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Cropping system influences on soil physical properties in the Great Plains

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Abstract

Agricultural systems produce both detrimental and beneficial effects on soil quality (SQ). We compared soil physical properties of long-term conventional (CON) and alternative (ALT) cropping systems near Akron, Colorado (CO); Brookings, South Dakota (SD); Bushland, Texas (TX); Fargo, North Dakota (ND); Mandan (ND); Mead, Nebraska (NE); Sidney, Montana (MT); and Swift Current, Saskatchewan (SK), Canada. Objectives were to quantify the changes in soil physical attributes in cropping systems and assess the potential of individual soil attributes as sensitive indicators of change in SQ. Soil samples were collected three times per year from each treatment at each site for one rotation cycle (4 years at Brookings and Mead). Water infiltration rates were measured. Soil bulk density (BD) and gravimetric water were measured at 0–7.5, 7.5–15, and 15–30 cm depth increments and water-filled pore space ratio (WFPS) was calculated. At six locations, a rotary sieve was used to separate soil (top 5 cm) into six aggregate size groups and calculate mean weight diameter (MWD) of dry aggregates. Under the CON system at Brookings, dry aggregates (>19 mm) abraded into the smallest size class (<0.4 mm) on sieving. In contrast, the large aggregates from the ALT system abraded into size classes between 2 and 6 mm. Dry aggregate size distribution (DASD) shows promise as an indicator of SQ related to susceptibility of soil to wind erosion. Aggregates from CON were least stable in water. Soil C was greater under ALT than CON for both Brookings and Mead. At other locations, MWD of aggregates under continuous crop or no tillage (ALT systems) was greater than MWD under CON. There was no crop system effect on water infiltration rates for locations having the same tillage within cropping system. Tillage resulted in increased, decreased, or unchanged near-surface BD. Because there was significant temporal variation in water infiltration, MWD, and BD, conclusions based on a single point-in-time observation should be avoided. Elevated WFPS at Fargo, Brookings, and Mead may have resulted in anaerobic soil conditions during a portion of the year. Repeated measurements of WFPS or DASD revealed important temporal characteristics of SQ that could be used to judge soil condition as affected by management.

Key words: soil bulk density, dry aggregate stability, rotary sieve, aggregate size distribution, water infiltration rate, water filled pore space, soil organic carbon

Introduction

Considerable research has been conducted on relationships among cropping sequence, soil organic matter (SOM), and various biological and physical soil properties. It is generally accepted that crop production alone has caused a decline in SOM throughout the Great Plains[1,2]. Wheat-fallow crop sequence, being a common agricultural practice, has been implicated as the cause of serious declines in SOM[2–4].

SOM is linked to fertility and desirable soil tilth. Boyle et al.[5], in a review of the influence of SOM on soil aggregation and water infiltration, concluded SOM had a disproportionate effect on soil physical behavior. Hudson[6] reported that soils high in SOM have greater available water-holding capacity than soils of similar texture with less SOM. Bauer and Black[7] found that available water

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Table 1. Contrasting management treatments within eight long-term cropping systems. Treatments selected at each site differed in management intensity as characterized by either type or frequency of tillage, cropping intensity, and/or crop rotation diversity and are termed conventional (CON) or alternative (ALT).

Location/Soil series	Treatment	Crop sequence	Tillage	N rate[1]
Akron, CO	CON	WW–F[2]	Sweep (fallow)	Varied
Weld silt loam	ALT	WW–C–M	No tillage	Varied
Brookings, SD	CON	C–C	Chisel plow and disk	High
Barnes sandy clay loam	ALT	C–SB–SW–A	Chisel plow and disk	0
Bushland, TX	CON	WW–SO–F	No tillage	Varied
Pullman silty clay loam	ALT	WW–WW	No tillage	0
Fargo, ND	CON	DW–P	Fall plow	0
Fargo silty clay	ALT	DW–P	No tillage	0
Mandan, ND	CON	SW–F	Chisel plow and disk	Medium
Wilton silt loam	ALT	SW–WW–SU	No tillage	Medium
Mead, NE	CON	C–C	Tandem disk, 2 ×	High
Sharpsburg silty clay loam	ALT	C–SB–SO–OCL	Tandem disk, 2 ×	High
Sidney, MT	CON	SW–F	Tandem disk	45 kg ha^{-1}
Vida loam	ALT	SW–SW	No tillage	45 kg ha^{-1}
Swift Current, SK	CON	SW–F	Chisel plow and harrow	Varied
Swinton silt loam	ALT	SW–L	Chisel plow and harrow	Varied

[1] Varied = N fertilizer application rate based on soil test results.
[2] Abbreviations: A = alfalfa, C = corn, DW = durum spring wheat, F = summer fallow, L = lentil, M = proso millet, OCL = oat + clover, P = field pea, SB = soybean, SO = sorghum, SU = sunflower, SW = spring wheat, WW = winter wheat.

