Surface Soil Physical Properties After Twelve Years of Dryland No-Till Management

T. M. Shaver,* G. A. Peterson, L. R. Ahuja, D. G. Westfall, L. A. Sherrod, and G. Dunn

ABSTRACT

Water is the principle limiting factor in dryland cropping systems. Surface soil physical properties influence infiltration and cropping systems under no-till management may affect these properties through residue addition. The objectives of this study were: (i) to determine how cropping intensity and topographic position affect soil bulk density, porosity, sorptivity, and aggregate stability in the surface 2.5 cm of soils at three eastern Colorado sites; and (ii) to relate these properties to crop residue returned to the soil surface. No-till cropping systems had been in place on three slope positions, at three sites, for 12 yr prior to this study. Wheat (*Triticum aestivum* L.)-corn (*Zea mays* L.)-fallow (WCF) and continuous cropping (CC) systems were compared with wheat-fallow (WF) on summit and toeslope positions at two sites (Sterling and Stratton), and at the third site (Walsh) wheat-sorghum [*Sorghum bicolor* (L.) Moench]-fallow (WSF) replaced WCF. Cropping systems (CC and WCF or WSF) that returned more crop residue decreased bulk density and increased total and effective porosities compared with WF. Site and slope positions that produced more crop residue also improved these properties. However, sorptivity developed no significant differences as a result of cropping system. Macroaggregates made up a higher percentage of total aggregates in CC and WCF or WSF compared with WF in proportion to residue added and were also a function of clay content of the soil at different sites and slope positions. These factors enhance the potential for greater infiltration and hence greater water availability for crops.

Water is the most important and limiting factor in dryland cropping systems in eastern Colorado (Peterson et al., 1993). Average precipitation for this region ranges from 395 mm yr^{-1} in southeastern Colorado to 440 mm yr^{-1} in northeastern Colorado (Peterson et al., 1993; Peterson et al., 1999). Growing season (March–October) open-pan evaporation averages 1600 mm in the northeast region of Colorado to 1975 mm in the southeast region of Colorado (Peterson et al., 1993; Peterson et al., 1999). These conditions create a water deficit for crops and therefore it is important to maximize infiltration rates to capture as much precipitation as possible for plant use. This will decrease evaporation, runoff, and potential erosion.

Historically, the WF cropping system has dominated Central Great Plains agriculture. In the western Central Great Plains this system requires a 14-mo fallow period between the harvest and planting of wheat crops. Unfortunately, water storage efficiencies during fallow are <25%. Consequently >75% of the precipitation is lost to evaporation, runoff, weed use, etc. (Peterson and Westfall, 1996). Research over the past 12 yr has shown that no-till management permits cropping intensification from one crop every 2 yr to systems like WCF (two crops every 3 yr) and even continuous (annual) cropping in some instances. For example, annualized grain yields for WCF are 75 to 100% greater than WF (Peterson et al., 2000). Cropping intensification has been possible because no-till practices improve soil water storage efficiencies in the early phases of fallow (Farahani et al., 1998). Since nearly 75% of the annual precipitation in this region occurs during April to September, relatively small net increases in soil water storage can provide the necessary water to sustain crop growth between rainfall events. Thus water capture via increased water infiltration rates becomes a significant factor in maximizing water storage at all points in the system. An added benefit of cropping intensification is that increased amounts of crop residue are returned to the soil capared with WF. We believe this residue may greatly improve soil physical properties resulting in increased water infiltration and capture efficiency.

Soil physical properties such as bulk density, porosity, sorptivity, and aggregation dictate the infiltration characteristics and potentials of the soil. Most important are the physical properties of the surface soil (top 2.5 cm), as this is the initial soil-water interface. However, long-term infiltration can be affected by the hydraulic conductivity characteristics of deeper soil layers. Site latitude (evaporation potential), landscape slope, and cropping system intensity interact to affect surface soil physical properties important to water capture and infiltration. By determining the extent to which these factors influence surface soil physical properties, we can determine which cropping systems maximize potential infiltration, water availability for crops, and precipitation use efficiency (PUE) of the system.

Numerous studies have been conducted to address soil physical properties. Dao (1996) found that tillage initially decreased bulk density, but no-till had a lower bulk density than the more traditional methods by the end of the growing season. He also found that increased crop residue amounts decreased bulk density in the 0- to 0.05-m soil layer. Hammel (1989) found that no-till soil had a higher bulk density relative to tillage systems in the surface 0.3 m of soil. However, when 2- and 3-yr cropping systems were included in the comparison, differences because of tillage were nonexistent when averaged over a depth of 0 to 0.5 m. These studies also reflect total porosity because of the direct relationship of bulk density and porosity. If no-till decreases bulk density, it must also increase total porosity. Roseberg and McCoy (1992) found that tillage increased total porosity, but that macropores (effective pores) decreased in number, stability, and continuity compared with no-till soil.

