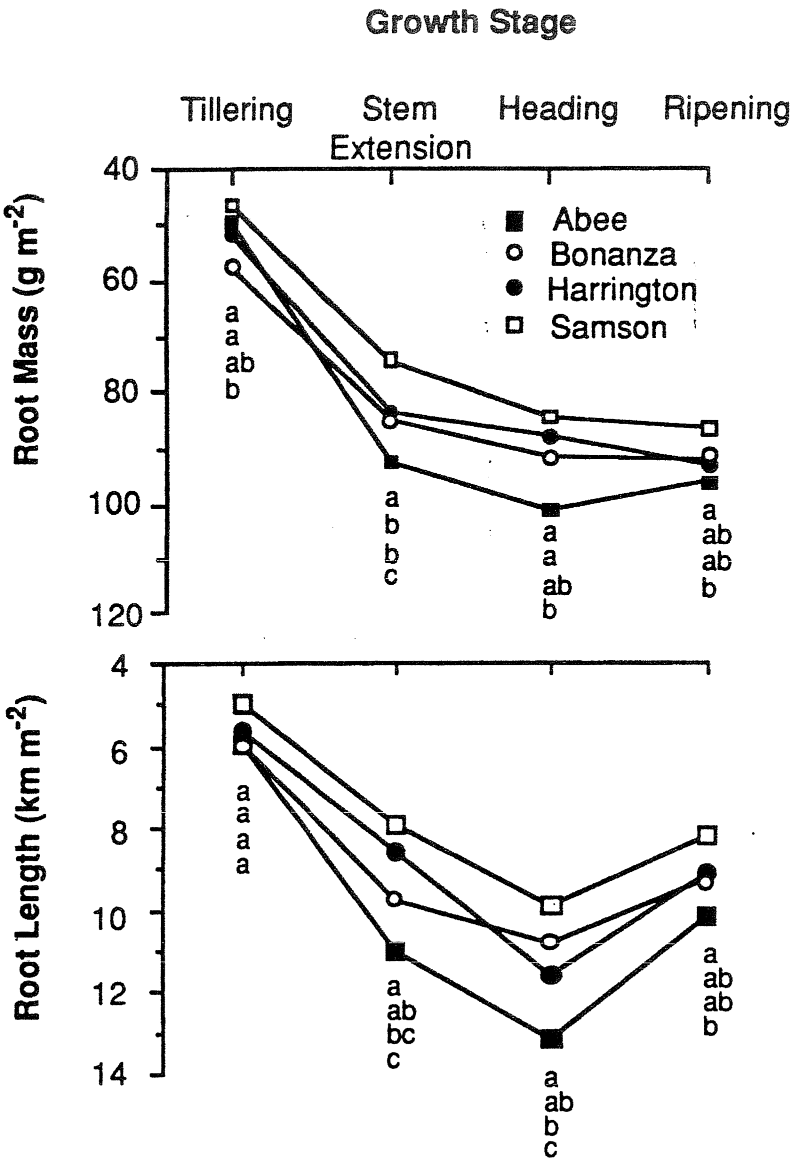


Figure 1. Total root mass and root length of four barley cultivars at various growth stages over 1989 and 1990. The means of the cultivars bearing the different letters are significantly different in root mass or root length at the given growth stage ($P < 0.05$) and refer to the magnitude of these variables from the lowest to the highest.

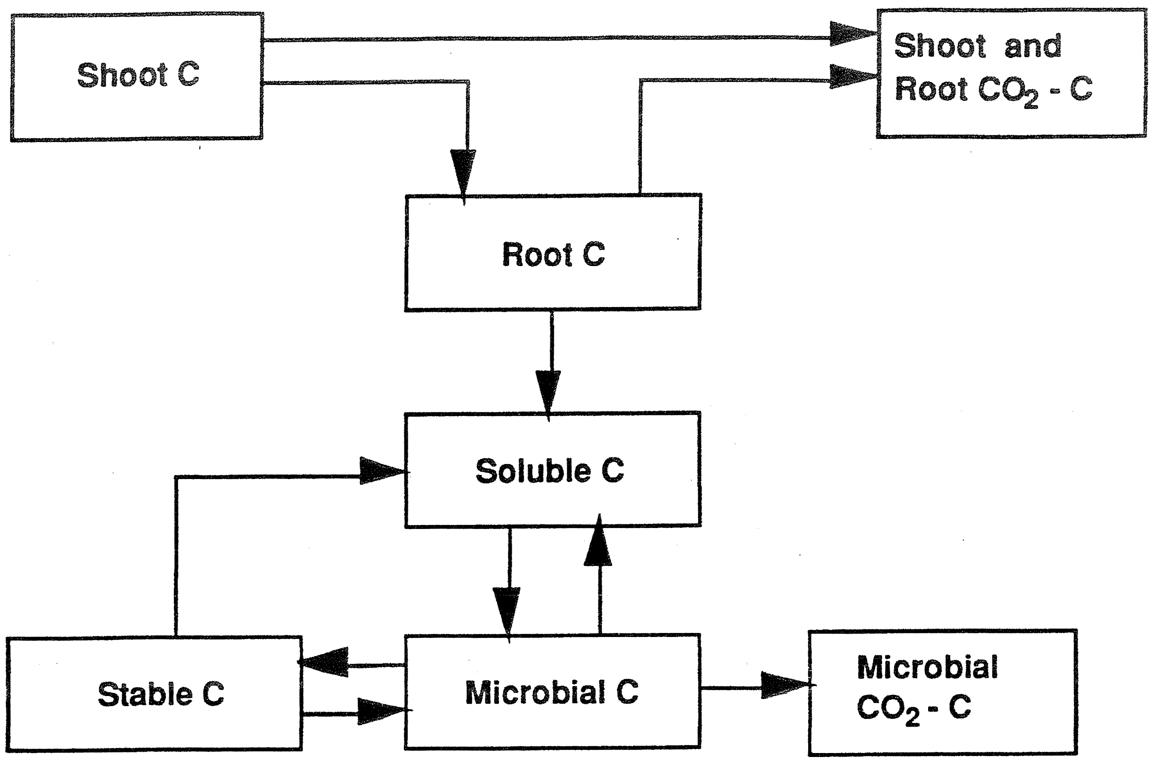


Figure 2. Conceptual model of C flow in plant-soil system.

