Reprinted from the *Soil Science Society of America Journal*
Volume 62, no. 6, Nov.–Dec. 1998
677 South Segoe Rd., Madison, WI 53711 USA

Aggregation of Soil Cropped to Dryland Wheat and Grain Sorghum

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ABSTRACT

Successful and sustainable semiarid dryland cropping depends on effective soil water storage and erosion control, which are influenced by surface soil aggregate size and stability. We hypothesized long-term tillage and cropping system treatments affect water-stable aggregate size distribution, aggregate water stability, and dry soil aggregation. A study on a Torrertic Paleustoll from 1982 to 1994 at Bushland, TX, involved tillage methods (no-tillage, NT; stubble mulch tillage, SMT) and cropping systems for dryland winter wheat (*Triticum aestivum* L.) and grain sorghum [*Sorghum bicolor* (L.) Moench] production. In 1994, mean percentages of >4-mm water-stable aggregates at 0 to 2 cm were 3.5 with NT and 1.0 with SMT in wheat, sorghum, fallow, rotation phase, or crop comparison plots. Mean percentages of <0.25-mm aggregates were 49.0 with NT and 37.8 with SMT. More small aggregates with NT help explain why infiltration was 90% greater with SMT than with NT during fallow after sorghum and 26% greater with SMT during fallow after wheat in a similar study on the same soil when surface coverage by residues was limited (25% with SMT, 57% with NT for sorghum; 73% with SMT, 86% with NT for wheat). Aggregate sizes differed due to cropping system, rotation phase, and crop, but aggregate water stability and dry aggregation differences generally were nonsignificant. Both NT and SMT are deemed suitable for dryland crops under conditions as in this study because neither resulted in unfavorable soil conditions or major yield differences.

Effective soil water storage and protection of the soil from erosion are essential for successful and sustainable dryland (rain-fed) crop production in semiarid regions. Soil surface conditions that influence water infiltration, soil water storage, and erosion include soil aggregate size distribution and stability. Water-stable aggregates resist breakdown due to raindrop impact and help maintain favorable infiltration rates whereas unstable aggregates lead to surface sealing and reduced infiltration. Fine soil particles, especially those <0.125 mm in diameter, are primarily responsible for surface seal development. Surface compaction due to raindrop impact on bare soils after aggregate breakdown further decreases infiltration, thus potentially decreasing soil water storage and increasing erosion (Loch, 1994; Shainberg et al., 1992; Fiès and Panini, 1995).

Dry aggregate (including clod) size distribution and stability affect soil erosion by wind (Armbrust et al., 1982), with aggregates >0.84 mm in diameter generally considered nonerodible (Chepil, 1943). To control erosion by wind in large, bare, smooth, unprotected fields, 60 to 75% of the aggregates should be >0.84 mm in diameter (Woodruff and Siddoway, 1965; Fryrear, 1984).

Many factors affect aggregate size distribution and stability (Gish and Browning, 1948; Rost and Rowles, 1940). We were interested primarily in the effects of tillage methods and cropping systems. Use of NT or reduced tillage often results in larger and more water-stable aggregates than more intensive tillage methods (Douglas and Goss, 1982; Angers et al., 1993). Cropping system (or rotation) effects on water-stable aggregation ranged from slight or nonsignificant to large, with the effects often being related to soil organic matter (OM) (Gish and Browning, 1948; Angers et al., 1992, 1993). Aggregate size and stability in water generally increased with increased OM. Wetted aggregates generally are smaller and less stable for small grain or row crops than for sod crops (Gish and Browning, 1948), but differences due to crops with the same tillage methods are slight (Angers et al., 1992). Mean weight diameter of dry aggregates was greater where tillage rather than NT was used (Unger, 1984; Layton et al., 1993).

No-tillage is being adopted for dryland crops in the U.S. Great Plains (Norwood, 1994; Peterson et al., 1996; Jones and Popham, 1997) and other semiarid regions (Cogle et al., 1991; Laryea et al., 1994; Larney and Lindwall, 1995). Soil water storage and yields of NT dryland winter wheat and grain sorghum in continuous and rotation cropping systems in the Great Plains have equaled or exceeded those with other tillage methods (Norwood, 1994; Unger, 1994; Jones and Popham, 1997). Runoff was greater, however, from NT than SMT watersheds in the southern Great Plains (Jones et al., 1994; Peterson et al., 1996), suggesting the full potential for storing soil water with NT was not achieved. With limited surface residues, aggregate breakdown due to raindrop impact led to surface sealing, which impeded infiltration. Use of SMT reduced runoff by disrupting the surface seal. Infiltration was less during fallow after sorghum than after wheat, mainly because sorghum residues provided

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Published in Soil Sci. Soc. Am. J. 62:1659–1666 (1998).

Abbreviations: CP-n, comparisons of data possible, where n identifies data sets from 1 to 5; CS, continuous sorghum; CW, continuous wheat; D, soil depth; LSD, protected least significant difference; MWD, mean weight diameter; NS, not significant; NT, no-tillage; OC, organic carbon; OM, organic matter; P, crop rotation phase; S, cropping system; SMT, stubble mulch tillage; T, tillage method; WF, wheat–fallow; WSF, wheat–sorghum–fallow.

less surface cover and were not as uniformly distributed on the surface as wheat residues (Jones et al., 1994). Whereas residue cover was assumed to be a major factor affecting aggregate breakdown in the above study, we hypothesized that aggregate size distribution and stability in water contributed to the infiltration differences. Our objective was to determine tillage method and cropping system effects on the size distribution and stability of wetted aggregates of a soil used for dryland wheat and grain sorghum production in the southern Great Plains. Dry aggregate size distribution also was determined.

