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Nitrates in Soil After Long-Term Management for Dryland Grain Sorghum and Winter Wheat

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ABSTRACT

Long-term cropping with clean and stubble mulch tillage (SMT) resulted in soil organic carbon and total nitrogen (N) decreases at numerous Great Plains locations. Crops at some locations now respond to applied N fertilizers. Objective of this study was to compare soil nitrate-N (NO_3-N) contents after a 12-year field study for which different management practices [cropping systems (rotations or continual cropping), tillage methods (SMT or no-tillage), land leveling (level or nonlevel), and N fertilizer (applied or not applied)] were used for dryland grain sorghum [*Sorghum bicolor* (L.) Moench] and winter wheat (*Triticum aestivum* L.) production. Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) was sampled by increments to a 20-cm depth. Relatively few differences in NO_3-N contents due cropping system, land leveling, or tillage treatments were significant for individual depths or means across all depths. Cropping systems had no effect, but contents were greater in wheat than in sorghum or fallow plots. Land leveling and tillage methods

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resulted in no consistent differences, but contents usually were greater with than without applied fertilizer. Although N fertilizer treatments were imposed early in the field study because plant N deficiencies symptoms were noted, crops did not respond to applied fertilizer. This suggests the NO_3-N content differences found will have little effect on dryland crop yields under present management conditions.

INTRODUCTION

Major decreases in soil organic matter (OM) and associated plant nutrient [total nitrogen (N)] contents occurred at numerous U.S. Great Plains locations because of long-term use of clean and stubble-mulch tillage (SMT) for dryland crops (Haas et al., 1957; Hobbs and Brown, 1965). Organic matter decreases generally were greater when cropping systems included a fallow period than when crops were grown continually (Greb et al., 1974; Haas et al., 1974; Johnson et al., 1974). Nitrogen decreases were much less with continual cropping or alternate cropping and fallowing for small grains than with row cropping (Hobbs and Brown, 1965; Haas et al., 1974).

Adoption of conservation tillage systems (reduced and no-tillage [NT]) has potential to reduce organic carbon (OC) loss from soil (Reicosky and Lindstrom, 1993; Reicosky et al., 1995) or even sequester it in soil (Potter et al., 1997; Reicosky et al., 1995). The close association between soil OM (also OC) and total N indicates soil total N loss and, hence, soil NO_3-N contents also could be affected by adoption of conservation tillage. When sampled by small increments, the OC concentration in Pullman clay loam was greater at 0- to 1- and 1- to 2-cm depths with NT than with SMT, but decreased sharply with depth with NT. With SMT, the concentration was relatively uniform throughout the tillage zone (Potter et al., 1997; Unger, 1991). The trends for soil total N and NO_3-N were similar to the OM trends (Unger, 1991).

As a result of total N decreases due to long-term cropping, yield increases due to N fertilization occur on many soils, especially when use of improved practices results in greater water conservation for crop use (Black et al., 1974; Halvorson and Reule, 1994; Nyborg and Malhi, 1989; Porter et al., 1996; Smika, 1990). For cropping systems involving a fallow period, however, adequate soil NO_3-N may accumulate so that responses to applied N may be low (Black et al., 1974; Haas et al., 1974). Total soil NO_3-N contents to a 1.8-m depth in wheat-fallow plots on Pullman soil were 324 kg ha^{-1} with SMT and 517 kg ha^{-1} with one-way disk (inversion) tillage (Johnson et al., 1974). In continual wheat plots, the respective contents were 178 and 416 kg ha^{-1}. The naturally-high N fertility level of the soil led Johnson et al. (1974) to state that the "nitrate-nitrogen of the one-wayed fallow plots is equivalent to the amount of nitrogen that would be removed in the wheat harvested over a period of about 45 years," suggesting that dryland wheat would not respond to applied N fertilizer for many years on Pullman soil.

