Reprinted from *Agronomy Journal*
Vol. 87, No. 4

Crop and Soil Response to Long-Term Tillage Practices in the Northern Great Plains

J. Kristian Aase* and Joseph L. Pikul, Jr.

ABSTRACT

Summer fallow is the most common cultural practice in the northern Great Plains. With proper cultural management, however, annual cropping may be feasible and economical. Our objective was to determine crop and soil response to nontraditional annual cropping practices (till and no-till) in lieu of conventional fallow–crop rotation for the production of spring wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) in the northern Great Plains. The study, initiated in 1983, was on a Dooley sandy loam (fine-loamy, mixed Typic Argiboroll) 11 km north of Culbertson, MT. Tillage practices on annually cropped treatments included sweep tillage in autumn and disk tillage in spring; sweep tillage in spring; and no-tillage. Conventional fallow–spring wheat rotations were included as the control. With three exceptions, there were no statistical differences among treatments in soil P, soil nitrate N, and pH. Phosphorus and N were nonlimiting in all years; pH decreased about 0.06 units per year in the 0- to 8-cm layer because of N fertilization. Bulk density differences in the 0- to 10-cm layer appeared after 7 yr, with the lowest bulk density for the no-tillage annual crop treatment. Grain and straw yields with the no-tillage treatment were both 80% of yields with the fallow–crop treatment. Total water use efficiency, based on soil water differences between harvest of one crop and harvest of the next, was significantly greater with no-tillage than with the fallow–crop treatment. Soil organic C decreased nearly 0.4 g kg^{-1} per year with the fallow–crop treatment; there was a negligible decline with the no-tillage annual crop treatment. No-tillage annual spring wheat crop production was the most efficient crop and soil management practice from the standpoint of yield, water use efficiency, soil organic C, and bulk density.

SUMMER FALLOW is the most common cultural practice in the northern Great Plains. Accepted benefits from summer fallow include weed control, water conservation, and release of plant nutrients. On the other hand, poor soil water storage efficiency, enhanced soil erosion, and development of saline seeps are associated with summer fallow (Tanaka and Aase, 1987; Black and Bauer, 1988; Steiner, 1988). Brown et al. (1983) described saline seep problems that have occurred on more than 800 000 hectares of northern Great Plains crop lands as a consequence of many years of summer fallow. When conditions permit, annual cropping is encouraged to prevent water from passing through the root zone. To successfully grow a crop every year, however, it is necessary to conserve as much precipitation as possible between harvest and seeding.

Conservation tillage practices, including no-tillage, are encouraged for reasons of water conservation and erosion control. Stubble left standing after harvest uniformly traps snow across fields, protecting winter crops and contributing to soil water storage. Stubble maintenance also controls wind erosion on the drylands of the plains.

Although it is possible to grow winter wheat (*Triticum aestivum* L.) in the northern Great Plains with adequate management practices, the major crop remains spring wheat. For example, of approximately 1.6 million hectares of wheat grown in Montana, 71% is spring wheat and about 24% is continuously cropped (Mont. Agric. Stat. Serv., 1993). Nearly 30% of the area receives some form of conservation tillage, but only about 7% is no-tillage.

Tillage practices influence many soil properties. For example, Mielke et al. (1986), Bruce et al. (1990), Rhoton et al. (1993), and Vyn and Raimbault (1993) reported higher bulk density under no-tillage than under conventional or plow treatments. On the other hand, Blevins et al. (1983), Mielke et al. (1984), Unger (1991), and Ismail et al. (1994) reported no effect of tillage treatments on bulk density. Lal et al. (1994) found lower bulk density under continuous corn (*Zea mays* L.) no-tillage as compared with conventional tillage, similar to results reported in a companion paper (Pikul and Aase, 1995) for continuous spring wheat no-tillage.

Blevins et al. (1977) reported that pH was decreased by increasing N rates and that pH decreased under no-tillage as compared with conventional tillage. Dick (1983) also found decreased pH under no-tillage conditions, whereas Lal et al. (1994) found no effect of tillage on pH.

