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Addition of Cover Crops Enhances No-Till Potential for Improving Soil Physical Properties

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Inclusion of cover crops (CCs) may be a potential strategy to boost no-till performance by improving soil physical properties. To assess this potential, we utilized a winter wheat (*Triticum aestivum* L.)–grain sorghum [*Sorghum bicolor* (L.) Moench] rotation, four N rates, and a hairy vetch (HV; *Vicia villosa* Roth) CC after wheat during the first rotation cycles, which was replaced in subsequent cycles with sunn hemp (SH; *Crotalaria juncea* L.) and late-maturing soybean [LMS; *Glycine max* (L.) Merr.] CCs in no-till on a silt loam. At the end of 15 yr, we studied the cumulative impacts of CCs on soil physical properties and assessed relationships between soil properties and soil organic C (SOC) concentration. Across N rates, SH reduced near-surface bulk density (ρ_b) by 4% and increased cumulative infiltration by three times relative to no-CC plots. Without N application, SH and LMS reduced Proctor maximum ρ_b, a parameter of soil compactibility, by 5%, indicating that soils under CCs may be less susceptible to compaction. Cover crops also increased mean weight diameter of aggregates (MWDA) by 80% in the 0- to 7.5-cm depth. The SOC concentration was 30% greater for SH and 20% greater for LMS than for no-CC plots in the 0- to 7.5-cm depth. The CC-induced increase in SOC concentration was negatively correlated with Proctor maximum ρ_b and positively with MWDA and cumulative infiltration. Overall, addition of CCs to no-till systems improved soil physical properties, and the CC-induced change in SOC concentration was correlated with soil physical properties.

Abbreviations: CC, cover crop; HV, hairy vetch; MWDA, mean weight diameter of aggregates; SH, sunn hemp; LMS, late-maturing soybean; SOC, soil organic carbon.

Cover crops are receiving increased attention for their ability to enhance the multifunctionality of cropping systems, particularly in no-till farming. Specifically, the addition of CCs to no-till systems may be a strategy to enhance the performance of no-till technology. In some soils, the potential of no-till for improving soil properties and increasing the SOC concentration may be limited due to reduced residue input, such as in corn (*Zea mays* L.)–soybean and crop–fallow rotations (Zhu et al., 1989; Peterson and Westfall, 2004) or residue removal for off-farm uses (Karlen et al., 2009). Because CCs provide additional biomass input, the inclusion of CCs in no-till cropping systems can provide additional benefits to protect the soil from water and wind erosion, improve soil physical, chemical, and biological properties, increase SOC concentration, and sustain crop production (Fronning et al., 2008). There is an emerging interest in removing crop residues for cellulosic ethanol production (Karlen et al., 2009; Regalbuto, 2009; Tilman et al., 2009). By adding residues, CCs may ameliorate some of the adverse impacts that crop residue removal may have on soil and water conservation and soil productivity.

The impact of CCs on soil physical properties is inconsistent (Keisling et al., 1994; Dabney et al., 2001; Kaspar et al., 2001; Villamil et al., 2006; Fronning et al., 2008; Mubiru and Coyne, 2009). Some studies have found significant changes in soil physical properties under CCs. On a sandy loam and loam, oat (*Avena sativa* L.), HV, brome (*Bromus inermis* Leyss), and strawberry clover (*Trifolium fragiferum* L.) under conventional tillage reduced soil penetration resistance and increased

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cumulative infiltration after 5 yr of management (Folorunso et al., 1992). On a silt loam and loam, rye (*Secale cereale* L.), HV, and crimson clover (*Trifolium incarnatum* L.) reduced ρ_b and increased the saturated hydraulic conductivity (K_{sat}) and water-holding capacity after 17 yr of management (Keisling et al., 1994). On a silt loam, rye and HV in no-till corn–soybean rotations increased soil aggregate stability, total porosity, and plant-available water, while it reduced ρ_b and penetration resistance, although K_{sat} was unaffected, compared with plots without CCs after 4 yr of management (Villamil et al., 2006).

Other studies have found little or no effects of CCs on soil physical properties. On a sandy loam, HV and winter wheat in no-till corn had no effect on ρ_b, porosity, or K_{sat} after 3 yr of management (Wagger and Denton, 1989). On a loam, rye and oat in no-till soybean did not affect ρ_b and had mixed impacts on water infiltration and soil water content during a 3-yr study (Kaspar et al., 2001). On a sandy loam, rye, HV, and crimson clover under conventional tillage did not affect MWDA after 4 yr of management (Sainju et al., 2003). Similarly, on a loam, red fescue (*Festuca rubra* L.), bird's-foot trefoil (*Lotus corniculatus* L.), and alfalfa (*Medicago sativa* L.) in no-till, after 2 yr of management, had no effects on soil hydraulic conductivity although macroporosity was improved (Carof et al., 2007). After 3 yr, crimson clover and HV increased wet aggregate stability on a sandy clay loam under conventional tillage but had no effects on a clay loam (McVay et al., 1989). The same study showed that HV increased water infiltration in both soils. In a 2-yr study, Mubiru and Coyne (2009) found no differences in ρ_b among four CCs including mucuna [*Mucuna pruriens* (L.) DC. var. *utilis* (Wall. ex Wight) Baker ex Burck], Dolichos lablab (*Lablab vulgaris* Savi, cv. Rongai), canavalia [*Canavalia ensiformis* (L.) DC.], and crotalaria (*Crotalaria paulina* Schrank) when planted into fallow in degraded sandy clay, sandy loam, and loamy sand.

This literature review indicates that the impact of CCs on soil physical properties can be variable. Cover crop impacts may depend on the type of CC, type of soil, tillage and cropping system, management history, and climate. The literature also indicates that most of the previous studies on CCs in relation to soil physical properties were short term (<5 yr). Further assessment of the soil response to no-till CCs under long-term experiments for different soils and climatic conditions is warranted to better understand the impacts of CCs. Specifically, the extent to which the inclusion of SH and LMS in long-term no-till systems alters soil physical properties has not been widely documented (Martins et al., 2009).

The additional input of above- and belowground biomass from CCs can increase the SOC concentration (Keisling et al., 1994; Dabney et al., 2001; Reddy et al., 2003; Sainju et al., 2003; Villamil et al., 2006; Martins et al., 2009). This increase in SOC concentration may improve soil physical properties. Some studies have indicated, however, that CCs may not always increase SOC concentration (Mendes et al., 1999; Fronning et al., 2008; Mubiru and Coyne, 2009). The influence of CCs on soil physical properties may depend on whether CCs increase the SOC concentration. Studies assessing the relationships between soil physical properties and SOC concentration under crop rotations have found mixed results. In the central Great Plains, Benjamin et al. (2008) found that an increase in SOC with diverse crop rotations was poorly correlated with soil physical properties. Similar studies assessing the magnitude of the influence of CC-induced SOC increase on soil physical properties are needed. Thus, the objective of this study was to quantify 15-yr cumulative impacts of no-till CCs on soil physical properties and to study the relationships between CC-induced changes in SOC concentration and the physical properties of an Argiustoll in south-central Kansas. The hypotheses for the study were: (i) CCs would have a significant effect on soil physical and hydraulic properties, and (ii) the CC-induced changes in SOC concentration would be strongly associated with changes in soil physical and hydraulic properties.

MATERIALS AND METHODS

This study was conducted on a long-term experiment of CCs at Hesston, KS, that was established in 1995. The experiment was on a Geary silt loam (a fine-silty, mixed, superactive, mesic Udic Argiustoll) with a <3% slope. This soil is deep and moderately well drained, with some risks of runoff. The mean annual precipitation for the study region is 874 mm and the mean annual temperature is 14.4°C.