MATERIALS AND METHODS

A field study, initiated in 1982 on Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll) at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX, involved SMT and NT in several cropping systems for dryland grain sorghum and winter wheat production. Plots (9 by 160 m) established across 0.5 to 1.5% slopes were leveled end-to-end and side-to-side with laser-controlled equipment, and farmed with 4.6-m-wide equipment. Berms prevented water from flowing onto or off the plots. All cropping system phases were not fully established until 1984. Soil aggregation was evaluated in 1994.

Some details for the cropping systems are given in Table 1. Tillage in SMT plots was 7 to 10 cm deep with a Richardson[1] sweep plow (Sunflower Manufacturing Co., Inc., Beloit, KS) having one 1.5- and two 1.8-m-wide blades. The average number of SMT operations used for each crop is also given in Table 1. We achieved additional weed control in SMT plots and all weed control in NT plots with herbicides (Jones and Popham, 1997).

We seeded 'TAM 107' winter wheat in 0.30-m-spaced rows with a high-clearance drill equipped with hoe openers and press wheels, and 'DK42y' grain sorghum in 0.75-m-spaced rows with a six-row John Deere Max-Emerge planter. A plant N deficiency was noted in 1987 and, starting in 1988, we broadcast NH_4NO_3 on subplots to provide 0 or 40 to 45 kg N ha^{-1} before planting each crop. Precipitation at the plot area averaged 520 mm yr^{-1} from 1984 to 1993 (Jones and Popham, 1997), with annual totals ranging from 360 to 639 mm (unpublished laboratory records, Bushland, TX).

We obtained bulk samples for water-stable aggregate determinations with a flat-bottomed spade at two sites in each fertilizer subplot at depths of 0 to 2, 2 to 4, 4 to 7, 7 to 10, 10 to 15, and 15 to 20 cm when the soil water content was near the wilting point. Soil from the two sites was composited into one sample for each depth. While still moist, we passed the soil through a screen with 12.7-mm square openings, then air dried it before determining aggregate size distribution by sieving duplicate subsamples in water by the procedure of Kemper and Rosenau (1986). We calculated the percentages of the total in the <0.25-, 0.25- to 1.0-, 1.0- to 2.0-, 2.0- to 4.0-, and 4.0- to 12.7-mm size ranges. We also calculated the mean weight diameter (MWD) for the water-stable aggregates. Stability determinations involved sieving duplicate subsamples of 1- to 2-mm-diameter aggregates in water by Kemper's (1965) procedure.

[1] 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. A listing of the cropping systems evaluated in a study at Bushland, TX.

System†	Tillage†	SMT operations per crop	Crops	Crop frequency
		no.		
WSF	SMT–NT	5	Wheat–sorghum	Two crops per 3 yr
CW	SMT–NT	3	Wheat	One crop per year
WF	SMT–NT	7	Wheat	One crop per 2 yr
CS	SMT–NT	3	Sorghum	One crop per year

† WSF, wheat–sorghum–fallow; CW, continuous wheat; WF, wheat–fallow; CS, continuous sorghum; SMT, stubble mulch tillage; NT, no-tillage.

We obtained three 4- to 6-kg bulk samples for dry aggregate determinations from the 0- to 2-cm depth of each subplot with a flat-bottomed spade. Each sample was a composite of soil from three sites in each subplot. The soil was air dried before we determined aggregate size distribution with a rotary apparatus having sieves with 0.42-, 0.84-, 2.0-, 6.4-, and 18.3-mm square openings (Chepil, 1962). Maximum aggregate size was 76.2 mm. We determined the percentage of the aggregates in each size range (<0.42, 0.42–0.84, 0.84–2.0, 2.0–6.4, 6.4–18.3, and 18.3–76.2 mm) and calculated the MWD according to Kemper and Rosenau (1986).

Although fertilizer subplots were sampled, initial analyses showed fertilizer treatments had no effects on aggregate variables. Data for fertilizer subplots, therefore, were not included in final analyses of the data. For the final analyses, the study was treated as having a randomized block, split-split plot design with three replications. Cropping system, rotation phase, or continuous cropping treatments were randomly assigned to whole plots, tillage methods were assigned to split plots, and sampling depths were associated with split-split plots. We used the analysis of variance technique (SAS Institute, 1989) to analyze the data. Data for each water-stable aggregate size were analyzed separately. Where soil depth was not a variable, we analyzed the data using a randomized block, split plot design for the experiment (blocks for cropping system, rotation phase, or continuous cropping treatments; split plots for tillage methods). Although all cropping system, rotation phase, and continuous cropping treatments were included in a common study, a common statistical analysis for a given factor involving all treatments was not appropriate because the variances were not homogenous. For example, three cropping systems involved wheat, but only two involved sorghum. Also, two systems of fallow could be compared for wheat, but none for sorghum. Separate analyses, therefore, were performed for those treatments where effects of cropping systems, tillage practices, crop rotation phases, and crops (for continuous cropping systems) could be compared. This permitted five comparisons (CPs) of the data, which were:

