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Cropping Intensity Effects on Physical Properties of a No-till Silt Loam

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No-till cropping systems in the semiarid West have the potential to improve soil physical properties by increasing cropping intensity and crop diversity. An investigation at Akron, CO, compared soil conditions in winter wheat (*Triticum aestivum* L.)–summer fallow (WF) plots with soil conditions in wheat–corn (*Zea mays* L.)–fallow (WCF), wheat–corn–sunflower (*Helianthus annus* L.)–fallow (WCSF), wheat–corn–millet (*Panicum miliaceum* L.) (WCM), and a perennial grass/legume mix. The study began in 1990. Bulk density, pore size distribution, and saturated hydraulic conductivity were measured 7, 11, and 15 yr after inception. Bulk density in the grass plots decreased from 1.39 to 1.25 Mg m^{-3} in 15 yr. Bulk density in the annually cropped plots decreased from 1.38 to 1.30 Mg m^{-3} during the same time period. The pore size distribution became more uniform among the cropped treatments 15 yr after the start of the experiment. Saturated hydraulic conductivity increased in the grass plots from 27 mm h^{-1} to 98 mm h^{-1} in 15 yr. Saturated hydraulic conductivity in the annually cropped plots increased from about 14 to about 35 mm h^{-1} during the same period. The results from this study show that improving soil physical properties by cropping system alone may take many years. Perennial vegetation may be more effective than annually cropped systems at improving soil physical conditions because of less surface compaction from planting operations and the apparent ability of perennial root systems to create a more stable, continuous pore network.

During the last 90 yr in the Great Plains, much of the native range has been converted to crop production. This conversion has resulted in significant soil degradation from the loss of organic C. Bauer and Black (1981) showed that cultivated soils lost between 28 and 38% of the original organic C, compared with virgin grassland, after 25 yr of cultivation, depending on the tillage system. Bowman et al. (1990) showed that, after 60 yr of tillage, approximately 60% of the original organic C was lost in the surface 150 mm of a sandy soil in eastern Colorado. Most of the C loss occurred in the first 3 yr after the onset of cultivation.

Soil physical conditions have a direct effect on soil productivity for crop production by determining water holding capacity, aeration, and soil strength limitations for root activity (Benjamin et al., 2003). Some researchers have suggested that study of the functional traits of soil structure, as exemplified by the pore system, may be instructive to determine the effects of cropping system on soil physical quality (Young et al., 2001; Ball et al., 2005).

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Soil physical properties may change with the loss of organic matter. Bowman et al. (1990) measured lower water content at field capacity (–33 kPa) and lower cation exchange capacity associated with the loss of organic matter. On the other hand, Bauer and Black (1981) measured no significant soil bulk density differences between cropped and grassland soils at depths to 450 mm.

Organic matter increases from additions of manure have been shown to improve selected soil physical properties. Pikul and Allmaras (1986) reported lower bulk density, increased volume of soil pores >50 μm, and greater saturated hydraulic conductivity in a wheat–fallow cropping system when manure was added to the soil compared with only returning the straw to the system.

The use of no-till cropping systems in the semiarid western USA has resulted in significant water savings and has allowed greater cropping intensity and crop diversity for this region. To take advantage of summer rainfall, there has been a shift from a predominately wheat–fallow rotation to rotations that include summer annuals. Some of the crops being grown in rotation with wheat include corn, sorghum [*Sorghum bicolor* (L.) Moench], proso millet, and sunflower. Increasing cropping intensity, while decreasing fallow, in no-till systems has the potential to increase organic C in the soil profile both by increasing C additions to the system and by decreasing oxidation caused by tillage (Bowman et al., 1999; Mikha et al., 2006; McVay et al., 2006). Ball et al. (2005) showed that changes in crop species and soil management may influence soil structure. It is conceivable that different crop species may affect soil properties differently because of different rooting characteristics and rooting depths.

Most changes in soil organic matter caused by a change in cropping system have been limited to the surface 50 to 75 mm (Bowman et al., 1999; Mikha et al., 2006; McVay et al., 2006). Changes in other soil physical properties, however, may extend to significantly greater depths. Plant roots exert forces on the soil and can be used to change soil physical conditions, particularly

by changing pore size distribution and pore continuity (Elkins, 1985). Many of the effects of plant roots may be found in the subsoil. *Biological drilling* is a term used for the improvement of compacted subsoil by selecting plant species in a rotation that will loosen the soil for subsequent crops (Cresswell and Kirkegaard, 1995). Certain plant species have been selected specifically for their ability to penetrate compacted subsoil (Cresswell and Kirkegaard, 1995). Little information exists on the effects of commonly grown crops on changing pore space and pore continuity in soil, nor is there much information on how much time must elapse for pore changes to occur.

