Continuous Cropping Systems Reduce Near-Surface Maximum Compaction in No-Till Soils


ABSTRACT

Because of increased concerns over compaction in no-till (NT) soils, it is important to assess how continuous cropping systems influence risks of soil compaction across a range of soils and NT management systems. We quantified differences in maximum bulk density (BD$_{\text{max}}$) and critical water content (CWC) by the Proctor test, bulk density ($\rho_b$), and their relationships with soil organic carbon (SOC) concentration across three (>11 yr) cropping systems on a silty clay loam, silt loam, and loam in the central Great Plains. On the silty clay loam, BD$_{\text{max}}$ in sorghum [Sorghum bicolor (L.) Moench]–fallow (SF) and winter wheat [Triticum aestivum (L.)]–fallow (WF) was greater than in continuous wheat (WW) and continuous sorghum (SS) by 0.1 mg m$^{-3}$ in the 0- to 5-cm soil depth. On the loam, BD$_{\text{max}}$ in WW was greater than in winter corn (Zea mays L.)–millet (Panicum virgatum L.) (WCM) by 0.24 mg m$^{-3}$ and perennial grass (GRASS) by 0.11 mg m$^{-3}$. On the silt loam, soil properties were unaffected by cropping systems. Elimination of fallowing increased the CWC by 10 to 25%. The $\rho_b$ was greater in WW (1.52 Mg m$^{-3}$) than in WF (1.16 Mg m$^{-3}$) in the silty clay loam, while $\rho_b$ under WW and WCM was greater than under WCM and GRASS in the loam for the 0- to 5-cm depth. The BD$_{\text{max}}$ and $\rho_b$ decreased whereas CWC increased with an increase in SOC concentration in the 0- to 15-cm depth. Overall, continuous cropping systems in NT reduced near-surface maximum soil compaction primarily by increasing SOC concentration.

Continuous cropping systems under NT are being recognized as an important alternative to crop–fallow systems in the central Great Plains of the United States. Intensified cropping systems have greater benefits than crop–fallow systems (e.g., WF or SF) for conserving soil and water (Petterson and Westfall, 2004), improving soil properties (Shaver et al., 2003; Pikul et al., 2006; Benjamin et al., 2007; Benjamin et al., 2008), and increasing SOC concentration (Bowman et al., 1999; Mikha et al., 2006) while improving crop production (Anderson et al., 1999; Petterson and Westfall, 2004). Diverse crop rotations and continuous cropping systems return more above- and belowground biomass to soil than cropping systems with extended fallow periods. Annual return of crop residues in NT systems is essential to protect the soil surface from water and wind erosion, reduce water evaporation, increase soil macro-aggregation, and enhance C accumulation.

An additional benefit of intensified cropping systems under NT technology may be the reduced susceptibility of soil to compaction. No-till soils are often susceptible to compaction due to lack of disturbance and field equipment traffic. Because of the greater biomass C input than crop–fallow systems, intensified cropping systems often increase SOC concentration over crop–fallow systems (Liebig et al., 2004; Petterson and Westfall, 2004). This increase in SOC may induce resilient properties to soil and provide a buffer against compaction. Influence of increased SOC concentration by continuous cropping systems on soil compactibility requires further research.

The Proctor test is a useful approach to determine soil's susceptibility to compaction (American Society for Testing and Materials, 2007). The Proctor test has been used to determine the BD$_{\text{max}}$ which is equivalent to the maximum compactibility of a soil (Thomas et al., 1996; Aragon et al., 2000; Blanco-Canqui et al., 2009). The Proctor test allows the determination of relative soil bulk density at different soil water contents under standardized compaction forces. The soil water content at which the Proctor bulk density of a soil reaches a maximum value (BD$_{\text{max}}$) is known as the CWC (Krzic et al., 2004; Zhao et al., 2008). The Proctor test has important agronomic uses, but it has not been widely used for assessing differences in soil compactibility among diverse crop rotations managed under NT.

