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Winter-Associated Changes in Dry-Soil Aggregation as Influenced by Management

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ABSTRACT

Changes in surface soil structure during winter can increase soil erodibility. This study was conducted to examine winter-associated changes in dry-soil aggregation as influenced by crop, residue, and tillage system. These changes were studied at Hays, KS, on a Harney silt loam (fine, montmorillonitic, mesic Typic Argiustoll) in a winter wheat (*Triticum aestivum* L.)–grain sorghum [*Sorghum bicolor* (L.) Moench]–fallow rotation. Three tillage systems were used — clean tillage with residue buried, stubble-mulch tillage, and zero tillage. Residue and crop cover present during the winter was wheat residue, sorghum residue, and winter wheat. Measurements of dry aggregate stability, aggregate-size distribution as geometric mean diameter, and aggregate density were made before and after the winters of 1988–1989 and 1989–1990. Little difference occurred between clean and stubble-mulch tillage systems, which were usually different from the zero-tillage system. Greater changes in aggregation occurred during the 1989–1990 winter when precipitation was greater. Residue maintained higher surface water contents, decreased freeze–thaw cycling and drying by sublimination, and decreased fluctuations in water content. Aggregates from plots with low residue cover decreased in stability more than aggregates from high residue treatments. Generally, differences in aggregation between tillage systems were maintained during the drier winter and minimized during the wetter winter. Soil aggregates were smaller, less dense, and less stable on the zero-tillage plots in March 1989. Therefore, insufficient residue production for wind erosion control in a zero-tillage system could lead to more erodible conditions than in a conventional tillage system.

CHANGES IN SURFACE SOIL STRUCTURE during winter can result in conditions highly conducive to wind erosion. Stability of soil aggregates against wind-blown soil particles, and the potential for movement by wind as functions of size and density are changed by wetting, freezing, thawing, and drying. These processes are moderated by soil properties, weather, and crop residues. Tillage systems provide management options for altering prewinter residue amount and configuration as well as soil structure.

Field data indicate that, during winter, aggregates tend to degrade into smaller aggregates that are more erodible by wind or to consolidate into larger aggregates or a massive structure (Chepil, 1954; Bisal and Nielsen, 1964; Anderson and Wenhardt, 1966; Bisal and Ferguson, 1968). Differing results can be explained by differences among years in winter weather and soil water content. The processes that change soil structure are not as effective with low soil water. During wet winters, high soil water content promotes consolidation by the winter-associated processes. During winters with water contents between these extremes, aggregates have the highest potential to degrade into smaller and weaker structural units.

Results from laboratory studies indicate that soil water content at freezing and phase of soil water during drying determine aggregate response to freezing (Bisal and Nielsen, 1964; Hinman and Bisal, 1968). As pore water expands during freezing, aggregate volume increases and disrupts structural bonds. If the water changes phase to liquid before drying, the consolidating action of decreasing matric potential leaves a more stable aggregate structure. In contrast, a single drying by sublimination can lead to a loss of structure, minimizing aggregate size and stability.

The processes that change aggregation during winter are influenced by snow and residue cover, which alters soil water content, soil temperature, and drying conditions. Consolidation of soil aggregates occurred under a continuous snow cover (Anderson and Bisal, 1969). Conversely, aggregates disintegrated when snow cover was prevented using plywood shelters. Snow provides water for consolidation and protects the soil from drying while frozen. Data from a 7-yr study of summer fallow methods (Anderson and Wenhardt, 1966) show that the largest overwinter decrease in the erodible soil fraction (aggregates <0.84-mm diam.) occurred in treatments that left the highest amounts of surface residue. Surface residue provides insulation and reduces the occurrence and depth of soil frost formation (Pikul et al., 1986). Soil thermal properties can be altered by modifying reflectance, thermal conductivity, heat capacity, heat loss, and the shape of the soil surface (Voorhees et al., 1981). All of these properties can be modified using different tillage systems and residue management. Residue or snow cover prevents high vapor pressure deficits between frozen soil water and the atmosphere that causes high sublimination rates (de Jong and Kachanoski, 1988). Frequent wetting and drying initiates unequal swelling and shrinking that causes microcrack formation (Utomo and Dexter, 1981). By maintaining soil water, residue cover reduces the influence of wetting and drying on aggregation.

