0038-075X/90/1506-0851$02.00/0
SOIL SCIENCE

December 1990
Vol. 150, No. 6
Printed in U.S.A.

CHANGES IN SOIL PROPERTIES IN A CENTRAL PLAINS RANGELAND SOIL AFTER 3, 20, AND 60 YEARS OF CULTIVATION[1]

R. A. BOWMAN,[2] J. D. REEDER,[3] and R. W. LOBER[3]

Cultivation of native rangeland generally leads to a reduction in its organic C and N. However, most studies comparing duration of cultivation to organic matter changes are usually confounded by differences in soil type and/or management practices or are restricted to comparisons of a single long-term cultivation period with an adjacent rangeland site. Our study was conducted to determine short- and long-term changes in soil properties due to cultivation where major influences from soil type and management were minimal. Four contiguous sites where cultivation had occurred for 0, 3, 20, or 60 years were sampled. Soil samples were analyzed for total and labile organic C, N, and P concentrations and for selected physical and chemical properties. Increasing years of cultivation resulted in decreasing silt content of the soil surface and a decrease in depth to lime. After 60 years of cultivation, total soil organic C, N, and P had declined by 55–63% in the surface 15 cm, but about half of this loss occurred during the first 3 years of cultivation. In comparison, the labile fractions of the organic C and N declined by 67–72% after 60 years, but over 80% of labile C loss and more than 60% of the labile N loss occurred during the first 3 years of cultivation. Although half of the total decline in P came from the organic P pool, this decline represented about a 60% decrease in the organic P level in the first 3 years. The proportion of organic C in labile form declined after 3 years of cultivation but thereafter increased to a proportion comparable to the adjacent rangeland condition. The proportion of organic N in labile form was not significantly affected by cultivation. The data indicate that this sandy soil is highly susceptible to organic matter decomposition with cultivation.

[1] Contributions from the USDA-ARS Great Plains Systems Research and Hydro-Ecosystem Research Units.

[2] USDA-ARS Crops Research Laboratory, 1701 Center Ave., Fort Collins CO 80526.

[3] USDA-ARS, P. O. Box E, Fort Collins CO 80522.

Received 8 Feb. 1990; revised 26 April 1990.

The effects of cropping virgin or rangeland sites on soil nutrient content have been documented in the Great Plains since 1910 when Stewart and Hirst (1914) reported changes in soil N content as a consequence of dryland wheat farming. Two decades later, Salter and Green (1933) showed that losses of soil N were least with rotations containing a legume and greatest with continuous row crops. These researchers developed quantitative equations for N losses which were later modified by Jenny (1941) who introduced a factor for annual N additions. Although early results were mixed regarding losses or gains in organic matter due to cropping, generally losses of 25 to 40% have been documented (Russel 1929; Newton et al. 1945). Haas et al. (1957) summarized the bulk of the early work on C and N changes for 24 dryland research stations in the Great Plains and reported losses of 24 to 60% (average = 39%) of total soil N on soils cropped 30 to 43 years. Subsequent studies have reported similar levels of organic C and N losses with cultivation on the Great Plains (Bauer and Black 1981; Aguilar et al. 1988).

With the advent of conservation tillage, deterioration of soil properties (Blevins et al. 1984) and losses in nutrients have been essentially reversed (Blevins et al. 1977; Doran 1980; Black and Siddoway 1979; Greb 1979). Lamb et al. (1985) evaluated wheat-fallow tillage systems for N changes in western Nebraska fields cultivated for 12 years and found decreasing losses as the level of clean tillage decreased. Janzen (1987) reported decreased losses of organic matter with decreasing frequency of fallow in the cropping system for Canadian Chernozemic soils. However, in areas where conventional or clean tillage predominate, losses of soil, water, and nutrients have continued to be appreciable (Campbell and Souster 1982; Dick 1983; Hill and Blevins 1973).

