MANAGEMENT AND LANDSCAPE VARIABILITY EFFECTS ON SELECTED COASTAL PLAIN SOIL PHYSICAL PROPERTIES

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MANAGEMENT AND LANDSCAPE VARIABILITY EFFECTS ON SELECTED COASTAL PLAIN SOIL PHYSICAL PROPERTIES

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THESIS ABSTRACT

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Crop production has become more costly over the years. Improved tillage practice recommendations and implementation of site-specific crop management (SSM) can help farmers achieve soil conservation, better yields, input optimization and consequent savings. Southeastern Coastal Plain soils are highly weathered soils that typically have been intensely cropped under conventional tillage practices and are susceptible to erosion, runoff and degradation. Understanding tillage practices, topography and spatial variability impacts on soil physical properties is important for aiding in the development of management practice recommendations and implementation of SSM. In order to assess management practices and landscape variability effects on soil physical properties, total carbon (TC), particle size distribution (PSD), bulk density (Db), aggregate stability (AS), infiltration rate (IR), hydraulic conductivity of saturated soil (Ksat) and water retention (WR) were measured in 2006 in a 9 ha field in the central Alabama Coastal Plain. Based on the local soil properties, the field was divided into three management zones (MZ) corresponding to summit (Z1), backslope (Z2) and toeslope (Z3). Four tillage systems treatments [conventional system with (CTM) or without (CT) 10 Mg ha^{-1} yr^{-1} of dairy manure, and conservation system with (NTM) or without (NT) 10 Mg ha^{-1} yr^{-1} of dairy manure] were established in a corn (*Zea mays* L.)-cotton (*Gossypium hirsutum* L.) rotation in 2000 at the research site after 30 years of cotton monoculture under conventional tillage. Overall, conservation system significantly improved TC, IR, AS, Ksat and WR in the top 5cm of this soil, compared to conventional system. Conservation system improved WR at higher suctions (300, 500 and 1000cm H_2O), and conventional system improved WR at lower suctions (0 and 20cm H_2O). Trends of TC and Db values were very similar. Impacts of tillage system on soil properties had no clear trend at 5-10 and 10-15cm of depth. Manure additions significantly improved TC, Db and WR in the top 5cm for conservation and conventional systems, and at 5-10cm of depth for conventional system. Differences among MZ were significant only for Db, WR, Ksat and IR. Overall, WR was greater at Z1 and Ksat at Z2. Infiltration rate, AS and Db trends among MZ varied according to tillage system. Response of IR and AS to the conservation system were greater in Z2 than the other MZ. We conclude that six years of conservation tillage and manure additions was enough time to improve most of the soil properties measured only in the top 5cm of these soils. Except for WR at higher suctions, soil

physical properties at the 5-15cm layer were generally improved by the conventional system. Perhaps a longer period of time is needed to observe significant changes in soil physical properties at lower depths. Regarding differences among MZ, erosion and depositional processes associated with tillage system were the most important factors affecting the spatial variability of soil physical properties on this landscape.

Results of this research can help farmers, extension personnel and consultants to decide about the suitability of management practices for conditions similar to the southeastern Coastal Plain soils studied here. In addition, observed differences in soil properties through the landscape positions could be used as complementary information to support SSM decisions. However, longer term research is needed to better describe observed impacts on this landscape.

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GENERAL INTRODUCTION

Crop production has become more costly over the years, which significantly impacts farmer’s decisions in adopting management practices. Improved tillage practice recommendations and implementation of site-specific crop management (SSM) can help farmers achieve soil conservation, better yields, input optimization and consequent savings (Menegatti et al., 2004; Franzen et al., 2000; Terra et al., 2006). However, a better understanding of the consequences of adopting new soil and crop management systems is needed for southeastern US Coastal Plain soils.

The Southeast US region is characterized by warm and moist conditions, which are conducive for high rates of carbon (C) decomposition. Soils in this region commonly have a sandy surface, highly weathered mineralogy, weak structure, with low water holding capacity, and compacted subsurface layers are common (Reeves, 1997; Franzluebebers, 2005; Shaw et al., 2002; Schomberg et al., 2006). Additionally, the southeastern Coastal Plain soils have traditionally been intensively cropped under conventional tillage practices, mostly under cotton monoculture, which promote organic matter decomposition, disrupt soil structure, and leaves the soil susceptible to compaction, erosion and runoff.

Conservation systems have significant potential as a management tool for the degraded soils in the southeastern US (Truman et al., 2005), because it reduces erosion and runoff, increases infiltration and water holding capacity, and improves soil quality, soil water conservation and crop yields (Truman et al., 2005; Terra et al., 2006; Siri-Prieto et al., 2007). Although complete absence of soil tillage has been reported to improve soil properties and crop yield (Radcliffe et al., 1988; Reynolds et al., 2007), the use of non-inversion deep tillage, like paratill® (Bingham Brothers, Lubbock, TX) and striptill, has been a common and necessary practice in the southeastern Coastal Plain, due to common presence of hardpans (Raper, 2007). However, the transition of conventional tillage systems to a conservation system can have detrimental impacts on soil physical properties, especially on degraded soils, and can influence the opinion of farmers to adopt conservation systems (Terra et al., 2006).

The susceptibility to degradation of these soils can be affected by changes in landscape position, which strongly affects water movement through the soil profile, and can result in significant differences in physical properties, profile development and differentiation (Jenny, 1941). Therefore, characterizing landscape variability and its effect on soil physical properties is essential to determine proper crop management practices in order to optimize inputs and improve profitability. Besides the financial benefits (Menegatti et al., 2004; Franzen et al., 2000), environmental concerns have become one more reason farmers should consider the adoption of SSM techniques.

We believe that the benefits of conservation systems to southeastern Coastal Plain soils are associated with improvements in soil properties that enhance soil hydraulic properties in general. In addition, those properties can vary between landscape positions, and could be used as supplementary information for delineating management zones in order to support SSM decisions. Therefore, the objective of this study was to assess management practices and landscape variability effects on selected soil physical properties.

I. MANAGEMENT EFFECTS ON SELECTED COASTAL PLAIN SOIL PHYSICAL PROPERTIES

ABSTRACT

Knowledge of the impacts of tillage practices on soil physical properties is essential for aiding in recommendation of management practices. Degraded soil conditions, like in the southeastern Coastal Plain, make the transition from conventional systems to conservation systems difficult, which impacts farmer's decisions to adopt conservation systems. In order to assess the effects of management practices on soil physical properties, total carbon (TC), particle size distribution (PSD), bulk density (Db), aggregate stability (AS), infiltration rate (IR), hydraulic conductivity of saturated soil (Ksat) and water retention (WR), a study was established in a 9 ha field in central Alabama. Soils in this landscape were mostly fine and fine-loamy, siliceous, subactive, thermic Typic, Oxyaquic and Aquic Paleudults. Tillage treatments included a conventional system with (CTM) or without (CT) 10 Mg ha^{-1} yr^{-1} of dairy manure, and a conservation system with (NTM) or without (NT) 10 Mg ha^{-1} yr^{-1} of dairy manure. Treatments were established in a corn (*Zea mays* L.)-cotton (*Gossypium hirsutum* L.) rotation in 2000, after 30 years of cotton monoculture under conventional tillage. After six years, TC, IR, AS, Ksat and WR were improved in the top 5cm of the conservation system compared to the conventional system. The conservation system improved WR at

higher suctions (300, 500 and 1000cm H_2O), while the conventional system improved WR at lower suctions (0 and 20cm H_2O). Trends of TC and Db values were very similar. Impacts of tillage system on soil properties had no clear trend at 5-10 and 10-15cm of depth. Manure additions significantly improved TC, Db and WR in the top 5cm for conservation and conventional system, and at 5-10cm of depth for conventional system. Except for WR at higher suctions, soil physical properties at the 5-15cm layer were generally improved by conventional system, when compared do conservation system. We conclude that six years of conservation tillage and manure additions to this degraded sandy soil was enough time to improve most soil properties herein assessed only in the top 5cm.

Results of this research can help farmers, extension personnel and consultants to decide about the suitability of management practices for conditions similar to the southeastern Coastal Plain soils studied here. However, longer term research is needed to better describe observed impacts on this landscape.

INTRODUCTION

Southeastern US Coastal Plain Soils

Feasible solutions to recover and stop soil degradation in the southeastern US Coastal Plain have been intensely investigated (Terra et al., 2006; Siri-Prieto et al., 2007; Balkcom et al., 2006), mostly in relation to natural susceptibility to degradation associated with intense use of conventional tillage practices in this region. Soils in the Southeast Coastal Plain are commonly classified as Ultisols, of udic moisture regime, with coarse-textured surface horizons overlaying clayey acidic horizons, highly weathered mineralogy, weakly structured, low in organic matter content, with low water holding capacity, and commonly having compacted subsurface layers that can limit water availability for plant growth (Radcliffe et al., 1988; Miller and Radcliffe, 1992; Reeves, 1997; Franzluebebers, 2005; Shaw et al., 2002; Truman et al., 2005; Schomberg et al., 2006). This is a region characterized by warm and moist conditions, where precipitation tends to exceed potential evapotranspiration (Franzluebbers, 2005). Such conditions are conducive for high rates of C decomposition, stimulating high soil activity and fast crop residue break down, which can negatively affect soil aggregation and structure, and consequently create conducive conditions for soil degradation. Although most of these soils are suitable for crop production, weathering conditions affect soil properties which can be detrimental for crop productivity. Truman et al. (2005) reported that these highly weathered soils tend to be drought-prone, and are susceptible to compaction, erosion and runoff, which consequently reduce crop productivity and threaten the environment.

Conventional Tillage Practices Impact on Southeastern Coastal Plain Soils

In addition to inherent susceptibility to degradation, the southeastern Coastal Plain soils have traditionally been intensively cropped under conventional tillage systems, mostly disk and chisel plow (Truman et al., 2005; Siri-Prieto et al., 2007). These conditions stimulate rapid residue and organic C decomposition (Motta et al., 2002), and accelerate erosion, sedimentation of waterways, and transport of pollutants into water bodies through colloidal facilitated transport of nutrients and pesticides (Shaw et al., 2002). In addition to unsustainable tillage practices, a large portion of these soils have been cultivated with continuous cotton monoculture (Shaw et al., 2002), which is another contributing factor for soil degradation.

Tillage involves the mechanical manipulation of the soil, and has been used by farmers for centuries in order to control weeds, create a suitable seedbed for the crop, and to incorporate organic residues into the soil (Brady and Weil, 1996). The immediate effects of most conventional tillage practices can be beneficial, like breaking down crop residues quicker and increasing soil porosity. Diaz-Zorita et al. (2004) reported that seedbed tillage for winter wheat (*Triticum aestivum* L.) enhanced grain yields because of decreased compaction and warmer soil temperatures compared to a no-till system. However, by leaving the soil surface bare and subject to wind and water erosion, tillage practices hasten mineralization of soil organic matter (SOM) with increasing aeration and temperature (Skopp et al., 1990). Also, by loosening the surface soil, conventional tillage practices have a tendency to compact the soil below their working depth (Brady and Weil, 1996). Kay (1990) reported that in agricultural soils, tillage and traffic are major factors involved in soil structure degradation due to soil fragmentation and compaction process. Franzluebbers (2005) compared the effects of tillage practices on soil erosion, and reported that most of the soil erosion experienced in the southeast US during the 19th and 20th centuries was a consequence of inversion tillage practices. Frequent use of tillage in crop cultivation releases organic matter protected in aggregates and redistributes C in the soil profile, creating conditions more favorable for C decomposition (Franzluebbers, 2005; Rothon 2000). Soil organic carbon (SOC) has been frequently reported to improve soil properties, and was recognized by Reeves (1997) as a keystone soil quality indicator. Based in a series of tillage studies, the author concluded that continuous cropping results in a decline of SOC, and that the rate and magnitude of the decline is dependent on climate and soil type.

Conservation Systems and their Suitability for Southeastern Coastal Plain Soils

Conservation systems have been accepted as a potential tool for managing crop fields in the Southeast because they have demonstrated to increase soil C and crop yields, reduce erosion and runoff, increase infiltration and water holding capacity, improve soil quality and water conservation (Terra et al., 2006; Reeves, 1997; Siri-Prieto et al., 2007; Truman et al., 2005; Franzluebbers, 2005). The main objective of conservation tillage is to keep at least 30% of the soil surface covered with crop residue (Brady and Weil, 1996). Examples of conservation systems are no-tillage, ridge till, striptill, paratill® (Bingham Brothers, Lubbock, TX), mulch till and reduced till, which vary according to the tillage operation involved prior and during planting (Brady and Weil, 1996). Striptill, which is extensively used in the southeast US, consists of an in-row subsoiling shank of approximately 40cm deep and 2.5cm wide, and can include coulters and rolling baskets

(Busscher and Baurer, 2003). A typical striptill implement disturbs 15 to 30cm of the row zone, but the inter-row surface area remains undisturbed and covered by plant residues (Kaspar et al., 1990).

Although complete absence of soil tillage has been reported to improve soil properties and crop yield (Bescansa et al., 2006; Radcliffe et al., 1988; Reynolds et al., 2007), the use of non-inversion deep tillage, like paratill and striptill, has been a common practice because of naturally or anthropogenic induced soil compaction, consolidation, and formation of hardpans (Schomberg et al., 2006; Truman et al., 2005). Raper and Bergtold (2007) attributed the formation of hardpans to the use of tillage equipment for several years at the same depth, and to naturally occurring interactions between small and large soil particles. These dense subsoil layers, often called hardpans, affect plants by restricting roots development and limiting water and nutrient uptake (Ewing et al., 1991). Subsoiling has become a common practice to alleviate those compacted soil zones. Siri-Prieto et al. (2007) assessed the effects of tillage system on soil properties for three years in a cotton-peanut (*Arachis hypogaea* L.) rotation with integrated winter annual grazing in a sandy southeastern US Coastal Plain soil with an inherent hardpan, and found improvements in IR, cone index, Db, SOC, total nitrogen (N), and greater yields for cotton and peanuts for non-inversion deep tillage (paratill), compared with other tillage systems including no-till. Similarly, Schomberg et al. (2006) compared the impact of tillage systems on cotton production in a Georgia Coastal Plain soil, and found increased yields and annual returns for striptill, compared to no-tillage. Terra et al. (2006) observed a 14 and 15% increase in crop productivity for corn and cotton, respectively, due to conservation system use in central Alabama.

Adoption of Conservation System and Effects on Soil Physical Properties

Conservation systems have been frequently reported to improve soil properties, and consequently crop yields. Rhoton (2000) compared the effects of no-tillage adoption on soil properties to a conventional system after four and eight years in a silt loam soil of Mississippi. The author reported significant improvements in soil chemical properties, soil C and AS within the first four years of the experiment, compared to the conventional system, and attributed the improvement in soil properties to SOM increase. Sharratt et al. (2006) compared tillage effects on soil hydraulic properties in a semi-arid region of Alaska, and concluded that after 20 years, Ksat and WR were greater for no-tillage, compared to a conventional tillage system. Lal et al. (1994) assessed the effects of no-tillage on soil properties after 28 years, and reported improvements in AS and lower Db at 0-15cm of depth.

However, the transition from a conventional tillage system to a conservation system can have detrimental effects on soil physical properties and can influence the adoption of conservation systems by farmers (Terra et al., 2006). Diaz-Zorita et al. (2004) reported that two years of no-tillage was not long enough time to allow soil structure improvement from conventional tillage practices on winter wheat in Kentucky. Hussain et al. (1998) assessed the effect of tillage system on soil properties of a silt loam soil with a fragipan under a corn-soybean (*Glycine max* L.) rotation in southern Illinois, and after eight years observed greater Db in the surface layer for continuous no-till compared to moldboard plow. Similarly, Mahboubi et al. (1993) detected greater Db for the top 15cm of two fields in Ohio under no-till for 28 years compared to moldboard and chisel plowing.

Winter Cover Crops and Manure Additions: Other Options for Increasing Soil C

As already mentioned, the benefits of conservation tillage system on soil properties are in large part attributed to the abundance of residues and SOM increases. Increases in SOC are linked to soil structural stability, and is considered essential for long-term sustainable agriculture, since declining SOC levels generally lead to decreased crop productivity (Allison, 1973). Humified organic mater has the ability to bind mineral particles into aggregates, intensifying cohesive forces among clay particles (Gomez et al., 2001), and reducing susceptibility of soil to erosion. Consequently, researchers and farmers have been encouraged to look for alternative sources for increasing SOC. Crop rotation, manure additions and winter cover crops can increase soil C, and be used in association with conservation tillage.

Increased productivity of conservation tillage systems in the Southeast is often observed with the inclusion of winter cover crops (Schomberg et al., 2006; Langdale et al., 1990). Although the reasons for growing cover crops can vary by region and cropping system, its benefits are usually attributed to the increased soil cover and erosion control, immobilization of soluble nutrients (like nitrates) to prevent their loss by leaching, conversion of atmospheric N (by legumes) to organic N for use by the following crop, addition of organic matter to soils, and to provide cover and protection to seedlings of crops during establishment (Unger and Vigil, 1998). According to Unger and Vigil (1998), increases in soil water storage by cover crops are attributed mainly to reducing runoff and increasing infiltration. Balkcom et al. (2006), concluded that cover crops can improve cotton yield in a sandy loam soil of central Alabama. More specifically, rye (*Secale cereale* L.) and wheat cover crops increased lint yields by 12 and 5%, respectively, compared to no cover. The authors reported that soil moisture content was 5% greater with the use of a cover crop compared to no cover plots. Schomberg et al. (2006) evaluated the impact of seven different cover crops on cotton yield in a sandy Coastal Plain soil in Georgia, and concluded that rye and black oats (*Avena strigosa* Schreb.) were the best choices for that region, due to consistent biomass production and good cotton yields. Striptill with either rye or black oats was considered the best system. However, negative impacts from the use of cover crops have also been reported. Ewing et al. (1991), for example, evaluated cover crops in a loamy sand Coastal Plain soil of North Carolina, and observed depletion of soil water between 28 and 55%, and corn grain yield reduction between 0.5 and 0.9 Mg ha^{-1} for two consecutive years due to use of crimson clover (*Trifolium incarnatum* L.), compared to fallow treatments. The authors suggested that earlier desiccation of cover crop would minimize the effects of soil water depletion.

Animal manure has been used to increase soil C. In addition to the potential benefits to soil properties, the use of manure on crop fields can be a feasible disposal alternative (Butler and Muir, 2006). Singh et al. (2007) reported that farmers in India started to use dairy manure to recover soil C levels, which had decreased due to excessive use of inorganic fertilizers. The same authors reported that manure additions and crop residues restored damaged soil structure in rice (*Oryza sativa* L.) fields by increasing organic C, AS, WR and IR. Annual additions of manure to the soil have been reported to improve soil properties most of the time (Shirani et al., 2002; Mohanty et al., 2007; Singh et al., 2007; Bhattacharyya et al., 2007). Miller et al. (2002) reported that after 24 years of cattle manure applications on a clay loam soil in the Great Plains, WR, soil water content, IR, Ksat and the number of large soil pores were increased. Arriaga and Lowery (2003) assessed the effects of manure additions for 10 years on an eroded silt loam soil of southwestern Wisconsin, and observed Db decreases, and increases in WR, Ksat and corn yield. Butler and Muir (2006), observed increases in SOM, pH, IR, P, K and tall wheatgrass yield in sandy loam soil of north-central Texas from one and two years of manure applications.

