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Corn stover harvest and tillage impacts on near-surface soil physical quality

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ABSTRACT

Excessive harvest of corn (*Zea mays* L.) stover for ethanol production has raised concerns regarding negative consequences on soil physical quality. Our objective was to quantify the impact of two tillage practices and three levels of corn stover harvest on near-surface soil physical quality through the Least Limiting Water Range (LLWR). We evaluated no harvest, moderate and high stover harvest treatments within no-tillage and chisel plow plots following seven years of continuous corn production. Forty undisturbed soil samples were taken from the 0–7.5 cm deep layer within each treatment and used to determine water retention curves, soil resistance to penetration and bulk density values (Bd). No-tillage plots had higher average soil bulk density and resistance to penetration values, and were more affected by stover harvest than chisel plow plots. The results confirmed that soil resistance to penetration determined the lower limit of the LLWR regardless of tillage or stover treatment, whereas soil aeration controlled the upper limit only at Bd > 1.45 and Bd > 1.55 Mg m^{-3} for chisel plow and no-tillage, respectively. The LLWR was smallest for no-tillage with moderate or high corn stover harvest, indicating poor soil physical condition for plant growth, while the largest LLWR occurred with moderate stover harvest and chisel plowing. The introduction of alfalfa (*Medicago sativa* L.) into an extended rotation with no-tillage improved the LLWR by reducing the potential crop growth restriction due to resistance to penetration. Although bulk density values were only occasionally higher than the critical level (Bd = 1.60 Mg m^{-3} for chisel plow and Bd = 1.64 Mg m^{-3} for no-tillage), lower soil structure quality was evident with no-tillage under moderate or high stover harvest and with chisel plowing under high stover removal. The LLWR was more sensitive than available soil water content for detecting tillage and stover harvest effects on soil structural degradation.

1. Introduction

Corn stover has been identified as a potential feedstock for biofuel production because of its high cellulosic content, large volume of production and generally wide availability (Karlen et al., 2011b, 2014) in the USA and other countries around the world. However, as the amount of corn stover left on the soil surface is diminished, organic C inputs are reduced, which over the time can potentially decrease soil organic matter – SOM (Karlen et al., 2011a; Jin et al., 2015) and thus affect soil structure formation and stability (Six et al., 2000). Maintaining a sustainable soil structure should be a prerequisite for harvesting corn stover for biofuel production or any other use.

Adverse effects of excessive corn stover harvest on soil structure and physical quality have been expected and documented by several authors (e.g., Wilhelm et al., 2004; Blanco-Canqui et al., 2007; Blanco-Canqui and Lal, 2007, 2009a). Therefore, the impacts of corn stover harvest and various tillage practices on soil physical quality for crop production should be assessed using properties or processes that can quantify the physical stresses being imposed on crops by various soils (da Silva and Kay, 2004). A multitude of indicators such as soil bulk density, hydraulic conductivity and air permeability, air-filled porosity, aggregates tensile strength, aggregation parameters, soil resistance to penetration and soil

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water availability have been used to quantify soil physical conditions associated with various corn stover harvest and tillage practices (e.g., Blanco-Canqui et al., 2006; Villamil et al., 2015). However, there are many interactions between soil physical properties (e.g., the influence of bulk density and water content on resistance to penetration and aeration), and individually, many of the indicators may not clearly quantify the impacts of management practices on the physical environment for plant growth.

Good soil physical quality means that the soil provides aeration, available water, and has a mechanical resistance that is non-impeditive to root proliferation. Soil is considered a water reservoir for plants and quantification of plant-available water (AW) has been used as an indicator of its physical quality. Despite the AW concept assume that all water is fully and equally available to plants throughout the entire matric potential range (Asgarzadeh et al., 2011), progressive changes in soil water content within this range of matric potentials can also modify other soil physical properties and processes that affect plant growth such as aeration and resistance to penetration. Both soil aeration and resistance to penetration are dynamic soil physical properties that are affected by soil composition, compaction, and water content (Lipiec and Hakansson, 2000).

Crop production may be potentially limited by soil physical conditions that restrict aeration and water availability or increase mechanical resistance to root growth. The Non-Limiting Water Range concept was proposed by Letey (1985), which was improved and redefined by da Silva et al. (1994) as Least Limiting Water Range (LLWR). The LLWR defines a range of soil water content within which root growth is least limited by water availability (water potential), aeration and soil resistance to root penetration. LLWR considers oxygen deficit and impeditive soil resistance to penetration in addition to AW, and is thus becoming a useful soil physical quality indicator for identifying if a specific management practice is improving or degrading potential soil productivity. This indicator has been used to evaluate soil structural and physical quality for plant growth for a wide range of soils, crops and management conditions (Betz et al., 1998; Tormena et al., 1999; Lapen et al., 2004; Mishra et al., 2015). The LLWR combines into a single number non-thermal soil physical properties that directly influence plant growth. Benjamin et al. (2003) suggested LLWR as a useful tool for evaluating soil management effects on potential soil productivity and for helping managers optimize crop growing conditions through their management decisions.

Management practices that widen the LLWR can improve potential crop and soil productivity (Benjamin et al., 2003; da Silva and Kay, 2004). However, LLWR is often narrowed as soil compaction increases (*i.e.*, higher soil bulk density), thus indicating an increased potential for negative impacts of soil physical conditions on root growth (Betz et al., 1998; Benjamin et al., 2013; Benjamin and Karlen, 2014) due to poor aeration at the upper limit or greater soil resistance to root penetration at the lower limit. da Silva and Kay (1997a) reported that as LLWR became smaller, the frequency with which soil water content fell outside the LLWR increased and negatively impacted the corn shoot growth rate (da Silva and Kay, 1996). Benjamin et al. (2003) used LLWR to calculate the Water Stress Day index and reported that restrictive soil physical conditions which reduced corn yield were associated with lower LLWR values. LLWR is reduced with the increasing in bulk density (Bd) and when LLWR = 0 the correspondent Bd value is taken as critical bulk density (Bd_c), meaning that for $Bd \geq Bd_c$ a strongly restrictive Bd for root and plant growth has been reached.

