Quantitative soil profile-scale assessment of the sustainability of long-term maize residue and tillage management

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Abstract

Both surface and subsoil layers can be a significant source of soil moisture and nutrients for crop growth, but the changes in subsoil properties due to management are rarely assessed. This study was conducted to determine tillage and residue management effects on soil nutrient availability, as well as soil biological and physical conditions throughout soil layers ranging from 0-60 cm. We utilized an experiment with 40-year long continuous maize (*Zea mays* L.) cropping under crossed plow-till (PT) vs. no-till (NT) and residue removed (Harv) vs. residue returned (Ret) treatments on a silt loam soil in Chazy, NY. We assessed soil properties that are indicative of soil processes important for crop growth. Soil physical indicators (texture, bulk density (BD), water stable aggregation (WSA), available water capacity (AWC), and air-filled porosity (AFP)), soil biological indicators (soil organic matter (SOM), permanganate oxidizable carbon, mineralizable carbon, and soil protein), and soil chemical indicators (pH and plant available nutrients) were measured at five depth increments (0-6, 6-18, 18-30, 30-45, and 45- to 60-cm depth). A novel statistical approach of marginal R^2 (R^2m) was used to show percent variance of each measured soil indicator explained by tillage and residue management as well as the depth of soil sample. R^2m was higher for soil biological indicators ($0.66 < R^2m < 0.91$), compared to AWC and those nutrients that are not applied through fertilizer application ($0.11 < R^2m < 0.53$). NT-Ret showed the highest concentration of majority of the measured soil nutrients, and higher accumulation of SOM related properties across depths. This was partly explained by favorable soil physical conditions indicated by BD, WSA, and AFP at the transition layer (18- to 30-cm depth) that allowed for the vertical exchange of soil water, nutrients, and SOM related properties between the topsoil and the subsoil layers. The PT treatments showed the absence of SOM

transfer across the transition layer, whereas NT-Harv showed nutrient depletion at the transition and subsoil layers. This study revealed significant alteration of soil biological, chemical, and physical indicators depending on the treatment combinations, which can be ignored if surface sampling is solely used. Benefits of residue return appears more significant when combined with no-till for 1) providing better soil physical conditions and 2) maintaining adequate nutrient availability across a soil profile especially when considering subsoil properties.

Keywords

Crop residue, Maize, Soil Health, Subsoil, Tillage

1. Introduction

The health of soils impacts their ability to perform critical functions, including the support of crop growth. In rainfed agriculture, limited or excessive amounts of soil moisture during critical growth stages are important regulators for yield levels and yield stability (Calviño et al., 2003), and subsoil layers (> 30 cm depth) have been identified as an important source of soil moisture (Ewing et al., 1991; Gaiser et al., 2012; Kirkegaard et al., 2007) and nutrients (Carter and Gregorich, 2010; Gransee and Merbach, 2000; Heming, 2004). Distinct soil microbial communities may also be present in subsoil layers compared to surface layers due to unique nutrient dynamics, soil physical properties, and redox potential (Fischer et al., 2013; Leininger et al., 2006), and can be a sink for a large amount of soil organic carbon (SOC; Batjes, 1996). However, limited attention has been paid to the effects of land management on subsoil soil properties even with this recognized importance of subsoil functions (Baker et al., 2007;

Rumpel and Kögel-Knabner, 2010).

One such land management technique is the removal of crop residue. In recent years, the use of crop residue has been debated due to increasing demand for biofuel production (Lal and Pimentel, 2007), and a US-wide assessment indicating that less than 28 % of maize (*Zea mays* L.) residue can be collected sustainably (Graham et al., 2007). Any management change in the amount of biomass and nutrient removal from a field needs to be evaluated carefully. Many of current evaluations are constrained by factors including i) the depth of soil sampling, and ii) particular focus on a narrow set of soil measurements. For fields under crop production, tillage practices are known to significantly affect the vertical distributions of SOC, and no-till (NT) showed to have higher SOC stocks in the surface layer (0-10 cm) while moldboard plow (PT) treatments have higher stocks in the deeper layers (20-40 cm) across eight sites of varying soil types in eastern Canada (Angers et al., 1997). The assessment of residue removal under NT solely in the topsoil may miss potential depletion of SOC in the subsoil layer, which have been found to rely on the exchanges to and from topsoil via plant root systems and soil fauna (Kautz et al., 2013), and dissolved SOM by preferential flow (Rumpel and Kögel-Knabner, 2010). Under PT systems, assessment of soil physical conditions at the interface between the plow layer (cultivated soil layer) and the subsoil may also be important to determine whether the vertical exchange of SOC is not restricted (Peigné et al., 2013).

Although SOC is a fundamental property related to numerous soil functions and an important component of global C cycle (Magdoff and van Es, 2009), it does not fully address the changes in soil conditions for plant growth, nor does higher SOC necessarily mean higher crop productivity (Sojka et al., 2003). There is a need to assess how the changes in the vertical distribution of SOC through residue removal impact the soil's biological, chemical, and physical conditions, important for crop production, across the soil profile. In recent years, combinations of soil measurements including i) soil biological assessment of total and labile components of soil organic matter (SOM), ii) soil physical assessment of water stable aggregation (WSA), available water capacity (AWC) and soil strength, and iii) soil nutrient and pH indicators have been shown to be important in determining yield constraints, and have been utilized as a soil health or soil quality test (Idowu et al., 2008; Karlen et al., 2001; Schindelbeck et al., 2008). Such a set of measurements has been successfully applied to detect aspects of soil degradation caused by tillage (Moebius-Clune et al., 2008; Van Eerd et al., 2014) and land use change (Moebius-Clune et al., 2011). Aziz et al. (2013) assessed the effects of 5 year tillage and crop rotation on soil quality and showed NT to have higher soil microbial biomass and activity, total C and N, permanganate oxidizable C (POXC), WSA, and particulate organic matter compared to PT in 0-to 30-cm depth on a silt loam soil. The evaluation of the interactions among soil biological, chemical, and physical properties also helps to determine the mechanisms behind the changes in soil conditions due to particular soil and crop management practices. Therefore, there is a need to utilize soil health test framework across the soil profile to thoroughly assess the effects of residue and tillage management.

This study was conducted on 40-year continuous maize experimental plots with tillage and maize residue management treatments. Our hypothesis is that PT creates a root growth-restricting layer that does not allow the effective movement of residue-derived organic materials and nutrients through the subsoil. Also, we hypothesize that the absence of residue return causes unfertilized nutrients to become depleted, especially from the deeper soil layers where the amount of root residue is lower.

The objective of this study was to investigate the degree of impacts of surface tillage and crop residue management on surface as well as subsurface layer soil conditions using soil physical, chemical, and biological indicators.

2 Materials and methods

2.1 Study site

The study site is located in Chazy, NY (44°53’N, 73°28’W) to test the effects of tillage (PT vs. NT) and residue management (residue returned (Ret) vs. residue harvested (Harv)) in two by two factorial design. Each plot (6 by 15.2 m) was arrayed in randomized complete block design with four replicated plots for each treatment combination.

The experiment was established in 1973 after many years of continuous mixed grass sod (SOD) while the periphery was maintained as SOD. Continuous maize cropping was maintained during the experiment, and a maize hybrid with maturity class of 85 to 90 days was planted. Fertilizer management consisted of banded application of 17 kg N ha^{-1}, 67 kg P_2O_5 ha^{-1}, and 67 kg K_2O ha^{-1} at the time of planting. In addition, a side-dress application of 140 kg N ha^{-1} was added when the maize plants were between V5 and V7. Weed management in the recent years consisted of pre-emergence herbicide applications of an S-metolachlor, atrazine, and mesotrione mixture followed by glyphosate early in the growing season depending on the level of weed pressure. The PT plots were moldboard plowed at a depth of 15 to 20 cm (Ramsey, 1984) and disked annually in the fall, and maize was planted in the spring; while the NT plots were not tilled and planted with a NT planter (Idowu et al., 2009).