The experiment was a randomized complete block design consisting of 12 treatments in quadruplicate resulting from a factorial combination of three treatments of CCs and four N rates. It thus had a total of 48 plots, each 6 by 13.5 m. The treatments were evaluated in a winter wheat–grain sorghum rotation. In all years, wheat was no-till planted into grain sorghum stubble in the fall and harvested in June of the next year. The CC treatments were imposed after wheat, and grain sorghum was planted in June of the following year.

The CC treatments were changed during the course of this long-term experiment, as shown in Table 1. Hairy vetch was used as a winter CC between 1995 and 2000, while two summer CCs, SH and LMS, were used between 2002 and 2008. Between 1995 and 1996, a no-CC rotation was compared with two rotations in which HV was planted in the fall and terminated either early (May) or late (June) using reduced tillage (Table 1). Between 1997 and 2000, the no-CC rotation was compared with two rotations in which HV was terminated either by reduced tillage or by herbicide (no-till).

Beginning in 2002, the two HV rotations or treatments were replaced with two summer CCs, SH and LMS. In other words, LMS and SH were assigned to plots where HV had been grown, and the remaining plots retained the no-CC treatment. The existing factorial arrangement of N rates was also retained, and thus the treatment substitutions were accomplished without changing the number of treatments, plots, or replications. The summer CCs were planted shortly after wheat harvest in summer and terminated in September or October. These plots, as well as the no-CC treatment, were managed under no-till. Wheat under no-till was grown without fertilizer across all plots in the transition year between 2000 and 2002.

The HV was seeded in mid-September or early October in rows spaced at 20 cm. Volunteer wheat and winter annual grasses were controlled in HV with fluazifop-P-butyl [butyl (2*R*)-2-[4-[[5-

Table 1. Description of the management of three cover crop treatments at Hesston, KS.

Year	Cover crop treatment	Seedbed preparation	Seeding rate	Termination date	Termination method
			— kg ha^{-1} —		
1995–1996	1. no cover crop	reduced tillage†			–
	2. hairy vetch terminated early	reduced tillage	17	May	reduced tillage
	3. hairy vetch terminated late	reduced tillage	17	June	reduced tillage
1997–1998	1. no cover crop	reduced tillage			–
	2. hairy vetch terminated by tillage	reduced tillage	22	May	reduced tillage
	3. hairy vetch terminated by herbicide	reduced tillage	22	May	herbicide in no-till
1999–2000	1. no cover crop	reduced tillage			–
	2. hairy vetch terminated by tillage	no-till	28	May	reduced tillage
	3. hairy vetch terminated by herbicide	no-till	28	May	herbicide in no-till
2002–2008	1. no cover crop	no-till			–
	2. late-maturing soybean	no-till	67	Sept. or Oct.	herbicide in no-till
	3. sunn hemp	no-till	11	Sept. or Oct.	herbicide in no-till

† Seedbed preparation for sorghum was the same as that indicated in Column 3 for Treatment 1 and in Column 6 for Treatments 2 and 3.

(trifluoromethyl)-2-pyridinyl]oxy]phenoxy]propanoate]. In no-till HV plots, glyphosate [*N*-(phosphonomethyl)glycine] alone or with 2,4-D [(2,4-dichlorophenoxy) acetic acid] or dicamba (3,6-dichloro-2-methoxybenzoic acid) or both were used to control CCs and weeds between crops. For the summer CCs, LMS and SH were planted in rows spaced at 20 cm and terminated in the fall with a crop roller followed by herbicide application. The SH and LMS were last grown in the summer of 2008 followed by grain sorghum in 2009 (Table 1).

Grain sorghum was planted in the corresponding years at a rate of 103,780 seeds ha^{-1} at 76-cm row spacing. Plots received 18 kg P ha^{-1} as triple superphosphate (0–46–0 N–P_2O_5–K_2O) at sorghum planting. Nitrogen was broadcast before planting (1996–2000) as ammonium nitrate (34–0–0 N–P_2O_5–K_2O)or injected after planting (2003–2009) as urea-ammonium nitrate (28–0–0 N–P_2O_5–K_2O) at 25 cm from the row in the corresponding plots at the rates specified above. Atrazine (6-chloro-*N*-ethyl-*N*′-(1-methylethyl)-1,3,5-triazine-2,4-diamine) plus metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide] provided pre-emergence weed control in grain sorghum. Wheat was planted at a rate of 100 kg ha^{-1} at 20-cm row spacing. Plots received 17 kg P ha^{-1} at wheat planting, and N was broadcast before planting as ammonium nitrate (34–0–0 N–P_2O_5–K_2O) in all years except 2008, when urea (46–0–0 N–P_2O_5–K_2O) was utilized. In this CC experiment, CC aboveground residues were not hayed or removed for off-farm uses. For this study, data on CC residue produced for the last three CC rotation cycles (2004, 2006, and 2008) were analyzed to explain any differences in soil properties among CC treatments. Further information on the CC aboveground residue production for this experiment was discussed by Claassen (2009).

Field measurements and soil sampling were conducted in early spring 2010 in nontrafficked rows. Penetration resistance was measured, in triplicate within the same plot, for the 0- to 4-, 4- to 8-, 8- to 12-, and 12- to 20-cm soil depths by a static hand cone penetrometer (Lowery and Morrison, 2002). The diameter of the cone base was 2 cm and the angle was 30°. Volumetric water content was determined for the same soil depths as for penetration resistance using time domain reflectometry (Field Scout TDR 300 soil moisture meter, Spectrum Technologies, Plainfield, IL; Topp and Ferré, 2002). Because penetration resistance, as expected, was significantly correlated with differences in soil water content among CC treatments, the data on penetration resistance were adjusted to eliminate their dependence on soil water content. Several approaches were studied (Yasin et al., 1993), but the ratio of exponential functions proposed by Busscher et al. (1997) and Busscher and Bauer (2003) fit our data for all treatments. After adjustment, the correlation between penetration resistance and soil water content was not significant. For example, before adjustment, penetration resistance was correlated (r^2 = 0.31, P < 0.01) with water content, but, after adjustment, it was not correlated (r^2 = 0.02, P > 0.10) for the 0- to 4-cm depth. Treatment effects are thus discussed based on the adjusted data. Details on the procedure for the adjustment of the penetration resistance data were given by Blanco-Canqui et al. (2006). It is important to recognize the difficulty, however, in correcting the dependence of penetration resistance on soil water content because, at this point, no universal corrective equation or model exists (Yasin et al., 1993; Busscher et al., 1997; Busscher and Bauer, 2003).

Soil temperature was measured using a digital thermometer in triplicate within each treatment plot at 4-, 8-, 12-, and 20-cm depths between 1200 and 1400 h. Water infiltration was measured using double-ring infiltrometers under constant head for 3 h (Reynolds et al., 2002). The diameter of the inner ring was 15 cm, while the diameter of the outer ring was 27 cm. Earthworms contained in 0.2- by 0.2-m soil blocks excavated with a spade were carefully hand sorted and counted in each plot. Infiltration measurements and earthworm counts were made only for plots receiving 60 kg N ha^{-1} because this rate of N application is typical for the wheat–sorghum rotations in the region.