- CP-1. Cropping system (Wheat–sorghum–fallow [WSF], continuous–wheat [CW], wheat–fallow [WF]) and tillage method (SMT, NT) effects in wheat plots,
- CP-2. Cropping system (WSF, continuous–sorghum [CS]) and tillage method (SMT, NT) effects in grain sorghum plots,
- CP-3. Cropping system (WSF, WF) and tillage method (SMT, NT) effects in fallow plots,
- CP-4. Crop rotation phase (wheat, sorghum, fallow) and tillage method (SMT, NT) effects in WSF plots, and
- CP-5. Crop (wheat, sorghum) and tillage method (SMT, NT) effects in continuous cropping plots.

When significant (P = 0.05 level), we separated means by

Table 2. Size distribution of water-stable aggregates in wheat plots as a function of soil depth averaged across cropping systems and tillage methods, Bushland, TX.

Aggregate size	0–2 cm	2–4 cm	4–7 cm	7–10 cm	10–15 cm	15–20 cm	LSD†
mm	%						
>4.0	2.4	3.7	5.6	8.7	13.6	9.7	2.4
2.0–4.0	2.1	2.9	5.7	8.2	9.7	8.7	1.9
1.0–2.0	4.5	7.4	10.9	12.2	13.3	12.8	2.1
0.25–1.0	48.3	53.4	48.0	41.9	37.2	42.0	4.0
<0.25	42.7	32.6	29.8	29.0	26.2	26.8	2.1

† Least significant difference ($P = 0.05$ level) for comparing values for the given aggregate size.

the protected least significant difference (LSD) procedure or Duncan's multiple range test.

We used regression analyses to test for relationships between MWD of water-stable aggregates, MWD of dry aggregates, and OM concentration, all for soil from the 0- to 2-cm depth. The OM concentrations were from the study by McClenagan (1995), which involved soil taken from the field plots of this study.

RESULTS AND DISCUSSION

Water-Stable Aggregate Size Distribution

Soil surface sealing and water infiltration are strongly influenced by the percentage of small aggregates (Loch, 1994). Aggregate MWDs (discussed below) were calculated from the percentages of water-stable aggregates and are convenient to show the overall effect of different practices on water-stable aggregation. Use of only MWDs, however, would mask the effects the practices had on soil aggregation as related to soil surface sealing and water infiltration.

Soil Depth Effect

Water-stable aggregate size distribution differed due to depth, with trends similar for all comparisons. Data for wheat plots, which are typical of all comparisons, are in Table 2. For >4.0-, 2.0- to 4.0-, and 1.0- to 2.0-mm aggregates, percentages were lowest at 0 to 2 cm and generally greatest at 10 to 15 cm. The trends were reversed for 0.25- to 1.0- and <0.25-mm aggregates, except that the percentage of 0.25- to 1.0-mm aggregates was greatest at 2 to 4 cm.

Fine (<0.125- or <0.25-mm) soil materials greatly affect water infiltration. Although we determined percentages of <0.25-mm materials by a vacuum-wetting procedure, which gives results not as closely related to infiltration as with high-energy rain wetting (Loch, 1994), these fine materials undoubtedly affected infiltration as evidenced by the greater surface sealing and runoff due to rains when surface residues were limited under similar conditions on the Pullman soil (Jones et al., 1994). In that study, cumulative infiltration of simulated rainfall applied at 48 mm h^{-1} for 2 h was (i) 90% greater on SMT than on NT watersheds for tests conducted during fallow after grain sorghum, and (ii) 26% greater during fallow after wheat. Infiltration was greater with SMT because it disrupted the consolidated surface crust, decreased density of the tillage zone, and increased surface roughness and depression storage capacity. The first water application compacted and smoothed the surface of the SMT watershed. As a result, infiltration during subsequent tests was similar for both tillage methods. Surface residue cover was (i) 25% with SMT and 57% with NT after grain sorghum, and (ii) 73% with SMT and 86% with NT after wheat. Although infiltration was less, soil water contents at planting of wheat and sorghum with NT equaled or exceeded those with SMT in other studies on this soil (Jones et al., 1994; Jones and Popham, 1997). The favorable soil water contents with NT were attributed to more surface residues and nondisturbance of soil that would expose moist soil to the atmosphere, which reduced evaporative losses.

Cropping System Effect

Cropping systems affected percentages of >4.0- and 0.25- to 1.0-mm aggregates in all cases, had no affect on <0.25-mm aggregates, and had variable effect on other sizes (Table 3). Mean percentages of >4.0-mm aggregates increased with cropping frequency, being highest for CW and lowest for WF in wheat plots, higher for CS than for WSF in sorghum plots, and higher for WSF than for WF in fallow plots. Trends in mean percentages were reversed for 0.25- to 1.0-mm aggregates. No definite trends were noted for other size ranges.

Although mean differences due to cropping systems were not large, the results suggest systems involving fallow are less conducive to maintaining large aggregates than systems involving more frequent cropping. These differences seem related to system effects on soil OM. Soil OM generally is lower with systems involving fallow than with continuous cropping (Johnson and Davis, 1972; Wood et al., 1990), which was found also

Table 3. Cropping system† effects on size distribution of aggregates in wheat, sorghum, and fallow plots averaged across tillage methods and soil depths, Bushland, TX.