All the experimental plots share one soil series: Roundabout silt loam (Aeric Endoaquept: coarse-silty, mixed, active, nonacid, frigid; Soil Survey Staff, 2015). The soil was formed from medium-textured glaciolacustrine and glaciomarine deposits of Wisconsin Age on the Lake Champlain Plain, near Plattsburgh, NY. According to the Official Series Description, surface 18 cm is in Ap horizon, 18-43 cm in Bw, 43-66 cm in Bg, 66-76 cm in BCg, and 76-165 cm in C horizon (Soil Survey Staff, 2015). The soil is poorly to somewhat poorly drained, and the plots are tile drained to the depth of 100 cm at the spacing of 15.24 m.

2.2 Soil sampling

Soil sampling was undertaken in July 2013 with two subsamples at two locations within each experimental plot in non-traffic inter-rows of maize away from field edges. A soil sampling probe (ST-104, Giddings Machine Company Inc., Windsor, CO) was used, which provided the actual soil sample, 3.81-cm in diameter. The soil sampling probe was inserted to the soil continuously to 60-cm depth using a tractor-mount hydraulic powered soil sampler (GSRTS; Giddings Machine Company Inc., Windsor, CO) while making sure that no soil compaction occurred by visually checking the soil surface through the view slots of the sampling tube. The collected soil samples were cut in 0-6, 6-18, 18-30, 30-45, and 45- to 60-cm increments and subsamples were mixed thoroughly. The first two increments were generally in the Ap horizon, the third and the fourth in the Bw horizon, and the last increment in the Bg horizon. Five additional samples were taken in SOD using the same equipment, which was in the periphery of the experimental plots and was trafficked by farm machineries regularly. The soil samples were kept at 4 °C until analysis.

2.3 Soil analysis

Whole soil samples were weighed to estimate percent field soil moisture content and a subsample was subsequently weighed again, after being oven-dried at 105 °C, to determine dry sample weight. Dry soil bulk density (BD) was determined based on the volume of sample, dry sample weight, as well as calculated volume of rock fragments (> 2 mm), which were sieved from the whole soil sample and converted from mass to volume based on standard rock density (2.65 g cm^{-3}). Soil texture was assessed using a rapid quantitative method developed by Kettler et al. (2001). The soil sample was dispersed with 3% sodium hexametaphosphate ($(NaPO_3)_n$). A combination of sieving and sedimentation steps was used to separate size fractions. WSA was assessed using soil samples that were dried at 40 ºC. A rainfall simulator (Ogden et al., 1997) that allows the soil particles to receive the impacts of known rainfall energy was utilized, applying 2.5 J of energy for 300 s on aggregates (0.25–2 mm) placed on a 0.25-mm mesh sieve. The fraction of soil aggregates remaining on the sieve, corrected for stones >0.25 mm, was regarded as the percent WSA after drying at 105°C (Gugino et al., 2009). Water retention at -10 kPa, -33 kPa, -100 kPa, and -1500 kPa were assessed gravimetrically using disturbed samples (1-cm height; 5-cm inner diameter). Saturated soil samples were equilibrated at each pressure point on ceramic high pressure plates (Dane and Hopmans, 2002). Volumetric water content was derived using the measured BD multiplied by the measured gravimetric water content at each pressure point. -10 kPa is often regarded as field capacity in coarse textured soils whereas -33 kPa is used for medium- to fine-textured soils (Hudson, 1994). In this study, the difference between -10 kPa and -1500 kPa was described as available water capacity (AWC) to be consistent with a previous study (Moebius-Clune et al., 2008). Air-filled porosity (AFP) was also determined using -100 kPa water content.

Various fractions of SOM were quantified to assess both the quantity and the quality of SOM. Total SOM content was analyzed by mass loss on ignition in a muffle furnace at 500 °C for two hours. Labile component of SOM was estimated as POXC using dilute potassium permanganate ($KMnO_4$), which is an effective method to quantify easily oxidizable C by measuring absorbance at 550 nm using a hand-held colorimeter (Weil et al., 2003). Preserved field moist samples were used for mineralizable C (C-min). C-min was determined using sealed chamber alkali trap respirometers using capillary rewetted soil (Haney and Haney, 2010), and it measures the metabolic activity of the soil microbial community (Moebius-Clune et al., 2014). Carbon dioxide evolved from rewetted soils over a four day room temperature incubation was trapped in KOH and quantified by conductivity change in an alkali trap. The autoclaved citrate extractable fraction of soil proteins and protein-like substances (Protein) was measured, which is a proxy measurement of the large fraction of organically bound N in total SOM (Moebius-Clune et al., 2014). The extraction was with 0.02-M sodium citrate at pH7, and the extract was then quantified by bicinchoninic acid assay against a bovine serum albumin standard curve for soil protein concentration after a sequence of centrifugation and autoclaving steps (Walker, 2002; Wright and Upadhyaya, 1996). The ratio of Protein to SOM (Protein:SOM) was calculated as an indicator of the relative quality of the SOM. A higher ratio indicates a relative richness of organically bound N in the SOM, and it relates to potential N availability through mineralization (Moebius-Clune et al., 2014).

Soil pH was measured in 1:1 water slurry. Plant available soil nutrient concentrations were measured by extracting the nutrients using Modified Morgan, an ammonium acetate solution, buffered at pH 4.8 (McIntosh, 1969), and analyzed using inductively coupled plasma emission spectroscopy (ARCOS FHE12; SPECTRO Analytical Instruments GmbH, Kleve, Germany).

2.4 Data analysis

We assessed a scatter matrix of the dataset to confirm linear associations among the measured soil indicators. We calculated Pearson correlation coefficients to assess the relationships among the soil indicators within the experimental plots (n = 80).

The effects of fixed factors (tillage, residue, depth, and their interactions) and random factors (block, replicate, and their interactions) on soil indicators were assessed using a linear mixed model (SAS Institute Inc., 2015). Ca values were log transformed because of the identified unequal variances. In order to assess goodness-of-fit of the mixed model, we employed a novel approach to calculate R^2 (Nakagawa and Schielzeth, 2013) in order to show the percent variance of each measured soil indicator explained by tillage and residue management, and depth of soil layer. In this approach, the variance explained by the fixed factors, and the variance explained by both the fixed and random factors, are defined as marginal R^2 (R^2m) and conditional R^2 (R^2c), respectively. These were calculated as:

$$R_m^2 = \frac{\sigma_f^2}{\sigma_f^2+\sigma_\gamma^2+\sigma_\alpha^2+\sigma_\varepsilon^2} \qquad (1)$$

$$R_c^2 = \frac{\sigma_f^2+\sum_{l=1}^{u}\sigma_l^2}{\sigma_f^2+\sum_{l=1}^{u}\sigma_l^2+\sigma_\varepsilon^2} \qquad (2)$$

where σ_f^2 is the variance calculated from the mixed linear model with fixed factors only, σ_γ^2 is the variance of block-specific effect, σ_{α}^2 is the variance of plot specific effect, σ_{ε}^2 is the residual variance, and σ_l^2 is the variance component of the lth random factor. They were calculated using the *MuMIn* package (Bartoń, 2015) in the R statistical computing environment. Post hoc tests were carried out to compare the means of measured soil indicators in each fixed factor treatment at α = 0.05 using Tukey's method. The soil test results from SOD were included as references to assess the changes in soil conditions but were not used for statistical comparisons due to a lack of randomization with the tillage and residue treatments.