linear relationship between ^{14}C in root and ^{14}C in soil ($r = 0.796^{***}$, $n = 24$). This implied that the photosynthetically fixed C stabilized in soil was controlled mainly by the amount of root-released C. The amount of ^{14}C stabilized in soil was higher under Samson than Abee, although Samson had a lower root C than Abee. The specific activity of roots of Samson was higher than that of Abee. This implied that at the stem extension and heading stages, more ^{14}C was released by roots of Samson than Abee.

The specific activity of ^{14}C in microbial C was higher than that in water soluble organic C but was lower than respired C under both barley cultivars. This also supports the argument that microbes preferred to use root derived organic C. However, the stable C was also enriched with ^{14}C. Assuming that the C from soluble organic C is used at an efficiency of 30 to 50% (McGill et al., 1981), a portion of root and soil derived C is concurrently stabilized in soil. The throughput through the roots was more important than the standing root mass. Our results showed that C input under Samson was higher than under Abee and more C was stabilized in microbial C and soil C.

LINKAGE BETWEEN C INPUT, MINERALIZATION/IMMOBILIZATION OF N, AND FORMATION OF NEW SOIL ORGANIC MATTER

Jansson (1958) used short-term ^{15}N studies to discern soil organic N into an active and a passive N phase. Paul and Juma (1981), using the chloroform fumigation incubation technique, extended Jansson's approach and divided the active N phase into a living component (microbial N) and a non-living component (non-microbial active N). Non-microbial active N consists of microbial metabolites and recently stabilized materials. These microbial N and non-microbial active N pools are an important source of mineralizable N and accounted for more than 67% of the net N mineralized in a 12-week laboratory study (Paul and Juma, 1981). These pools build rapidly when the ratio of available energy to N in the soil is high (Jansson, 1958).

Microbial biomass serves two major purposes: (i) it is a source and sink of N, and (ii) it is a transformation agent for soil N (Anderson and Domsch, 1980; Paul and Voroney, 1980). Since microbes have a potentially high growth rate, they can assimilate available N rapidly and convert a major portion of this material into non-microbial organic N when sufficient C is available. Generally, the recovery of fertilizer N in microbial biomass is 1 to 3% after one field season but the recovery of fertilizer N in non-microbial organic N ranges from 14 to 21% (Rutherford and Juma, 1989). The ratio of ^{15}N recovered in microbial biomass to ^{15}N recovered in non-microbial organic N represents the amount of N remaining in the microbial community relative to the total amount of N transformed by the community.

Rutherford and Juma (1992) studied the effects of microbial activity due to glucose amendment at the time of fertilization and planting on the distribution of fertilizer ^{15}N at harvest amongst various N pools. Microbial activity resulting from glucose amendment had a marked effect on N partitioning and barley growth. The high C/N ratio of glucose C and urea N amendments (20:1), and the quantity of glucose added, caused net N immobilization and formation of microbial materials. Recovery of fertilizer ^{15}N within the plant-soil system was 82% in glucose treatment (GT) and 50% in non-glucose treatment (NGT).

Shoot mass, root mass and root N in NGT were 1.8-fold, 1.9-fold and 2.2-fold greater, respectively, than in GT. A larger proportion of roots were below the 10 cm depth in GT than in NGT, which may have been related to low levels of available N caused by microbial immobilization in the surface layer. This was reflected in the 3.0-fold greater shoot ^{15}N recovery in NGT plots compared to GT plots. Also, a larger proportion of shoot N consisted of fertilizer N in NGT plants (approximately 16%) compared to GT plants (approximately 10%). In both treatments most soil ^{15}N remaining at harvest was present as non-microbial organic ^{15}N (NMO^{15}N), but recovery of NMO^{15}N was 3.4-fold greater in GT soil than in NGT soil. Thus, microbial response to glucose addition effectively conserved fertilizer N as organic N and reduced the losses of NO_3-N by leaching and denitrification; however, significant remineralization of immobilized N did not occur so as to meet plant N demand.

Glucose addition increased the absolute size of microbial ^{15}N and NMO^{15}N pools in the 0-10 cm interval but did not affect the ratio of these pools in both treatments (Rutherford and Juma, 1992). This implies that partitioning of added N between these pools by microbial transformations was similar. This suggests that in the long-term, microbial transformations in soil result in a constant ratio of NMON formed per unit of microbial N formed, and this ratio is not affected by C amendments.

Haugen-Kozyra et al. (1993) measured the partitioning of ^{15}N urea injected in zero tillage (ZT) and conventional tillage (CT) plots sown to barley (Table 1). There were no significant differences in the average recovery of total soil ^{15}N between the two tillage treatments. By the fifth leaf stage, which occurred almost one month after seeding, only 8% of the fertilizer was utilized by plants. Approximately 75% of the fertilizer still remained as mineral N at this stage and a significant amount of mineral ^{15}N had moved into the 5-15 cm depth under ZT. The high recovery of ^{15}N in the microbial biomass by the fifth leaf stage showed that N was rapidly immobilized by the microbes. The non-microbial organic nitrogen (NMON) was approximately 20-25% at this time and remained stable for the rest of the growing season. These studies show that partitioning of fertilizer N occurs quickly and contributes to the formation of new soil organic matter.