Objective and Rationale

Considering the degraded condition of southeastern US Coastal Plain soils and ambiguous information about the impacts of conservation tillage on soil properties and crop yields of this region, a better understanding of soil management is needed. The objective of this study was to assess the effect of management practices on selected soil physical properties of southeastern Coastal Plain soils.

MATERIAL AND METHODS

Site Description

The research site was located at the Alabama Agricultural Experiment Station's E.V. Smith Research Center in Macon County, central Alabama, USA. This is a region of humid climate where rainfall and accumulated soil moisture exceeds evapotranspiration most of the year (White, 2005). The soils are predominantly fine and fine-loamy, siliceous, subactive, thermic Typic, Oxyaquic and Aquic Paleudults, derived from Pleistocene age alluvial terrace deposits, which are distributed across a variable landscape on the Coastal Plain formation. For the present study, three zones typifying summit, backslope and drainage way landscape positions were selected from the previous work by Terra et al. (2006), and recognized as Zone 1, 2 and 3, respectively.

The research site consists of a 9ha field with slope ranging between 0 to 8%, and has had a long history of row cropping. Cotton under conventional tillage consisting of moldboard or chisel plowing and disking was the cropping practice for 30 years before treatments were established in 2000.

Field Practices and Treatments

Four management treatments were established during a previous study in late summer of 2000 on a corn and cotton rotation with both crops present each year. The management systems were established in 6.1 m wide and 240 m long strips crossing the landscape in a randomized complete block design (RCB), and divided into cells to simplify sampling and field measurements. Management practices included a conventional system (chisel- followed by disc-plow + in-row subsoiling) with 10 Mg ha^{-1} yr^{-1} (dry matter) dairy manure (CT+M) and without manure (CT), and a conservation system (no surface tillage with in-row subsoiling) that incorporated the use of winter cover crops with 10 Mg ha^{-1} yr^{-1} (dry matter) dairy manure (NT+M) and without manure (NT). A mixture of rye with black oats, and a mixture of crimson clover with white lupin (*Lupinus albus* L.) and fodder radish (*Raphanus sativus* L.) were typically used in the conservation system as winter cover before cotton and corn, respectively. All in-row subsoiling operations were performed immediately prior to planting with a KMC (Kelly Manufacturing Co., Tifton, GA) striptill equipped with closing rubber tires to a depth of 40cm in an attempt to disrupt any hardpan.

Data Collection and Measurements

Soil samples and field measurements were taken during the Summer and Fall of 2006 (approximately 6 years after the beginning of the experiment) from 24 cells (between crop rows, on non-traffic positions) after cotton cropping, with 6 replications in the entire field. Differences in row spacing between corn and cotton (76 and 100cm) crops could had influenced the results, however, it was not considered on the study. Two hundred and sixteen undisturbed cylindrical soil cores of 5cm in height and 7.4cm in diameter were collected at 0-5, 5-10 and 10-15cm of depth between crop rows (non-traffic), and analyzed for WR, Ksat and Db. Soil samples were saturated in deaerated 0.005 M calcium chloride solution prior WR determination by the hanging water column technique (Dane and Hopmans, 2002a), for suctions of 20, 80, 140 and 200cm H_2O. Consecutively, the samples were transferred to a pressure plate extractor (Dane and Hopmans, 2002b) in order to determine WR for suctions of 300, 500 and 1000cm H_2O. Hydraulic conductivity of saturated soil was determined by the falling head method (Reynolds and Elrick, 2002), following sample saturation in 0.005 M calcium chloride solution. Bulk density was determined by measuring the dry mass of soil in the cylinders (Grossman and Reinsch, 2002).

Total carbon and PSD were analyzed at 0-5, 5-10 and 10-15cm of depth, and due to time constraints and limited resources, one composite sample consisting of 20 sub-samples was collected per cell. Soil samples for TC were dried at 55ºC for 48 hours, ground to pass a 2 mm sieve, finely ground for 12 hours in a conveyor-belt roller mill apparatus and analyzed at 950 ºC by dry combustion using a LECO® Truspec instrument (Leco Corp., St. Joseph, MI, 2003). Three IR measurements per cell were taken at the soil surface with a mini-disk tension infiltrometer (Decagon Devices Inc., Pullman, WA) between crop rows (non-traffic). Soil samples for wet-aggregate stability analysis were collected at 0-10cm of depth, air dried for 48 h, and analyzed in the laboratory by a method similar to the one described by Nimmo and Perkings (2002).

Statistical Analysis

Generalized mixed models were used to analyze the data. All response variables fulfilled the normal distribution assumption, except for Ksat, which was then fitted with a lognormal distribution. Data were analyzed with the GLIMMIX procedure in SAS (SAS Institute Inc., Cary, NC). The experiment was analyzed as a nested RCB within the three zones. Treatments, depths, and their interactions were considered fixed effects, and replication and its interactions with treatments were treated as random effects. Quantitative treatment variables were modeled in a mixed model environment in SAS. Zone effects on soil properties are acknowledged in this study and were included in the analysis, however, this discussion is focused on treatment effect only. An F statistic with $P \leq 0.10$ was used to determine the significance of the fixed effects for all analyses.

RESULTS AND DISCUSSION

Total Carbon

After 6 years since the experiment was started, TC content of this Coastal Plain soil was significantly ($P = 0.042$) affected by the interaction between tillage system, manure addition and depth (Table 1).

Manure significantly ($P \leq 0.01$) increased TC content for conservation and conventional systems in the top 5cm of this Coastal Plain soil (Figure 1). Total carbon content for NTM and CTM were 69.3 and 82.6% greater than NT and CT, respectively. Greater crop residue and manure accumulation on the soil surface due to the lack of soil mixing yielded the greatest TC content for NTM (14.7 g kg^{-1}) at 0-5cm of depth. These results are in agreement with the findings of Terra et al. (2005) for the same field (Table 2), where TC contents for NTM and CTM at the 0-5cm layer were greatly increased by annual manure application 30 months after the experiment was established. Shirani et al. (2002) have also reported significant increases in organic matter content from manure additions in the top 5cm of a silty clay loam soil that was conventionally tilled. In that study, farmyard manure was applied for 2 years to a soil with low initial organic matter content (4.6g kg^{-1}) in central Iran.

Manure addition significantly increased TC for the lower depths of the CTM treatment (Figure 1). At 5-10cm of depth, TC content for CTM was significantly greater than any other treatment, and 77.7% greater than CT. Although overall TC content at 10-15cm of depth was lower than at 5-10cm, results at the lower depth had the same trend as the 5-10cm layer; TC content for CTM was significantly greater than CT, NT and NTM (Figure 1). Significant increases in TC content observed below 5cm of depth for CTM can be attributed to manure incorporation to deeper soil layers by conventional tillage practices. Arriaga and Lowery (2003) found significant increases in TC content throughout a soil profile due to long-term (10 years) manure application in a conventionally (fall chisel-plow and spring disking) tilled soil of southwestern Wisconsin. The authors assessed the effect of manure application on physical properties of a soil with three different erosion phases, and found that most differences in TC content due to manure additions were observed down to 25cm of depth.

Focusing on tillage type only, tillage system effect on TC was greatest at 0-5cm of depth. At this depth, the conservation system significantly ($P \leq 0.01$) increased TC compared to the conventional system: total carbon for NT was 51.9% greater than CT, and 40.9% greater for NTM than CTM. Despite promoting a significant increase in TC at 0-5cm of depth, the conservation system did not increase TC content at 5-10 and 10-15cm of depth when compared to the conventional system (Figure 1). Lopez-Fando et al. (2007) found similar results when assessing the impact of tillage system on SOC content of a loamy sand soil from a semi-arid region in central Spain. The authors found significantly greater SOC for no-till treatments at 0-5cm of depth, compared to conventional and minimum tillage. Similarly, no significant differences were observed among tillage systems at depths below 5cm.

As already mentioned, greater impacts of management practices on TC content were observed at 0-5cm of depth. Overall, TC decreased with increasing depth (Figure 2). However, the smallest difference in TC content with depth was observed for CT (Figure 1), which can be explained by the lower C input and the mixing of the soil surface, which breaks aggregates and increases aeration of soil, enhancing organic matter mineralization (Lopez-Fando et al., 2007). Below 5cm of depth, TC only increased in CTM.

Although overall TC content for the present study was inexplicably lower than the findings of Terra et al. (2005) (Table 2), differences among treatments were very similar and had a similar trend. For the former study, conservation system and manure addition imposed for only one rotation cycle significantly increased SOC for the same field. Major impacts of soil management practices on TC were also observed in the 0-5cm depth.

Bulk Density

Bulk density for this Coastal Plain soil was significantly affected by tillage system, manure addition and depth (Table 1). Trends in Db values were very similar to TC content for most treatments and depths (Figure 3). Overall, soil Db significantly increased with increasing depth (Figure 4). Tillage system and its interaction with depth was significant (P = 0.01), and can be observed on Figure 5.

Manure impacts on soil Db varied according to tillage system and depth. For the conservation system, differences were significant only at 0-5cm of depth. At 0-5cm of depth, Db for NTM was significantly (P = 0.012) lower (6.2%) than NT. Differences between NT and NTM at 5-10 and 10-15cm of depth were minimal and not significant (P = 0.995 and 0.562, respectively) (Figure 3).

Manure significantly decreased soil Db at 0-5 and 5-10cm of depth (P = 0.100 and 0.033, respectively) for the conventional system (Figure 3). Soil bulk density for CTM at 0-5 and 5-10cm of depths was 4.0 and 5.5% lower than CT, respectively. Although not significant (P = 0.339), manure also decreased (2.1%) Db at 10-15cm for CTM when compared to CT. Increases in soil TC due to manure applications is the most probable reason for the decrease in Db observed. Several studies have reported decreases in soil Db due to manure additions (Bhattacharyya et al., 2007; Arriaga and Lowery, 2003; Shirani et al., 2002; Terra et al., 2005), and most of them have related decreases in soil Db to TC content increases. Singh et al. (2007) reported a decrease in soil Db due to manure addition in a conventionally tilled loamy sand soil under a rice-wheat system in India. The authors found greater reduction in Db at 0-5cm, followed by 5-10 and 10-15cm of depth, and attributed the Db reduction to increasing SOC.

Tillage system impact on soil Db varied according to soil depth. At 0-5cm, Db values for CT and NT were very similar (1.56 and 1.54 Mg m^{-3}, respectively). Differences between NTM and CTM were greater (1.45 and 1.50 Mg m^{-3}), however not significant ($P = 0.176$). The lowest Db value (1.45 Mg m^{-3}) among all depths and treatments was for NTM at 0-5cm of depth, which can be attributed to a high TC content from crop and cover crop residues and annual manure application.

Greatest differences in Db due to tillage system were at 5-10cm of depth. At this depth, conventional system significantly ($P < 0.01$) decreased Db compared to conservation system; soil Db for CT was 12.3% lower than NT, and 16.9% lower for CTM than NTM. We suspect that the mixing of the soil surface for conventional tillage associated with manure additions enabled greater amounts of C to reach deeper layers of the soil, decreasing soil Db at this depth. This was also observed at 10-15cm of depth, where Db for CTM was significantly lower ($P = 0.023$) than NTM, and although not significant ($P = 0.433$), Db for CT was lower than NT. Greater soil Db found with conservation systems is in agreement with other research (Bescansa et al., 2006). Afyuni and Wagger (2006) assessed tillage system impacts on soil physical properties of a sandy loam Coastal Plain and a sandy clay loam Piedmont soil, and reported greater Db values for both soils in the top 15cm for no-till, compared to conventional. However, tillage system effects on soil Db has been reported as controversial, and in some cases not clear (Blanco-Canqui et al., 2004; Jiang et al., 2007; Bhattacharyya et a., 2006; Lopez-Fando et al., 2007). The result of this study is, to some extent, similar to the findings of previous research in the same field (Terra et al., 2005), where the authors assessed changes in SOC caused by the management practices discussed here (Table 3).

Overall, Db in CT was lower than or similar to NT. Tillage in the CT treatment mixed the top 15 to 20cm of the soil surface and can be partially attributed to the lower Db. Further, translocation of organic materials into the soil profile under NT takes a longer period of time compared to CT; manure had no effect on Db for NTM at 5-10 and 10-15cm of depth. Tillage and manure treatments in the study area have been maintained for six years and indicate that significant effects of NT and NTM on soil Db could take longer than this period of time for this soil.

Aggregate Stability

It was expected that AS would be improved with increases in TC content from manure additions. Increases in TC are typically associated with soil structure improvement resulting from greater soil biological activities and binding of mineral particles into aggregates by organic matter (Singh et al., 2007; Bhattacharyya et al., 2007). However, averaged across tillage treatments, AS on the soil surface was not significantly affected by manure ($P = 0.572$) (Table 1), even though TC content was increased significantly by manure application. Although not significant ($P = 0.114$), AS for CTM was 8.7% greater than CT (Figure 6).

Averaged across manure treatments, AS for this soil was significantly ($P = 0.087$) greater (6.7%) for conservation than conventional system (Figure 7). Improvement in AS and soil structure due to absence or reduction of surface soil tillage was expected and is supported by other research (Lal et al., 1994; Mahboubi et al., 1993; Rhoton, 2000; Wright et al., 1999; Anders et al., 2005; Zhang et al., 2007; Gomez et al., 2001; Hajabbasi and Hemmat, 2000). For example, Rhoton (2000) assessed the influence of time on soil response to no-till practices in a silt loam soil located in Mississippi, and observed significant improvement in AS within the first four years of no-tillage, compared to a conventional system.

Overall, the increase in AS from conservation tillage observed on this Coastal Plain soil is in agreement with similar studies, however the lack of difference in AS due to manure additions is contrary to the literature. Although TC content of this soil increased with manure additions, we assume that 6 years was not enough time to build and improve soil structure, and consequently AS.

Infiltration Rate

Manure application had no significant (P = 0.632) effect on IR (Table 1 and Figure 8). The mean IR values for the treatments including manure (CTM and NTM) were 10.16 and 20.14 cm h^{-1}, respectively, and were very similar to corresponding tillage treatments without manure (CT and NT, 9.84 and 22.56 cm h^{-1}, respectively). No manure effect on IR was unexpected, especially after 6 years of annual manure application. However, this is in agreement with the results observed for AS. In contrast, Bhattacharyya et al. (2007), attributed an increase in IR after 8 years of manure addition to a silty clay loam soil in India to higher C content and subsequent increases in total porosity, better pore size distribution, continuity and stability of pores. Therefore, the findings of this research disagrees with the findings of other studies (Butler and Muir, 2006; Singh et al., 2007; Shukla et al., 2004; Miller et al., 2002), which have reported increased IR from manure application to soil.

Averaged across manure treatments, IR for the conservation system was significantly ($P \leq 0.01$) greater than the conventional system (Figure 9). Mean IR for the conservation system (21.3 cm h^{-1}) was 113.5% greater than for the conventional system (10.0 cm h^{-1}). Similarly, Radcliffe et al. (1988) measured IR in a sandy clay loam soil after 10 years of winter wheat and soybean double-cropping in the southeastern US and found significantly greater IR for no-till, compared to conventional tillage (moldboard plow). The authors used a sprinkler infiltrometer and concluded that it was not clear whether the difference in IR was due to the presence of large macropores in the no-till plots, or a surface crust in the conventional system.

It is expected that reductions in surface tillage will result in greater C content and better soil structure, which can improve soil hydraulic properties (Zhang et al., 2007; Wahl et al., 2004). However, Siri-Prieto et al. (2007) reported IR values to be very similar between chisel plowing + disking (conventional tillage) and non-inversion deep tillage (paratill) after 3 years of integrated winter-annual grazing in a cotton-peanut-cotton cropping sequence. The authors assessed IR with a Cornell sprinkler infiltrometer in a loamy sand soil in southern Alabama, US, with a thick tillage or traffic pan (20 to 35cm) below the soil surface. Significantly lower IR values in no-till were attributed to higher Db and cone index of that soil. Similarly, Sharratt et al. (2006) compared four different tillage systems in a silt loam soil in Alaska, and found greater IR for an autumn chisel plow field. The other tillage treatments included no-till, spring disk and intensive tillage, all maintained in continuous barley (*Hordeum vulgare* L.) for 20 years.

Hydraulic Conductivity of Saturated Soil

The findings of this research indicate that Ksat was not affected by manure (Table 1 and Figure 10), which is in agreement with IR measurements (Figure 8). Tillage system and its interaction with depth significantly (P = 0.01) affected Ksat (Table 1). Although not significant, manure increased Ksat at 0-5cm of depth for CTM and NTM, when compared to CT and NT, respectively.

Overall, Ksat for conservation system treatments was significantly (P = 0.039) greater than the conventional system at 0-5cm of depth (Figure 11). However, compacted sub-layers commonly found on conservation system fields can restrict water flow, requiring the use of non-inversion tillage. Hydraulic conductivity of saturated soil at 5-10cm of depth was significantly (P = 0.070) greater for the conventional system compared to the conservation system (Figure 11). At 10-15cm of depth, tillage system did not significantly affect Ksat (P = 0.253).

Greater Ksat observed for the top 5cm is expected for crop fields under a conservation system when compared to a conventional system. The findings of this research, for the surface layer, are in agreement with other studies (Park and Smucker, 2005; Bhattacharyya et al., 2006; Mahboubi et al., 1993). Reynolds et al. (2007) studied the impact of different tillage and crop systems on soil physical quality and found greater Ksat from long-term (14-17 years) no-till than a conventionally moldboard plow tilled soil. The authors assessed Ksat at the top 10cm of a poorly drained clay loam soil located in Ontario, Canada, and attributed the high Ksat values found on no-till to a small number of highly water-conductive macropores, like continuous cracks, worm holes and abandoned root channels. Buczko et al. (2006) also found greater surface Ksat values for a silt loam field that was under conservation tillage for approximately 10 years, compared to a conventional one. However, in the same study, differences in Ksat due to tillage system were hardly apparent for a sandy loam soil in another location. Jiang et al. (2007) reported Ksat for a corn-soybean-wheat rotation of approximately 10 years under no-till to be ~156% greater than Ksat for a mulch tillage in a corn-soybean rotation.

Impacts of no-till or non-inversion tillage practices on soil physical properties can be detrimental (Mahboubi et al., 1993), especially if soils are subjected to conditions that favor belowground compaction, such as those found in the southeastern US (Raper and Reeves, 2007). Decreases in Ksat from 0 to 15cm of depth observed for conservation systems (NT and NTM) on the present study can be explained by increases in Db values observed at lower depths. Several studies have shown soil physical properties to be negatively affected by the adoption of conservation practices (Ferreras et al., 2000; Moret and Arrue, 2007). Lampurlanes and Cantero-Martinez (2006) attributed decreases in unsaturated hydraulic conductivity of a 4 to 5 years no-till field to higher Db and consequently porosity reduction. The authors measured unsaturated hydraulic conductivity at the soil surface with a tension infiltrometer in a fine-loamy soil of a semiarid area of Spain. Similarly, Moret and Arrue (2007) found unsaturated hydraulic conductivity measured at the soil surface in a 8 years no-tillage field to be lower than conventional system and reduced tillage. The authors used a tension infiltrometer in order to measure Ksat in a loam soil of a semiarid region of Spain.

We believe that greater Ksat values found for the conventional system at 5-10cm of depth, compared to conservation system, is due to increasing soil macroporosity created by soil plowing of that layer. In general, decreases in Ksat with depth are expected for soils with compacted sublayers, and can be related to increasing Db for this field.

