Cultivation Effects on the Amounts and Concentration of Carbon, Nitrogen, and Phosphorus in Grassland Soils[1]

H. Tiessen, J. W. B. Stewart, and J. R. Bettany[2]

ABSTRACT

Cultivation has substantially reduced the organic matter contents of many prairie soils. This study attempts to quantify the losses of C, N, and P from three prairie soils of different textures during cultivation. For this purpose cultivated and adjacent uncultivated soils (2 Cryoborolls and 1 Cryorthent) were sampled and their C, N, and P contents as well as their bulk densities and horizon depths were compared.

Reductions of about 35% in the C concentration were observed in clay and silt loam soils after 60 to 70 years of cultivation. At the same time reductions in N concentrations were greatly influenced by the presence or absence of legume [alfalfa, (*Medicago sativa* L.)] crops grown in the fields and losses varied between 18 and 34%. Phosphorus concentrations were reduced by 12% and all P losses were accounted for by the organic fraction. During a similar period of cultivation a lighter textured sandy loam had experienced greater reductions in C, N, and P concentrations of 46, 46, and 29%, respectively. In this soil P was lost from both the organic and inorganic fractions. Prolonged cultivation of 90 years did not result in a decrease in the rates of losses of C, N, and P on the silt loam soil.

Conversion of concentration data to area based total C, N, and P budgets resulted in a decrease in the differences seen between cultivated and uncultivated soils. This was caused by an increase of soil bulk densities under cultivation and by an increase in the standard deviations of the data due to variability of horizon depths in cultivated fields.

Additional index words: **Organic matter losses, Erosion losses.**

A NUMBER of investigators have studied the depletion of organic matter in cultivated soils by a comparison of the C and N contents of a cultivated soil with those of a similar soil that has remained under permanent pasture or virgin vegetation (Shutt, 1925; Newton et al., 1945; Haas et al., 1957). From these studies, it appears that soils cultivated for small grain production lose about 1% of their organic C per year during the first 20 to 30 years of cultivation. Losses of N were usually of similar magnitude but were found to depend greatly on cropping practices (Haas et al., 1957; Unger, 1968). The fate of P associated with organic matter during cultivation has so far attracted much less attention than C and N. This is partly due to the difficulties encountered in the separate determination of organic and inorganic P (Fares et al., 1974). The percentage of soil P that is in organic form varies widely, and even in a small area of closely related soils it may range from 27 to 41% (Spratt and McCurdy, 1966). Phosphorus losses amount to only about 0.3% per year and frequently the organic P fraction accounts for all P losses (Haas et al., 1961). The rate of loss of organic P relative to C losses, has been found to vary considerably depending on management and climatic conditions (Barrow, 1961).

Much of the literature agrees on these general trends, but data for individual sites show great variations. Actual losses of C and N ranged from 0 to 2.5 and 0 to 2% per year, respectively. Some workers even report increases of organic matter, N, or P under cultivation (Wheeting, 1937; Dorman, 1933). Some of the reasons for such variability may lie in the dependence of the rates of loss of soil organic matter on the initial amounts of C or N present (Haas et al., 1957; Reinhorn and Avnimelech, 1974) and on soil texture (De Haan, 1977; Kruglov and Proshlyakov, 1980; Herlihy, 1979).

It has frequently been suggested that the losses of organic matter diminish after an initial flush and eventually cease when the soil has attained an organic matter content that represents an equilibrium for the type of cultivation and crop rotation to which it is subjected. Shutt (1925) suggested that the degradation of soil organic matter effectively ceased after 22 years of cultivation. Based on radio-carbon dating of bulk surface soil samples of Prairie soils, Martel and Paul (1974) revised this figure to between 60 and 70 years, and more recently Paul and Van Veen (1978) and Voroney et al. (1981) suggested that losses of organic matter may continue due to the effects of wind and water erosion on cultivated fields. It has also been shown that with prolonged cultivation (Chang, 1950), N losses extend below the surface soil and thus may continue at a greater rate than could be deduced from surface soil samples alone. Barber (1979) calculated the net P export from a field by monitoring crop export and fertilizer inputs and compared the results to observed changes in P concentration in the topsoil. The observed concentration changes accounted for only half of the P export. These results, as well as Dorman's (1933) data, suggest that P may be taken up by the plants from lower soil layers and recycled into the topsoil.

