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Bulk density as a soil quality indicator during conversion to no-tillage

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Abstract

Producers often identify compaction as an important problem, so bulk density is usually included in minimum data sets used to evaluate tillage and crop management effects on soil quality. The hypothesis for this study was that bulk density and associated water content would be useful soil quality indicators for evaluating the transitional effects associated with changing tillage and crop management practices on deep-loess soils. The study was conducted on three deep-loess, field-scale watersheds located in western Iowa, USA. The soils are classified as Haplic Phaeozems, Cumulic-Haplic Phaeozems, and Calcaric Regosols. Watersheds 1 and 2 were converted in 1996 from conventional tillage to no-tillage, while watershed 3 was maintained using ridge-tillage and continuous corn (*Zea mays* L.), a practice implemented in 1972. Watershed 1 was converted to a corn—soybean (*Glycine max* (L.) Merr.) rotation while watershed 2 was converted to a 6-year rotation that included corn, soybean, corn plus 3 years of alfalfa (*Medicago sativa* L.). Bulk density and water content were measured at three landscape positions (summit, side-slope, and toe-slope), in 20 mm increments to a depth of 300 mm, five times between September 1996 and May 2000. Organic C and total N were also measured to a depth of 160 mm during the initial sampling. Neither bulk density nor water content showed any significant differences between the two watersheds being converted to no-tillage or between them and the ridge-till watershed. There also were no significant differences among landscape positions. Bulk densities and water contents showed some differences when adjacent sampling dates were compared, but there was no overall or consistent trend. Our results show that bulk density is not a useful soil quality indicator for these soils within the bulk density range encountered (0.8–1.6 Mg m^3). Our results also confirm that producers do not necessarily have to worry about increased compaction when using ridge-tillage or changing from conventional to no-tillage practices on these or similar deep-loess soils.
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1. Introduction

A recent Iowa Residue Management Partnership (Beeler, 2001) survey found that soil compaction was a major concern among farmers and the reason that 7.5% of the respondents did not adopt conservation tillage. Those survey results demonstrate the need for field-scale tillage research, because when farmers perceive their soils are becoming compacted, it is easier to justify subsoiling or other forms of tillage and the subsequent operations needed to prepare a seedbed.

Soil compaction increases bulk density and decreases pore volume (Kooistra and Tovey, 1994). At a constant water content, compaction increases the proportion of soil pores filled with water as average pore size decreases. This can lead to aeration stress

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(Stepniewski et al., 1994), lower soil temperature and changes in biological processes (Brussaard and Van Faassen, 1994), increased denitrificaiton (Linn and Doran, 1984), and loss of mycorrhizal fungi (Ellis, 1998). If bulk density becomes too high, it can limit plant root growth. For these reasons, bulk density is frequently identified as an indicator of soil quality (USDA-NRCS, 1996) and included in many minimum data sets (Doran and Parkin, 1994). The specific bulk density that will adversely affect plant root growth and development depends on many factors including the parent material, soil texture, the crop being grown, and management history. For silt and silt loam soils, a bulk density of 1.55 Mg m^{-3} is often the minimum value at which root restriction may be observed (USDA-NRCS, 1996).

Predicting the specific effects of soil compaction on crop growth is complicated because interactions among physical, chemical, and biological factors are extremely variable. In deep, moist soils that are easily permeable to air, water, and plant roots, crop production is unconstrained. Crop yield will be reduced only if compaction limits root development and function such that crops cannot obtain air, water, and nutrients at an adequate rate (Boone and Veen, 1994; Lindstrom and Voorhees, 1994). However, compaction can cause other adverse effects that are associated with poor soil quality (e.g. reduced infiltration, increased runoff, lower soil temperature, and reduced rates of nutrient cycling).

Compaction is of particular concern for seed germination and early root growth which are necessary to establish the crop and take up nutrients and water. Near-surface bulk density is vital information to assess seedbed properties. The near-surface zone is also the volume of soil showing the greatest variability due to weather and management. In the short term, soil management generally does not change the bulk density below 300 mm (Logsdon et al., 1990). Therefore, with regard to soil quality, an important question is whether bulk density can be considered a static property or if small temporal changes are important. Logsdon et al. (1999a) and Logsdon and Cambardella (2000) showed significant temporal changes in near-surface incremental bulk density for tillage systems in a sub-humid climate. Sharratt (1996) also evaluated incremental sampling for a semi-arid climate. This study adds a cropping system component and was conducted at different landscape positions within three field-scale watersheds.