The fate of fertilizer N gives a partial picture of N cycling in the soil-plant system. Generally, the crop N uptake is more than the N supplied through fertilization. The portion of shoot N derived from fertilizer decreased over the growing season which shows that fertilizer N is partitioned into different soil and plant compartments and that some of it is lost. The bulk of N in shoots is derived from the mineralization of soil organic N over the growing season. Insight into the dynamics of ^{14}N and ^{15}N is shown by the mineral and soil N isotope comparisons (Table 2). For most of the season, most of the N present in the

Table 1. Recovery of fertilizer N in the soil compartments under conventional and zero tillage (from Haugen Kozyra et al., 1993).

N Compartment	Depth (cm)	Growth Stage: Fifth leaf	Ear emergence	Grain filling	Ripening
		Percent recovery under conventional tillage			
Total Mineral N	0 - 5	72.2a†	0.9d	0.4d	0.3d
	5 - 15[z]	1.9d	0.1d	0.3d	0.3d
	15 - 30[z]	0.9d	0.1d	0.1d	0.1d
Microbial N	0 - 5	12.8a	1.9d	3.0c	2.4d
	5 - 15	0.4d	0.3d	0.9d	0.6d
	15 - 30	0.1d	0.2d	0.2d	0.2d
Non-microbial Organic N	0 - 5	17.4a	23.0a	23.1a	20.1a
	5 - 15	2.9bc	2.7bc	3.1bc	5.1bc
	15 - 30	-	0.8c	0.7c	0.8c
		Percent recovery under zero tillage			
Total Mineral N	0 - 5	63.3b	0.4d	0.4d	0.4d
	5 - 15	12.3c	0.2d	0.3d	0.1d
	15 - 30	0.2d	0.1d	0.0d	0.1d
Microbial N	0 - 5	6.9b	2.0d	3.6c	2.5cd
	5 - 15	1.7d	0.5d	0.8d	0.6d
	15 - 30	0.2d	0.3d	0.3d	0.3d
Non-microbial Organic N	0 - 5	18.0a	20.5a	22.7a	20.6a
	5 - 15	8.4b	7.4bc	4.3bc	6.2bc
	15 - 30	-	4.9bc	1.6bc	1.6bc

† Same lowercase letter indicates no significant differences between the means of tillage treatments for a given date or depth ($P \leq 0.05$).

mineral N pool is derived from the native organic matter. This emphasizes the substantial N supplying power of the large soil N reserves in the Black Chernozem. Shoot N is a continuous monitor of net mineralization; the amount of soil derived N was more than two times the amount of N derived from fertilizer. The partitioning and plant recovery of added fertilizer showed the response of inherent subsystem feedback to a large mineral N addition at the time of seeding.

Numerous studies by Nyborg et al. (1990), have shown that the recovery of ^{15}N urea or ammonia fertilizers in soils at the end of the season range from 26.7 to 37.5%. Using a conservative estimate of 25%, 835 500 tonnes of fertilizer N applied between 1984-1989 to the prairie provinces may have been transformed to 208 875 tonnes of new organic matter. However, a systems budget indicates that these additions are small compared to total N present in the prairie soils (Table 2).

IMPACT OF FERTILIZER ADDITIONS ON CROP YIELDS AND SOIL ORGANIC MATTER

Breton Plots

The Breton Plots were established in 1930 to find "a system of farming suitable for the wooded soil belt" (Robertson, 1979). The original plots (31.5 m x 8.5 m each) were designed to compare two cropping systems and to test several soil amendments and fertilizers. The original cropping systems were continuous wheat and a four-course rotation with three years of cereal grains and one year of legumes. In 1938 the continuous wheat system was converted to a wheat-fallow rotation to help control weeds. In 1939, the four-course rotation was changed to a five-course rotation of wheat, oats, barley, forage, forage. The forage crop has varied over the years but has always included a legume. For the 1939-1954 period, the forage component consisted of "mixed legumes". For the 1955-1966, the forage component was a five-crop mixture (alfalfa, red clover, brome, creeping red fescue, timothy). In 1967, the forage mixture was changed to alfalfa and brome to reflect commonly recommended forage mixture for the area. All phases of the two

Table 2. Summary of partitioning and dynamics of N in the two systems (all units are in g m^{-2} to a depth of 15 cm) (from Haugen-Kozyra et al., 1993).

Variable	Growth Stage: Fifth leaf	Ear emergence	Grain filling	Ripening
	Conventional Tillage			
Shoot N	1.1	7.7	10.6	7.6
Shoot ^{15}N	0.4	3.2	3.1	2.0
Shoot ^{14}N	0.7	4.5	7.5	5.6
Root N	0.44	1.02	0.75	0.55
Root ^{15}N	0.11	0.21	0.16	0.11
Root ^{14}N	0.33	0.81	0.59	0.44
Mineral N	7.80	0.70	0.60	1.00
Mineral ^{15}N	4.33	0.05	0.03	0.03
Mineral ^{14}N	3.47	0.65	0.57	0.97
Microbial N	5.74	4.48	7.04	6.49
Microbial ^{15}N	0.77	0.14	0.23	0.18
Microbial ^{14}N	4.97	4.32	6.81	6.31
Soil N	649	692	638	714
Soil ^{15}N	6	2	2	2
Soil ^{14}N	643	690	636	712
	Zero Tillage			
Shoot N	1.3	7.6	8.1	7.8
Shoot ^{15}N	0.8	3.4	3.0	2.3
Shoot ^{14}N	0.5	4.2	5.2	5.5
Root N	0.46	1.23	0.59	0.46
Root ^{15}N	0.16	0.32	0.19	0.11
Root ^{14}N	0.30	0.91	0.40	0.35
Mineral N	8.60	0.80	0.80	0.80
Mineral ^{15}N	4.45	0.03	0.04	0.03
Mineral ^{14}N	4.15	0.77	0.76	0.77
Microbial N	6.03	4.08	6.50	5.60
Microbial ^{15}N	0.53	0.15	0.26	0.19
Microbial ^{14}N	5.51	3.94	6.25	5.42
Soil N	771	777	674	639
Soil ^{15}N	5	2	2	2
Soil ^{14}N	766	775	672	637