Macropores are responsible for the effective porosity

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Abbreviations: CC, continuous cropping; HMP, hexametaphosphate; PUE, precipitation use efficiency; SOM, soil organic matter; WCF, wheat-corn-fallow; WF, wheat-fallow; WSF, wheat-sorghum-fallow.

of the soil. Effective porosity has been related to saturated hydraulic conductivity (Ahuja et al., 1984; Ahuja et al., 1989). However, it also reflects the percentage of total pores that are open to infiltration during a rain event. Little work has been done relating effective porosity and macropores.

Sorptivity is defined as the cumulative infiltration proportionality constant (Philip, 1957). We found no reported studies that used sorptivity as a measure of cropping system effects on soil water properties. However, there are several reported infiltration studies using rainfall simulators and double ring infiltrometers. Although the methods differ, they should give us an idea of what to expect. Unger (1992), using simulated rainfall, found that soil-loosening tillage increased infiltration on plots with limited residues, but residue cover alone had no effect on infiltration. Dao (1993), using double ring infiltrometers, found that no-till with surface residues significantly increased ponded infiltration relative to traditional tillage methods. The residue cover decreased the potential for crusting from raindrop impact and decreased the surface bulk density allowing for higher infiltration. Freese et al. (1993), using a sprinkling infiltrometer, also found that no-till had higher infiltration rates than chisel and moldboard plowing immediately after tillage, and after corn harvest. Chisel and moldboard plowing caused more surface sealing and wheel compaction than no-till, resulting in less water infiltration.

Elliott (1986) showed that aggregate stability decreased in cultivated land compared with native grassland, and that decreases in soil organic matter (SOM) paralleled the decrease in stability. Although his was not a cropping system comparison, we can deduce that higher cropping intensity systems should have greater aggregate stability than lower intensity systems because of greater organic C addition. Less intensive tillage results in more macroaggregates because fewer are destroyed (Cambardella and Elliot, 1993; Tisdall and Oades, 1980). Tillage had no effect on individual microaggregates (Tisdall and Oades, 1980).

Previous work on soil physical properties concentrated on tillage effects but few studies have compared the effects of cropping systems on soil physical properties within no-till management. Also, few studies have concentrated only on the surface 2.5 cm of soil, the initial soil-water interface. Our study is unique in that it examined the effect of cropping systems on surface soil physical properties over a soil catena. It was also unique in studying these properties across sites with differing evaporation potentials. By accounting for climatic, topographic, and soil factors, the potential for extrapolation and interpolation of the data to other areas increases. Finally, our long-term Dryland Agroecosystem Project allowed us to measure these effects whose cumulative impact may be obvious only after several years.

Our objectives were:

1. To determine how cropping system (WF is the baseline cropping system for comparison) and slope position affect bulk density, total and effective porosity, sorptivity, and aggregate stability in the surface 2.5 cm of soil at three eastern Colorado sites.
2. To relate bulk density, total and effective porosity, sorptvity, and aggregate stability in the surface 2.5 cm of soil to crop residue returned to the soil by site, slope, and cropping system.

We hypothesized that cropping systems more intensive than WF will decrease bulk density, increase porosity (both total and effective), increase soil sorptivity, and increase aggregate stability in the surface 2.5 cm of soil because more residue is returned to the surface. We also hypothesized that toeslope positions would have decreased bulk density, increased porosity, sorptivity, and aggregate stability compared with summit slope positions because of the increased crop residue production on the toe slopes of all sites.

MATERIALS AND METHODS

Sampling for this study was conducted in the summer of 1998 after 12 yr of research in the Dryland Agroecosystem Project (Peterson et al., 1993). The study included three sites, three cropping systems, and two slope positions per site. All samples were taken from the surface 2.5 cm of the soil.

Sites

Three sites located near Sterling (40°22′12″ N, 103°7′48″ W), Stratton (39°10′48″ N, 102°15′36″ W), and Walsh (37°13′48″ N, 102.17° W) in eastern Colorado represent an evaporation gradient from the northern site (Sterling) to the southern site (Walsh). Sterling has the lowest open-pan evaporation, 1600 mm during the cropping season, Stratton has 1725 mm, and Walsh has 1975 mm (Peterson et al., 1999; Peterson et al., 1993). All sites had been managed with tillage in either WF (Sterling and Stratton) or sorghum-fallow (Walsh) systems for more than 50 yr until no-till management was imposed in 1985.