Changes in cropping practices such as crops grown and cropping systems and tillage methods used may result in different rates of N mineralization (Evans et al., 1994; Lamb et al., 1985; Lavake and Wiese, 1979) and, hence, affect the amount available to a crop at a given time. Nitrogen-deficiency symptoms were noted for continual wheat and continual sorghum crops under dryland conditions on Pullman soil, but application of N fertilizer did not increase grain yields of these crops (Jones and Popham, 1997). However, changes in management practices have led to increased soil water contents at grain sorghum planting time and, consequently, greater yields of sorghum under dryland conditions on Pullman soil (Unger and Baumhardt, 1999). Differences in NO_3-N accumulation with depth also have occurred in the Pullman soil (Eck and Jones, 1992).

Objective of this study was to compare NO_3-N contents where different management practices (cropping systems, tillage methods, land leveling, and N fertilizer treatments) were used for dryland grain sorghum and winter wheat production for 12 years.

MATERIALS AND METHODS

A field study, established in 1982 on Pullman clay loam at the USDA-ARS, Conservation and Production Research Laboratory, Bushland, TX, involved SMT and NT in several dryland grain sorghum and winter wheat cropping systems. Plots (9 m x 160 m) were established lengthwise across a 0.5 to 1.5% slope, and were leveled or not leveled. All soil moved during leveling was retained within the plot being leveled. Commercially-available equipment was used for all field operations. Berms prevented water flow onto or off the plots, except that water could flow from nonleveled plots. Each phase of all systems was in place each year. Soil was sampled for NO_3-N determinations in 1994, about 12 years after initiating the study.

The cropping systems evaluated are given in Table 1. A Richardson[2] plow with one 1.5-m-wide and two 1.8-m-wide blades was used for weed control and seedbed preparation in SMT plots. Tillage depth was 7 to 10 cm. During the study, the average number of tillage operations between crops was two and one half in continual sorghum plots, three in continual wheat plots, seven in wheat-fallow plots, and five during each fallow period in wheat-sorghum-fallow (WSF) plots (Jones and Johnson, 1996). Herbicides were applied at recommended rates for growing-season weed control in SMT plots and for all weed control in NT plots (Jones and Popham, 1997). Additional weed control was obtained with a pre-

[2]The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by the USDA-ARS. Mention of a pesticide does not constitute a recommendation for use nor does it imply registration under FIFRA as amended.

TABLE 1. Dryland cropping systems evaluated at Bushland, TX.

System	Crops	Crop frequency
Wheat-sorghum-fallow (WSF)	Winter wheat and grain sorghum	Two crops/3 years
Continual wheat (CW)	Winter wheat	One crop/year
Wheat-fallow (WF)	Winter wheat	One crop/2 years
Continual sorghum (CS)	Grain sorghum	One crop/year

emergence application of propazine [6-chloro-*N,N'*-bis(1-methylethyl)-1,3,5-triazine-2,4-diamine] at 1.7 kg ha^{-1} [a.i.] after planting in sorghum plots where SMT was used. Sorghum in SMT plots was not cultivated. In wheat plots, 2,4-D [(2,4-dichlorophenoxy)acetic acid] was applied at 0.6 kg ha^{-1} (a.i.) in late February of some years to control *Descurainia sophia* (L.) Webb ex Prantl (flixweed).

'TAM 107' winter wheat was sown in late September or early October in 0.30-m-spaced rows with a high-clearance drill equipped with hoe openers and press wheels. 'DK42y' hybrid grain sorghum was sown in early to mid-June in 0.75-m-spaced rows with a six-row John Deere Max-Emerge planter.

A plant N deficiency was noted in 1987. As a result, before planting wheat and sorghum in 1988, two 9-m x 40-m subplots in each plot received a 40- to 45-kg ha^{-1} broadcast application of N fertilizer (as ammonium nitrate) and two such subplots remained unfertilized. Precipitation at the plots averaged 520 mm annually from 1984 through 1993 (Jones and Popham, 1997). In 1994, total precipitation was only 10 mm before soil samples were obtained in March to determine soil physical and chemical properties, including soil NO_3-N contents.