Studies comparing tillage practices have found greater LLWR in tilled than in non-tilled soils (e.g., Betz et al., 1998; Tormena et al., 1999; Kadziene et al., 2011; Guedes Filho et al., 2013; Chen et al., 2014; Mishra et al., 2015). On the other hand, there are few studies that used LLWR to quantify possible stover/residue harvest impacts on soil physical quality (e.g., Benjamin and Karlen, 2014). Blainski et al. (2012) reported that soil water content fell more frequently outside of the LLWR when soil cover by residues had decreased. To date, the LLWR has not been quantified to evaluate the long-term tillage practices and corn stover harvest associate impacts on soil physical quality for crop production in the Midwestern USA. Our objective was to quantify the impact of two tillage practices and three levels of corn stover harvest on near-surface soil physical quality using the LLWR.

2. Materials and methods

This study was carried out at the Iowa State University Agricultural Engineering/Agronomy (AEA) Research farm near Ames, IA (Latitude 42.018°N, Longitude −93.764°W). Three soil series {Canisteo [poorly and very poorly drained Typic Endoaquoll], Clarion [well drained Typic Hapludolls], and Webster [poorly drained Typic Haplaquolls]} are located at the site. The dominant texture ranges from loam to clay loam. The site was being used to compare Chisel Plow (CP) and No-Tillage (NT) practices for corn production in combination with three stover harvest treatments: i) no harvest with all corn stover remaining on the soil surface; ii) moderate harvest with about 50% of corn stover left in the field, and iii) high harvest which removed approximately 90% of the corn stover. Corn was planted in rows spaced 75 cm apart at a population of 84,000 plants ha^{-1}. The study was initiated in 2008 on 12 × 90 m plots with each treatment replicated four times in a randomized complete block design. Due to adverse weather during the fall of 2014, the CP treatment for 2015 was imposed in the spring of 2015 by first chiseling to a depth of 25 cm and then smoothing the seedbed with a field cultivator that performed secondary tillage to a depth of 10 cm just before planting. Also, due to consistently lower corn grain yields, and therefore a lack of interest by stakeholders, the no-tillage, no stover harvest treatment was discontinued in 2013 and replaced by an extended NT rotation that included three years of alfalfa followed by two years of corn with high stover harvest.

Sampling was carried out in May 2015 about 40 days after the CP plots were tilled. Within each plot, 10 undisturbed soil samples were collected in a random manner from tracked and non-tracked areas, thus providing 40 samples per treatment or a total of 240 samples for the site. Each sample was collected to a depth of 7.5 cm using a hammer to drive cores with an inner diameter of 7.2 cm and height of 7.5 cm into the soil. Each core was sealed with a plastic lid and taken to the laboratory. The soil cores were stored under refrigeration at 4 °C until processing. Each sample was prepared by removing excess soil, so that the volume would be exactly that of the core, and then saturated over a period of 48 h by gradually raising the water level in a tray up to approximately two thirds the height of each core.

The soil water retention curve and soil resistance to penetration were determined according procedures suggested by da Silva et al. (1994). For each treatment, the soil cores were divided into 10 groups of 4 cores corresponding to the soil water retention measurements at the matric potentials of −4, −6, −8, −10, −30, −50, −70, −100, −500 and −1500 kPa. The soil water retention curve (WRC) was determined using an adaptation of the evaporation method (Schindler and Müller, 2006). Saturated samples were subsequently dried in a room with a controlled temperature of 22 °C while measuring water potential (Ψ) and water content (θ) continuously. The Ψ was determined using T5-X tensiometers (UMS GmbH München, 2009) for the range $0 > \Psi \geq -100$ kPa, while the $\Psi < -100$ kPa was determined using a pressure plate apparatus (Dane and Hopmans, 2002). The tensiometer had porous 0.5 cm in diameter ceramic cup that was 0.6 cm in length and had a 6 cm acrylic glass shaft that was connected to a datalogger. To determine Ψ with tensiometers, one reading was obtained within each sample at a depth of 3.75 cm. A reading of soil water potential was taken when variation of Ψ was at most ±0.1 kPa per minute. The drying time for soil samples at each water potential were previously determined using samples collected from the same site. All measured water potentials were very close to the pre-determined values, but small adjustments (*i.e.*, additional drying or wetting) were made for samples with high soil bulk density values. Immediately after determining Ψ, the samples were weighed to determine soil water content and soil resistance to penetration was measured using a manual digital penetrometer according to Guedes Filho et al. (2013). The cores were then oven dried at 105 °C for 48 h to determine the volumetric water content (θ) and bulk density (Bd) according to Grossman and Reinsch (2002). For the −500 and −1500 kPa determinations, samples were passed through a 2 mm sieve and then placed in small rubber cores on the ceramic plates and placed into the chamber. After equilibration, gravimetric soil water content was measured and the volumetric water content was calculated using soil bulk density of the same samples.

The soil water retention curve was determined as the relationship between volumetric water content (θ) and matric potential (ψ) as described by Ross et al. (1991) using the procedure outlined by da Silva et al. (1994) and summarized in equation 1:

$$\theta = a\Psi^{b} \quad (1)$$

or alternatively

$$\ln \theta = \ln a + b \ln\Psi \quad (2)$$

where θ is the soil water content ($m^3 m^{-3}$); ψ is the soil water potential (kPa) and a and b are model-fitting parameters. The Bd, tillage and stover harvest effects on the model parameters were evaluated following the procedure described by da Silva and Kay (1997b) using SAS software. Tillage and stover harvest were included as indicator variables according to da Silva et al. (1994).