Aggregate size	Wheat plots				Sorghum plots			Fallow plots		
	WSF	CW	WF	LSD‡	WSF	CS	LSD	WSF	WF	LSD
mm	mean %									
>4	6.9	9.1	5.7	2.3	6.3	9.7	1.9	6.9	3.1	1.5
2–4	6.2	6.4	6.0	NS§	6.4	8.1	1.0	6.6	4.5	1.0
1–2	10.1	9.8	10.8	NS	10.7	11.6	NS	10.6	9.1	1.3
0.25–1	45.6	43.6	46.3	2.0	46.3	41.6	1.8	44.7	51.0	1.7
<0.25	31.2	31.1	31.2	NS	30.3	29.0	NS	31.2	32.3	NS

† WSF, wheat–sorghum–fallow; CW, continuous wheat; WF, wheat–fallow; CS, continuous sorghum.
‡ Least significant difference ($P = 0.05$ level) for comparing values or the given aggregate size and comparison.
§ Not significant.

Table 4. Tillage† effects on size distribution of water-stable aggregates in wheat, sorghum, and fallow; crop rotation phase; and continuous cropping plots averaged across cropping systems and soil depths, Bushland, TX.

	Wheat		Sorghum		Fallow		Rotation		Crop	
Aggregate size	SMT	NT	SMT	NT	SMT	NT	SMT	NT	SMT	NT
mm	%									
>4	4.3b‡	10.2a	5.8b	10.3a	3.1b	6.9a	4.0b	9.5a	5.8b	13.1a
2–4	5.2b	7.2a	6.2b	8.2a	4.4b	6.7a	5.2b	7.6a	5.4b	9.0a
1–2	9.9a	10.5a	10.2b	12.1a	8.8b	10.9a	9.6b	11.3a	9.1b	12.2a
0.25–1	49.1a	41.2b	46.7a	41.2b	52.4a	43.4b	49.8a	41.3b	46.9a	38.4b
<0.25	31.5a	30.9a	31.1a	28.2b	31.3a	32.1a	31.4a	30.3a	32.8a	27.3b

† SMT, stubble mulch tillage; NT, no-tillage.
‡ Percentages in a given row for a given comparison followed by the same letter are not significantly different at the $P = 0.05$ level.

by McClenagan (1995) and Potter et al. (1997) in other studies conducted on these field plots. For example, the OM concentration at 0 to 2 cm averaged 24.3 g kg^{-1} in plots involving fallow (WSF and WF) and 26.3 g kg^{-1} in continuous cropping plots (CW and CS) (McClenagan, 1995). Also, total organic C (OC) at 0 to 20 cm averaged 28.4 Mg ha^{-1} in WF plots, 29.8 Mg ha^{-1} in WSF plots, and 31.6 Mg ha^{-1} in continuous cropping plots (wheat and sorghum) (Potter et al., 1997). Using the data of Potter et al. (1997), we found that the percentage of >4.0-mm water-stable aggregates (y) was significantly ($P = 0.05$) related to the total OC mass in Mg ha^{-1} (x) for the 0- to 20-cm soil depth:

$$y = -41.221 + 1.696x \qquad (r^2 = 0.619) \qquad [1]$$

The relationships between other aggregate sizes and total OC mass were not significant.

Tillage Effect

Aggregate percentages in the different size ranges differed due to tillage method when averaged across depths (Table 4). In each case, NT resulted in more >4.0- and 2.0- to 4.0-mm aggregates than SMT, and more 1.0- to 2.0-mm aggregates except in the wheat comparison. In contrast, SMT resulted in more 0.25- to 1.0-mm aggregates in all cases and more <0.25-mm aggregates for the sorghum and continuous cropping conditions. Douglas and Goss (1982) and Angers et al. (1993) showed or implied that NT resulted in more large aggregates than more intensive tillage methods (SMT), which was related to more OM in surface soil with NT. Our results lend support to their findings. Mean OC contents (0–20 cm depth) were 3.17 kg m^{-2} with NT and 2.75 kg m^{-2} with SMT after wheat and sorghum in the study conducted by Potter et al. (1998) on these field plots.

Crop Rotation Phase Effect

Mean aggregate percentages were similar due to crop rotation phase in WSF plots involving NT and SMT, but differed in WSF and WF plots involving only SMT. Differences due to rotation phase for both cropping systems, however, were small (data not shown), probably because of a carry-over effect from one rotation phase to the next. Although differences for both systems were small, the results indicated that cropping was more conducive for maintaining large aggregates than fallowing, which, as discussed above, was related to soil OM (or OC) contents.

Crop Effect

Mean percentages of larger aggregates in continuous cropping plots were lower for wheat than for sorghum (9.1 vs. 9.7 for >4.0-mm, 6.4 vs. 8.1 for 2.0- to 4.0-mm, and 9.8 vs. 11.6 for 1.0- to 2.0-mm aggregates). Smaller aggregates were more common with wheat than with sorghum (43.5 vs. 41.6 for 0.25- to 1.0-mm and 31.2 vs. 29.0 for <0.25-mm aggregates). Crop effects on aggregation in our study differ from those of Angers et al. (1992), who found no or only slight differences in aggregation due to crops when cropping systems and tillage methods were the same. The differing crop effects may be related to surface cover differences resulting from the crop residues, as noted above.