Previous studies have reported that soils under long-term NT systems can be less susceptible to compaction than plowed soils due to NT-induced increase in SOC concentration (Thomas et al., 1996; Blanco-Canqui et al., 2009). Soil resilience or buffering capacity can increase with increasing years following NT adoption as a result of greater accumulation of SOC (Blanco-Canqui et al., 2009). On a silt loam in Kentucky, Thomas et al. (1996) observed...
that long-term NT management decreased BD\textsubscript{max}, a parameter of soil compactivity, by about 0.20 Mg m\(^{-3}\) compared with plowed soils. The same study reported that BD\textsubscript{max} in soils under NT was as low as that in soils under permanent sod (Thomas et al., 1996). Recently, across four soils in the central Great Plains, Blanco-Canqui et al. (2009) reported that near-surface BD\textsubscript{max} under long-term (between 19 and 43 yr) NT systems was lower than under moldboard plowed and conventionally tilled soils by about 6 to 13%. Not till induced increase in SOC concentration explained 92% of the variability in BD\textsubscript{max} in Kentucky (Thomas et al., 1996) and 62% in the central Great Plains (Blanco-Canqui et al., 2009), showing that soil’s susceptibility to compaction decreased as the NT induced SOC concentration increased. The BD\textsubscript{max} may be sensitive to small changes in SOC concentration (Davidson et al., 1997).

Published studies on BD\textsubscript{max} using the Proctor test in agricultural soils have mostly compared differences between plow till and NT practices (Thomas et al., 1996; Blanco-Canqui et al., 2009) and not much those among cropping systems within the same tillage system. On a loam in Oklahoma, moldboard plow continuous cotton (Gossypium hirsutum L.) had higher BD\textsubscript{max} and lower soil organic matter concentration than soils under lespedeza (Lespedeza striata) disked once annually (Davidson et al., 1967). Some studies have compared BD\textsubscript{max} in cultivated against that in uncultivated soils. Across various soils in Argentina, Quirgera et al. (1999) observed that disked and moldboard plowed soils had greater BD\textsubscript{max} (1.57 Mg m\(^{-3}\)) than uncultivated soils under native vegetation (1.31 Mg m\(^{-3}\)). In the same region, Díaz-Zorita and Grosso (2000) found that BD\textsubscript{max} decreased from cultivated to uncultivated regardless of differences in soil textural class.

Because of increased concerns over compaction in NT soils, it is imperative to assess how continuous cropping systems can influence risks of soil compaction across a range of soils and NT management systems. To date, no study has documented the possible differences in soil compaction risks among long-term NT cropping systems on regional scales. Characterization of BD\textsubscript{max} under cropping systems with different levels of biomass C input is needed for a better understanding of effects and causes of soil compaction. Increased SOC in continuous cropping systems may or may not influence soil structural and hydraulic properties (Benjamin et al., 2008), and its impacts on BD\textsubscript{max} have not been widely researched.

The objectives of this study were to determine differences in BD\textsubscript{max}, CWC, and ρ\textsubscript{b} and the influence of SOC concentration on these compaction parameters for various cropping systems managed under NT in soils in the central Great Plains. Our study hypotheses were that (i) cropping systems differ in their susceptibility to compaction and (ii) changes in SOC concentration due to differential biomass C input by different cropping systems are responsible for changes in BD\textsubscript{max}, CWC, and ρ\textsubscript{b}. This study differs from previous studies in that it compares differences in soil compactivity among long-term cropping systems within the same tillage system (NT). This study also differs from other studies because it compares the relative differences in BD\textsubscript{max} against those of ρ\textsubscript{b}.

**MATERIALS AND METHODS**

**Description of the Study Soils**

This study was conducted across three soils under long-term (>11 yr) cropping systems managed under NT in the central Great Plains. The cropping systems represented common dryland practices in the region. The experiments were at Hays (38°30' N, 99°11'24" W) and Tribune (38°16'48" N, 101°27'36" W), KS; and Akron (40°8'60" N, 103°9' W), CO. These experiments have been in place for 33 yr at Hays, 11 yr at Tribune, and 19 yr at Akron. The soils were Crete silt loam (fine, smectitic, mesic Pachic Argiustolls) in Hays; Richfield silt loam (fine, smectitic, mesic Aridic Argiustoll) in Tribune, and Weld loam (fine, smectitic, mesic Aridic Argiustoll) in Akron. The soils at Tribune and Akron are deep and well drained, while the soil at Hays is also deep but moderately slowly permeable. The soil slope at the three sites is <1%. Average annual precipitation is 580 mm in Hays, 440 mm in Tribune, and 421 mm in Akron.