In much of the literature only changes in the concentrations of C, N, or P with cultivation are reported or such data are converted to an area basis by using a single conversion factor (such as 2 million kg of soil per hectare—furrow slice of 0 to 15 cm) (Shutt, 1925; Newton et al., 1945). Such an approach assumes an average bulk density for all fields under study. It is known, though, that cultivation may increase bulk densities of the top soil by up to 100% (Martel and Deschenes, 1976; Davidson et al., 1967; De Haan, 1977). Changes in bulk density may also vary considerably depending on soil texture (Martel and Deschenes, 1976; De Haan, 1977) and organic matter content (Curtis and Post, 1964). Combining concentration, bulk density, and horizon depth data to obtain area based organic matter budgets leads to an increase in the variability of results. Standard deviations of combined data are frequently such that relationships seen with concentration data are entirely obscured (Martel and Deschenes, 1976).

The present investigation attempts to evaluate the losses of C, N, and P from three soils of different

[1] Publication No. R285 of the Saskatchewan Institute of Pedology, Saskatoon, Sask., Canada. Received 4 May 1981.

[2] Graduate student, professor, and associate professor, prespectively, Dep. of Soil Science, Univ. of Saskatchewan, Saskatoon, Sask., Canada S7N OWO.

Table 1. Comparison of A and B horizons of Blaine Lake native and cultivated soils (4, 60, and 90 years of cultivation).†

		Native prairie	4 yr. cultivation		60 yr. cultivation		90 yr. cultivation	
A Horizon				Δ%‡		Δ%		Δ%
Organic C	mg/g	47.9 ± 10.2	49.0 ± 10.2	NS¶	32.8 ± 5.2	−32	20.0 ± 3.2	−58
Total N	mg/g	4.42 ± 0.74	4.39 ± 0.75	NS	2.91 ± 0.37	−34	2.18 ± 0.11	−51
Total P	μg/g	823 ± 92	970 ± 94	NS	724 ± 53	−12	625 ± 32	−24
Inorganic P	μg/g	178 ± 47	185 ± 47	NS	196 ± 8	NS	207 ± 5	NS
Organic P	μg/g	645 ± 125	686 ± 138	NS	528 ± 54	−18	418 ± 37	−35
C:N		10.8	11.2	--	11.3	--	9.2	--
C:Porg		74	71	--	62	--	48	--
Depth	cm	10.8 ± 1.7	13.3 ± 3.9	NS	14.5 ± 5.6	NS	9.0 ± 1.4	−16
Bulk density	6/cm^3	1.04 ± 0.06	1.04 ± 0.19	NS	1.22 ± 0.11	+17	1.30 ± 0.10	+25
B Horizon				Δ%		Δ%		Δ%
Organic C	mg/g	15.5 ± 3.2	18.2 ± 3.8	NS	14.8 ± 5.0	NS	11.3 ± 4.4	−27
Total N	mg/g	1.65 ± 0.32	1.77 ± 0.29	NS	1.29 ± 0.29	−22	1.14 ± 0.28	−31
Total P	μg/g	567 ± 62	591 ± 36	NS	589 ± 138	NS	518 ± 95	NS
Inorganic P	μg/g	171 ± 51	161 ± 21	NS	204 ± 37	NS	199 ± 13	NS
Organic P	μg/g	397 ± 67	431 ± 52	NS	385 ● 116	NS	319 ± 94	NS
Depth§	cm	29.8 ± 6.3	30.6 ± 6.2	NS	31.2 ± 8.0	NS	20.0 ± 1.5	−33
Bulk density	g/cm^3	1.33 ± 0.06	1.39 ± 0.11	NS	1.39 ± 0.06	NS	1.38 ± 0.08	NS

† Data presented give means and standard deviations of replicate sample sites.
‡ Δ% indicate the % change of a quantity with cultivation based on values of the native site.
§ Depth from soil surface to the bottom of the B horizon.
¶ NS indicates Δ% that are not significant at 95% probability level.

textures that have been cultivated for different lengths of time.