Each site is located on a soil catena consisting of a summit slope, side slope, and toeslope. Only the summit and toeslopes of each site were sampled for this study. The Sterling summit is classified as a fine, mixed, mesic Ardic Argiustoll and the toe is a fine-loamy, mixed mesic Pachic Argisutoll. The Stratton summit is a fine-silty, mixed, mesic, Aridic Argiustoll and the toe is a fine-silty, mixed, mesic, Pachic Argiustoll. The Walsh summit is classified as a fine-loamy, mixed, mesic Aridic Ustochrept, and the toe is a fine, montmorillonitic, mesic Aridic Argiustoll.

Each site had two replications and each replication had each phase of every cropping system each year (i.e., for the WCF cropping system there were three separate strips in each replication; one in wheat, one in corn, and one in fallow). Cropping systems were set up as strips that go along each slope on the catena. Each strip was 6.1 m wide and varied in length from 225 to 325 m depending on site. Each cropping system was sampled in each replication at both the summit and toeslope positions.

Cropping Systems

Wheat-fallow (WF), wheat-corn-fallow (WCF), and continuous cropping (CC) were the cropping systems of interest for this study. The WF system serves as the baseline for comparison since it is the predominant dryland cropping system in this region. At Walsh, sorghum replaces corn in the 3-yr system because of the high evaporation potential in that area (Peterson et al., 1993).

Sampling was done after the first 12-yr cycle of the experiment. To standardize sample times within a system, we sampled after wheat harvest so that all sampling positions were in a similar condition. Continuous cropping systems at Sterling and Stratton were in wheat in 1998, so wheat phases of the WCF and WF systems were selected for sampling. At Walsh however, CC was in grain sorghum at the time of soil sampling.

Bulk Density, Total Porosity, and Effective Porosity

Bulk density was determined using a modified version of the core method (Blake, 1986). A 100.9-cm^3 metal cylinder was pressed into the soil surface leaving a 5-mm gap (approximate) between the soil surface and the top edge of the cylinder. The soil around the cylinder was excavated and the cylinder with the core in place was removed by sliding a trowel under the cylinder. Cores were dried to 105°C. and weighed. The air space left in the cylinder was back filled with laboratory test sand of known density and the sample was weighed again. The difference between these two weights was the mass of the sand. Sand mass divided by the density of the sand yielded the volume of the cylinder displaced by the sand. Bulk density was then back calculated by subtracting the volume of the cylinder by the volume displaced by the test sand giving the volume of the remaining soil core. Core mass divided by the core volume resulted in the surface soil bulk density.

Total porosity was calculated using the equation and relationship developed by Danielson and Sutherland (1986).

$$\text{Total Porosity} = \frac{1 - \text{Bulk Density (g cm}^{-3})}{2.65\ (\text{g cm}^{-3})}$$

Effective porosity was determined based on the concepts developed by Ahuja et al. (1984). The aforementioned soil cores were saturated and placed on pressure plates at −10 kPa suction and then weighed. The wet weight minus the dry weight yields the volumetric water content at −10 kPa. This value was subtracted from the total porosity yielding effective porosity.

Sorptivity

Sorptivity measurements were made using methods reported by Smith (1999), with one change. Steel rings, 15 cm long, and 5 cm in diameter were driven ~3 cm deep into the soil. A measured volume of water that equaled a 1-cm depth in the ring was then instantly poured. Then the complete infiltration time was recorded, the 50% infiltration measurement was not recorded as this measurement is subjective and prone to error. The equation $1/\sqrt{t}$ was then used to determine sorptivity; where 1 is the head of water applied in centimeters, and t is the time for the water to infiltrate. Thirty-nine measurements were taken at each soil position to account for spatial variability. Also, four random soil samples were taken at each soil position to determine the initial water content of the surface soil at the time of sampling. Measured sorptivities were then adjusted to correspond to the average initial water deficit ($\theta_s - \theta_i$) of all positions for comparisons within site. Here θ_s equals the porosity estimated from soil bulk density and θ_i is the initial soil water content. The relationship $s^2 = 2GK_s\ (\theta_s - \theta_i)$ (Eq. [1] of Smith, 1999) was used for this purpose, with parameters G (capillary length scale) and K_s (saturated conductivity) assumed constant within a given cropping system and slope position.

Aggregates

Water-stable aggregates were determined following procedures developed by Kemper and Rosenau (1986). Fifty-gram surface soil samples were placed in a stack of sieves of progressively smaller size attached to a dipping mechanism. The sieves were cycled through a column of water for 10 min. (30 times per minute, 3.8-cm stroke) yielding a delineated size fraction of water stable aggregates. The percentage of aggregates as a fraction of the total soil sample was then calculated. Aggregates were then fractionated into macro (>0.25 mm) and microaggregate (<0.25 mm) categories. All aggregate fractions were corrected for sand content by dispersion with Na-hexametaphosphate (HMP).