Losses of soil organic matter with the use of clean-till cultivation result from increased exposure to losses by wind and water erosion and from enhanced organic matter decomposition through mixing, increased aeration, and other factors. Thus, the length of cultivation significantly effects the quality and quantity of soil organic matter. However, studies comparing duration of cultivation with organic matter changes usually have been confounded by differences in soil type and management practices or have been restricted to comparisons of a single long-term cultivation period with a rangeland site (Bauer and Black 1981). Additionally, although research conducted during the past 60 years has provided valuable information about the degradation of soil organic matter with cultivation, most of these investigations have been concerned with total losses of organic matter as measured by changes in total C, N, or P contents, and little is known about changes in the labile fraction of the organic matter. The objectives of this study were to document short- and long-term changes over time in selected soil physical and chemical properties and in total and labile organic C, N, and P concentrations resulting from cultivation where major influences from soil type and management were minimal.

MATERIALS AND METHODS

Field description and sampling

The study site was located in Weld County in northeast Colorado near the town of Grover. Average precipitation for the area is about 330 mm. Frost-free period averages 135 days, with an average daily minimum temperature of 9°C and an average daily maximum of 26°C. The study site was located on a relatively flat (<3% slope) area mapped as an Ascalon sandy loam (aridic Argiustoll), one of the predominant series of the Central Great Plains.

Four contiguous sites, one native rangeland site, and three cultivated sites were selected in 1986. These sites were either adjacent to one another or divided by a county road; maximum distance separating the sites was 1600 m. The rangeland site (zero time of cultivation) is typical short-grass prairie steppe and had been heavily grazed. Predominant species were blue grama (*Bouteloua gracilis*) and Buffalo grass (*Buchole dactyloides*), with pockets of western wheatgrass (*Agropyron smithii*), cheatgrass (*Bromus tectorum*), and pricklypear cacti (*Opuntia polyacantha*). The three cultivated areas had been under cultivation since 1983 (3 years of cultivation), 1966 (20 years of cultivation), and 1926 (60 years of cultivation). While farming history prior to 1966 was diverse (wheat, beans, potatoes), the area has been essentially in clean-till dryland wheat-fallow rotations for the last 25 years. Fertilizer was rarely applied to the cropland and when applied was usually N only. The last recorded application of fertilizer to the cultivated sites was in 1983. Average wheat yields in 1986 were about 2700 kg hectare^{-1} for the 3-year site and about 1500 kg hectare^{-1} for the 20-year site. Yield information for the 60-year site was not known definitely except that it was lower than the 20-year site. In comparison, average yield for the area (northeast Colorado) in 1986 was about 1750 kg hectare^{-1}. Both the 20- and 60-year fields were put into the Conservation Reserve Program (CRP) in 1987.

Soil samples were collected in September 1986. All samples from the three cropped sites were taken from fallowed areas. Each site was at least 64 hectares (800 × 800 m) in size. Field sampling consisted of three replications spaced approximately 300 m from one another. At each replication location three subsamples were taken at least 20 m apart and composited. Because the main objective of the study was to assess physical and chemical changes resulting from surface perturbations (i.e., cultivation and wind erosion), samples were taken only at two depths: 0 to 15 cm (the approximate plow layer) and 15 to 30 cm. Data below 30-cm depth were collected to document solum depth and depth to free lime only.

Soil samples were brought back to the laboratory and air-dried for 1 week. Visible plant material (crop residues and roots) was handpicked from the soil samples before they were ground to pass through a 2-mm sieve and stored at room temperature for physical, chemical, and biological analyses.

Laboratory analyses

Selected physical and chemical soil properties of the four sites are presented in Table 1. Soil pH was determined on a 1:1 soil to distilled water mixture (McLean 1982). Primary particle size analysis was determined by a hydrometer method slightly modified from Gee and Bauder (1986) and bulk density by a single-cylinder core method (Blake and Hartge 1986). Cation exchange capacity was determined by Na saturation (Rhoades 1982). Soil water content at

TABLE 1

Selected physical and chemical properties of a rangeland site and three adjacent cultivated sites

Length of cultivation	Depth to lime	Depth sampled	pH (1:1)	Sand	Silt	Clay	Bulk density	Water content at: −0.03 MPa	Water content at: −1.5 MPa	Cation exchange capacity
y	cm				%		$Mg \cdot m^{-3}$	$kg \cdot kg^{-1}$		$cmol_c \cdot kh^{-1}$
0	50–65	0–15	7.1	63	23	14	1.54	0.130	0.070	14.2
		15–30	7.5	67	18	15	1.55	0.130	0.070	17.5
3	50–66	0–15	6.4	71	15	14	1.40	0.070	0.070	8.8
		15–30	7.2	73	14	13	1.60	0.090	0.065	11.6
20	20–55	0–15	6.9	71	16	13	1.50	0.101	0.065	9.4
		15–30	7.2	67	16	17	1.62	0.095	0.065	9.2
60	5–50	0–15	6.7	79	9	12	1.51	0.087	0.055	7.6
		15–30	7.2	71	12	17	1.65	0.085	0.055	12.1