Interactions

Some interactions between tillage method, cropping system, crop rotation phase, crop grown, or soil depth were observed for aggregate percentages in different size ranges for all comparisons. The greatest differences in mean percentages were observed for the soil depth × tillage method interaction. For this interaction, percentages of >4.0-mm aggregates differed in sorghum and continuous cropping plots while those of 2.0- to 4.0-mm

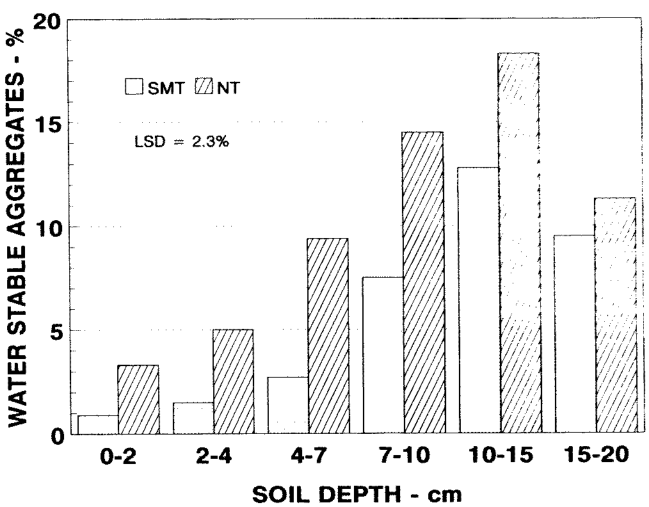

Fig. 1. Percentages of >4.0-mm water-stable aggregates due to tillage method (stubble mulch [SMT] and no-tillage [NT]) and soil depth in sorghum plots, Bushland, TX, 1994.

aggregates differed only in continuous cropping plots. Percentages of 0.25- to 1.0- and <0.25-mm aggregates differed for each comparison. Data in Fig. 1 for >4.0-mm (sorghum plots), Fig. 2 for 0.25- to 1.0 -mm (wheat plots), and Fig. 3 for <0.25-mm aggregates (wheat plots) are typical for all comparisons involving soil depth and tillage method. For all comparisons, percentages of >4.0-mm aggregates at 0 to 2 cm ranged from 0.9 to 1.1 (1.0 mean) with SMT and from 2.9 to 4.4 (3.5 mean) with NT. For those <0.25-mm, the range was from 35.6 to 41.7 (37.8 mean) with SMT and from 46.4 to 51.0 (49.0 mean) with NT. No-tillage also resulted in more >4.0-mm aggregates to 15 cm (Fig. 1). Our results generally agree with those of Angers et al. (1992) and Douglas and Goss (1982), who found more large aggregates with NT than with more intensive tillage methods. Under similar conditions as in this study, OM content of surface soil was greater with NT than with SMT (Unger, 1991). By inference, the greater OM content helped stabilize the near-surface large aggregates in this study. Our results for 2.0- to 4.0-mm aggregates with continuous cropping (data not shown) were similar to those for >4.0-mm aggregates. Again, greater OM content undoubtedly helped stabilize these relatively large aggregates.

Because percentages of large aggregates were greater with NT, it follows that percentages of smaller aggregates would be less with NT. This was the case for 0.25- to 1.0-mm aggregates at most depths (Fig. 2), but the trend was reversed at 0 to 2 cm for <0.25-mm aggregates (Fig. 3). Under conditions similar to those of this study, soil OM content was greater at 0 to 1 cm and tended to be greater at 1 to 2 cm with NT than with SMT (Unger, 1991). Why the percentage of small surface soil aggregates was greater with NT for which the OM content was greater is not clear, but results of Beare et al. (1994) and Biederbeck et al. (1994) suggest OM condition (labile, total, whole soil, particulate, mineral associated, or aggregate protected) may be involved. Regardless of the reason, presence of more <0.25-mm aggregates at the surface helps explain why runoff was greater with NT when surface residues were limited in a similar study (Jones et al., 1994), as discussed above. For another study on these field plots, residues at harvest averaged about 3.87 Mg ha^{-1} for wheat and 5.05 Mg ha^{-1} for sorghum with NT (Jones and Popham, 1997). The greater percentage of small aggregates with NT also points to the importance of maintaining surface residues for achieving effective soil water storage under conditions such as those involved in this study.

Differences in mean aggregate percentages were observed also for the cropping system × tillage method, crop rotation phase × tillage method, and soil depth × cropping system × tillage method interactions. Most differences, however, were small and undoubtedly of little importance relative to understanding the effects of management practices on soil aggregation. These interactions, therefore, are not discussed.

Water-Stable Aggregate Mean Weight Diameter

For all comparisons, the MWD of water-stable aggregates was lowest (not significantly different) at the 0- to 2- and 2- to 4-cm, similar at 7- to 10- and 15- to 20-cm, and greatest at the 10- to 15-cm depth (Table 5). At 4 to 7 cm, the MWD was greater than at 2 to 4 cm and less than at 7 to 10 cm (not different for the CP-3 comparison). For tillage, the overall mean MWD for each comparison and the mean MWD for individual cropping systems, rotation phases, and crops within the comparisons always was greater with NT than with SMT.