The soil resistance to penetration (SRP) data were regressed against Bd ($Mg\ m^{-3}$) and soil water content (θ) using the model proposed by Busscher (1990) to obtain a soil resistance to penetration curve as described in the equation 3:

$$SRP = cBd^{d}\theta^{e} \quad (3)$$

or alternatively

$$\ln SRP = \ln c + d \ln Bd + e \ln\theta \quad (4)$$

where c, d and e are constants; Bd is the bulk density ($Mg\ m^{-3}$); and SRP is the soil resistance to penetration (MPa). The influence of tillage and stover harvest on SRP was assessed according to da Silva et al. (1994).

The LLWR was computed using the procedure outlined by da Silva et al. (1994). For soil water content at field capacity (θ_{fc}), we define Ψ = −10 kPa based on the findings of Asgarzadeh et al. (2011). Through the concept of integral energy ("energy for plants to take up a unit mass of soil water over a defined water content range") they found there was large amount of water retained between −10 to −33 kPa that could be easily taken up by plants than at $\Psi \leq -33$ kPa. Therefore, the upper limit was defined by soil water content at field capacity (θ_{fc}) taking Ψ = −10 kPa or by the soil water content at air-filled porosity (θ_{afp}) of 10% or 0.10 $m^3 m^{-3}$ according to Grable and Siemer (1968), whichever is smaller. For each sample, θ_{afp} was calculated as described by the equation 5:

$$\theta_{afp} = [(1 - Bd/2.65) - 0.1] \quad (5)$$

where Bd is the soil bulk density ($Mg\ m^{-3}$) and 2.65 $Mg\ m^{-3}$ is the assumed value for particle density.

The lower limit was defined by the soil water content at the permanent wilting point (θ_{pwp}) at Ψ = −1500 kPa (Savage et al., 1996) or by the soil water content where soil resistance to root penetration reached 2.5 MPa (θ_{srp}), whichever is higher. In a comprehensive review, Bengough and Mullins (1990) reported that root growth may be reduced by 50% at SRP between 2.0 and 3.0 MPa and stops if SRP is equal or higher than 3.0 MPa. Despite a critical SRP = 2.0 MPa has been used to calculate θ_{SRP}, the results from Taylor et al. (1966) showed that root growth stopped when SRP reached 2.5 MPa. Then, we choose a critical SRP = 2.5 MPa.

For each sample, the LLWR was estimated from water content at the critical limits of θ_{fc}, θ_{pwp} and θ_{srp} using equations fitted for soil water retention curve and soil resistance to penetration curve while θ_{afp} was easily estimated using the equation 5. According to Wu et al. (2003), the LLWR can be estimate through the following options:

If $\theta_{afp} \geq \theta_{fc}$ and $\theta_{SRP} \leq \theta_{pwp}$ then LLWR = $\theta_{fc} - \theta_{pwp}$
If $\theta_{afp} \geq \theta_{fc}$ and $\theta_{SRP} \geq \theta_{pwp}$ then LLWR = $\theta_{fc} - \theta_{SRP}$
If $\theta_{afp} \leq \theta_{fc}$ and $\theta_{SRP} \leq \theta_{pwp}$ then LLWR = $\theta_{afp} - \theta_{pwp}$
If $\theta_{afp} \leq \theta_{fc}$ and $\theta_{SRP} \geq \theta_{pwp}$ then LLWR = $\theta_{afp} - \theta_{SRP}$

All statistical analyses were performed using Statistical Analysis System – SAS v.9.3 statistical package (SAS Inc., Cary, USA). The effects of stover harvest and tillage as well as their interactions on Bd, AW and LLWR were evaluated by Proc Anova procedure and means comparison were done through Tukey's test at the $p < 0.05$. The adjustments of equation for soil water retention curve and soil resistance to penetration curve were carried out using the Proc GLM procedure ($p < 0.05$) available in SAS.

3. Results and discussion

The average bulk density (Bd) values for both tillage practices and corn stover harvesting treatments are presented in Table 1. A significant interaction between corn stover harvest and the tillage practice was identified. Our results indicate that regardless of corn stover harvest, no-tillage had higher Bd than chisel plow (Table 1). Soil bulk density was impacted more by tillage practice than stover harvest as previously reported by Moebius-Clune et al. (2008). Lower Bd with chisel plowing is attributed to annual loosening of the soil surface, whereas higher Bd with no-tillage reflects the absence of soil mechanical fracturing as suggested by Singh and Malhi (2006), Guedes Filho et al. (2013) and Villamil et al. (2015). However, our results disagree with those published by Lal (1999) and Blanco-Canqui et al. (2004) who found no significant Bd differences between no-tillage and chisel plow treatments under long-term continuous corn in Ohio and Missouri, respectively.

The cropping system change (planting alfalfa) that was made to the original no-tillage x no-harvest plots in 2014 had an immediate impact on Bd as evidenced by lower values than for either the moderate or high harvest, no-tillage treatments (Table 1).

Table 1
Average values of soil bulk density ($Mg\ m^{-3}$) for two tillage practices and three corn stover harvest levels after seven years (2008–2014).

Tillage system	Corn stover harvest levels		
	No-harvest	Moderate	High
No-tillage	1.30 B a[*]	1.42 A a	1.40 A a
Chisel Plow	1.27 A b	1.19 B b	1.31 A b

[*] Average values followed by the same lower case letter within each stover harvest level and by capital letter within each tillage practice are not significantly different at $p < 0.05$ level.