At Hays, there were five cropping systems (SF, SS, WSF, WF, and WW) arranged in a split-plot RCB design with three replicates under reduced till and NT. Cropping systems were the main plots and the tillage systems were the subplots. Each phase of the rotations was present each year. Main plots were 24.4 by 24.4 m in size and subplots were 12.2 by 24.4 m in size. Each phase of the rotation was present each year. The average precipitation in Hays was 440 mm in Tribune, and 421 mm in Akron.

At Akron, there were five cropping systems (WF, WCF, WCM, and GRASS) under NT were selected within a larger cropping system experiment. This experiment is laid out in a randomized complete block design (RCBD) with three replicates. Further details of all the cropping systems as well as plot management are reported by Anderson et al. (1999) and Benjamin et al. (2008). Each phase of the rotation was present each year. The phases under wheat were used for this study. The plots under GRASS were under perennial grass including smooth brome (Bromus inermis L.) and wheat grass (Agropyron trichophorum (Link) Richt.). Wheat and millet were planted in 0.19 m rows while corn was planted in 0.76 m rows.

**Soil Sampling and Analysis**

Approximately 3 kg of bulk soil was collected from each treatment plot at each site for the 0- to 5-cm and 5- to 15-cm depths in summer 2009 for the determination of BD\textsubscript{max}, CWC, particle-size fractions, and SOC concentration. The samples were air dried at about 20°C for 72 h, gently crushed, and passed through 2-mm sieves for the determination of BD\textsubscript{max} and particle-size fractions. The BD\textsubscript{max} and CWC were determined by the Proctor test (American Society for Testing and Materials, 2007). This test consisted of mixing the soil passed through the 2-mm sieves with different amounts of water between air-dry and near saturation and applying a standardized compactive force with the Proctor hammer. The soil sample was thoroughly mixed with water and compacted in three layers in a 0.10-m diam. and 0.12 m high standard Proctor mold. Twenty-five blows per soil layer were applied using a 2.5-kg Proctor drop hammer falling from a 0.30-m height. The compacted soil in the Proctor mold was carefully trimmed and weighed, and 50 g of the compacted soil was oven dried at 105°C for 24 h.
The gravimetric water content of the subsample was extrapolated to that of the compacted soil, and the Proctor bulk density was computed in Mg m\(^{-3}\) by dividing the oven-dry mass of the compacted soil by the volume of the Proctor mold. The computed bulk densities were plotted against the gravimetric water content to obtain the Proctor compaction curve. A fifth-order polynomial curve was fitted to the data points to determine both the BD\(_{\text{max}}\) and the corresponding CWC for each soil sample. The highest point of the polynomial curve was selected as the BD\(_{\text{max}}\).

At the time of soil sampling for the Proctor test, intact 5- by 5-cm soil cores were collected from the 0- to 5-cm depth and from the center of 5- to 15-cm depth for the determination of BD\(_{\text{max}}\). The BD\(_{\text{max}}\) was determined by the standard method (Grossman and Reinsch, 2002). The sand, silt, and clay content were determined by the hydrometer method using samples passed through 2-mm sieves (Gee and Or, 2002). The particle-size fractions were determined only for the 0- to 5-cm soil depth. The SOC concentration in each sample was determined on air-dry and ground samples passed through 0.25-mm sieves by the dry combustion method (Nelson and Sommers, 1996). The BD\(_{\text{max}}\), CWC, and SOC concentration were determined for the 0- to 5-cm and 5- to 15-cm soil depths. The bulk soil samples and soil cores were collected from the nontrafficked rows at each site.