Tillage system and cropping history govern prewinter soil structure and residue type, amount, and configuration, which, in turn, influence the processes that change soil structure. The objective of this experiment was to determine the cumulative effects of winter-associated weathering processes on dry-soil aggregation in a common Great Plains crop rotation with various tillage, crop, and residue conditions.

MATERIALS AND METHODS

We conducted the research at the Ft. Hays Experiment Station at Hays, KS, on plots established in 1965. The soil is a Harney silt loam. The original experimental design was a randomized split plot replicated in four blocks. Only three blocks were sampled in this experiment. The treatment structure con-

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Abbreviations: CT, clean tillage with buried residue; RT, reduced (stubble-mulch) tillage; ZT, zero tillage; WR, wheat residue; SR, sorghum residue; WW, winter wheat crop; DAS, dry aggregate stability; GMD, geometric mean diameter; AD, aggregate density.

Table 1. Percentage of soil surface covered by flat residue during each winter for each tillage and cover combination†.

Tillage‡	Cover§	Surface covered by residue 1988–1989	Surface covered by residue 1989–1990
		%	%
CT	WW	7.4 ± 2.1	2.2 ± 1.5
	WR	5.5 ± 1.4	1.9 ± 1.2
	SR	10.2 ± 10.0	7.0 ± 3.8
RT	WW	5.6 ± 7.2	3.0 ± 1.8
	WR	32.4 ± 4.5	8.7 ± 2.2
	SR	6.9 ± 6.4	13.7 ± 4.4
ZT	WW	27.3 ± 9.0	10.4 ± 5.8
	WR	74.5 ± 9.7	80.2 ± 6.3
	SR	34.6 ± 3.7	84.1 ± 5.4

† Mean ± standard deviation of pre- and postwinter measurements.
‡ Tillage treatments: CT = residues buried, RT = stubble-mulch, ZT = zero tillage.
§ Cover treatments: WW = winter wheat, WR = wheat residue, SR = sorghum residue.

sisted of three tillage systems in a winter wheat–grain sorghum–fallow rotation. Fallow periods were from midsummer after wheat was harvested until sorghum was planted the following spring (approximately 9 mo), and from fall when sorghum was harvested until wheat was drilled the next fall (approximately 12 mo). The whole-plot treatments were the cover present during the winter period of the rotation. These treatments were winter wheat (WW), sorghum residue (SR), and wheat residue (WR). The subplot treatments were tillage systems, and were classified as clean tillage (CT) or burial of residues, reduced tillage (RT) with stubble-mulch tillage, and zero tillage (ZT) with direct planting using only herbicides for weed control. Subplot dimensions were 20.4 by 30.4 m.

The CT plots were tilled with a tandem disk, the RT with a sweep plow. Seedbeds were prepared with a stubble-mulch treader in both tillage treatments for both crops. This implement breaks up heavy stubble and uproots weeds. The last tillage operations before prewinter samples were taken in December were: WR, tandem disk on CT plots and sweep plow on RT plots around the third week in November; WW, stubble-mulch treader prior to drilling winter wheat in early October on the CT and RT plots; and SR, chisel plow around the third week in November on both CT and RT plots. The only difference between prewinter tillage on the CT and RT plots was on the WR surface. The ZT plots were undisturbed except for drilling of wheat in early October.

Soil samples were taken from each of 27 plots in December and March for the winters of 1988–1989 and 1989–1990. Areal residue fractions were measured on nine 1-m transects on each plot. A meter stick was placed randomly on the surface perpendicular to the rows, and contact lengths with residue along one edge were summed. Residue is reported as average combined pre- and postwinter samples (Table 1). A flat shovel was used to remove a 5-kg soil sample from the surface 50 mm for laboratory determination of aggregate-size distribution, dry aggregate stability, and aggregate density. Spring samples were taken from within 1 m of the fall sample.