Nevertheless, it worth mentioning that Bd decreases can be also associated to chiseling operation (down to 10 cm depth) performed before alfalfa sowing. Negative effects of corn stover harvest on Bd under no-tillage were also reported by Blanco-Canqui et al. (2006, 2007), who consistently found lower structural stability and consequently an increased susceptibility to compaction. However, other studies have reported no effects of stover harvest on Bd (Karlen et al., 1994, 2011b; Villamil et al., 2015). We hypothesize that leaving corn stover on the soil surface reduced Bd through a combination of effects including protection against soil compression by machinery wheel traffic as verified by Braida et al. (2006), reduced axel load associated with machinery used for alfalfa production, and perhaps preservation of active organic carbon fractions involved in stabilizing soil aggregates resulted in lower average Bd values for the no-tillage treatment.

Within the chisel plow treatments, Bd was significantly lower with moderate corn stover harvest than either no- or high-harvest rates (Table 1). We suggest that soil fracturing by the chisel plow was more effective within moderate stover harvest compared to no-harvest, whereas the high-rate of stover harvest favored soil compaction as suggested Blanco-Canqui et al. (2006). It is also important to note that soil samples for this study were collected about 40 days after tillage, so the soil was still unstable and subject to temporal changes in Bd that should be much smaller at the end of the cropping season.

An analysis of variance indicated that soil resistance to penetration (SRP) data were also influenced by tillage practice and corn stover harvest rate. The average values (Table 2) show that SRP was significantly higher in no-tillage compared to chisel plow ($p = 0.0120$) treatments and under no-harvest than for the high harvest level ($p = 0.0181$). Interaction effects between tillage and stover harvest treatments were non-significant.

Many studies have reported higher soil resistance to penetration under no-tillage compared to tilled practices (e.g., Cornish and Lymbery, 1987; Leão et al., 2014; Gao et al., 2016). Higher Bd in no-tillage (Table 1) leads to higher SRP, while soil disruption with chisel plowing breaks soil aggregates thus decreasing SRP. As the amount of stover harvest increased, SRP values increased steadily from 1.55 to 2.16 MPa, but due to variability in the data, only the no- and high-harvest treatments were statistically different at $p < 0.05$ (Table 2). These results are not consistent with those of Karlen et al. (1994) or Moebius-Clune et al. (2008) who did not find any detectable, adverse effects of stover harvest on SRP. However, Blanco-Canqui et al. (2007) reported that SRP increased as stover harvest rates increased. Furthermore, in this study the higher SRP values under no-tillage and with stover harvest are consistent with results found for Bd measurements (Table 1).

Data from this study were used to calculate a soil water retention curve for the site that explained 82% of the variation and was influenced by tillage and Bd (Table 3). The most probable effects of stover harvest on soil water retention (*i.e.*, a decrease as harvest increased because of reduced C input) may have been indirectly incorporated into the equation through changes in Bd. There was a significant interaction between tillage practice and Bd, indicating that retention characteristics varied with tillage practice. Soil water content consistently showed a negative correlation with Ψ but was positively correlated with Bd in chisel plow treatments and negatively correlated with Bd in no-tillage treatments (Table 3, Eqs. (5) and (6)). The resultant equations for soil water retention curve that were subsequently used to estimate field capacity and wilting point for no-tillage and chisel plow treatments are as follows:

$$\text{No-tillage} - \theta = e^{(-1.3767 - 0.2298 * \text{Bd})}\ \Psi^{-0.1274} \quad (5)$$

$$\text{Chisel Plow} - \theta = e^{(-2.0587 + 0.3067 * \text{Bd})}\ \Psi^{-0.1274} \quad (6)$$

With chisel plowing, the positive Bd effect on soil water retention was due to a reduction in the volume of large water conducting macropores and an increase in capillary pores due to a redistribution of pore sizes. This created a soil structure that holds water more tightly than in macropores (da Silva et al., 1994; Tormena et al., 1999). As larger pores decrease in diameter, they become active in water retention, especially at high water potentials. Similar results were found by Betz et al. (1998) in a clay loam in Minnesota and Guedes Filho et al. (2013) in a silt loam soil in Kansas. Other studies have documented positive effects of soil Bd on soil water retention for different soils and management systems (da Silva et al., 1994; Guedes Filho et al., 2013; Silva et al., 2015). Within no-tillage plots at this site, the volume of large capillary pores was probably reduced as Bd increased, thus resulting in decreased soil water retention. These results are consistent with those of Chen et al. (2014) who reported negative effects of Bd on soil water retention in plots previously submitted a different soil compaction levels.

The SPR curve was significantly influenced only by tillage practice (Table 3). Soil resistance to penetration was negatively correlated with soil water content (θ) and positively correlated with Bd for both tillage practices as reported in other studies (da Silva et al., 1994; Betz et al., 1998; Leão et al., 2006; Chen et al., 2014; Silva et al., 2015). The increase in SRP with Bd could be attributed to higher friction between particles and/or aggregates associated with the higher effective stress resulting of soil

Table 2
Average soil penetration resistance values (MPa) for two tillage practices and three corn stover harvest treatmentsafter seven years (2008–2014).

Tillage system	
No-tillage	2.08 A*
Chisel Plow	1.64 B
Corn stover harvest levels	
No-harvest	1.55 b
Moderate	1.87 ba
High	2.16 a

* Average values followed by the same letter are not significantly different at $p < 0.05$ level.

Table 3
Multiple regression results for soil water retention curve and soil resistance to penetration curve. Indicator variable – No-tillage = 0 and Chisel Plow = 1.