Particle-Size Analysis (Texture)

Particle-size analysis was conducted using the hydrometer method (Gee and Bauder, 1986). Samples were dispersed chemically using HMP and then physically by a reciprocating shaker for 16 h. Samples were transferred to 1-L graduated cylinders and allowed to equilibrate for 2 h. They were stirred with a plunger and a hydrometer reading was recorded. The samples were undisturbed for 6 h and then a second hydrometer reading was recorded. All measurements were recorded at a lab temperature of 25°C.

Statistical Analysis

Analyses of Variance were done using the Mixed Procedure of the Statistical Analysis System (SAS) (SAS Institute, 1999) for tests of all main effects and interactions. The option Means in the GLM procedure was used to attain all mean values and main effect LSDs. Significant Interaction ($P \leq 0.1$) LSDs for mean separation were calculated by comparing slopes within sites (site × slope), cropping system within site (site × cropping system), cropping system within slope (slope × cropping system), and cropping system within site and slope (site × slope × cropping system).

RESULTS AND DISCUSSION

Texture

The soil texture of each sample position is important as it directly affects bulk density, porosity, sorptivity, and aggregation. The sandy loam texture at the Walsh summit (Table 1) allowed for lower overall porosity

Table 1. Soil separates and soil textural classes in the surface 2.5 cm of soil at Sterling, Stratton, and Walsh, CO by cropping system and replication.

Site	Slope	Cropping System†	Texture	Sand/Silt/Clay
				%
Sterling	Summit	WF	Loam	45/35/20
		WCF	Loam	39/40/21
		CC	Loam	37/41/22
	Toe	WF	Loam	34/45/21
		WCF	Loam	33/45/22
		CC	Loam	33/46/21
Stratton	Summit	WF	Clay Loam	26/44/30
		WCF	Clay Loam	25/41/34
		CC	Clay Loam	24/45/31
	Toe	WF	Clay Loam	27/45/28
		WCF	Silty Clay Loam	20/47/35
		CC	Clay Loam	25/47/28
Walsh	Summit	WF	Sandy Loam	72/16/12
		WCF	Sandy Loam	74/17/9
		CC	Sandy Loam	78/13/9
	Toe	WF	Loam	39/35/26
		WCF	Loam	41/35/24
		CC	Loam	41/35/24

† WF = wheat-fallow, WCF = wheat-corn-fallow, CC = continuous cropping.

(total and effective) and related sorptivity. This was also the case for macroaggregates at this position and bulk density was higher within this texture. With the high sand and low clay content there is little particle cohesion to aid in pore and aggregate formation, and sand particles have a higher density than silt or clay particles resulting in the higher bulk density. These reasons also help explain the results within the other textures. The clay loam and silty clay loam textures at the Stratton summit and toe (Table 1) had the highest levels of clay and therefore, the highest potential for particle cohesion. This resulted in the highest levels of porosity, sorptivity, and macroaggregation and lowest bulk density. The loam textures at the Sterling summit and toe, and the Walsh toe have intermediate levels of clay (compared with the other textures) and resulted in intermediate levels of porosity, sorptivity, aggregation, and bulk density. Textural effects on the results become important when analyzing site by slope, and site by slope by cropping system interactions. When analyzing site, slope, and cropping system individually the results are averaged across sample positions, this takes texture into account.

Residue Production

The amount of residue produced at each sample position from 1986 to 1997, as well as the average annual production for each position is listed in Table 2. Stratton produced the greatest amount residue (38.6 Mg ha^{-1}) over the 12-yr period, Sterling was intermediate (30.3 Mg ha^{-1}), and Walsh produced the least with 16.8 Mg ha^{-1} (Table 2). The toeslope produced more residue (33.1 Mg ha^{-1}) than the summit slope (24.0 Mg ha^{-1}) overall and at all sites (Table 2). Overall the CC cropping system had the highest production (36.6 Mg ha^{-1}) with WCF being intermediate (27.8 Mg ha^{-1}), and WF being the lowest (21.2 Mg ha^{-1}) (Table 2). Sites (Stratton), slopes (toeslope), and cropping systems (CC) that produced the highest levels of residue should also produce the highest quantities of organic C in the soil. Organic C acts as a glue to aid in the formation of macroaggregates and pores, which will affect sorptivity and bulk density. Therefore, with greater plant residue there should be greater organic C, and subsequently higher aggregation, porosity, sorptivity, and lower bulk density.

Table 2. Total and average yearly crop residue production from 1986 to 1997 at Sterling, Stratton, and Walsh, CO by cropping system and slope position.