Aggregate-size distribution was measured by rotary sieving using the improved rotary sieve (Lyles et al., 1970). The size distribution was expressed as the GMD assuming lognormality (Gardner, 1956). The rotary sieve provides seven sieve cuts at aggregate diameters of 44.5, 19.05, 6.36, 2.0, 0.84, and 0.42 mm. The GMD was calculated using the equation (Campbell, 1985, p. 9)

$$\mathrm{GMD} = \exp(\Sigma\, m_i \ln d_i)$$

except that the midpoint diameter, d_i, of each sieve cut is the geometric mean, and m_i is the mass fraction of the sample in a sieve cut.

Dry aggregate stability was measured as described by Skidmore and Powers (1982) with the crushing device built by Boyd et al. (1983). The device diametrically loads an individual aggregate between parallel plates. A force is applied until the aggregate is crushed. We then integrated force applied by distance traveled during crushing to find the amount of energy consumed in crushing the aggregate. The DAS is defined as the amount of energy needed to crush an aggregate of unit mass until all remaining parts of the aggregate pass a 6.35-mm sieve. Analysis of large data sets (data not shown) showed that DAS is a lognormal variate. Consequently, a natural-log transformation was used for statistical analysis. Thirty aggregates were crushed from each plot and sampling date.

Aggregate density was measured on three aggregates per plot by coating the aggregates with paraffin and weighing each while suspended in air and in water (Blake and Hartge, 1986).

Data for the March samples and overwinter change were analyzed using analysis of variance for the split-plot design. Overwinter change was defined as December minus March values and is denoted as ΔDAS, ΔGMD, and ΔAD. Least significant difference was used to separate means after a significant *F* test. Comparison of overwinter change between winters for each specific tillage and cover combination was done by adding year, which represents winter weather, to the analysis of variance and testing the hypothesis that overwinter change was equal between years. The split-plot analysis of variance allowed examination of overwinter changes in aggregation as influenced by tillage and cover with the same weather. The other analysis allowed comparisons between the same tillage and cover treatment exposed to different weather. We used

Table 2. Comparisons of overwinter changes (ΔW†) between winters of 1988–1989 ($W1$) and 1989–1990 ($W2$) in dry aggregate stability, geometric mean diameter, and aggregate density for tillage and cover combinations.

Tillage‡	Cover§	Dry aggregate stability $\Delta W1$	Dry aggregate stability $\Delta W2$	Dry aggregate stability $P > \|t\|$	Geometric mean diameter $\Delta W1$	Geometric mean diameter $\Delta W2$	Geometric mean diameter $P > \|t\|$	Aggregate density $\Delta W1$	Aggregate density $\Delta W2$	Aggregate density $P > \|t\|$
		ln (J kg^{-1})			mm			Mg m^{-3}		
CT	WW	0.17	0.94	0.02	1.7	0.4	NS¶	−0.02	0.13	0.05
	WR	−0.05	0.60	0.05	0.5	0.8	NS	0.05	0.04	NS
	SR	0.09	0.66	0.08	0.3	0.2	NS	−0.01	−0.03	NS
RT	WW	0.35	0.97	0.06	0.7	0.8	NS	0.12	0.11	NS
	WR	0.09	1.09	0.01	−0.4	0.3	NS	−0.01	0.16	0.03
	SR	−0.32	0.40	0.03	1.3	0.5	NS	−0.05	0.02	NS
ZT	WW	0.24	0.45	NS	−0.3	−0.2	NS	0.07	0	NS
	WR	0.34	0.60	NS	−0.9	−2.0	NS	0.12	0.02	NS
	SR	0.13	−0.54	0.04	0.5	−9.8	0.01	0.06	−0.03	NS

† Overwinter change is the March value subtracted from the December value.
‡ Tillage treatments: CT = residues buried, RT = stubble-mulch, ZT = zero tillage.
§ Cover treatments: WW = winter wheat, WR = wheat residue, SR = sorghum residue.
¶ Not significant at $\alpha = 0.1$ level.

Table 3. Probabilities of larger F values from the analysis of variance for dry aggregate stability, geometric mean diameter, and aggregate density for spring samples and overwinter change (ΔW†) each winter.