Soil organic matter has received much attention as it relates to tillage treatments. Soil organic matter content is related to amount of residue returned to the soil (Black, 1973; Campbell and Zentner, 1993; Eghball et al., 1994). Fallow–crop rotation systems decrease organic matter content as compared with continuous cropping (Haas et al. 1957; Rasmussen and Parton, 1994). There also is greater opportunity for biological oxidation to take place during the fallow cycle than under continuous cropping (Biederbeck et al., 1984; Rasmussen and Parton, 1994). Rasmussen and Parton (1994) ascribe the greater loss of C with time to biological oxidation where soil erosion is minimal. Eghball et al. (1994), Ismail et al. (1994), and Lal et al. (1994) all report that soil organic matter was greatest under no-tillage and increased with time in some instances. Ismail et al. (1994) concluded that changes in soil organic matter content are probably the most important effect of tillage practices on soil properties. Bauer and Black (1994) attempted to quantify the contribution of soil organic matter to soil productivity and wheat grain yield, and concluded that 1 Mg ha^{-1} organic matter in the surface 31 cm of soil contributed the equivalent of 15.6 kg ha^{-1} of wheat grain yield.

Our objective was to evaluate crop and soil response to nontraditional till and no-till annual cropping in lieu of conventional fallow–crop rotation for the production of spring wheat and barley in the northern Great Plains.

MATERIALS AND METHODS

We started the study in 1983 on a Dooley sandy loam 11 km north of Culbertson, MT. The plot area had been cropped every year since 1975. Prior to that the plot area was in grass variety trials for several years. Barley was grown in 1982. The study

J.K. Aase, USDA-ARS N.W. Irrigation & Soils Res. Lab., 3793 North 3600 East, Kimberly, ID 83341-5076; J.L. Pikul, Jr., USDA-ARS Northern Plains Soil and Water Res. Ctr., P.O. Box 1109, Sidney, MT 59270. Contribution from the USDA-ARS in cooperation with Montana State Univ. Agric. Exp. Stn., Journal Series J-2993. Received 5 Aug. 1994. *Corresponding author (Email: !a03lckimberl@attmail.com).

Published in Agron. J. 87:652-656 (1995).

was laid out as a randomized complete block, replicated four times, with plot size 30 by 12 m. The treatments were as follows: Treatment 1, annual spring wheat (cv. Lew) with sweep tillage in the fall and disk tillage in the spring to prepare a seedbed; Treatment 2, annual spring wheat with no fall tillage (fall weed control with herbicides when needed), and sweep tillage prior to seeding to prepare seedbed which maintained surface residue; Treatment 3, annual spring wheat with no-tillage; Treatments 4 and 5, annual cropping with alternate year rotations of barley (cv. Hector) and spring wheat with tillage the same as on Treatment 1; and Treatments 6 and 7, alternate year fallow–spring wheat rotations with no after-harvest tillage and with disk prior to seeding for seedbed preparation. Depending on soil and weather conditions, fallowing was accomplished either with mechanical or chemical means. Glyphosate [(*N*-phosphonomethyl) glycine], bromoxynil (3,5-dibromo-4-hydroxybenzonitrile), and 2,4-D (2,4-dichlorophenoxyacetic acid) were used as necessary on all plots for weed control.[1]

A double-disk opener drill with a 20.3-cm row spacing was used to seed both wheat and barley in north–south rows at 74 kg ha^{-1} for wheat and 84 kg ha^{-1} for barley, except in the first 2 yr, when a hoe-drill with 25.4-cm row spacing was used on Treatments 2 and 3 and a double-disk opener drill with 22.9-cm row spacing on the other treatments. All plots except fallow received 56 kg N ha^{-1} as NH_4NO_3 (34–0–0 N-P-K) broadcast at time of seeding in 1983, 1984, and 1985. In 1986 the rate was changed to 34 kg ha^{-1}. Fallow plots received 34 kg N ha^{-1} in every crop year. Long-term phosphorus requirements were met by broadcast applications totalling 560 kg P ha^{-1} of $(NH_4)_2HPO_4$ (18–46–0 N-P-K) prior to the establishment of the study. The phosphate fertilizer was incorporated into the surface 5 cm of soil.