Current soil quality indexing methods (Andrews et al., 2002) consider that crop growth could be reduced if bulk density is higher than a critical level that varies with soil texture (USDA-NRCS, 1996). However Logsdon et al. (1992) have shown that crop growth is not reduced if continuous macropores allow root growth through dense horizons. Some soils have dense layers without continuous macropores because soil type and climate do not permit formation of macropores through bio-activity, freeze-thaw, or wet-dry cycles. For these soils, bulk density could be more closely related to yield than for soils with continuous macropores.

Another factor affecting the relation between bulk density and crop performance is the depth or range of depths at which bulk density is measured. Soil quality assessment guidelines (Arshad et al., 1996) suggest that bulk density be measured near the soil surface, but the compacted zone that impedes crop growth may occur deeper within the soil profile. Another frequently unanswered question concerning bulk density sampling is whether the depth increments are long enough to get a consistent sample. For example is a 200 mm depth unit, split in two 100 mm units, appropriate? Is this depth range adequate, or do management transitions such as changes in tillage or cropping sequence result in important bulk density changes at even smaller increments?

The hypothesis for this study was that bulk density and associated water content would be useful soil quality indicators for evaluating the transitional effects associated with changing tillage and crop management practices on deep-loess soils.

2. Materials and methods

2.1. Site

Our study was conducted within three of field-scale watersheds that are between 30 and 43 ha (76 and 110 acres) in size. The watersheds were established by the US Department of Agriculture Agricultural Research Service (USDA-ARS) near Treynor, IA, in 1964, to determine how various soil conservation practices affected runoff and water-induced soil erosion. The agronomic practices and hydrologic characteristics of the watersheds are representative of the deep-loess hills found in Major Land Resource Area (MLRA) 107, located in western Iowa and northwestern Missouri, USA (USDA-SCS, 1981). Classification is given by two system: (FAO (USDA)). The soils are Monona (Haplic Phaeozems (Fine-silty, mixed superactive mesic Typic Hapludolls)), Ida (Calcaric Regosols (Fine-silty, mixed superactive (calcareous), mesic Typic Udorthents)), Dow (Calcaric Regosols (Fine-silty, mixed superactive (calcareous), mesic typic Udorthents)), Napier (Cumulic-Haplic Phaeozems (Fine-silty, mixed superactive mesic Cumulic Hapludolls)), or Kennebec (Cumulic-Haplic Phaeozems (Fine-silty, mixed superactive, mesic Cumulic Hapludolls)).

The topography, hydrology, and agronomic practices for the first 30 years, and their combined effects on rainfall and N use efficiencies were summarized by Karlen et al. (1999), Kramer et al. (1999), and Logsdon et al. (1999b). We measured the changes in bulk density during the first 5 years after watersheds 1 and 2 were converted from conventional tillage to no-tillage operations in 1996. Watershed 1 was also converted from continuous corn to a corn–soybean rotation, while watershed 2 was switched from continuous corn to a 6-year rotation (corn, soybean, corn, 3 years alfalfa). Watershed 3 was considered the control, because it had been in continuous ridge-tillage corn for 24 years prior to this study and remained in ridge-tillage corn throughout its duration. The ridge-tillage operation at this location involved scraping away the old crop residue prior to planting and generally cultivating once to rebuild the ridges. The amount of soil disturbance each year was much less than that associated with many ridge-tillage operations (Bill Vorthmann (farmer-cooperator), personal communication, 2002). Watershed 3 thus provided information that could be extrapolated to represent long-term effects of reduced tillage operations on bulk density or compaction of deep-loess soils.

2.2. Soil sampling

Details for incremental sampling of bulk density have been described extensively in the literature (Pikul and Allmaras, 1986; Allmaras et al., 1988; Logsdon et al., 1999a; Logsdon and Cambardella, 2000). Briefly we used a volumetric sampling tool that had a relief cutting tip 19 mm diameter, which screwed on to a 425 mm long cylinder. The cylinder was welded to a pin-fitting sample handle. The inside of the cylinder was sprayed with cooking spray lubricant before sampling. The cylinders were inserted by hand using gentle pressure, and were not used if any compaction occurred during insertion. Sampling induced compaction was detected if the sample within the tube was shorter than the insertion length.