Increases in Ksat due to manure additions can be expected, especially in soils with low TC content. Arriaga and Lowery (2003) found similar results for the top 7.6cm of a tilled silt loam soil in southwestern Wisconsin, when assessing the impact of manure additions on soil physical properties of a field with different erosion phases. Although not significant, Ksat at the soil surface was greater on plots that received manure for 10 years, and was attributed to greater TC content.

Water Retention

Manure effects on WR for the sandy loam soil surface studied varied according to tillage system and depth. For conventional systems, manure increased soil WR for all depths (Figure 12), however, differences were greater only at lower suctions (0 to 80cm H_2O). At 10-15cm of depth, WR at higher suctions for CT and CTM (Figure12.C) was greater than for the above depths (Figures 12.A and B), and lower at lower suctions.

Manure additions also increased WR for conservation systems, however, trends were different than for conventional systems. Manure significantly increased WR for the majority of the suction range measured (except for 200 and 300cm H_2O, $P = 0.197$ and 0.118, respectively) in the top 5cm of this soil (Table 4). However, impacts on WR for deeper layers were minimal and not significant (Figure 12.E and F, and Table 4). Although WR at lower suctions was slightly increased by manure at 5-10cm of depth, its impact at 5-10 and 10-15cm of depth were not significant (Table 4).

The increase in WR from manure application for this Coastal Plain soil is consistent with the observation of other similar studies (Miller et al., 2002; Masto et al., 2007). Arriaga and Lowery (2003) assessed the effects of long-term (10 years) manure addition on soil physical properties of a tilled silt loam soil of southwestern Wisconsin. Similarly, WR for that soil was significantly increased with manure additions, with greatest increase at the shallower depth (0-7.6cm). The authors found high correlation between WR, soil C content and Db, and concluded that improvement in soil WR due to manure additions can increase crop yields due to greater water availability for plant uptake. Hati et al. (2007) also found considerable differences in WR due to manure additions at lower suctions on the topsoil (0-15cm) of a conventionally tilled clayey soil in sub-tropical India. The authors assessed WR over a range of 100 to 15,300cm H_2O, and attributed improvements in WR from manure additions to an increased number of small pores.

Tillage effects on WR varied according to depths and manure application. Soil WR for the conservation system was generally greater than the conventional system at higher suctions (300, 500 and 1000cm H_2O) (Figure 13.A, B, C, D, E), but differences were significant only at 0-5 and 5-10cm of depth (Figure 13.A, B, D). These results are in agreement with Bescansa et al. (2006), who found that WR for a conventional system was 11% lower than a conservation system at a water potential of 300cm H_2O in the top 15cm of a clay loam soil of semiarid northern Spain. For that same study, small pores occupied the majority (about 60%) of the pore volume in the conservation system. We speculate that lack of soil tillage keeps structure and integrity of micropores, which guarantees greater WR at higher suctions. Bhattacharyya et al. (2006) reported that at any water potential they tested, soil under no-till retained greater amounts of water compared to conventional tillage. The authors noted that the lack or reduction of soil tillage reduced the volume fraction of large pores and increased the volume fraction of small pores with better pore continuity.

Differences in soil WR at lower suctions varied according to depth. At 0-5cm, WR for NTM was significantly greater than CTM at 20 and 80cm H_2O ($P = 0.094$ and 0.001, respectively), and statistically not significant ($P = 0.395$) at 0cm H_2O. A possible reason for this difference is that manure applied on NTM stayed on the top 5cm of the soil surface, supplying that layer with greater amounts of C, while the manure applied on CTM was distributed through the arable soil layer. Also for the 0-5cm of depth, soil WR at lower suctions was very similar between NT and CT (Figure 13.A). Contrary, Diaz-Zorita et al. (2004) reported greater WR at lower suctions for no-till than a tilled silt loam soil in Kentucky.

At 5-10cm of depth, WR at lower suctions (0 and 20cm H_2O) was significantly greater for conventional than conservation system (Figure 13.B, E). Changes in soil structure caused by soil surface mixing due to disc and chisel plowing are probable causes of increased soil macroporosity of this soil, and consequent increase in WR at lower suctions. These findings are in agreement with Bescansa et al. (2006), where large pores occupied the majority of pore volume for conventional system, compared to conservation system. However, Jiang et al. (2007) found greater WR for no-till than mulch tillage at lower suctions (less than 10cm H_2O) in the top 10cm of claypan soils in central Missouri. The authors measured WR in the suction range of 0 to 200cm H_2O, and observed lower differences due to tillage systems at 10-20 and 20-30cm of depth, compared to the upper layer. At 10-15cm of depth, WR for CTM was also greater than NTM at lower suctions (Figure 13.F).

Although tillage system significantly affected WR at all depths studied for this soil, Blanco-Canqui et al. (2004) found no differences in WR while comparing a 13 year old no-till field with chisel and moldboard plow in a silt loam soil of Missouri.

Overall, manure increased WR at lower suctions for the conventional system, and for all suctions in the top 5cm of the conservation system. Soil tillage increased WR at lower suctions, and conservation system increased WR at higher suctions.

CONCLUSIONS

After six years, the conservation system significantly improved TC, Ksat and WR in the top 5cm of this Coastal Plain field, compared to the conventional system. Aggregate stability and IR, measured at 0-10cm of depth and soil surface, respectively, were significantly greater in the conservation system. Effects of tillage system on WR varied according to matric potential. Conservation system improved WR at higher suctions (300, 500 and 1000cm H_2O), and conventional system improved WR at lower suctions (0 and 20cm H_2O).

Trends of TC and Db values were very similar. Impacts of tillage system on soil properties had no clear trend at 5-10 and 10-15cm of depth. Greater Db values at 5-10 and 10-15cm of depth in the conservation system is an indication of a compacted subsurface layer, and is a probable reason for smaller Ksat values at lower depths. However, we suspect that Db was lower and Ksat values were greater in the row positions for the conservation system due to pre-planting in-row subsoiling compared to the data presented here, where soil samples were collected between crop rows.

Manure application significantly improved TC and Db in the top 5cm for both the conservation and conventional system, and at 5-10cm for the conventional system. Although not significant, those properties were also improved at 10-15cm of depth for CTM. Manure generally increased WR at lower suctions, however, this was not always significant. The combination of surface soil mixing and manure addition on CTM increased TC content at lower depths, and lowered soil Db and increased WR. Although manure additions significantly increased TC content for this soil, improvements in AS, IR and Ksat were very low or non-existent.

Overall, conservation system and manure additions improved some physical properties of this Coastal Plain soil, however, most of the positives effects were at the top 5cm. Perhaps a longer period of time is needed to observe significant changes in soil physical properties at lower depths.

Results of this research can help farmers, extension personnel and consultants to decide about the suitability of management practices for conditions similar to the southeastern Coastal Plain soils studied here.

Reference to trade or company name is for specific information only and does not imply approval or recommendation by Auburn University or USDA - ARS – NSDL to the exclusion of others that may be suitable.

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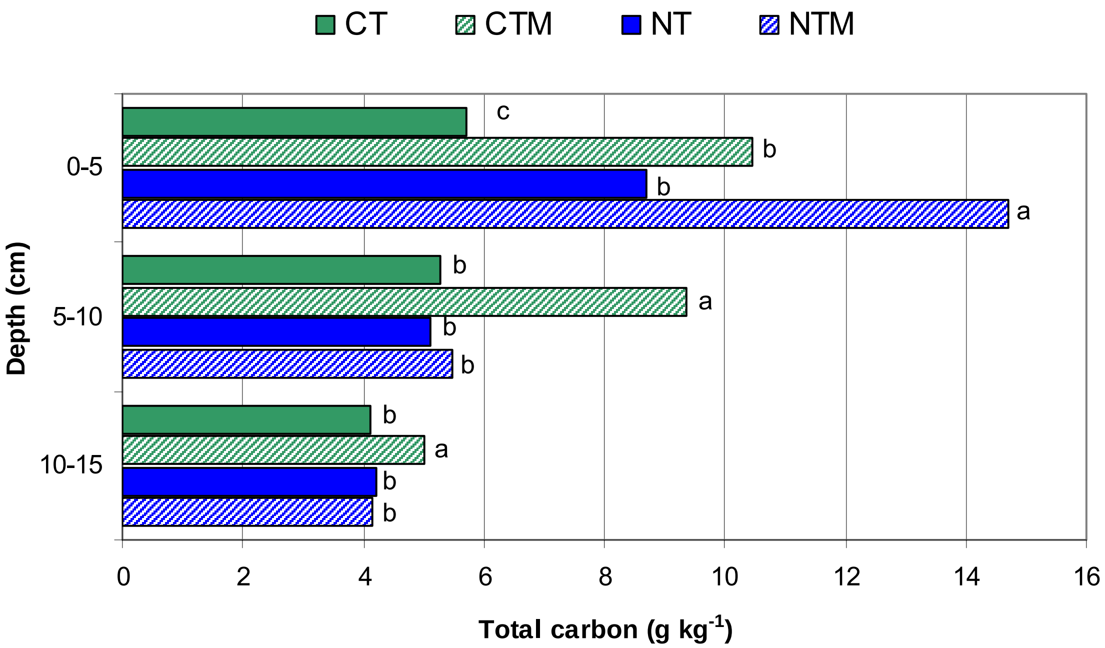

Figure 1. Treatments effect on total carbon for the three measured depths. Letters denote means separation between treatments at the same depth by LSD $_{(0.10)}$.

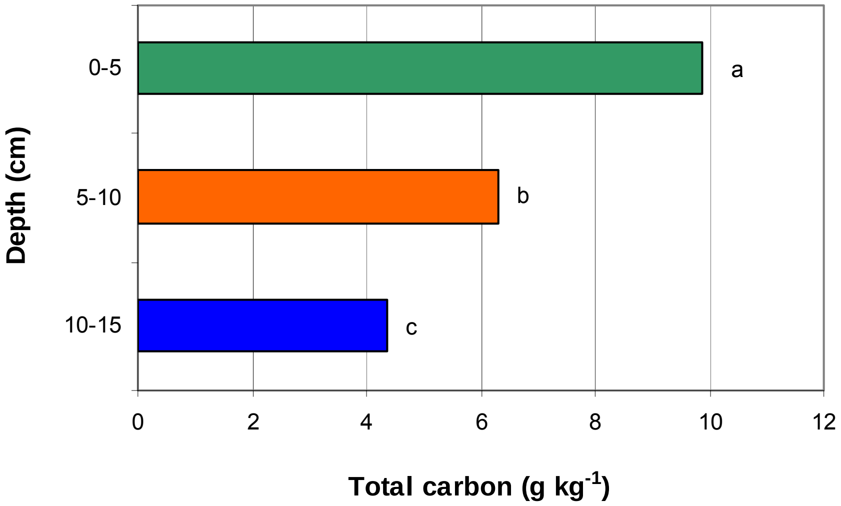

Figure 2. Total carbon content by depth, averaged across treatments. Letters denote means separation between depths by LSD $_{(0.10)}$.

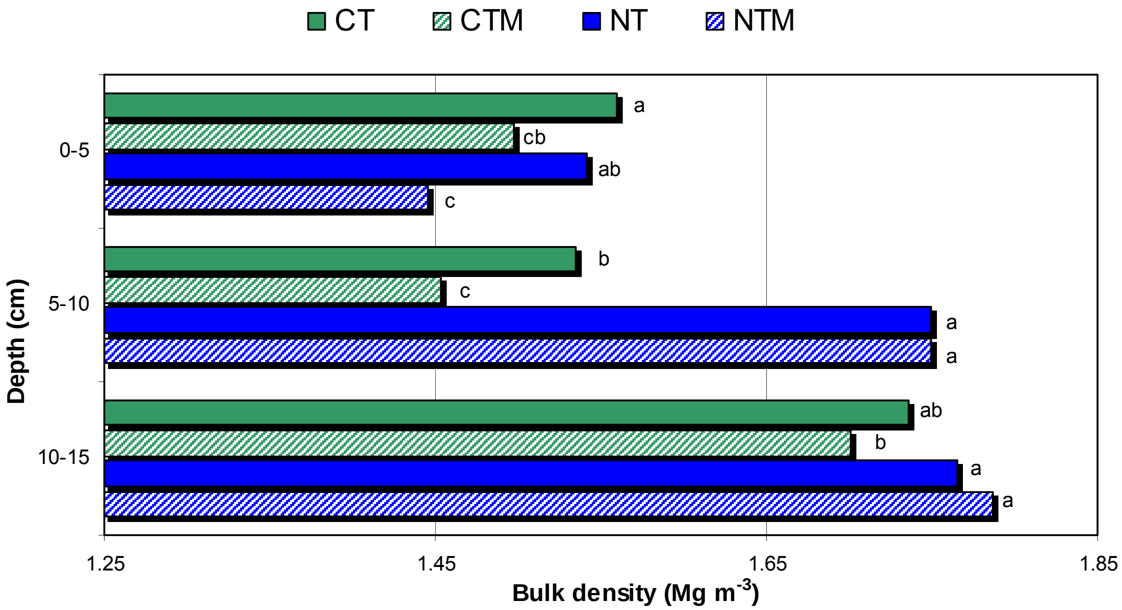

Figure 3. Treatment effect on soil bulk density in the three measured depths. Letters denote means separation between treatments at the same depth by LSD $_{(0.10)}$.

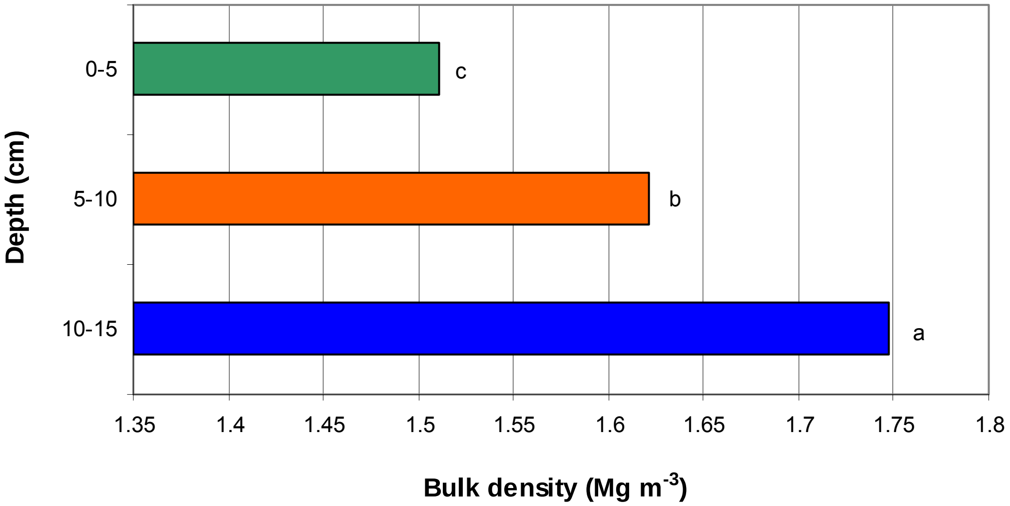

Figure 4. Bulk density values by depth, averaged across treatments. Letters denote means separation between depths by LSD $_{(0.10)}$.

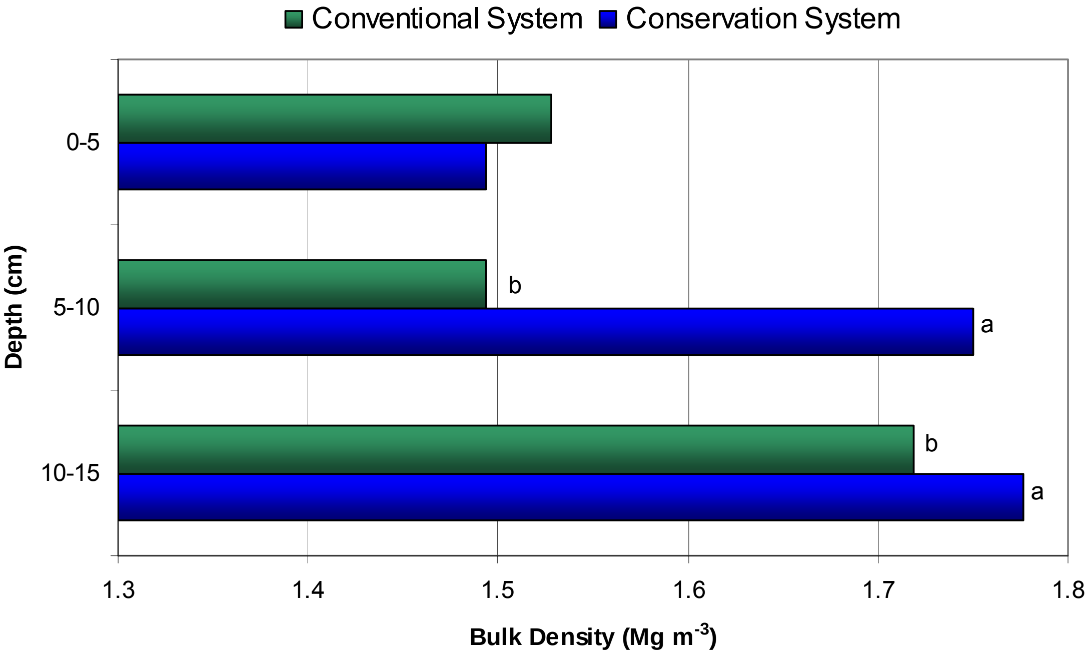

Figure 5. Tillage system effect on soil bulk density, averaged across manure treatments, by depth. Letters denote means separation between tillage systems at the same depth by LSD $_{(0.10)}$.

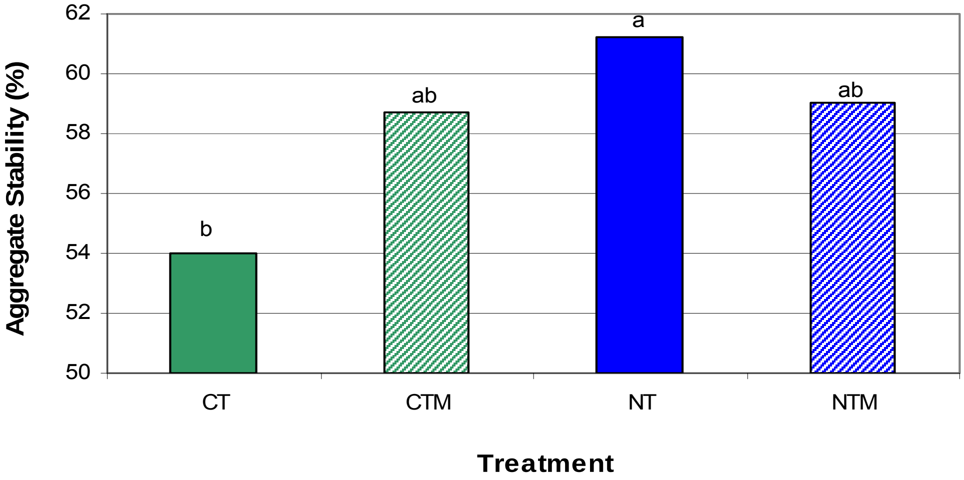

Figure 6. Treatment effect on aggregate stability. Letters denote means separation between treatments by LSD $_{(0.10)}$.

