ABSTRACT


Tillage plays a key role in production agriculture soil management and can influence myriad soil processes and properties, depending on its intensity. Tillage can chop and bury residue; change soil physical structure; and alter how water moves on, into, and through the soil matrix. If improperly implemented, it can lead to problems such as drought stress, poor root penetration, and erosion. Consequently, it is important to understand how soils are affected by long-term tillage practices. Our research examined tillage practices at a long-term (28 year) research site in the North Carolina piedmont. Our primary objectives were to determine the effects of tillage on: 1) soil erosion using ground-based lidar; 2) soil physical properties such as bulk density, particle size distribution, water retention, plant-available water, carbon, and carbon stratification ratio in three row positions (in-row, trafficked interrow, and untrafficked interrow) and to depths of 105 cm; and 3) soil profile moisture conditions to estimate water-use efficiency and depletion and recharge during and following dry periods.

The tillage methods were no-till (NT), in-row subsoiling (IRS), chisel plow in spring (CHsp) or fall (CHfa), disk (D), chisel plow in spring or fall followed by disk (CHspD, CHfaD) and moldboard plow in spring or fall followed by disk (MPspD, MPfaD). Soil type at the site was a Casville sandy loam (fine, mixed, semiactive, mesic Typic Kanhapludult). Lidar elevation data showed that the natural elevation gradient (i.e., trend) at the site was best removed using a second order polynomial; the de-trended data were used for analysis of erosion losses. The elevation of MPspD was 13.3 cm lower than NT, which corresponded to a soil loss of 1891
Mt ha⁻¹. In general, estimated soil loss was greatest in tillage treatments of higher tillage intensity. Bulk density was greatest in the trafficked row position of all treatments, an effect detected only at a depth of 10 cm. Particle size distribution was not affected by tillage and changed only with depth. Few differences were detected for water retention and plant-available water. Carbon content was greatest at 2.5 cm and decreased substantially with depth, especially in low tillage intensity treatments such as NT and IRS. The carbon stratification ratio that compared shallow (2.5 cm) vs. deeper depths (10 cm) was greatest in NT, CHsp, and D. Treatments with the greatest carbon stratification ratios tended to be the same treatments that produced the greatest yields over the life of the study. Water-use efficiency was highest in NT and IRS, and lowest in CHsp and MPspD in all five years that soil moisture data were collected. During periods of near-zero rainfall, more water was removed from the soil profile in low-intensity tillage treatments than others, and subsequently these treatments gained more water after rainfall, indicating the influence of tillage on a soil’s ability to provide water during dry periods. Overall, results show that conditions conducive to crop growth, yield, and soil conservation coincided with long-term low-intensity tillage management.
Long-term Tillage Effects on Soil Erosion, Physical Properties, and Soil Moisture

by
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A dissertation submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Soil Science

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DEDICATION

This dissertation is dedicated to my wife Charlene, our children Catherine, Laurel, Seth, and Lily; my parents Max and Liz Meijer; my in-laws Holly and the late Case Van Staalduinen; and my grandparents John and Johanna Vaandering.
BIOGRAPHY

Alan was born in Hamilton, Ontario, Canada. He graduated from Smithville District Christian High School in 1989 and earned a B.Sc. in Biology at Redeemer College in Ancaster, Ontario in 1994. From 1996 - 2006, Alan worked as a technician for Dr. Ron Heiniger of NC State University’s Crop Science Department, earning both a Graduate Certificate in Geographic Information Systems (2002) and a M.Sc. in Crop Science (2004) during that time. The title of Alan’s thesis was “Characterizing a Crop Water Stress Index for Predicting Yield in Corn”. Throughout those years, a strong interest in, GIS, precision farming, and the spatial dependence of natural phenomena grew. In 2006, Alan accepted a position as an Extension Associate for Tillage and Soil Management in the Soil Science Department at NC State University, and started working on his Ph.D. in Soil Science in 2008. Alan continues to live in eastern North Carolina with his wife, Charlene, and their four wonderful children: Catherine, Laurel, Seth, and Lily.
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1. Introduction

Tillage has been a part of growing crops since the advent of agriculture and has played a role in allowing more land to be made arable and for fewer people to produce food for an ever increasing population. However, altering a soil’s physical state from native and untouched to one disrupted by tillage can be dramatic and has caused a number of severe problems throughout history, even to the extent of degrading the soil to a greater degree in less time in this era than at any point throughout history (Faulkner, 1943).