MATERIALS AND METHODS

Three field sites representing three soil associations (Acton and Ellis, 1978) were sampled for analysis:

1. *Blaine Lake association:* an orthic black (udic moisture regime) chernozemic (Typic Cryoboroll) formed on very uniform lacustrine silt loam with approximately 10 cm A_h (A1) and a 20-cm thick B_m (B2) horizon underlain by a calcareous C. Four different fields were sampled, all within an area of 1 km^2. The fields represented a virgin prairie, a long-term stocked pasture that was broken and cultivated 4 years ago, a 60-year-old cultivated field and a 90-year-old cultivated field. The topography over the entire area was uniform gently undulating (0.5 to 2.0% slope gradients).
2. *Bradwell association:* an orthic dark brown (typic moisture regime) chernozemic (Typic Cryoboroll) soil formed on lacustrine and glacio-fluvial sandy loam with an A_h of 15 cm and a B_m of 25 cm thickness underlain by a calcareous C horizon. Virgin prairie and a field under 65 years of cultivation were sampled at sites 200 m apart. The topography in the area is roughly undulating (1 to 5% gradients).
3. *Sutherland association:* a dark brown (typic moisture regime) chernozemic soil with mainly rego (Vertic Cryorthent) and some orthic profile development (Vertic Cryoboroll). It has formed on heavy lacustrine, calcareous deposits of clay to heavy clay texture that give it a vertic nature. The topography is very gently sloping with gradients of 0.5 to 2%. A virgin prairie and a field under 70 years of cultivation were sampled at sites, about 150 m apart.

Method of Soil Sampling

Approximately 20 points across each site were sampled with a 2.5-cm hand probe to a depth of approximately 1.5 m and examined to establish uniformity of profiles and parent material. Eight or nine cores of 15-cm diam were then taken with a mechanical punch from each field and sectioned into A, B, and C horizons, or into about 16-cm increments in the case of the grumic (vertic) clay soil. Air dry bulk densities were determined for each horizon or layer of each core (no stones >2 mm were present in these lacustrine soils). Individual sections were then crushed to 2 mm, mixed, and subsampled. Subsamples were ground to 100 mesh for analysis. All results reported are the means of determinations made on equivalent sections of the eight or nine replicate cores from each field.

Chemical Analyses

Carbon was determined by dry combustion as described by Tiessen et al. (1981). Samples were treated with 1 *N* HCl at 70 C to remove carbonates and burnt in a tube furnace. The evolved CO_2 was trapped in NaOH and titrated, utilizing the dissociation points of carbonic acid.

Total N and total P were determined by digestion of the soil with H_2SO_4 and H_2O_2 followed by analysis on a Technicon Auto Analyser (Thomas et al., 1967). Inorganic phosphate was extracted by shaking for 18 hours with 0.5 *M* H_2SO_4 and determined by automated analysis. Organic phosphorus (Po) was calculated as the difference between inorganic and total phosphorus.

RESULTS AND DISCUSSION

Changes in the Concentrations of C, N, and P with Cultivation

Four years of cultivation have not significantly changed the C, N, and P concentrations of the Blaine Lake pasture soil (Table 1). The depth of cultivation in Saskatchewan is usually only about 10 cm. The A horizon therefore remained uncontaminated with B horizon material.

Cultivation of 60 to 70 years duration has reduced concentrations of organic carbon and of P by approximately 35 and 12%, respectively, in the Sutherland clay and the Blaine Lake silt loam (Tables 1 and 2). The reduction of P concentration in both soils is entirely accounted for by the organic P fraction. Nitrogen concentrations in the Blaine Lake soil were reduced by 34% while figures for the Sutherland show a decrease of only 18%. This discrepancy (of about 900 kg/ha) can in part be explained by a 7-year alfalfa (*Medicago sativa* L.) ley that was grown on the Sutherland soil between 1971 and 1977. The N fixed during this period appears to persist and raise the N status

Table 2. Comparison of the top 18 cm and 18 to 31 cm layers of Sutherland native prairie and cultivated soils (70 years of cultivation).†