rotations and fertilizer and soil amendment are present every year, however, the individual treatments are not replicated.

The soil amendments included several combinations of the nutrients (N, P, K and S) as well as lime and farmyard manure (Robertson and McGill, 1983). In this paper, the results of three treatments (Check, NPKS and Manure) are discussed (Table 3). Fertilizer application methods varied over the years. Initially, all fertilizers were annually broadcast. From 1946 to 1966, fertilizers were added every second year. In 1964, annual applications were resumed and phosphate was drilled with the seed. Manure was applied once every five years. In 1972, lime was added to the east half of all plots of the 5-year rotation and to the entire area of the 2-year rotation. The check or control plots have not received fertilizers since 1930.

Major revisions were introduced in 1980 (Cannon et al., 1984; Robertson and McGill, 1979). Some of the fertilizer treatments were revised and the nutrient applications were brought into line with current recommendations to farmers. The annual applications of N, P and K were also increased substantially (Table 3).

Crop yield trends: The 5-year running averages for wheat grain yields in the check plots of the 2-year wheat fallow rotation (Fig. 3A) were about 1 t ha^{-1}, however, the running averages of the crops in the 5-year rotation showed an upward trend over a period of 50 years (Figs. 3B-F). Since all above-ground residues were removed from all the plots, the increases in wheat grain yields in the check plots of the 5-year rotation can be attributed to increased nutrient supply, especially N, through biological N fixation and increased root mass. It is possible that a greater amount of root residues and N could contribute more available nutrients for crops.

The wheat grain yields in the manure treated plots in the 2-year and 5-year rotation were consistently greater than those obtained in the check plots (Figs. 3A and 3B). We calculated that the addition of manure provided approximately 70 kg N ha^{-1} yr^{-1} (Table 3), and was reflected in the yields which were at least two-fold greater than the Check plots

Table 3. Comparison of original and revised fertilizer application rates (kg ha^{-1} yr^{-1}) on the long-term plots at Breton.

	Former treatment 1930 - 1979 inclusive				Current cereal crop treatments 1980 - present			
	N	P	K	S	N	P	K	S
Manure	76†	42	91	20	‡	-	-	-
NPKS	10	6	16	10	§	22	46	5.5
Control	0	0	0	0	0	0	0	0

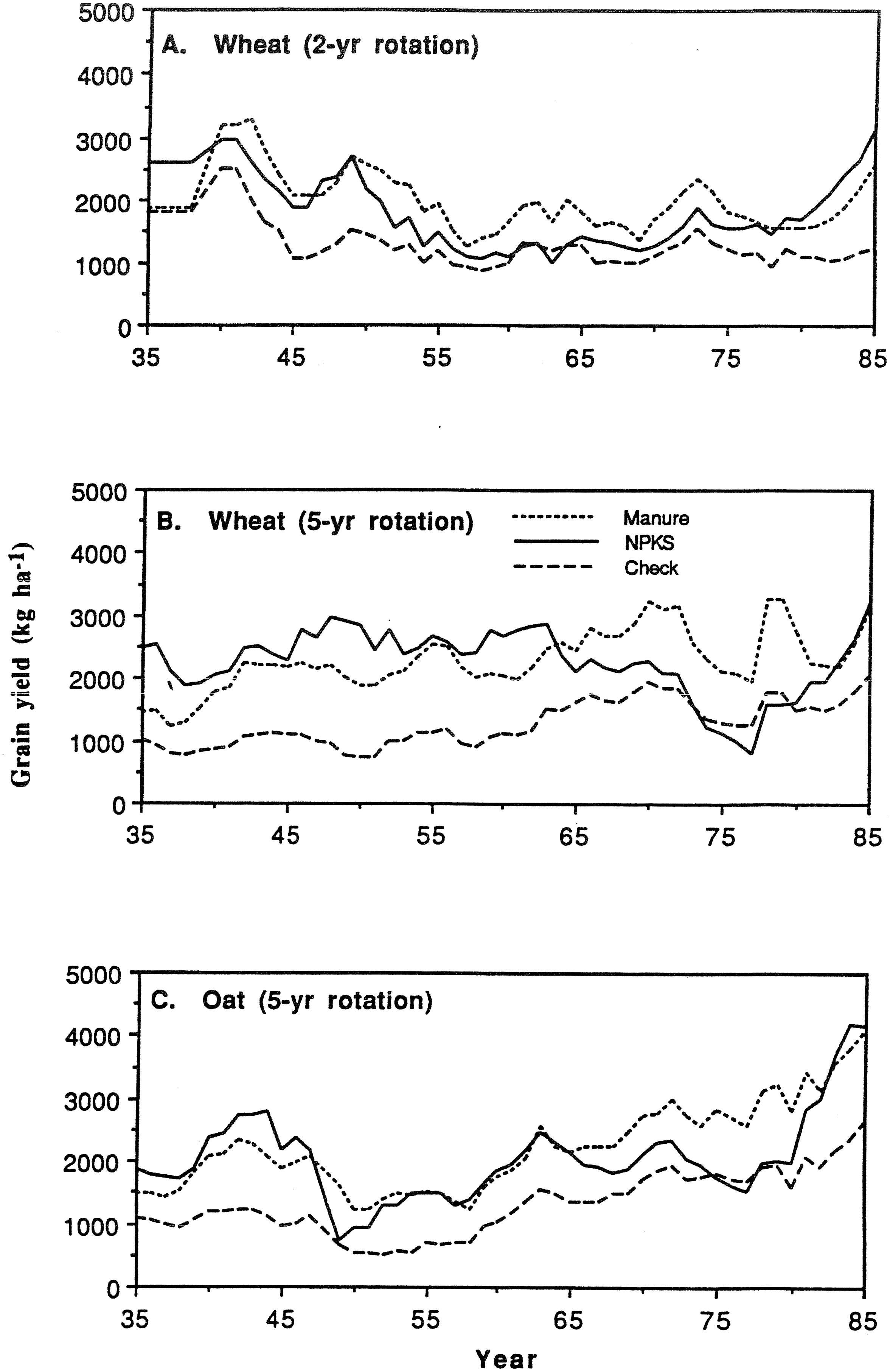
† Applied every fifth year, in later years at 44 t ha^{-1}. Nutrient rates shown are annual equivalents, and are estimates based on manure applied from 1976-1986 inclusive.