−0.033 and −1.5 MPa (megapascals) were determined by the pressure cell method (Klute 1986). Total organic C was determined by the Wakley-Black method adapted for spectrophotometric determination (Sims and Haby 1971). This colorimetric method was previously tested against dry combustion for a similar Ascalon soil series and yielded greater than 90% of combustion C values. Soil carbohydrate was extracted by a procedure similar to that of Cheshire (1979). Sugars were quantified by the anthrone procedure (Brink et al. 1960). Total soil N was determined by the standard Kjeldahl procedure described by Bremner and Mulvaney (1982), and mineral N (NH_4-N and NO_3-N) were determined by KCl extraction and colorimetric analyses of the extracts with a Lachat[4] Automated Ion analyzer. Total P was determined by a $H_2SO_4/H_2O_2/HF$ digestion method (Bowman 1988), total organic P by an ignition procedure (Saunders and Williams 1955), and labile P by bicarbonate extraction (Olsen et al. 1954).

An aerobic incubation procedure was used to determine the potential of each soil to mineralize organic C and N. The incubation unit consisted of a tightly closed 0.95 L Mason[4] jar which contained (1) a 15-g soil sample in a 125-mL Erlenmeyer flask, wetted with distilled water to soil water content corresponding to −0.33 MPa soil water potential and (2) a small vial containing 6 mL of 0.5 *M* NaOH used to evaluate CO_2 production. Samples were incubated at 30°C for 21 days. Periodically throughout the incubation period (every 3 to 7 days), the jars were opened for approximately 5 minutes to aerate the jar and replenish the soil water content if needed. The base traps used to evaluate CO_2 production were replaced at 3-, 7-, 14-, and 21-day intervals. At the end of a 21-day incubation period, triplicate soil samples were analyzed for NH_4-N and NO_3-N contents by extraction with 2 *M* KCl in a 1:5 ratio soil:liquid mixture. The KCl extracts were analyzed colorimetrically for NH_4-N and NO_3-N contents with a Lachat[4] Automated Ion analyzer. Carbon dioxide production was measured by adding $BaCl_2$ to the NaOH traps and titrating the excess base with standardized HCl.

[4] Trade names are included only for the benefit of the reader and do not constitute any preferential endorsement by the USDA over similar products on the market.

Statistical analyses

The possibility of locating other sites with similar cultivation periods and soil characteristics in close proximity with one another is virtually impossible. Therefore, for interpretation of the data in this study, the four lengths of cultivation were compared by treating the three composite samples as replicates within each site. This can be considered a statistically valid testing approach in lieu of "true" replications because the 300-m sampling distance between replications was sufficient to ensure an adequate variation estimation within each site. Analysis of variance and Tukey's honest significant difference (HSD) test were used to compare significant differences in soil properties to length of cultivation. Given the study design, the Tukey's comparison was selected because of its conservative nature in determining significant differences among treatment means. Depth was treated as a repeated measures effect. The use of regression techniques was explored and discounted because too few cultivation times were examined to evaluate the curvilinear function accurately. Application of regression with four cultivation times would have been appropriate in this case only if a general linear response had been obtained.

RESULTS AND DISCUSSION

Increasing years of cultivation resulted in an increasing sand (+16%) and decreasing silt (−14%) contents of the soil surface (0 to 15 cm) (Table 1). Since the sites were relatively flat, this decrease in fine materials is not likely due to water erosion. More likely, wind erosion by the frequent winds of the Plains has caused the bulk of the loss of fine materials. These data on the loss of fine materials are also consistent with the reduction of water holding capacity in the cultivated sites compared to the rangeland site. The reduction in cation exchange capacity with cultivation is primarily due to losses of organic matter and silt since declines in the clay content with cultivation were minimal.