The objective of this study was to test the hypothesis that increasing cropping intensity (cropping intensities greater than wheat–summer fallow) is correlated with an improvement in selected soil physical properties.

MATERIALS AND METHODS

The study was conducted on the Alternative Crops Rotation study at the USDA-ARS Central Great Plains Research Station near Akron, CO (40.15° N, 103.15° W). The elevation of the station is 1384 m above mean sea level. The research station location is within a semiarid climate with approximately 400 mm annual precipitation. The soil is a Weld silt loam (fine, smectitic, mesic Aridic Paleustolls). This soil has a silt loam Ap horizon from about 0 to 120 mm with fine granular structure. A silty clay loam Bt1 horizon with fine to medium subangular blocky structure extends from about 120 to 240 mm, with a smooth boundary to a silty clay loam Bt2 horizon, also with fine to medium subangular blocky structure, which extends to about 410 mm. A silty clay loam Btk horizon with fine to medium subangular blocky structure extends to about 640 mm.

The cropping systems experiment started in 1990. The experiment is organized as a randomized complete block design with three replications. Rotations of crops suited for dryland crop production in the central Great Plains are the experimental units. Crops included in the rotations are wheat, corn, sunflower, and proso millet. Each phase of each rotation occurs each year. Rotations selected for study varied by cropping intensity. A wheat–fallow (WF) rotation harvests one crop every 2 yr, so the cropping intensity is 0.5. A wheat–corn–fallow (WCF) rotation harvests two crops every 3 yr, so has a cropping intensity of 0.66. A wheat–corn–sunflower–fallow (WCSF) rotation harvests three crops every 4 yr, so has a cropping intensity of 0.75. A wheat–corn–millet (WCM) rotation harvests a crop every year, so has a cropping intensity of 1.0. We also selected plots that were seeded to a perennial grass/legume mixture of 45% smooth brome (*Bromus inermis* Leyss.), 40% pubescent wheat grass [*Agropyrons trichophorum* (Link) Richt.], and 15% alfalfa (*Medicago sativa* L.) at the start of the experiment. The alfalfa quickly died so, by the time the first samples were taken, the plots were almost exclusively grass.

No tillage is conducted on any of the plots. Plot size and machinery working widths are such that the wheel tracks for field operations follow a controlled wheel traffic pattern. The only soil disturbance in untracked areas is by planter or drill operations to plant the seed. Chemical weed control is used during the fallow and cropped seasons. A typical herbicide application scheme for each rotation consists of a residual herbicide application of atrazine (2-chloro-4-ethylamino-6-isopropylamina-*s*-triazine) after wheat harvest. A burn-down application of glyphosate [isopropylamine salt of *N*-(phosphonomethyl) glycine] is applied shortly before planting the next crop. Several glyphosate applications are made, as needed, during the fallow period for weed control. In sunflower, a combination of sulfentrazone (*N*-[2,4-dichloro-5-[4-(difluromethyl)-4,5-dihydro-3-methyl-5-oxo-1*H*-1,2,4-triazol-1-yl] phenyl] methanesulfonamide) and pendimethalin (*N*-[1-ethylpropyl]-3,4-dimethyl-2,6-dinitrobenzenamine) were used for in-crop weed control.

Wheat planting occurred in mid to late September for each year of the study. Corn planting occurred in mid to late May. Millet and sunflower planting occurred in late May or early June. Wheat and millet were planted in 0.19-m rows. Corn and sunflower were planted in 0.75-m rows. Additional detail about the experimental design and crop management techniques can be found in Bowman and Halvorson (1997), Anderson et al. (1999), and Bowman et al. (1999).

Soil cores to determine soil physical properties were taken from each plot in each rotation 7, 11, and 15 yr after the start of the experiment (in 1997, 2001, and 2005, respectively). One set of samples was collected between the rows from each plot. Samples were collected before planting in May for the corn, millet, and sunflower. Samples were collected in June for all of the fallow plots, and immediately after wheat harvest in July for the wheat plots. Wheel-trafficked areas were purposely avoided during sampling. Previous work on these plots indicated little in-season variation of infiltration or bulk density for no-till cropping systems at this location (Pikul et al., 2006). Sampling was conducted with a Giddings hydraulic probe that used aluminum sleeves to contain the undisturbed soil sample. Soil cores 75mm diam. by 75 mm long were taken to a depth of 0.5 m. Two 10-mm spacer rings were inserted between each core to facilitate trimming. The surface 20 mm of soil was discarded to ensure a smooth surface on the confined ring. Samples represented depth increments of 20–95 mm (depth 1), 115–180 mm (depth 2), 200–275 mm (depth 3), 295–370 mm (depth 4) and 390–465 mm (depth 5). The cores were trimmed to the size of the ring and transported to the lab.