Bulk and intact soil core (7.5 cm in diameter by 7.5 cm tall) samples were collected from the 0- to 7.5- and 7.5- to 15-cm depths from all the CC and N-rate treatments. Bulk samples were used for the determination of wet aggregate stability, Proctor ρ_b, and SOC concentration, while the intact soil cores were used for the determination of K_{sat}, soil water retention, and ρ_b. Bulk samples were air dried, gently crushed, and passed through 2-, 4.75-, and 8-mm sieves. A fraction of each bulk soil sample was crushed, ground, and passed through a 250-μm sieve to determine the SOC concentration by the dry combustion method (Nelson and Sommers, 1996). Wet aggregate stability was determined by the wet-sieving method for the 4.75- to 8-mm air-dry aggregates (Nimmo and Perkins, 2002). The amount of soil remaining in sieves with 4.75-, 2-, 1-, 0.5-, and 0.25-mm openings was oven dried and used to determine the proportion of water-stable aggregates and compute the

MWDA. Aggregates between 0.25 and 8 mm in diameter were classified as macroaggregates and those <0.25 mm in diameter were classified as microaggregates (Tisdall and Oades, 1982).

The Proctor ρ_b at different levels of soil water content was determined by the Proctor test to assess soil compactibility (American Society for Testing and Materials, 2007). Air-dry soil samples sieved through 2-mm mesh were mixed with water, transferred to the standard Proctor mold, and carefully compacted in three layers with 25 blows per layer using the Proctor drop hammer. The amount of water added to the soil samples in each case varied from air dry to near saturation. The compacted soil in the Proctor mold was trimmed, weighed, and a subsample oven dried to determine the gravimetric water content, which was used to compute the total dry weight of the compacted soil. The Proctor ρ_b for each amount of water added was computed by dividing the dry weights by the Proctor mold volume (in Mg m^{-3}). The Proctor ρ_b was plotted against the gravimetric water content to obtain the compaction curves for each individual sample. A third-order polynomial curve was fitted to the data for determining both the Proctor maximum ρ_b of the soil sample and the corresponding soil water content, known as the Proctor critical water content. The peak of the polynomial curve was selected as the Proctor maximum ρ_b. The Proctor critical water content is the soil water content at which the Proctor ρ_b reaches a maximum value or the Proctor maximum ρ_b. The Proctor tests were performed only for plots receiving 0 and 66 kg N ha^{-1}. Proctor maximum ρ_b will be referred to as ***maximum*** ρ_b and Proctor critical water content as *critical water content*.

The K_{sat} was determined on the intact soil cores by the constant-head method (Reynolds et al., 2002). Following K_{sat} determination, soil cores were resaturated for 24 h, weighed, drained sequentially at matric potentials of 0, −0.5, −1, −3, −6, −10, −30, −100, and −1500 kPa by pressure extractors, and the volumetric water content determined at each pressure head (Dane and Hopmans, 2002). After water retention measurements, ρ_b was determined by the core method (Grossman and Reinsch, 2002).

It is important to restate that, in this experiment, HV was the CC for three crop cycles during the first 6 yr followed by either SH or LMS during the last 6 yr of the experiment. Thus, it is possible that changes in soil properties observed at the end of the 15 yr may not be solely due to the cover cropping of SH and LMS but rather to the cumulative effect of HV plus either SH or LMS because HV was grown in the same plots before SH or LMS. Soil properties were not characterized at the end of the HV phase in 2000; however, any residual effect of HV was expected to be minimal. Wheat was grown across all plots in the transition year between 2000 and 2002, which possibly reduced any residual effect of HV on soil properties. Furthermore, based on other studies, HV may (Folorunso et al., 1992; Keisling et al., 1994; Villamil et al., 2006) or may not (McVay et al., 1989; Wagger and Denton, 1989; Sainju et al., 2003) influence soil properties.

Data Analysis

Differences in soil properties and residue amount among the CC treatments and the N application rates were tested using PROC MIXED in SAS (SAS Institute, 2011). For the analysis of the data on penetration resistance, volumetric water content, soil temperature, wet aggregate stability, ρ_b, Proctor ρ_b, maximum ρ_b, critical water content, K_{sat}, soil water retention, and SOC concentration, the fixed factors were CC treatment, N application level, and soil depth, while the random factors were replicate and its interactions with CC treatment and N application level. For the analysis of the data on cumulative water infiltration, earthworm population, and CC residue amount, the fixed factor was CC treatment and the random factor was replicate. Means among treatments were compared using LSMEANS in PROC MIXED. Before the use of PROC MIXED, the collected data were tested for normality using the Shapiro–Wilk test, and the results showed that the data were normally distributed except the K_{sat} data (SAS Institute, 2011). The K_{sat} values were logarithmically transformed to normalize the data. The PROC CORR procedure in SAS was used to study correlations among the soil properties. Correlations between the soil physical properties and SOC concentration were studied for plots under both 0 kg N ha^{-1} and across the N levels. Correlations at 0 kg N ha^{-1} were performed to assess the independent effects of the CCs on the soil physical properties without any possible confounding effects of N application. Statistical differences were computed at the 0.05 probability level unless otherwise indicated.

RESULTS

Soil Compaction Properties and Their Relationships with Organic Carbon

Cover crops and N rates had no effect on penetration resistance but affected other soil compaction properties. Cover crop × N rate interaction was not significant for any soil property. Mean penetration resistance across N rates was 0.88 ± 0.15 MPa (mean ± SD) for SH, 0.89 ± 0.14 MPa for LMS, and 0.91 ± 0.08 MPa for plots without CCs at the 0- to 7.5-cm depth. Cover crops affected ρ_b in the 0- to 7.5-cm depth, but N rates had no effect. Sunn hemp (1.23 ± 0.05 Mg m^{-3}) reduced ρ_b by about 4%, but LMS (1.24 ± 0.07 Mg m^{-3}) had no effect relative to plots without CCs (1.27 ± 0.06 Mg m^{-3}). Differences in ρ_b between SH and LMS were not significant.

Both CCs and N rates had significant effects on Proctor ρ_b, maximum ρ_b, and critical water content at the 0- to 7.5-cm depth but not at the 7.5- to 15-cm depth (Fig. 1 and 2). Cover crops influenced Proctor ρ_b at 0 kg N ha^{-1} (Fig. 1A) but had no effect at 66 kg N ha^{-1} at any depth (Fig. 1C and 1D). Figure 1A shows that values of Proctor ρ_b below the critical water content under CCs were 4% lower than in plots without CCs. For soil water content at or near saturation, Proctor ρ_b between plots with and without CCs did not differ. At 0 kg N ha^{-1}, maximum ρ_b under SH and LMS was about 5% lower than in plots without CCs (Fig. 2A). Similarly, the critical water content in plots without CCs was 12% lower than under SH and 8% lower than under LMS (Fig. 2B). At 66 kg N ha^{-1}, SH and LMS also tended to reduce the maximum ρ_b (Fig. 2C) and increase the critical water content (Fig. 2D), but differences were not statistically significant. Nitrogen application reduced the maximum ρ_b from 1.65 Mg m^{-3} at 0 kg N ha^{-1} to 1.62 Mg m^{-3} at 66 kg N ha^{-1}, but it had no effect on the critical water content.