About 7 kg of surface soil (0–5 cm) was randomly (approximately six locations per plot) collected on each plot with a shovel in order to measure dry aggregate size distribution (DASD). Measurements were taken at Brookings and Mead for 3 years, at Bushland, Fargo, and Mandan for 2 years, at Swift Current for only 1 year, and none were taken at Akron and Sidney. After air drying, aggregate size distribution was determined by using a rotary sieve[33]. Mean weight diameters (MWDs)[34] were calculated based on the mass fraction of dry aggregates in six size groups. Group 1 was soil < 0.4 mm, group 2 was 0.4–0.8 mm, group 3 was 0.8–2 mm, group 4 was 2–6 mm, group 5 was 6–19 mm, and group 6 was > 19 mm. Representative particle diameter for groups 2–5 was the arithmetic mean of upper and lower sieve diameters, 0.4 mm diameter for group 1, and 19 mm for group 6.

Soil aggregates obtained using the rotary sieve from the Brookings and Mead sites were further processed to measure dry aggregate stability, water stability, and SOC. The rotary sieve tends to abrade aggregates and a measure of this abrasion was determined by running individual aggregate groups through the sieve a second time. The second run provides an estimate of dry aggregate stability and is closely related to susceptibility of the soil to wind erosion[35]. Water stability was measured using a wet sieving device[36]. We measured water stability of dry aggregates to evaluate treatment effect on soil slaking. Soil organic C was determined by combustion using a LECO CN 2000 analyzer (LECO Corp., St Joseph, MI, USA).

Infiltration was measured at six locations on each plot using a single ring infiltrometer[36]. An aluminum infiltration ring, 15 cm diameter by 13 cm long, was inserted into the soil to a depth of 7.5 cm. A piece of plastic wrap was inserted into the ring with the edges of the plastic draping over the edges of the infiltration ring. Distilled water was added to the ring to correspond to a 25 mm depth in the ring. The plastic wrap was removed from the ring and the time required for the water to infiltrate into the soil was measured. After infiltration of the first 25 mm of water, a second volume of water (wet run) was added to the ring to correspond to a 25 mm depth in the ring. The purpose of the first volume of water was to remove the confounding effects of having different antecedent soil water contents at the time of each infiltration test. The time required for the second volume of water to infiltrate was measured and those measurements are reported here. Duplicate infiltration measurements were made within the row (for row crop systems), on trafficked interrow, and non-trafficked interrow.

Analysis of variance was applied to each soil property measured, to determine differences between treatments and sampling times within each location. Analysis of variance and statistical comparisons were completed using the PROC MIXED procedure of SAS[37] assuming a completely randomized block design at each location. Cropping system (treatment) and sampling time were designated as fixed effects and plot replicates nested within treatment was designated as a random effect. Probabilities of WFPS exceeding a critical soil-aeration-threshold (SAT) value were determined using parametric distribution analysis (MINITAB Statistical Software, State College, PA, USA).

native grassland to 1.6 g cm^{-3} for the lower depth increment (loam to sandy clay loam textures) at two locations. Typically, BD was greatest for cropped land as compared with native grassland (Table 4, grassland not shown). The greatest source of variation in BD was attributable to the time (T) of sampling (Table 5).

In tilled plots, there was a tendency for BD in the surface depth increment (0–7.5 cm) to increase during the growing season, probably as a result of soil reconsolidation after spring tillage operations. The tendency for soil reconsolidation is illustrated in Figure 1 for the Brookings site, where surface BD increased during the growing season and subsequently decreased at the beginning of the season except for the end of 2001 and in 2002 when tillage was suspended to permit the growth of alfalfa. Most changes in BD with time probably represent seasonal and annual variations generated by phases in the rotation, tillage and subsequent reconsolidation, and wetting–drying histories. For all locations, measured BD did not exhibit any obvious trend with GW (typical of soils having a low coefficient of linear extensibility). Moreover, there was no observable pattern in the error with which BD was estimated at each sampling time. Hence, we cannot recommend a single crop phase or time of the year at which BD should be measured to obtain the most reliable data for SQ assessments.