Soil Water Retention Curve – F = 247.55, $r^2 = 0.82$
$\text{Ln}\theta = (a_0 + a_1{*}\text{Bd} + a_2{*}\text{tillage} + a_3{*}\text{Bd}{*}\text{tillage}) + (b_0{*}\text{Ln}\Psi)$

Parameter	Estimate	Standard Error	T value	P > t
a_0	−1.377	0.128	−10.77	<0.0001
a_1	−0.229	0.093	−2.46	0.0145
a_2	−0.6826	0.160	−4.26	<0.0001
a_3	0.536	0.120	4.47	<0.0001
b_0	−0.127	0.004	−31.33	<0.0001

Soil Resistance to Penetration Curve – F = 161.87, $r^2 = 0.78$
$\text{LnSRP} = (c_0 + c_1{*}\text{tillage}) + (d0 + d1{*}\text{tillage})\ln\text{Bd} + (e0 + e1{*}\text{tillage}){*}\ln\theta$

Parameter	Estimate	Standard Error	T value	P > t
c_0	−3.162	0.225	−14.05	<0.0001
c_1	−1.348	0.346	−3.90	0.0001
d_0	1.933	0.402	4.82	<0.0001
d_1	1.892	0.502	3.77	0.0002
e_0	−2.459	0.157	−15.66	<0.0001
e_1	−0.536	0.259	−2.06	0.0402

compaction. Decreased SRP with θ is a consequence of a reduction in cohesion and angle of internal friction. The adjusted equations which explained 78% of variability in SRP and the SRP curves for no-tillage and chisel plow are as follows:

$$\text{No-tillage} - \text{RP} = 0.0423\,\text{Bd}^{1.9339}\,\theta^{-2.4596} \quad (7)$$

$$\text{Chisel Plow} - \text{RP} = 0.0109\,\text{Bd}^{3.8256}\,\theta^{-2.9955} \quad (8)$$

After adjusting these equations using the soil water retention and SRP curves, the restrictive soil aeration limit as well as the upper and lower limits of LLWR [*i.e.*, soil water content at field capacity (θ_{FC}) and permanent wilting point (θ_{WP}), soil water content at the critical resistance to penetration (θ_{SR}) and water content at air-filed porosity of 10% (θ_{AFP})] were calculated for each sample. The soil water content at the critical limits of soil physical properties for tillage practices and corn stover harvest are shown in Fig. 1.

For both tillage practices, Bd had a greater impact on field capacity than wilting point, indicating that soil structure affects soil water retention more at elevated potentials. The available water content (AW = θ_{FC}-θ_{WP}) varied positively with Bd in chisel plow treatments and negatively in no-tillage treatments. As reported by other studies (da Silva et al., 1994; Tormena et al.,