One-way ANOVA model using the PROC GLM in SAS was used to test whether differences in BD\(_{\text{max}}\), CWC, sand, silt, and clay content, and SOC concentration were significant. To test differences in Proctor bulk density below BD\(_{\text{max}}\), data points for each treatment and replicate were determined from the polynomial curves at selected levels of soil water content. The PROC CORR in SAS was used to establish any relationships among BD\(_{\text{max}}\), CWC, particle-size fractions, and SOC concentration. Statistical differences were reported at the 0.05 probability level unless otherwise indicated. The statistical analysis was conducted using SAS statistical software (SAS Institute, 2009).

**RESULTS AND DISCUSSION**

**Maximum Bulk Density and Critical Water Content**

The Proctor bulk density vs. soil water content curves for the 0- to 5-cm and 5- to 15-cm depth for the three soils are depicted in Fig. 1A through 1F. Mean BD\(_{\text{max}}\) for the two depth intervals for each soil is shown in Fig. 2A-2C. The Proctor bulk density curves show that bulk density among the cropping systems differed at soil water contents below the CWC level of the 0- to 5-cm soil depth. Differences were larger for the silty clay loam (Fig. 1A) and loam (Fig. 1C) than for the silt loam (Fig. 1B). On the silty clay loam, mean Proctor bulk density below the CWC in SF and WF was 5 to 15% greater than in WW and SS, while on the loam, it was about 8% greater in WF and WCF than in WCM and GRASS. On the silt loam, WSSF had greater bulk density than WW by 0.1 Mg m\(^{-3}\) below 0.10 kg kg\(^{-1}\), but there were no differences at greater water contents (Fig. 1B). For the 5- to 15-cm soil depth, differences in Proctor bulk density were not significant (Fig. 1D-1F).

The BD\(_{\text{max}}\) was lower in continuous cropping systems than in systems which included fallow (Fig. 2A-2C). On the silty clay loam, mean BD\(_{\text{max}}\) in SF and WF (1.57 Mg m\(^{-3}\)) was greater than in WW and SS (1.47 Mg m\(^{-3}\)) by 0.1 Mg m\(^{-3}\) (Fig. 2A). On the loam, mean BD\(_{\text{max}}\) in WF was greater than in WCM by 0.24 Mg m\(^{-3}\) and GRASS by 0.11 Mg m\(^{-3}\) (Fig. 2C). The BD\(_{\text{max}}\) in WCF did not differ from that in WCF in the loam. Cropping systems did not influence BD\(_{\text{max}}\) in the silt loam (Fig. 2B). The BD\(_{\text{max}}\) did not differ in the 5- to 15-cm soil depth.

These results show that long-term continuous cropping systems had a significant impact on reducing near-surface maximum compaction (BD\(_{\text{max}}\)). Results also show that the magnitude of changes in near-surface BD\(_{\text{max}}\) among cropping systems depended on soil type and duration of the experiment. The BD\(_{\text{max}}\) in intensively cropped systems was lower than in crop-fallow systems in the silty clay loam and loam but not in the silt loam. In general, data supported our first hypothesis stating that soil's susceptibility to the relative compaction differs with cropping systems.

The small or no changes in Proctor bulk density in the silt loam but larger differences in the silty clay loam and loam might be due to the following reasons. First, the experiment in the silt loam at Tribune (11 yr) has been in place for shorter time period than the experiments at Hays (33 yr) and at Akron (19 yr). Since changes in soil properties in this climate are often detected after long periods of experimentation, we hypothesize that significant differences in BD\(_{\text{max}}\) and SOC concentration in the silt loam may surface in the longer term. Second, cropping systems differed among the three soils. The experiment in the silty clay loam and loam included more contrasting cropping systems (crop-fallow vs. continuous cropping systems) than that in the silt loam with only three systems (WSSF, WSSF, and WW).

Fallow periods occurred every 2 yr for the SF and SS in the silty clay loam and WF in the loam, whereas in the silt loam, they occurred every 4 yr. Thus, the less contrasting differences in cropping systems in the silt loam than in other soils probably reduced differences in soil compactibility due to smaller differences in surface residue cover, biomass C input, and soil properties.