Bulk soil samples were taken at two sites midway between the sides of each subplot at depths of 0 to 4, 4 to 10, and 10 to 20 cm. The sites were about 20 m apart and soil was taken from two positions about 2 m apart at each site with a flat-bottom spade. Soil from the two sites and positions was combined into one sample for each depth separately. Each sample weighed 3 to 4 kg. The soil was thoroughly mixed, passed through a screen with 12.7-mm square openings, and a portion was frozen until NO_3-N concentration was determined on duplicate subsamples using a nitrate reduction procedure (Perstorp Analytical Environmental, 1994). The NO_3-N concentrations were converted to a NO_3-N content basis (kg ha^{-1}) using soil bulk density values previously reported for the different soil depths (Potter et al., 1997).

The study was treated as having a randomized block, split-split plot design with three replications. Cropping system, rotation phase, land leveling, or continual crop treatments were randomly assigned to whole plots; tillage methods to split plots; and fertilizer treatments to split-split plots. Data were analyzed separately for each depth or for the total for all depths (summed before analyses were performed) by the ANOVA technique (SAS, 1989).

All treatments were included in a common study, but involving data for all treatments in common statistical analyses was not appropriate because of inherent differences among treatments. For example, three cropping systems involved winter wheat, but only two involved grain sorghum, which is a summer crop. Also, two fallow systems could be compared for wheat, but fallow for sorghum occurred only in the WSF system. Therefore, data were analyzed separately for those treatments where effects of cropping systems, tillage methods, rotation phases, land leveling, or crops could be compared. This provided for eight comparisons (CPs) of the data. The fertilizer effect was a variable in all analyses. The comparisons analyzed were:

CP-1: Cropping system [WSF, continual wheat (CW), wheat-fallow (WF)] and tillage method (SMT, NT) effects on level plots cropped to wheat,
CP-2: Cropping system [WSF, continual sorghum (CS)] and tillage method (SMT, NT) effects on level plots cropped to grain sorghum,
CP-3: Cropping system (WSF, WF) and tillage method (SMT, NT) effects on level plots in fallow,
CP-4: Rotation phase (wheat, sorghum, fallow) and tillage method (SMT, NT) effects on level WSF plots,
CP-5: Land condition (level, nonlevel) and rotation phase (wheat, sorghum, fallow) effects on WSF plots with SMT,
CP-6 Land condition (level, nonlevel) and rotation phase (wheat, fallow) effects on WF plots with SMT,
CP-7: Land condition (level, nonlevel) and crop (wheat, sorghum) effects on continual cropping plots with SMT, and
CP-8: Crop (wheat, sorghum) and tillage method (SMT, NT) effects on level continual cropping plots.

When the F-value was significant at the $P \leq 0.05$ level of probability, means were separated using the protected least significant difference (LSD) procedure. Some differences at the $P \leq 0.10$ level of probability are given and discussed. Total NO_3-N content differences due to crops and fertilizer treatments were analyzed by the *t*-test.

RESULTS AND DISCUSSION

Soil NO_3-N contents differed ($P \leq 0.05$ level) at some individual depths or for the total due to treatments for all comparisons, except the CP-3. The high variability in data and few degrees of freedom, however, resulted in some rather large differences to be nonsignificant at the $P \leq 0.05$ level. Interaction effects were significant only in a few cases.

In wheat plots (CP-1 comparison, Table 2), cropping systems had no effect on NO_3-N contents at individual depths nor on the total for the 0- to 20-cm depth.

TABLE 2. Soil NO_3-N contents in level plots cropped to winter wheat as affected by cropping system, tillage method, and N fertilizer treatment, Bushland, TX.