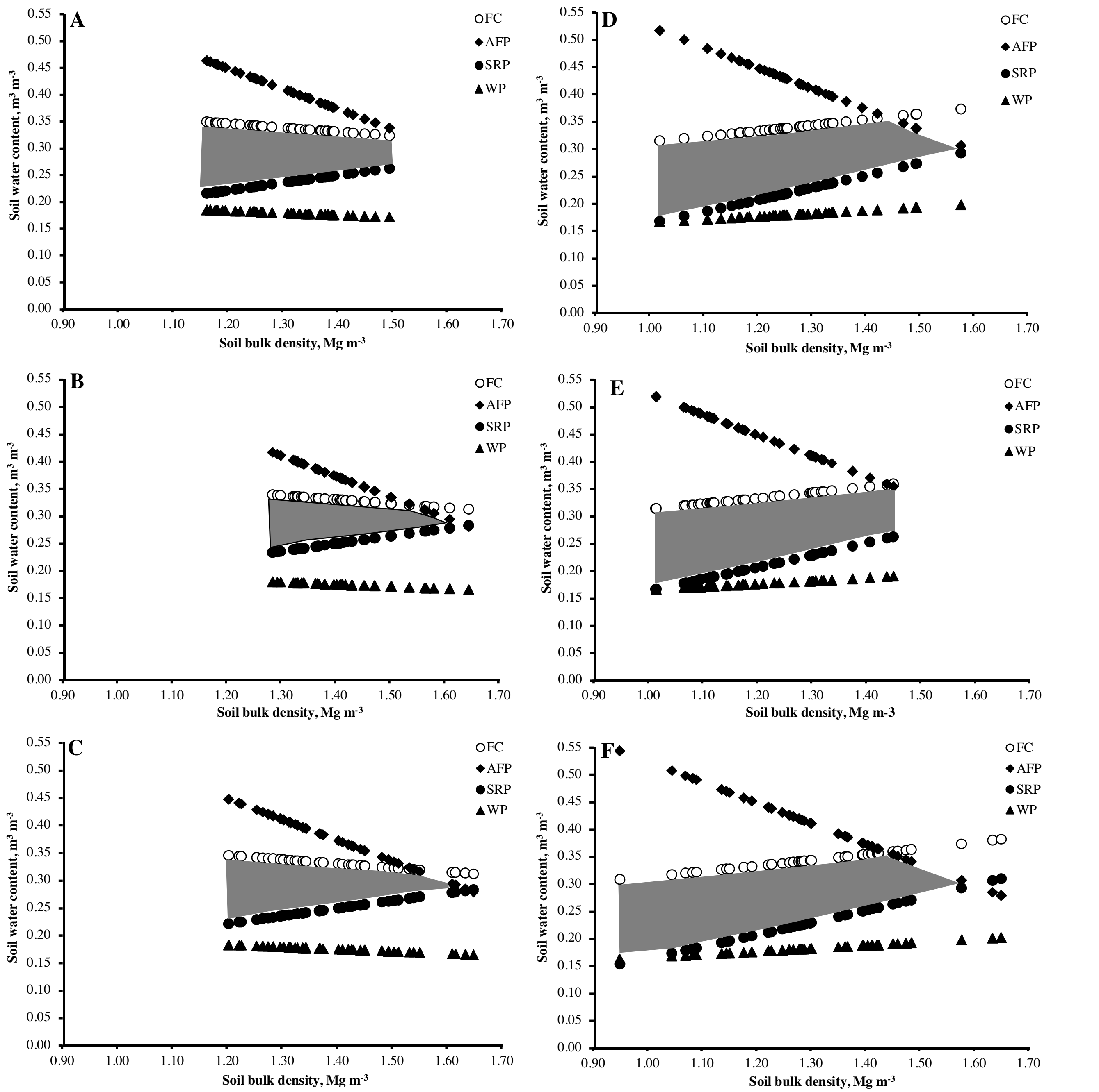

Fig. 1. Soil water content variation with bulk density at field capacity (FC), at the permanent wilting point (WP) and at the critical levels of air-filled porosity (AFP) and soil penetration resistance (SRP) for no-tillage under no-harvest + alfalfa (A), moderate (B) and high stover harvest (C) and chisel plow under no-harvest (D), moderate (E) and high stover harvest (F). The shaded area represents the least limiting water range.

1999) θ_{SRP} and θ_{afp} were more severely affected by soil compaction than θ_{fc} and θ_{wp}. Increased Bd increased θ_{SRP} but decreased θ_{AFP} for both tillage practices and all three stover management scenarios (Fig. 1).

Increased soil compaction (*i.e.*, >Bd) often occurs at the expense of macropores, which means that more water is required to keep the SPR below its critical limit, and additional drying is needed to maintain a functional threshold of air-filled pores. Overall, the results in this study were consistent with those reported in the literature. An air-filled porosity of 10% had little influence on the LLWR and θ_{afp} replaced θ_{fc} only at the end of Bd range. These results, however, are in contrast with those obtained for a clay loam soil by Lapen et al. (2004), who reported that air-filled porosity frequently reached values considered to be limiting for appropriate aeration and plant growth. Air-filled porosity is a very dynamic physical property, but in general, degraded soils require more time to reach the 10% air-filled porosity after soil saturation (Verma and Sharma, 2008) than soils in good health.

For no-tillage and chisel plow treatments, θ_{afp} replaced θ_{fc} in Bd values of 1.55 and 1.45 Mg m^{-3}, respectively. These differences reflect the contrasting effects of increased Bd on water retention within both tillage practices (see Eqs. (5) and (6)). We also calculated field estimates of air-filled porosity (AFP = total porosity-θ) for each undisturbed sample considering the soil water content measured at sampling and total porosity estimated using Bd and particle density. The relationships between air-filled porosity and Bd showed a steeper slope in samples from the chisel plow treatment (slope = −0.4601) than from the no-tillage treatment (slope = −0.3999). This was expected due to enhanced soil water retention with Bd, justifying the lower Bd value in which θ_{afp} replaced θ_{fc}. Among the no-tillage samples, only five from the moderate and high stover harvest treatments had Bd values greater than 1.55 Mg m^{-3} (Fig. 1b and c). However, for the alfalfa plots which had been a no-tillage, no-harvest treatment from 2008 through 2013, the LLWR upper limit (Fig. 1a) suggested that alfalfa was having a positive effect on soil structure as reported by Mueller et al. (2009). Within the chisel plow, high-harvest treatment, LLWR was negatively impacted by θ_{afp} in seven of the forty samples, while for the moderate and no-harvest treatments, $\theta_{afp} < \theta_{fc}$ occurred in only one and four samples, respectively. Our results thus confirm that within the 0–7.5 cm soil layer, the upper LLWR limit was often determined by θ_{fc} and suggest that soil aeration was a serious physical limitation for plant growth only at Bd values >1.45 and 1.55 Mg m^{-3} for chisel plow and no-tillage treatments, respectively. Similar results were found by Guedes Filho et al. (2013) within the surface 0–5 cm layer of a silt loam under different tillage and cropping systems in Kansas, USA. Assuming that 10% air-filled porosity as the minimum value required for the diffusion of oxygen to roots, in no-tillage practice, a Bd = 1.55 Mg m^{-3} can be taken as a limit for monitoring soil compaction and impaired soil physical conditions related to restrictive aeration at the field capacity in soils at this location. As stated previously, soil structure in soils from the chisel plow treatments was still undergoing reconsolidation which may modify the pore size distribution and therefore the Bd value where θ_{afp} crosses θ_{fc}.

As expected, θ_{SRP} increased as Bd increased and was thus caused a narrowing of the LLWR in all treatments (Fig. 1a–f). Only one sample (Bd = 0.95 Mg m^{-3}) from a chisel plow, high-harvest treatment had θ_{wp} as the lower limit of the LLWR (Fig. 1f). These results are consistent with others studies confirming that θ_{SRP} often replaces θ_{WP} as the lower limit of LLWR within different soils, climate regimes, and management systems (da Silva et al., 1994; Betz et al., 1998; Tormena et al., 1999; Mishra et al., 2015). In this study, SRP appears to be the most important physical limitation to root growth and water uptake within 0–7.5 cm soil layer. In order to keep SRP = 2.50 MPa, an increasing in Bd requires higher soil water

Table 4
Average values of soil available water (AW, $m^3\,m^{-3}$), least limiting water range (LLWR, $m^3\,m^{-3}$) and of ratio LLWR/AW for tillage practices and corn harvest stover levels.