Soil compaction parameters were correlated with changes in SOC concentration. Cover crops and N rates affected SOC concentration at the 0- to 7.5-cm depth, but the CC × N rate interaction was not significant. Averaged across N rates, the SOC

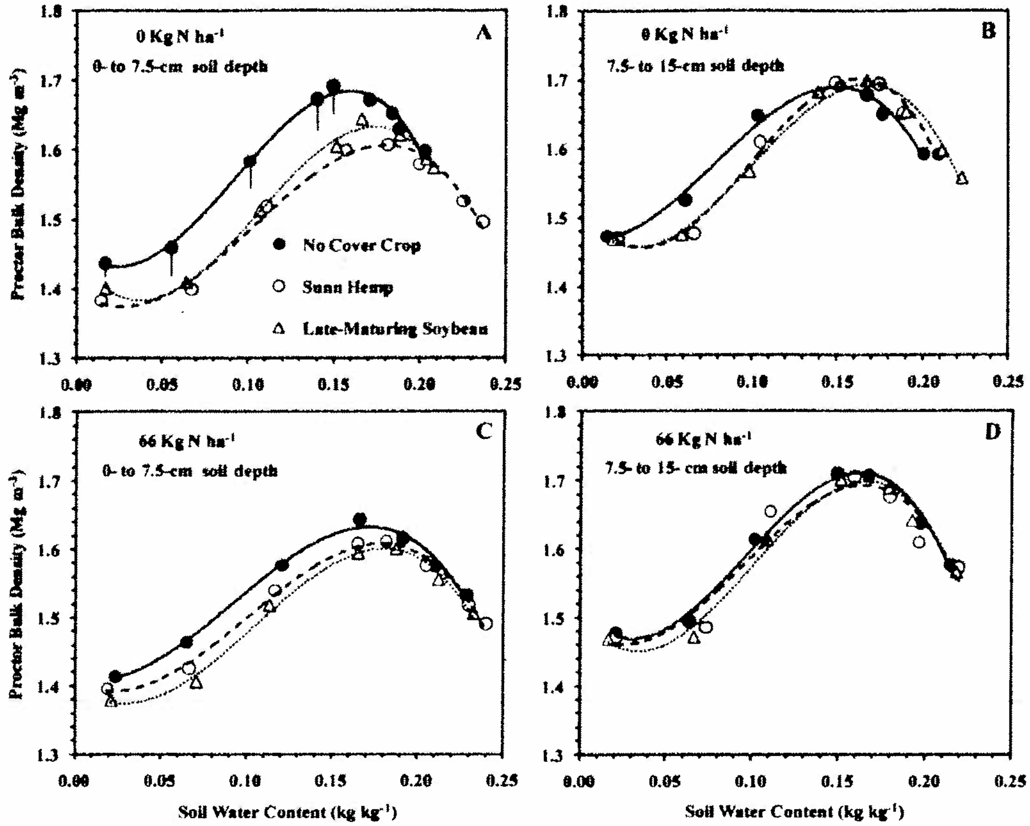

Fig. 1. Mean Proctor bulk density at (A and B) 0 kg N ha^{-1} and (C and D) 66 kg N ha^{-1} for three cover crop treatments at two soil depths. Error bars are LSD values to indicate significant differences among the cover crop treatments. Differences among the three cover crop treatments in B to D were not significant.

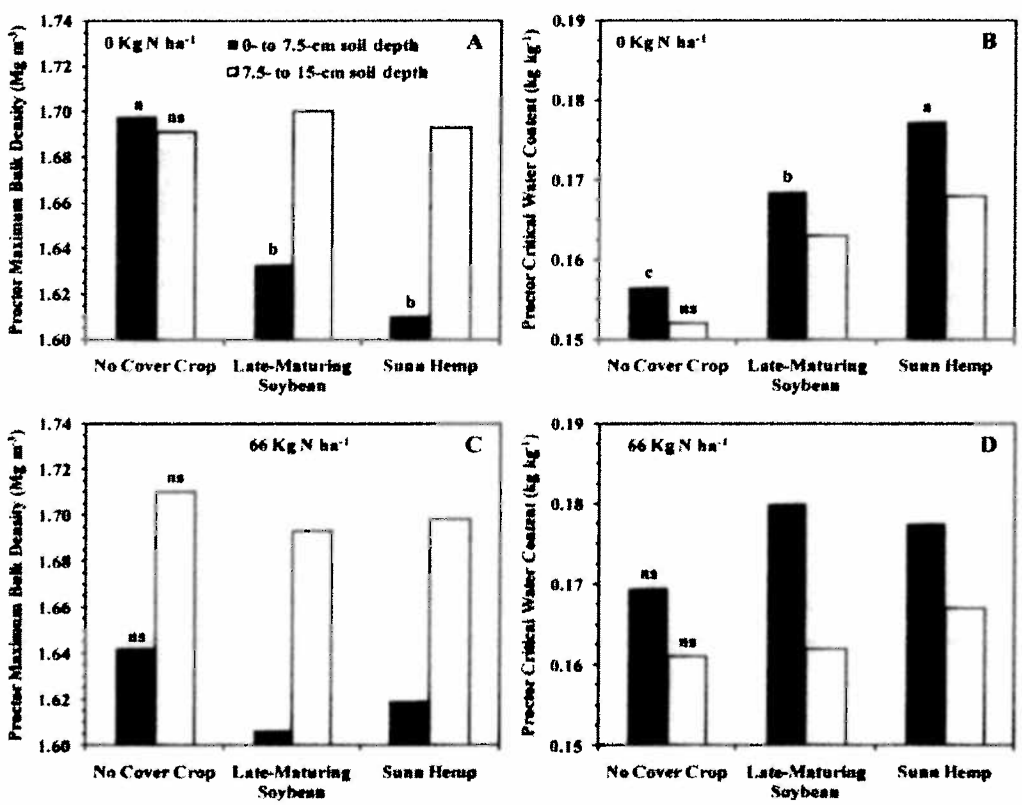

Fig. 2. Mean Proctor maximum bulk density and Proctor critical water content at (A and B) 0 kg N ha^{-1} and (C and D) 66 kg N ha^{-1} under three cover crop treatments at two soil depths. Bars with different lowercase letters within the same soil depth indicate significant differences; ns indicates no significant differences among the three cover crop treatments within the same depth.

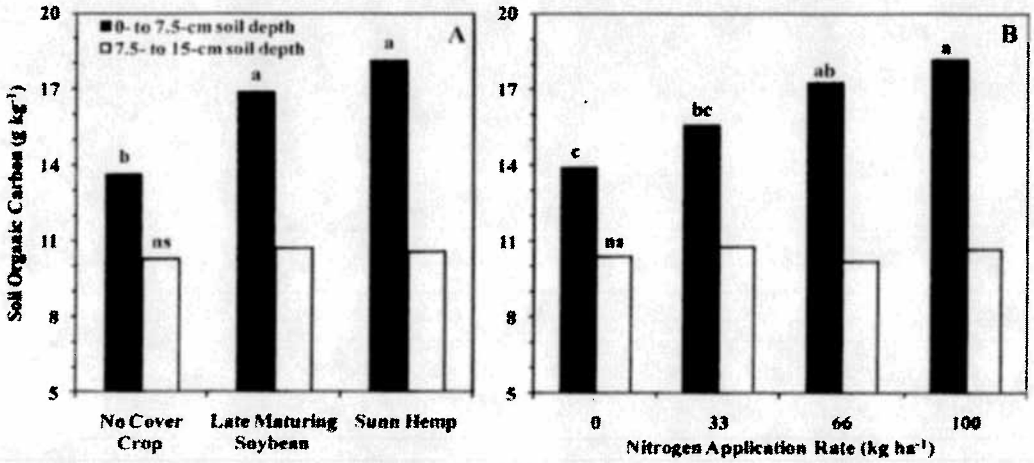

Fig. 3. Mean soil organic C concentration under (A) three cover crop treatments and (B) four N application rates at two soil depths. Means with different lowercase letters within the same soil depth indicate significant differences; ns indicates no significant differences among treatments within the same depth.

concentration was 1.3 times greater under SH and 1.2 times greater under LMS than in plots without CCs for the 0- to 7.5-cm depth (Fig. 3A). At the same depth, averaged across CC treatments, the SOC concentration increased systematically with an increase in the N application rate (Fig. 3B). The SOC concentration increased by 1.3 times, from 0 to 100 kg N ha^{-1} (Fig. 3B). Figure 4A shows that penetration resistance was negatively correlated (r = −0.51) with SOC concentration at the 0 kg N ha^{-1} application rate at the 0.09 probability level, suggesting that an increase in SOC concentration may reduce soil compaction. Across the four N levels, however, penetration resistance was not correlated with SOC concentration (Fig. 4B). While ρ_b was not correlated with SOC concentration at 0 kg N ha^{-1} (Fig. 4C), it was significantly correlated across the four N levels (Fig. 4D), decreasing with an increase in SOC concentration.