Cropping System†	Cummulative residue (1986–1997)		Average annual residue	
	Slope position		Slope position	
	Summit	Toeslope	Summit	Toeslope
	Mg ha^{-1}			
		Sterling		
WF	17.6	22.0	1.5	1.8
WCF	26.1	32.9	2.2	2.7
CC	37.2	45.5	3.1	3.8
Mean	27.0	33.5	2.3	2.8
	Site Mean = 30.3		Site Mean = 2.6	
		Stratton		
WF	24.5	35.3	2.0	2.9
WCF	27.1	43.7	2.3	3.6
CC	44.5	56.6	3.7	4.7
Mean	32.0	45.2	2.7	3.7
	Site Mean = 38.6		Site Mean = 3.2	
		Walsh		
WF	11.0	17.0	0.9	1.4
WCF	15.0	22.1	1.3	1.8
CC	13.4	22.3	1.1	1.9
Mean	13.1	20.5	1.1	1.7
	Site Mean = 16.8		Site Mean = 1.4	

† WF = wheat-fallow, WCF = wheat-corn-fallow, CC = continuous cropping.

Porosity

Our hypothesis that cropping systems which produce and return more crop residue compared with WF to the soil increase total porosity is supported by the data in Table 3. Continuous cropping had a total porosity of 0.54 m^3 m^{-3}, which was significantly higher than WF with 0.50 m^3 m^{-3}. Wheat-corn-fallow total porosity was not significantly different than CC or WF with 0.52 m^3 m^{-3}. No interactions were present among the variables so each factor can be considered independently. Cropping systems that returned the most residue resulted in the highest levels of total porosity (Table 2).

Total porosity also differed for site and slope, but there were no significant interactions among site, slope, and cropping system. Toeslopes were higher than summit slopes with 0.55 and 0.49 m^3 m^{-3}, respectively (Table 3). These results are also related to the amount of residue produced at each site and slope position (Table 2). As residue (and therefore organic C) increased so did total porosity (Fig. 1). Figure 1 also shows that when regressed, 72% of the variability in total porosity can be explained by the amount of crop residue production.

Bulk density values showed the same results as total porosity since they are inversely related to one another. Positions that had the highest porosity also had the lowest bulk density and vice versa (Table 3).

Effective porosity results showed that CC had the highest level of effective pores with 0.29 m^3 m^{-3}, WCF had 0.26 m^3 m^{-3}, and WF had 24 m^3 m^{-3}. Wheat-Corn-Fallow and WF were not significantly different (Table 3). Site and slope positions also significantly altered effective porosity, but there were no interactions of the variables. When averaged over cropping systems, the toeslope had more effective porosity than the summit slope with 0.28 and 0.25 m^3 m^{-3}, respectively (Table 3). When effective porosity is regressed 67% of the variability can be explained by crop residue production (Fig. 1). Again, as crop residue increased so did effective porosity (Fig. 1).

Sorptivity

Sorptivity is a measure of ponded-water infiltrability of the soil matrix and it should be related to saturated hydraulic conductivity (Phillip, 1957) or its surrogate the effective porosity (Ahuja et al., 1984). Sorptivity was not affected by cropping system (Table 4) and our hypothesis was rejected. It is possible that in a long-term no-till soil, what we measured is not the sorptivity

Table 3. Bulk density, total porosity, and effective porosity in the surface 2.5 cm of soil as affected by site, slope position, and cropping system after 12 yr of no-till management.

	Bulk density			Total porosity			Effective porosity		
	Cropping system†			Cropping system			Cropping system		
Slope position	WF	WCF	CC	WF	WCF	CC	WF	WCF	CC
	g cm^{-3}			m^3 m^{-3}					
			Sterling						
Summit	1.39	1.44	1.35	0.48	0.46	0.49	0.20	0.19	0.23
Toeslope	1.35	1.24	1.17	0.49	0.53	0.56	0.22	0.25	0.31
Mean	1.37	1.34	1.26	0.48	0.50	0.52	0.21	0.22	0.27
			Stratton						
Summit	1.18	1.11	0.95	0.56	0.58	0.64	0.24	0.30	0.35
Toeslope	1.00	1.03	0.91	0.62	0.61	0.66	0.31	0.33	0.38
Mean	1.09	1.07	0.93	0.59	0.60	0.65	0.27	0.32	0.36
			Walsh						
Summit	1.66	1.56	1.58	0.37	0.42	0.40	0.20	0.24	0.24
Toeslope	1.38	1.28	1.36	0.48	0.52	0.49	0.24	0.26	0.26
Mean	1.52	1.42	1.47	0.43	0.47	0.45	0.22	0.25	0.25
Cropping System Mean	1.32	1.27	1.22	0.50	0.52	0.54	0.24	0.26	0.29
Slope Position Mean									
Summit	1.41	1.37	1.29	0.47	0.49	0.51	0.22	0.25	0.28
Toeslope	1.24	1.18	1.15	0.53	0.55	0.57	0.25	0.28	0.31
Analysis of variance	$P > F$	$LSD_{0.1}$		$P > F$	$LSD_{0.1}$		$P > F$	$LSD_{0.1}$	
Site	0.0118	0.07		0.0116	0.03		0.0666	0.5	
Slope	0.0053	0.04		0.0054	0.02		0.0375	0.02	
Site × Slope	0.1202	–		0.1220	–		0.6050	–	
Cropping System	0.0608	0.07		0.0596	0.03		0.0430	0.04	
Site × Cropping System	0.3564	–		0.3418	–		0.6077	–	
Slope × Cropping System	0.8000	–		0.8502	–		0.9854	–	
Site Slope × Cropping System	0.3697	–		0.3617	–		0.5395	–	