		Native prairie	70 year cultivation	
A Horizon				Δ%‡
Organic C	mg/g	37.7 ± 6.5	23.7 ± 1.8	−37
Total N	mg/g	3.04 ± 0.45	2.50 ± 0.15	−18
Total P	μg/g	756 ± 28	661 ± 31	−12
Inorganic P	μg/g	256 ± 44	254 ± 19	NS¶
Organic P	μg/g	492 ± 52	407 ± 30	−17
C:N		12.4	9.5	--
C:Porg		77	58	--
Depth	cm	18	18	--
Bulk density	g/cm³	0.98 ± 0.07	1.28 ± 0.12	+13
B Horizon				
Organic C	mg/g	22.5 ± 7.5	19.6 ± 5.9	NS
Total N	mg/g	2.35 ± 0.85	1.92 ± 0.57	NS
Total P	μg/g	696 ± 58	594 ± 54	−15
Inorganic P	μg/g	281 ± 54	249 ± 40	NS
Organic P	μg/g	416 ± 92	345 ± 62	NS
Depth§	cm	31	31	--
Bulk density	g/cm³	1.21 ± 0.08	1.38 ± 0.27	NS

† Data presented give means and standard deviations of replicate sample sites.
‡ Δ% indicate the % change of a quantity with cultivation based on values of the native site.
§ Depth from soil surface to the bottom of the B horizon.
¶ NS indicates Δ% that are not significant at 95% probability level.

Table 3. Comparison of A and B horizons of Bradwell native prairie and cultivated soils (65 years of cultivation).†

		Native prairie	65 year cultivation	
A Horizon				Δ%‡
Organic C	mg/g	32.2 ± 8.0	17.4 ± 1.6	−46
Total N	mg/g	3.28 ± 0.54	1.76 ± 0.14	−46
total P	μg/g	746 ± 101	527 ± 15	−29
Inorganic P	μg/g	300 ± 84	212 ± 46	−29
Organic P	μg/g	446 ± 46	315 ± 21	−29
C:N		9.8	9.9	--
C:Porg		72	55	--
Depth	cm	14.8 ± 0.8	13.8 ± 4.9	NS¶
Bulk density	g/cm³	1.07 ± 0.12	1.45 ± 0.12	+36
B Horizon				
Organic C	mg/g	12.6 ± 0.9	10.8 ± 0.7	−14
Total N	mg/g	1.29 ± 0.14	1.13 ± 0.03	−12
Total P	μg/g	588 ± 42	538 ± 29	NS
Inorganic P	μg/g	241 ± 45	284 ± 44	+3
Organic P	μg/g	317 ± 32	255 ± 20	−20
Depth§	cm	33.9 ± 7.3	36.1 ± 6.5	NS
Bulk density	g/cm³	1.39 ± 0.14	1.42 ± 0.8	NS

† Data presented give means and standard deviations of replicate sample sites.
‡ Δ% indicate the % change of a quantity with cultivation based on values of the native site.
§ Depth from soil surface to the bottom of the B horizon.
¶ NS indicates Δ% that are not significant at 95% probability level.

of the soil significantly for at least four growing seasons after the legumes were plowed under. A similar, though smaller effect was reported by Haas et al. (1957) after a 3-year legume ley.

A comparable period of cultivation on the lighter textured Bradwell association resulted in much greater decreases in C, N, and P concentrations in the top soil (Table 3). This finding substantiates conclusions by Kruglov and Proshlyakov (1980) who observed that sandy soils under cultivation need the greatest inputs of organic matter in order to maintain organic matter levels. At the same time losses extended significantly into the B horizon, with reductions of C, N, and P concentrations in the B of 14, 12, and 20% respectively, while the heavier soils showed essentially no significant losses from the B horizons (Tables 1, 2, and 3). It is of interest to note that in the coarse textured Bradwell soil, organic and inorganic P contributed equally to the decrease in P content with cultivation while in the other soils only organic P was depleted.