The various physical, chemical, and biological processes that occur within the soil profile are partially governed by soil physical properties, all of which can be altered by the physical disruption of soil that occurs with tillage and the trafficking of the soil surface with farm equipment. By mixing and breaking up the natural soil structure and aggregation of soil particles, properties such as bulk density (Hill and Cruse, 1985), soil strength (Ehlers et al., 1983; Lindstrom et al., 1984; Tollner et al., 1984), and porosity (Voorhees and Lindstrom, 1984) are dramatically altered. These changes can adversely affect root penetration (Ehlers et al., 1983), infiltration (Lindstrom and Onstad, 1984; Freese et al., 1993), runoff (Afunyi, 1997), and soil water retention (Bescansa et al., 2006), which can all affect crop growth.

Impacts of tillage on soil water relations are of particular importance. Before water can move through a soil, it must first infiltrate. Tillage can foster conditions of compacted or crusted soil surfaces which limit infiltration (Freese et al., 1993; Pikul and Zuzel, 1994). In tilled soils that are unprotected by crop residue, runoff ensues, and soil erosion can occur when soil
particles are dislodged by the force of the moving water (Lal, 1994). Additionally, soils can suffer from wind erosion.

In the mid-1980s, there was a shift towards conservation tillage methods that involved little soil mixing and left much of the plant residue on the surface. These tillage methods were known collectively as conservation tillage practices. With the soil surface covered year-round with living plants or residue, infiltration may be improved along with a corresponding reduction in erosion (Brady and Weil, 2002). With less residue incorporation into soil, organic matter breaks down at a reduced rate, allowing for its buildup on or just below the soil surface. Soil organic matter is known to benefit soil physical, chemical, and biological properties by increasing aggregation; infiltration; decomposition and nutrient cycling; and biological activity (Franzluebbers, 2010). Conservation tillage use has been increasing in the United States, from approximately 71 million acres in 1989 to almost 114 million acres in 2008 (Conservation Technology Improvement Center, 2008).

In some areas, such as the Great Plains region of the United States where irrigation water is pumped from the shrinking Ogallala aquifer, water resources are more limited now than what they once were. With the natural limitation of rainfall, and a natural or potentially legislated limitation on irrigation, the need for efficient soil water storage and use efficiency is critical.

The Nine Tillage Study was implemented in 1984 in an effort to determine tillage practices that improve infiltration, reduce erosion, and improve crop yields for growers in the Piedmont of North Carolina (Cassel et al., 1995). Nine tillage methods representing a range
Numerous experiments have been conducted at the Nine Tillage Study, with varied objectives and methods. Early work focused on the effects of two years of tillage on soil physical properties such as bulk density and cone index (Cassel et al., 1995). In 1998, research shifted to processes such as infiltration and runoff (Freese et al., 1993; Myers and Wagger, 1996). Unpublished work related to macroaggregate stability, volumetric porosity, and plant-available water has been carried out and briefly summarized in proceedings papers (White et al., 2009).

Technologies that utilize non-invasive techniques to estimate or measure some parameter of the soil continue to be developed and have provided new methods for understanding the current status of soils. Lidar is one such technology; it has been used to characterize topography, with data usually captured from an airplane. A recent development of the technology has allowed this data to be collected in an extremely dense manner in a ground-based system. This method of collecting elevation data can be used to characterize long-term effects of soil management techniques on a soil’s surface.

1.1 Research Objectives and dissertation organization

We undertook research to study the effects that 28 years of various tillage methods have had on: soil erosion and physical condition; moisture available for crops; and long- and short-term yield. The main objectives were to: 1) estimate the effects of tillage on long-term soil
loss using ground-based lidar scanning; 2) determine the effects of tillage, traffic (row
position), and depth on soil physical properties; and 3) examine the effects of tillage on soil
moisture parameters at multiple depths.

To address Objective 1, a ground-based laser scanner was used to generate a cloud of points
representing the soil surface (Kessler et al., 2012). Polynomial linear regression was used to
apply a 2nd order model to remove the effects of hillslope, leaving elevation data representing
the relative elevations of the individual plots. From these, soil loss and accumulation were
estimated relative to the no-till treatment, which was considered the most stable soil surface
over the history of the experiment (Chapter 2).