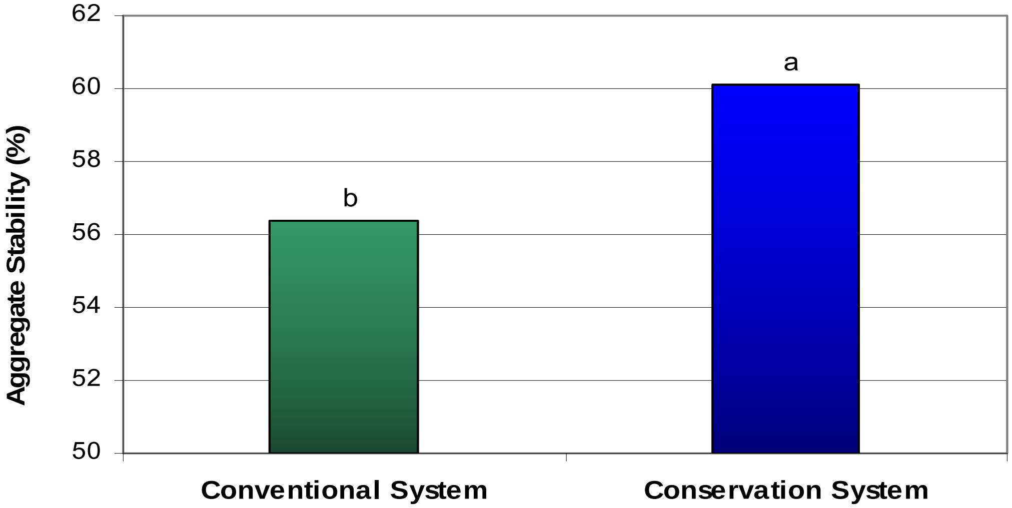

Figure 7. Tillage system effect on aggregate stability, averaged across manure treatments. Letters denote means separation between tillage systems by LSD $_{(0.10)}$.

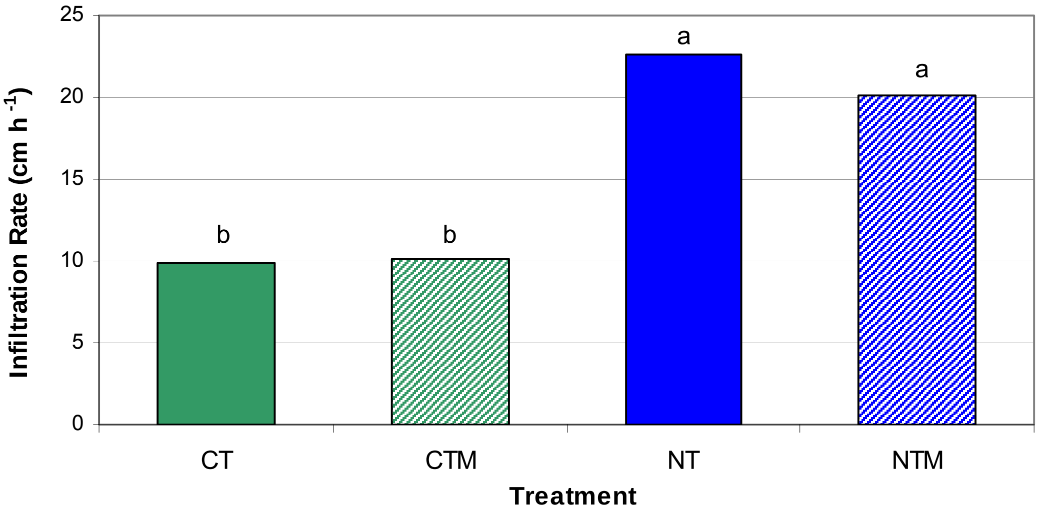

Figure 8. Treatment effect on infiltration rate. Letters denote means separation between treatments by LSD $_{(0.10)}$.

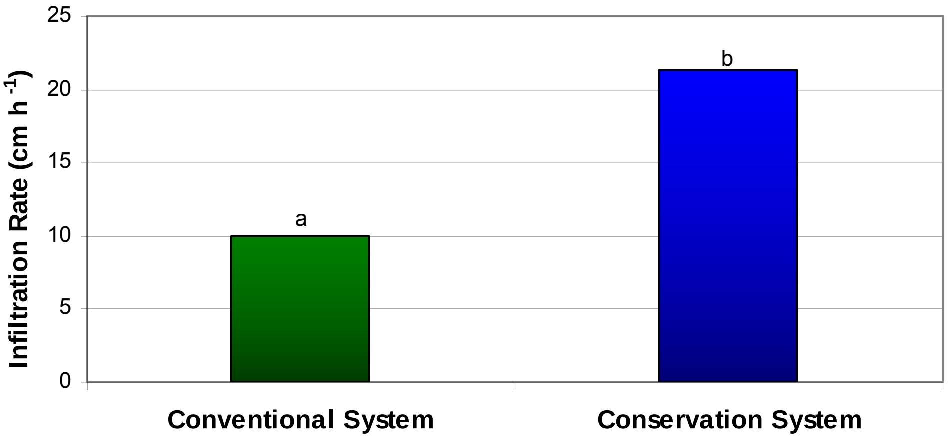

Figure 9. Tillage system effect on infiltration rate, averaged across manure treatments. Letters denote means separation between tillage systems by LSD $_{(0.10)}$.

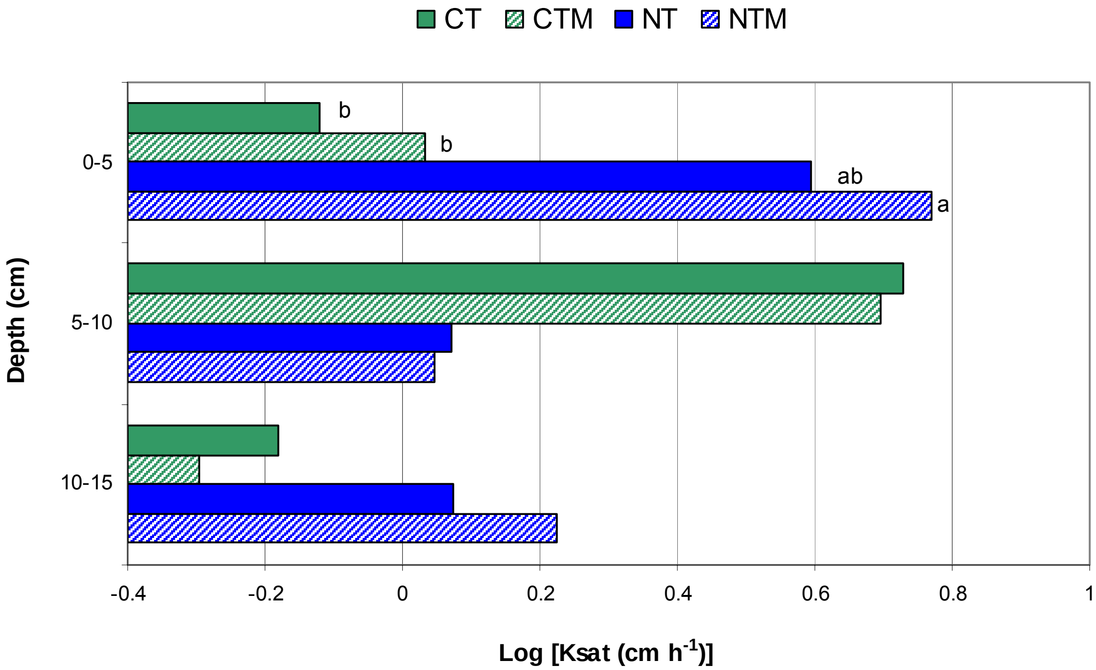

Figure 10. Treatment effect on hydraulic conductivity of saturated soil at the three measured depths. Letters denote means separation between treatments at the same depth by LSD $_{(0.10)}$.

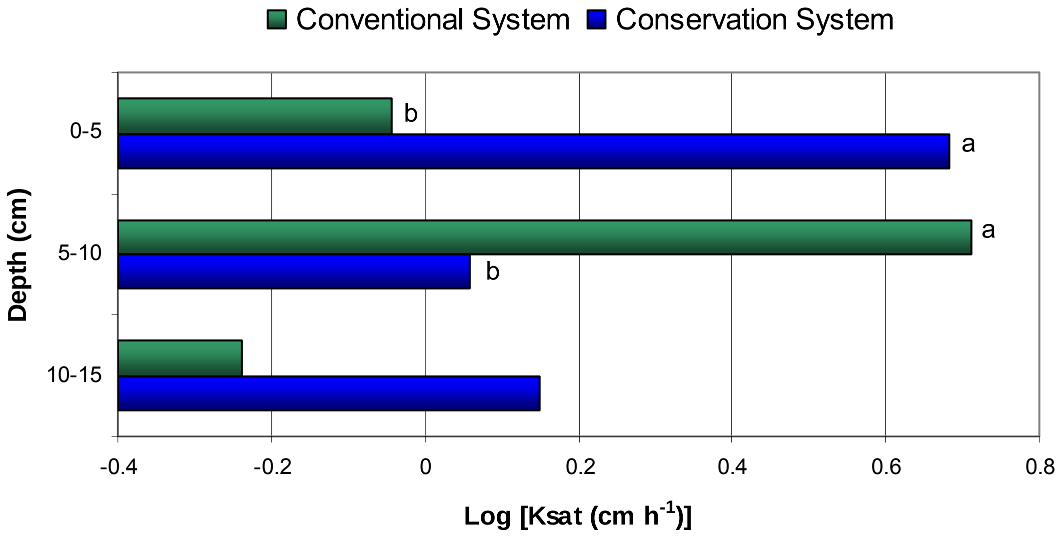

Figure 11. Tillage system effect on hydraulic conductivity of saturated soil, averaged across manure treatments, by depth. Letters denote means separation between tillage systems at the same depth by LSD $_{(0.10)}$.

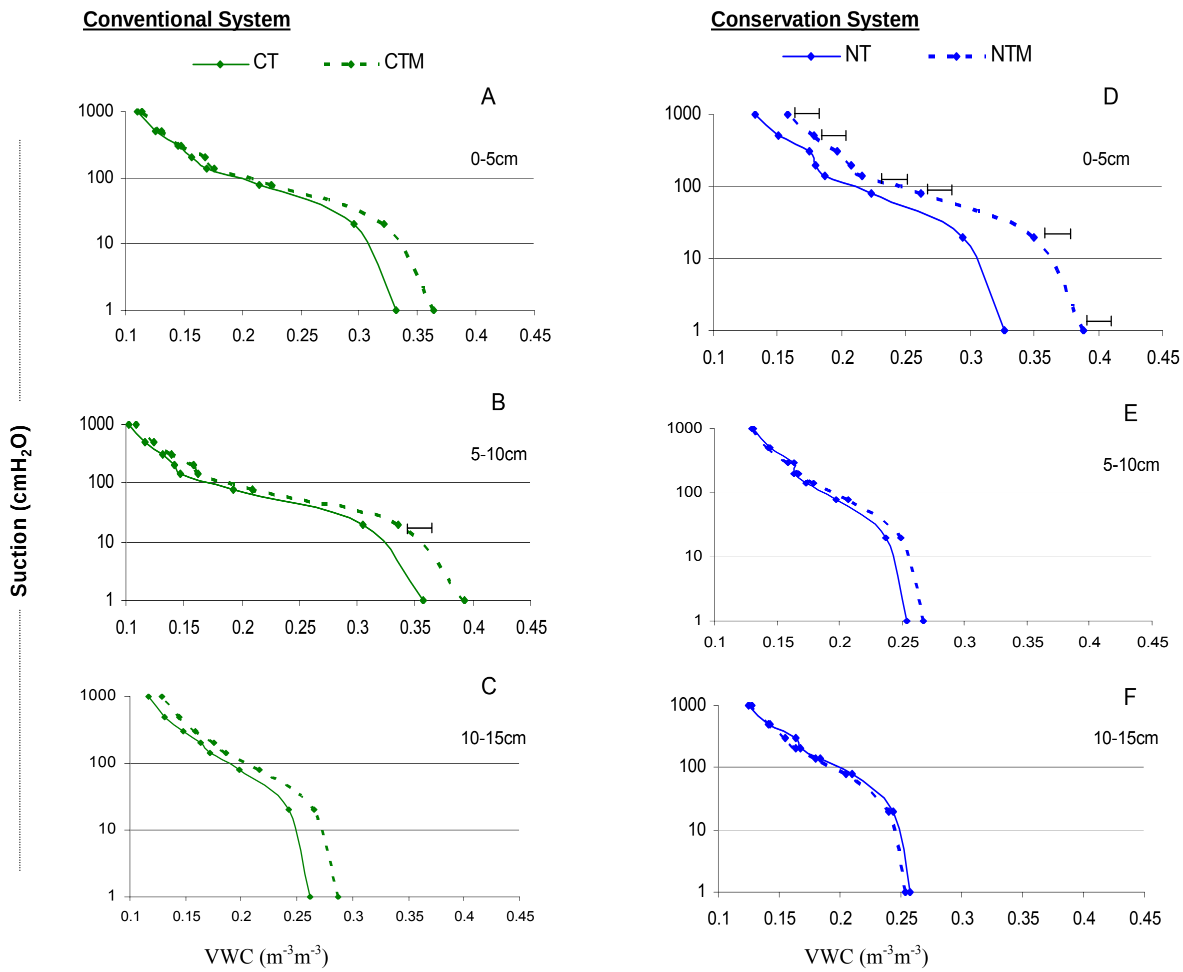

Figure 12. Manure effect on water retention by depth and tillage system. Horizontal bars denote means separation between treatments by LSD $_{(0.10)}$.

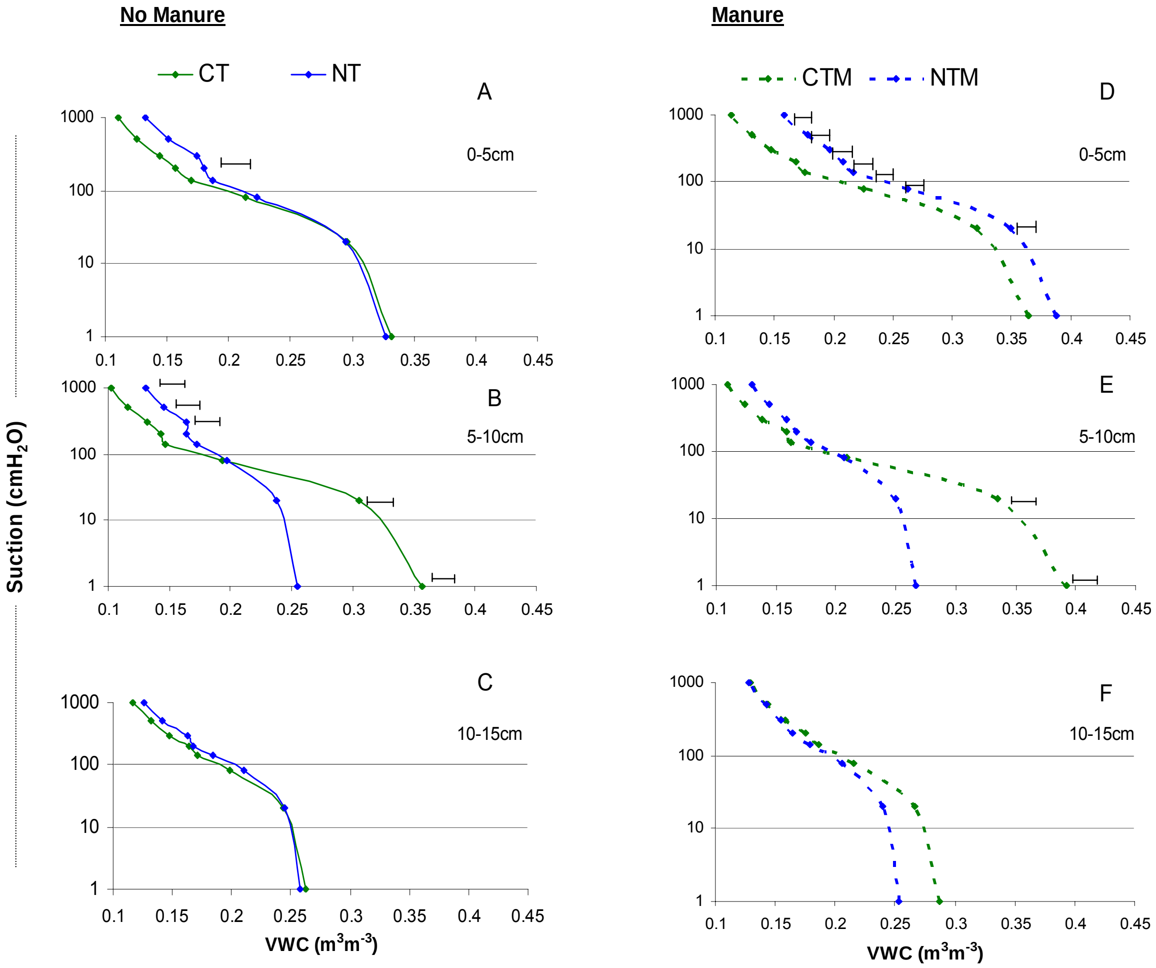

Figure 13. Tillage system effect on water retention by depth, with and without manure. Horizontal bars denote means separation between treatments by LSD $_{(0.10)}$.

Table 1. Analysis of variance summary for total carbon (TC), soil bulk density (Db), aggregate stability (AS), infiltration rate (IR) and hydraulic conductivity of saturated soil (Ksat).

Source of variation	TC	Db	AS	IR	Ksat
Tillage (T)	0.342	<0.01	0.087	< 0.01	0.564
Manure (M)	<0.01	0.033	0.572	0.632	0.848
T *M	0.197	0.341	0.114	0.534	0.851
Depth (D)	<0.01	<0.01	na †	na	0.042
T*D	<0.01	<0.01	na	na	<0.01
M*D	<0.01	0.107	na	na	0.857
T*M*D	0.042	0.203	na	na	0.923

† na = not applicable.

Table 2. Total carbon mean values for the present study and for a study in the same field conducted after one crop rotation cycle (30 months) and prior to experiment implementation.

	Total Carbon (g kg^{-1})				
		After 30 months			
Depth cm)	**Initial†**	**CT**	**CTM**	**NT**	**NTM**
0-5	7.76 c††	7.44 c	11.44 b	10.96 a	19.86 a
5-15	6.13 b	6.12 b	7.75 a	5.81 b	6.01 b
		After 6 years (present study)			
Depth cm)		**CT**	**CTM**	**NT**	**NTM**
0-5		5.72 c	10.44 b	8.69 b	14.72 a
5-15		4.70 b	7.19 a	4.66 b	4.81 b

† Initial = measurement taken before beginning of experiment in 2000.

†† Least square means followed by the same letter within a row are not significantly different at $P \leq 0.10$ level.

Table 3. Bulk density values after 30 months for a study conducted after on crop rotation and 6 years since the beginning of the experiment.

	Bulk density (Mg m^{-3})			
	After 30 months			
Depth (cm)	**CT**	**CTM**	**NT**	**NTM**
0-5	1.35 ab†	1.28 b	1.39 a	1.30 b
5-15	1.58 b	1.52 c	1.62 a	1.62 a
	After 6 years (present study)			
Depth (cm)	**CT**	**CTM**	**NT**	**NTM**
0-5	1.56 a	1.50 ab	1.54 a	1.45 b
5-15††	1.64 b	1.58 b	1.76 a	1.77 a

† Least square means followed by the same letter within a row are not significantly different at $P \leq 0.10$ level.

†† The 5-15cm bulk density values for the present study was averaged from 5-10 and 10-15cm in order to compare it with previous research data.

Table 4. Analysis of variance for water retention: contrast between manure and no manure treatments.