Saturated hydraulic conductivity (K_{sat}) was determined for each core with the constant-head method (Reynolds and Elrick, 2002). Each core was then placed in an individual pressure chamber and the water desorption was measured at 2.5- and 33-kPa air pressure (Flint and Flint, 2002). Water outflow was measured daily until no more water was expelled from the core. The cores were then removed from the chamber and the gravimetric water content (θ_{g33})was determined. The bulk density (ρ_b) of each core was determined and the volumetric water content at −33 kPa (θ_{v33}) was calculated from θ_{g33} and ρ_b by

$$\theta_{v33} = \theta_{g33}\,\rho_b \qquad [1]$$

The water content at 2.5 kPa ($\theta_{v2.5}$) was calculated by

$$\theta_{v2.5} = V_{(2.5-33)}/V_c + \theta_{v33} \qquad [2]$$

where $V_{(2.5-33)}$ is the volume of water drained from the core between the 2.5- and 33-kPa pressure step and V_c is the volume of the core. An estimate of the wilting point water content (θ_{v1500}) was determined by placing disturbed soil samples from each sampling depth on a high-pressure desorption apparatus and determining the water content at 1500-kPa pressure. The gravimetric water content was multiplied by the bulk density of the individual core to determine θ_{v1500}.

Pore sizes that emptied of water at each pressure step were determined by the capillary rise equation (Flint and Flint, 2002)

$$d = 2(-2\sigma\cos\alpha/P) \qquad [3]$$

Table 1. Analysis of variance for bulk density (ρ_b), total porosity (ϕ_{total}), macropore volume (ϕ_{macro}), mesopore volume (ϕ_{meso}), water storage pore volume (ϕ_{ws}), and saturated hydraulic conductivity (K_{sat}).

Year	Rotation	ρ_b	ϕ_{total}	ϕ_{macro}	ϕ_{meso}	ϕ_{ws}	K_{sat}
		$P > F$					
1997	crop rotation	0.052	0.052	0.015	0.064	0.026	0.056
	depth	<0.0001	<0.0001	0.256	<0.0001	<0.0001	0.033
	rotation × depth	<0.0001	<0.0001	0.015	0.0001	0.002	<0.0001
2001	crop rotation	0.0021	0.015	0.103	0.033	0.751	<0.0001
	depth	<0.0001	<0.0001	0.735	<0.0001	<0.0001	0.017
	rotation × depth	0.844	0.844	0.468	0.228	0.049	0.474
2005	crop rotation	0.218	0.218	0.301	0.301	0.748	<0.0001
	depth	<0.0001	<0.0001	0.104	0.063	<0.0001	0.020
	rotation × depth	0.209	0.209	0.729	0.0465	0.162	0.993

where d is the pore diameter (m), σ is the surface tension of water (0.0728 J m^{-2}), α is the contact angle of the water–soil interface (assumed to be 0), and P is the pressure in the chamber (Pa). Pore size classes were divided into three sections: macropores >100-μm diameter (ϕ_{macro}), determined between saturation and $\theta_{v2.5}$; mesopores between 100 and 8.8 μm (ϕ_{meso}), determined between $\theta_{v2.5}$ and θ_{v33}; and water storage pores, or plant-available water, between 8.8 and 0.2 μm (ϕ_{ws}),determined between θ_{v33} and θ_{v1500}. Total porosity (ϕ_{total}) was calculated from the measured ρ_b by

$$\phi_{total} = 1 - \rho_b/2.65 \quad [4]$$

Statistical Analysis

Statistical analysis of crop rotation effects on ρ_b, ϕ_{total}, ϕ_{macro}, ϕ_{meso}, ϕ_{ws}, and K_{sat} was conducted using Proc GLM of SAS Version 8 (SAS Institute, 1999). For statistical analysis of K_{sat}, a natural-log transformation was used to normalize the data. The data were then retransformed for tables and figures. Statistical analysis of the crop phase within each year and depth showed no significant effect of the particular crop growing that year on any of the physical properties measured. Therefore, data were pooled across crop species to determine crop rotation effects on physical property variables. The probability values for the main effects of crop rotation and depth and the interaction between crop rotation and depth are shown in Table 1. Means separation for a significant F statistic on the main effect was conducted with Duncan's means comparisons ($P = 0.05$).

RESULTS

After 7 yr, there were no significant differences due to cropping intensities for ρ_b or ϕ_{total} averaged across depths (Table 2). There was a change in the pore size distribution caused by cropping intensity. Grass plots had the lowest ϕ_{macro} and WCSF plots had the greatest ϕ_{macro} with the other cropping intensities having intermediate values. The WCSF plots had the lowest ϕ_{ws} and the WF plots had the greatest ϕ_{ws} with the other cropping treatments having intermediate values. There were no significant differences among cropping intensities for K_{sat}.

