Continuous cropping systems under no-till (NT) systems are 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 for conserving soil and water, improving soil properties, and increasing soil organic carbon (SOC) concentration while improving crop production. Diverse crop rotations and continuous cropping systems return more above- and below-ground 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 macroaggregation, and enhance C accumulation.

The Proctor test is a useful approach to determine soil’s susceptibility to compaction and allows the determination of relative soil bulk density at different soil water contents under standardized compactive forces. The Proctor maximum bulk density is equivalent to the maximum compatibility of a soil. The soil water content at which Proctor maximum bulk density is reached is known as the critical water content. The Proctor test has important agronomic uses, but it has not been widely used for assessing differences in soil compatibility among diverse crop rotations managed under NT.

A recent report in *Agronomy Journal* studied the differences in Proctor maximum bulk density, critical water content, and bulk density and the influence of SOC concentration on these compaction parameters for various cropping systems managed under NT in the central Great Plains. The 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 maximum bulk density, critical water content, and bulk density. This study differs from others in that it compares (i) differences in soil compatibility among long-term cropping systems within the same tillage system (NT) as well as (ii) the relative differences in maximum bulk density against those of bulk density.

This study was conducted across three soils under long-term (>11 years) 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 and Tribune in Kansas and Akron in Colorado. These experiments have been in place for 33 years at Hays, 11 years at Tribune, and 19 years at Akron. The soils were Crete silty clay 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 Tribune.


**Effect of continuous cropping systems on compaction in no-till soils**
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 23 inches in Hays, 17 inches in Tribune, and 16 inches in Akron. At Hays, there were five cropping systems: grain sorghum–fallow (SF), continuous sorghum (SS), wheat–sorghum–fallow (WSF), winter wheat–fallow (WF), and continuous wheat (WW). At Tribune, there were three cropping systems: wheat–sorghum–sorghum–fallow (WSSF), wheat–wheat–sorghum–fallow (WWSF), and WW. At Akron, there were four crop rotations: WF, wheat–corn–fallow (WCF), wheat–corn–millet (WCM), and perennial grass (GRASS).

**Maximum bulk density and critical water content**

Proctor bulk density curves show that bulk density among the cropping systems differed at soil water contents below the critical water content level in a shallow-depth testing area. Differences were larger for the silt clay loam and loam than for the silt loam. On the silty clay loam, mean Proctor bulk density below the critical water content in SF and WF was 5 to 15% greater than in WW and SS. On the loam, mean Proctor bulk density below the critical water content was about 8% greater in WF and WCF than in WCM and GRASS. The silt loam showed that WSSF had greater bulk density than WW, but there were no differences at greater water contents. For deeper soil depths, differences in Proctor bulk density were not significant.

Changes in Proctor bulk density in the silt loam were small or nonexistent, but larger differences in the silt clay loam and loam were found. This might be due to the following reasons: First, the experiment in the silt loam at Tribune has been in place for shorter time period (11 years) than the experiments at Hays (33 years) and Akron (19 years). Since changes in soil properties in this climate are often detected after long periods of experimentation, the researchers hypothesized that significant differences in maximum bulk density 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 (WSF, WWSF, and WW). Fallow periods occurred every two years for WF and SF in the silty clay loam and WF in the loam, whereas in the silt loam, they occurred every four years. Thus, the less contrasting differences in cropping systems in the silt loam than in other soils probably reduced differences in soil compatibility due to smaller differences in surface residue cover, biomass C input, and soil properties.

Similar to maximum bulk density, cropping systems also altered critical water content in the silty clay loam and loam but not in the silt loam. The critical water content in the silty clay loam differed only at the shallow depth (0 to 5 cm), but in the loam, it differed at both depth intervals (0 to 5 cm and 5 to 15 cm). On the silty clay loam, the critical water content in WW and SS was greater than in WF and WSF. On the loam, the critical water content in WCM was greater than in GRASS, WF, and WCF at the shallow depth. At the same depth, the critical water content in GRASS was greater than in WF and WCF. The maximum bulk density was very strongly and negatively correlated (r > −0.8; P < 0.001) with critical water content in all soils and decreased with an increase in critical water content. The critical water content explained 64, 74, and 75% of the variability in the maximum bulk density in the silty clay loam, silt loam, and loam, respectively. Across all soils, the critical water content explained 88% of the variations in maximum bulk density.

The results of this study showed that the relative maximum soil compaction in continuously cropped systems occurred at a greater soil water content than in crop–fallow systems. This suggests that soils in continuously cropped 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 occurred only below the critical water content, which indicates that continuous cropping systems can alleviate some of the risks of excessive compaction at low rather than high soil water contents. Above the critical water content, all soils were equally compacted regardless of differences in cropping systems.