	Cropping system												Means						
	WSF[†]				CW				WF				Cropping system			Tillage		Fertilizer	
	SMT		NT		SMT		NT		SMT		NT								
Depth	F	NF	F	NF	F	NF	F	NF	F	NF	F	NF	WSF	CW	WF	SMT	NT	F	NF
- cm -	kg ha^{-1}																		
0-4	29	15	33	19	38	10	26	8	36	32	63	20	24a[‡]	21a	38a	27a	28a	38a	17b
4-10	28	19	21	11	37	11	21	6	54	25	27	13	20a	19a	30a	29a	16a	31a	14b
10-20	39	31	29	18	71	26	29	9	71	41	30	19	29a	34a	40a	47a	22b	45a	24b
0-20	96	65	83	48	146	47	76	23	161	98	120	52	73a	74a	108a	103a	66a	114a	55b

[†]Abbreviations: WSF=wheat-sorghum-fallow; CW=continual wheat; WF=wheat-fallow; SMT=stubble mulch tillage; NT=no-tillage; F=fertilized; NF=not fertilized.

[‡]Row values for a given set of means (cropping system, tillage method, or fertilizer treatment) followed by the same letter are not different at the $P \leq 0.05$ level of probability.

Contents for all cropping systems tended to be lower with NT than with SMT at all depths, both with and without applied fertilizer, but means due to tillage methods across cropping systems differed only at the 10- to 20-cm depth. The totals due to tillage were not different. At all depths and for the total, contents were greater with than without applied fertilizer.

Cropping systems and fertilizer treatments did not affect NO_3-N contents at any depth in grain sorghum plots (CP-2 comparison), but contents were greater with SMT than with NT at 10 to 20 cm (22 vs. 12 kg ha^{-1}). No differences in the totals were significant (data not shown).

Overall NO_3-N contents were lower in sorghum than in wheat plots with or without applied fertilizer. In fertilized plots, this possibly resulted from differences in time since the last application (about 270 d in sorghum plots and 150 d in wheat plots). Under both conditions, removal by the crop (sorghum was harvested whereas wheat was still growing) and immobilization by crop residues, as suggested by Varvel and Peterson (1990), may have been involved also. Movement to greater depths is another possibility, as suggested by the results of Eck and Jones (1992), provided it occurred before sorghum harvest and wheat planting the previous year. Only 10 mm of precipitation occurred from January until the samples were obtained in March 1994.

Nitrate-N contents did not differ due to cropping systems, tillage methods, and fertilizer treatments at any depth in fallow plots (CP-3 comparison, data not shown). As for in sorghum plots (CP-2 comparison), the overall NO_3-N contents in fallow plots were lower than in wheat plots.

For the CP-4 comparison, NO_3-N content differed only at the 0- to 4-cm depth due to crop rotation phase (wheat, sorghum, or fallow), with it being greater for the wheat than the sorghum or fallow phases (24, 7, and 9 kg ha^{-1}, respectively). The total due to rotation phases was greater for the wheat phase (72 kg ha^{-1}) than the sorghum and fallow phases (both at 33 kg ha^{-1}). These results parallel the results or trends found for the CP-1, CP-2, and CP-3 comparisons, and largely reflect the recency of fertilizer application and NO_3-N use in wheat and sorghum plots. Nitrogen immobilization by residues or mineralization of soil N in fallow plots may have been involved also. The content was greater with than without applied fertilizer at the $P \leq 0.09$ level at all depths, and the total was greater with applied fertilizer at the $P=0.06$ level (57 vs. 35 kg ha^{-1}), which was similar to the results in other comparisons.

Land condition in SMT plots (CP-5 comparison) had no direct effect on NO_3-N content at any depth, but some interactions involving land conditions were significant. The contents differed due to rotation phase and fertilizer treatments at all depths (Table 3). Contents were greater for the wheat than the sorghum and fallow phases and with than without applied fertilizer. Although only SMT was used in CP-5 comparison plots, rotation phase effects were similar to those found and discussed above for the CP-4 comparison that involved SMT and NT, but for which the contents did not differ due to tillage method. Greater NO_3-N contents

TABLE 3. Soil NO_3-N contents in stubble mulch tillage plots as affected by land condition, crop rotation phase, and N fertilizer treatment, Bushland, TX.