Similar to BD\(_{\text{max}}\), cropping systems also altered CWC in the silty clay loam and loam but not in the silt loam (Fig. 3A-3C). The CWC in the silty clay loam (Fig. 3A) differed only in the 0- to 5-cm depth, but, in the loam, it differed at both depth intervals (Fig. 3C). On the silty clay loam, the CWC in WW and WW was greater than in WW and WSSF by 0.02 kg kg\(^{-1}\) and SS by 0.04 kg kg\(^{-1}\) (Fig. 3A). On the loam, the CWC in WCM was greater than in GRASS by 0.015 kg kg\(^{-1}\) and WF and WCF by 0.05 kg kg\(^{-1}\) in the 0- to 5-cm depth. At the same depth, the CWC in GRASS was greater than in WW and WCF by about 0.04 kg kg\(^{-1}\). For the 5- to 15-cm depth, CWC in WCM and GRASS was greater than in WW and WCF by 0.025 kg kg\(^{-1}\). The BD\(_{\text{max}}\) was very strongly and negatively correlated (r = -0.8; P < 0.001) with CWC in all soils (Fig. 4A-4D). The BD\(_{\text{max}}\) decreased with an increase in CWC. The CWC explained 64% of the variability in BD\(_{\text{max}}\) in the silty clay loam (Fig. 4A), 74% in the silt loam (Fig. 4B), and 75% in the loam (Fig. 4C). Across all soils, CWC explained 88% of the variations in BD\(_{\text{max}}\) (Fig. 4D).

Results of this study showed that the relative maximum soil compaction in continuously cropped systems occurred at greater soil water content than in crop-fallow systems (Fig. 3A-3C). For example, mean CWC increased by about 0.05 kg kg\(^{-1}\) from SF to WW and SS in the silty clay loam (Fig. 3A) and from WF to WCM in the loam (Fig. 3C). Thus, results suggest that soils in continuous cropping systems may be trafficked at greater soil water contents than those in crop-fallow systems without causing excessive compaction. It is also clear from the results that differences in near-surface Proctor
bulk density differed only below the CWC, which indicate that continuous cropping systems can alleviate some of the risks of excessive compaction at low rather than at high soil water contents. Above the CWC, all soils were equally compacted regardless of differences in cropping systems.

Field Bulk Density, Particle-Size Fractions, and Soil Organic Carbon

Cropping systems altered $p_b$ only in the silty clay loam and loam (Fig. 5A-5C). Differences in $p_b$ were similar to those in $BD_{max}$ and CWC. On the silty clay loam, mean $p_b$ averaged...
across SF, WF, WSF, and SS (1.41 Mg m⁻³) was greater than in WW (1.16 Mg m⁻³) by about 22% in the 0- to 5-cm depth. For the 5- to 15-cm depth, there were no statistical differences in \( \rho_b \). On the loam soil, mean \( \rho_b \) averaged across WF and WCF (1.38 Mg m⁻³) was greater than that averaged across WCM and GRASS (1.21 Mg m⁻³) by 14% in the 0- to 5-cm depth. There were no differences in sand, silt, and clay content among the cropping systems at any of the soils (data not shown). Sand content averaged across all cropping systems was 166, 140, 250 g kg⁻¹ at Hays, Tribune, and Akron locations, respectively, while clay content was 370, 400, and 320 g kg⁻¹ at Hays, Tribune, and Akron locations, respectively.

The SOC concentration differed among cropping systems except in the silt loam (Fig. 6A-6C). On the silty clay loam, SOC concentration under WW was 1.5 times greater than the average across WF, WSF, and SS and 2.0 times greater than in SF in the 0- to 5-cm depth (Fig. 6A). For the 5- to 15-cm depth, SOC concentration in WW was greater than in WF and SF by 1.4 times, while that in SS was greater than in SF by 1.5 times. On the loam, SOC concentration under GRASS was greater by 1.4 times while that under WCM was greater by two times than the average across WF and WC in the 0- to 5-cm depth (Fig. 6C). There were no differences in SOC concentration in the 5- to 15-cm depth in the silt loam and loam.