For the cropping system comparisons (CP-1, CP-2, and CP-3), the MWD decreased with increases in the length of fallow (or no fallow between crops) in the systems, being least for the WF system and greatest for the CS system (no fallow). As indicated above, soil OM (or OC) concentrations generally are lower for cropping systems involving long rather than short or no fallow periods. These results, therefore, suggested that the MWD of water-stable aggregates was related to soil OM or OC concentration, as was found by Unger (1997). Unger's (1997) study, which also involved Pullman soil,

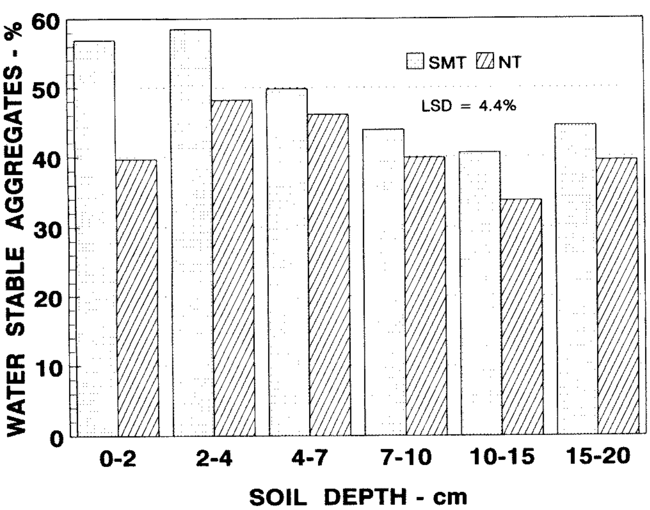

Fig. 2. Percentages of 0.25- to 1.0-mm water-stable aggregates due to tillage method (stubble mulch [SMT] and no-tillage [NT]) and soil depth in wheat plots, Bushland, TX, 1994.

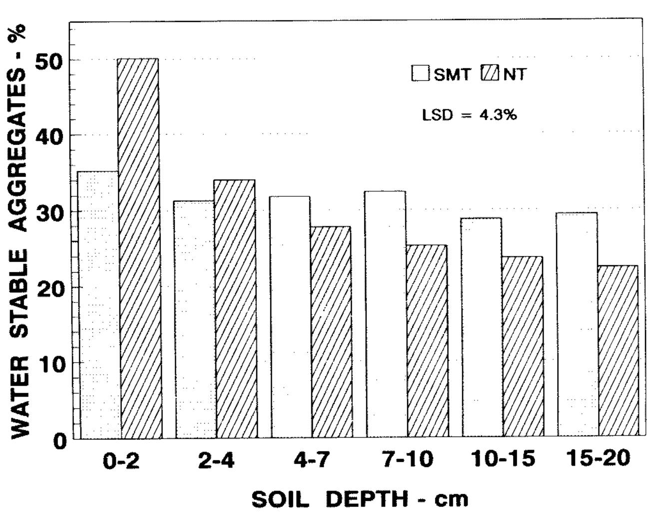

Fig. 3. Percentages of <0.25-mm water-stable aggregates due to tillage method (stubble mulch [SMT] and no-tillage [NT]) and soil depth in wheat plots, Bushland, TX, 1994.

Table 5. Mean weight diameters of water-stable aggregates due to soil depth and tillage methods of soil from cropping system, rotation phase, and continuous cropping comparison plots, Bushland, TX.