Variance source	March 1989	March 1990	$\Delta W1$ (1988–1989)	$\Delta W2$ (1989–1990)
		Dry aggregate stability		
Tillage (T)	<0.001	0.909	0.531	0.001
Cover (C)	0.215	0.004	0.391	<0.001
T × C	0.245	0.064	0.591	0.074
		Geometric mean diameter		
Tillage	0.018	<0.001	0.359	<0.001
Cover	0.168	0.010	0.643	0.053
T × C	0.003	<0.001	0.724	0.007
		Aggregate density		
Tillage	<0.001	0.114	0.114	0.105
Cover	0.086	0.249	0.249	0.049
T × C	0.137	0.172	0.172	0.385

† Overwinter change is the March value subtracted from the December value.

SAS software (SAS Institute, 1985) for all statistical analyses. Differences were considered significant at the 0.1 level.

RESULTS AND DISCUSSION

Differences in overwinter change for tillage–cover combinations between winters (Table 2) were attributed to variation in precipitation amount, type, and distribution between the two winters. Tillage system and cover effects on overwinter change in the winter of 1989–1990 (Tables 3 and 4) were attributed to variations in soil water content caused by different residue cover. Similar overwinter change between tillage and cover treatments in the winter of 1988–1989 (Tables 3 and 4) was attributed to dry weather. Precipitation varied from 13 mm between sampling dates in the first winter to 81 mm in the second. Observations of rainfall, snowfall, and snow on the ground made at a weather station 2 km from the plots are presented in Fig. 1. The winter of 1988–1989 was dry with snow cover on only 3 d. The winter of 1989–1990 was wetter, with 35 d when snow cover was measurable at the weather station. We assumed that greater and more frequent precipitation, coupled with frequent additions of water from melted snow, caused the surface soil water content to be higher during the winter of 1989–1990 than the winter of 1988–1989. Both winters were characterized by many days when daytime air temperatures above 0 °C were followed by subzero nighttime air temperatures (Fig. 1). These fluctuations were conducive to freezing and thawing of soil water. The differences observed in this experiment were probably related to changes in aggregation caused by weathering processes (freeze–thaw, wet–dry, freeze-dry) moderated by differing soil water contents.

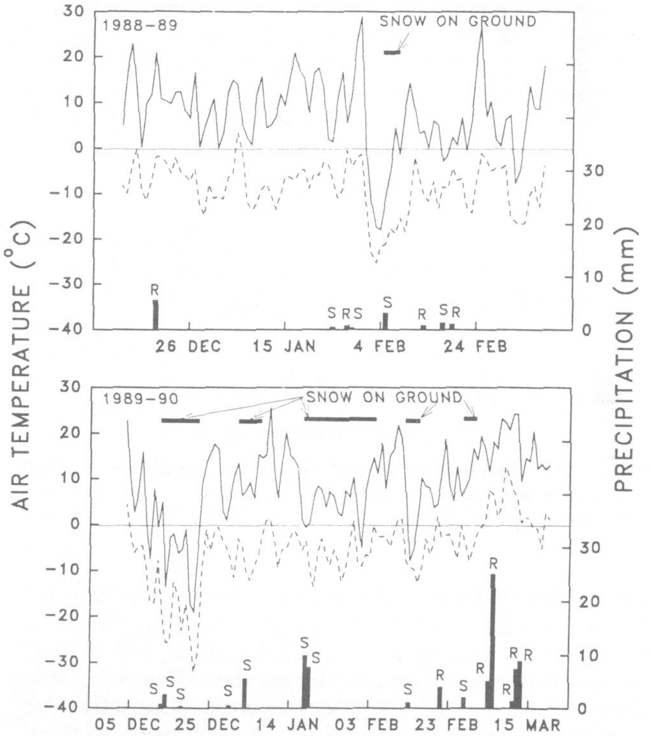

Fig. 1. Daily maximum (solid line) and minimum (dashed line) air temperatures and precipitation (R = rain, S = melted snow) for the winters of 1988–1989 and 1989–1990 at a Kansas weather station 2 km from the plots. Days when snow was on the ground are denoted by solid horizontal lines.