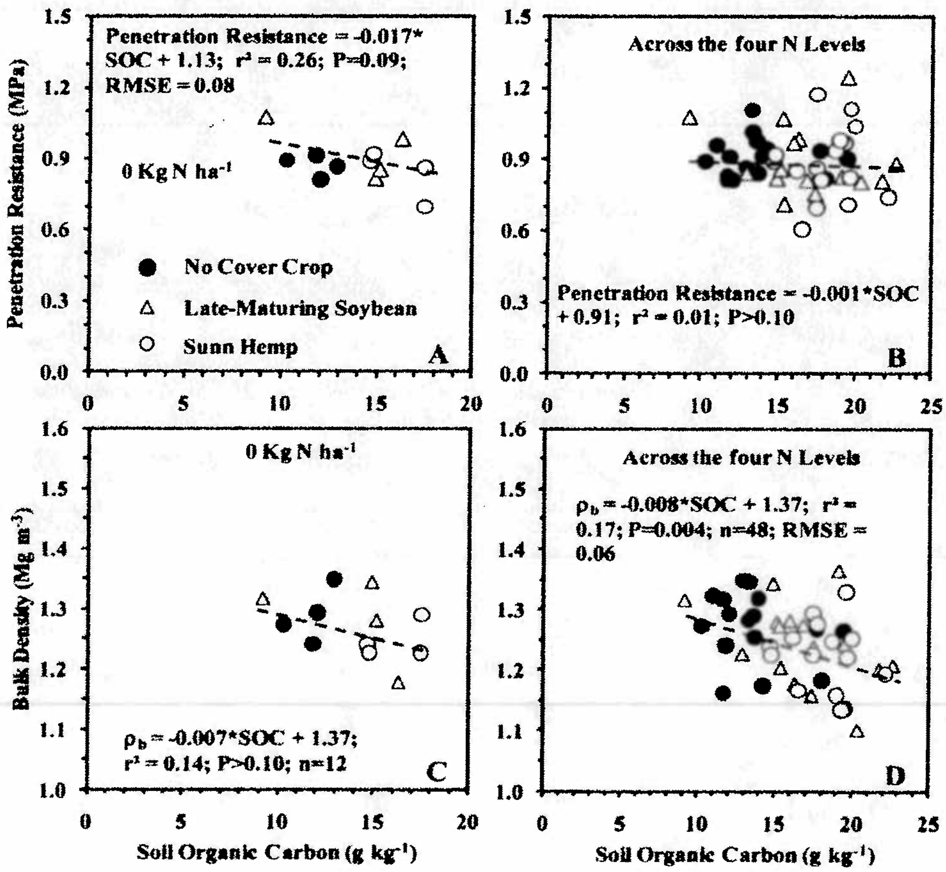

Fig. 4. Relationship of soil organic C (SOC) concentration with (A and B) penetration resistance and (C and D) bulk density (ρ_b) at (A and C) 0 kg N ha^{-1} and (B and D) across four N application rates (0, 33, 66, and 100 kg N ha^{-1}) for the 0- to 7.5-cm soil depth.

Soil compactibility as determined by the Proctor test was more strongly influenced than penetration resistance and ρ_b by the CC-induced increase in SOC concentration regardless of N application level. The maximum ρ_b was negatively correlated with a CC-induced increase in SOC concentration at 0 kg N ha^{-1} ($r = -0.79$; Fig. 5A) and across N levels ($r = -0.77$; Fig. 5B). Similarly, the critical water content was strongly and positively correlated with a CC-induced increase in SOC concentration at 0 kg N ha^{-1} ($r = 0.85$; Fig. 5C) and across N levels ($r = 0.82$; Fig. 5D). The maximum ρ_b decreased whereas the critical water content increased linearly with an increase in SOC concentration.

Aggregate Stability and Its Relationships with Organic Carbon

Cover cropping improved soil aggregate stability (Table 2; Fig. 6), but N rates had no effect on aggregate stability. The CC × depth interaction was significant, indicating that the CC effect on aggregate stability depended on soil depth. For the 0- to 7.5-cm depth, CCs increased the amount of 8- to 4.75-mm aggregates by 3.6 times, 2- to 4.75-mm aggregates by 1.8 times, and 0.25- to 0.5-mm aggregates by 1.3 times over plots without CCs (Table 2). In contrast, the amount of <0.25-mm aggregates in plots without CCs was greater by 1.2 times in the 0- to 7.5-cm depth (Table 2). For the 7.5- to 15-cm depth, LMS increased the amount of 2- to 4.75-mm aggregates by 1.5 times over the other treatments. Cover crops also increased the MWDA by about by 1.8 times in the 0- to 7.5-cm depth (Fig. 6A). For the 7.5- to 15-cm depth, LMS increased the MWDA by about by 1.2 times relative to plots without CCs (Fig. 6A). The increased aggregate stability with CCs agrees with the findings by Villamil et al. (2006) but contrasts with those of McVay et al. (1989) and Sainju et al. (2003), who reported no significant impacts of CCs on aggregate stability. Wet aggregate stability was strongly correlated with changes in the SOC concentration. At 0 kg N ha^{-1}, the MWDA was positively correlated ($r = 0.71$; Fig. 6B) with SOC concentration in the 0- to 7.5-cm but not in the 7.5- to 15-cm depth (data not shown). Across the four N levels, the MWDA was also correlated ($r = 0.40$; Fig. 6C) with SOC concentration.