To address Objective 2, tillage treatment effects on soil physical properties were determined
from non-intact soil cores extracted from the in-row, trafficked, and untrafficked interrow
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of tillage, depth, and row position on soil bulk density and volumetric water content. We also
tested the effects of tillage and depth on: percent sand, silt, and clay; water-retention at 10,
30, 100, 500, and 1500 kPa; plant-available water from 5- to 45-cm depth; total carbon; and
carbon stratification ratio (Chapter 3).

To address Objective 3, soil moisture data were recorded periodically since 2008. Using
access tubes installed in six of the nine tillage treatments, volumetric soil water content was
measured with a capacitance probe at depths of 10, 20, 30, 40, 60, and 100 cm. The resulting
data were examined for the effects of tillage, and depth in some cases, on water use
efficiency, and the effects of dry periods on the volume of soil water lost during those
periods, as well as the subsequent increase in water content following rainfall (Chapter 4). Chapter 5 summarizes our work and conclusions.
1.2 References


2. Measuring Erosion in Long-Term Tillage Plots Using Ground-Based Lidar

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Abstract
Erosion remains a serious problem for agricultural soils throughout the world. Tillage significantly affects a soil’s susceptibility to erosion. Erosion research is usually conducted \textit{in situ} by capturing eroded sediment in brief, natural or artificial rainfall events. Methods for measuring long-term erosion are needed to better understand long-term effects of soil management. Landscape change resulting from erosion may be accurately characterized using ground-based lidar. Ground-based lidar data were collected in 2010 at a long-term (28-yr) trial of nine tillage treatments in the North Carolina Piedmont. Tillage effects on plot-surface elevations were examined after removing large-scale variation in elevation (slope) by detrending with first- through fourth-order polynomials. Residuals represented the elevation difference from the trend for each location. Mean plot elevations were calculated for datasets from each detrending model and used to assess erosion. In the subsequent elevation analysis, data derived from the second-order polynomial had the highest $R^2$, attributing 66% of the variation in elevation to block and treatment. Treatment elevations relative to no-till (NT) ranged from +3.20 cm in the fall chisel (CHfa) plots to -13.28 cm in the fall moldboard plow plus disk treatment. Weeds in lesser-tilled treatments such as CHfa and no-till plus in-row subsoiling resulted in artificially high elevation measurements. In general, the most
intensely-tilled treatments had the lowest elevations and the least-tilled treatments had the highest. NT was used as the reference elevation for no change, and soil loss was calculated using these data along with field-collected estimates of bulk density. The relative elevation differences corresponded to a maximum treatment mean soil loss of 1891 Mg ha\(^{-1}\), which corresponds to an average annual soil loss of 67.5 Mg ha\(^{-1}\) yr\(^{-1}\). Soil loss estimates were similar to others estimated from soil profile truncation. This research indicates that ground-based lidar data can be used to estimate soil elevation changes and thus soil loss due to tillage-induced erosion.

2.1 Introduction

Erosion is a serious and well-documented problem with 1.73 Gt of soil lost from agricultural fields in the U.S.A. annually (Hassel, 2005). Erosion leads to the sedimentation of waterways, air quality degradation, the transport of nutrients and pesticides offsite, and the loss of topsoil, organic matter, nutrients, and soil productivity in agricultural areas. Erosion rates vary with rainfall duration and intensity; tillage method, timing, and frequency; soil type, and slope (Chouhadry et al., 1997; Meyer and Harmon, 1989; Valmis et al., 2004). Soils exposed to wind, rainfall, and runoff are most susceptible to erosion. Minimizing runoff and optimizing infiltration by maintaining plant residue cover and soil aggregation are critical to reducing erosion (Raczkowski et al., 2009, Raczkowski et al., 2002).