Twelve individual samples were taken within crop rows (top of ridge for ridge-tillage) and composited to measure bulk density and water content for each 20 mm increment at each sampling date. After removing the cylinder tip, each soil sample was carefully pushed out, top end first, with a solid metal rod. The sample was pushed into a sampling tray (half of a metal pipe) that had been previously marked in 20 mm increments. Each sample was cut into 20 mm increments to a depth of 300 mm, with soil from below 300 mm being discarded. For each increment, we pooled the 12 sub-samples, and stored them in plastic bags. The volume of the each combined sample was 68 cm^3. All measurements were made at the same general locations on each sampling date.

The sampling dates were 4–5 September 1996, 24–25 April 1997, 31 July–1 August 1998, 17–18 June 1999, and 28–29 April 2000. The April sampling data occurred before any spring field operations, while the July through September dates allowed time for settling the soil by precipitation after disturbance for planting, fertilizing, or weed control. The June sampling occurred after rain had settled the disturbance from planting, but before the ridges were reformed by cultivation. For each date and watershed, samples were collected from within each crop at three landscape positions. Since corn was the only crop on watershed 3, two replicates were sampled at each landscape position. Soil map units at each location are Monona (summit), Ida and Dow (side-slope), and Napier and Kennebec (toe-slope).

To help characterize each landscape position in 1996, samples from the top 160 mm were also analyzed for organic C (after removal of carbonates) and total N using standard methods of analysis (Page, 1986). This was done because soil organic matter (soil carbon) can significantly affect bulk density and the potential for compaction by influencing soil water retention (Hudson, 1994). In addition, soil organic matter usually has a low particle density than minerals, which may reduce overall soil bulk density.

Cropping systems were compared on a watershed basis because of the rotations. For each landscape position, the cropping systems were treated as replicates for each landscape position–watershed combination. For watersheds 1 and 3 there were two replicates, but for watershed 2, there were six replicates for each combination. The statistical analysis was analogous to that described by Karlen and Colvin (1992) and Logsdon and Cambardella (2000). We used the 95% confidence interval of paired differences to detect statistical significance. For each depth-increment, we tested differences between watersheds (1 versus 2, 2 versus 3, 1 versus 3), landscape positions, and between adjacent sampling dates (after pooling landscape position within a watershed). We compared both density and soil water content differences.

2.3. Calculations and statistics

To determine the effect of sampling interval and critical cut-off value, we calculated densities for 100 mm increments. We paired sampling location with the associated yield location. For each of these paired locations, we determined the maximum bulk density from the fifteen 20 mm increments, and from the three 100 mm increments. For each set, we divided into those greater than the cut-off value (1.55 Mg m^{-3}), and those less than the cut-off values, and used *t*-test to compare corn and soybean yields for the two groups. (Alfalfa yields were not available.) We also compared the two increment intervals for fraction of samples with bulk densities greater than the cut-off values.

3. Results and discussion

Organic carbon and total nitrogen were not significantly different between the watersheds, and the combined data show a moderate amount of organic carbon and total nitrogen, both of which declined with depth (Fig. 1). Higher amounts of organic carbon can result in smaller bulk densities in some cases because organic carbon has a lower particle density than mineral particles.

Field operations when the soil is near the plastic limit can cause compaction. Table 1 lists some field operations that may have resulted in compaction because of recent rains. Use of 2.54 cm of rain as a cut-off for possible compaction effects merely suggested that rainfall less than 2.54 cm over a few days would probably not result in significant compaction. Some of the