Tillage	Corn stover harvest levels		
	No-harvest	Moderate	High
Available water ($m^3\,m^{-3}$)			
No-tillage	0.159 A a*	0.155 B a	0.155 B b
Chisel Plow	0.159 A a	0.156 B a	0.162 A a
Least limiting water range ($m^3\,m^{-3}$)			
No-tillage	0.102 A b	0.075 B b	0.079 B b
Chisel Plow	0.114 AB b	0.126 A a	0.107 B a
Ratio LLWR/AW (%)			
No-tillage	64	48	51
Chisel Plow	72	81	66

* Means followed by the same lower case letter within each stover harvest level and capital letter within each tillage system are not significantly different at $p < 0.05$ level.

content in no-tillage than in chisel plow, which is clearly shown in Fig. 1. Therefore, higher soil compaction observed in no-tillage had a more significant negative impact on LLWR and soil physical quality than with chisel plowing (Fig. 1a–f and Table 4). The Bd value at which the upper limit is crossed by the lower limit (*i.e.* Bd_c in which LLWR = 0) was Bd ≥ 1.64 Mg m^{-3} for no-tillage (Fig. 1b and c) and Bd ≥ 1.60 for chisel plowing (Fig. 1f). Our results reveal that, despite the very low frequency of Bd > Bd_c, lower soil physical quality was reached in no-tillage under moderate and high stover harvest and with chisel plowing at the high rate of stover harvest.

The LLWR was negatively influenced by Bd regardless of tillage practice and stover harvest rate (Fig. 1). With no-tillage, LLWR varied from 0 to 0.1334 $m^3\,m^{-3}$ whereas with chisel plowing, LLWR ranged from 0 to 0.1474 $m^3\,m^{-3}$. For stover harvest levels, within no-tillage LLWR ranged from 0.0610–0.1334, 0–0.1080 and 0-0,1246 $m^3\,m^{-3}$ while within chisel plow treatments, LLWR ranged from 0.0140–0.1469, 0.0916–0.1474 and 0–1448 $m^3\,m^{-3}$, respectively for the alfalfa transition, moderate and high stover harvest treatments. A significant interaction between corn stover harvest levels and tillage system was verified for both AW and LLWR. Average values of AW and LLWR in tillage practices and corn stover harvest levels are presented in Table 4. We also calculated a ratio between LLWR and AW to demonstrate the impacts of tillage and corn stover harvest on available water that would be effectively taken by crops. According to Verma and Sharma (2008), a higher ratio LLWR/AW supported better soil physical condition for wheat (*Triticum aestivum*) yield.

The results confirm that LLWR was more sensitive to tillage and stover harvest treatments than AW due to SRP impacts on soil water availability (Table 4). Despite the statistical differences between tillage practices and corn stover harvest rates, AW was minimally affected by the treatments and the differences have little practical significance. However, Siczek et al. (2015) showed that mulched soils had less negative matric potential compared to non-mulched, improving soil water availability to plants. We emphasize that the no-tillage alfalfa transition and chisel plow, no-harvest treatment had exactly the same amount of soil available water (Table 4). The no-tillage, alfalfa transition treatment had a 25% higher LLWR than treatments with corn stover harvest, suggesting that transition to an extended alfalfa-based crop rotation could be crucial for improving near surface soil physical quality in no-tillage plots. The LLWR/AW ratio shows that removing corn stover reduced the LLWR by about 50% with no-tillage and by as much as 34% (1–0.66) with chisel plowing (Table 4). This was probably driven by soil compaction which can have a strong negative impact on soil physical quality. These results are consistent with those reported by others (e.g., Blanco-Canqui et al., 2006; Blanco-Canqui and Lal, 2008, 2009a,b; Laird and

Chang, 2013) with regard to stover harvest effects on soil physical quality. The average LLWR values suggest better soil physical quality under chisel plow than no-tillage, but the smaller LLWR and the higher frequency of $Bd > Bd_c$ with chisel plowing and high stover harvest, indicate that the soil structure is exposed to degradation processes that may culminate in loss of soil functionality and resilience.

The sensitively of LLWR is affected by the critical limits of the soil physical properties used for it calculation (da Silva et al., 1994). This is important because those properties are dependent on soil, crop and management practices (Reichert et al., 2009). No-till soils are characterized by continuous macropores built by plant roots and macrofauna activity, which are preserved due to absence of tillage. Macropores are important as they can be used as alternative routes for root growth by succeeding crops. Tormena et al. (1999) reported that the presence of biopores in no-tillage makes the LLWR more sensitive than in tilled soils. In our study, a critical SRP = 2.5 MPa was indistinctly used for both tillage practices and the LLWR was more negatively impacted by SRP in no-tillage than in chisel plow treatments (Fig. 1). However, Ehlers et al. (1983) suggested a higher value of limiting SRP for no-till soils because macropores offer greater opportunities for deeper root growth, thus bypassing zones of high SRP. Hakansson and Lipiec (2000) also argued that due to preferential root growth into macropores, the critical limits of soil compaction should be increased. Therefore, based on Ehlers et al. (1983) report for the root growth of oats (*Avena sativa* L.), we recalculated the LLWR using SRP = 4.9 MPa as the critical limit for no-tillage and SRP = 3.6 as the critical limit for chisel plowing (Fig. 2).

Fig. 2 suggest that plants grown under no-tillage practices may take advantage of more effective bioporosity, enlarging the LLWR and improving the soil physical quality in comparison with tilled soils. These results are consistent with those of Chen et al. (2014) who reported higher LLWR in plots with tap-rooted cover crops such as forage radish (*Raphanus sativus*) and rapeseed (*Brassica napus*). We emphasize that using crop rotations with deep-rooted plant species such as alfalfa may also penetrate dense layers, thus providing relief from soil compaction and improving soil physical quality (Chen and Weil, 2010; Kadziene et al., 2011). Increasing SOM also has a significant impact on LLWR as shown by Benjamin and Karlen (2014). This generally occurs due to positive impacts enlarging θ at the upper limits and reducing θ at the lower limits. Other studies that emphasize the importance of SOM for LLWR include those reported by da Silva et al. (1994), da Silva and Kay (1997b) and Verma and Sharma (2008).