In order to illustrate the overall soil condition, we scored each treatment at each depth increment as Soil Health Score using 12 selected indicators (SOM, C-min, Protein, Protein:SOM, P, K, Ca, Mg, BD, WSA, water content at -100kPa, and AWC) to represent soil biological, chemical, and physical properties uniformly. Apart from BD, each indicator was ranked from the 1st to the 4th as "more is better" for all measured values, except BD which was ranked as "less is better". We assigned four points to the 1st, three points to the 2nd, two points to the 3rd, and one point to the 4th rank.

3. Results and discussion

3.1 The magnitude of influence of tillage and residue management on measured soil properties

Marginal R^2 values were calculated for each fitted mixed model using tillage management, residue management, depth of soil samples, and their interactions as fixed factors (Nakagawa and Schielzeth, 2013). We found this statistic extremely useful in showing how much these fixed factors impact each measured soil indicator regardless of inherent soil property variations among the experimental blocks and plots. The R^2m values were higher for soil biological indicators ($0.66 \leq R^2\text{m} \leq 0.91$; Table 1) compared to soil physical ($0.33 \leq R^2\text{m} \leq 0.85$) and chemical indicators ($0.11 \leq R^2\text{m} \leq 0.88$). These suggest that tillage and residue management most strongly determine the variation of soil biological indicators within this experimental site regardless of inherent soil variations. The incorporation of random factors was represented by the R^2c values, which showed a large increase from R^2m especially for S, water content at -1500 kPa and -33 kPa, and Zn (Table 1). This result indicates that the variance between the experimental blocks and plots can explain the variance of those soil properties, which we assume to be correlated to factors such as soil texture, clay mineralogy, and drainage. In this study, S and Zn were not applied through fertilizer application and the correlations between S and other soil properties were, in general, low.

We presented the p-values of the mixed models, to determine whether significant interaction effects are present among tillage and residue management, as well as the depth of soil sample (Table 2). For soil biological indicators, we found the tillage and depth of soil sample interaction to be more significant compared to the residue and depth interaction, showing more significant effects of tillage compared to residue management across the soil profile (Table 2). Significant interaction between tillage and residue management was only found for POXC and Protein, whereas the interaction between residue and the depth of soil sample was found for C-min and Protein. For soil chemical indicators, the interaction among tillage, residue, and the depth of soil sample was significant for Ca, and Zn, and the interaction between tillage and residue was significant for P (Table 2). For soil physical indicators, less interaction effects were found, and the tillage and depth of soil sample interaction was present for WSA, water content at -33 and -100 kPa (Table 2). BD and AFP showed significant p-values for tillage and residue management, as well as the depth of soil sample, but with no interactions among them. As it was also seen for the difference between R^2c and R^2m, water content at -1500 kPa as well as -10 kPa and AWC showed significant p-values only for the depth of soil sample. This indicates that tillage and residue management practice have only marginal influence on these soil properties.

3.2 Surface (0-to-18 cm) soil indicators

Surface layer is the most frequently tested zone for soil properties, such as for fertilizer recommendations. In this layer, NT-Ret showed the overall highest Soil Health Score (Fig. 1), and tillage had the most significant changes in the soil indicators (Table 3, 4, and 5). The effects of residue treatment was significant under NT at 0- to 6-cm depth for all of the measured soil biological properties but became insignificant at 6- to 18-cm depth, indicating the sampling depth can greatly affect the results. When contrasting NT-Ret and PT, P, K, and Zn, contents were significantly higher for NT-Ret, and were significantly positively correlated to soil biological indicators. P was most correlated to Protein (r = 0.75) whereas K and Zn were most correlated to C-min (r = 0.62 and r = 0.71). This demonstrates the presence of positive benefits from NT and Ret management on soil nutrient availability, which is analogous to previous studies that indicated positive effects of surface enrichment of P, K, Zn, and Mn under NT-Ret (Franzluebbers and Hons, 1996). The P contents were in “High” category, K contents in “Medium”, and Mg contents in “High” for all treatments (Jokela et al., 2004). High surface accumulation of P could cause leaching of P into the tile drainage systems, and there have been reports of NT increasing P loss (Gaynor and Findlay, 1995) especially after manure applications.

BD, WSA, and water content at -100 kPa showed some treatment effects at the topsoil layer (Table 5). For BD, significant treatment effects were only apparent in the first 6-cm layer, and it was significantly lower in NT-Ret compared to PT-Harv (Table 5). Moebius-Clune et al. (2008) reported the presence of erosion on these PT plots, and also reported resettlements of soil particles throughout the growing season under PT, which may partly explain our findings. This was contradictory to some past studies with shorter experimental duration. Deen and Kataki (2003) found higher BD under NT compared to PT across 0- to 20-cm depth on a silt loam soil in a 20-year trial. Angers et al. (1997) found higher BD under NT compared to PT on silty clay to sandy loam soils under 3- to 5-year experiments. Most of the water retention parameters showed no treatment effects, and indicated that soil management has a small impact on AWC at this layer.

3.3 Transition layer (18-to-30 cm) soil indicators

This is the layer comprised of the lower part of topsoil and also the upper-most part of subsoil affected by soil management.

We observed the direct effects of residue return with the PT-Ret treatment at this layer. Some of the indicators showed the order of NT-Ret> PT-Ret> PT-Harv>NT-Harv such as SOM, C-min, K, and Mg, whereas other indicators showed PT-Ret> NT-Ret> PT-Harv>NT-Harv such as POXC and Protein (Fig. 1; Table 3, 4, and 5). In either case, NT-Harv had the lowest Soil Health Score (Fig. 1). The effects of fresh residue return was apparent in POXC, which has been found to be correlated with heavy and small particulate organic C, thus representing a relatively stable fraction of labile C (Culman et al., 2012). Labile C is known to be an important component of SOM which affects cycling of nutrients, soil aggregation, and water retention

(Amézketa, 1999; Culman et al., 2013, 2012; Hudson, 1994). The ratio of Protein:SOM also showed a significantly lower value for NT-Harv (Fig. 2d; Table 3), which indicates a relatively small fraction of protein rich SOM under this treatment, and suggests a lower potential of mineralizable nutrient pool. The measured soil chemical properties show the lowest concentrations under NT-Harv for P, K, Mg, and Zn (Table 4), and also showed a zone of nutrient depletion at this layer and below (Fig. 2e; Table 4). Active uptake of the nutrients by the maize crop and the lack of surface residue return is likely to cause this depletion, as also shown by the low concentration of POXC and the lower Protein:SOM value. P was the only soil nutrient that showed significant correlations to soil biological indicators with the highest correlation with Protein ($r = 0.59$). It is interesting to note that significant differences in Mg and Zn contents between NT-Ret and NT-Harv are visible for the first time at this layer (Table 4). As discussed earlier, Mg and Zn were not supplied through fertilizer applications, and therefore the nutrients are cycled both vertically and horizontally due to the movement of water, plant uptake, and re-deposition (Kautz et al., 2013). NT-Harv was the only treatment with available P, K, and Zn to be in the “Low” category under the guideline (Jokela et al., 2004) though it was intended for use in assessing the topsoil.