‡ N application via manure depends upon the rotation. Wheat-fallow rotation 90 kg N ha^{-1} for each wheat crop. Wheat, oat, barley, forage, forage rotation 175 kg N ha^{-1} every five years. Applied in two equal applications: after oat harvest and at the time of forage plowdown.

§ N amounts depend on the crop and its place in rotation: wheat on fallow 90 kg N ha^{-1}; wheat after forage 50 kg N ha^{-1}; oats after wheat 75 kg N ha^{-1}; barley as nurse crop 50 kg N ha^{-1}; and legume-grass forages 0 kg N ha^{-1}.

Table 4. Trends of total soil N (g kg^{-1} soil) in Check, Manure and NPKS treatments of the 2-year and 5-year rotation at Breton.

Rotation	Treatment	Equation	R^2
2-year	Check	Total N = 1.04 (±0.0676) - 0.00182 (±0.0234) x Year	0.16 ns
	NPKS	Total N = 1.09 (±0.0732) - 0.000664 (±0.00254) x Year	0.02 ns
	Manure	Total N = 1.14 (±0.121) + 0.00687 (±0.00421) x Year	0.47 ns
5-year	Check	Total N = 0.940 (±0.0539) + 0.00942 (±0.00187) x Year	0.89 **
	NPKS	Total N = 0.881 (±0.112) + 0.0163 (±0.00391) x Year	0.85 **
	Manure	Total N = 0.926 (±0.117) + 0.0248 (±0.00407) x Year	0.92 **



A. Wheat (2-yr rotation)
B. Wheat (5-yr rotation)
Manure
NPKS
Check
C. Oat (5-yr rotation)
Grain yield (kg ha-1)
Year
5000
4000
3000
2000
1000
0
35
45
55
65
75
85