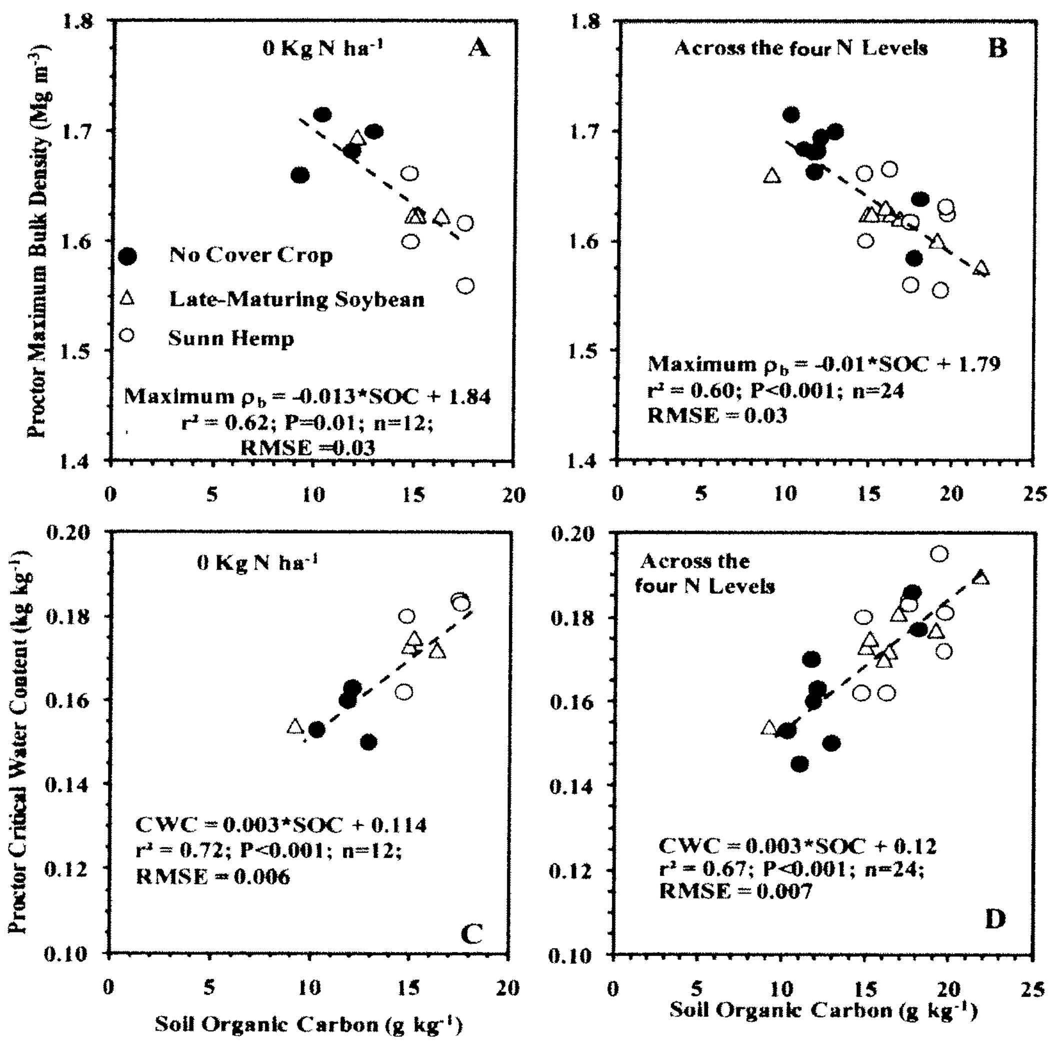

Fig. 5. Relationship of soil organic C (SOC) concentration with maximum bulk density (ρ_b) at (A) 0 kg N ha^{-1} and (B) across four N application rates and the relationship of SOC concentration with critical water content (CWC) at (C) 0 kg N ha^{-1} and (D) across four N application rates for the 0- to 7.5-cm soil depth.

Table 2. Water-stable aggregates for each aggregate size fraction from 8 to <0.25 mm at two soil depths as influenced by cover crop treatment across four levels of N.

Treatment	Water-stable aggregates					
	8–4.75 mm	4.75–2 mm	2–1 mm	1–0.5 mm	0.5–0.25 mm	<0.25 mm
	g kg^{-1}					
		0- to 7.5-cm depth				
No cover crop	15 b†	24 b	37 a	83 a	115 b	728 a
Late-maturing soybean	56 a	44 a	42 a	85 a	138 a	635 b
Sunn hemp	52 a	41 a	46 a	95 a	149 a	612 b
		7.5- to 15-cm depth				
No cover crop	3 a	14 b	39 a	102 a	172 a	670 a
Late-maturing soybean	9 a	24 a	54 a	104 a	170 a	641 a
Sunn hemp	5 a	18 b	42 a	98 a	169 a	670 a

† Means followed by the same lowercase letter within a column and soil depth are not statistically different.

Hydraulic Properties and Their Relationships with Organic Carbon

Sunn hemp increased water infiltration rates and cumulative infiltration by three times relative to no-CC plots (Fig. 7A). The mean (± SD) steady-state water infiltration rate was 4.8 ± 2.5 cm h^{-1} for SH, 3.5 ± 2.0 cm h^{-1} for LMS, and 1.7 ± 1.2 cm h^{-1} for no-CC plots. Differences in steady-state infiltration rates and cumulative infiltration between the LMS and no-CC treatments were not, however, significant. Cumulative infiltration was positively correlated (r = 0.52) with SOC concentration at the 0.07 probability level (Fig. 7B). Steady-state infiltration rates were also correlated (r = 0.50) with SOC concentration at the 0.10 probability level. The increase in water infiltration with SH was related to earthworm population. The number of earthworms, mostly *Lumbricus terrestris* L., was six times greater in SH plots than in plots without CCs (Fig. 8).

The effect of CCs on K_{sat} was not, however, significant. Mean geometric (± SD) K_{sat} for the 0- to 7.5-cm soil depth was 1.58 ± 3.43 mm h^{-1} for plots without CCs, 1.05 ± 1.38 mm h^{-1} for plots under LMS, and 1.35 ± 1.77 mm h^{-1} under SH. Data on K_{sat} within the same treatment were highly variable. The coefficient of variation was 217% for plots with no CCs and 131% for those with CCs. Similarly, there was no significant impact of CCs on soil water retention or plant-available water (data not shown). Correlations of K_{sat}, water retention, and plant-available water with SOC concentration were not significant.

Water Content, Temperature, and Cover Crop Residues

Cover crops affected the field volumetric water content (Fig. 9A) and soil temperature (Fig. 9B). Soil water content was greater under CCs than in plots without CCs by an average of 35% at the 0- to 20-cm depth. Soil temperature during the day was also consistently lower under CCs than in plots without CCs. On the average, CCs reduced the soil temperature during our field measurements in early spring by 4°C at the 5-cm depth, 2°C at 15 cm, and 1°C lower at 30 cm. As expected, the volumetric water content was highly correlated with soil temperature (Fig. 9C). Differences in soil temperature explained about 62% of the variability in water content in the 0- to 15-cm soil depth.

The amount of residue produced between SH and LMS differed significantly. The CC vs. N rate interaction for residues was not significant. Averaged across the three previous rotation cycles and N rates, SH returned more residues than LMS. Sunn hemp produced 7.02 ± 2.2 Mg ha^{-1} of residues while LMS produced 5.32 ± 2.4 Mg ha^{-1}, indicating that SH returned about 32% more residues than LMS.

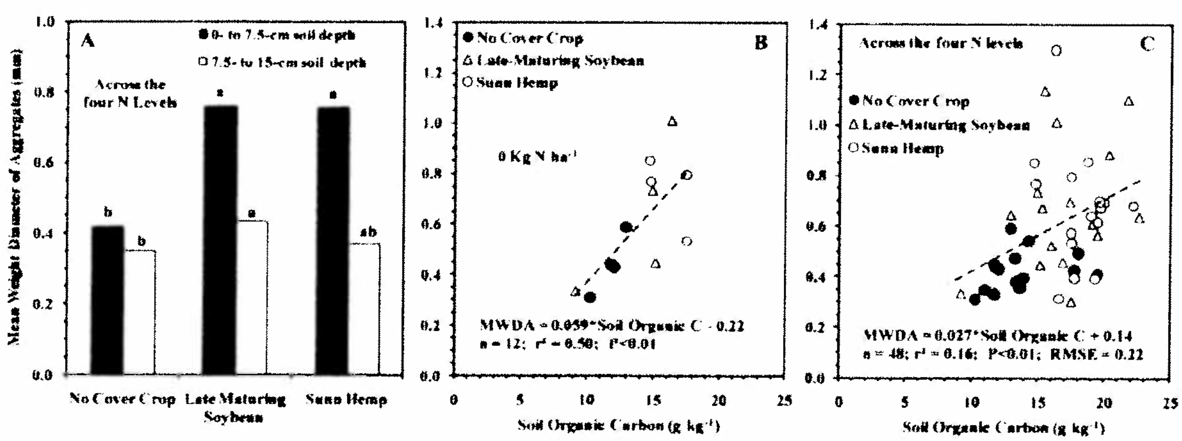

Fig. 6. Mean weight diameter of aggregates (MWDA) (A) under cover crop treatments and its relationships with soil organic C at (B) 0 kg N ha^{-1} and (C) across four N application rates (0, 33, 66, and 100 kg N ha^{-1}) for the 0- to 7.5-cm soil depth. Bars with different lowercase letters within the same soil depth indicate significant differences.