Two access tubes for neutron probe soil water content measurements were installed in each plot and soil water measured at 30-cm increments to a depth of 1.20 m. Measurements were made at 14-d intervals during the crop season until 1988, at which time they were changed to twice yearly: at seeding and at harvest. Based on soil water measurements, water use efficiency (designated as *total water use efficiency*) was calculated by subtracting soil water content at harvest from soil water content at harvest of the previous crop and adding the intervening precipitation. No significant runoff was observed from any of the plots. Each spring prior to seeding, two soil cores (3.5 cm in diameter) were taken per plot to a depth of 15 cm and divided into two equal segments for analyses of organic C, P, and pH. Six 10-cm-deep cores per plot from Treatments 1, 3, and 6 and 7 were taken each spring for bulk density determinations and a 1.2-m-deep core from each plot, divided into 30-cm segments, for soil nitrate analyses. Organic C was determined with a Carlo Erba NA 1500 C-N analyzer (Carlo Erba Instruments, Milan, Italy), P was determined using the sodium bicarbonate method (Olsen et al., 1954), and pH with a standard pH meter using a 1:1 mixture of soil and water. Soil nitrate N was determined using an Alpkem rapid flow analyzer (Perstop Analytical, Clackamas, OR).

Grain and straw yield harvest samples were obtained by cutting bundle samples from five 1-m-long rows from six areas in each plot. The bundle samples were later weighed and threshed, following which the grain was weighed and straw yield determined by difference.

Analysis of variance and regression analysis were used to analyze the data. When appropriate, statistical significance was expressed as an LSD ($P \leq 0.05$).

[1] Mention of trade names is for the benefit of the reader and does not constitute an endorsement by the U.S. Department of Agriculture over other products not mentioned, nor does mention of specific pesticides imply registration under FIFRA as amended.

RESULTS AND DISCUSSION

For brevity, only Treatments 1, 3, and 6 and 7 will be discussed. Results from the two treatments not discussed were intermediate. Fallow–crop sequence with flexible mixes of mechanical and chemical weed control is the standard cultural practice in the area of the study and was considered the control. Annual no-tillage cropping is the opposite of fallow–crop, and fall and spring tilled annual cropping is somewhere in the middle in terms of tillage operations. The reader is referred to Aase and Schaefer (1996) for details on grain yield and economics of all treatments.

The 10 yr of the study included what Aase and Schaefer (1996) defined as five high-yield years and five low-yield years. The high- and low-yield years are grouped within the corresponding high and low groupings of growing season total rainfall represented in Table 1, but not necessarily in the same order. Total yearly rainfall did not necessarily correspond to a particular yield grouping, as in 1989. Factors such as distribution of rainfall, air temperatures, and hot dry winds influence grain yield.

Sodium bicarbonate-extractable soil P concentration is considered adequate when the surface 15 cm of soil contains about 16 mg P kg^{-1}. There were no statistically significant differences in soil P concentration among treatments. Treatments averaged about 41 mg kg^{-1} soil P at the start of the study and about 16 mg kg^{-1} at the end, so P concentration was not affected by any of the treatments. Nitrate N concentrations to a depth of 1.2 m varied greatly, particularly on the fallow–crop sequence, and only in 1985, 1987, and 1989 were there statistically significant differences among treatments. The differences were not consistent among years. However, additions of 34 kg ha^{-1} of N fertilizer have been shown to be adequate on similar soils at this research site and there was no response to higher rates (Black and Aase, 1988). Nitrogen availability was therefore considered adequate on all treatments and was not affected by tillage differences.

Although tillage treatments did not affect pH, yearly application of NH_4NO_3 decreased pH by about 0.06 pH units per year in the surface 8 cm of the soil; after 10 yr, pH was about 5.6 (Fig. 1). At the 8- to 15-cm depth there was no decline, and the pH was stable at about 6.5. Our finding that tillage method on a sandy loam had no effect on pH agrees with those of Lal et al. (1994) on a Wooster silt loam (Typic Fragiudalfs) in Ohio.

At the onset of the study we postulated that, since the tillage layer was no deeper than 10 cm, a 10-cm deep soil sample ought to define differences in soil bulk density between tillage and no-tillage treatments if any were to develop. We consistently sampled in that fashion from year to year. A significantly greater bulk density in the fallow–crop treatment than in no-tillage first appeared in 1990 (1.51 vs. 1.47 Mg m^{-3}), 7 yr after establishment of the study. The differences were significant again in 1991 and in 1993, but not in 1992. Apparently, the large sample masked small differences in soil bulk density that may occur as a consequence of different types of tillage operations. In related work reported in a companion paper (Pikul and Aase, 1995), we sampled using thin soil slices and found that the no-tillage treatment had the least bulk

Table 1. Growing-season rainfall, yearly precipitation, and long-term average precipitation (Culbertson, MT). *Italics* denote high-yield years.