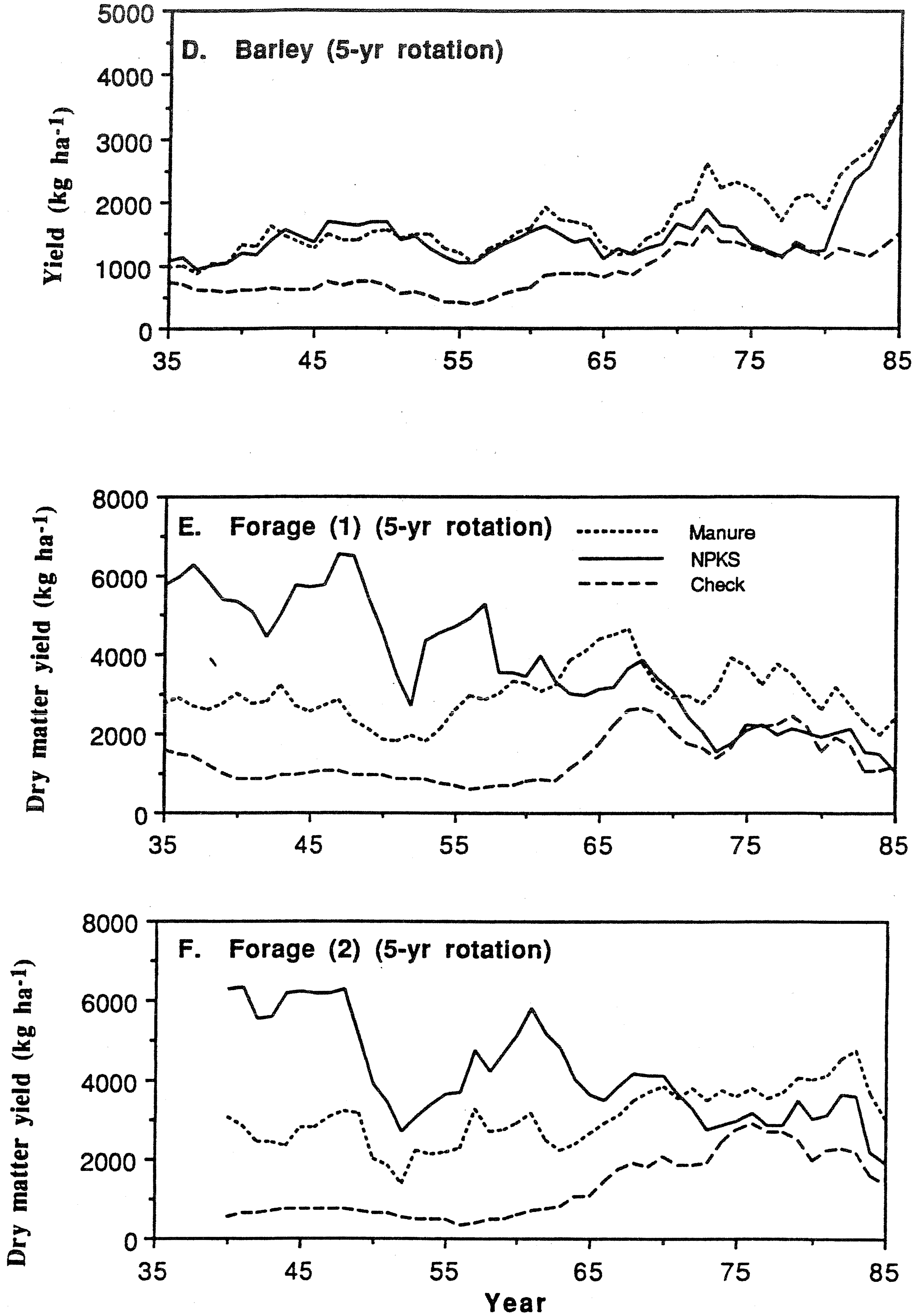


Figure 3. Five year running averages of wheat grain yields for the 2-year rotation, wheat, oat, and barley grain yields and dry matter yields of two forage crops for the 5-year rotation for the period 1935-1985.

over the past 35 years (Figs. 3A and 3B). The wheat grain yield from manured plots of the 5-year system were consistently higher than the grain yields from the manured treatment of the 2-year rotation. This suggests a synergistic effect of the 5-year crop rotation on wheat yields.

Wheat grain yields in the NPKS treated plots decreased after the first 20 years and became similar to those obtained in the Check plots. These plots were N limited up to 1979 because fertilizer N had been applied at a rate of 10 kg ha^{-1}. In 1980, an adjustment in fertilizer application rate brought a balance between the N removed by harvest and that applied as fertilizer (Robertson and McGill, 1983). An almost three-fold increase in grain yields was observed when fertilizer rates were adjusted. The grain yield in the NPKS treated plots of the 5-year rotation were generally greater than those for the same treatment in the 2-year rotation up to 1970 which suggests that N supplied by legumes helped to maintain grain yields. In the late 1970s, there was a marked decrease in crop yields in the NPKS treatment of 5-year rotation. This might have been due to increased weed competition. Use of herbicides and higher fertilizer rates in the 1980s resulted in comparable yields in the NPKS and manure treatments in both rotations (Figs. 3A and 3B).

In the 5-year rotation, the yield trends observed for oat (Fig. 3C) and barley (Fig. 3D) were similar to those for wheat. Generally, crop yields showed an upward trend with time. Yield ranking by treatment up to 1980 placed manure first followed by NPKS and Check. On all plots, the average (1935-1979) wheat yields were greater than barley yields because the wheat crop greatly benefited from the N contributed by the legume in the preceding forage crop. By the time the barley crop was grown much of the benefit of the legume in the forage crop was gone and the barley yields were considerably lower than the wheat yields. In these experiments the forages have been removed for hay in early to mid-July and the second year forages have been "plowed down" in late July without much regrowth. After the adjustment of fertilizer rates in 1979, the grain yields of manured and NPKS fertilized crops were similar (Figs. 3A-D).

The running average of first year hay yields obtained in the fourth year of the rotation in the Check plots was around 1.0 t ha^{-1} from 1935 to 1960 (Fig. 3E). After that time, the yield in the check plots rose to about 2 t ha^{-1}. We speculate that increased oil drilling in the area resulted in increased S in the atmosphere and hence some S added to the soil. The yields of manure-treated plots were almost two- to three-fold higher and consistently greater than the check plots. Farmyard manure, added at about 44 t ha^{-1} every fifth year, produced a yield of 3.0 t ha^{-1}. The nutrient content of the manure was not determined, but based on values from the literature and some recent analyses, the amounts of N, P and K added were several times larger than those added in the fertilizers (Table 2). The NPKS treatment had generally very high yields (4-6 t ha^{-1}) until about 1955, somewhat lower yields (about 3 t ha^{-1}) from 1955 to 1967 and still lower yields (about 2 t ha^{-1}) from 1967 to 1979. The likely explanation of this decline is the gradual acidification of the soil through application of ammonium-containing fertilizers (21-0-0 and 16-20-0). Such an effect would be particularly evident after 1967 when the legume crop was changed from red clover and alfalfa to alfalfa alone. Alfalfa is less tolerant of acidity than is red clover. The opposite trends obtained with manure and NPKS treatments during the first 50 years of the rotation may also be due to N and S deficiency. Since legumes can fix N, S deficiency may have been limiting growth.

The running average of second year hay yields obtained in the fifth year of the rotation showed similar trends as the first year forage yields (Fig. 3F). The effect of increasing fertilizer rate in 1980 resulted in a marked increase of hay yields in first and second year forage. This perturbation showed that crop performance in the NPKS plots were limited by the supply of major nutrients.