Prolonged cultivation caused the reduction of C and N concentrations in the Blaine Lake soil to extend into the B horizon, resulting in reductions of 27 and 31% of C and N, respectively, after 90 years (no significant changes in P concentrations were observed) (Table 1). At the same time, concentrations of C, N, and P in the A horizon continued to decline without any indication of levelling off. Changes in C:N ratios with cultivation varied widely while C:Po ratios showed a very similar behavior in all three soils, decreasing from about 75 to 60 in 65 years of cultivation and dropping further to about 50 after 90 years. Under the present management of low fertilizer inputs, organic P shows a very constant decline relative to the loss of organic carbon. The apparent relative stability of organic P as compared to C and N could be attributed to an inherent property of the biological-biochemical mineralization processes during which organic P is mineralized as a result of a demand for P and is not released as a consequence of C mineralization (McGill and Cole, 1981) or it may reflect a biocycling of P through deeper reaching plant roots causing a relative P enrichment in the top soil (Barber, 1979).

Total Losses of C, N, and P per Hectare

Total losses of C, N, and P on an area basis were calculated by multiplying concentration values of each individual core section with the bulk density and the thickness of that section. The amounts of C, N, and P found in this way were summed for each core to the bottom of the B horizon (or to a depth of 31 cm in the case of the vertic Sutherland soil). The means for each field were calculated from the replicate cores (Table 4).

Cultivation has significantly increased the bulk density of the top horizons of all three soils (Tables 1, 2, and 3). Such an increase in bulk density would be expected to be paralleled by a decrease in A horizon thickness. The data obtained, however, show no such effect because A horizon thickness becomes much more variable under cultivation (Tables 1 and 3). The increased variability renders most changes in A horizon thickness statistically insignificant. This effect can be explained by cultivation induced translocations of top soil within the field, that gradually fill the lower areas and deplete A horizons on the knolls. Observations in the field substantiated this assumption.

Since area based data are obtained by multiplying concentration data with bulk density and horizon thickness, the decreases in the total quantities of C, N, and P per hectare with cultivation appear much smaller than would be expected from concentration data alone (in addition percent changes appear smaller due to the incorporation of B horizon data). No significant changes in the total amounts of C, N, or P

Table 4. Area-based total contents and losses of C, N, and P in the Blaine Lake, Sutherland, and Bradwell soils under native prairie and after cultivation.†

Soil	Years of cultivation			C	N	Pt	Pi	Po
Blaine Lake§	native	content	metric tons/hectare	87 ± 12	8.7 ± 1.1	2.3 ± 0.4	0.7 ± 0.2	1.6 ± 0.4
	90	content	metric tons/hectare	43 ± 12	4.9 ± 0.5	1.6 ± 0.2	0.6 ± 0.02	1.0 ± 0.2
		loss	metric tons/hectare	44	3.8	0.7	–	0.6
		loss	Δ%‡	−51	−44	−30	NS¶	−38
Sutherland	native	content	metric tons/hectare	109 ± 20	9.2 ± 0.8	2.4 ± 0.1	0.8 ± 0.1	1.6 ± 0.1
	70	content	metric tons/hectare	80 ± 10	8.4 ± 1.2	2.6 ± 0.3	1.1 ± 0.2	1.5 ± 0.2
		loss	metric tons/hectare	29	0.8	–	–	–
		loss	Δ%	−27	−9	NS	NS	NS
Bradwell	native	content	metric tons/hectare	90 ± 9.6	9.0 ± 1.0	2.9 ± 0.5	1.2 ± 0.4	1.7 ± 0.2
	65	content	metric tons/hectare	73 ± 11	7.2 ± 0.9	2.9 ± 0.4	1.5 ± 0.3	1.4 ± 0.2
		loss	metric tons/hectare	17	1.8	–	–	0.3
		loss	Δ%	−19	−20	NS	NS	−18

† Data presented give means and standard deviations of replicate sample sites.
‡ Δ% indicate the % change of a quantity with cultivation based on values of the native site.
§ The 60-year-old field was not significantly different from the native prairie.
¶ NS indicates Δ% that are not significant at 95% probability level.

were in fact recorded for the Blaine Lake soil after 60 years of cultivation. On the Sutherland and Bradwell soils net losses of C were 29 and 17 metric tons per hectare, respectively, and N losses amounted to 0.8 and 1.8 metric tons per hectare. Changes in P contents were obliterated by the conversion to an area basis with the exception of a small loss of organic P from the Bradwell soil (Table 4).