Cropping systems altered bulk density only in the silty clay loam and loam. Differences in bulk density were similar to those of maximum bulk density and critical water content. On the silty clay loam, mean bulk density averaged across SF, WF, WSF, and SS was greater than in WW by about 22% at the shallow depth (0 to 5 cm). At the deeper depth (5 to 15 cm), there were no statistical differences in bulk density. On the loam, mean bulk density averaged across WF and WCF was greater than that averaged across WCM and GRASS by 14% in the shallow depth. There were no differences in sand, silt, and clay content among the cropping systems in any of the soils.

**Relationships between soil compaction parameters and soil organic carbon**

The reduction in maximum bulk density by continuous cropping systems is largely attributed to the near-surface accumulation of SOC. The maximum bulk density was highly and negatively correlated with SOC concentration for the shallow depth in all soils, supporting the second
hypothesis. The maximum bulk density decreased in a linear function with an increase in SOC concentration and was less strongly correlated with SOC concentration for the silty clay loam than for the silt loam and loam. Changes in SOC concentration explained 28, 43, and 72% of the variations in maximum bulk density for the silty clay loam, silt loam, and loam, respectively. Across the three soils, changes in SOC concentration explained 71% of the variations in maximum bulk density. It is important to note that while the maximum bulk density and SOC concentration among crop rotations did not statistically differ in the silt loam, maximum bulk density significantly decreased with an increase in SOC concentration as a result of lower, although not statistically significant, maximum bulk density and greater SOC concentration in WW than in WWSF and WSSF.

The bulk density was also significantly correlated with SOC concentration. Similar to maximum bulk density, the bulk density decreased with an increase in SOC concentration in all soils. Changes in SOC concentration explained 23, 39, and 66% of the variations in maximum bulk density for the silty clay loam, silt loam, and loam, respectively. Across the three soils, changes in SOC concentration explained 32% of the variations in maximum bulk density. The relationship between bulk density and SOC concentration was, however, weaker than that between maximum bulk density and SOC concentration. Across all soils, changes in SOC concentration explained 71% of the variability in maximum bulk density, but they explained only 32% of the variability in bulk density. The maximum bulk density and bulk density were significantly related. Changes in bulk density explained about 30% of the variability in maximum bulk density.

The increase in critical water content was also attributed to an increase in SOC concentration with continuous cropping systems as the critical water content was strongly correlated with SOC concentration. The critical water content increased with an increase in SOC concentration, but the magnitude of the relationships varied with soil. Changes in SOC concentration explained 16, 44, and 45% of the variability in critical water content in the silty clay loam, silt loam, and loam, respectively. Across the three soils, SOC concentration accounted for 65% of the variations in critical water content. The sand, silt, and clay content were not correlated with maximum bulk density, critical water content, and SOC concentration in any soil.

The soil's reduced susceptibility to compaction and compression with increased SOC concentration is attributed to the following mechanisms induced by soil organic matter. 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 microaggregates, 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 compacted depends on the SOC concentration. These results may have large implications because they suggest that near-surface excessive maximum compaction may be somewhat managed by adopting continuous cropping systems, which increase SOC concentration. Crop–fallow systems had lower SOC concentration than continuous cropping systems and thus were more prone to compaction than cropping systems without fallow periods. The confinement of the beneficial impacts of increased SOC concentration on reducing soil compaction to the upper 0- to 5-cm soil depth is attributed to the stratification of the SOC concentration in these NT soils.

Soil water content, particle-size distribution, and SOC concentration are among the soil factors influencing soil compatibility. 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 and manure application may be alternatives to 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 grass in cultivated soils increased SOC concentration and reduced the risks of soil compaction.

It is important that the results from this study should be interpreted cautiously. The Proctor test provides information on the relative differences in soil compatibility 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 bulk density 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 maximum bulk density and bulk density ($r^2 = 0.30; P < 0.001$) in the study.

Characterization of relative bulk density using the Proctor test provides the following additional information over bulk density determinations. First, the Proctor test permits the identification of maximum bulk density 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 for maximum soil compaction so that the soil can be trafficked below this critical water content 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 a greater effect on reducing bulk density at low rather than at high soil water contents. Both maximum bulk density and bulk density decreased linearly with an increase in SOC concentration, but maximum bulk density was more strongly correlated with SOC concentration than with bulk density.

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 under no-till management. The near-surface maximum bulk density, a parameter of soil compatibility, 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 the SOC concentration. The increase in SOC concentration was primarily responsible for the reduced relative compatibility in these no-till soils. The data suggest that increasing the SOC concentration through appropriate management practices such as continuous cropping systems may be a potential way to manage compaction within the surface layers.