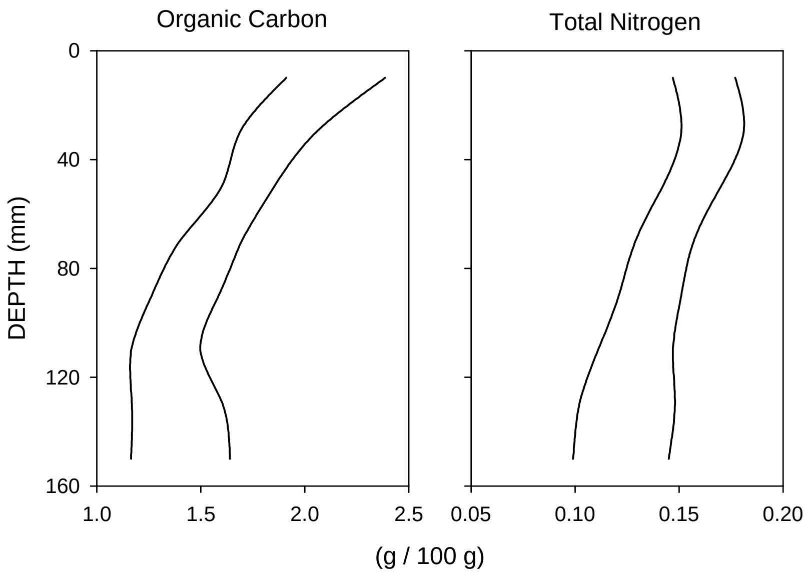

Fig. 1. The 95% confidence intervals for organic carbon and total nitrogen pooled for watersheds 1, 2 and 3.

Table 1
Timing of field operations relative to rain >25 mm during 7 days prior to operation

Year	Watershed	Date	Rain (mm)	Crop	Operation
1996	1	30 May	44	Soybean	Cultivate
1996	1	19 June	58	Soybean	Re-drill
1996	1	25–26 June	85	Corn	Cultivate
1996	1, 2	6 July	28	Soybean	Traffic
1996	2	1 May	33	Corn	Disk
1996	2	27–28 June	85	Corn	Anhydrous, cultivate
1996	3	30 May–4 June	54–13	Corn	Plant
1996	3	28 June	58	Corn	Traffic
1996	3	3–8 July	24–34	Corn	Cultivate/ridge
1997	1, 2	7–8 May	51	Corn	Traffic, plant
1997	1, 2	28 June	87	Soybean	Traffic
1997	1	10–22 October	3–36	Corn, soybean	Harvest
1997	2	8 September	72	Alfalfa	Traffic
1997	3	None			
1998	1, 2	19 May	34	Soybean	Traffic
1998	1	13–18 June	80–138	Corn	Anhydrous
1998	1, 2	29 June	29	Soybean	Traffic
1998	2	14 May	27	Soybean	Drill
1998	2	13 June	80	Alfalfa	Traffic
1998	3	1 June	44	Corn	Traffic
1998	3	20–24 June	109–2	Corn	Cultivate/ridge
1999	1, 2	30 April–2 May	33	Corn	Plant
1999	1, 2	24–25 May	39	Soybean	Drill
1999	1, 2	14 June	33	Corn	Traffic
1999	1, 2	8 July	51	Soybean	Traffic
1999	3	1–2 May	38	Corn	Anhydrous
1999	3	14–19 May	3–66	Corn	Plant
1999	3	14 June	35	Corn	Traffic

operations occurred over a range of days because of rain, and may not have been as influenced by high recent rainfall rates as the range might suggest because wet soil would prevent the field operations.

For each depth increment, there were no significant differences in soil bulk density or water content for watersheds or for landscape position; therefore, the data are pooled for the rest of the analyses. Bulk density changed significantly over time, but not in any consistent trend (Table 2). Bulk densities were highest in 1998, and lowest in 1999. The soil was significantly wetter in 1999 (Table 2), which resulted in buoyancy that prevented the soil from becoming denser. When the soil is very wet, the density cannot be increased except by squeezing out water, which is more difficult than displacing air. Also wet fields prevent field operations on these silty soils, which have low strength when wet; therefore, wheel traffic compaction would not occur until the soil water content would dry down to a level permitting field operations.

These temporal changes in bulk density have been shown by others (Logsdon et al., 1999a; Logsdon and Cambardella, 2000). Some of the differences between dates were significant even though management and landscape affects were not significant. The timing of the measurement and the water content at the time of measurement have a great influence on the values. This calls into question the appropriateness of a single critical cut-off value that does not take into account conditions at the time of measurement for soil quality assessments.