Table 4. Average March values and overwinter change (ΔW†) in dry aggregate stability, geometric mean diameter, and aggregate density for the 1988–1989 ($W1$) and 1989–1990 ($W2$) winters as influenced by tillage system and cover.

	Dry aggregate stability				Geometric mean diameter				Aggregate density			
	March 1989	March 1990	$\Delta W1$	$\Delta W2$	March 1989	March 1990	$\Delta W1$	$\Delta W2$	March 1989	March 1990	$\Delta W1$	$\Delta W2$
	ln (J kg^{-1})				mm				Mg m^{-3}			
Tillage‡												
CT	3.61	2.95	0.08	0.73	2.7	1.7	0.8	0.4	1.48	1.44	0.01	0.05
RT	3.56	2.89	0.04	0.82	3.0	1.9	0.5	0.6	1.43	1.41	0.02	0.10
ZT	2.46	2.95	0.24	0.17	1.5	5.9	−0.2	−4.0	1.23	1.34	0.08	0.01
$LSD_{(0.1)}$	0.29	NS§	NS	0.27	0.8	1.2	NS	1.7	0.06	0.05	NS	0.06
Cover¶												
WW	3.34	2.72	0.25	0.79	1.4	1.6	0.7	0.3	1.41	1.39	0.06	0.08
WR	3.02	2.87	0.13	0.76	2.1	2.3	−0.3	−0.3	1.33	1.40	0.06	0.09
SR	3.26	3.20	−0.03	0.18	3.7	5.7	0.7	−3.0	1.40	1.41	0	−0.01
$LSD_{(0.1)}$	NS	0.14	NS	0.06	NS	1.6	NS	2.1	0.06	NS	NS	0.06

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‡ Tillage treatments (averaged across cover treatments): CT = residues buried, RT = stubble-mulch, ZT = zero tillage.
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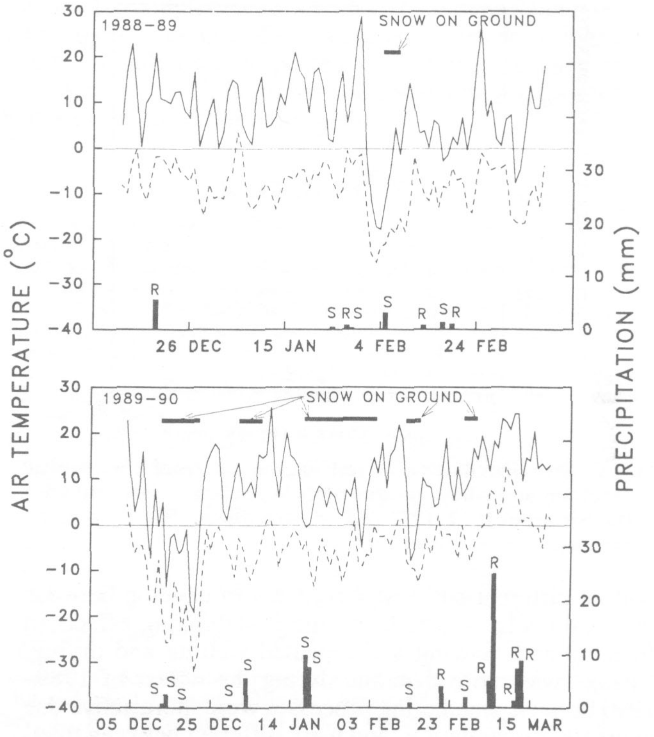

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ZT	2.46	2.95	0.24	0.17	1.5	5.9	−0.2	−4.0	1.23	1.34	0.08	0.01
LSD$_{(0.1)}$	0.29	NS§	NS	0.27	0.8	1.2	NS	1.7	0.06	0.05	NS	0.06
Cover¶												
WW	3.34	2.72	0.25	0.79	1.4	1.6	0.7	0.3	1.41	1.39	0.06	0.08
WR	3.02	2.87	0.13	0.76	2.1	2.3	−0.3	−0.3	1.33	1.40	0.06	0.09
SR	3.26	3.20	−0.03	0.18	3.7	5.7	0.7	−3.0	1.40	1.41	0	−0.01
LSD$_{(0.1)}$	NS	0.14	NS	0.06	NS	1.6	NS	2.1	0.06	NS	NS	0.06