After 90 years of cultivation on the Blaine Lake soil C, N, and P concentrations were greatly reduced (Table 1), the bulk density of the A horizon was increased by 25% and the solum thickness was reduced by 30% indicating considerable erosive losses. The net effect is a significant loss of 44, 3.8 and 0.7 metric tons per hectare of C, N, and P, respectively (Table 4).

CONCLUSION

This study shows that losses of soil organic matter do not appear to level off after 60 to 70 years of cultivation as suggested by previous reports (Martel and Paul, 1974). The continued decline is caused by increased erosive losses associated with lowered organic matter contents of the soil (Model of Voroney et al., 1981), and by an extension of the zone of depletion into lower soil horizons. It is, therefore, necessary to sample the entire solum if changes in the concentrations of the soil organic matter and plant nutrients with long-term cultivation are to be described adequately.

Soil P is primarily lost from the organic P fraction until this fraction is depleted sufficiently to allow the dissolution of apatites to occur. Alternatively, in soils with greater water infiltration, dissolution of apatites may occur concurrently with the mineralization of organic P. In agreement with this observation Williams and Walker (1968) and Westin and Buntley (1967) report a more pronounced depletion of calcium-bound P relative to organic P in sequences of increasingly weathered soils.

The evaluation of total organic matter budgets on an area basis requires that characteristics of the entire solum such as horizon thickness, total solum depth, and bulk density be considered. The added variability of data resulting from the inclusion of these factors necessitates very careful site selection and sampling techniques as well as sufficient sample replicates in each field for adequate statistical analysis (Martel and Deschenes, 1976). The basic units in which organic matter levels are to be expressed depend on the purpose of the investigation. Concentration data (wt./wt.) can give a measure of the stability and turnover of organic matter in soil. Such data would show the amounts of organic matter associated with amounts of stable mineral matter and could be treated in a manner similar to the weathering indices of the mineralogist (St. Arnaud and Sudom, 1981), in which the decay of the labile mineral is assessed relative to a more inert mineral component of the soil. Concentration data, corrected for changes in bulk density (wt./vol.), give an indication of the abundance of organic matter relative to plant rooting volume (Mehlich, 1980). The incorporation of values for horizon thickness into such data (wt./area-solum depth) gives a measure for the total amounts of organic matter lost from a soil due to the combined effects of mineralization and erosion processes. At this level fertility data attempt to describe field conditions of considerable complexity and are therefore subject to relatively large errors.

LITERATURE CITED

1. Acton, D. F., and J. G. Ellis. 1978. The soils of the Saskatoon map area 73-B Saskatchewan, Univ. of Saskatchewan Extension Division. Saskatoon. Publication 306.
2. Barber, S. A. 1979. Soil phosphorus after 25 years of cropping with five rates of phosphorus application. Comm. in Soil Sci. Plant Anal. 10:1459–1468.
3. Barrow, N. J. 1961. Phosphorus in soil organic matter. Soils Fert. 24:169–173.
4. Brown, A. L., F. A. Wyatt, and J. D. Newton. 1942. Effects of cultivation and cropping on the chemical composition of some western Canadian prairie soils. Sci. Agric. 23:229–232.
5. Chang, C. W. 1950. Effect of long-time cropping on soil properties in northeastern New Mexico. Soil Sci. 69:359–368.
6. Curtis, R. O., and B. W. Post. 1964. Estimating bulk density from organic matter content in some Vermont forest soils. Soil Sci. Soc. Am. Proc. 28:285–286.
7. Davidson, J. M., F. Gray, and D. I. Pinson. 1967. Changes in organic matter and bulk density with depth under two cropping systems. Agron. J. 59:375–378.
8. De Haan, S. 1977. Humus, its formation, its relation with the mineral part of the soil, and its significance for soil productivity. p. 21–30. *In* Soil Organic Matter Studies. I.A.E.A., Vienna. 1977. Vol. 1.
9. Dorman, C. 1933. A comparative study of cropped and virgin soils Soil Sci. 36:101–112.