Using a longer depth-increment resulted in a lower fraction of measurement sites that had bulk densities greater than the cut-off value of 1.55 Mg m^{-3} (Table 3). Only in 1998 were any of the 100 mm increments greater than the cut-off value. None of the crop yields were significantly affected by bulk density

Table 2
Bulk density variation over time, and water content at the time of measurement

Depth (mm)	Bulk density ($Mg\,m^{-3}$)					Water content ($m^3\,m^{-3}$)				
	1996	1997	1998	1999	2000	1996	1997	1998	1999	2000
10	1.18*	0.84*	0.99*	0.87	0.84	0.160	0.167	0.192*	0.360*	0.125
30	1.22	1.15*	1.34*	1.11	1.21	0.208	0.237*	0.291*	0.485*	0.238
50	1.25	1.31	1.34*	1.19	1.31	0.181*	0.297	0.289*	0.485*	0.238
70	1.36	1.32*	1.42*	1.24*	1.44	0.190*	0.306	0.323*	0.544	0.281
90	1.36	1.34*	1.51*	1.25*	1.52	0.184*	0.303	0.329*	0.567*	0.300
110	1.43	1.43	1.52*	1.28*	1.48	0.214*	0.314	0.334*	0.571*	0.293
130	1.37	1.41	1.44*	1.26*	1.42	0.210*	0.314	0.334*	0.571*	0.293
150	1.36*	1.44	1.46*	1.25*	1.42	0.190*	0.352	0.310*	0.568*	0.304
170	1.33*	1.41*	1.46*	1.24	1.39	0.181*	0.332	0.320*	0.553*	0.290
190	1.35*	1.45*	1.40*	1.25*	1.42	0.190*	0.342*	0.310*	0.568*	0.304
210	1.34*	1.44	1.37*	1.22*	1.33	0.237*	0.336	0.313*	0.517*	0.282
230	1.30	1.35	1.37*	1.15*	1.32	0.180*	0.319	0.311*	0.517*	0.282
250	1.27*	1.36	1.33*	1.15*	1.27	0.184*	0.326	0.302*	0.536	0.277
270	1.26*	1.36	1.38*	1.22	1.25	0.175*	0.330	0.318*	0.572	0.128
290	1.27	1.33*	1.54*	1.28	1.31	0.179*	0.324*	0.361*	0.602*	0.302

* Significant differences between adjacent dates at $P = 0.05$.

Table 3
Affect of increment length on the critical cut-off value for bulk density and crop yield affect

Depth increment (mm)	Corn					Soybean			
	1996	1997	1998	1999	2000	1996	1997	1998	1999
Number of samples above cut-off value/total number of samples									
20	3/14	3/16	10/14	0/12	7/12	1/9	2/6	3/6	0/5
100	0/14	0/16	2/14	0/12	0/12	0/9	0/6	0/6	0/5
Crop yield[a] ($Mg\,ha^{-1}$)									
Cut-off (20 mm increment)									
Greater than cut-off	7.38	10.39	8.52	None	9.53	4.22	4.04	3.84	None
Less than cut-off	6.41	9.45	7.76	9.42	8.50	3.56	4.30	4.30	3.35

[a] These are for yield sites corresponding to the location where the bulk density samples were taken. For the 100 mm increment in the 1998 corn crop, the yield comparisons for above and below the cut-off values were 8.95 and 8.20 $Mg\,ha^{-1}$, respectively.

greater than the cut-off value, either for the 20 mm increments or for the 100 mm increments. These soils are subject to freeze-thaw in the winter, and the clays present have some degree of shrink-swell potential. Both of these factors as well as old root channels presumably provide macropore pathways through the soil. This reduces the effect of high bulk density on crop yield.

4. Conclusions

This study failed to detect any benefit of the small-depth increments in detecting small changes during management conversion. The larger increments better showed that bulk density did not reduce crop yield in this study. Timeliness of the measurement appeared to be the most critical factor in utilizing bulk density within a soil quality index. Soil is able to recover to some extent from compaction due to biological and physical processes. A one-time measurement showing high bulk density should probably be followed-up with a repeat measurement under different soil moisture conditions to see if the effect was transient. Presence of continuous macropores would increase the critical cut-off bulk density value for a given soil texture.

This study also showed that switching to no-till on watersheds 1 and 2 and changing from continuous corn to either a 2- or 6-year rotation did not negatively impact bulk densities or crop yields. Continuous macropores probably allowed continual root growth even during transient times of higher bulk density, and the soil was able to recover from these transient high bulk densities.

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