	Land condition												Means						
	Level						Nonlevel						Land condition		Phase			Fertilizer	
	Wheat		Sorghum		Fallow		Wheat		Sorghum		Fallow								
Depth	F[†]	NF	F	NF	F	NF	F	NF	F	NF	F	NF	L	NL	Wh	Sor	Fal	F	NF
- cm -	kg ha^{-1}																		
0-4	29	15	11	4	6	3	29	14	4	5	6	4	11a[‡]	10a	22a	6b	5b	14a	8b
4-10	26	19	10	7	6	5	58	15	7	8	7	4	12a	17a	29a	8b	6b	19a	10b
10-20	39	31	25	23	12	9	74	31	20	17	19	8	23a	28a	44a	21b	12b	32a	20b
0-20	94	65	46	34	24	17	161	60	31	30	32	16	47a	55a	95a	35b	23b	65a	38b

[†]Abbreviations: F=fertilized; NF=not fertilized; L=level; NL=nonlevel; Wh=wheat; Sor=sorghum; Fal=fallow.

[‡]Row values for a given set of means (land condition, rotation phase, or fertilizer treatment) followed by the same letter are not different at the $P \leq 0.05$ level of probability.

with than without applied fertilizer also parallel the results shown and discussed above. The total contents was greater ($P \leq 0.06$ level) for wheat than for sorghum and fallow phases with applied fertilizer under level and nonlevel land conditions. Without applied fertilizer, totals under both the level and nonlevel conditions were greater ($P \leq 0.06$ level) for the wheat than for the fallow phase. The total for the sorghum phase was not different from those for the other phases. For individual rotation phases, the total content was greater ($P=0.08$ level) with than without fertilizer (161 vs. 60 kg ha^{-1}) only for the wheat phase under nonlevel conditions.

The rotation phase x fertilizer treatment interaction effect was significant at the 4- to 10-cm depth, with the mean of 42 kg ha^{-1} on fertilized wheat plots being greater than all other means (LSD=12 kg ha^{-1}). The land condition x rotation phase interaction and the land condition x rotation phase x fertilizer treatment interaction effects also were significant at the 4- to 10-cm depth. For the land condition x rotation phase interaction, the mean was greatest (37 kg ha^{-1}) for the wheat phase under nonlevel conditions and intermediate (23 kg ha^{-1}) for the wheat phase under level conditions, with both contents being greater than for all other conditions (LSD=12 kg ha^{-1}). For the three-way interaction, the content was greater (58 kg ha^{-1}) for nonlevel fertilized wheat plots than for all other conditions for which most differences did not exceed the LSD of 16 kg ha^{-1}. The reason for the unusually high content for the nonlevel fertilized wheat plots is not known.

For the CP-6 comparison, which involved only SMT, the NO_3-N content was greater for wheat than for fallow plots (38 vs. 6 kg ha^{-1}) at the 0- to 4-cm depth. Although not significant, the same trends were noted for the other depths (data not shown). The overall total content was greater for wheat than for fallow plots (111 vs. 42 kg ha^{-1}). These differences are similar to those found for the CP-4 and CP-5 comparisons for which contents were or tended to be greater in wheat than in fallow plots.

In CP-7 comparison plots, the land condition x fertilizer treatment interaction effect for NO_3-N content was significant at the 0- to 4-cm depth. The content was greater (23 g ha^{-1}) under level fertilized conditions than under all other conditions (6 to 10 kg ha^{-1}, LSD=13). The total content was greater ($P=0.06$) in wheat than in sorghum plots (79 vs. 26 kg ha^{-1}). These results are similar to those for the WSF rotation (CP-4 and CP-5 comparisons), indicating the crop effect is independent of the fallow effect. Contents were greater ($P \leq 0.07$) with applied fertilizer at 4 to 10 and 10 to 20 cm. The total was greater ($P=0.08$) with than without applied fertilizer (67 vs. 38 kg ha^{-1}). Also, the land condition x fertilizer treatment interaction effect for the total was significant at the $P=0.06$ level (93 kg ha^{-1} for fertilized level plots vs. 35 to 42 kg ha^{-1} for other plots, LSD=45). Different results under level and nonlevel conditions suggest some NO_3-N may have been lost from nonlevel plots when runoff occurred.