After 11 yr, the grass plots had significantly lower ρ_b and correspondingly greater ϕ_{total} than the wheat rotation treatments. Cropping intensity among the wheat rotation treatments had no effect on ρ_b. Grass plots had greater ϕ_{macro} and ϕ_{meso} than the WF treatment. Plots with other cropping intensities were intermediate between the grass and the WF systems, with no discernable pattern related to cropping intensity. Lower ρ_b and greater ϕ_{macro} and ϕ_{meso} in the grass plots were associated with greater K_{sat} for the grass treatment than the cropped treatments.

After 15 yr, grass plots had significantly lower ρ_b and greater K_{sat} than the wheat rotation treatments but there was no difference in ϕ_{macro} or ϕ_{ws}. There was greater ϕ_{meso} in the grass treatment than the wheat rotation systems. The lack of difference in ϕ_{macro} but greater K_{sat} in the grass treatment suggests greater pore continuity of the ϕ_{macro} in

Table 2. Mean bulk density (ρ_b), total porosity (ϕ_{total}), macropore volume (ϕ_{macro}), mesopore volume (ϕ_{meso}), water storage pore volume (ϕ_{ws}), and saturated hydraulic conductivity (K_{sat}) averaged across depths for 1997, 2001, and 2005. Rotations include winter wheat–fallow (WF), winter wheat–corn–fallow (WCF), winter wheat–corn–sunflower–fallow (WCSF), winter wheat–corn–millet (WCM), and continuous grass.

Year	Rotation	ρ_b	ϕ_{total}	ϕ_{macro}	ϕ_{meso}	ϕ_{ws}	K_{sat}
		Mg m^{-3}	m^3 m^{-3}				mm h^{-1}
1997	WF	1.39 a†	0.47 a	0.078 bc	0.086 a	0.162 a	11.1 a
	WCF	1.36 a	0.49 a	0.098 ab	0.093 a	0.154 ab	11.9 a
	WCSF	1.36 a	0.49 a	0.114 a	0.090 a	0.128 b	23.6 a
	WCM	1.38 a	0.48 a	0.098 ab	0.086 a	0.139 ab	11.8 a
	grass	1.39 a	0.47 a	0.067 c	0.109 a	0.145 ab	26.6 a
	critical range	NS‡	NS	0.026	NS	0.026	NS
2001	WF	1.34a	0.50 a	0.105 b	0.106 b	0.136 a	14.4 c
	WCF	1.31a	0.51 a	0.121 ab	0.106 b	0.136 a	27.6 b
	WCSF	1.32a	0.50 a	0.121 ab	0.114 ab	0.130 a	36.0 b
	WCM	1.34a	0.50 a	0.108 b	0.102 b	0.138 a	37.7 b
	grass	1.25b	0.53 b	0.127 a	0.126 a	0.137 a	75.5 a
	critical range	0.038	0.015	NS	0.017	NS	12.5
2005	WF	1.30 a	0.51 a	0.132 a	0.092 a	0.142 a	37.2 b
	WCF	1.31 a	0.51 a	0.138 a	0.092 a	0.139 a	34.4 b
	WCSF	1.31 a	0.51 a	0.135 a	0.092 a	0.141 a	36.8 b
	WCM	1.30 a	0.51 a	0.125 a	0.094 a	0.147 a	35.2 b
	grass	1.26 a	0.53 a	0.114 a	0.118 a	0.155 a	98.1 a
	critical range	NS	NS	NS	NS	NS	14.7

† Means followed by the same letter within year are not significantly different using Duncan's multiple range test.

‡ NS denotes that the F statistic was not significant at the 0.05 level.

the grass treatment than the wheat rotation treatments.

Analysis of ρ_b changes with years shows that ρ_b decreased with time in all treatments for most depths (Fig. 1). Grass plots had the fastest and greatest ρ_b decrease and grass was the only treatment to have a significant ρ_b decrease in Depth 1. In the 4 yr between 1997 and 2001, ρ_b in Depth 1 of the grass plots decreased from 1.48 to 1.28 Mg m^{-3}. At Depth 2, the decrease between 1997 and 2001 was from 1.43 to 1.29 Mg m^{-3}. Other depths in the grass plots had similar declines as those nearer the surface. There were no differences among wheat rotation treatments for the magnitude or speed of ρ_b decline. Using WF as an example, between 1997 and 2001, ρ_b in Depth 1 decreased from 1.41 to 1.37 Mg m^{-3}. In 2005, the ρ_b in Depth 1 of the WF treatment was 1.37 Mg m^{-3}. In Depth 2, the ρ_b decrease of the WF treatment between 1997 and 2001 was from 1.43 to 1.38 Mg m^{-3}. In 2005, the ρ_b in Depth 2 of the WF treatment was 1.33 Mg m^{-3}. For the wheat rotation treatments, significant ρ_b changes did not occur until 2005. Because the samples were removed from untrafficked areas of the field, the lack of ρ_b change with time near the surface of the cropped treatments could be attributed to near-surface compaction from disk openers, press wheels, and gauge wheels of planting equipment.