**Relationships between Soil Compaction Parameters and Soil Organic Carbon**

The reduction in BD_max by continuous cropping systems is largely attributed to the near-surface accumulation of SOC. The BD_max was highly and negatively correlated (Fig. 7A-7D) with SOC concentration for the 0- to 15-cm depth in all soils, supporting our second hypothesis. The BD_max decreased in a linear function with an increase in SOC concentration. The BD_max was less strongly correlated with SOC concentration for the silt loam than for the silt loam and for the loam. Changes in SOC concentration explained 28% of the variations in BD_max.
for the silty clay loam (Fig. 7A), 43% for the silt loam (Fig. 7B), and 72% for the loam (Fig. 7C). Across the three soils, changes in SOC concentration explained 71% of the variations in BD$_{\text{max}}$ (Fig. 7D). It is important to note that while the BD$_{\text{max}}$ and SOC concentration among crop rotations did not statistically differ in the silt loam, BD$_{\text{max}}$ significantly decreased with an increase with SOC concentration as a result of lower, although not statistically significant, BD$_{\text{max}}$ (Fig. 2B) and greater SOC concentration (Fig. 6B) in WW than in WWSF and WSSF.

The $p_b$ was also significantly correlated with SOC concentration (Fig. 8A-8D). Similar to BD$_{\text{max}}$, the $p_b$ decreased with an increase in SOC concentration in all soils. Changes in SOC concentration explained 23% of the variations in BD$_{\text{max}}$ for the silty clay loam (Fig. 8A), 39% for the silt loam (Fig. 8B), and 66% for the loam (Fig. 8C). Across the three soils, changes in SOC concentration explained 32% of the variations in BD$_{\text{max}}$ (Fig. 8D). The relationship between $p_b$ and SOC concentration was, however, weaker than that between BD$_{\text{max}}$ and SOC concentration. Across all soils, changes in SOC concentration explained 71% of the variability in BD$_{\text{max}}$ (Fig. 7D), but they explained only 32% of the variability in $p_b$ (Fig. 8D).

The BD$_{\text{max}}$ and $p_b$ were significantly related. Changes in $p_b$ explained about 30% of the variability in BD$_{\text{max}}$.

The increase in CWC was also attributed to an increase in SOC concentration with continuous cropping systems as the CWC was strongly correlated with SOC concentration (Fig. 9D). The CWC increased with an increase in SOC concentration (Fig. 9A-9D), but the magnitude of the relationships varied with soil. Changes in SOC concentration explained 16% of the variability in CWC in the silty clay loam (Fig. 9A), 44% in the silt loam (Fig. 9B), and 45% in the loam (Fig. 9C). Across the three soils, SOC concentration accounted for 65% of the variations in CWC (Fig. 9D). The sand, silt, and clay content were not correlated with BD$_{\text{max}}$, CWC, and SOC concentration in any soil (data not shown).

The reduced soil's susceptibility to compaction and compression with increased SOC concentration is attributed to the following mechanisms induced by soil organic matter (Soane, 1990; Aragón et al., 2000; Ball et al., 2000). First, soil organic matter increases the soil's resistance to deformation by improving the elasticity and rebounding capacity of the soil matrix. Soil organic materials are more elastic and looser than mineral particles. Second, soil organic matter lowers the bulk density of the whole soil by the "dilution effect" as it has a lower bulk and particle density than mineral particles. Third, organic compounds of high molecular weight contribute to the bonding of organic and mineral particles at the contact points inside the macro- and micro-aggregates, improving the resilience against soil consolidation and compaction. Fourth, soil organic matter may alter the electrical charge of organomineral contact points and increase friction between organic and mineral particles, which would reduce consolidation of aggregates.