A soil with wide LLWR values would be desirable since even with spatial and temporal θ variability, the probability of the θ falling outside the LLWR is low, as verified by da Silva and Kay (1997a) that reported that θ more often felt outside the LLWR when it got narrowed. Thus, better soil physical conditions to plant growth is expected with chisel plowing and moderate stover harvest (Fig. 1e) and from the no-tillage treatment being transitioned into an extended alfalfa-corn rotation (Fig. 1a). Soil resistance to penetration was the major cause for decreasing LLWR for both tillage practices and all three corn stover harvest rates. Our data also suggest that the near-surface soil physical quality was, comparatively, more degraded with stover harvest in no-tillage than in chisel plow. The smallest LLWR in the no-tillage treatment with stover harvest indicates poor soil physical conditions for plant growth that can be associated with the absence of soil protection, higher susceptibility to compaction (Blanco-Canqui et al., 2006) and persistence of soil compaction due to cumulative wheel traffic events and the absence of soil disturbance.

Although to date, axel load and wheel traffic intensity have not been documented for this research site, we recognize that corn stover harvest operations impose additional stress and compactive forces on soils within the field. Therefore, a judicious, site-specific stover management plan should to be developed to prevent excessive compaction and soil physical quality degradation. The positive impact of a single year of alfalfa growth on the LLWR suggests that using tap-rooted cover crops or extended, alfalfa-based crop rotations may be more important than previously thought in order to recover soil physical quality while keeping all other advantages associated with the adoption of no-tillage practices. A wider LLWR has been closely associated with soil physical quality and structural conditions that provide an early arrival of limiting air-filled porosity and late arrival of limiting SPR after draining a saturated soil. Our results confirm that LLWR is an

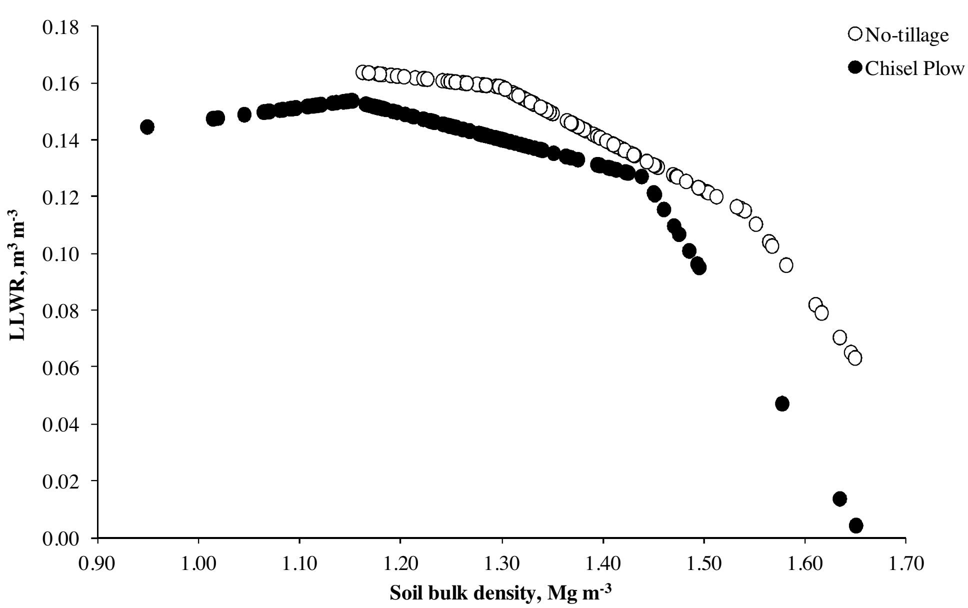

Fig. 2. Least limit water range variation using different critical limits of penetration resistance for no-tillage (SRP = 4.9 MPa) and chisel plow (SRP = 3.6 MPa) according to Ehlers et al. (1983).

effective index of soil physical quality for quantifying the combined effects of alternate tillage practices and corn stover harvest strategies. We suggest that additional research is needed to evaluate the potential impacts of corn stover harvest on soil physical quality in deeper layers, since the reduced C inputs may increase a soil's compaction susceptibility, especially since machinery loads are generally increasing and causing compressive forces to be transferred to layers that are deeper than we sampled in this study.

4. Summary and conclusions

Soil physical quality was affected by tillage practice and corn stover harvest strategy. No-tillage plots had higher soil bulk density and resistance to penetration than chisel plow plots. The no-tillage treatments were also more affected by stover harvest than chisel plow sites. The LLWR was more sensitive than available water and better able to detect soil structural changes induced by the tillage and stover harvest treatments. Within the 0–7.5 cm layer, soil aeration was a limiting physical factor at the upper end of the bulk density range. Soil resistance to penetration was also identified as a major cause for decreasing LLWR, suggesting that it imposes physical restrictions to root growth at lower soil water contents. Chisel plow treatments had higher LLWR values than no-tillage treatments. The LLWR was smallest in no-tillage under moderate and high corn stover harvest, indicating poor soil physical condition for plant growth. Moderate stover harvest in chisel plow resulted in the largest LLWR. The introduction of alfalfa in no-tillage improved the LLWR and reduced the potential restriction of penetration resistance to crop growth. Despite the very low frequency of Bd > Bdc, lower soil structural quality was identified in no-tillage plots with moderate and high stover harvest rates and in chisel plow treatments with high harvest levels. Collectively, the results suggest that soil structural degradation was primarily related to soil compaction as the level of stover harvest increased. Soil and crop management practices that alleviate or prevent soil compaction will presumably have a key role for improving or maintaining soil physical quality for sustained stover harvest for biofuel production.

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