Tillage method largely determines a soil’s susceptibility to erosion. The physical action of mixing the soil by tillage breaks apart soil aggregates and incorporates surface residue into the soil profile. Tillage methods vary in the amount of soil disturbance caused, and in the
quantity of residue left intact. In a simulated rainfall study on continuous corn (Zea mays, L.) on moderately (5%) sloping land in Nebraska, Dickey et al. (1984) measured residue cover and corresponding soil loss in various tillage operations. After applying water at a rate of 64 mm h\(^{-1}\) until runoff rates reached equilibrium (usually around 45 minutes, equaling 51 mm of simulated precipitation), they found that for moldboard plow (MP), chisel plow (CH), disk (D), and no-till (NT), where residue cover was 4, 17, 16 and 51%, soil loss was 46, 21, 19, and 6 Mg ha\(^{-1}\) h\(^{-1}\), respectively. Tillage also moves soil laterally in the same direction the implement is being pulled, a process called tillage erosion. Studies show that soil is most susceptible to this type of displacement in convex landscape positions (Govers et al., 1994; Lindstrom et al., 1992; Lobb et al., 1995). Net soil movement occurs from convex to concave landscape positions even if tillage is performed in both directions. Over time, erosion results in surface elevation change: negative in areas of erosion and positive in areas of deposition. Tillage can also affect the bulk density of the soil (Fraser et al. 2010). Soils with a lower bulk density occupy greater volumes, often resulting in an increased surface elevation as compared to that of a similar soil with higher bulk density. This effect may be transient as the soil compacts over time following tillage and may also confound short-term vs. long-term effects of erosion on surface elevation.

The effects of tillage on soil physical properties have been studied since 1984 at the Nine Tillage Study (NTS), a long-term tillage study in Reidsville, NC. At the initiation of the study, the use of moldboard plow and disk was common in Piedmont-region agriculture (Cassel et al., 1995). Researchers were searching for tillage systems that would promote soil
water storage, reduce soil erosion, and increase crop yield for regional growers (Cassel et al.,
1995). The sandy clay loam at this site was prone to drought-stress (Denton and Wagger,
1992), highly erodible, subject to crusting, and typical of Piedmont soils used extensively for
agriculture (Cassel et al., 1995), making the site suitable for testing various tillage systems.
Nine tillage treatments were used in the study, representing a range of tillage intensity
including; NT, CH, and MP. Residue cover in these systems ranged from 0% in moldboard
plow plots to 98% in NT plots (Freese et al., 1993).

At the NTS and another trial at a nearby site, both on sandy clay loams, researchers have
measured runoff, infiltration and sediment loss. In a two-year study, Myers and Wagger
(1996) applied 25 cm of rainfall at a rate of 51 mm h⁻¹ shortly after tillage. They noted that in
one year where the effect was significant, runoff in NT was 3.5 times that of CH for the first
application of rainfall. The associated soil erosion was 20 times greater for CH than NT
(1608 and 53 kg ha⁻¹). However, over both years, runoff in CH during a subsequent rainfall
application 7 days later was 2.5 times that of the initial rainfall application, indicating the
beginning of surface seal development. A similar trend was reported by Freese et al., (1993),
who applied simulated rainfall pre-tillage and on three dates post-tillage and post-plant to
MP, CH, and NT plots planted to corn at the same sites. Runoff was lower in MP and CH
compared to NT in only the first application. In CH plots combined with diskig, severe
crusting of the soil surface, which decreases infiltration and increases runoff, had been
observed by Denton and Wagger (1992). These observations, coupled with a slope of ~6%,
demonstrate that a range of conditions favorable to erosion existed amongst the treatments in this study.

Erosion is typically measured over relatively short periods of time such as in 10- to 30-minute simulated rainfall experiments like those performed by Freese et al. (1993), or by daily and seasonal events (Puustinen et al., 2007; Valmis et al., 2005). Few measurements have been collected to examine the long-term (decades) effect of tillage method on soil erosion in agricultural fields. While previous observations collected at the NTS are important, they provide only a snapshot of what has occurred over a longer term (i.e., 28 years). The cumulative effects of multiple rainfall-runoff events that occur in varied seasons, intensities, and durations, are not captured in these short term studies. Erosion rates vary over time. Modeling rainfall erosion, Julien and Frennette (1985) showed that for a rainfall event of steady intensity, erosion rate increased from zero to some maximum until it reached equilibrium. Upon rainfall cessation, soil erosion continued with runoff at a decreasing rate until it ceased some time later. Puustinen et al (2007) showed that more erosion occurred in autumn than in the rest of the year. Studying erosion occurring with natural rainfall, Valmis et al. (2005) showed that erosion rate correlated with maximum rainfall intensity, which varied with rainfall events. They determined that the soil’s instability index fluctuated throughout the season, with highest values in December through February. The NTS, in place 28 years with tillage treatments comprising a wide range of soil disturbance and crop residue cover, provides a unique opportunity to examine long-term implications of tillage on erosion.
Yet without continuous long-term collection of sediment loss from the site, we must rely on ancillary sources of information.