WSA was lower for PT-Ret even compared with NT-Harv though not statistically significant (Table 5). It is an indicator of aeration, water infiltration, and drainage (Kemper and Rosenau, 1986), which is highly important in medium to fine-textured soils because it helps to protect a range of pore sizes (Idowu et al., 2008). It is known that plant roots and hyphae support soil aggregation, and polysaccharides become more important for WSA when SOC is less than 10 g kg^{-1} (Tisdall and Oades, 1982). BD was significantly lower for NT-Ret (Table 5) and was comparable to the SOD treatment at this depth (Fig. 2b). Higher SOM content showed the strongest negative correlation to BD at this depth (r = -0.83). Based on the measured clay content, the optimum BD for root growth was calculated as 1.45 and the 20 % of the maximum rooting is expected when the BD approaches 1.70 at this depth (Allan Jones, 1983). AFP was also significantly higher for NT-Ret compared to NT-Harv and PT-Harv (Fig. 2f; Table 5), and indicating better soil aeration, though identifying the exact threshold AFP value at which root respiration starts to become limited has been difficult (Hillel, 1980). Water content at -33 kPa was positively correlated to BD (r = 0.60) but this may not be beneficial due to excess compaction diminishing root growth; and also AFP is significantly reduced at high BD. Therefore, we need to combine the AWC information with mechanical impedance or alternative information on plant root growth to conclude realistic in-situ plant water availability.

3.4 Subsoil (30-to-60 cm) soil indicators

At this layer, the majority of the soil biological indicators showed the trend of NT-Ret > NT-Harv > PT-Ret > PT-Harv analogous to the surface layer (Fig. 1; Table 3). Tillage showed statistical significance over residue management, and NT had significantly higher SOM in the sampled subsoil layers. Therefore, PT-Ret had a very small zone of high SOM related properties and they were not transferred into the deeper layers. There are three major sources of SOM to subsoil layers: i) crop roots and root exudates, ii) bioturbation by soil fauna, and iii) influx of dissolved SOM by preferential flow (Rumpel and Kögel-Knabner, 2010). Although not quantified in this study, there was a higher abundance of biopores observed in the NT plots, and also a significantly higher biomass of earthworms in the NT compared to PT at the same study site (Ramsey, 1984). Those were anecic earthworms with surface feeding with deep, permanent, and vertical burrows (Ramsey, 1984), and were suggested as either *Lumbricus terrestris* or *Allolobophora longa*. The higher anecic earthworm population could have contributed to the mixing of the topsoil with the subsoil through bioturbation, or by topsoil washing through continuous biopores into the subsoil layers (Kautz et al., 2013). This was also justified by the higher Protein:SOM value under NT-Ret, which indicates a relatively high content of N-rich SOM materials (Table 3). The AFP values were significantly higher for NT-Ret compared to PT-Harv (Table 5) indicating the restrictions of the influx of SOM both by crop roots and also through deep continuous biopores in plowed soil.

Franzluebbers and Hons (1996) found a large decrease in extractable Mg at 30-60 cm followed by an increase at 60- to 90-cm depth regardless of tillage treatments. They suggested the decrease of extractable Mg at 30- to 60-cm depth to be caused by plant uptake as well as a soil layer with inherently lower Mg content. In this study, Mg and Ca contents were high (Jokela et al., 2004) partly because of the presence of freshwater clay and fossiliferous marine deposit in these regions (USDA-NRCS, 2006). Nevertheless, the presence of the lower concentrations of the nutrients under NT-Harv suggests the presence of active uptake of these nutrients by plant roots combined with the absence of nutrient return, and requires further investigation of these nutrient pools for sustainable crop production.

WSA showed relatively high and comparable levels to the topsoil (Table 5) although SOM and other soil biological indicator values were significantly lower (Table 3). John et al. (2005) found the formation of macroaggregates (> 250 μm) in the subsoils where the C concentration of soil particle fraction < 53 μm was very low, which contradicted the previous concept that the formation of macroaggregates can only start after the SOM binding capacity of clay and silt are satisfied (Hassink, 1997; Tisdall and Oades, 1982). Inorganic binding can occur in subsoils through clay coating of sand grains, which bridge between the soil particles (Graham et al., 1995). Also, poorly crystalline Fe-oxide helps soil aggregate formation (Duiker et al., 2003), and Fe contents increased at greater depths in this study (data not shown). Furthermore, subsoil is generally less disturbed by soil management and is known to maintain biopores and soil structure longer compared to the topsoil (Beven and Germann, 1982).

3.5 Full profile soil conditions

In order to support optimum crop growth under stress conditions, sufficient availability and accessibility of soil moisture and nutrients are important (Boyer et al., 1990; Timlin et al., 2001). In this study, we found the combinations of tillage and residue return to affect multiple soil properties at different depths, which can in turn affect the overall availability and accessibility of soil moisture and nutrients from the soil system. Across the soil profile, the Soil Health Score was the highest under NT-Ret suggesting the most favorable conditions for crop growth (Fig. 1).

The topsoil layer (0- to 18-cm depth) is the most important reservoir of soil moisture and nutrients as well as oxygen for plant growth. We observed more significant effects of tillage compared to residue management at this depth on soil biological indicators, and the residue management effects were minimal under PT at 0- to 6-cm depth (Table 3). This is because the residue is diluted across the plow depth under PT, hiding the effects of residue return at the very shallow depth. At 6- to 18-cm depth, NT-Harv had significantly lower P concentration compared to NT-Ret though the values were in the optimum range (Jokela et al., 2004). NT treatments also maintained significantly higher aggregation, which could be a more sensitive indicator of management-induced change in soil physical properties compared to BD (Table 5). Soil water retention related properties did not change significantly at the topsoil layer and across the soil profile, possibly due to the negative relationship between BD and SOM.

The transition layer (18- to 30-cm depth) has been recognized as an important zone for soil physical assessment for root growth and water retention (Peigné et al., 2013). We found NT-Ret to maintain high AFP comparative to the surface layer indicating higher oxygen availability important for root growth (Table 5), whereas it was significantly lower under NT-Harv. In addition, we found nutrient depletion under NT-Harv for P, K, and Zn (Table 4). The P concentration was significantly correlated with Protein ($r = 0.59$) and emphasizes the importance of residue return for its availability, but attention needs to be paid to possible loss through leaching.

The subsoil layer (30- to 60-cm depth) has been recognized as an important reservoir of soil moisture, nutrients, and SOC (Batjes, 1996; Carter and Gregorich, 2010; Ewing et al., 1991; Gaiser et al., 2012; Gransee and Merbach, 2000; Heming, 2004; Kirkegaard et al., 2007). We found Ca, Mg, and Zn to be in high concentration reflecting the inherent soil properties. Higher SOM content and a higher Protein:SOM value under NT-Ret indicated the redistribution of SOM to the subsoil layer from the surface as an important pathway. In the subsoil layer, the knowledge of the availability of soil nutrients largely determined by soil formation is important, which may allow us to use deep rooting crops to utilize the nutrients and deposit at the surface through residue return. However, we should also consider the accessibility of the subsoil by roots, which is dependent on the soil physical conditions at the transition layer (Peigné et al., 2013). We showed the removal of residue at the surface under NT to modify nutrient cycling below the conventional soil sampling depth, and the depletion of soil nutrients in the transition layer may make the roots concentrate at a shallow depth (Zhang and Barber, 1992). This could potentially reduce the plants' ability to utilize the available soil moisture and nutrients in the subsoil.