Soil organic matter trends: Very few soil samples were taken or analyzed at the beginning of the Breton Plots so that soil changes from 1930 to 1979 cannot be assessed. Four samples were stored since 1936 and 1938, and their N contents were determined recently (Cannon et al., 1984). Various researchers over the years took samples and

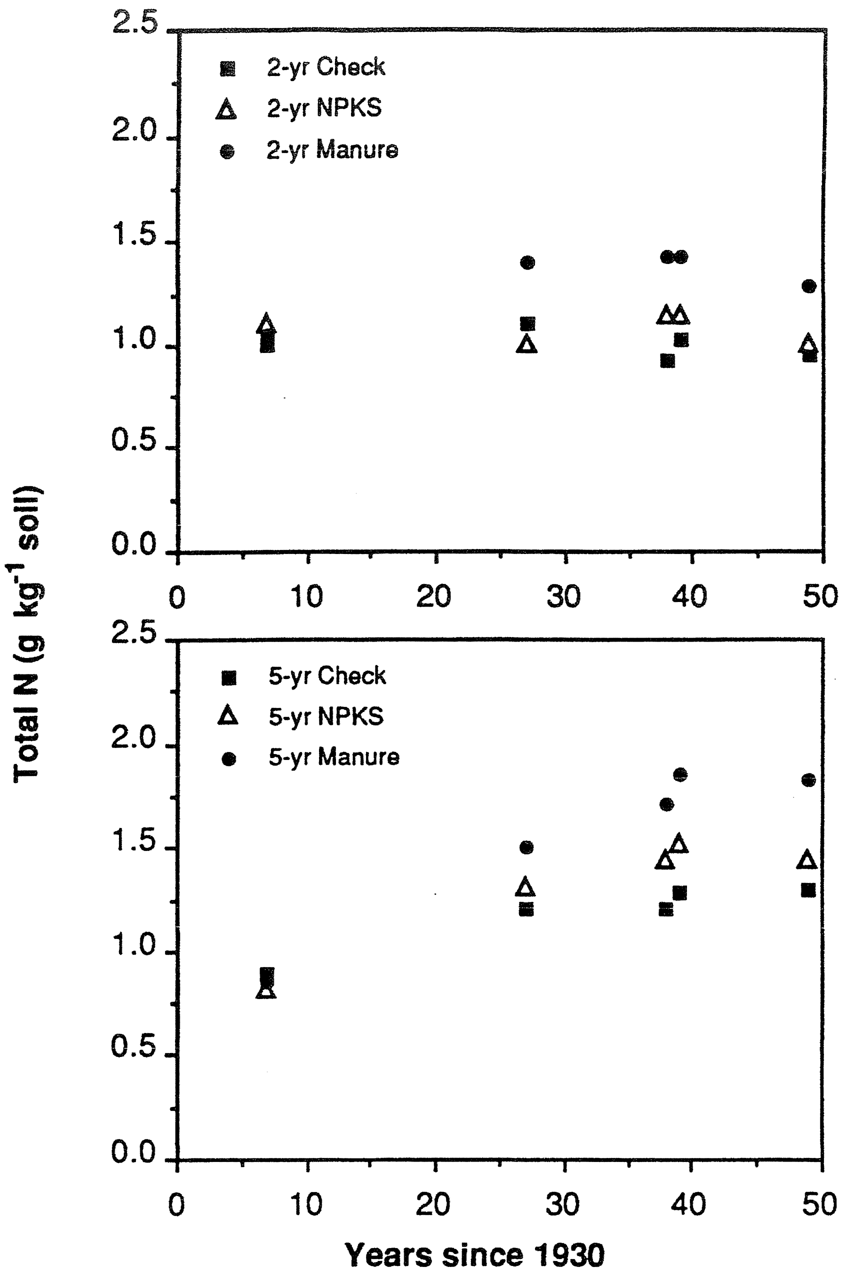


Figure 4. Total N in the Check, NPKS and Manure treatments of the two rotations over a period of 50 years.

measured soil N content. Thus, for N we were able to follow the soil content over a 40-year period (Fig. 4). Linear regression analyses showed that the slope of total N in the three treatments of the two-year rotation were not significantly different from zero, therefore, there were no significant changes of total soil N over 50 years (Table 4). In contrast, soil total N increased in all treatments of the 5-year rotation. The increase was the highest for the Manure treatment followed by NPKS and Check treatments (Table 4).

Cropping practices can greatly affect organic matter content of soils. After 50 year's cropping at the Breton Plots three important observations have been made. First, the soil organic matter content is about 20% higher in the soil of the five-year rotation plots than in that of the two-year (wheat-fallow) rotation plots (Fig. 4). This result can be explained in several ways. Crops are grown more continuously on the five-year rotation and therefore more plant material (stubble and roots) is added than on the two-year rotation plots. Further, the five-year rotation plots are bare for a smaller portion of the time so that decomposition processes are probably slower and erosion losses are smaller. Finally, a greater amount of N is probably left by forage crop roots than cereal crop roots and this would be conducive to higher soil organic matter.

The second important observation is that soil organic matter is higher on the NPKS fertilized plots than on the control plots (Fig. 4). The increase can be explained by the fact that crop yields (forages and grain) have been much higher on the fertilized plots. Thus the amount of stubble and root material added to the soil is greater on these plots although all forages are removed as hay and the straw of cereals is also removed.

Thirdly, organic matter content is generally higher on the manured plots than on plots receiving commercial fertilizer. This result arises from the fact that manure is organic matter and the average annual addition was approximately 9 t ha^{-1}. Besides, manure served as a fertilizer material and improved crop growth and hence organic matter additions via roots and stubble. It should be noted, however, that the amount of manure added was greater than could be generated if all the crop produced were fed to livestock (i.e., it was not a sustainable application rate).