† WF = wheat-fallow, WCF = wheat-corn-fallow, CC = continuous cropping.

of the soil matrix in the original sense, but rather a measure that is dominated by flow into macropores created by root channels. Such a flow would not be expected to relate to effective porosity, as the effective porosity measured on soil cores in the laboratory generally excludes the root channels that drain at a very small tension. Therefore, the results indicate that the cropping systems did not significantly influence the creation of stable root channels, but the higher residue producing sites and slope positions did create significant differences.

Macroaggregates

The proportion of aggregates as macroaggregates was a function of site, slope, and cropping system (Table 5). Their interaction was attributable to soil texture and

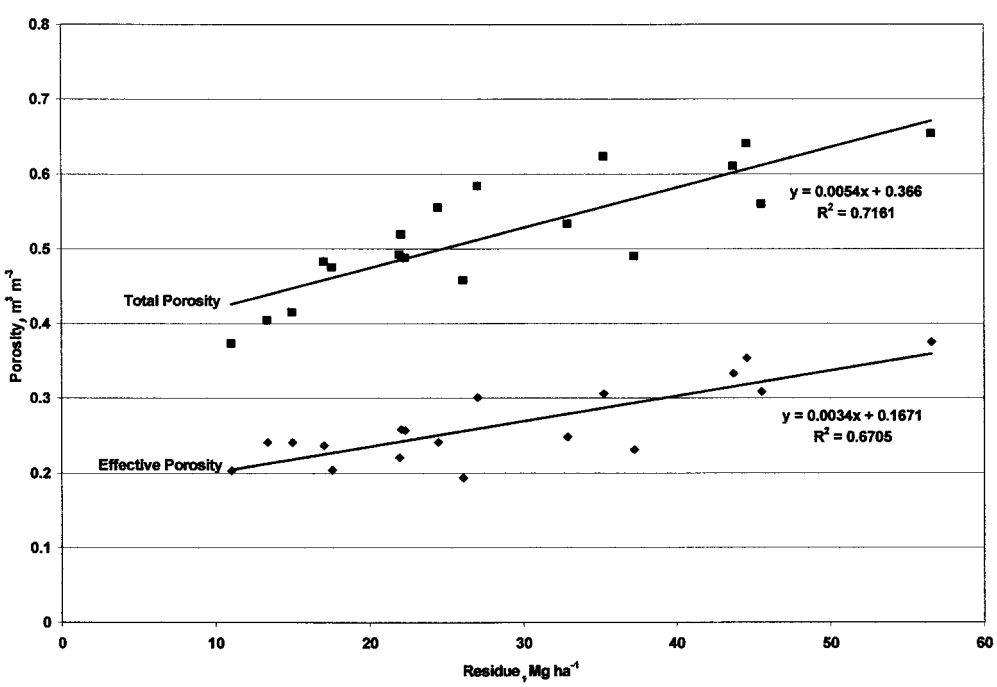

Fig. 1. Total and effective porosity in 1998 as a function of crop residue production over a 12-yr period.

Table 4. Soil sorptivity as affected by site, slope position, and cropping system after 12 yr on no-till management.

Slope position	Sorptivity		
	Cropping system†		
	WF	WCF	CC
	cm $s^{-1/2}$		
Sterling			
Summit	0.20	0.16	0.20
Toeslope	0.24	0.21	0.26
Mean	0.22	0.19	0.23
Stratton			
Summit	0.23	0.25	0.27
Toeslope	0.29	0.31	0.24
Mean	0.26	0.28	0.25
Walsh			
Summit	0.14	0.13	0.16
Toeslope	0.21	0.19	0.21
Mean	0.17	0.16	0.18
Cropping System Mean	0.22	0.21	0.22
Slope Position Mean			
Summit	0.19	0.18	0.21
Toeslope	0.24	0.24	0.25
Analysis of Variance	$P > F$	$LSD_{0.1}$	
Site	0.0593	0.04	
Slope	0.0231	0.02	
Site × Slope	0.6157	–	
Cropping System	0.7581	–	
Site × Cropping System	0.5472	–	
Slope × Cropping System	0.6151	–	
Site × Slope × Cropping System	0.5177	–	

† WF = wheat-fallow, WCF = wheat-corn-fallow, CC = continuous cropping.

crop residue production differences among sites and slopes. Since these interactions were significant it is necessary to evaluate how individual cropping systems affected macroaggregates within individual slopes where texture was not a factor.