4. Conclusions

This paper presents the importance of surface crop and soil management on surface (0- to 18-cm depth), transition (18- to 30-cm depth) and subsoil layer (30- to 60-cm depth) soil biological, chemical, and physical conditions. We show that no-till (NT) combined with crop residue return (Ret) maintains soil conditions closest to the original continuous mixed sod, compared to plow till (PT) or residue harvested (Harv) treatments, across the soil profile. Crop residue return was important to avoid the depletion of macro- and micro- nutrients under NT below the surface layer, which emphasized the importance of a full soil profile framework in soil nutrient budgeting. We presented potential importance of vertical exchanges of soil organic matter (SOM) and related soil nutrients through crop roots, root exudates, soil fauna, and influx of dissolved SOM by preferential flow. For soil moisture, the accessibility of larger soil volume by crop roots, as well as the reduction in evaporation by surface cover, appeared more manageable compared to the total quantity of available soil water by tillage and residue management.

Silage and bioenergy production are some of the potential users of removed maize residues from a farm. When considering the effects of the removal of crop residue, evaluation of soil biological, physical, and chemical properties below the surface layer is critical. We presented the mining of unfertilized nutrients as well as lower concentrations of SOM related properties at soil layers > 18 cm under NT-Harv. Therefore, the removal of the residue may not be justifiable in the long-term when considering the sustainability of this cropping system.

We conclude that the integrated assessment of surface, transition and subsoil layer soil conditions is important to understand the effects of management. The direct impacts of tillage and residue management occur mostly near the soil surface, but have effects on soil properties deep into the profile, where no-tillage and residue return positively influence subsoil conditions.

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Figure captions

Fig. 1. Overall profile soil health conditions scored using 12 indicators for no-till residue returned (NT-Ret), no-till residue harvested (NT-Harv), plow-till residue returned (PT-Ret), and plow-till residue harvested (PT-Harv). Simple scores were assigned based on relative ranking of the four treatments for each indicator, where 1^{st}, 2^{nd}, 3^{rd}, and 4^{th} rankings yielded scores of 4, 3, 2, and 1, respectively.

Fig. 2. Soil profile plots showing the variation of soil properties for no-till residue returned (NT-Ret), no-till residue harvested (NT-Harv), plow-till residue returned (PT-Ret), plow-till residue harvested (PT-Harv), and continuous mixed grass sod (SOD)

Figures

Fig. 1.

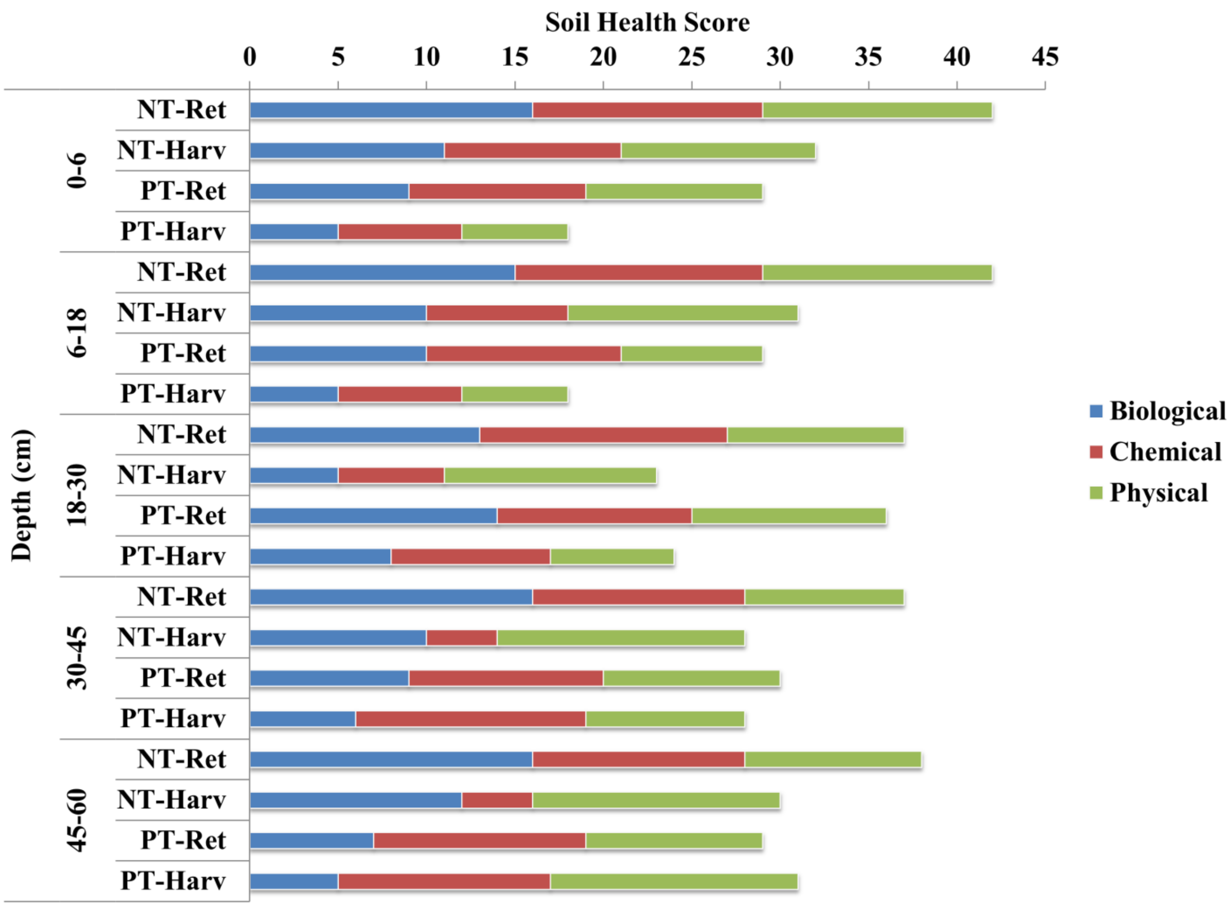
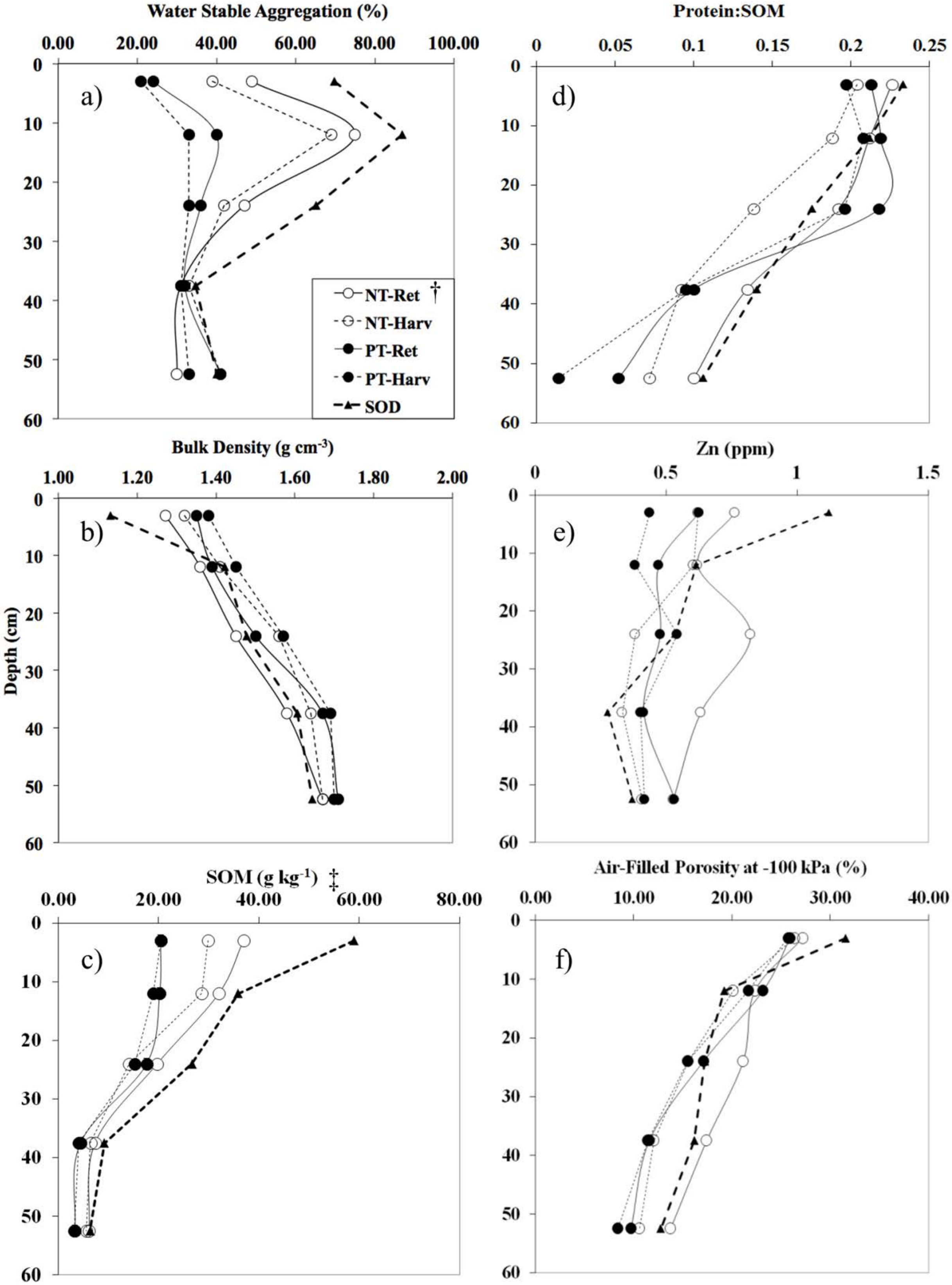