	Precipitation										
	1984	1985	*1986*	*1987*	1988	1989	1990	*1991*	*1992*	*1993*	27-yr avg.
	mm										
April	7.6	32.8	*18.0*	*13.5*	15.5	59.2	15.5	*68.1*	*72.6*	*5.1*	30.5
May	20.8	59.4	*79.8*	*102.1*	24.9	45.2	55.4	*66.6*	*29.7*	*25.9*	52.8
June	51.8	16.5	*64.0*	*29.2*	44.7	31.0	63.0	*112.5*	*103.1*	*59.7*	74.7
July	6.4	33.3	*92.5*	*99.6*	17.5	73.7	54.4	*40.6*	*47.5*	*130.6*	52.1
Season	86.6	142.0	*254.3*	*244.4*	102.6	209.1	188.3	*287.8*	*253.9*	*221.3*	211.8
Year	197.9	317.3	*449.3*	*356.4*	235.7	368.1	281.7	*412.2*	*400.6*	*377.4*	360.2

density in the fall of 1992 and that the differences persisted through the freezing–thawing cycle of the winter and bulk densities were the same in the spring of 1993. Our combined results (the present report and Pikul and Aase, 1995) agree with those of Lal et al. (1994) for continuous no-tillage and with those of Mielke et al. (1984) for no-tillage and plow on Duroc loam (Pachic Haplustolls) in Nebraska and disagree with those from other studies in which bulk density under no-tillage was found to be greater than under conventional cropping conditions (e.g., Rhoton et al., 1993).

The annual cropping treatment produced a larger average annual grain yield than the fallow–crop treatment during the 10-yr period (Fig. 2a). Grain yield for the fallow–crop treatment was divided by two, because it takes 2 yr or two units of land to produce one unit of crop. Aase and Schaefer (1996) showed that the annual crop no-tillage treatment gave the greatest economic return of all treatments when averaged across the 10-yr period. Annual cropping with fall and spring tillage resulted in a net negative return. Based on grain yield in the harvest year (fallow–crop yield not divided by two), grain yield with no tillage averaged nearly 80% of fallow crop grain yield during the 10-yr study.

Total water use efficiency, illustrated in Fig. 2b, is based on soil water differences between harvest of one crop and harvest of the next crop plus precipitation during the same period. In this fashion, all water received and lost or used is accounted for. Thus, there is a 2-yr period for the fallow–crop sequence, and grain yield obtained in the harvest year is used to calculate total water use efficiency. Total water use efficiency closely paralleled grain yield, and was significantly greater with the no-tillage treatment than with the fallow–crop treatment. The calculation of total water use efficiency underscores the poor water use efficiency of fallow. Fallow soil water storage efficiencies of only 20 to 30% are common in the Great Plains (Steiner, 1988). We feel that, with adequate water conservation measures, some of the water lost during the fallow season can be conserved and used to grow a crop. Haas and Boatwright (1960) and Haas and Willis (1962) expressed similar sentiments more than 30 yr ago.

Crop residues returned to the soil are important to the chemical, physical, and biological environment of the soil. We were primarily interested in looking at crop residue as it may influence soil organic C. As was the case with

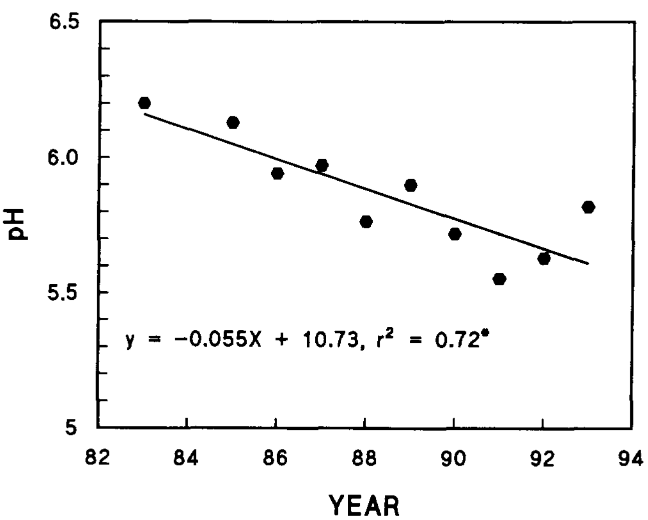

Fig. 1. Soil pH in the 0- to 8-cm depth as a function of time. No statistical differences among treatments; therefore, the data are combined.