Surface soil C, N, and P properties

Cultivation resulted in rapid declines in soil organic C and N concentrations in the surface 15 cm (Table 2). After 60 years of cultivation, total soil organic C concentration had declined by 62%, but over half of this loss occurred during the first 3 years of cultivation. The decline in the labile fractions of the organic C, as measured by carbohydrate concentration and mineralized CO_2-C, was even more rapid. Carbohydrate-C declined by 67% after 3 years of cultivation and remained relatively stable with additional years of cultivation. Mineralized CO_2-C concentration had declined by 72% after 60 years of cultivation, but 87% of this decline occurred during the first 3 years. Soil organic N concentration declined by 55% after 60 years of cultivation, with over half of this loss occurring during the first 3 years of cultivation. The decline in the labile fraction of soil organic N was more rapid and proportionately larger than the decline in total organic N but was not as rapid as the decline in the labile fraction of organic C. Campbell and Souster (1982) and Janzen (1987) also reported disproportionately higher losses of labile organic matter than losses of total organic matter as a result of long-term wheat-fallow cultivation. Dalal and Henry (1988), however, reported that carbohydrate-C did not show any higher rate of decomposition than total organic C in Australian soils under continuous cultivation and cereal cropping for 20 years.

The magnitudes of loss over the 60-year cultivation period in total organic C (62%) and N (55%) concentration were substantially higher for this Ascalon sandy loam soil than the average losses found by Haas et al. (1957) (42 and 39%, respectively) and by Bauer and Black (1981) (38 and 33%, respectively). Moreover, the initial rates of loss were more rapid than previously reported (Haas et al. 1957). However, the magnitudes and rates of loss of both total and labile forms of C and N after 3 years of cultivation are in agreement with the results of Woods and Schuman (1988) who evaluated changes in an Ascalon sandy loam soil after 1 year of cultivation. These scientists reported that after only 1 year of cultivation, declines of 14%, 62%, 18%, and 51% were found in the total organic C, mineralized C, total organic N, and mineralized N contents, respectively. The low clay content of this sandy loam soil may be an important factor in the magnitude of organic matter loss with cultivation because clay is thought to protect organic matter from decomposition (Van Veen and Paul 1979). Others have reported greater losses of organic matter from coarse textured soils than from medium or fine textured soils (Campbell and Souster 1982; Aguilar et al. 1988).

TABLE 2

Carbon, N, and P properties of the surface 15 cm of a rangeland and three adjacent cultivated sites

Length of cultivation	Organic C	Carbohydrate C	Mineralized CO_2-C	Kjeldahl N	NH_4^- N	NO_3^- N	Mineralized N	Total P	Total organic P	$NaHCO_3$ Pi
y		kg·m^{-3}					g·m^{-3}			
0	15.7a*	1.8a	0.875a	1.79a	3.9a	8.5c	55.0a	479a	163a	21.1
3	9.4b	0.6bc	0.325b	1.19b	2.8b	44.4a	31.5b	377b	99b	19.2a
20	8.6b	0.9b	0.357b	1.11b	1.9bc	24.8b	34.5b	336b	86bc	21.8b
60	5.9c	0.5c	0.245b	0.80c	1.8bc	19.2b	18.0b	281c	60c	9.1b

Properties in each column followed by the same letter are not significantly different at the 5% level (HSD).

The loss of total soil P from the surface 15 cm was less rapid than the losses of C and N, with only a 21% decline after 3 years of cultivation and a 41% decline after 60 years (Table 2). However, in the first 3 years, over 80% of the total P lost came from the organic P pool. These results were consistent with the labile bicarbonate-Pi results, which showed no change the first 3 years due to the concurrent processes of plant P uptake and organic P mineralization. Over the next 17 years (years 3 to 20) the major decline in P came from the mineral P, and again this was reflected in a 37% drop in bicarbonate inorganic P. Generally, losses of total soil organic P were similar to organic C and N losses. Approximately half of the total amount of P lost from the surface 15 cm of the soil profile during 60 years of cultivation was organic P even though organic P originally represented only about one third of the total soil P. These results are consistent with the conclusions of Dormaar (1972) who reported a greater depletion in organic than inorganic P with cultivation, and found that the depletion in organic P coincided better with plant P uptake. The levels of labile P (as measured by $NaHCO_3$ extractable inorganic P in the soil) showed significant declines only after 20 years.