The Sterling summit had higher proportions of macroaggregates in the CC (0.28 kg kg^{-1}) and WCF (0.28 kg kg^{-1}) cropping systems than in the WF (0.24 kg kg^{-1}) system. This was also the case on the toeslope, where CC had 0.33 kg kg^{-1}, WCF had 0.33 kg kg^{-1} macroaggregation, and WF had 0.28 kg kg^{-1} (Table 5). The toeslope values were significantly higher than the summit slope within cropping system because of the increased residue production on the toeslope (Table 2). This comparison is valid at Sterling because summit and toe positions have the same soil texture (Table 1). Both CC and WCF had higher total amounts of crop residue production than WF on both slope positions through the 12 yr of the Dryland Agroecosystem Project. Continuous cropping residue production was greater than WCF production (Table 2). However, this did not lead to higher levels of macroaggregation in the CC cropping system compared with WCF in this case.

Aggregation for the Stratton summit was similar to the Sterling summit, but at a higher level. Both CC and WCF had high levels of macroaggregates at 0.48 and 0.49 kg kg^{-1}, respectively, and WF was significantly lower at 0.41 kg kg^{-1} (Table 5). Higher crop residue production in the CC and WCF systems explains this difference. Interestingly, the toeslope at Stratton had higher percentages in WCF (0.44 kg kg^{-1}) than in CC (0.39 kg kg^{-1}). Wheat-Fallow had 0.42 kg kg^{-1} macroaggregates which was not significantly different than CC or WCF (Table 5). These results were not related to cropping system effects or residue production, but most likely

Table 5. Macro and microaggregation in the surface 2.5 cm of soil as affected by site, slope position, and cropping system after 12 yr of no-till management.

Slope position	Macroaggregates			Microaggregates		
	Cropping system†			Cropping system†		
	WF	WCF	CC	WF	WCF	CC
	Kg Kg^{-1}					
Sterling						
Summit	0.24	0.28	0.28	0.22	0.18	0.21
Toeslope	0.28	0.33	0.33	0.18	0.17	0.17
Mean	0.26	0.30	0.30	0.20	0.18	0.19
Stratton						
Summit	0.41	0.49	0.48	0.25	0.20	0.18
Toeslope	0.42	0.44	0.39	0.20	0.22	0.23
Mean	0.41	0.47	0.44	0.23	0.21	0.21
Walsh						
Summit	0.08	0.06	0.07	0.10	0.09	0.07
Toeslope	0.28	0.31	0.34	0.21	0.18	0.16
Mean	0.18	0.18	0.21	0.16	0.14	0.12
Cropping System Mean	0.28	0.32	0.31	0.19	0.17	0.17
Slope Position Mean						
Summit	0.24	0.28	0.28	0.19	0.16	0.16
Toeslope	0.32	0.36	0.35	0.20	0.19	0.19
Analysis of Variance	$P > F$	$LSD_{0.1}$		$P > F$	$LSD_{0.1}$	
Site	0.0153	0.08		0.0448	0.02	
Slope	0.0079	0.03		0.1262	–	
Site × Slope	0.0063	0.06		0.0325	0.07	
Cropping System	0.0040	0.01		0.0241	0.01	
Site × Cropping System	0.0680	0.02		0.4225	–	
Slope × Cropping System	0.9570	–		0.1985	–	
Site × Slope × Cropping System	0.0223	0.03		0.0811	0.03	

† WF = wheat-fallow, WCF = wheat-corn-fallow, CC = continuous cropping.

to landscape topography. The Stratton toe experiences deposition and erosion processes from three slopes. This causes extreme variability in texture (Table 1), and macroaggregate percentages.

Cropping systems had no effect on macroaggregates on the summit position at Walsh (Table 5). This was because of the sandy loam texture at this soil position (Table 1). The high sand content of the Walsh summit does not allow particle cohesion and thus limited aggregation is present. Soils need 15% clay to form aggregates (Horn et al., 1994), and the Walsh summit had <15% clay. Few aggregates formed at this position in any of the cropping systems; CC, WSF, and WF had 0.07, 0.06, and 0.08 kg kg^{-1}, respectively (Table 5). Crop residue production across the three cropping systems also was relatively similar at this position. Because of the low clay and high sand contents, even higher levels of residue input into the soil could not increase macroaggregation.