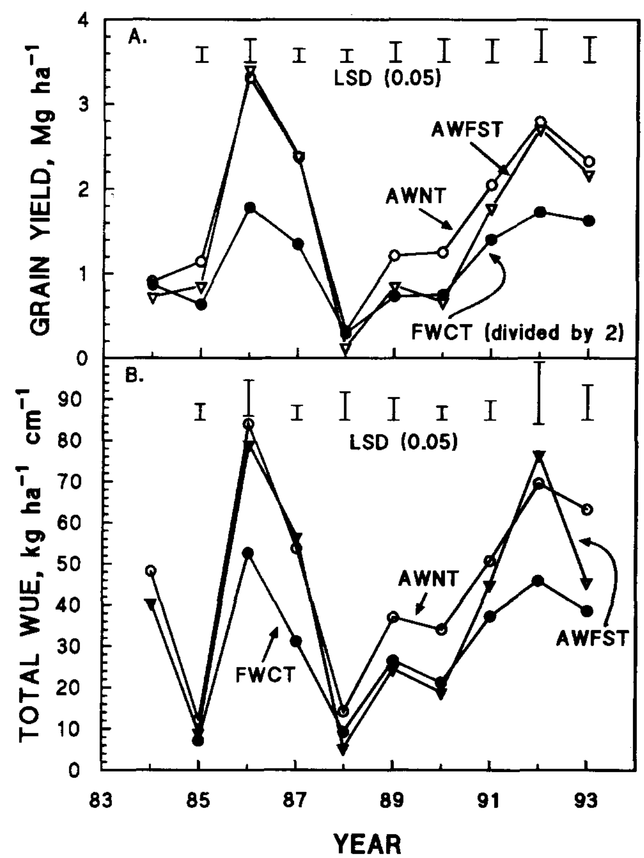

Fig. 2. Average annual grain yield and total water use efficiency of wheat for fall and spring tillage (AWFST) and no-tillage annually cropped (AWNT) treatments and for the fallow–crop (FWCT) treatment.

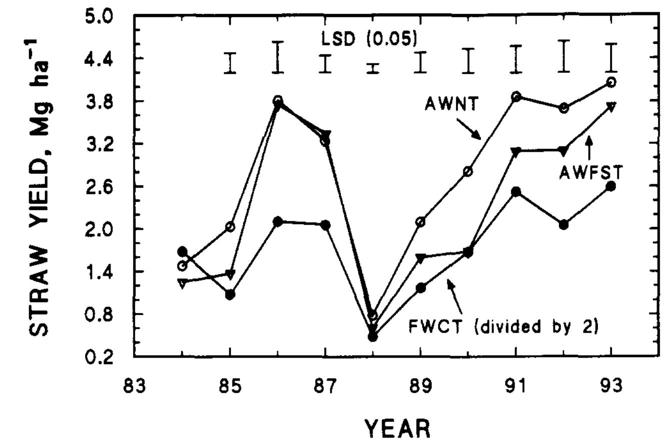

Fig. 3. Average annual wheat straw yield for fall and spring tillage (AWFST), and no-tillage annually cropped (AWNT) treatments and for fallow–crop (FWCT) treatment.