	Suction (cm H_2O)							
	p-value (CT vs. CTM) †							
depth (cm)	0	20	80	140	200	300	500	1000
0-5	0.157	0.163	0.711	0.969	0.877	0.985	0.961	0.982
5-10	0.105	0.082	0.364	0.535	0.620	0.848	0.884	0.906
10-15	0.375	0.245	0.301	0.642	0.849	0.564	0.644	0.627

depth (cm)	p-value (NT vs. NTM) ††							
0-5	< 0.01	< 0.01	< 0.01	0.097	0.197	0.118	0.063	0.057
5-10	0.833	0.753	0.790	0.954	0.996	0.669	1.000	1.000
10-15	0.992	0.985	0.968	0.981	0.993	0.727	0.999	0.997

† CT = conventional system; CTM = conventional system with manure.

†† NT = conservation system; NTM = conservation system with manure.

II. LANDSCAPE VARIABILITY EFFECTS ON SELECTED COASTAL PLAIN SOIL PHYSICAL PROPERTIES

ABSTRACT

Characterizing landscape variability and its effect on soil physical properties is essential for aiding in site-specific crop management (SSM), optimization of inputs and improving farmer's profitability. Topography influences plant water availability and the movement of water and chemicals throughout the soil profile, which in turn have a great impact on crop production. Therefore, understanding the impact of topography and spatial variability on soil physical properties is important for developing and implementing SSM. In order to assess landscape variability effects on soil physical properties, total carbon (TC), particle size distribution (PSD), bulk density (Db), aggregate stability (AS), infiltration rate (IR), hydraulic conductivity of saturated soil (Ksat) and water retention (WR) were measured in 2006 in a 9 ha field with high spatial variability in the central Alabama Coastal Plain. In a previous study, the field was divided into three management zones (MZ) corresponding to summit (Z1), backslope (Z2) and toeslope (Z3), based on local soil properties. Soils in this landscape were mostly fine and fine-loamy, siliceous, subactive, thermic Typic, Oxyaquic and Aquic Paleudults. Tillage system treatments included a conventional system with (CTM) or without (CT) 10 Mg ha^{-1} yr^{-1} of dairy manure, and a conservation system with (NTM) or without (NT) 10 Mg ha^{-1} yr^{-1} of dairy manure. Treatments were established in a corn (*Zea mays* L.)-cotton

(*Gossypium hirsutum* L.) rotation in 2000, after 30 years of cotton monoculture with conventional tillage. Differences among MZ were significant only for Db, WR, Ksat and IR. Water retention was greater in Z1 and Ksat was greater at Z2. Great contrast in WR between Z1 and Z3 reflects the relationship between soil PSD and WR. Although differences in clay content among MZ were not significant, values ranged from 101.0 g kg^{-1} on Z3 to 177.7 g kg^{-1} on Z2. Infiltration rate, AS and Db trends among MZ varied according to tillage system. Conservation system benefits for AS and IR on Z2 and Z3, respectively, were greater than for the other MZ. For conservation system, IR on Z3 was 96.5% greater than Z2, and for conventional system, IR on Z1 was ~161.7% greater than Z2 and Z3. Overall, erosion and depositional processes associated with tillage system were the most important factors affecting the spatial variability of soil physical properties on this landscape.

Results of this research can help farmers, extension personnel and consultants to decide about the suitability of SSM for conditions similar to the southeastern Coastal Plain soils studied here. Observed differences in soil properties through the landscape positions could be used as complementary information to support SSM decisions.

INTRODUCTION

Soil Spatial Variability and Site-Specific Management

Landscape variability can affect soil physical properties and, consequently, plant growth. The movement of water and chemicals through the soil profile can be described and predicted by these properties, which in turn have a great impact on crop yields. Topography influences plant water availability, which is an important factor of temporal yield variability (Kravchenko and Bullock, 2000). If drainage is limited, ponding or lack of aeration can negatively impact yields. However, when rainfall is limited lower landscape positions can benefit from greater soil moisture levels from increased water drainage on those positions. Haws et al. (2004), described WR and flow dynamics in agricultural soils as the primary drivers for crop growth, nutrient cycling, and contaminant transport. As a soil-forming factor, topography also leads to soil differentiation (Jenny, 1941), and can significantly vary patterns of soil physical properties within a field (Warrick and Nielsen, 1980). Changes in landscape also affect water movement through soil profile, and can result in significant differences in physical properties and profile development and differentiation (Jenny, 1941). However, these effects can vary based on management and climate. Undesired processes like water runoff and soil erosion can be highly accelerated in places where patterns of high slopes, temperature and precipitation are present. Van Es (2002) classified the sources of variability for soil physical properties as spatial and temporal, where each may be the result of intrinsic processes that are the consequence of geological, hydrological, and biological processes that affect pedogenesis, or extrinsic, which are cultural or management related.

Crop production has become more costly, and improving recommendations and the implementation of SSM can help farmers achieve input optimization and acquire subsequent savings (Menegatti et al., 2004; Wang et al., 2001; Franzen et al., 2000). Besides the financial benefits, environmental concerns have become one more reason farmers should consider the adoption of the SSM techniques. Groundwater and surface water contamination, generally from mineral nitrogen (N) fertilizers, is strongly related to leaching and runoff rates, and are a potential threat to human health and environmental quality. Therefore, characterizing landscape variability and its effect on soil physical properties is essential for establishing a more profitable and environmentally sound crop management plan.

Management Zones Delineation

In order to improve crop management decisions, the delineation of MZ becomes a crucial step on a farmer's SSM plan. Doerge (1999) defined MZ as "subregions of a field with homogeneous yield-limiting factors, for which a single rate of specific crop input is appropriate." The delineation of a field in smaller management units can potentially save plant and soil inputs, and this is strongly dependent on the degree of spatial variability present within a field. Also, reducing sampling costs by targeting sampling locations based on homogeneity of zones can compensate for the higher cost involved with denser sampling schemes commonly used in precision agriculture (PA). A variety of techniques have been assessed and used in order to successfully delineate MZ on SSM studies. Remote sensing (Sullivan, et al., 2005), yield maps (King, et al., 2005; Vrindts et al., 2005;), topography (Fraisse et al., 2001; Terra et al., 2005), soil electrical conductivity

(EC) (Johnson et al., 2001; Johnson et al., 2003; Corwin and Lesch, 2005; Jung et al., 2005; Jabro et al., 2005), soil survey maps (Franzen et al., 2002; Tomer and James, 2004), soil chemical (Chang et al., 2003) and physical analysis (Shukla et al., 2004; Vrindts et al., 2005; Chen et al., 2004), and crop scouting maps for diseases, insect and weed occurrence have commonly been used to support MZ delineation. Among SSM practices, variable rate (VR) fertilization has been the most used so far, due to the relatively easiness to detect and adjust soil chemical properties.

While studying the effectiveness of the use of landscape attributes to delineate MZ that characterize soil chemical properties in a 51 ha center-pivot-irrigated corn field of rolling topography, Schepers et al. (2004) found distinct differences in pH, EC, P and soil organic matter (SOM) among the four MZ created based on landscape attributes, including soil brightness, elevation and EC. For this study, SOM had a difference of nearly 50% from upland to lowland soils. Franzen et al. (2000) found nitrate (NO_3^-) and phosphorous (P) patterns related to topography in a 31 ha field of variable topography with a winter wheat (*Triticum aestivum* L.), sunflower and spring wheat rotation in North Dakota. The samples were collected on MZ created based on topography. The field was divided in three parts, with greater nutrient variability found in the part where topography varied the most. In another study, Franzen et al. (2002) found MZ based on topography to be more consistently related to soil NO_3^- than an Order 1 soil survey. Balkcom et al. (2005) found pH and P concentration to be affected by landscape positions in a 9 ha corn-cotton rotation in a southeastern Coastal Plain field. However, potassium concentration was more variable among the different MZ, which were created based on topography, EC, crop yields and SOM. Walley et al. (1996) examined the spatial distribution of soil N in forest soils of Canada, and found that spatial variability was not related to any landform element, indicating an absence of topographic control at the scale studied. Wang et al. (2001) found variable soil nutrient response to landscape positions depending on transect and location of land use types in a semi-arid small catchment on the loess plateau in China. Total N, SOM and available N amounts were greater at middle and footslope positions in two different land uses involving croplands and woodlands.

Soil biological properties have also been assessed in different landscape positions. McCulley and Burke (2004) assessed microbial biomass and composition across lowland and upland topographic positions in three grassland sites from eastern Colorado to eastern Kansas. The authors found a slightly different microbial community composition between the landscape positions, with more nonspecific bacteria in lowlands. There were no differences in microbial biomass across the landscape.

Landscape Variability and Crop Yield

In SSM decisions, MZ are usually delineated based on parameters that considerably impact costs and crop yields. Therefore, farmers focus on field parameters which provide support for VR input application that can be feasibly assessed. Among the techniques and data being used to support MZ delineation, the use of topographic-related information has been widely explored and considered as valuable information of low cost and acquisition time. Fraisse et al. (2001) used topographic attributes and soil EC to delineate potential MZ in two poorly drained claypan soils located in central Missouri, and used yield maps in order to evaluate the MZ delineation. Elevation and soil EC were the most important attributes related to yield, with slope and compound topographic index (CTI) being less important. The authors attributed soil moisture conditions and crop tolerance to water stress as the main factors affecting the optimum number of zones. In a different study, Terra et al. (2005) characterized changes in soil properties and crop yield with changes in landscape positions. The authors delineated five different MZ in a 9 ha southeastern Coastal Plain soil in order to assess landscape effects on cotton yield. Soil and topographic surveys, EC, soil organic carbon (SOC) and surface PSD were the factors most correlated to crop yield and were used to delineate MZ. Soil properties explained 16 to 64% of yield variability, which fluctuated through the years among the MZ. Greater cotton lint yields were present in the summit position on wet years, and in the footslope (drainageway) position on dry years, while the backslope had lowest yields for all the years. In another study, Kravchenko and Bullock (2000) assessed the correlation between corn and soybean (*Glycine max* L.) grain yield with topography and soil properties on eight fields located in Illinois and Indiana. The authors found that topography was negatively correlated to SOM, P and K concentrations and explained about 30% of the observed variability of the fields studied. Weather conditions had a considerable influence on the yield-topography relationship. For this study, plant available water was considered to be a main effect on temporal variability, and thus, higher yields were frequently observed at lower landscape positions.

Hornung et al. (2006) compared two MZ delineation methods on three very deep and well drained soils of northeast Colorado. The methods classified the field zones based on their yield potential into high, medium and low. The authors found a method which included topography, bare-soil imagery and farmer’s experience to be relatively more accurate than another one which included SOM, cation exchange capacity (CEC), PSD, bare-soil imagery and season yield map. Kaspar et al. (2004) compared 20 soil properties and terrain attributes of a 16 ha mollisol field of low relief and swale topography located in central Iowa, in order to explain corn and soybean yield spatial variability. Soil attributes, which included horizon depth, carbonate depth, pH, PSD, SOC, N, Fe, K and Zn, explained more of the yield variability than EC, soil color, elevation, slope, profile curvature, plan curvature and depression depth. For that study, landscape position and curvature were the most related to yield. The factors explaining yield variability differed between corn and soybean and between wet and dry years.

Soil Physical Properties and Landscape Variability

Despite that several studies have shown how to successfully delineate the spatial variability of soil physical properties for SSM without considering landscape positions (Shukla et al., 2004, Gaston et al., 2001; Iqbal, 2005a; Logsdon and Jaynes, 1996; Johnson et al., 2001), the interaction of hydraulic soil properties with landscape positions can be useful for farm management decisions but it has seldom been investigated in the southeastern Coastal Plain. Norton and Smith (1930), highlighted the importance of topography on profile characterization, stressing that slope can aid extensively in mapping soils. The authors hypothesize that the character of a soil is determined by the parent material and the environment to which it has been subjected, which includes slope of the land surface. In this study, PSD, structure, color, consistence and depth to horizons related to slope in mature forest soils and prairies of southern Illinois. Data indicated that a correlation between topography and soil characteristics existed. In general, as the slope increased, soil PSD changed from heavy clay to silt loam, horizon depth decreased, color changed from light gray to a reddish yellow, structure from large angular to small subangular particles, and consistence from compact and plastic to friable and loose.

Elsenbeer et al. (1992) assessed Ksat in three different landscape positions in a first-order rain forest catchment of western Amazonia in Peru. Ultisols and Inceptisols covered by primary rain forest were the soils investigated in this study. Surface Ksat was lowest on side slopes, and Ksat decreased sharply with depth in all topographic positions. The authors considered the detailed survey of Ksat in the study to reveal an obvious link between Ksat and topographic positions. Mohanty and Mousli (2000) investigated the influence of landscape features on the spatial variability of Ksat and soil WR functions along two orthogonal transects of a glacial till landscape in central Iowa. Significant differences in Ksat and WR functions were found between the landscape positions. However, no significant changes in Ksat as a function of topography and depth were found in a study conducted by Sobieraj et al. (2002). The authors used transects to assess the spatial variability of Ksat along a tropical rainforest catena located on Typic Kandiudult and Plinthic Hapludox soils of north Brazil.

Mzuku et al. (2005) assessed the spatial variability of Db, cone index, surface soil color, SOC, PSD, sorptivity, and surface water content in irrigated corn fields, located in low slope, very deep and well drained soils of northeastern Colorado. The authors directed the investigation to MZ delineation based on bare soil aerial imagery of conventionally tilled land, farmers perception of field topography and past soil management practices. Bulk density, SOC, sand, silt, porosity and soil moisture were found to be significantly different between the two most distinct MZ. Schoeneberger et al. (1995) evaluated Ksat within a soil and saprolite continuum and among geomorphic positions of a 10-ha area within a 40 year old pasture on a Typic Kanhapludult soil located in the Piedmont region of North Carolina. Samples were collected from Bt, B/C and C horizons at the center of 15 by 30 m areas located on the ridge top, shoulder and ridge nose landscape positions. Hydraulic conductivity of saturated soil was not assessed on the topsoil-surface (Ap), which was not considered a relevant property for the study. For all geomorphic positions, Ksat was consistently the highest in the clayey Bt horizon, diminishing with depth until the transitional B/C, and then increased with depth into the upper part of C. The authors found that Ksat was closely related with major soil horizons. Besides the C horizon located on the ridge nose position, there was not a significant difference among Ksat values at the three geomorphic positions for the Bt or B/C horizons.

While quantifying harvesting impacts on soils of the boreal forest of Saskatchewan in Canada, Block et al. (2002) assessed landscape position impact on soil Db. Samples were collected from five different sites using a systematic grid pre- and post-harvest at 10 and 20cm of depth. Landscape position showed no significant differences in Db between the shoulder, backslope and footslope positions. Lopez et al. (2003) assessed selected soil physical and chemical properties in the top soil of a pasture field in a northern island of New Zealand in order to evaluate the influence of topography and pasture management on soil characteristics. Soil samples at the depth of 7.5cm were taken from three slope categories, low (0-12%), medium (13-25%) and high (>25%), and two fertility-stocking rates (high and low). The authors found that increasing slopes increased unsaturated hydraulic conductivity and Db, and that volumetric water content (VWC) was greater on low slope areas. In another study, in order to quantify the relationship between soil physical properties and topographical attributes, Iqbal et al. (2005b) collected soil samples based on low, median and high NDVI (normalized difference vegetation index) of a very fine Vertisol in a 42 ha field of rolling topography in east-central Mississippi. Topographical attributes explained 10 to 62% of the variation in PSD, Ksat, Db and WR. Slope, flow length and flow direction explained 45 to 56% of the variation in soil WR. For this same study, topographic attributes in combination with soil variables consistently explained cotton lint yield variability on a field scale. Nolan et al. (2000), examined four methods of separating MZ in a 81 ha no-till field of strong rolling topography with a clay loam soil located in semi-arid prairie conditions of Alberta, Canada. Among Db, SOM, clay and water holding capacity, Db and water holding capacity were most related to the MZ, which were predominantly created based on elevation.

Afyuni et al. (1994 and 1993) evaluated the magnitude of lateral and vertical transport of Bromide (Br^-) as a function of landscape position. They assessed soil physical properties through two transects in a footslope, linear slope and interfluve landscape positions in a corn and wheat silage production field, located in the Piedmont of North Carolina. Clay content was found to be lower on footslope positions, while Ksat decreased with depth, but not with respect to landscape position. Soil water content and thickness of the Ap horizon increased with progression from the footslope to the interfluve, and soil water pressure changed with time and landscape position. The authors believe that the increase in clay content with elevation occurs due to the mixing of soil horizons by tillage implements, surface erosion and soil development. Thompson et al. (1998) described water movement in a Mollisol catena of single hillslope and erosion surface in southeastern Minnesota using soil water monitoring data and terrain analysis. The authors found that at the hillslope scale, stratigraphy and topography have a strong influence on water flow and accumulation. On this study area, the presence of a sandy subsurface over dense till promoted lateral shallow subsurface flow downslope.

Among the studies where soil physical properties and landscape variability relationship are assessed, the impact of slopes on soil quality are frequently reported. Most of the time, intensive tillage associated with higher slopes can potentially cause the movement of large quantities of soil, resulting in different soil patterns. While studying the influence of soil and terrain properties on corn and soybean yield in two minimum tilled fields located in MI, Jiang and Thelen (2004) found elevation to be positively correlated with horizon thickness, and slope positively correlated with coarse sand content. The authors believe that the relationship of slope position to soil properties is controlled by erosion processes, altering soil particle distribution and water redistribution in the field. Pierson and Mulla (1990) also attributed to soil erosion differences in soil properties on summit, shoulder, toeslope and footslope landscape positions of a highly erodible soil located in southeastern Washington. Soil samples were collected in four 800 m transects and analyzed for AS at a slow and a fast rate of wetting, SOC, amorphous Fe, soil water content and PSD. Aggregate stability under slow wetting, SOC and clay content were significantly different at the four landscape positions. More specifically, AS and SOC were highest in footslope and toeslope positions, and lowest at the summit; clay content was highest at the summit and lowest in the footslope positions. The other soil properties assessed on that study were not different at any of the landscape positions. Similarly, Kreznor et al. (1989) attributed to erosion process, cultivation, and especially slope length, the changes in soil properties assessed in a 10 ha cultivated watershed located in northwest Illinois. The fields, originally classified as Mollisols before cultivation, have eroded hillslopes currently classified as Alfisols. The area was divided in hillslope summits, erosional backslopes and upper footslopes, and depositional footslopes and channel. These zones were assessed through transects for surface soil color, thickness of A and Bt horizons, clay and SOC, among other properties. Lower backslopes and upper footslopes were considered either severely or very severely eroded, with near shoulder positions being the least eroded. There was a trend of decreasing thickness of A and Bt horizons with increasing distance along the hillslope from the summit to the footslope. The A horizon thickness and SOC decreased, and clay content increased as a consequence of erosion and cultivation. Unfortunately, there was no direct comparison of those properties through the different landscape positions.

Objective and Rationale

The study of relationships between landscape positions and soil physical properties is essential to provide solid basis for site-specific management, and consequent establishment of a more profitable and environmentally sound crop management plan. The objective of our research was to quantify impacts of landscape variability on selected soil physical properties of a southeastern Coastal Plain soils.

MATERIALS AND METHODS

Site Description

The research site was located at the Alabama Agricultural Experiment Station's

E.V. Smith Research Center in Macon County, central Alabama, US. This is a region of humid environment where rainfall and accumulated soil moisture exceeds evapotranspiration most times of the year (White, 2005). The soils are predominantly fine and fine-loamy, siliceous, subactive, thermic Typic, Oxyaquic and Aquic Paleudults, derived from Pleistocene age alluvial terrace deposits, which are distributed across a variable landscape on the Coastal Plain formation.