Significant changes in ϕ_{macro} generally occurred below Depth 1 (Fig. 2). Together with the decrease in ρ_b in the grass treatment was an increase in ϕ_{macro}. The greatest increases for grass plots were in Depths 2 and 3. Changes in ϕ_{macro} with the wheat rotation treatments occurred only sporadically with the WF, WCF, and WCM treatments. In Depth 3, there was a significant increase in ϕ_{macro} for the WF treatment but not for the other wheat rotation treatments. In Depth 4, there was a significant increase in ϕ_{macro} for the WCF and WCM treatments but not for the other wheat rotation treatments. None of the wheat rotation treatments resulted in an increase in φ_{macro} in Depth 5.

There were no significant changes with time in ϕ_{meso} or ϕ_{ws} for any of the treatments (Fig. 3 and 4). The decrease in ρ_b with time exhibited in many of the wheat rotation treatments was not reflected in a change in the smaller pore sizes, but only in ϕ_{macro}.

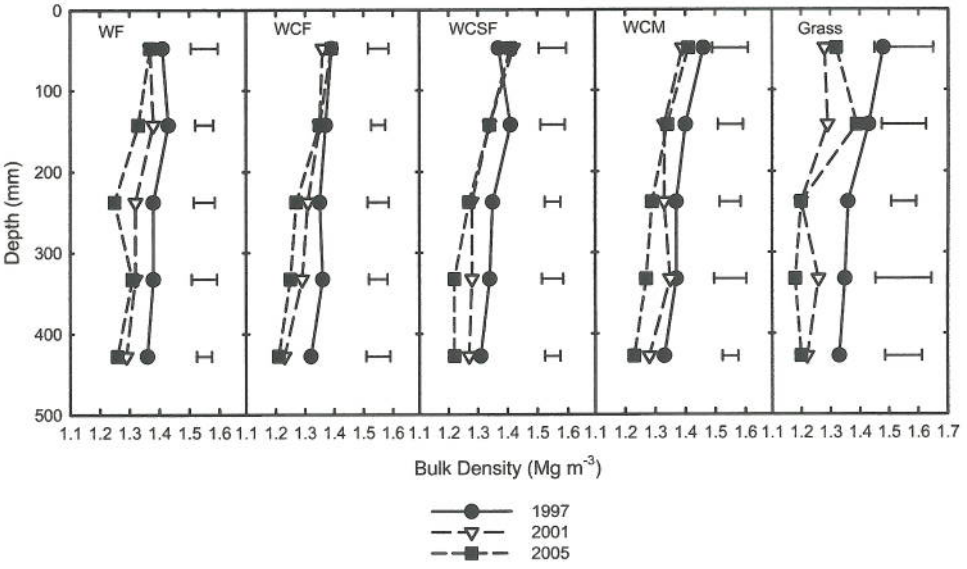

Fig. 1. Bulk density distribution with depth for wheat–fallow (WF), wheat–corn–fallow (WCF), wheat–corn–sunflower–fallow (WCSF), and wheat–corn–millet (WCF) crop rotations and continuous grass plots in 1997, 2001, and 2005. Bars indicate the critical difference for means comparisons between years for each rotation and depth.

The greatest increase in K_{sat} occurred with the grass treatment (Fig. 5). After 7 yr, the K_{sat} of the grass plots was approximately 21 mm h^{-1} to Depth 3 and was not significantly different from the cropped treatments. After 11 yr, the K_{sat} in Depth 1 of the grass plots was approximately 54 mm h^{-1}. After 15 yr, the K_{sat} in Depth 1 of the grass plots was approximately 178 mm h^{-1}. A similar K_{sat} increase was observed at other depths. The wheat rotation treatments showed little change in K_{sat} during the years of the study with the exception of the WF rotation. There was a significant increase in K_{sat} at Depths 2, 3, and 4 for this rotation alone in the 8 yr between 1997 and 2005.