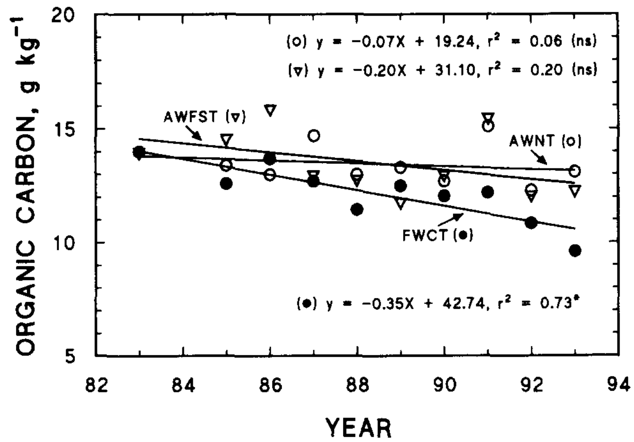

Fig. 4. Soil organic carbon in the 0- to 8-cm layer as a function of time for fall and spring tillage (AWFST), and no-tillage annually (AWNT) cropped treatments and for fallow–crop (FWCT) treatment.

grain yield, straw yield was the greatest with the no-tillage treatment and least with the fallow–crop treatment when considering the 2-yr cycle for fallow–crop production (Fig. 3). Based on straw yields in the harvest year, straw yield with the no-tillage treatment was 80% of that with the fallow–crop treatment, nearly identical to the results for grain yield. Thus, the significant decline in soil organic C of nearly 0.4 g kg^{-1} per year with the fallow–crop treatment may be attributed in large measure to the low return of residue with that treatment and to biological oxidation of organic matter (Biederbeck et al., 1984; Rasmussen and Parton, 1994) (Fig. 4). Soil erosion was minimal; therefore, loss of organic matter cannot be attributed to erosion. There was a nonsignificant, negligible decline in organic C with the no-tillage treatment.

Based on the results of our 10-yr study on a sandy loam in the northern Great Plains, no-tillage annual spring wheat crop production was the most efficient crop and soil management practice from the standpoint of yield, water use efficiency, soil organic C, and bulk density. We recognize that there are years, particularly drought years, when fallow may be the best choice; however, in only two of the 10 yr of the study were there no significant differences in grain yield between no-till annual cropping and average annual grain yield from fallow–crop. If accurate forecasts of cropping conditions are available, farmers may wish to adopt a flexible approach to crop and soil management. We also recognize that annual no-tillage monoculture may be undesirable from, for example, a disease point of view, and that other profitable crops that can be used in rotation with wheat may be needed for diversity. Our results differ from those reported by Matthews (1951) and Haas et al. (1957) for similar studies in the Great Plains during the first half of the century, wherein it was reported that fallow–wheat rotation was a more stable and profitable system than annual cropping and, as Seamans (1948) claimed, essential to successful agriculture in the Great Plains. However, the data they report on were collected from bare (plow) tillage studies, whereas our best results for annual cropping were obtained using no-till techniques. With modern, improved farming techniques, including appropriate use of herbicides, conserving soil water and protecting soil from erosion, we have shown that successful farming in the northern Great Plains need not include a summer fallow rotation.

ACKNOWLEDGMENTS

We acknowledge Messrs. Larry L. Reitz (deceased) and David C. Harris for help with field and laboratory work.

REFERENCES

Aase, J.K., and G.M. Schaefer. 1996. Economics of tillage practices and spring wheat and barley crop sequence in the northern Great Plains. J. Soil Water Conserv. 51(2) (in press).

Bauer, A., and A.L. Black. 1994. Quantification of the effect of soil organic matter content on soil productivity. Soil Sci. Soc. Am. J. 58:185–193.

Biederbeck, V.O., C.A. Campbell, and R.P. Zentner. 1984. Effect of crop rotation and fertilization on some biological properties of a loam in southwestern Saskatchewan. Can. J. Soil Sci. 64:355–367.

Black, A.L. 1973. Soil property changes associated with crop residue management in a wheat–fallow rotation. Soil Sci. Soc. Am. Proc. 37:943–946.

Black, A.L., and J.K. Aase. 1988. The use of perennial herbaceous barriers for water conservation and the protection of soils and crops. Agric. Ecosyst. Environ. 22/23:135–148.

Black, A.L., and A. Bauer. 1988. Strategies for storing and conserving soil water in the northern Great Plains. p. 137–139. *In* P.W. Unger et al. (ed.) Challenges in dryland agriculture: A global perspective. Proc. Int. Conf. on Dryland Agric., Amarillo, TX. Aug. 1988. Texas Agric. Exp. Stn., College Station.

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. 69:383–386.

Blevins, R.L., G.W. Thomas, M.S. Smith, W.W. Frye, and P.L. Cornelius. 1983. Changes in soil properties after 10 years continuous non-tilled and conventionally tilled corn. Soil Tillage Res. 3:135–146.