Comparison	Cropping system, rotation phase, or crop†	Tillage‡	0–2 cm	2–4 cm	4–7 cm	7–10 cm	10–15 cm	15–20 cm	Means: Tillage	Means: Cropping system, rotation phase, or crop
			mm							
CP-1	WSF	SMT	0.60	0.60	0.78	1.10	1.49	1.13	0.95d†§	1.24†§
		NT	0.61	0.97	1.35	1.91	2.31	2.03	1.53b	
	CW	SMT	0.55	0.60	0.90	1.04	1.30	1.36	0.96d	1.40a
		NT	0.96	1.52	1.86	2.23	2.66	1.83	1.84a	
	WF	SMT	0.68	0.68	0.94	1.28	1.72	1.29	1.10cd	1.15b
		NT	0.68	0.89	0.99	1.16	1.78	1.65	1.19c	
Mean			0.68d†	0.88d	1.14c	1.45b	1.88a	1.55b		
Overall means: Tillage—SMT, 1.00; NT, 1.52 (LSD¶ = 0.13).										
CP-2	WSF	SMT	0.54	0.59	0.78	1.27	1.69	1.48	1.06d	1.21b
		NT	0.76	0.91	1.20	1.44	2.19	1.64	1.36b	
	CS	SMT	0.56	0.68	0.97	1.46	2.13	1.68	1.25c	1.53a
		NT	0.78	1.13	1.87	2.65	2.54	1.89	1.81a	
Mean			0.66d	0.83d	1.20c	1.71b	2.14a	1.67b		
Overall means: Tillage—SMT, 1.15; NT, 1.58 (LSD = 0.09).										
CP-3	WSF	SMT	0.62	0.63	0.88	0.99	1.40	1.09	0.94b	1.25a
		NT	0.89	1.41	1.70	1.70	2.16	1.52	1.56a	
	WF	SMT	0.57	0.56	0.78	1.14	1.01	1.00	0.84b	0.89b
		NT	0.52	0.66	0.90	1.12	1.39	1.04	0.94b	
Mean			0.65c	0.81c	1.07b	1.24b	1.49a	1.16b		
Overall means: Tillage—SMT, 0.89; NT, 1.25 (LSD = 0.14).										
CP-4	Wheat	SMT	0.60	0.60	0.78	1.10	1.49	1.13	0.95c	1.24a
		NT	0.61	0.97	1.35	1.91	2.31	2.03	1.53ab	
	Sorghum	SMT	0.55	0.62	0.78	1.27	1.69	1.48	1.06c	1.21a
		NT	0.76	0.91	1.20	1.44	2.19	1.64	1.36b	
	Fallow	SMT	0.62	0.63	0.88	0.99	1.40	1.09	0.94c	1.25a
		NT	0.89	1.41	1.70	1.70	2.16	1.52	1.56a	
Mean			0.67d	0.86d	1.12c	1.40b	1.87a	1.48b		
Overall means: Tillage—SMT, 0.98; NT, 1.48 (LSD = 0.12).										
CP-5	Continuous wheat	SMT	0.55	0.60	0.91	1.07	1.37	1.36	0.97c	1.41a
		NT	0.96	1.52	1.86	2.23	2.66	1.83	1.84a	
	Continuous sorghum	SMT	0.56	0.68	0.97	1.46	2.13	1.68	1.25b	1.52a
		NT	0.75	1.13	1.87	2.64	2.54	1.89	1.80a	
Mean			0.70d	0.98d	1.40c	1.84b	2.17a	1.69b		
Overall means: Tillage—SMT, 1.11; NT, 1.82 (LSD = 0.14).										

† WSF, wheat–sorghum–fallow; CW, continuous wheat; WF, wheat–fallow; CS, continuous sorghum.
‡ SMT, stubble mulch tillage; NT, no-tillage.
§ Column or row values within a given comparison are not significantly different at the $P = 0.05$ level when followed by the same letter or letters.
¶ Least significant difference.

however, involved samples from the 0- to 3-cm soil depth, whereas the mean MWDs for cropping systems given in Table 5 (this study) are for the 0- to 20-cm depth. The mean MWDs for cropping systems (CP-1, CP-2, and CP-3 comparisons) were not closely related ($P = 0.10$) to total OC mass reported by Potter et al. (1997) for the 0- to 20-cm depth for the same field study (relationship not shown). However, a highly significant ($P = 0.001$) relationship was obtained when using mean values for tillage for the different systems. The relationship was:

$$y = -2.938 + 0.147x \qquad (r^2 = 0.782) \qquad [2]$$

where y is MWD and x is soil total OC mass in Mg ha^{-1}. For regressions involving tillage methods separately, the relationship for SMT was not significant ($r^2 = 0.057$). For NT, the relationship was significant at the $P = 0.02$ level, namely:

$$y = -4.139 + 0.187x \qquad (r^2 = 0.754) \qquad [3]$$

where y and x are the same as above. These results clearly show the value of NT for enhancing the MWD of water-stable aggregates, which is related to soil OC concentration and, in turn, is important for sustaining or enhancing the quality and productivity of this soil.

Aggregate Water Stability

Aggregate stability was affected in relatively few cases by tillage methods and cropping systems. The only variable affecting aggregate water stability for all comparisons was soil depth (Table 6). Mean stability was lowest at 0 to 2 cm in all cases, but not different from some other depths for some comparisons. Stabilities tended to be greatest at 15 to 20 cm, but not different from those at 2 to 4 and 4 to 7 cm in most cases. The stability of 1.0- to 2.0-mm aggregates is positively related to soil OM content (Kemper and Koch, 1966). Thus, stability should have been greater for the surface increment where OM was greatest (Potter et al., 1998). Condition of the OM and soil wetting and drying probably affected the results. Another factor is soil clay content, which

Table 6. Mean water stability due to soil depth of 1–2-mm aggregates obtained from plots where tillage methods, cropping systems, crop rotation phases, and continuous cropping were compared, Bushland, TX.

Comparison†	0–2 cm	2–4 cm	4–7 cm	7–10 cm	10–15 cm	15–20 cm	LSD‡	Mean§
	%							
CP-1	64.5	72.9	71.8	68.6	67.5	70.3	3.9	69.3
CP-2	57.3	64.7	64.6	62.5	65.4	68.0	5.3	63.7
CP-3	58.4	64.5	65.8	62.1	63.4	70.4	3.5	64.1
CP-4	60.8	65.3	67.3	63.9	63.7	69.1	3.7	65.1
CP-5	60.8	67.5	65.9	62.7	66.4	70.7	4.2	65.7
Mean§	60.4	67.0	67.1	64.0	65.3	69.7	–	–

† CP-1, cropping system and tillage method effects in wheat plots; CP-2, cropping system and tillage method effects in grain sorghum plots; CP-3, cropping system and tillage method effects in fallow plots; CP-4, crop rotation phase and tillage method effects in wheat–sorghum–fallow plots; CP-5, crop and tillage method effects in continuous cropping plots.
‡ Least significant difference (P = 0.05 level) for comparing depth values for the given comparison.
§ Means were not analyzed statistically, but are given to show trends that occurred.

increases with depth for Pullman soil (Unger and Pringle, 1981). Kemper and Koch (1966) showed a strong positive correlation between soil aggregate water stability and clay content.