Results of this study also indicate that the relative maximum compactive force that these soils can resist without being...
Fig. 6. Soil organic C concentration by depth for three soils under (A) wheat-fallow (WF), sorghum-fallow (SF), wheat-sorghum-fallow (WSF), continuous sorghum (SS), and continuous wheat (WW); (B) wheat-sorghum-sorghum-fallow (WSSF), wheat-sorghum-fallow (WWSF), and WW; and (C) wheat-fallow (WF), wheat-corn-fallow (WCF), wheat-corn-millet (WCM), and perennial grass (GRASS).

Soil water content, particle size distribution, and SOC concentration are among the soil factors influencing soil compactibility (Aragón et al., 2000; Ball et al., 2000; Díaz-Zorita and Grosso, 2000). Among these factors, SOC concentration is probably the only factor that can be altered by cropping systems as soil water content changes dynamically with precipitation. Improved management strategies that increase SOC concentration at lower depths and reduce SOC stratification are needed. Growing deep-rooted plant species such as forage grass (Peterson and Westfall, 2004; Benjamin et al., 2007) and manure application (Blanco-Canqui et al., 2005) may be alternatives to

Fig. 7. Relationship between maximum bulk density and soil organic C concentration for three soils (A–C) and across all soils (D) under different cropping systems.

Fig. 8. Relationship between field bulk density and soil organic C concentration for three soils (A–C) and across all soils (D) under different cropping systems.
increase SOC concentration with depth in cultivated soils and offset some of the risks of soil compaction in deeper soil depths. Data for the loam from Akron indicate that growing perennial in cultivated soils increased SOC concentration and reduced risks of soil compaction.

It is important to indicate that the results from this study should be interpreted cautiously. The Proctor test provides information on the relative differences in soil compactibility because it uses homogenized soil samples, which do not fully reflect in situ field conditions. The Proctor bulk density is determined using large and disturbed soil samples, whereas field \( \rho_b \) is determined on small and undisturbed soil cores. These differences in size and disturbance in soil samples may partly explain the relatively weak relationship between \( BD_{\text{max}} \) and \( \rho_b \) (\( r^2 = 0.30; P < 0.001 \)) in our study.

Characterization of relative bulk density using the Proctor test provides nevertheless the following additional information over \( \rho_b \) determinations. First, the Proctor test permits the identification of \( BD_{\text{max}} \) of a soil under a systematic, uniform, and repeatable application of compactive forces, simulating the pressure exerted by field equipment. Second, it permits the determination of the "critical water content" (CWC) for maximum soil compaction so that the soil can be trafficked below this CWC level without causing excessive compaction. Third, it allows the breakdown of soil compaction risks at various soil water contents, simulating the effects of field soil water dynamics on soil compaction. For example, in this study, the Proctor test allowed the determination that continuous cropping systems had greater effect on reducing bulk density at low rather than at high soil water contents. As stated earlier, both \( BD_{\text{max}} \) and \( \rho_b \) decreased linearly with an increase in SOC concentration, but \( BD_{\text{max}} \) was more strongly correlated (Fig. 7D) with SOC concentration than with \( \rho_b \) (Fig. 8D).

**CONCLUSIONS**

This regional study across three contrasting soils in the central Great Plains shows that long-term continuous cropping systems may alleviate some of the risk of excessive near-surface soil compaction over crop-fallow systems in no-till systems. The near-surface maximum bulk density, a parameter of soil compactibility, under continuous cropping systems was significantly lower than under crop-fallow systems in two of the three soils studied. These results indicate that reduction or elimination of fallow periods may reduce some of the risks of soil compaction near the soil surface layers. Continuous cropping systems also increased the soil water content at which a soil can be trafficked without significantly inducing excessive compaction. For the same compactive force, soils under crop-fallow systems become compacted at lower water content than those under continuous cropping systems. Continuous cropping systems increased SOC concentration over crop-fallow systems, and the maximum bulk density decreased and critical water content increased with an increase in SOC concentration. Thus, continuous cropping system induced increase in SOC concentration was primarily responsible for the reduced relative compactibility in these no-till soils. Data suggest that increasing SOC concentration through appropriate management practices such as continuous cropping systems may be potential means for managing compaction within the surface layers.

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