The site consists of a 9ha field with a slope ranging from 0 to 8%, and a long history of row cropping. Cotton under conventional tillage consisting of moldboard or chisel plowing and disking was the cropping practice for 30 years until 2000. In a previous study, Terra et al. (2004) subdivided the field in five distinct management zones using a clustering procedure. Elevation, slope, compound topographic index (CTI), EC, clay content, sand content, SOC and depth to seasonal water table explained most of the field variability and were the variables selected for the cluster analysis and zone delineation (Terra et al., 2004). For the present study, three zones typifying the most distinct landscape positions of the field were selected from the previous work by Terra et al. (2004) and recognized as Zone 1, 2 and 3 (Z1, Z2 and Z3, respectively). Zone 1 corresponded to the summit, a relatively flat topographic area dominated by well-drained soils with sand surfaces and deep seasonal high water table (Terra et al., 2005). Zone 2, the backslope, has a sloping and eroded soil with high EC and clay content, and low SOC. Zone 3 corresponded to a drainage way, which is the part of the field with lowest elevation and more poorly drained soils. This section of the field is known for accumulating eroded sediments from upslope areas.

Field Practices and Treatments

Four management treatments were established during a previous study in late summer of 2000 on a corn and cotton rotation that had both crops present each year. The management systems were established in 6.1 m wide and 240 m long strips crossing the landscape in a randomized complete block design (RCB), and divided into cells to simplify sampling and field measurements. Management practices included a conventional system (chisel- followed by disc-plow + in-row subsoiling) with 10 Mg ha^{-1} yr^{-1} (dry matter) dairy manure (CT+M) and without manure (CT), and a conservation system (no surface tillage with non-inversion in-row subsoiling) that incorporated the use of winter cover crops with 10 Mg ha^{-1} yr^{-1} (dry matter) dairy manure (NT+M) and without manure (NT). A mixture of rye (*Secale cereale* L.) with black oat (*Avena strigosa* Schreb.), and a mixture of crimson clover (*Trifolium incarnatum* L.) with white lupin (*Lupinus albus* L.) and fodder radish (*Raphanus sativus* L.) were typically used as winter cover before cotton and corn, respectively. All in-row subsoiling operations were performed immediately prior to planting to a depth of 40cm with a KMC (Kelly Manufacturing Co., Tifton, GA) striptill with rubber tire closing wheels in order to disrupt the hardpan present in these soils.

Data Collection and Measurements

Soil samples and field measurements were taken during Summer and Fall of 2006 (approximately 6 years after the beginning of the experiment) from 24 cells (between crop rows, on non-traffic positions) distributed through Z1, Z2 and Z3, with 2 replications per zone. Two hundred and sixteen undisturbed cylindrical soil cores of 5cm in height and 7.4cm in diameter were collected at 0-5, 5-10 and 10-15cm of depth between crop rows (non-traffic), and analyzed for WR, Ksat and Db. Soil samples were saturated in deaerated 0.005 M calcium chloride solution before WR determination by the hanging water column technique (Dane and Hopmans, 2002a), for suctions of 20, 80, 140 and 200cm H_2O. Consecutively, the samples were transferred to a pressure plate extractor (Dane and Hopmans, 2002b) in order to determine WR for suctions of 300, 500 and 1000cm H_2O. Hydraulic conductivity of saturated soil was determined by the falling head method (Reynolds and Elrick, 2002), following sample saturation in 0.005 M calcium chloride. Bulk density was determined by determining the dry mass of soil in core sample (Grossman and Reinsch, 2002).

Total carbon and PSD were analyzed at 0-5, 5-10 and 10-15cm of depth, and due to time constraints and limited resources, one composite sample composed of 20 sub-samples was collected per cell. Soil samples for TC were dried at 55ºC for 48 hours, ground to pass a 2 mm sieve, finely ground for 12 hours in a conveyor-belt roller mill apparatus and analyzed at 950 ºC by dry combustion using a LECO® Truspec instrument (Leco Corp., St. Joseph, MI, 2003). Particle-size distribution samples were dried at 55ºC, ground to pass a 2 mm sieve, and analyzed by the sieve-hydrometer method, following organic matter removal (Gee and Or, 2002).

Infiltration rate measurements were taken at the soil surface with a mini-disk tension infiltrometer (Decagon Devices Inc., Pullman, WA). Soil samples for wet-aggregate stability analysis were collected at 0-10cm of depth, air dried for 48 h, and analyzed in the laboratory by a method similar to the one described by Nimmo and Perkings (2002).

Statistical Analysis

Generalized mixed models were used to analyze the data. All response variables fulfilled the normal distribution assumption, except for Ksat, which was then fitted with a lognormal distribution. Data were analyzed with the GLIMMIX procedure in SAS (SAS Institute Inc., Cary, NC), and the experiment was analyzed as a RCB nested within the three zones. Treatments, depths, and their interactions were considered fixed effects, and replication and its interactions with treatments were treated as random effects. Quantitative treatment variables were modeled in a mixed models environment in SAS. Zone effects on soil properties are acknowledged for this study and were included in the analysis as a fixed effect. In order to assess differences in soil properties through MZ, soil properties were compared by treatments and depths. An F statistic with $P \leq 0.10$ was used to determine the significance of the fixed effects for all analyses.

RESULTS AND DISCUSSION

Total Carbon

Total carbon content among MZ was very similar and not significantly different (Table 1). Also, there was no significant interaction between MZ and the other fixed effects. Although not significant, TC content among MZ showed a trend, and will be discussed and compared to previous research in the same field, as well as with similar studies relating C content and landscape positions. Mean values of TC for each MZ are shown on Table 2.

Averaged across treatments and depths, TC content was greater on Z1, followed by Z3 and Z2 (Figure 1). Lowest TC value found for Z2 is in agreement with the findings of Terra et al. (2004 and 2005). The authors attributed lowest TC content on that MZ to topography and historical erosion, as well as to attributes more related to low SOC, like field-scale water regime, biomass production and C mineralization. Similarly, Kreznor et al. (1989) reported a decrease in organic C content as a consequence of cultivation and erosion on backslope positions of a landscape in northern Illinois. However, Arriaga and Lowery (2005), assessed the impact of three soil erosion levels on soil C, and although not significant, C content increased with increasing soil erosion phase at the top 0-10cm of depth. The authors attributed the findings to greater clay content observed on higher erosion levels, and the interaction between organic materials and clay particles.

Total carbon content for Z1 and Z3 had an opposite trend than expected. Zone 3 is a concave drainage way of low elevation and is a depositional landscape with poorly drained soils (Terra et al., 2006). Therefore, it is expected that eroded sediments from upslope soils, like SOM, would accumulate on this part of the field and increase TC content. However, greatest TC content measured was in Z1, which corresponded to an elevated area of relatively flat topography dominated by well-drained soils (Terra et al., 2006). The trend of TC content for Z1 and Z3 is contrary to previous research at this field (Terra et al., 2004) and to the literature reviewed (McCulley and Burke, 2004; Wang et al., 2001; Landi et al., 2004; Kravchenko and Bullock, 2000; Pierson and Mulla, 1990), where greater C content have been reported to be on lower landscapes, and lower C on higher landscape positions.

Landscape variability can influence soil C distribution through many factors, including vegetation production, soil erosion, water infiltration and drainage (Arriaga and Lowery, 2005). We speculate that low TC content found on Z3 can be related to the dry weather conditions of the previous years, which associated with greater sand content of this zone stimulated higher microbiological activity and consequent C decrease.

Particle Size Distribution

Overall, clay content was greater on Z2, followed by Z1 and Z3, and although differences were not significant, values ranged from 101.0 g kg^{-1} on Z3 to 177.7 g kg^{-1} on Z2 (Figure 2 and Table 2). The only significant treatment effect on clay content was at 10-15cm of depth, where clay content was greater in Z2 than Z3 for the conservation system (Figure 3). Sand content was greater on Z3, but not significantly different to Z1 and Z2 (Figure 4). Sand content was greater on Z3 than Z1 and Z2, and significantly greater at 10-15cm of depth (Figure 5). Treatments and zones had no interaction.

The observed trend of clay content among the MZ is, to some extent, similar to the findings of Terra et al. (2006) for the same field. However, in the previous study clay was compared at 0-30cm of depth.

Increasing clay content with increasing depth can be expected, and was observed for this soil on Z1 and Z2 of the conservation system (Figure 3). However, this trend was not observed on Z3 for any tillage system, neither for Z1 and Z2 on conventional system (Figure 3). Lack of differences in clay content with increasing depth on Z3 can be a consequence of sediment accumulation from upland on lower parts of the field, composed mostly if sand particles. Also, we consider the mixing of the top soil due to tillage operations to be a contributing factor for the lack of a trend of increasing clay content with depth in all MZ with conventional tillage.

Pierson and Mulla (1990) found greater clay content for summit, followed by slope shoulders and footslope/toeslope positions in a highly erodible loessial soil in southeastern Washington, and attributed differences in clay content to erosion. Contrary to that study, Iqbal et al. (2005b) observed a significant negative correlation between clay content and elevation in a very fine soil of complex rolling topography under soybean-cotton-corn rotation located in Mississippi. The authors found clay content to be low on summit positions and high on steeper slopes and toeslope, and attributed greater clay content on lower soils to downslope colloidal movement.

Based on the findings of this research and on the literature reviewed, we conclude that erosion and deposition processes associated with tillage system, were the most important factors impacting horizontal and vertical spatial distribution of soil PSD for this landscape. Erosion processes increased clay content on Z2 due to partial removal of the sandy soil surface, and deposition processes increased sand content on Z3, the toeslope, due to sediment accumulation.

Bulk Density

Overall Db values for the study site, averaged across treatments and depths, was significantly greater on Z1, compared to Z2 and Z3 (P = 0.063 and 0.016, respectively) (Figure 6). However, tillage system significantly affected differences in soil Db among MZ by depth (Figure 7). Soil bulk density for the conventional system was greater on Z1, and significantly (P = 0.042) greater than Z3 at 0-5cm of depth. Differences between Z2 and Z3 varied according to depth (Figure 7). For the conservation system, Db at 0-5cm of depth was significantly greater on Z1 compared to Z2 and Z3 (P = 0.003 and 0.027, respectively). At 5-10cm of depth, Db on Z2 was significantly greater than Z3 (P = 0.027), but not significantly different to Z1 (P = 0.282). At 10-15cm of depth, Db on Z2 was greater than on Z3 and Z1, although not significant (P = 0.564 and 0.803, respectively). Mean values of Db for each MZ, separated by tillage system, are shown on Table 3.

In summary, soil Db for conventional system was greater on Z1, and for conservation system, except for 0-5cm and 10-15cm of depth, it was greater on Z2. Lowest Db varied according to tillage system and depth, and did not have a clear trend. Greater soil Db found on Z1, the summit position, is not in agreement with the findings of other properties for the same part of the field. One would expect lower Db on Z1 due to relatively greater TC and clay content, and lower sand content found on this MZ, compared to Z3.

We speculate that the benefits of the conservation system associated with greater clay content on Z2 have provided lowest Db for the top 5cm of that soil, compared to the other MZ. However, after 6 years of conservation system, the 5-15cm soil layer of Z2 had greater Db among all MZ under conservation system, suggesting that historical erosion and soil degradation of that area have increased Db of this soil layer.

The literature reporting landscape position effects on soil Db does not suggest a clear trend. Afyuni et al. (1994) assessed lateral and vertical bromide ion transport in a Piedmont landscape of a conventionally tilled clayey soil, and reported greater Db for the Ap horizon of the backslope, followed by shoulder and footslope. Contrarily, Schoeneberger et al. (1995) found increasing soil Db for ridge top, shoulder and ridge nose positions, respectively, across a typical landscape of clayey soil in the Piedmont region of North Carolina. Although not significant, Block et al. (2002) found greater Dd on shoulder than backslope and footslope positions of a landscape in a silt loam soil of the boreal forest of Saskatchewan, Canada. Lopez et al. (2003) assessed the impact of three slope categories on soil properties of an Inceptisol under pasture for 40 years located in southern North Island of New Zealand, and found greater soil Db in zones of higher slope. Contrary, Iqbal et al. (2005b) found lower Db on steeper slopes of clayey soils located in east-central Mississippi.

Based on the findings of this research and on the literature found, we assume that landscape variability can potentially affect soil Db, however, relationships between landscape positions and Db can not be predicted. We suggest that differences in factors like soil PSD, climate and others interact with topography and affect soil Db.

Aggregate Stability

Averaged across treatments, differences in AS were very low and not significantly different among MZ (Table 1, Figure 8). There was a significant ($P = 0.018$) interaction between MZ and tillage system within Z2 only (Figure 9).

Although not significant, there were some differences in AS between MZ in conservation tillage (Figure 9). Aggregate stability on Z2 was 24.9% greater than Z3, and 19.6% greater than Z1 ($P = 0.156$ and 0.223, respectively). We speculate that greater clay content of Z2, associated with the lack of surface soil tillage and greater TC content provided better soil structure to this MZ due to association of clay and organic matter. Greater TC content on the topsoil of the conservation system provides more biding agents such as roots, fungi, and mucilaginous gums, required for the formation of stable aggregates (Boehm and Anderson, 1997).

Literature describing impacts of landscape positions on AS is scarce, and results are not coherent with our findings. Pierson and Mulla (1990), assessed landscape variability effect on AS of a highly erodible loessial soil in southeastern Washington and found significantly different AS at summit, shoulder, toeslope and footslope positions. More specifically, AS for that soil was greater in lower slope positions than in upper slope positions. The authors attributed decreasing AS through landscape positions as a result of topsoil erosion and a reduction in organic C content. Similarly, Boehm and Anderson (1997) reported greater AS on footslope, followed by backslope and shoulder positions, for a soil quality study in glaciolacustrine landscape located in Saskatchewan, Canada.

Infiltration Rate

Averaged across treatments, IR values were not significantly ($P = 0.240$) different among the MZ (Table 1). Although not significantly different, IR for Z1 was 100.3% greater than Z2 ($P = 0.120$), and 21.5% greater than Z3 ($P = 0.502$) (Table 1 and Figure 10).

However, the interaction between tillage system and MZ was significant ($P = 0.042$) (Figure 11). For conservation system, IR on Z3 was 96.5% greater than Z2 ($P = 0.058$), and similar (14.4% greater) to Z1 ($P = 0.556$). For conventional system, IR on Z1 was ~161.7% greater than Z2 and Z3, however, differences were not significant ($P = 0.109$ and 0.107, respectively). Different trend of IR among MZ were observed for the conservation system. Although IR on conservation system was greater for all MZ compared to conventional system, Z3 had greater IR than Z1 and Z2. Greater sand content and lowest Db values associated with lack of surface soil tillage could have contributed to the greater IR for Z3 under conservation system.

Tillage system affected IR among MZ for this landscape. The greatest IR was observed in Z1, and the similarity between Z2 and Z3 on conventional system were expected results for this field, and agree with previous description of the site, where Z1 and Z3 are described as well-drained and poorly-drained soils, respectively (Terra et al., 2006).

Similarly to the findings of this research for conservation system, Sauer et al. (2005) reported consistently greater IR for soils in the valley bottom than upland and side slope soils of a watershed under forest and pasture located in Arkansas. Contrary, Kennedy and Schillinger (2006) assessed the impacts of tillage systems on summit, backslope and toeslope positions of soils in the Palouse region of Washington, and found no differences in ponded water IR through the landscape studied.

Hydraulic Conductivity of Saturated Soil

Management zones significantly (P = 0.093) affected Ksat (Table 1). Hydraulic conductivity of saturated soil on Z2 was significantly greater than Z1 (P = 0.044), and although not significant (P = 0.110), it was greater than Z3 (Figure 12). There was no significant interaction between MZ and the other fixed effects (Table 1).

Trends of Ksat values among MZ was not expected for this landscape, especially for Z2, where Ksat was greatest and had an opposite trend to IR (Figure 10). Historical erosion due to relatively greater slope, associated with 30 years of conventional tillage practices have increased clay content in the surface soil of Z2 (Figure 2) and reduced TC contents (Figure 1). However, greatest Ksat values observed on Z2 can be partially attributed to increased AS for conservation system (Figure 9) and low Db values (Figure 6). Trends of Ksat in Z3 can be attributed to relatively high sand content and low Db, however, trends between Z1 and Z3 are not in agreement with the drainage description of the site. Terra et al. (2006) reported Z1 and Z3 as well-drained and poorly-drained soils, respectively.

The trends observed in this study for Z1 and Z3 are in agreement with the findings of other researchers. Afyuni et al. (1994) measured Ksat in the Ap horizon of a Piedmont landscape of North Carolina in order to assess Bromide ion transport, and found greater and lower Ksat for footslope and summit, respectively. The authors concluded that the most rapid solute transport occurred in the footslope due to lower clay content and that this landscape position accumulates water from higher elevations.

High Ksat values observed on Z2 are not in agreement with the findings of Jiang et al. (2007) for a claypan-soil toposequence in central Missouri. For that study, Ksat was lower in the backslope position, and greater in the footslope. Mohanty and Mousli (2000) assessed soil physical properties across a soil-slope transition in a complex terrain of loam soils located in central Iowa, and found greater Ksat on the hilltop than shoulder positions in the top 15cm. An unexpected increase in Ksat due to soil surface erosion was also observed by Arriaga and Lowery (2003), who reported a slight increase in Ksat with increasing erosion phase in a conventionally tilled silt loam soil of southwestern Wisconsin.

Landscape position sometimes does not affect Ksat (Sobieraj et al., 2002, Schoeneberger et al., 1995). For example, Iqbal et al. (2005b) found similar Ksat values between summit and steeper slope positions in a poorly drained soil of a complex rolling topography located in Mississippi.

Water Retention

Water retention for this landscape was significantly affected by MZ (Table 4), and although tillage system and manure addition had little interaction with MZ, discussion will be focused only on the MZ effects on WR. Mean values of WR for each MZ are shown on Table 4.

Greatest contrast in WR among MZ was between Z1 and Z3 (Figure 13). Water retention on Z1 was significantly greater than Z3 for lower suctions (0, 20 and 80cm H_2O), and significantly greater than Z2 at 20 and 80cm H_2O. At higher suctions, the trend between Z2 and Z3 changed, and WR values for Z2 increased and approached those values of Z1.

Similarity in WR between Z1 and Z2 observed at higher suctions can be related to greater clay content of those MZ (Figure 2). In addition, lower WR for Z3 at higher suctions can be attributed to PSD; sand content was greatest in Z3. Based on the reviewed literature, the relationship between WR and landscape positions is mainly related to PSD through the landscape, and to some extent, to TC and Db. In agreement with this research, Iqbal et al. (2005b) reported greater WR at higher suctions (300, 680 and 15,000cm H_2O) for landscape positions where the clay content was high. For that landscape, clay content was greater on steeper slopes and toeslope positions. Similarly, Jiang et al. (2007) measured WR at the 0 to 300cm H_2O suction range, and found greater WR in the backslope position, which had the shallowest claypan occurrence. The authors attributed greater clay content in the claypan as the cause of greater WR for backslope, compared to summit and footslope positions, respectively. Although no differences in clay content among landscape positions were reported, Schoeneberger et al. (1995) found greater WR on shoulder, followed by ridge top and ridge nose positions for a 0 to 400cm H_2O suction range in clayey soils of a Piedmont landscape of North Carolina. However, in a study comparing soil properties across a soil-slope transition in central Iowa, Mohanty and Mousli (2000) found greater WR at the hilltop than shoulder positions of the same PSD class, at a suction range of 10 to 15,000cm H_2O. The hilltop position was described as a Nicollet loam with 1-3% slope, and the shoulder was described as a Clarion loam with 2-5% slope.