Net erosion or deposition can be determined by measuring differences in surface elevations, calculating the corresponding volumetric change, and converting to soil mass using bulk density data. Soil surface elevation measurements are typically performed using level survey techniques (Fraser et al., 2010), total stations (Hsiao et al., 2004), or aerial and ground-based lidar. Lidar is an optical remote sensing technology that measures distance by scanning a target with a pulsed laser. The time for a pulse reflection to return to the scanner is recorded and converted to distance (Wehr and Lohr, 1999). The result is a three-dimensional point cloud of irregularly spaced points with x, y, and z coordinates representing their location relative to the scanner head. Airborne lidar data have been used to characterize gullies and channels (Ritchie et al., 1994), vegetation cover (Moffiet et al., 2005), beach erosion (Shrestha et al., 2005), shoreline mapping (Leatherman, 2003), landslides (Hsiao et al., 2004; McKean and Roering, 2004; Glenn et al., 2006), tectonic scarps and glacial fluting (Haugerud et al., 2003), channel-bank erosion (Kessler et al., 2012; Thoma et al., 2005), floodplain maps for hydraulic modeling (Pereira and Wicherson, 1999), and surface roughness coefficients for hydraulic modeling (Cobby et al., 2001). Ground-based lidar has been used to study: forest canopy structure (Lovell, et al., 2003; Henning and Radtke, 2006), landscapes affected by landslides and earthquakes (Kreylos et al., 2008; Sturzeneggar et al., 2007), emergency management (Adams et al., 2005), large-scale urban modeling (Hu et al., 2003).
Lidar appears to be well-suited for quantifying erosion, but it is a relatively new technology that has seen limited use in agricultural research. The objective of this study was to quantify soil loss associated with nine long-term tillage treatments by using ground-based lidar to measure the surface elevation of tillage plots and determine soil loss based on the relative mean elevations of the treatments with respect to a reference elevation. The side by side long-term tillage comparisons of the NTS provided an excellent site for measuring surface elevation differences resulting from tillage-driven erosion. A significant challenge in this analysis was the absence of high-resolution data characterizing the original, pre-tillage surface topography. Our approach was therefore to compare present-day relative elevation differences among the treatments in order to estimate long-term erosion rates. However, further complicating this analysis was the location of the plots on a hillslope. Present-day differences in elevation of the NTS plots are the product of both natural topography and tillage. We describe lidar data collection and a detrending procedure to remove the effects of topography in order to estimate and compare erosional losses amongst the long-term tillage treatments.
2.2 Materials and Methods

2.2.1 Location and Soils

Lidar scanning was performed on 17 June, 2010 in the NTS at the Upper Piedmont Research Station near Reidsville, NC (36.383883 N,- 79.701895 W). The NTS was initiated in 1984 to study the effects of tillage on soil physical properties and yield. The site had most previously been managed as pasture. Soil is mapped as a Casville sandy loam (fine, mixed, semiactive, mesic Typic Kanhapludult). Corn was cropped continuously from 1984 through 1989. Since then, a corn-soybean (Glycine max L. Merr.) rotation has been implemented, except for 2006 when corn was substituted for soybean. The site has a slope of approximately 6% that runs diagonally across the plots (Fig. 2.1).

2.2.2 Experimental Design & Treatments

The experimental design was randomized complete block with nine tillage treatments arranged in four blocks. Blocks were arranged ~45° relative to the slope so that each consecutive block from southwest to northeast, and each plot from northwest to southeast, was situated at a higher elevation than the previous (Fig. 2.1). Plot- and whole-experiment dimensions were 15.5 x 5.5 m and 80 x 49.5 m, respectively. Tillage was performed annually along the length of the plots parallel to 0.92-m crop rows. Wheel traffic has been controlled since the experiment’s inception so that traffic occurred in every other interrow. Treatments were NT, in-row subsoiling (IRS), fall chisel (CHfa), spring chisel (CHsp), D, fall chisel plus disk (CHfaD), spring chisel plus disk (CHspD), fall moldboard plow plus disk (MPfaD), and
spring moldboard plow plus disk (MPspD). All disking was performed in the spring prior to planting. Tillage was performed in alternating directions every year. For moldboard plowing, this left a dead furrow on alternating sides of the plot from year to year.