Differences in BD between cropping systems were most frequently observed at the soil surface depth increment (Table 5, five locations). For locations in which no-tillage was compared with CON tillage, tillage resulted in increased (Mandan), decreased (Fargo), or unchanged (Akron) BD near the surface. Soil texture and the time of tillage relative to sampling probably influenced how and the degree to which tillage influenced BD. Some BD in the lower depth increment of 15–30 cm approached threshold

Table 4. Dry aggregate size distribution (means of all dates) expressed as mean weight diameter (MWD) of surface soil (top 50 mm) and bulk density (BD) (0–75 mm and 75–150 mm) for conventional (CON) and alternative (ALT) cropping systems. Locations identified in bold type used the same tillage in the cropping system (other than no till).

	MWD		BD			
	Surface soil		0–75 mm		75–150 mm	
	CON	ALT	CON	ALT	CON	ALT
	mm		mg m^{-3}			
Akron			1.27	1.30	1.36	1.38
Brookings	8.32	8.41	1.36	1.35	1.54	1.54
Bushland	8.95	10.85	1.31	1.22	1.43	1.48
Fargo	8.04	10.63	1.00	1.17	1.12	1.22
Mandan	3.99	4.75	1.33	1.14	1.37	1.29
Mead	4.98	5.03	1.17	1.15	1.42	1.39
Sidney	NM	NM	1.44	1.51	1.54	1.52
Swift Current	21.86	22.69	1.23	1.23	1.38	1.42

NM, not measured.

Table 5. Analysis of variance dry aggregate size distribution expressed as mean weight diameter of surface soil (top 50 mm) and bulk density at 0–75 mm and 75–150 mm depths. Locations identified in bold-italic type used the same tillage in the cropping system (other than no till).

Effect	Akron	***Brookings***	Bushland	Fargo	Mandan	***Mead***	Sidney	***Swift Current***
				P-value, MWD of surface soil				
CS	NM	NS	0.051	0.016	NS	NS	NM	NS
T	NM	< 0.001	< 0.001	< 0.001	0.004	< 0.001	NM	0.001
CS × T	NM	0.056	0.083	NS	NS	< 0.001	NM	NS
				P-value, BD (0–75 mm)				
CS	NS	NS	0.014	0.005	0.004	0.018	0.012	NS
T	NS	< 0.001	< 0.001	NS	NS	< 0.001	0.013	NS
CS × T	NS	NS	0.039	NS	NS	NS	NS	NS
				P-value, BD (75–150 mm)				
CS	NS	NS	NS	NS	0.011	0.004	NS	NS
T	< 0.001	< 0.001	< 0.001	0.033	0.008	< 0.001	< 0.001	NS
CS × T	NS	NS	NS	NS	NS	NS	NS	NS

NM = not measured, T = time, significant treatment effects at $P = 0.05$, NS = not significant.

Soil aggregates

Cropping system significantly affected MWD at Fargo and Bushland (Tables 4 and 5). Cropping systems at Fargo have a tillage variable where no tillage in the ALT treatment was compared with fall plow tillage in the CON treatment. Both systems at Bushland are under no tillage. MWD was greater under the ALT system at both Bushland and Fargo. Average (all dates) MWD at Bushland was 10.85 mm under ALT and 8.95 mm under CON (Table 4). Soil Microbial biomass C and N at Bushland was greatest under continuous wheat (ALT plots, 331 kg ha^{-1}) compared with a wheat–sorghum–fallow (CON plots, 209 kg ha^{-1}) rotation. This agrees with Liebig et al.[41] who found greater levels of glomalin, and wet aggregate stability under ALT management at Bushland. Mycorrhizal fungi are the source of glomalin and can improve soil structure (as suggested by greater wet aggregate stability and MWD under ALT management compared with CON) by forming water-stable soil aggregates[42].

A large MWD represents a DASD having a large portion of large aggregates. Data suggest that soil aggregates formed under no tillage (a system having elevated organic C) resist disintegration compared with aggregates under tillage. Studies at Brookings of a no tillage and CON tillage corn–soybean rotation (J.L. Pikul, unpublished data 2003) support the observation that dry aggregate stability is greater under no tillage compared with CON tillage. Bisal and Ferguson[43] showed that finer textured soils undergo tremendous changes with time over a multi-year weather cycle. Merrill et al.[44] found that the geometric mean diameter of aggregates on a silt loam soil increased from about 1–2 mm to about 20–30 mm with time. Average MWD for the Swift Current site (Table 4) was similar to that reported by Merrill et al.[44]