Although greater WR for backslope positions have been frequently reported, this relationship can be dependent on erosion severity level, and consequent increases in clay content might not be beneficial for WR. Arriaga and Lowery (2003) assessed soil properties in three erosion levels of a silt loam soil of Wisconsin, and observed lower WR at higher suction for the most severe erosion phase studied.

Greatest WR observed for Z1 can be related to greater TC content (Figure 1), relatively high clay content (Figure 2), and lower erosion and depositional process than Z2 and Z3, providing better soil structure. Although one would expect greater WR for Z2 and Z3 at lower suctions due to its lower Db values (Figure 6), this was not the case.

CONCLUSIONS

Differences among MZ were significant only for Db, WR, Ksat and IR. Infiltration rate, Db and AS trends among MZ varied according to tillage system. Soil bulk density on Z1 was greater for conventional system, and on Z2 was greater for conservation system, except at 0-5cm of depth. The greater soil Db values on conservation system observed for lower depths on Z2 can be related to soil consolidation from the lack of surface tillage, and to historical erosion and soil degradation of that part of the field. On the other hand, conservation system benefits for AS and IR on Z2 and Z3, respectively, were greater than for the other MZ.

Although IR values for conventional system were in agreement with previous site description, where Z1 and Z2 were described as well and poorly drained soils, respectively, trends of IR for conservation system and Ksat among MZ were not similar. Hydraulic conductivity of saturated soil on Z2 was significantly greater than Z1, and IR on Z2 was always low.

Great contrast in WR between Z1 and Z3 reflects the direct relationship between soil particles and WR. The sandy surface and presence of a Bt horizon on this field caused erosion process to increased clay content on the soil surface of Z2, and depositional process increased sand content on Z3.

Literature and data from this study suggest that differences in soil parent material, and consequently in soil PSD, are important factors affecting differences in soil properties across the landscape. Erosion and depositional processes associated with tillage system were the most important factors affecting the spatial variability of soil PSD and related soil properties for this landscape.

Results of this research can help farmers, extension personnel and consultants to decide about the suitability of SSM for conditions similar to the southeastern Coastal Plain soils studied here. Observed differences in soil properties through the landscape positions could be used as complementary information to support SSM decisions.

Reference to trade or company name is for specific information only and does not imply approval or recommendation by Auburn University or USDA - ARS - NSDL to the exclusion of others that may be suitable.

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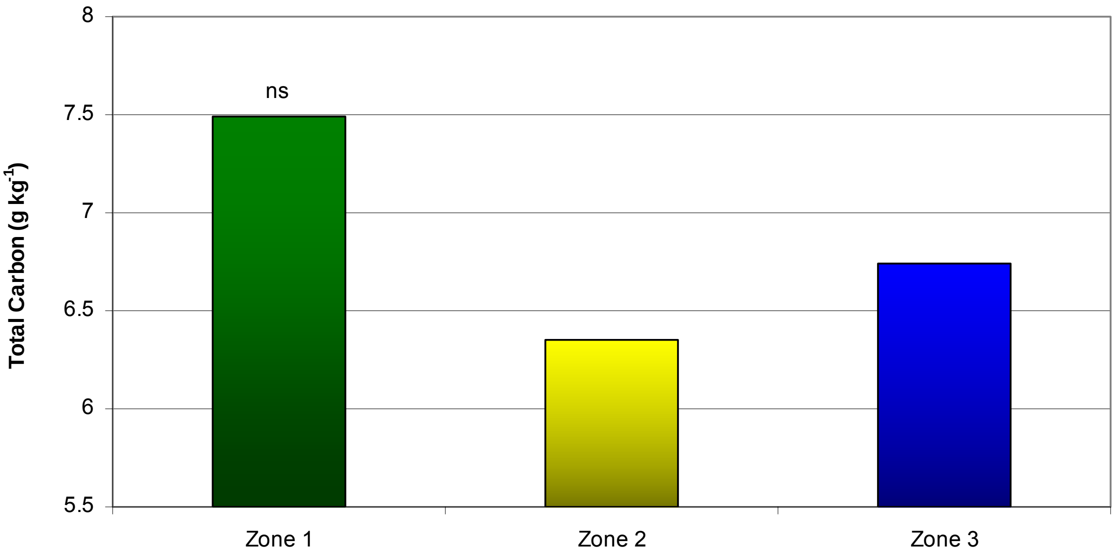


Figure 1. Management zones effects on total carbon, averaged across treatments and depths. ns = differences were not significant.

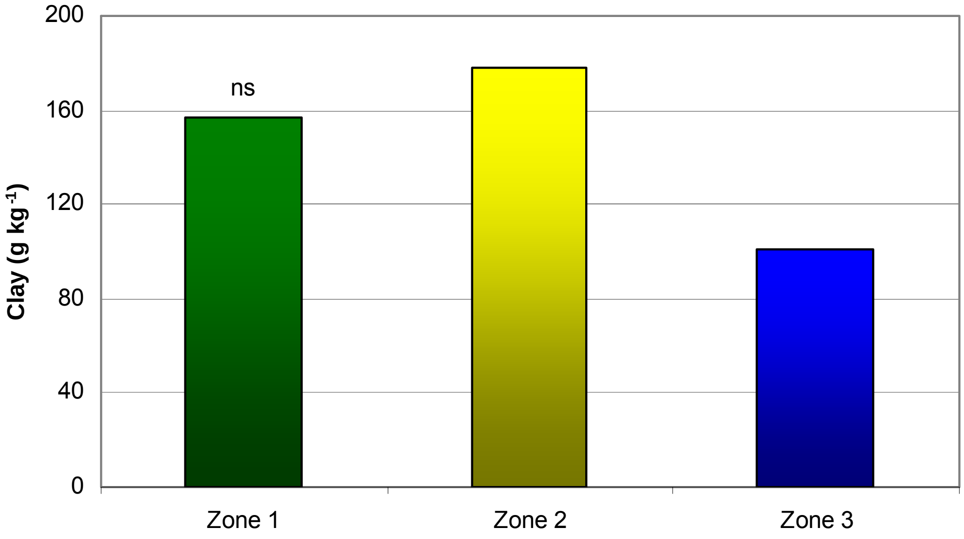
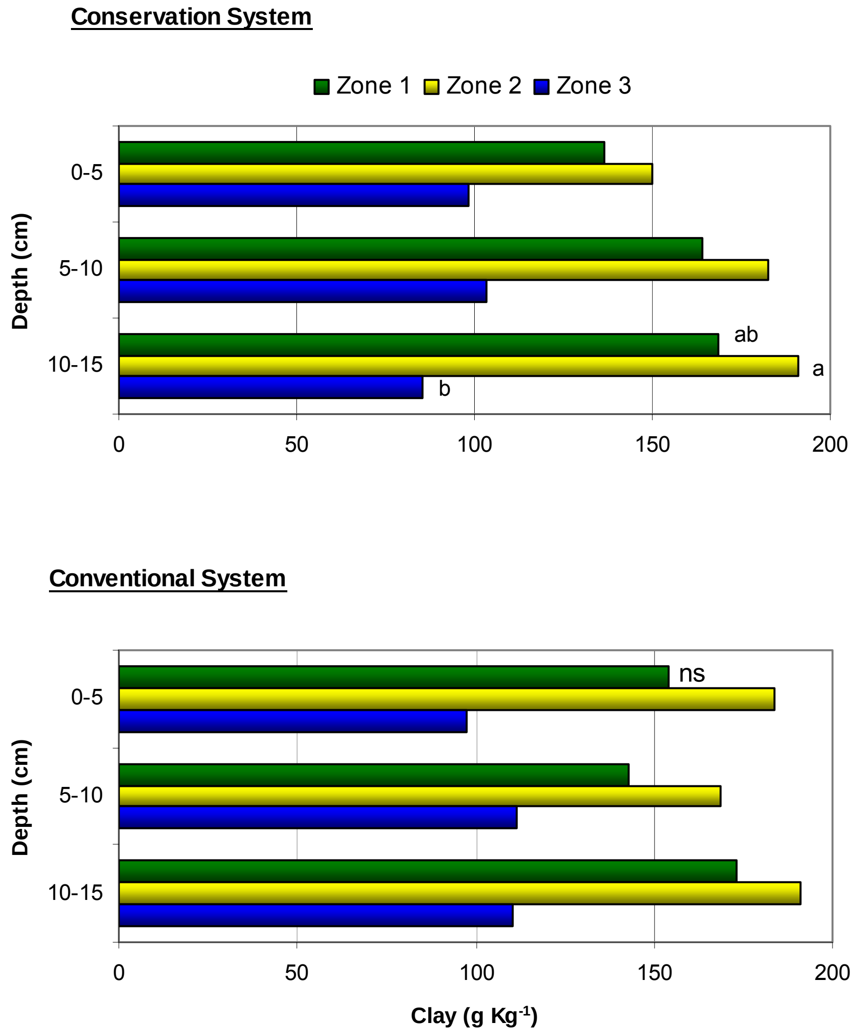


Figure 2. Management zones effects on clay content, averaged across treatments and depths. ns = differences were not significant.


Conservation System

Conventional System

Figure 3. Management zones, tillage system and depths effects on clay content. Letters denote means separation between management zones at the same depth by LSD $_{(0.10)}$. ns = differences were not significant.

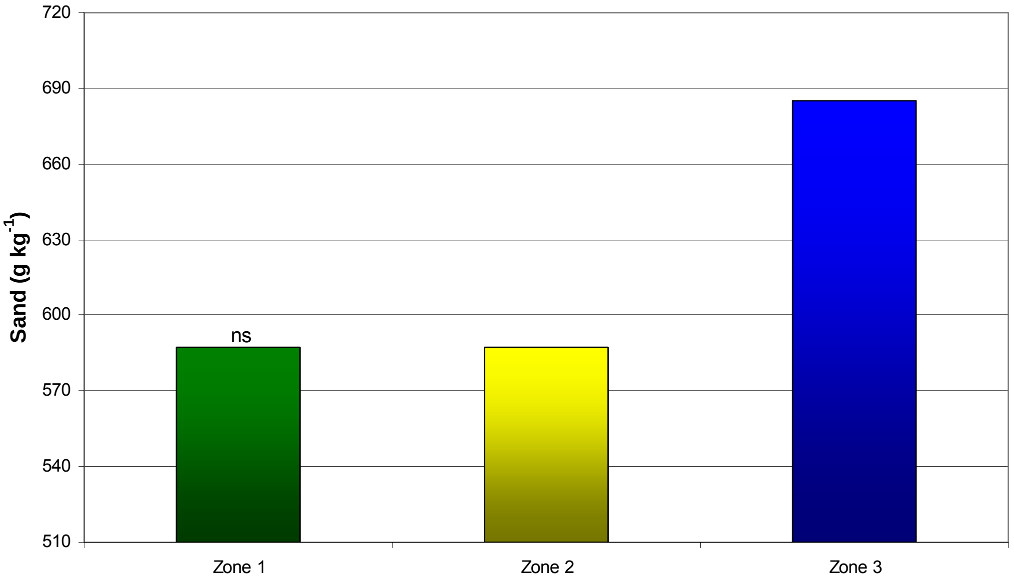


Figure 4. Management zones effects on sand content, averaged across treatments and depths. ns = differences were not significant.

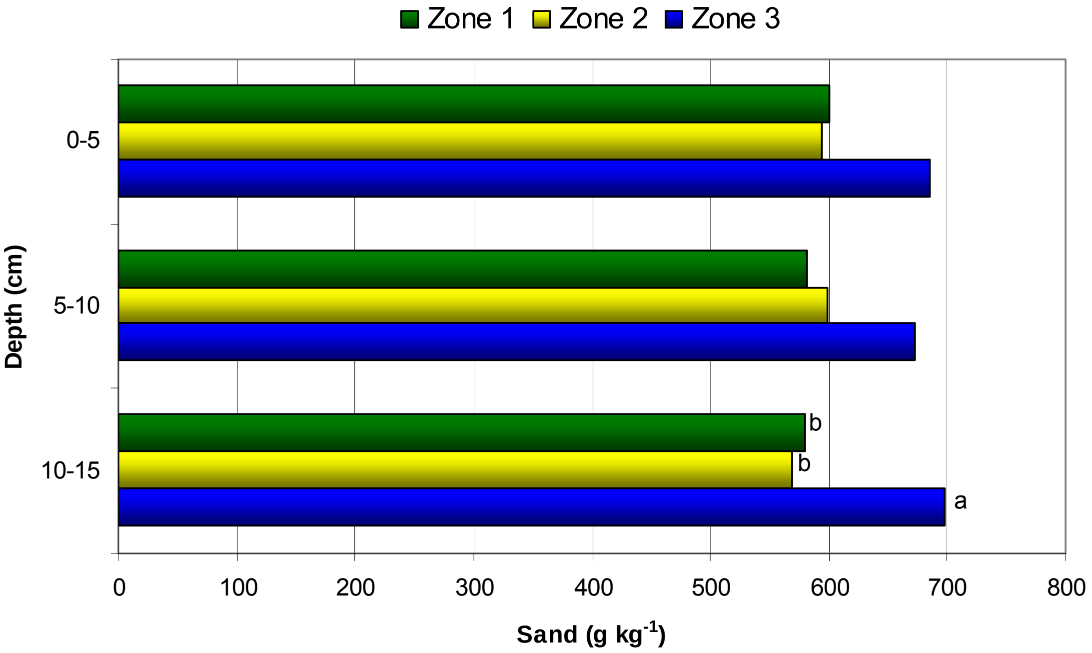


Figure 5. Management zones and depth effects on sand content. Letters denote means separation between management zones at the same depth by LSD $_{(0.10)}$.

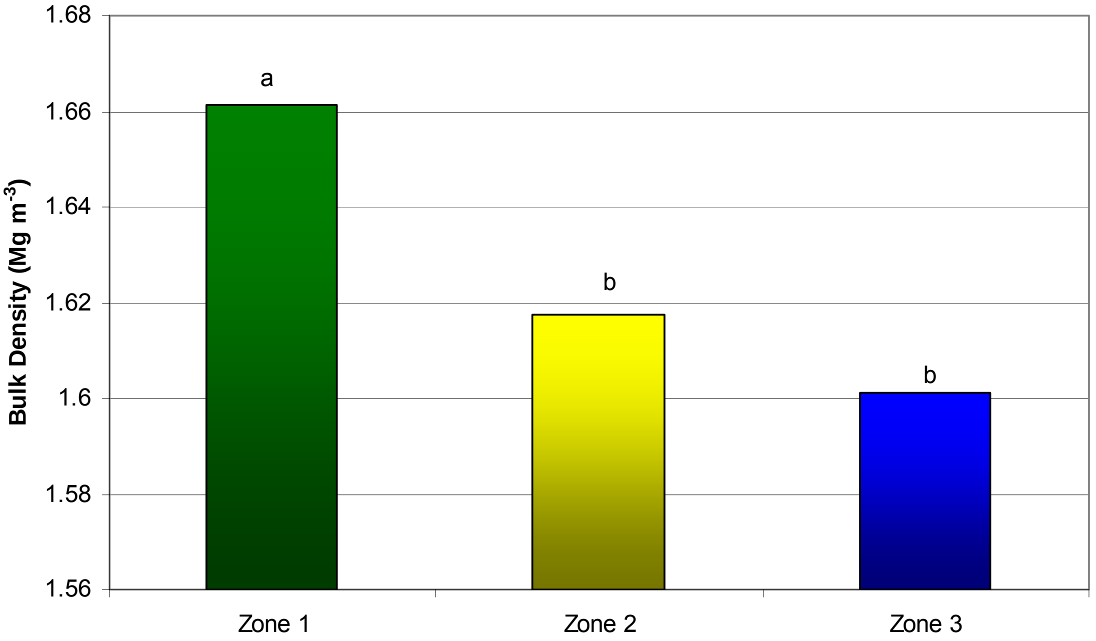
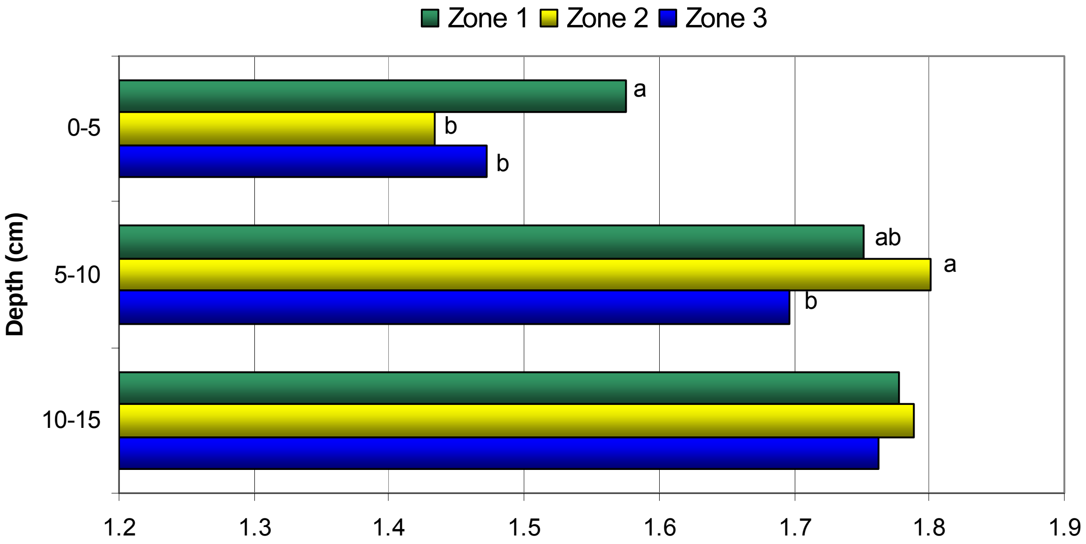


Figure 6. Management zones and depth effects on soil bulk density. Letters denote means separation between management zones by LSD (0.10).

Conservation System



Conventional System

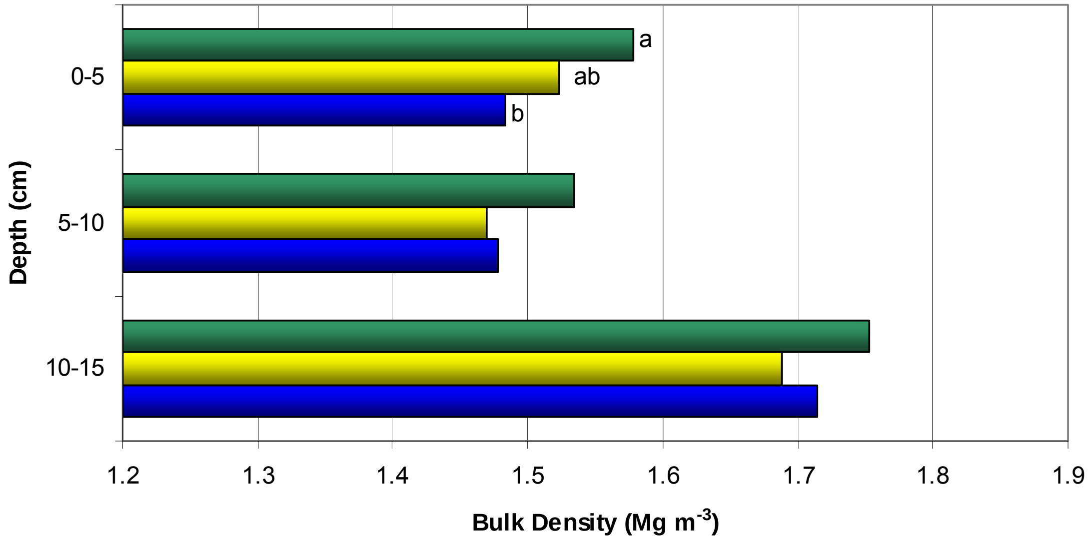


Figure 7. Management zones, tillage system and depth effects on soil bulk density. Letters denote means separation between management zones at the same depth by LSD $_{(0.10)}$.