Cultural practices including weed- and insect control have been carried out in a manner consistent with regional practices over the life of the study. For corn, some N was applied as starter, with the rest following 4 to 5 weeks after emergence. Lime, P, and K were applied based on North Carolina Department of Agriculture and Consumer Sciences soil-testing recommendations. Crops were harvested using a two-row combine, with its traffic pattern matching that of all other equipment passes in the field.

Crop yields have ranged widely at this site, depending mostly on precipitation, but over the course of the study, corn and soybean yields of 5.85 and 1.88 Mg ha\(^{-1}\), respectively, were similar to yield averages for the North Carolina Piedmont (North Carolina Department of Agriculture & Consumer Sciences). Maximum corn yield from any one treatment was 10.95 Mg ha\(^{-1}\) (NT, 2006), while the minimum over the whole experiment in one year was only 1.41 Mg ha\(^{-1}\). At 3.89 Mg ha\(^{-1}\), the top-yielding soybean treatment was CHfa (2000), while in 1998 and 2002, drought-related crop failure occurred and no soybeans were harvested. Treatment differences in crop yield were not always significant. When significant, lower-intensity tillage treatments (NT, IRS, and CHfa) out-yielded tillage treatments of higher intensity (CHfaD, MPfaD).
2.2.3 Lidar Scanning

Ground-based lidar data were collected in June 2010 using a Leica ScanStation 2 (Leica Geosystems, St. Gallen, Switzerland), a survey-grade, pulsed, dual-axis compensated laser scanner. The unit has a 360° (horizontal) and 270° (vertical) field of view with fully selectable vertical and horizontal point-to-point spacing of <1 mm if striking a surface oriented perpendicular to the scanner at a distance of 10 m. Point spacing increases as a function of distance from the scanner head. Accuracy of a single measurement taken at a distance of 1 to 50 m is 6 mm (vertical) and 4 mm (horizontal). The lidar scanning unit was mounted on a survey-grade tripod at a height of 1.42 m and leveled. The unit was controlled by Leica Cyclone v7.0 software installed on a laptop connected to the scanning head. Pre-scan settings defined the collection parameters used during the scanning process. Scans were set to cover 360° horizontally and +15° to -45° (Σ = 60°) vertically. The scanner was set to collect elevation data (z) at a 2-cm spacing (x,y), 10 m from the instrument. Maximum scan distance was 300 m, but data were clipped during post-processing to the experimental boundaries before spatial analysis. Two stationary tie-point reflectors served as static reference points and were used during post-processing to merge scans collected at different locations into a single, commonly referenced dataset. These reflectors, erected at a height of 1.67 m, were situated between the first and second, and the third and fourth blocks, equidistant from the lateral bounds of the trial. To limit the range of point densities across the experimental site and to minimize gaps resulting from micro- and macro-topography, four scans were collected and merged together using the static reference targets as control points.
Initial point-cloud processing and export was performed using Leica Cyclone. A multipoint file was exported for spatial analysis in ArcGIS (Environmental Systems Research Institute, Redlands, CA), and clipped to the experiment boundary.

At the time of scanning, emerging soybeans stood 2.5 to 5 cm tall. Similar-sized broad-leaf and grass weeds remained in some areas, especially in plots less disturbed by tillage. Individual 0.7-m tall plants of horseweed (*Conyza canadensis*, L. Cronquist) also stood in these plots at a low density. Corn stubble from the previous crop was primarily distributed flat on the ground although individual stalks rose to a height of approximately 10 cm in places.