Subsurface soil C, N, and P properties

Declines in soil organic C, N, and P concentrations with cultivation were in general less severe and less rapid in the 15- to 30-cm profile compared with the surface 15-cm profile, although the trends were similar (Table 3). For the first 3 years of cultivation, the decline in P came primarily from the organic P pool. This decline was as large in magnitude as that found in the top 15 cm. For this lower depth, the bicarbonate values did not change appreciably during the entire 60 years. Total organic P was the only parameter higher in the 15- to 30-cm depth than in the surface 15 cm for all 4 cultivation periods. After 20 years of cultivation, the organic N, total P, and total organic P contents of the surface 15 cm were lower than in the 15- to 30-cm depth. These reductions in the N and P concentrations of the surface 15-cm profile are assumed to be primarily due to enhanced mineralization and depletion of the surface layer by erosion and mixing of the surface and subsurface soil by plowing. Since the concentration of organic P in the native soil is naturally lower in the surface 15-cm profile than in the 15- to 30-cm depth, natural distribution may account for some of the variation in organic P concentration in the profile. However, declines in the P concentration of the surface may also be due in part to movement of organic P from the surface 15 cm to the 15- to 30-cm depth (Hannapel et al. 1964).

C, N, and P ratios

The effects of length of cultivation on the proportions of soil organic matter in labile forms and on C/N and C/P ratios are presented in Table 4. In the surface 15 cm, the proportions of organic C in labile form declined after 3 years of cultivation but thereafter increased to a proportion comparable to the native rangeland condition. The proportion of organic N in labile form was not significantly affected by cultivation. The proportion of organic P in labile form steadily increased with length of cultivation, primarily because of the significant decline in total organic P relative to new labile organic P inputs. Cultivation narrowed the C/N ratio but did not significantly affect the C/P ratio. The data indicate that although the loss of organic C exceeded that of organic N, it paralleled that of organic P.

The effects of cultivation on the organic mat-

TABLE 3

Subsurface (15- to 30-cm depth) C, N, and P properties of a rangeland and three adjacent cultivated sites

Length of cultivation	Organic C	Carbohydrate	Mineralized CO_2^-C	Kjeldahl N	NH_4^- N	NO_3^- N	Mineralized N	Total P	Total organic P	$NaHCO_3$ Pi
y		kg·m^{-3}					g·m^{-3}			
0	10.5a*	0.85a	0.436a	1.33	2.6	5.0c	30.5a	465a	191a	5.6
3	9.0b	0.62bc	0.234b	1.20	1.9	20.2a	26.9a	387b	125b	7.8
20	8.1bc	0.73ab	0.134b	1.25	1.6	17.2a	12.2b	379b	120b	7.3
60	7.1c	0.53c	0.132b	1.07	1.7	12.4b	13.2b	345b	102b	4.8

* Properties in each column followed by the same letter are not significantly different at the 5% level (HSD).

TABLE 4

Effect of length of cultivation on the fertility related fractions of soil organic matter at two profile depths

Length of cultivation	Mineralized C / Organic C %	Carbohydrate C / Organic C %	Mineralized N / Organic N %	C/N	C/P	Mineralized C / Mineralized N % %
y			0–15 cm			
0	5.4a*	11.8a	3.2	8.9a	96.5	15.9
3	3.5b	6.0b	2.7	8.1b	96.4	10.7
20	4.2ab	10.3a	3.2	7.9bc	100.5	10.4
60	4.2ab	9.3a	2.3	7.5c	96.4	14.4
			15–30			
0	4.1a*	8.0	2.3a	8.1	55.8	14.2
3	2.6ab	7.0	2.3a	7.6	72.6	8.7
20	1.7b	9.1	1.0b	6.6	67.4	11.2
60	1.9b	7.5	1.3b	6.7	70.0	10.2

* Numbers within a column and in the same profile increment followed by the same letter are not significantly different at the 5% level (HSD).

ter properties of the 15- to 30-cm depth were in some ways different from the effects of cultivation on the surface 15 cm. At this lower depth the proportion of organic C as carbohydrate C and the C/N ratio were not significantly affected by cultivation whereas the proportion of organic N in labile form declined with cultivation.