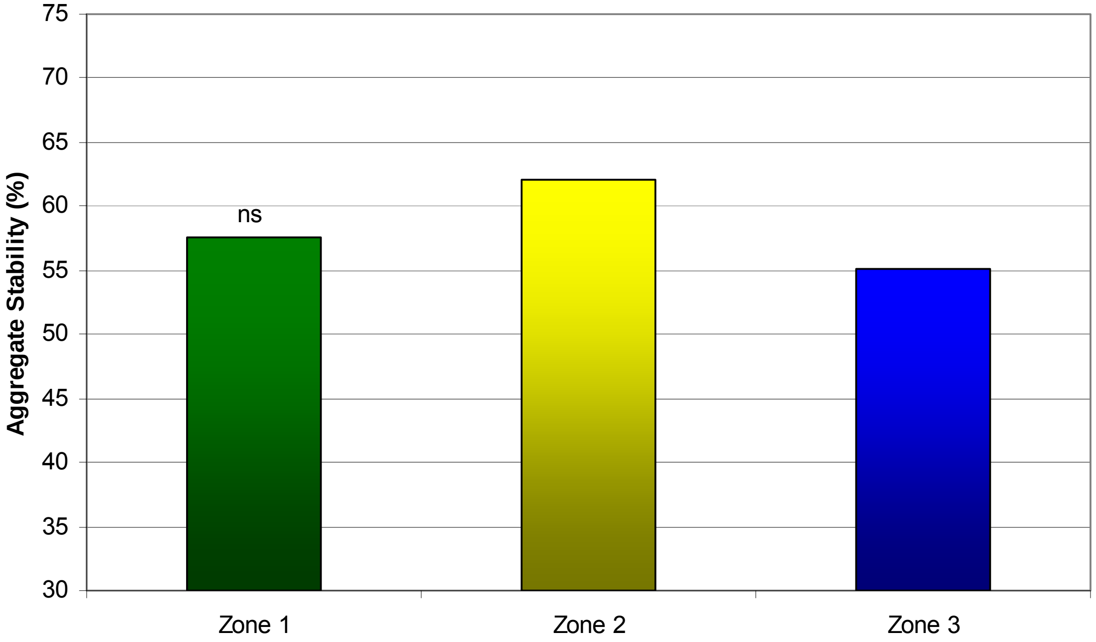


Figure 8. Management zones effects on aggregate stability, averaged across treatments. ns = differences were not significant.

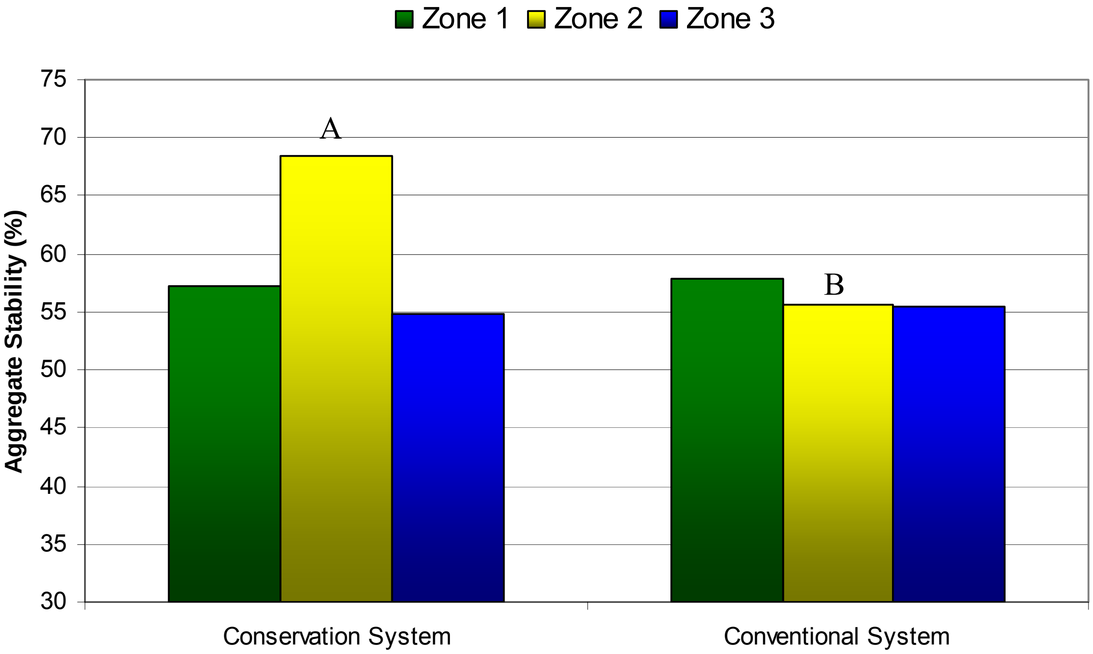


Figure 9. Management zones and tillage system effects on aggregate stability. Capital letters denote means separation between tillage systems for Z2 by LSD $_{(0.10)}$. Differences between management zones were not significantly different within tillage system.

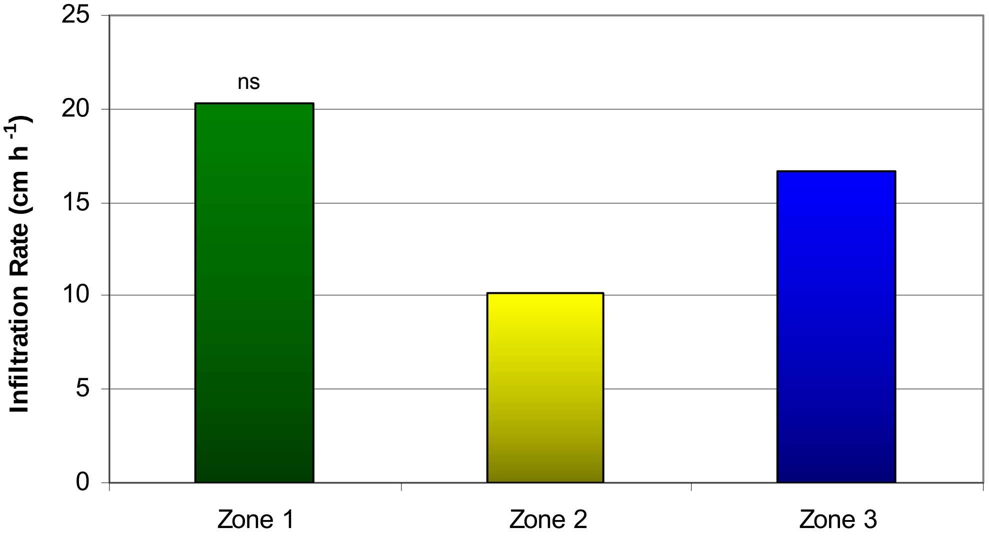


Figure 10. Management zones effects on infiltration rate, averaged across treatments. ns = differences were not significant.

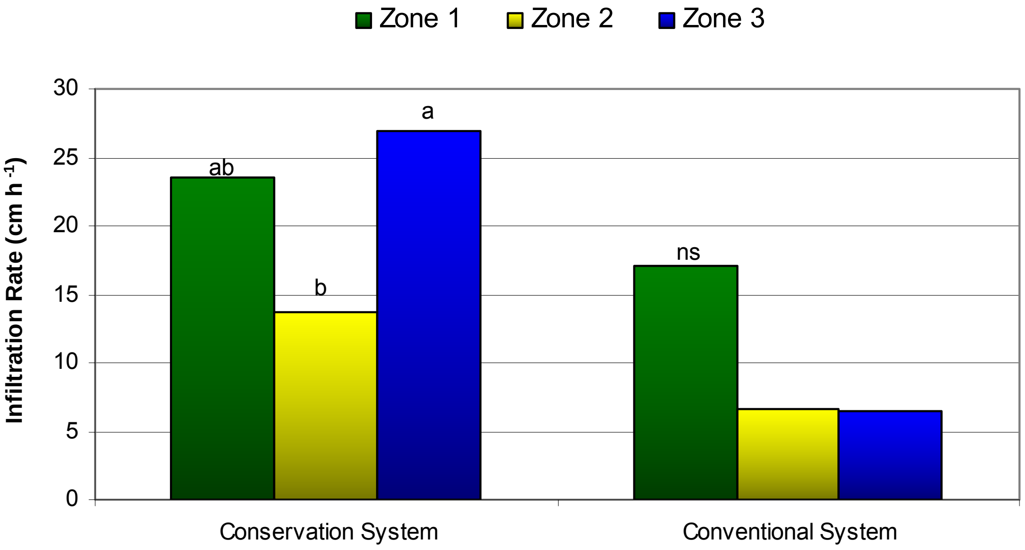


Figure 11. Management zones and tillage system effects on infiltration rate. Letters denote means separation between management zones for the same tillage system by LSD $_{(0.10)}$. ns = differences were not significant.

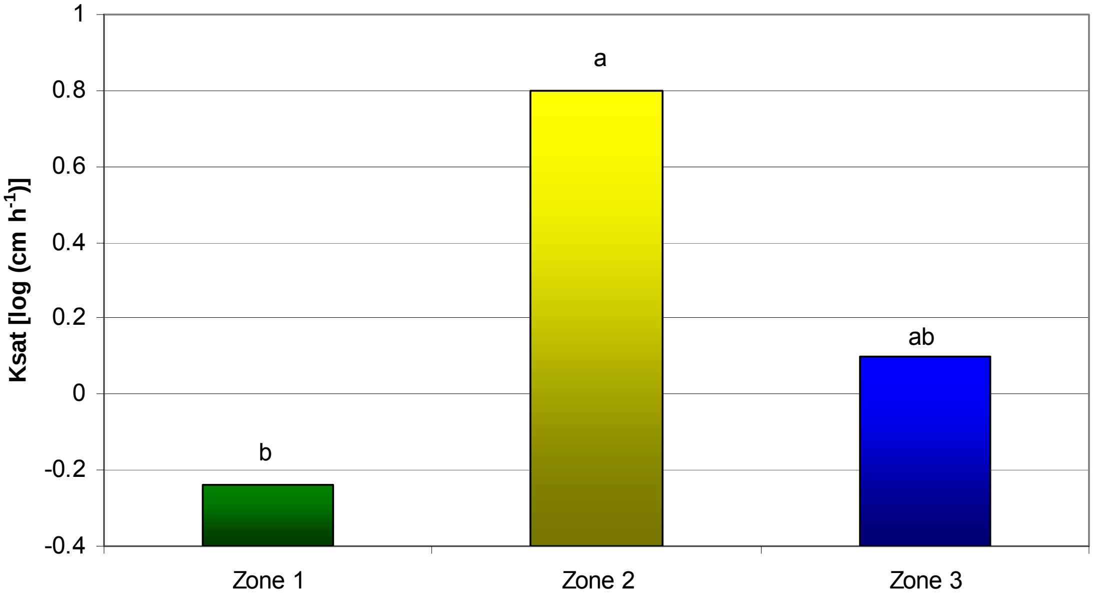


Figure 12. Management zones effects on hydraulic conductivity of saturated soil, averaged across treatments and depths. Letters denote means separation between management zones by LSD $_{(0.10)}$.

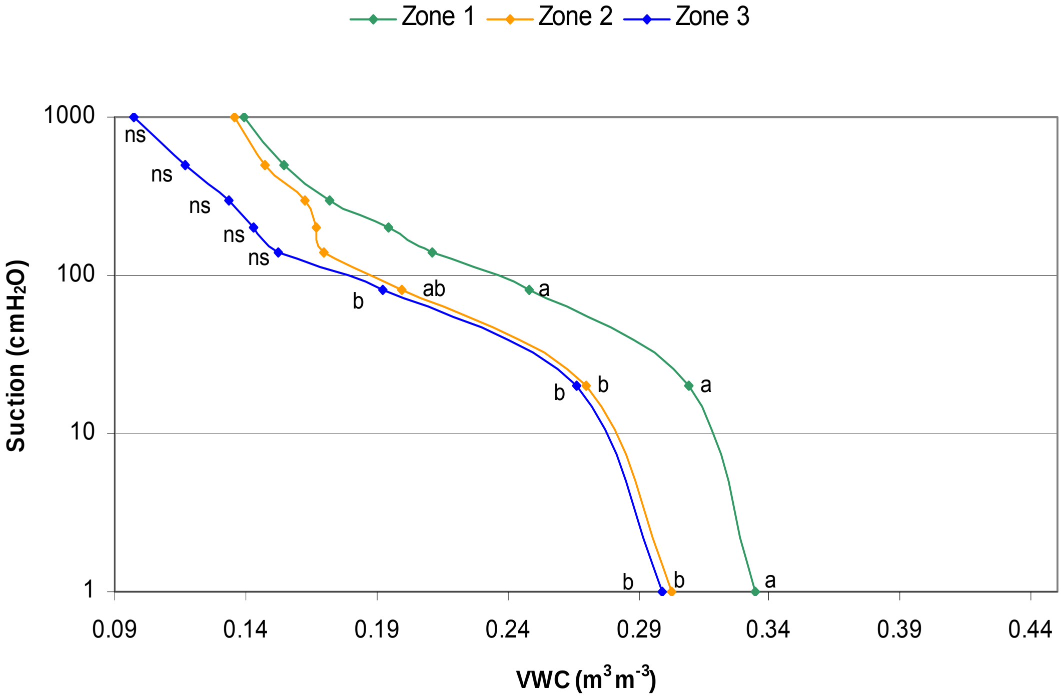


Figure 13. Management zones effects on water retention, averaged across treatments and depths. Letters denote means separation between management zones by LSD $_{(0.10)}$.
ns = differences were not significant.

Table 1. Analysis of variance summary for total carbon (TC), clay content, sand content, soil bulk density (Db), aggregate stability (AS), infiltration rate (IR) and hydraulic conductivity of saturated soil (Ksat).

	ANOVA P > F						
Source of variation	TC	Clay	Sand	Db	AS	IR	Ksat
Management Zone (MZ)	0.443	0.323	0.192	0.041	0.668	0.240	0.093
Depth (D)	< 0.01	<0.01	0.235	<0.01	na †	na	0.042
Tillage (T)	0.342	0.499	0.685	<0.01	0.087	< 0.01	0.564
Manure (M)	< 0.01	0.521	0.887	0.033	0.572	0.632	0.848
MZ*D	0.826	0.067	0.034	0.152	na	na	0.294
MZ*T	0.944	0.871	0.409	0.710	0.018	0.042	0.580
MZ*M	0.684	0.943	0.951	0.998	0.508	0.366	0.585
MZ*D*T	0.986	0.052	0.106	0.089	na	na	0.461
MZ*D*M	0.606	0.153	0.748	0.914	na	na	0.538
MZ*T*M	0.976	0.633	0.776	0.744	0.699	0.546	0.838
MZ*D*T*M	0.868	0.312	0.965	0.917	na	na	0.637

† na = not applicable.

Table 2. Total carbon (TC), clay content, sand content, soil bulk density (Db), aggregate stability (AS), infiltration rate (IR) and hydraulic conductivity of saturated soil (Ksat) means for each management zone (MZ).

	TC	Clay	Sand	Db	AS	IR	Log Ksat
MZ	------------------ g kg^{-1}	------------------		- Mg m^{-3} -	--- % ---	-(cm h^{-1})-	Log (cm h^{-1})
Zone 1	7.5ns††	156.5ns	587.35ns	1.66a†	57.5ns	20.2ns	-0.24b
Zone 2	6.30	177.7	587.3	1.62b	62.0	10.1	0.80a
Zone 3	6.74	101.0	685.1	1.60b	55.1	16.7	0.10ab

† Letters within same column denote means separation between management zones by LSD $_{(0.10)}$;

†† ns = differences were not significant.

Table 3. Soil bulk density (Db), clay content, sand content, aggregate stability (AS) and infiltration rate (IR) means for each management zone (MZ) by tillage system and depth.

	Conservation System			Conventional System		
	Z1	Z2	Z3	Z1	Z2	Z3
Depth (cm)	Db (Mg m^{-3})					
0-5	1.58a†	1.43b	1.47b	1.58a	1.52ab	1.48b
5-10	1.75ab	1.80a	1.70b	1.53	1.47	1.48
10-15	1.78††	1.79	1.76	1.75	1.69	1.71
	Clay (g Kg^{-1})					
0-5	136.8	150.0	98.0	153.9	183.5	97.4
5-10	164.3	182.4	103.2	142.9	168.4	111.7
10-15	168.3ab	190.8a	85.2b	173.1	191.0	110.4
	Sand (g Kg^{-1})					
0-5	609.6	561.5	688.8	592.6	626.4	681.1
5-10	579.6	588.4	676.8	583.2	608.8	669.0
10-15	579.8	573.1	701.0	579.3	565.4	693.5
	AS (%)					
0-10	57.2	68.4	54.8	57.9	55.7	55.5
	IR (cm h^{-1})					
Soil surface	23.5	13.7	26.9	17.0	6.5	6.5

† Letters within same depth and treatment denote means separation between management zones by LSD $_{(0.10)}$;

†† = numbers without any letter were not different between management zones.

Table 4. Analysis of variance summary and management zones (MZ) means for volumetric water content (VWC) at different suctions.

	ANOVA P > F							
	Suction (cm H_2O)							
Source of variation	0	20	80	140	200	300	500	1000
MZ	< 0.01	< 0.01	0.074	0.148	0.206	0.241	0.150	0.132
Depth (D)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.01	0.012
Tillage (T)	< 0.01	< 0.01	0.142	0.040	0.155	< 0.01	0.010	< 0.01
Manure (M)	< 0.01	< 0.01	0.017	0.163	0.251	0.460	0.205	0.198
MZ*D	0.114	0.130	0.313	0.183	0.124	0.347	0.349	0.321
MZ*T	0.876	0.835	0.287	0.421	0.446	0.069	0.330	0.248
MZ*M	0.178	0.050	0.029	0.200	0.416	0.443	0.733	0.717
MZ*D*T	0.873	0.867	0.739	0.749	0.360	0.421	0.300	0.239
MZ*D*M	0.670	0.673	0.752	0.813	0.570	0.653	0.820	0.674
MZ*T*M	0.722	0.772	0.963	0.893	0.925	0.074	0.483	0.475
MZ*D*T*M	0.643	0.504	0.178	0.156	0.415	0.529	0.876	0.822
	VWC means (m^3m^{-3})							
MZ								
Zone 1	0.33a †	0.31a	0.25a	0.21 ns††	0.19ns	0.17ns	0.15ns	0.14ns
Zone 2	0.30b	0.27b	0.20ab	0.17	0.17	0.16	0.15	0.14
Zone 3	0.30b	0.27b	0.19b	0.15	0.14	0.13	0.12	0.10

† Letters within same column denote means separation between management zones by LSD $_{(0.10)}$;

†† ns = differences were not significant.