Thus, it is clear from these long-term experiments that appropriate management practices, including growing legumes, reducing fallowing, adding fertilizers and returning manure, have resulted in increased soil organic matter primarily as a result of increased crop production. Similar results were obtained on a Black Chernozem soil at Indian Head, Saskatchewan (*see Chapter 12, Fig. 1*).

Crop Rotation Studies on the Canadian Prairies

A summary of 68 completed and 20 continuing crop rotation studies undertaken by Agriculture Canada in the Prairie provinces have been compiled and synthesized by Campbell et al. (1990). Few of the studies conducted by Agriculture Canada have provided detailed analysis of N and P dynamics in the soil and plant. The influence of fertilizer additions on organic C content and total N content, C/N ratio, potentially mineralizable N content (No), and potentially mineralizable N as a proportion of total N for soils in Brown, Dark Brown and Black soil zones and Solonetzic soil have been reported by Campbell et al. (1990). Nitrogen fertilization for 16 years significantly enhanced content and quality of organic matter in soil at Swift Current (Brown soil zone) (Biederbeck et al., 1984). Carbon and N concentrations were 21 and 15% higher, respectively, in a continuous wheat treatment receiving both N and P than in the continuous wheat receiving P only; the potentially mineralizable N concentration was 24% higher in the treatment receiving both N and P (Table 5). This enhancement of soil quality can be probably be attributed to increased amounts and higher nutrient contents of crop residues applied to soil (Campbell et al., 1990).

Fertilizer affected soil quality in a Dark Brown soil at Lethbridge (Table 5). Application of fertilizer N at a rate of 45 kg ha^{-1} for 18 consecutive years increased the concentrations of soil organic C and N by about 15% over treatments receiving no fertilizer

Table 5. The influence of fertilizer application on organic C and total N contents, C:N ratio, potentially mineralizable N content (No) and potentially mineralizable N as a proportion of total N (Campbell et al., 1990).

Location and duration	Depth	Rotation sequence	Fertilizer treatment	Organic matter characteristics: Organic C	Total N	C:N ratio	No	Total N ratio
	(cm)			------- (%)	-------		(mg kg-1)	(%)
Brown soil zone								
Swift Current 1967-1982	0-7.5	Contin. W	P	1.78	0.197	9.0	185	9.4
			N + P	2.15	0.226	9.5	230	10.2
Dark Brown soil zone								
Lethbridge 1912-1975	0-13	F-W-W	none	1.43	0.141	10.3	151	10.7
			P	1.46	0.138	10.6	140	10.1
			N	1.67	0.155	10.7	207	13.4
			N + P	1.64	0.141	10.6	213	15.1
		Contin. W	none	1.62	0.149	10.9	192	12.9
			P	1.61	0.141	11.5	221	15.7
			N	1.80	0.162	11.1	255	15.7
			N + P	1.88	0.171	11.0	250	14.6
Black soil zone								
Indian Head	0-7.5	F-W	none	2.21	0.179	12.3	-	-
			N + P	2.28	0.186	12.2	-	-
			F-W-W	none	2.25	0.186	12.1	- -
			N + P	2.38	0.200	11.9	-	-
		Contin. W	none	2.43	0.198	12.3	-	-
			N + P	2.59	0.223	11.6	-	-
Melfort	0.7.5	F-W-W	none	5.30	0.501	10.6	-	-
			N + P	5.04	0.498	10.1	-	-
		Contin. W	none	5.92	0.527	11.2	-	-
			N + P	6.02	0.532	11.3	-	-

in continuous wheat or fallow-wheat-wheat (F-W-W) rotations (Janzen, 1987). Phosphorus application had no significant effect on organic matter, probably because of relatively high levels of indigenous soil P, and hence, little response to P. Fertilizer affected the labile organic matter fractions more than total concentrations of soil organic matter. Potentially mineralizable N levels were increased by an average of 33% in N-fertilized soil compared with soil receiving no fertilizer; P fertilizer had no significant effect (Campbell et al., 1990).

The application of N and P fertilizer was shown to enhance concentrations of C and N in the surface soil of the rotation experiment in a Black soil at Indian Head (Table 5) although not all differences were statistically different (Campbell et al., 1990). The benefits of fertilizer application appeared to increase with progressive decline in fallowing frequency. Thus, increases in organic C concentrations amounted to 3, 6, and 7% in the F-W, F-W-W, and continuous wheat treatments, respectively. The corresponding increases in total N concentrations were 4, 8, and 13%, respectively. This interactive effect of fertilizer application and crop rotation can probably be attributed to higher yield responses for wheat grown on stubble than wheat grown on fallow (Campbell et al., 1990).

Application of N and P fertilizer had inconsistent and generally little effect on the content of organic matter of a Black soil at Melfort (Table 5) (Campbell et al., 1990). The absence of beneficial effect of fertilizer application to the organic matter content of this soil, in contrast to results obtained for other soil zones, may be related to the comparatively high original content of organic matter in this soil (Campbell et al., 1990).

CONCLUSIONS

Voluminous data on crop yields of different crop rotations have been complied by Campbell et al. (1990) and will not be summarized here. However, the data from the Breton Plots and long-term rotations of Agriculture Canada in the Prairies, clearly show that fertilizer inputs, especially N, have increased the productive capacity of soils in different soil zones. The addition of C through roots and input of N through biologically fixed N or fertilizers have improved marginal soils. The formation of organic matter is a continual process mediated by microorganisms and soil fauna and is directly dependent on the quantity, quality and placement of above- and below-ground residues. Data from the Breton plots and from Indian Head long term rotations suggest that the impact of root C inputs on organic matter content should be re-evaluated.

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