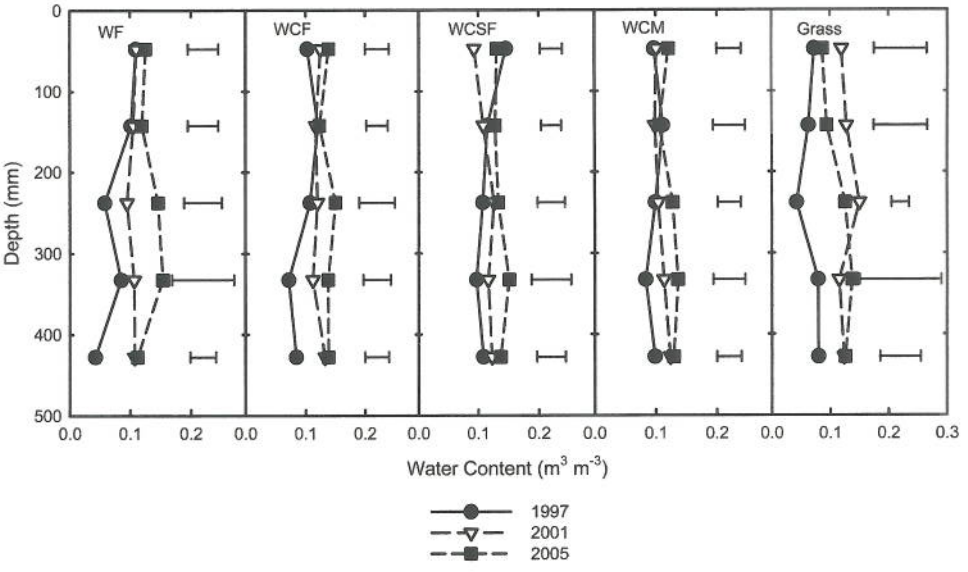

Fig. 2. Macroporosity with depth for wheat–fallow (WF), wheat–corn–fallow (WCF), wheat–corn–sunflower–fallow (WCSF), and wheat–corn–millet (WCF) crop rotations and continuous grass plots in 1997, 2001, and 2005. Bars indicate the critical difference for means comparisons between years for each rotation and depth.

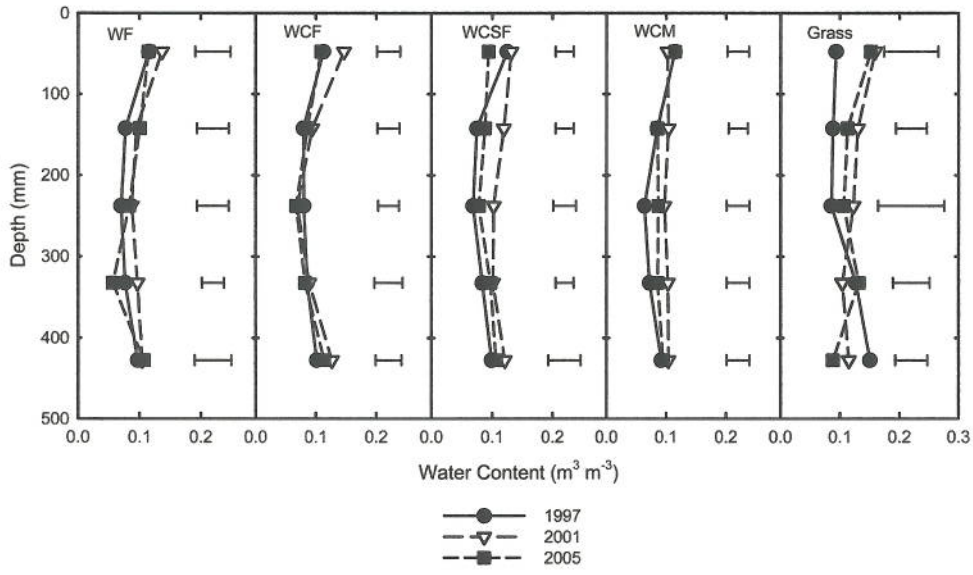

Fig. 3. Mesoporosity with depth for wheat–fallow (WF), wheat–corn–fallow (WCF), wheat–corn–sunflower–fallow (WCSF), and wheat–corn–millet (WCF) crop rotations and continuous grass plots in 1997, 2001, and 2005. Bars indicate the critical difference for means comparisons between years for each rotation and depth.

DISCUSSION

Most of the changes in the soil physical properties investigated in this study were found below Depth 1 (20–95 mm). Other studies on cropping systems (Bowman et al., 1999; Mikha et al., 2006; McVay et al., 2006) found changes in soil organic matter in the surface 50 mm but seldom found any differences in water holding capacity, bulk density, or aggregate stability among treatments at any depth.

Changes in soil physical properties caused by cropping system in this study were limited to the larger pore sizes. We found no differences in ϕ_{ws} in our study at any depth. Bulk density changes for the wheat rotation treatments were at depths below Depth 1. This is consistent with McVay et al. (2006), who found no differences in ϕ_{ws} even though there were differences in bulk density. Much time is needed for cropping system alone to alter soil physical properties. In this study, changes in soil physical properties were apparent only after 11 yr had passed. The most effective cropping system was permanent grass. This agrees with Cresswell and Kirkegaard (1995), who noted that a plant species whose roots grow for a long time and thus experience a range of soil water content is more effective at penetrating a compacted subsoil than a plant species that has some intrinsic ability to penetrate hard soil. The advantages of permanent vegetation include the lack of soil surface disturbance from annual planting operations and the maintenance of root channels throughout the year.