There was a significant effect of time on MWD at all locations (Table 5). At Brookings, MWD under ALT (4-year rotation) was significantly greater than CON (continuous corn) in the 4th year of the rotation (alfalfa phase). A similar comparison at Mead showed a smaller MWD under ALT compared with CON. MWD throughout three seasons are shown in Figure 4 for Brookings, SD and Figure 5 for Mead, NE. With the exception of the final measurements in 2002, there was not a statistically significant difference between treatments in MWD for either Brookings or Mead. The crop ending the 4-year rotation at Brookings is alfalfa and the improvement in aggregate stability (represented by a larger MWD value for ALT) may be a consequence of having a perennial like alfalfa in rotation.

MWD is a convenient way to generalize DASD, but expressing a distribution as a single number (e.g., MWD) fails to show differences in properties that influence aggregate stability. Chepil[33] proposed that dry aggregate stability could be measured by multiple passes through a rotary sieve, and we followed those ideas proposed by Chepil. We found differences in the distribution and stability of dry aggregates between treatments at Brookings and, to a lesser extent, treatments at Mead (Table 6).

Erodible fraction is defined as the percentage of soil mass < 0.84 mm diameter, and this parameter has been related to soil wind erodibility. Merrill et al.[44] have shown that the erodible fraction was more sensitive to soil management effects than indices describing aggregate size distribution (e.g., MWD). The ALT treatment at Brookings had significantly greater fraction of large aggregates in groups 5 and 6 (Table 6) following the first sieving than did the CON treatment. As shown by the change in mass on second sieving, aggregates under ALT also had less tendency to abrade into small aggregates (groups 1 and 2) when

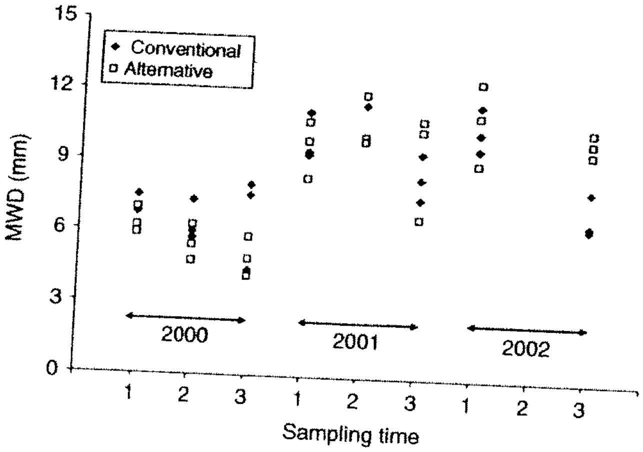

Figure 4. The time course of dry aggregate stability expressed as mean weight diameter (MWD) throughout three seasons for the conventional (CON) and alternative (ALT) rotations at Brookings, SD. In each year, soils were sampled prior to planting, at peak crop biomass, and after harvest. MWD based on aggregate fractions following second sieving.

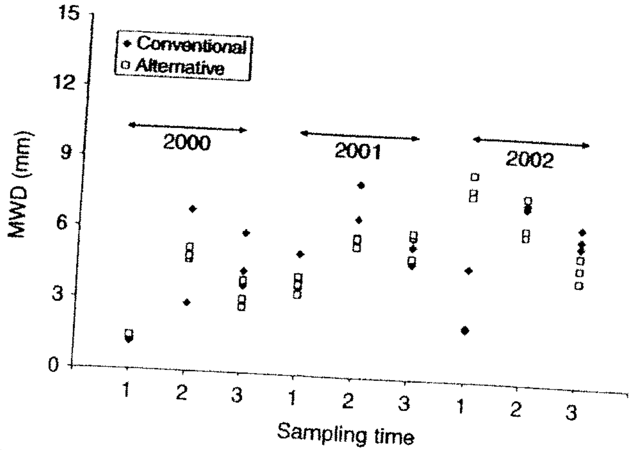

Figure 5. The time course of dry aggregate stability expressed as mean weight diameter (MWD) throughout three seasons for the conventional (CON) and alternative (ALT) rotations at Mead, NE. In each year, soils were sampled prior to planting, at peak crop biomass, and after harvest. MWD based on aggregate fractions following second sieving.

same soil type, we think that aggregate stability is directly related to SOM status (J.L. Pikul, unpublished data 2005); however, we do not understand the temporal variation of this property within a system.