10. Fares, F., J. C. Fardeau, and F. Jacquin. 1974. Etude quantitative du phosphore organique dans differents types de sols. Phosphore Agric. 63:25–41.
11. Haas, H. J., C. E. Evans, and E. F. Miles. 1957. Nitrogen and carbon changes in great plains soils as influenced by cropping and soil treatments. U.S.D.A. Tech. Bull. 1164.
12. ———, D. L. Grunes, and G. A. Reichman. 1961. Phosphorus changes in great plains soils as influenced by cropping and manure applications. Soil Sci. Soc. Am. Proc. 25:214–218.
13. Herlihy, M. 1979. Nitrogen mineralization in soils of varying texture, moisture, and organic matter. I. Potential and experimental values in fallow soils. Plant Soil 53:255–268.
14. Kruglov, L. V., and A. A. Proshlyakov. 1980. Humus replenishment in the plowed soils of the non-chernozem belt. Sov. Soil Sci. 11:313–317.
15. Martel, Y. A., and E. A. Paul. 1974. Effects of cultivation on the organic matter of grassland soils as determined by fractionation and radiocarbon dating. Can. J. Soil Sci. 54:419–426.
16. ———, and J. M. Deschenes. 1976. Les effets de la mise en culture et de la prairie prolonges sur le carbone, l'azote et la structure de quelques sols due Quebec. Can. J. Soil Sci. 56:373–383.
17. Mehlich, A. 1980. Why not use relevant data in soil-plant relationships? Soil Sci. Soc. Am. J. 44:440.
18. McGill, W. B., and C. V. Cole. 1981. Comparative aspects of cycling of organic C, N, S, and P through soil organic matter. Geoderma 26: 267–286.
19. Newton, J. D., F. A. Wyatt, and A. L. Brown. 1945. Effects of cultivation and cropping on the chemical composition of some Western Canada prairie province soils, Part 3. Sci. Agric. 25:718–737.
20. Paul, E. A., and J. A. Van Veen. 1978. The use of tracers to determine the dynamic nature of organic matter. Proc. 11th Congr. Soil Sci., Edmonton, Alberta. Vol. 3:61–102.
21. Reinhorn, T., and Y. Avnimelech. 1974. N-release associated with the decrease in soil organic matter of newly cultivated soils. J. Environ. Qual. 3:118–121.
22. Shutt, F. T. 1925. Influence of grain growing on the nitrogen and organic matter content of western prairie soils of Canada. Dominion of Canada Dep. of Agric. Bull. 44. N.S.
23. Spratt, E. D., and E. V. McCurdy. 1966. The effect of various long-term soil fertility treatments on the phosphorus status of a clay chernozem. Can. J. Sci. 46:29–36.
24. St. Arnaud, R. J., and M. D. Sudom. 1981. Mineral distribution and weathering in chernozemic and luvisolic soils from central Saskatchewan. Can. J. Soil Sci. 61:79–89.
25. Thomas, R. L., R. W. Sheard, and J. R. Moyer. 1967. Comparison of conventional and automated procedures for N, P, and K analysis of plant material using a single digestion. Agron. J. 59:240–243.
26. Tiessen, H., J. R. Bettany, and J. W. B. Stewart. 1981. An improved method for the determination of carbon in soils and soil extracts by dry combustion. Comm. Soil Sci. Plant Anal. 12:211–218.
27. Unger, P. W. 1968. Soil organic matter and nitrogen changes during 24 years of dry land wheat tillage and cropping practices. Soil Sci. Soc. Am. Proc. 32:427–429.
28. Voroney, R. P., J. A. Van Veen, and E. A. Paul. 1981. Organic C dynamics in grassland soils. 2. Model validation and simulation of the long-term effects of cultivation and rainfall erosion. Can. J. Soil Sci. 61:211–224.
29. Westin, F. C., and G. J. Buntley. 1967 Soil phosphorus in South Dakota: 3. Phosphorus fractions in some Borolls and Ustolls. Soil Sci. Soc. Am. Proc. 31:521–528.
30. Wheeting, L. C. 1937. Changes in organic matter in western Washington soils as a result of cropping. Soil Sci. 44:143–181.
31. Williams, J. D. H., and T. W. Walker. 1968. Fractionation of phosphate in a maturity sequence of New Zealand basaltic soil profiles: 2. Soil Sci. 107:213–219.