The hypothesis that increasing cropping intensity would improve soil physical properties at a faster rate than wheat–fallow was not supported for the soil properties investigated here. Cropping intensity with the wheat rotations had no effect on changes in bulk density, pore size distribution, water holding capacity, or saturated hydraulic conductivity during the 15 yr that this study has been in place. The only treatment that affected soil physical properties at a different rate than wheat–fallow was the continuous grass treatment. The grass treatment showed a bulk density decrease that was both faster and of greater magnitude than the annually cropped systems. Most of the changes in bulk density were reflected by greater pore volumes in the 100- to 8.8-μm pore sizes. In addition to a lower bulk density in the grass plots, there was a greater saturated hydraulic conductivity and the suggestion of greater pore continuity compared with the annually cropped systems.

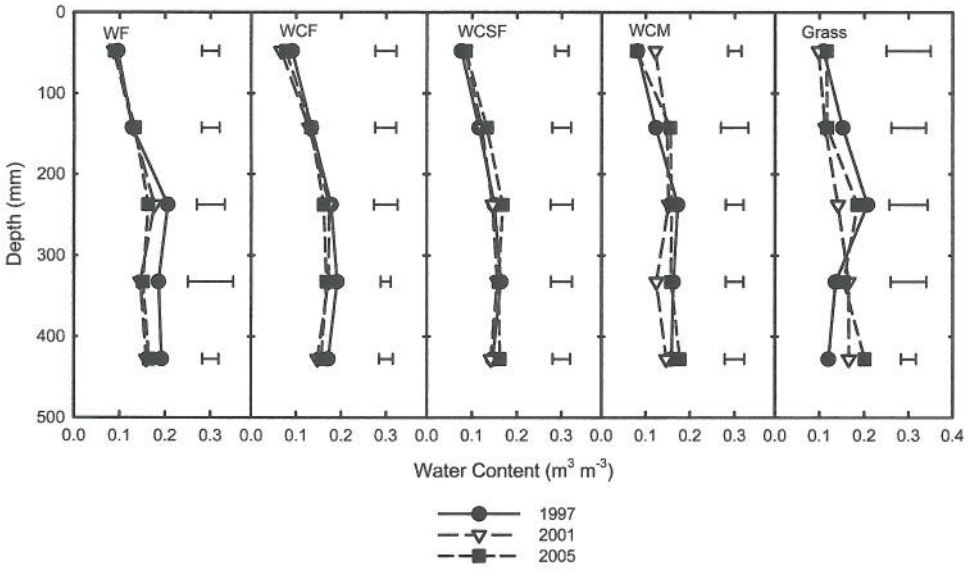

Fig. 4. Water storage porosity with depth for wheat–fallow (WF), wheat–corn–fallow (WCF), wheat–corn–sunflower–fallow (WCSF), and wheat–corn–millet (WCF) crop rotations and continuous grass plots in 1997, 2001, and 2005. Bars indicate the critical difference for means comparisons between years for each rotation and depth.

CONCLUSIONS

Changing crop rotations or cropping intensity may improve selected soil physical properties but, in this climate, the changes will occur over long periods of time. The most rapid improvement of soil physical properties comes from the use of perennial vegetation. The advantages of perennial vegetation include less annual surface compaction from planting and drilling operations, less total wheel traffic, and root systems that remains in the soil for a longer period of time to create a more stable, continuous