Values of MWD (calculated from aggregate distribution) provide a convenient way to show the dynamics of surface conditions with time as shown for Brookings (Fig. 4) and Mead (Fig. 5). Detailed analysis of aggregate properties, as conducted for the final soil samples (harvest 2002), at Brookings and Mead were laborious. Inspection of MWD values (Figs. 4 and 5) show that we conducted our detailed analysis of aggregates at a time when the MWD was close to an average value for the rotation cycle. For the Brookings site, MWD averaged across all dates was 8.3 mm for CON and 8.4 mm for ALT. Average MWD for the final sample was 7.0 mm for CON and 10.1 mm for ALT (Fig. 4). For the Mead site, MWD averaged across all dates was 5.0 mm for CON and 5.0 mm for ALT. Average MWD for the final sample was 6.2 mm for CON and 4.9 mm for ALT (Fig. 5).

DASD was expressed as MWD changes within a season and between seasons. Recognizing the temporal change in this surface soil property is important for understanding the dynamics of other soil properties linked to soil surface conditions such as water infiltration. Thus, MWD appears to be a useful trait for quantifying differences (at time of measurement) between management systems and as a measure to quantify temporal dynamics within a system.

Conclusions

Infiltration

Efficient water management requires attention to: (i) soil water use by crops (ii) reduction of water runoff, and (iii) opportunities to improve water recharge. Water intake rates are governed by surface and internal soil conditions and these conditions are ever-changing. Further, the inherently high spatial variability in water infiltration rates makes the interpretation of treatment effects difficult, especially in situations where tillage is used. We found no significant cropping system effects on infiltration for locations that had the same tillage system but differing cropping intensity or crop species in the cropping system. However, in the cases where no tillage was compared with tillage, infiltration was greater following tillage and declined over time in tilled systems. A cyclical pattern of infiltration rate was present for most cropping systems and locations, showing that a snap-shot of water infiltration (one-time measurement) would not be an appropriate SQ indicator because of significant temporal variation in infiltration rate. Measuring infiltration in wheel track and untracked parts of the field provides farmers with an understanding of how field operations affect this parameter and, in soils susceptible to reduced infiltration in traffic areas, will demonstrate the importance of controlling traffic patterns.

Bulk density and water-filled pore space

Long-term changes in BD indicative for use in SQ assessments would be difficult to establish and may be misleading if using a single sampling date, because BD changed significantly within each season and rotation. Multiple sampling dates throughout one or more rotational sequences are needed to ascertain long-term changes in BD.

Because most tillage operations on cropland are restricted to the upper 150 mm, and because soil root proliferation is typically greatest at shallow soil depths, BD measured near the surface was most sensitive to the effects of cropping systems. High BD (e.g., $>1.4\,\mathrm{g\,cm^{-3}}$) near the surface, such as those observed at the Sidney location, are clearly undesirable. However, it may be difficult to ascertain if minor but significantly different BD observed at the surface for some of these treatment comparisons in fact lead to improved SQ. At lower soil depths, where BD more strongly influences root proliferation, a critical threshold criterion proposed by Arshad et al.[45] may be useful in evaluating these effects within an assessment framework for SQ. Tillage pans with narrow zones of high soil strength will also impede root proliferation. However, these features may sometimes be difficult to detect when the sampling depth increment is large.

WFPS, a function of BD and GW, fluctuated during the season and different rotational phases. We used a WFPS ratio of 0.6 as SAT value to delineate between water-limiting and aeration-limiting soil microbial processes. This approach provided a practical criterion for a systematic evaluation of distribution functions for the probability of exceeding a critical WFPS (with time, treatment, or depth). Systems having a high probability of exceeding SAT might then be viewed as having a detrimental effect on SQ. This criterion should be especially appropriate for locations having a combination of climate (cool and wet) and soil conditions (poorly drained) that pose a risk. For example, management at the Fargo location had a significant effect on WFPS and there was a high probability of exceeding SAT under no tillage when compared with tillage.

Identification of areas of a field having BDs exceeding threshold values for root elongation will be of interest to farmers. Management practices can be modified to address areas having high BDs due to activities such as wheel traffic or tillage. WFPS is an attribute that is more difficult to measure, but if areas of a field that exceed 0.6 WFPS for extensive periods of time can be identified, management practices such as improved drainage or reduced application of N fertilizer can be undertaken to lower the water content or decrease the potential for emission of greenhouse nitrogenous gases.

Soil aggregates

Greater MWD values were found under systems with greater cropping intensity and less tillage at Bushland and Fargo, respectively. A large MWD value represents an

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