The narrowing of C/N ratios with cultivation, as well as the declines in the proportions of organic C and N in labile form, have been previously reported for soils of the Great Plains (Haas et al. 1957; Campbell and Souster 1982; and Woods and Schuman 1988). However, others have reported conflicting trends. Campbell (1978) and Dalal and Mayer (1986) have reported conflicting trends in C/N ratios with cultivation of different soils, and Schimel et al. (1985) reported that cultivation did not affect the proportion of organic C in labile form but did result in an increase in the proportion of organic N in labile form in cropland toposequences in North Dakota. The effect of cultivation on the organic matter properties of a soil depends on such factors as the original thickness of the A horizon and its original organic matter concentration, the susceptability of the site to erosion, and the type and intensity of cultivation practices which enhance organic matter mineralization and mix lower horizons of the profile into the surface horizon. Thus, the variations in the effects of cultivation on the soil organic matter properties in the studies cited above are reflected in the variations in site conditions among the studies.

SUMMARY

Although research conducted during the past 60 years has provided valuable information about the degradation of soil organic matter with cultivation, most of these studies have been limited to comparisons of rangeland sites with sites that have been cultivated for a single period of time, and most have not evaluated the losses of labile forms of organic matter but rather have evaluated only total losses. This study was conducted to evaluate short- and long-term changes in selected physical and chemical properties and in total and labile organic C, N, and P concentrations resulting from clean-till cultivation of an Ascalon sandy loam soil. This study showed that (1) after 60 years of cultivation, total organic N and C declined by 55–62%, but over half of this loss occurred during the first 3 years of cultivation, (2) declines in labile organic N and C were more rapid and proportionately larger than declines in total organic N and C, (3) the magnitudes of organic C and N losses due to cultivation were higher and the initial rates of loss more rapid than has been previously reported for other Great Plains soils, and (4) a high percentage of the short-term loss (3 years) in P occurred from the organic P pool.

REFERENCES

Aguilar, R., E. F. Kelly, and R. D. Heil. 1988. Effects of cultivation on soils in Northern Great Plains Rangeland. Soil Sci. Soc. Am. J. 52:1081–1085.

Bauer, A., and A. L. Black. 1981. Soil carbon, nitrogen, and bulk density comparisons in two cropland tillage systems after 25 years and in virgin grassland. Soil Sci. Soc. Am. J. 45:1166–1170.

Black, A. L., and F. H. Siddoway. 1979. Influence of tillage and wheat straw residue managment on soil properties in the Great Plains. J. Soil Water Conserv. 34:220–223.

Blake, G. R., and K. H. Hartge. 1986. Bulk density. *In* Methods of soil analysis, pt. 1, 2d ed. A. Klute (ed.). Agronomy 9:363–375.

Blevins, R. L., G. W. Thomas, and P. L. Cornelius. 1977. Influence of no-tillage and nitrogen fertilization on certain soil properties after 5 years of continuous corn. Agron. J. 69:383–396.

Blevins, R. L., M. S. Smith, and G. W. Thomas. 1984. Changes in soil properties under no-tillage. *In* No-tillage agriculture: Principles and practices. R. E. Phillips and S. H. Phillips (eds.). van Nostrand Reinhold, New York, pp. 190–230.

Bowman, R. A. 1988. A rapid method to determine total phosphorus in soils. Soil Sci. Soc. Am. J. 52:88–90.

Bremner, J. M., and C. S. Mulvaney. 1982. Nitrogen-total. *In* Methods of soil analysis, pt. 2, 2d ed. A. L. Paige (ed.). Agronomy 9:595–622.

Brink, R. H., Jr., P. Dubach, and D. L. Lynch. 1960. Measurement of carbohydrates in soil hydrolyzates with anthrone. Soil Sci. 89:157–166.

Campbell, C. A. 1978. Soil organic C, nitrogen and fertility. *In* Soil organic matter. M. Schnitzer and S. U. Kahn (eds.). Elsevier, New York, pp. 173–271.

Campbell, C., and W. Souster. 1982. Loss of organic matter and potentially mineralizable nitrogen from Saskatchewan soils due to cropping. Can. J. Soil Sci. 62:651–656.

Cheshire, M. V. 1979. Nature and origin of carbohydrates in soil. Academic Press, London.