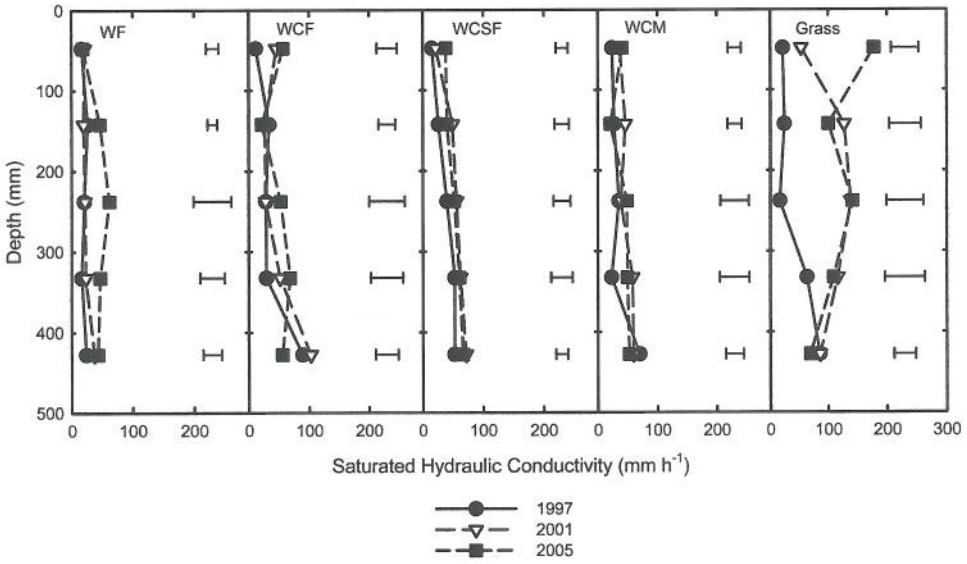

Fig. 5. Saturated hydraulic conductivity with depth for wheat–fallow (WF), wheat–corn–fallow (WCF), wheat–corn–sunflower–fallow (WCSF), and wheat–corn–millet (WCF) crop rotations and continuous grass plots in 1997, 2001, and 2005. Bars indicate the critical difference for means comparisons between years for each rotation and depth.

pore network. Increasing annual cropping intensity or changing crop species may help improve soil physical properties but the changes may not be apparent for decades.

REFERENCES

Anderson, R.L., R.A. Bowman, D.C. Nielsen, M.F. Vigil, R.M. Aiken, and J.G. Benjamin. 1999. Alternative crop rotations for the central Great Plains. J. Prod. Agric. 12:95–99.

Ball, B.C., I. Bingham, R.M. Rees, C.A. Watson, and A. Litterick. 2005. The role of crop rotations in determining soil structure and crop growth conditions. Can. J. Soil Sci. 85:557–577.

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.

Benjamin, J.G., D.C. Nielsen, and M.F. Vigil. 2003. Quantifying effects of soil conditions on plant growth and crop production. Geoderma 116:137–148.

Bowman, R.A., and A.D. Halvorson. 1997. Crop rotation and tillage effects on phosphorus distribution in the central Great Plains. Soil Sci. Soc. Am. J. 61:1418–1422.

Bowman, R.A., J.D. Reeder, and R.W. Lober. 1990. Changes in soil properties in a Central Plains rangeland soil after 3, 20, and 60 years of cultivation. Soil Sci. 150:851–857.

Bowman, R.A., M.F. Vigil, D.C. Nielsen, and R.L. Anderson. 1999. Soil organic matter changes in intensively cropped dryland systems. Soil Sci. Soc. Am. J. 63:186–191.

Cresswell, H.P., and J.A. Kirkegaard. 1995. Subsoil amelioration by plant roots—the process and evidence. Aust. J. Soil Res. 33:221–239.

Elkins, C.B. 1985. Plant roots as tillage tools. p. 519–523. *In* Proc. Int. Conf. on Soil Dynamics. Vol. 3: Tillage Machinery Systems as Related to Cropping Systems. 17–19 June 1985. Auburn Univ., Auburn, AL.

Flint, L.E., and A.L. Flint. 2002. Pore size distribution, water desorption method. p. 246–249. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. Physical methods. SSSA Book Ser. 5. SSSA, Madison, WI.

McVay, K.A., J.A. Budde, K. Fabrizzi, M.M. Mikha, C.W. Rice, A.J. Schlegel, D.E. Peterson, D.W. Sweeney, and C. Thompson. 2006. Management effects on soil physical properties in long-term tillage studies in Kansas. Soil Sci. Soc. Am. J. 70:434–438.

Mikha, M.M., M.F. Vigil, M.A. Liebig, R.A. Bowman, B. McConkey, E.J. Deibert, and J.L. Pikul, Jr. 2006. Cropping system influences on soil chemical properties and soil quality in the Great Plains. Renewable Agric. Food Syst. 21:26–35.

Pikul, J.L., Jr., and R.R. Allmaras. 1986. Physical and chemical properties of a Haploxeroll after fifty years of residue management. Soil Sci. Soc. Am. J. 50:214–219.

Pikul, J.L., Jr., R.C. Schwartz, J.G. Benjamin, R.L. Baumhardt, and S. Merrill. 2006. Cropping system influences on soil physical properties in the Great Plains. Renewable Agric. Food Syst. 21:15–25.

Reynolds, W.D., and D.E. Elrick. 2002. Constant head soil core (tank) method. p. 804–808. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. Physical methods. SSSA Book Ser. 5. SSSA, Madison, WI.

SAS Institute. 1999. The SAS system for Windows, version 8. SAS Inst., Cary, NC.

Young, I.M., J.W. Crawford, and C. Rappoldt. 2001. New methods and models for characterising structural heterogeneity of soil. Soil Tillage Res. 61:33–45.