Nitrate-N contents in CP-8 comparison plots did not differ due to crops or tillage methods at any individual depth or for the total (Table 4), but were greater with

TABLE 4. Soil NO_3-N contents in continually cropped level plots as affected by crop, tillage method, and N fertilizer treatment, Bushland, TX.

	Crop								Means					
	Wheat				Sorghum				Crop		Tillage method		Fertilizer	
	SMT[†]		NT		SMT		NT							
Depth	F	NF	F	NF	F	NF	F	NF	Wheat	Sorghum	SMT	NT	F	NF
- cm -	kg ha^{-1}													
0-4	38	10	26	8	8	3	9	3	21a[‡]	6a	15a	11a	20a	6b
4-10	37	11	21	6	7	5	9	4	19a	6a	15a	10a	18a	7b
10-20	71	26	29	9	26	13	14	8	34a	15a	34a	15a	35a	14b
0-20	146	47	76	23	41	21	32	15	74a	27a	64a	36a	73a	27b

[†]Abbreviations: SMT=stubble mulch tillage; NT=no-tillage; F=fertilized; NF=not fertilized.

[‡]Row values for a given set of means (crop, tillage method, or fertilizer treatment) followed by the same letter are not different at the $P \leq 0.05$ level of probability.

than without applied fertilizer. The total also was greater with than without fertilizer. For crops individually, the mean total was greater with than without fertilizer for wheat (111 vs. 35 kg ha^{-1}, P=0.01) and for sorghum (37 vs. 18 kg ha^{-1}, P=0.09). The crop x fertilizer treatment interaction effect was significant for the 0- to 4-cm depth. Contents were 32 and 9 kg ha^{-1} with and without fertilizer in wheat plots and 8 and 3 kg ha^{-1} with and without fertilizer in sorghum plots (LSD=11, P=0.04).

SUMMARY AND CONCLUSIONS

Relatively few differences in soil NO_3-N contents due to whole plot (cropping system, rotation phase, land leveling, or continual cropping) or split plot (tillage method) treatments were significant, either for individual depths or for the total contents. Cropping systems for wheat (WSF, CW, and WF) and sorghum (WSF and CS) had no effect, but contents were greater in wheat than in sorghum or fallow plots when compared for rotation phases or continual cropping. Land leveling and tillage methods resulted in no consistent differences, but contents were greater in fertilized than in nonfertilized plots in most cases. Nitrate contents (data not shown) usually were greatest for the 0- to 4-cm soil depth, but not different from those at other depths in many cases. Plant N deficiencies were noted early in the field study. As a result, N fertilizer treatments were imposed, starting in 1988. Jones and Popham (1997), however, found no yield responses to applied fertilizer. This suggests the natural fertility of Pullman soil is still adequate to meet winter wheat and grain sorghum crop needs under dryland conditions. Also, the NO_3-N content differences found, while of interest, will have little effect on dryland crop yields under present management conditions.

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REFERENCES

Black, A.L., F.H. Siddoway, and P.L. Brown. 1974. Summer fallow in the northern Great Plains (winter wheat). pp. 36-50. In: Summer fallow in the western United States. USDA-ARS Conserv. Res. Rpt. 17. U.S. Government Printing Office, Washington, DC.

Eck, H.V. and O.R. Jones. 1992. Soil nitrogen status as affected by tillage, crops, and crop sequences. Agron. J. 84:660-668.

Evans, S.D., G.A. Peterson, D.G. Westfall, and E. McGee. 1994. Nitrate leaching in dryland agroecosystems as influenced by soil and climate gradients. J. Environ. Qual. 23:999-1005.