Brown, P.L., A.D. Halvorson, F.H. Siddoway, H.F. Mayland, and M.R. Miller. 1983. Saline-seep diagnosis, control, and reclamation. USDA Conserv. Res. Rep. 30. U.S. Gov. Print. Office, Washington, DC.

Bruce, R.R., G.W. Langdale, and A.L. Dillard. 1990. Tillage and crop rotation effect on characteristics of a sandy surface soil. Soil Sci. Soc. Am. J. 54:1744–1747.

Campbell, C.A., and R.P. Zentner. 1993. Soil organic matter as influenced by crop rotations and fertilization. Soil Sci. Soc. Am. J. 57:1034–1040.

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.

Eghball, B., L.N. Mielke, D.L. McCallister, and J.W. Doran. 1994.

Distribution of organic carbon and inorganic nitrogen in a soil under various tillage and crop sequences. J. Soil Water Conserv. 49:201-205.

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. USDA Tech. Bull. 1164. U.S. Gov. Print. Office, Washington, DC.

Haas, H.J., and G.O. Boatwright. 1960. Let's take another look at summer fallow in the northern Plains. J. Soil Water Conserv. 15:176-179.

Haas, H.J., and W.O. Willis. 1962. Moisture storage and use by dryland spring wheat cropping systems. Soil Sci. Soc. Am. Proc. 26:506-509.

Ismail, I., R.L. Blevins, and W.W. Frye. 1994. Long-term no-tillage effects on soil properties and continuous corn yields. Soil Sci. Soc. Am. J. 58:193-198.

Lal, R., A.A. Mahboubi, and N.R. Fausey. 1994. Long-term tillage and rotation effects on properties of a central Ohio soil. Soil Sci. Soc. Am. J. 58:517-522.

Matthews, O.R. 1951. Place of summer fallow in the agriculture of the Western States. USDA Circ. 886. U.S. Gov. Print. Office, Washington, DC.

Mielke, L.N., J.W. Doran, and K.A. Richards. 1986. Physical environment near the surface of plowed and no-tilled soils. Soil Tillage Res. 7:355-366.

Mielke, L.N., W.W. Wilhelm, K.A. Richards, and C.R. Fenster. 1984. Soil physical characteristics of reduced tillage in a wheat-fallow system. Trans. ASAE 27:1724-1728.

Montana Agricultural Statistics Service. 1993. Montana agricultural statistics. Volume 30. Mont. Dep. of Agric., Helena.

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. U.S. Gov. Print. Office, Washington, DC.

Pikul, J.L., Jr., and J.K. Aase. 1995. Infiltration and soil properties as affected by annual cropping in the northern Great Plains. Agron. J. 87:656-662 (this issue).

Rasmussen, P.E., and W.J. Parton. 1994. Long-term effects of residue management in wheat-fallow: I. Inputs, yield, and soil organic matter. Soil Sci. Soc. Am. J. 58:523-530.

Rhoton, F.E., R.R. Bruce, N.W. Buehring, G.B. Elkins, C.W. Langdale, and D.D. Tyler. 1993. Chemical and physical characteristics of four soil types under conventional and no-tillage systems. Soil Tillage Res. 28:51-61.

Seamans, A.E. 1948. Recommended practices for soil erosion control. Circ. 190. Mont. Agric. Exp. Stn., Bozeman.

Steiner, J.L. 1988. Simulation of evaporation and water use efficiency of fallow-based cropping systems. p. 176-178. *In* P.W. Unger et al. (ed.) Challenges in dryland agriculture: A global perspective. Proc. Int. Conf. on Dryland Agric., Amarillo, TX. Aug. 1988. Texas Agric. Exp. Stn., College Station.

Tanaka, D.L., and J.K. Aase. 1987. Fallow method influences on soil water and precipitation storage efficiency. Soil Tillage Res. 9:307-316.

Unger, P.W. 1991. Organic matter, nutrient, and pH distribution in no- and conventional-tillage semiarid soils. Agron. J. 83:186-189.

Vyn, T.J., and B.A. Raimbault. 1993. Long-term effect of five tillage systems on corn response and soil structure. Agron. J. 85:1074-1079.