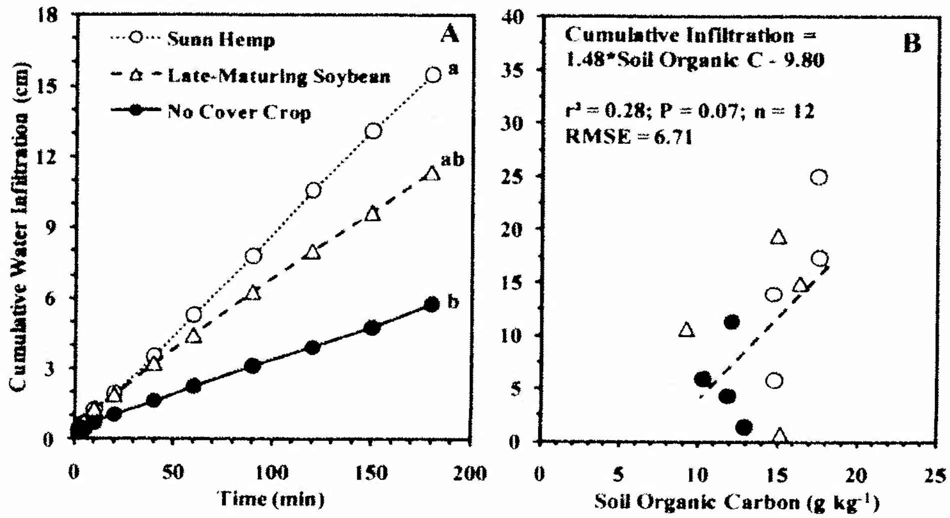

Fig. 7. Cover crop effects on (A) cumulative water infiltration and (B) the relationship between cumulative water infiltration and soil organic C. Means with different lowercase letters indicate significant differences.

DISCUSSION

The lower ρ_b, Proctor ρ_b, and maximum ρ_b, combined with the greater critical water content near the soil surface indicate that CCs reduced the near-surface soil's susceptibility to compaction. Although the application of N appeared to offset the benefits of CCs for reducing the maximum ρ_b (Fig. 1C) and increasing the critical water content at which the maximum ρ_b occurs (Fig. 1D), the results suggest that the addition of CCs to no-till systems may be a strategy to manage the risks of excessive soil compaction near the soil surface. While there were no differences in penetration resistance, the data on ρ_b and Proctor ρ_b suggest that CCs may reduce some risks of soil compaction. The reduced soil compactibility only at and below the critical water content (Fig. 1A) indicates that the beneficial effects of CCs for reducing compaction diminish when the soil is near saturation.

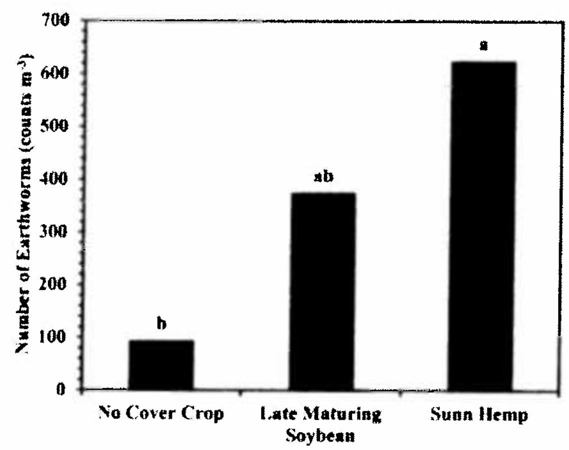

Fig. 8. Cover crop effects on earthworm counts. Means with different lowercase letters indicate significant differences.

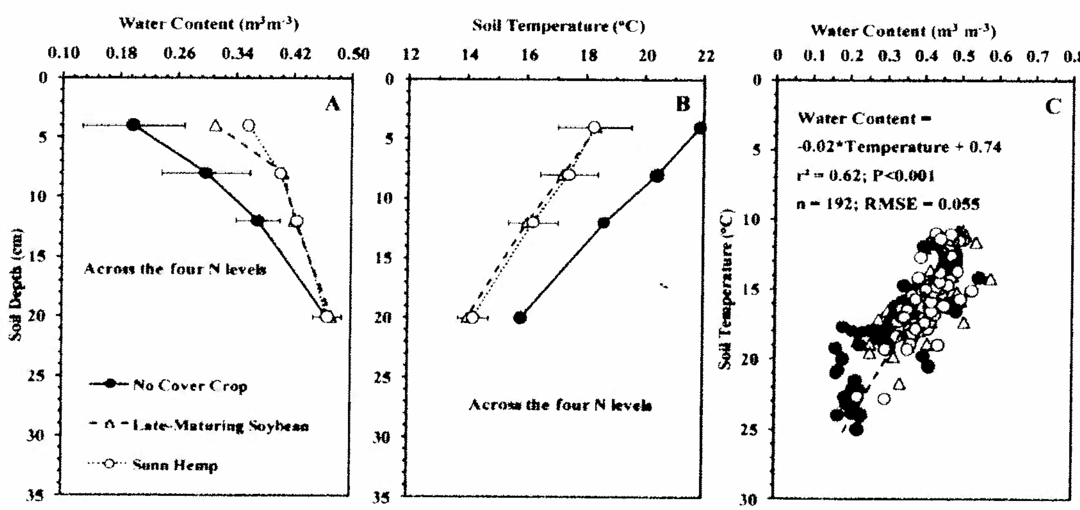

Fig. 9. Cover crop effects on (A) field volumetric water content, (B) soil temperature, and (C) the relationship between field volumetric water content and soil temperature across four N application rates (0, 33, 66, and 100 kg N ha^{-1}) and two soil depths. Error bars are LSD values to compare cover crop treatment differences within the same soil depth. Data on field volumetric water content and soil temperature were collected in late April 2010.

Furthermore, data on the critical water content at which maximum ρ_b occurs (Fig. 2B) suggest that soils under CCs can be trafficked at greater soil water contents without causing compaction than soils without CCs. Increased SOC concentration with CCs was partly responsible for the slight reduction in the soil susceptibility near the surface to compaction under CCs. It is worthwhile to note that while the Proctor ρ_b is determined on disturbed soil samples, it provides important information on the relative differences in maximum or extreme soil compactibility among CC treatments. The Proctor test also allows the determination of the soil water content at which relative extreme soil compaction occurs.

While tillage (Thomas et al., 1996; Díaz-Zorita and Grosso, 2000; Blanco-Canqui et al., 2009) and cropping (Davidson et al., 1967; Blanco-Canqui et al., 2010) system impacts on soil compactibility using the Proctor test have been reported, the specific implications of the use of CCs on soil compactibility have not been studied. Our results, particularly those from the Proctor test (Fig. 1, 2, and 5), suggest that the inclusion of CCs can enhance the potential of no-till systems for reducing soil compactibility. Thomas et al. (1996) and Blanco-Canqui et al. (2009) reported that soil compactibility under no-till soils was lower than under conventionally tilled soils.