Fig. 2.



† NT = no-till; Ret = residue returned; PT = plow-till; Harv = residue harvested‡ SOM = soil organic matter

Table 1. Marginal (R^2m) and conditional (R^2c) coefficient of determination for each mixed model result.

	R^2m‡	R^2c	Difference
BD†	0.85	0.88	0.03
WSA	0.73	0.82	0.09
−10 kPa	0.33	0.59	0.26
−33 kPa	0.53	0.88	0.35
−100 kPa	0.39	0.58	0.19
−1500 kPa	0.38	0.76	0.38
AWC	0.41	0.70	0.29
AFP	0.81	0.82	0.01
SOM	0.91	0.94	0.03
POXC	0.66	0.93	0.27
C-min	0.90	0.92	0.02
Protein	0.91	0.95	0.04
pH	0.88	0.92	0.04
P	0.88	0.89	0.01
K	0.71	0.72	0.01
Ca	0.38	0.68	0.30
Mg	0.49	0.72	0.23
Zn	0.33	0.62	0.29
S	0.11	0.62	0.51

† BD = dry bulk density; WSA = water stable aggregation; AWC = available water capacity; SOM = soil organic matter; POXC = permanganate oxidizable carbon; C-min = mineralizable carbon

‡ R^2m = marginal coefficient of determination; R^2c = conditional coefficient of determination

Table 2. Statistical significance of the experimental treatments shown by the p values for each measured indicators.

Soil Biological Indicators	SOM †	POXC	C-min	Protein	Protein:SOM
Tillage‡	-	-	-	-	-
Residue	-	<0.001	-	-	0.03
Depth	-	-	-	-	-
Tillage × Residue	0.02	0.05	0.94	0.002	0.50
Tillage × Depth	<0.001	<0.001	<0.001	<0.001	0.02
Residue × Depth	0.18	0.21	0.03	0.01	0.20
Tillage × Residue × Depth	0.36	0.21	0.88	0.25	0.71

Soil Chemical Indicators	pH	P	K	Ca	Mg	Zn	S
Tillage	-	-	-	-	-	-	-
Residue	0.07	-	-	-	0.07	-	0.91
Depth	-	-	-	-	-	-	-
Tillage × Residue	0.54	0.003	0.12	-	0.14	-	0.83
Tillage × Depth	<0.001	<0.001	0.01	-	<0.001	-	0.04
Residue × Depth	0.08	0.40	<0.001	-	0.86	-	1.00
Tillage × Residue × Depth	0.26	0.07	0.25	0.04	0.57	0.02	0.47

Soil Physical Indicators	BD	WSA	−10 kPa	−33 kPa	−100 kPa	−1500 kPa	AWC	AFP
Tillage	0.01	-	0.98	-	-	0.42	0.73	0.04
Residue	0.03	0.18	0.07	0.38	-	0.92	0.11	0.01
Depth	<0.001	-	<0.001	-	-	<0.001	<0.001	<0.001
Tillage × Residue	0.58	0.55	0.78	0.25	0.04	0.57	0.99	0.11
Tillage × Depth	0.65	<0.001	0.67	0.04	<0.001	0.21	0.72	0.19
Residue × Depth	0.26	0.23	0.81	0.10	0.02	0.17	0.89	0.64
Tillage × Residue × Depth	0.96	0.10	0.59	0.41	0.29	0.86	0.55	0.74

- In the presence of a significant interaction term, we did not further assess the significance of each fixed effect.

† SOM = soil organic matter; POXC = permanganate oxidizable carbon; C-min = mineralizable carbon; BD = dry bulk density; WSA = water stable aggregation; -10 kPa = water content at -10 kPa; −33 kPa = water content at −33 kPa; −100 kPa = water content at −100 kPa; −1500 kPa = water content at −1500 kPa; AWC = available water capacity calculated by the difference between -10 kPa and -1500 kPa; AFP = air-filled porosity at -100 kPa

‡ Tillage = tillage treatment; Residue = residue treatment; Depth = depth of soil sample

Table 3. Means for soil biological properties.