Dalal, R. C., and R. J. Mayer. 1986. Long-term trends in fertility of soils under continuous cultivation and cereal cropping in Southern Queensland. V. Rate of loss of total nitrogen from the soil profile and changes in carbon:nitrogen ratios. Aust. J. Soil Res. 37:493–504.

Dalal, R. C., and R. J. Henry. 1988. Cultivation effects on carbohydrate contents of soil and soil fractions. Soil Sci. Soc. Am. J. 52:1361–1365.

Dick, W. A. 1983. Organic carbon, nitrogen, and phosphorus concentrations and pH in soil profiles as affected by tillage intensity. Soil Sci. Soc. Am. J. 47:102–107.

Doran, J. W. 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. Am. J. 44:765–771.

Dormaar, J. F. 1972. Seasonal patterns of soil organic phosphorus. Can. J. Soil Sci. 52:107–112.

Gee, G. W., and J. W. Bauder. 1986. Particle-size analysis. *In* Methods of soil analysis, pt. 1, 2d ed. A. Klute (ed.). Agronomy 9:383–409.

Greb, W. 1979. Technology and wheat yields in the Central Great Plains. J. Soil Water Conserv. 34:269–273.

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. Tech. Bull. no. 1164, USDA. U.S. Government Printing Office, Washington, DC.

Hannapel, R. L., W. H. Fuller, S. Basma, and J. S. Bullock. 1964. Phosphorus movement in a calcareous soil. 1. Predominance of organic forms of phosphorus in phosphorus movement. Soil Sci. 97:350–357.

Hill, J. O., and R. L. Blevins. 1973. Quantative soil moisture use in corn grown under conventional and no-tillage methods. Agron. J. 65:945–949.

Janzen, H. H. 1987. Soil organic matter characteristics after long-term cropping to various spring wheat rotations. Can. J. Soil Sci. 67:845–856.

Jenny, H. 1941. Factors of soil formation. A system of quantative pedololgy. McGraw Hill, New York.

Klute, A. 1986. Water retention: Laboratory methods. *In* Methods of soil analysis, pt. 1, 2d ed. A. Klute (ed.). Agronomy 9:635–662.

Lamb, J. A., G. A. Peterson, and C. R. Fenster. 1985. Wheat-fallow stillage systems' effect on a newly cultivated grassland soils' nitrogen budget. Soil Sci. Soc. Am. J. 49:352–356.

McLean, E. O. 1982. Soil pH and lime requirement. *In* Methods of soil analysis, pt. 2, 2d ed. A. L. Paige (ed.). Agronomy 9:199–223.

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. Sci. Agric. 25:718–737.

Olsen, S. R., C. V. Cole, F. S. Watanabe, and L. A. Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA circ. 939.

Rhoades, J. D., 1982. Cation exchange capacity. *In* Methods of soil analysis, pt. 2, 2d ed. A. L. Page et al. (eds.). Agronomy 9:149–157.

Russel, J. C. 1929. Organic matter problems under dry-farming conditions. Am. Soc. Agron. J. 21:960–969.

Salter, R. M., and T. C. Green. 1933. Factors affecting the accumulation and loss of nitrogen and organic carbon in cropped soils. Am. Soc. Agron. J. 25:622–630.

Saunders, W. M., and E. G. Williams. 1955. Observations on the determination of total organic phosphorus in soils. J. Soil Sci. 6:254–267.

Schimel, D. S., D. C. Coleman, and K. A. Horton. 1985. Soil organic matter dynamics in paired rangeland and cropland toposequences in North Dakota. Geoderma 36:201–214.

Sims, J. R., and V. A. Haby. 1971. Simplified colorimetric determination of soil organic matter. Soil Sci. 112:137–141.

Stewart, R., and C. T. Hirst. 1914. Nitrogen and organic matter in dry-farm soils. Am. Soc. Agron. J. 6:49–56.

Van Veen, J. A., and E. A. Paul. 1979. Conversion of biovolume measurements of soil organisms, grown under various moisture tensions, to biomass and their nutrient content. Appl. Environ. Microbiol. 37:686–692.

Woods, L. E., and G. E. Schuman. 1988. Cultivation and slope position effects on soil organic matter. Soil Sci. Soc. Am. J. 52:1371–1376.