Similarly, the near-surface increase in the proportion of macroaggregates and the reduction in the proportion of microaggregates under CCs suggest that addition of CCs to no-till systems can result in reduced soil detachment and erosion, and improved soil structural and water transmission characteristics. The positive correlation between SOC concentration and aggregate stability (Fig. 6C) suggests that SOC has a significant impact on the formation and stabilization of soil aggregates and thus soil structural development. Cover crops not only reduced the risks of excessive soil compaction, improved aggregate stability, and increased the SOC concentration but also increased water infiltration. The significant increase in water infiltration under SH can be important for managing rain or irrigation water in this soil. Figure 7A indicates that only about 6 cm of water would have infiltrated into the soil in 3 h had we not added SH to this no-till soil. Adding SH increased the cumulative water infiltration by about 10 cm. This additional amount of water infiltrated could have been lost as runoff if SH had not been in place. The positive correlation between cumulative infiltration and SOC concentration suggested that SOC improved soil attributes (e.g., soil porosity and aggregation) that affect water infiltration. The abundant earthworms under SH probably developed more water-conducting macropores (e.g., burrows), improving soil structure and increasing water infiltration (Willoughby and Kladivko, 2002).

The lack of significant differences in K_{sat} and the significant differences in steady-state infiltration between SH and plots without CCs may be partly attributed to the differences in soil sample size. Soil cores (7.5 by 7.5 cm) used for the K_{sat} and water retention measurements may be too small, unlike the ring infiltrometers, to overcome the high variability in K_{sat}. Field techniques and the use of large samples may be preferable to detect treatment effects on K_{sat}. Published data on SH and LMS impacts on K_{sat} and water retention are unavailable to compare with the results from this study. Data from other CCs have shown mixed results. The K_{sat} and water retention may (Keisling et al., 1994; Villamil et al., 2006) or may not (Wagger and Denton, 1989; Carof et al., 2007) be affected by CCs, depending on the length of management, CC type, soil type, and climate.

The greater amount of residue returned from SH than from LMS may explain the more beneficial impacts of SH on ρ_b, water infiltration, and earthworm population compared with LMS. Increased residue input under SH probably protected the soil surface better from the direct impact of raindrops, thereby reducing soil consolidation and surface sealing while increasing water infiltration (Kladivko, 1994). The greater number of earthworms under SH relative to LMS may be due to the greater concentration of food and more favorable habitat under SH residues. Late-maturing soybean was, however, just as effective as SH in reducing the maximum ρ_b and soil temperature and increasing the critical water content, wet aggregate stability, SOC concentration, and field volumetric water content. Values of ρ_b, water infiltration, and earthworm population under LMS were intermediate between SH and the no-CC plots.

The greater field volumetric water content and lower soil temperature under both CCs indicate that additional residue input from CCs probably reduced evaporation and maintained soil water content under CCs compared with plots without CCs. The influence of a residue mulch cover on soil water dynamics and soil thermal processes is widely recognized (Kladivko, 1994; Dabney et al., 2001). Residue mulch insulates the soil and buffers the abrupt fluctuations of soil temperature with a magnitude depending on the quantity and quality of the residue left on the soil surface (Kladivko, 1994). The greater water infiltration and field volumetric water content under CCs, particularly SH, indicate that cover cropping influenced soil–water relationships. Cover crops probably impacted soil–water relationships through two opposite processes. Whereas growing CCs used water and reduced soil water storage due to evapotranspiration, residues from the CCs left on the soil surface after termination conserved soil water by reducing evaporation (Dabney, 1998; Joyce et al., 2002; Kahimba et al., 2008; Qi and Helmers, 2010). Growing CCs may have also contributed to water capture by reducing runoff and increasing the opportunity time for rain infiltration (Reicosky and Forcella, 1998). The literature shows that, in regions with relatively high precipitation (>500 mm yr^{-1}), CCs can readily replenish the water consumed during growth by reducing runoff losses and increasing water infiltration (Dabney, 1998; Unger and Vigil, 1998; Joyce et al., 2002). In regions with low precipitation (<500 mm yr^{-1}), however, CCs may reduce the available water for the subsequent crop in spite of increasing water infiltration and improving soil properties (Schlegel and Havlin, 1997; Unger and Vigil, 1998; Reicosky and Forcella, 1998).

The significant improvement of soil physical properties and the increase in SOC concentration in the 0- to 7.5- but not the 7.5- to 15-cm depth is attributed to the accumulation of CC residues on the soil surface, which is typical under no-till conditions. Differences in residue quality may also have contributed to differential impacts of SH and LMS on soil properties. Sunn hemp residues are coarser and heavier than soybean residues and can remain undecomposed for a greater length of time on the soil surface, providing longer soil surface protection. Furthermore, for the same experiment, Claassen (2009) reported that SH residues contained 23.7 g kg^{-1} of N while LMS residues had 31.1 g kg^{-1} of N, suggesting that SH residues may decompose at slower rate than LMS residues due to lower N content.

SUMMARY AND CONCLUSIONS

The addition of CCs enhanced no-till performance by improving near-surface soil physical and hydraulic properties and increasing the SOC concentration in an Argiustoll in south-central Kansas. The findings, in general, supported our hypothesis, which stated that CCs significantly impacted soil physical properties and their relationships with SOC concentration. Across N rates, CCs reduced ρ_b and increased wet aggregate stability and SOC concentration relative to plots without CCs. The effect of the CCs was, however, significant primarily in the 0- to 7.5-cm depth and only slightly in the 7.5- to 15-cm depth. Cover crops reduced the maximum ρ_b and increased the critical water content at 0 kg N ha^{-1} in the 0- to 7.5-cm depth, but they did not affect the Proctor parameters at 66 kg N ha^{-1} for the same soil depth.

Sunn hemp increased water infiltration and the earthworm population, but differences in these parameters between LMS and no-CC plots were not significant. The greater impacts of SH may be attributed to the greater amount of residue produced by SH than by LMS. Both CCs increased the soil water content and reduced the soil temperature during springtime over plots without CCs. The application of N at 0, 33, 66, and 100 kg N ha^{-1} had smaller effects on soil properties than CCs. An increase in the N application rate, however, linearly increased the SOC concentration. A CC-induced increase in SOC concentration reduced penetration resistance, ρ_b, and maximum ρ_b, while it increased aggregate stability and cumulative water infiltration. While the effect of CCs on compaction parameters, wet aggregate stability, and SOC concentration was confined to the 0- to 7.5-cm depth, the SH-induced increase in water infiltration suggests that the whole soil is affected, depending on the CC type.

Results from this study suggest that CCs may ameliorate some risks of excessive near-surface soil compaction and improve soil structure in no-till systems. They also suggest that CCs, particularly SH, may reduce runoff and soil loss by increasing water infiltration. Cover crops may change soil physical properties by increasing the SOC concentration. Cover crops appear to have more beneficial impacts on soil physical properties at 0 kg N ha^{-1} than at higher N rates or when averaged across the four N rates, suggesting that N fertilization may partly diminish the benefits from CCs.

The results from this work after 15 yr of CC management have important implications for the long-term use of cover crops. They suggest that no-till farming should be combined or integrated with CCs to enhance the potential of no-till technology for improving soil physical properties, increasing the earthworm population, and enhancing SOC storage. Cover crops may be particularly beneficial for no-till rotations with limited or no annual biomass input or in systems where crop residues are removed for off-farm uses. More specific research on the contributions of CCs for offsetting the adverse effects of crop residue removal on soil and the environment is warranted. Because, in regions with low precipitation (<500 mm yr^{-1}), growing CCs may reduce plant-available water for the main crops, management strategies, such as early termination of CCs, that minimize reductions in plant-available water should also be further researched.

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