Soil depth	Tillage	Residue	SOM ‡	POXC	C-min	Protein	Protein:SOM
cm			g kg^{-1}	ppm	mg CO2 g^{-1} day^{-1}	mg g^{-1}	
0-6	NT†	Ret	36.9 a §	674 a	0.257 a	8.33 a	0.226a
	NT	Harv	29.9 b	487 b	0.219 b	6.10 b	0.204a
	PT	Ret	20.4 c	340 c	0.190 bc	4.35 c	0.213a
	PT	Harv	20.4 c	299 c	0.157 c	4.02 c	0.197a
	NT Mean		33.4 A	580 A	0.238 A	7.22 A	0.215A
	PT Mean		20.4 B	320 B	0.173 B	4.18 B	0.205A
	Ret Mean		28.6 A	507 A	0.224 A	6.34 A	0.219A
	Harv Mean		25.1 B	393 B	0.188 B	5.06 B	0.200A
	SOD		58.9	869	0.670	13.60	0.233
6-18	NT	Ret	32.0 a	496 a	0.216 a	6.78 a	0.212a
	NT	Harv	28.6 a	429 a	0.203 a	5.35 b	0.188a
	PT	Ret	20.2 b	320 b	0.180 ab	4.43 bc	0.219a
	PT	Harv	18.9 b	285 b	0.149 b	3.94 c	0.208a
	NT Mean		30.3 A	463 A	0.209 A	6.06 A	0.200A
	PT Mean		19.6 B	303 B	0.164 B	4.19 B	0.213A
	Ret Mean		26.1 A	408 A	0.198 A	5.61 A	0.216A
	Harv Mean		23.8 A	357 A	0.176 B	4.64 B	0.198A
	SOD		35.9	514	0.276	7.56	0.212
18-30	NT	Ret	19.7 a	256 a	0.164 a	3.80 a	0.192ab
	NT	Harv	14.1 b	130 b	0.133 a	1.99 b	0.138b
	PT	Ret	17.6 ab	276 a	0.158 a	3.81 a	0.218a
	PT	Harv	15.2 b	209 ab	0.131 a	2.99 ab	0.196a
	NT Mean		16.9 A	221 A	0.148 A	2.89 A	0.165B
	PT Mean		16.4 A	242 A	0.145 A	3.40 A	0.207A
	Ret Mean		18.6 A	266 A	0.161 A	3.80 A	0.205A
	Harv Mean		14.6 B	194 B	0.132 B	2.49 B	0.167B
	SOD		26.6	324	0.219	4.64	0.175
30-45	NT	Ret	7.3 a	na	0.082 a	0.98 a	0.134a
	NT	Harv	6.4 a	na	0.078 a	0.59 a	0.092a
	PT	Ret	4.4 a	na	0.060 a	0.43 a	0.100a
	PT	Harv	4.0 a	na	0.060 a	0.37 a	0.095a
	NT Mean		6.9 A	na	0.080 A	0.79 A	0.113A
	PT Mean		4.2 B	na	0.060 B	0.40 A	0.098A
	Ret Mean		5.8 A	na	0.071 A	0.70 A	0.117A
	Harv Mean		5.2 A	na	0.069 A	0.48 A	0.094A
	SOD		9.2	53.4	0.107	1.29	0.140
45-60	NT	Ret	6.1 a	na	0.067 a	0.68 a	0.100a
	NT	Harv	5.6 a	na	0.065 a	0.45 a	0.072ab
	PT	Ret	3.3 a	na	0.049 a	0.18 a	0.052ab
	PT	Harv	3.2 a	na	0.055 a	0.04 a	0.014b
	NT Mean		5.8 A	na	0.066 A	0.56 A	0.086A
	PT Mean		3.3 B	na	0.052 A	0.11 A	0.033B
	Ret Mean		4.7 A	na	0.058 A	0.43 A	0.076A
	Harv Mean		4.4 A	na	0.060 A	0.24 A	0.043B
	SOD		6.3	4.93	0.066	0.67	0.106

† NT = no-till; PT = plow-till; Harv = residue removed; Ret = residue returned

‡ SOM = soil organic matter; POXC = permanganate oxidizable carbon; C-min = mineralizable carbon

§ Means of each property followed by an identical lowercase alphabet are not significantly different at the α = 0.05.Capital letters show an overall significance of tillage and residue effects.

Table 4. Means for soil chemical properties.

Soil depth cm	Tillage	Residue	pH	P mg kg^{-1}	K mg kg^{-1}	Ca mg kg^{-1}	Mg mg kg^{-1}	Zn mg kg^{-1}	S mg kg^{-1}
0-6	NT †	Ret	6.8 c §	14.81 a	132.0 a	3575 a	239 a	0.763 a	8.01 a
	NT	Harv	6.9 bc	12.15 a	66.3 b	3648 a	179 a	0.623 ab	8.63 a
	PT	Ret	7.1 ab	8.38 b	82.9 b	4601 a	165 a	0.625 ab	9.39 a
	PT	Harv	7.1 a	8.76 b	57.9 b	4286 a	143 a	0.438 b	8.74 a
	NT Mean		6.8 B	13.48 A	99.2 A	3611 A	209 A	0.693 A	8.32 A
	PT Mean		7.1 A	8.57 B	70.4 B	4443 A	154 A	0.531 A	9.07 A
	Ret Mean		6.9 B	11.59 A	107.5 A	4088 A	202 A	0.694 A	8.70 A
	Harv Mean		7.0 A	10.45 A	62.1 B	3967 A	161 A	0.530 B	8.69 A
	SOD		6.7	13.59	133.9	3648	307	1.120	12.20
6-18	NT	Ret	6.8 c	10.74 a	65.8 a	4787 a	203 a	0.620 a	6.92 a
	NT	Harv	6.8 bc	5.83 b	44.7 a	4882 a	156 a	0.605 a	7.66 a
	PT	Ret	7.0 b	5.96 b	69.5 a	4656 a	164 a	0.473 a	7.46 a
	PT	Harv	7.2 a	7.10 b	47.0 a	4531 a	147 a	0.383 a	6.90 a
	NT Mean		6.8 B	8.29 A	55.3 A	4834 A	180 A	0.613 A	7.29 A
	PT Mean		7.1 A	6.53 B	58.3 A	4593 A	156 A	0.428 B	7.18 A
	Ret Mean		6.9 B	8.35 A	67.7 A	4721 A	184 A	0.546 A	7.19 A
	Harv Mean		7.0 A	6.47 B	45.9 B	4707 A	152 A	0.494 A	7.28 A
	SOD		6.8	9.14	69.1	4277	224	0.616	8.95
18-30	NT	Ret	7.1 ab	4.13 ab	73.3 a	10483 a	274 a	0.823 a	11.86 a
	NT	Harv	7.2 a	1.92 b	43.2 c	7869 a	148 b	0.383 b	12.81 a
	PT	Ret	7.0 b	4.60 a	71.3 ab	5400 a	181 ab	0.478 b	7.30 a
	PT	Harv	7.1 ab	4.52 ab	45.5 bc	5741 a	171 ab	0.543 ab	7.20 a
	NT Mean		7.1 A	3.02 B	58.2 A	9176 A	211 A	0.603 A	12.33 A
	PT Mean		7.0 B	4.56 A	58.4 A	5570 A	176 A	0.510 A	7.25 B
	Ret Mean		7.0 A	4.37 A	72.3 A	7942 A	227 A	0.650 A	9.58 A
	Harv Mean		7.1 A	3.22 A	44.3 B	6805 A	159 B	0.463 B	10.00 A
	SOD		7.1	5.40	57.2	5850	176	0.534	9.38
30-45	NT	Ret	7.4 a	1.71 a	38.2 a	11046 ab	263 ab	0.633 a	8.16 a
	NT	Harv	7.3 a	1.11 a	32.8 a	6746 b	155 b	0.333 a	7.25 a
	PT	Ret	7.4 a	1.22 a	38.7 a	9618 ab	287 a	0.415 a	7.18 a
	PT	Harv	7.5 a	1.48 a	33.7 a	14790 a	294 a	0.403 a	9.30 a
	NT Mean		7.3 B	1.41 A	35.5 A	8896 A	209 B	0.483 A	7.70 A
	PT Mean		7.5 A	1.35 A	36.2 A	12204 A	291 A	0.409 A	8.24 A
	Ret Mean		7.4 A	1.47 A	38.5 A	10332 A	275 A	0.524 A	7.67 A
	Harv Mean		7.4 A	1.29 A	33.3 A	10768 A	225 A	0.368 A	8.27 A
	SOD		7.4	1.20	40.7	3136	139	0.278	5.57
45-60	NT	Ret	7.6 a	1.87 a	38.5 a	16318 a	298 a	0.528 a	9.07 a
	NT	Harv	7.6 a	1.20 a	30.4 a	8235 b	219 a	0.408 a	6.72 a
	PT	Ret	7.7 a	1.24 a	39.5 a	10811 ab	320 a	0.533 a	7.06 a
	PT	Harv	7.7 a	1.42 a	39.3 a	15542 ab	318 a	0.418 a	9.41 a
	NT Mean		7.6 A	1.53 A	34.4 A	12276 A	258 A	0.468 A	7.89 A
	PT Mean		7.7 A	1.33 A	39.4 A	13177 A	319 A	0.475 A	8.24 A
	Ret Mean		7.7 A	1.55 A	39.0 A	13565 A	309 A	0.530 A	8.06 A
	Harv Mean		7.6 A	1.31 A	34.8 A	11889 A	268 A	0.413 A	8.06 A
	SOD		7.5	1.63	33.6	5273	203	0.372	4.54

† NT = no-till; PT = plow-till; Harv = residue removed; Ret = residue returned

§ Means of each property followed by an identical lowercase alphabet are not significantly different at the α = 0.05.Capital letters show an overall significance of tillage and residue effects.