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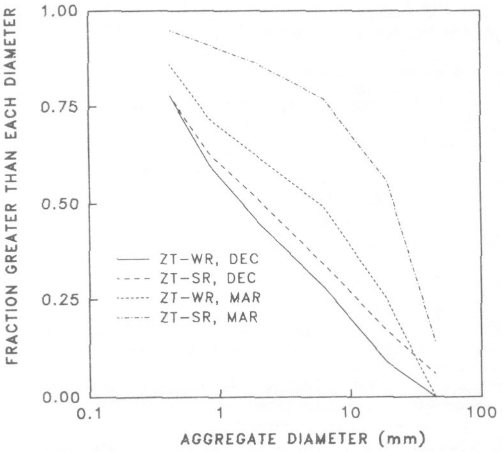

Fig. 2. Size distribution of soil aggregates from the zero-till sorghum and wheat residue plots in Kansas before and after the winter of 1989–1990 (ZT = zero tillage; SR = sorghum residue, WR = wheat residue).

widely different soil water contents to develop between the treatments, and reduced the destabilizing effects of freezing and thawing and repeated wetting and drying. Change was more dynamic during the winter of 1989–1990 because weathering processes were more active due to greater precipitation, and were different between treatments due to variation in surface-soil water content caused by residue. Residue retards evaporation, and surface-soil water content could have been further enhanced on the ZT plots by snow entrapment. In a Minnesota experiment, no-till plots with residue consistently trapped more snow than plow and chisel treatments (Benoit et al., 1986; Benoit and Van Sickle, 1991).

Physical processes that change soil structure during the winter are modified by the presence of surface residue. Treatments that had a small amount of surface residue (CT–WW, CT–WR, CT–SR, RT–WW, and RT–SR) each winter decreased more in stability during the 1989–1990 winter. Freeze-drying contributed to greater decreases in DAS on the CT and RT plots than the ZT plots, since residue reduced sublimation. Residue cover also prevents the soil from drying and, therefore, reduced the effects of repeated wetting and drying when compared with bare surfaces. More frequent wetting and drying could explain decreases in DAS on the CT and RT plots, while having little impact on the aggregates from the ZT plots. Less extreme temperature fluctuations limited the effects of freeze–thaw cycling on the ZT plots, when compared with tilled plots, by insulating the soil surface.

Aggregates from the ZT–SR plots consolidated into a highly stable structure during the 1989–1990 winter (Fig. 2). Freezing and thawing when wet is a possible explanation for the collapse of aggregate structure. During freezing of initially wet soil, water could have accumulated in the surface zone as ice lenses formed, followed by collapse while supersaturated after thawing. A consolidated structure with reduced frequency of flaws and cracks could result after thawing and drying. Water moves toward the surface in response to the pressure gradient established between frozen and unfrozen zones