The toeslope soil at Walsh had a loam texture, and this allowed for aggregation potential similar to that at Sterling, which also had a loam texture (Table 1). Continuous cropping had the highest percentage of macroaggregates with 0.34 kg kg^{-1}, but WSF and WF did not differ from each other with 0.31 kg kg^{-1} and 0.28 kg kg^{-1}, respectively (Table 4). As expected, CC had the highest levels of macroaggregates on the toeslope because of the high level of residue addition. However, we also expected that WSF macroaggregation would be increased relative to WF because crop residue production levels for WSF on the toeslope were similar to CC and higher than WF. Texture is a nonfactor on the toeslope as all cropping systems are loams. The inconsistency is not explainable with the existing data.

Our macroaggregation results support the initial hypotheses that increased crop residue production will increase macroaggregation because the more intensive cropping systems typically resulted in higher percentages of macroaggregates. We originally thought that the WCF system would be intermediate between the CC and WF systems. However, CC and WCF generally differed very little. Although CC produced more crop residue than WCF, it did not lead to greater levels of stable macroaggregates. It is possible that soils have a threshold organic matter requirement for aggregate stabilization and that this threshold was exceeded by both the WCF and CC. Macroaggregation was related to both clay content (Table 1) and crop residue production, and regression analysis showed that 95% ($R^2 = 0.95$) of the variability in macroaggregates was explained by these two factors.

Microaggregates

Microaggregate stability is not affected by management practices or SOM content (Elliott, 1986; Tisdall and Oades, 1980). Aromatic humic materials associated with amorphous Fe and Al compounds and polyvalent metal cations are thought to be responsible for microaggregate stability (Elliott, 1986; Tisall and Oades 1982), and these compounds are relatively permanent and do not fluctuate with changes in total organic matter content (Tisdall and Oades, 1982). Therefore, crop residue addition variances attributable to cropping systems do not affect microaggregate formation. However, microaggregates combine to form macroaggregates (Baver, 1956; Tisdall and Oades, 1982; and Elliot, 1986). Therefore we expected to see an inverse relationship between micro and macroaggregates because the number of microaggregates should decrease as they combine to form more macroaggregates. Areas with higher levels of macroaggregates should have lower levels of microaggregates and vice versa. Overall this did not turn out to be the case. The Stratton summit slope had lower levels of microaggregates in CC (0.18 kg kg^{-1}) and WCF (0.20 kg kg^{-1}) compared with WF (0.25 kg kg^{-1}), and the Walsh toeslope had lower levels in CC (0.16 kg kg^{-1}) than in WF (0.21 kg kg^{-1}) (Table 5). However, these were the only data that supported our expectations. Microaggregate levels do not appear to be significantly reduced by high levels of macroaggregates.

SUMMARY AND CONCLUSIONS

After 12 yr of continuous no-till management, physical properties of the surface 2.5 cm of soil were improved by more intensive cropping systems when compared with WF. Any combination of cropping systems, sites, and slope positions that increased crop residue production resulted in decreased bulk density and increased porosity (total and effective), which in turn should benefit long term productivity of the system.

Soil sorptivity, while related to effective porosity, showed no changes across cropping systems and appears to have no link to crop residue management. This may be because of root channels or other preferential flow characteristics that a long-term dryland no-till system can produce.

Overall proportion of macroaggregates increased as cropping intensity, crop residue, and subsequent SOM production increased. Greater proportions of macroaggregates provide opportunity for greater and more rapid precipitation capture which will improve long-term productivity.

Overall, the results of this study showed that cropping systems which increased crop residue production and returned more residue to the soil than WF also improved surface soil physical properties. No previous study has examined the effects of cropping systems and residue production in a dryland no-till system on bulk density, porosity, sorptivity, and aggregation. These effects have also never been examined across slope topography (soil catena) and site locations (evaporation gradients), or within in the surface 2.5 cm of soil (the initial soil-water interface). The final aspect of this study that makes it unique is the temporal component. Our sites and cropping systems had been in place for 12 yr prior to sampling. This afforded us the opportunity to study processes whose cumulative impact may only be obvious after several years. By decreasing bulk density and increasing porosity and aggregation in the surface 2.5 cm of soil, the potential for rapid capture of rainfall in-

creased. This, in turn leads to less of a potential for water runoff and evaporation, leaving more water available for plant use and an increased system PUE. This is extremely important in dryland agriculture where water is the most limiting factor. Crop intensification enhances soil physical properties potentially increasing PUE. These factors increase production potential and should ultimately lead to a more efficient, sustainable, and economically viable crop production system.

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