Table 5. Means for soil physical properties.

Soil depth	Tillage	Residue	BD ‡	WSA	−10 kPa	−33 kPa	−100 kPa	−1500 kPa	AWC	AFP
cm			Mg m^{-3}	%	m m^{-3}	m m^{-3}	m m^{-3}	m m^{-3}	m m^{-3}	%
0-6	NT †	Ret	1.27 b §	49 a	0.415 a	0.343 a	0.251 a	0.117 a	0.298 a	27 a
	NT	Harv	1.32 ab	39 a	0.428 a	0.348 a	0.238 ab	0.105 a	0.323 a	26 a
	PT	Ret	1.35 ab	24 b	0.432 a	0.353 a	0.230 ab	0.101 a	0.331 a	26 a
	PT	Harv	1.38 a	21 b	0.429 a	0.342 a	0.221 b	0.100 a	0.329 a	26 a
	NT Mean		1.29 B	44 A	0.422 A	0.346 A	0.245 A	0.111 A	0.311 A	27 A
	PT Mean		1.37 A	23 B	0.431 A	0.348 A	0.226 B	0.101 A	0.330 A	26 A
	Ret Mean		1.31 A	37 A	0.424 A	0.348 A	0.241 A	0.109 A	0.315 A	27 A
	Harv Mean		1.35 A	30 A	0.428 A	0.345 A	0.230 A	0.102 A	0.326 A	26 A
	SOD		1.13	70	0.487	0.343	0.258	0.134	0.353	32
6-18	NT	Ret	1.36 a	75 a	0.426 a	0.339 a	0.263 ab	0.123 a	0.303 a	22 a
	NT	Harv	1.41 a	69 a	0.443 a	0.356 a	0.268 a	0.115 a	0.328 a	20 a
	PT	Ret	1.39 a	40 b	0.402 a	0.349 a	0.245 ab	0.107 a	0.295 a	23 a
	PT	Harv	1.45 a	33 b	0.429 a	0.339 a	0.238 b	0.106 a	0.323 a	22 a
	NT Mean		1.39 A	72 A	0.434 A	0.348 A	0.265 A	0.119 A	0.315 A	21 A
	PT Mean		1.42 A	37 B	0.416 A	0.344 A	0.241 B	0.107 A	0.309 A	22 A
	Ret Mean		1.38 A	58 A	0.414 A	0.344 A	0.254 A	0.115 A	0.299 A	23 A
	Harv Mean		1.43 A	51 A	0.436 A	0.347 A	0.253 A	0.111 A	0.326 A	21 A
	SOD		1.42	87	0.468	0.340	0.271	0.125	0.343	19
18-30	NT	Ret	1.45 b	47 a	0.422 a	0.346 a	0.242 a	0.104 a	0.318 a	21 a
	NT	Harv	1.56 ab	42 ab	0.472 a	0.393 a	0.258 a	0.100 a	0.372 a	16 b
	PT	Ret	1.50 ab	36 ab	0.425 a	0.379 a	0.263 a	0.100 a	0.325 a	17 ab
	PT	Harv	1.57 a	33 b	0.446 a	0.383 a	0.253 a	0.105 a	0.341 a	15 b
	NT Mean		1.50 A	45 A	0.447 A	0.370 A	0.250 A	0.102 A	0.345 A	18 A
	PT Mean		1.54 A	35 B	0.435 A	0.381 A	0.258 A	0.102 A	0.333 A	16 A
	Harv Mean		1.56 A	38 A	0.459 A	0.388 A	0.256 A	0.102 A	0.356 A	19 A
	Ret Mean		1.48 B	42 A	0.423 A	0.362 A	0.252 A	0.102 A	0.321 A	16 A
	SOD		1.48	65	0.444	0.341	0.270	0.113	0.331	17
30-45	NT	Ret	1.58 b	31 a	0.463 a	0.373 a	0.229 b	0.082 a	0.381 a	17 a
	NT	Harv	1.64 ab	33 a	0.476 a	0.417 a	0.262 a	0.089 a	0.387 a	12 b
	PT	Ret	1.67 ab	32 a	0.462 a	0.423 a	0.253 ab	0.081 a	0.381 a	12 b
	PT	Harv	1.69 a	31 a	0.486 a	0.423 a	0.245 ab	0.085 a	0.401 a	11 b
	NT Mean		1.61 B	32 A	0.470 A	0.395 B	0.246 A	0.086 A	0.384 A	15 A
	PT Mean		1.68 A	31 A	0.474 A	0.423 A	0.250 A	0.083 A	0.391 A	12 A
	Ret Mean		1.63 A	31 A	0.463 A	0.398 A	0.241 A	0.082 A	0.381 A	15 A
	Harv Mean		1.66 A	32 A	0.481 A	0.420 A	0.255 A	0.087 A	0.394 A	12 A
	SOD		1.61	35	0.441	0.373	0.234	0.088	0.353	16
45-60	NT	Ret	1.67 a	30 a	0.491 a	0.416 a	0.234 b	0.083 a	0.408 a	14 a
	NT	Harv	1.67 a	41 a	0.494 a	0.419 a	0.265 a	0.086 a	0.408 a	11 ab
	PT	Ret	1.71 a	41 a	0.480 a	0.444 a	0.257 ab	0.079 a	0.401 a	9.7 ab
	PT	Harv	1.70 a	33 a	0.535 a	0.446 a	0.273 a	0.092 a	0.443 a	8.4 b
	NT Mean		1.67 A	35 A	0.492 A	0.417 B	0.249 B	0.085 A	0.408 A	12 A
	PT Mean		1.71 A	37 A	0.508 A	0.445 A	0.265 A	0.086 A	0.422 A	9.1 A
	Ret Mean		1.69 A	36 A	0.486 A	0.430 A	0.245 B	0.081 A	0.405 A	12 A
	Harv Mean		1.69 A	37 A	0.514 A	0.432 A	0.269 A	0.089 A	0.425 A	9.5 A
	SOD		1.64	40	0.451	0.398	0.252	0.080	0.371	13

† NT = no-till; PT = plow-till; Harv = residue removed; Ret = residue returned

‡ BD = dry bulk density; WSA = water stable aggregation; −10 kPa = water content at −10 kPa; −33 kPa = water content at −33 kPa; −100 kPa = water content at −100 kPa; −1500 kPa = water content at −1500 kPa; AWC = available water capacity calculated by the difference between −10 kPa and −1500 kPa; AFP = air-filled porosity at -100 kPa

§ Means of each property followed by an identical lowercase alphabet are not significantly different at the $\alpha = 0.05$.Capital letters show an overall significance of tillage and residue effects