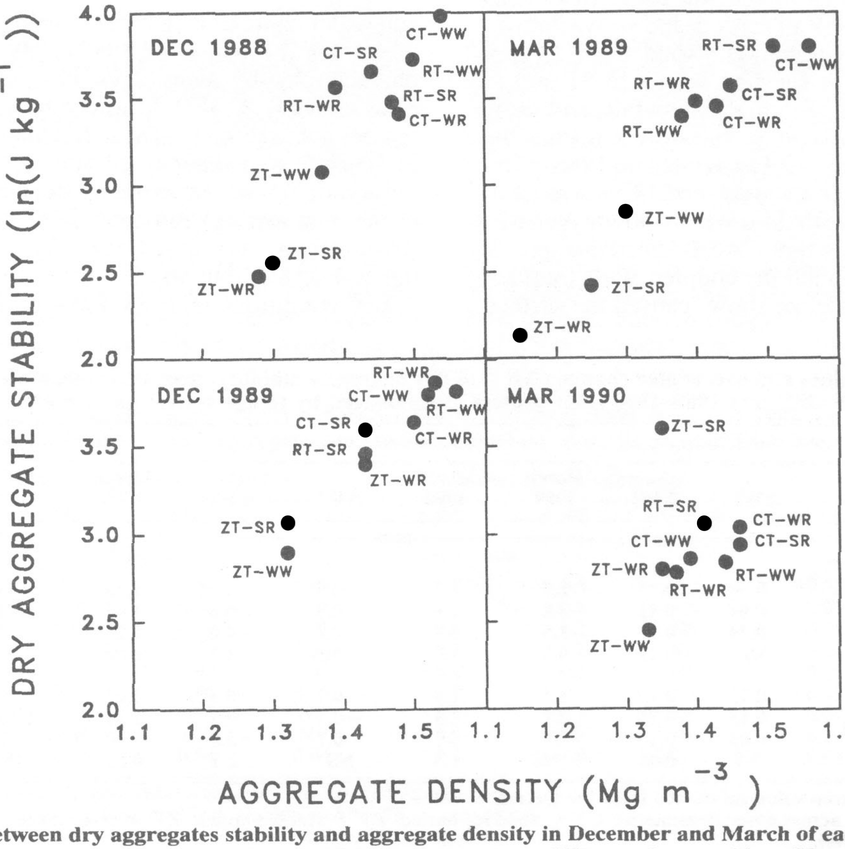

Fig. 3. Relationship between dry aggregates stability and aggregate density in December and March of each winter (CT = residues buried, RT = stubble-mulch, ZT = zero tillage, WW = winter wheat, WR = wheat residue, SR = sorghum residue).

(Cary et al., 1979; Pikul and Allmaras, 1985), accumulates in the surface layer, and freezes when it reaches the freezing plane. To further support this scenario, Kay et al. (1985) observed that the enlarged pores and ice lenses formed during freezing in a ZT system were unstable and collapsed as the soil thawed and drained. An additional explanation for this observation is the effect of late-winter precipitation. In a 3-yr Texas study, Unger (1991) concluded that the greatest decrease in dry aggregate-size distribution occurred during the wettest winter when late-winter precipitation was small. When precipitation was greater, the effects of loosening were negated by consolidation. The magnitude of ΔGMD on the ZT–SR plots compared with the other treatments, however, suggests that this was not the only consolidating process.

The effects of different residue material and prior crop on overwinter change in DAS and GMD are shown by comparing data for ZT–SR and ZT–WR treatments (Fig. 2, Table 2). Both treatments had >80% residue cover in the winter of 1989–1990, yet DAS increased on the ZT–SR plots and decreased on the ZT–WR plots. Aggregates from both treatments increased in size, but the increases with the ZT–SR treatment were greater. The effect of prior crop in terms of root exudates, rooting pressures, or other crop-specific changes to soil structure were manifested only after winter weathering, since DAS and GMD were similar for each treatment in December (DAS of 3.40 and 3.07 ln[J kg^{-1}] and GMD of 1.75 and 2.64 mm for ZT–WR and ZT–SR, respectively).

The pre- and postwinter relationships between DAS and AD for each year (Fig. 3) illustrate the different changes in aggregation. During the first winter, the range of values increased slightly due to decreases in AD and DAS on the ZT plots. In contrast, during the second winter, the range of values decreased (excluding ZT–SR). Generally, tillage-system differences in aggregation were maintained during the drier winter of 1988–1989 and were minimized during the wetter winter of 1989–1990.

Aggregation data from March 1989 show that aggregates from the ZT plots were smaller, less stable, and less dense than aggregates from the CT and RT plots (Table 4). Based on aggregate characteristics only, without considering the protection afforded by residue, the ZT plots were more susceptible to wind erosion.

Winter-associated decay of soil structure, high wind speeds, and little vegetation lead to the "wind erosion season" of late winter–early spring. Resistance to wind erosion takes two forms — protection of the soil surface by residues or crop and the presence of an aggregate structure of erosion-resistant size and stability. A ZT management system usually leaves enough residue at the soil surface to protect it from soil loss. However, consecutive years of low biomass production and low residue levels, coupled with smaller, less dense, and less stable aggregates in a ZT system could result in highly erodible conditions. Repeated crop failure caused by drought could result in higher soil loss using a ZT system than a more conventional system.

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