Cropping systems affected mean aggregate stability only for wheat plots, for which it was 72.6% for WF, 67.6% for WSF, and 67.5% for CW systems. These results are contrary to expectations because soil OM generally is lower for systems involving long fallow periods. The tendency toward more 1.0- to 2.0-mm aggregates in WF plots, as reported above for aggregate size distribution (data not shown), may have contributed to these results.

Tillage method did not affect mean aggregate stability, but crop rotation phase affected it in WSF plots (with NT and SMT) and WSF plots (with only SMT). For WSF plots with SMT and NT, the mean percentage was greater for wheat (67.6) than for sorghum and fallow phases (both at 63.7). For WSF plots with SMT, percentages were similar for wheat and sorghum phases (68.0 and 67.9), but both were greater than for the fallow phase (61.0). Stability for the wheat phase in WSF plots possibly was greater because a crop was actively growing at sampling time, which imparted a stability benefit not found in sorghum and fallow plots that were idle at sampling. Results of Gish and Browning (1948) and Wilson and Browning (1945), which indicated seasonal variations in aggregate stability, lend support to this possibility. The reason for different results for the sorghum phase of the two comparisons is not apparent.

Mean aggregate stability was greater in wheat than in sorghum (67.6 vs. 63.6%) continuous cropping plots with SMT. These results lend support to the probable cause for the differences noted for crop rotation phase effects discussed above. A crop was growing in wheat plots, but sorghum plots were idle when sampled.

Few significant interactions for aggregate stability were observed for the different comparisons. Although significant, the differences generally were small and undoubtedly of limited importance regarding the understanding of management effects on soil aggregate stability. The interactions, therefore, are not discussed.

Dry Aggregation

For dry aggregates, MWD differed in only a few cases. It was greater for the CS than the WSF system (15.5 vs. 8.8 mm) in sorghum plots and for the WSF than the WF system (14.0 vs. 8.1 mm) in fallow plots. In both cases, MWD was greater for systems involving more frequent cropping (CS for sorghum and WSF for fallow). Because soil OM was greater for systems involving more frequent cropping (Potter et al., 1997), the results suggested a possible link between MWD of dry aggregates and soil OM. The relationship between MWD of dry aggregates and soil OM content (data of Potter et al., 1997, for samples from the same field plots) was not significant (r^2 = 0.068). Such relationship also was not significant in other studies on Pullman soil (Unger, 1984, 1997). The reason for the above results of this study, therefore, is not apparent.

Crops affected the mean MWD in continuous cropping plots, with it being greater for sorghum than for wheat (15.3 vs. 8.8 mm). A possible reason for the difference is residue distribution on the soil surface with the crops. Wheat residues are more uniformly distributed, thus minimizing raindrop impact effects on the soil surface compared with sorghum residues. In sorghum plots, greater rearrangement and closer packing of surface particles occurs, which results in the greater MWD.

Unger (1997) found MWDs of water-stable and dry aggregates to be related at the P = 0.01 level of significance using a second-order polynomial (r^2 = 0.392). In this study, the MWD of water-stable aggregates was not related to the MWD of dry aggregates by simple lincar regression (r^2 = 0.061), but was related at a low level of significance (P = 0.20) by second- and third-order polynomial regressions. Aggregate water stability was not related to dry aggregate MWD (r^2 = 0.066).

SUMMARY AND CONCLUSIONS

We found numerous differences in water-stable aggregate size distribution due to soil depth, cropping system, tillage method, crop rotation phase, and crop grown, and some interactions between these factors. In contrast, few differences in aggregate water stability and dry aggregation due to the above factors were significant. Most aggregate size distribution differences were relatively small, but some were important with respect to helping explain observations and previous measurements in the field plots from which the samples were obtained. For example, NT resulted in more >4.0-mm and <0.25-mm water-stable aggregates than SMT at the

0- to 2-cm soil depth. The greater percentage of >4.0-mm water-stable aggregates with NT was related to the greater OM content of the NT soil, suggesting that NT may be a better tillage method than SMT for dryland crops on the Pullman soil. Small aggregates reduce infiltration and, thereby, the potential for soil water storage. The greater percentage of <0.25-mm aggregates, therefore, helps explain why runoff from precipitation often was greater with NT under field conditions when surface residue amounts were limited, as under dryland conditions in a semiarid region. Such conditions often exist under dryland conditions in the southern Great Plains, which consequently offsets, at least in part, the advantages of the larger aggregates. Both NT and SMT, therefore, are considered equally suitable for dryland winter wheat and grain sorghum production in continuous and rotation cropping systems under conditions similar to those of this study because neither tillage method resulted in development of highly unfavorable soil conditions or major differences in crop yields.

ACKNOWLEDGMENTS

The assistance of Larry J. Fulton, biological technician, in conducting this study and statistically analyzing the data is gratefully acknowledged.

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