Greb, B.W., D.E. Smika, N.P. Woodruff, and C.J. Whitfield. 1974. Summer fallow in the central Great Plains. pp. 51-85. In: Summer Fallow in the Western United States. USDA-ARS Conserv. Res. Rpt. 17. U.S. Government Printing Office, Washington, DC.

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. Government Printing Office, Washington, DC.

Haas, H.J., W.O. Willis, and J.J. Bond. 1974. Summer fallow in the Northern Great Plains (spring wheat). pp. 12-35. In: Summer fallow in the western United States. USDA-ARS Conserv. Res. Rpt. 17. U.S. Government Printing Office, Washington, DC.

Halvorson, A.D. and C.A. Reule. 1994. Nitrogen fertilizer requirements in an annual dryland cropping system. Agron. J. 86:315-318.

Hobbs, J.A. and P.L. Brown. 1965. Effects of cropping and management on nitrogen and organic carbon contents of a western Kansas soil. Bull. 144. Kansas Agricultural Experiment Station, Manhattan, KS.

Johnson, W.C., C.E. Van Doren, and E. Burnett. 1974. Summer fallow in the southern Great Plains. pp. 86-109. In: Summer fallow in the western United States. USDA-ARS Conserv. Res. Rpt. 17. U.S. Government Printing Office, Washington, DC.

Jones, O.R. and G.L. Johnson. 1996. A ten year comparison of cropping and tillage systems for dryland grain production. Rpt. 96-04. USDA-ARS, Conservation and Production Research Laboratory, Bushland, TX.

Jones, O.R. and T.W. Popham. 1997. Cropping and tillage systems for dryland grain production in the Southern High Plains. Agron. J. 89:222-232.

Lamb, J.A., G.A. Peterson, and C.R. Fenster. 1985. Fallow nitrate accumulations in a wheat-fallow rotation as affected by tillage system. Soil Sci. Soc. Am. J. 49:1441-1446.

Lavake, D.E. and A.F. Wiese. 1979. Influence of weed growth and tillage interval during fallow on water storage, soil nitrates, and yield. Soil Sci. Soc. Am. J. 43:565-569.

Nyborg, M. and S.S. Malhi. 1989. Effect of zero and conventional tillage on barley yield and nitrate nitrogen content, moisture and temperature of soil in north-central Alberta. Soil Tillage Res. 15:1-9.

Perstorp Analytical Environmental. 1994. Methodology: Nitrate + nitrite nitrogen in soil extracts (EnviroFlow 3500™). Perstorp Analytical Environmental, Wilsonville, OR.

Porter, L.K., R.F. Follett, and A.D. Halvorson. 1996. Fertilizer nitrogen recovery in a no-till wheat-sorghum-fallow-wheat sequence. Agron. J. 88:750-757.

Potter, K.N., O.R. Jones, H.A. Torbert, and P.W. Unger. 1997. Crop rotation and tillage effects on organic carbon sequestration in the semiarid southern Great Plains. Soil Sci. 162:140-147.

Reicosky, D.C. and M.J. Lindstrom. 1993. Effect of fall tillage on short-term carbon dioxide flux from soil. Agron. J. 85:1237-1243.

Reicosky, D.C., W.D. Kemper, G.W. Langdale, C.L. Douglas, Jr., and P.E. Rasmussen. 1995. Soil organic matter changes resulting from tillage and biomass production. J. Soil Water Conserv. 50:253-261.

SAS. 1989. SAS/STAT User's Guide. Version 6, 4th ed., Vol. 2. Statistical Analysis System Institute, Cary, NC.

Smika, D.E. 1990. Fallow management practices for wheat production in the central Great Plains. Agron. J. 82:319-323.

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

Unger, P.W. and R.L. Baumhardt. 1999. Factors related to dryland grain sorghum yield increases, 1939 through 1997. Agron. J. 91: (in press).

Varvel, G.E., and T.A. Peterson. 1990. Residual soil nitrogen as affected by continuous, two-year, and four-year crop rotation systems. Agron. J. 82:958-962.