### 2.2.4 Trend Removal

To examine the plot-to-plot elevation differences associated with tillage treatments, the slope trend was modeled with SAS PROC GLM (SAS Institute, Cary, NC) and removed using a series of polynomials of increasing order. The residuals were used as new elevation values. A planar surface was produced by a first-order polynomial, while higher order (second-, third-, fourth-) polynomials produced more complex surfaces. The first-order model, where elevation was modeled as a function of two variables is:

\[
z = ax + by + \varepsilon \tag{1}
\]

where \( z \) is a point elevation in the raw data, while \( x \) and \( y \) are horizontal coordinates in meters, in the north-south and east-west directions respectively, with coefficients \( a \) and \( b \).
Experimental error (residuals) is represented as \( \varepsilon \). The second-, third-, and fourth-order polynomials used to model the slope present at the site are:

\[
z = ax + by + cx^2 + dy^2 + exy + \varepsilon \quad [2]
\]

\[
z = ax + by + cx^2 + dy^2 + exy + fx^3 + gy^3 + hx^2y + ixy^2 + \varepsilon \quad [3]
\]

\[
z = ax + by + cx^2 + dy^2 + exy + fx^3 + gy^3 + hx^2y + ixy^2 + jx^4 + ky^4 + lx^3y + mxy^3 + nx^2y^2 + \varepsilon \quad [4]
\]

where \( c, d, e, f, g, h, i, j, k, l, m, \) and \( n \) are coefficients. Residuals generated in this process were output as new datasets. The residuals contained the same \( x \) and \( y \) locations with a \( z \)-value equal to the elevation relative to the modeled slope (trend). While a first-order model may be too simple, the complexity in the surface modeled with higher order polynomials may remove some of the plot-to-plot variability we sought to understand.

Choosing the appropriate model for subsequent elevation change analyses was based on the success of the model to detrend the data, as well as how well elevation variability in the detrended datasets was explained in ANOVA by block and treatment. Initial criteria included high \( R^2 \), significant treatment (tillage) effects on elevation, and reduced or non-significant block effects. Topographic position and local physiographic characteristics were also used to guide model selection, as the pre-tillage slope was likely more complex than a planar (first-order) surface. A model of second-order or higher was most likely needed.


2.2.5 Soil loss calculation

Bulk density measurements taken at the site for another study (unpublished) were used in the calculation of soil loss. Soil cores, 7.6 cm in diameter and 105 cm long, were collected in April 2009 in the center of all plots in each of three row positions: in-row as well as trafficked and untrafficked interrow. The cores were segmented such that core sections were kept for depths of 5-15, 15-25, 25-35, 35-45, 55-65, and 95-105 cm. For this analysis, the proportions of area occupied by the row (22%), and untrafficked (39%) and trafficked (39%) interrows were used to calculate a weighted average bulk density from the 5- to 15-cm depth range for each plot. Soil loss was calculated for each plot in the second-order dataset by combining the weighted bulk density for each plot with that plot’s elevation.

2.2.6 Analysis

Individual experimental unit (plot) boundaries were buffered inward by 1 m on all sides to account for errors in tillage, resulting in areas of interest (AOIs) with dimensions of 13.5 X 3.5 m. The data (both raw and detrended) were then clipped to buffered plot boundaries. From this point forward, the term “raw” will be used for the original elevation dataset, and “X-order” will be used for the detrended datasets.

An elevation value for each AOI was calculated as the average of the individual point elevations. Soil surface variations unrelated to hillslope and tillage were present in all plots due to the presence of weeds and stubble, clods of soil, and emerged soybeans. Among potential alternatives to using the AOI-average elevation, the minimum elevation point
within an AOI was not used to avoid favoring an abnormally low point such as a dead furrow left by the moldboard plow. Similarly, the maximum was not used to avoid favoring abnormally high points, associated with non-soil objects such as weeds and stubble. SAS PROC MEANS was used to calculate the mean elevation for each AOI and dataset; these means were then used in PROC GLM to determine the difference in elevation between the treatment and the trend surfaces. Means separation was performed using Fisher’s protected LSD. The residuals from this ANOVA were checked for normality and homoscedasticity in SAS with Shapiro-Wilk and Levene’s tests. Analysis of variance was performed using PROC MIXED in SAS to determine tillage effects on weighted bulk density. Analysis of variance using PROC GLM was performed to determine the effect of tillage treatment on soil loss.

2.3 Results and Discussion

2.3.1 Lidar Scanning

The four lidar scans generated a total of 2,221,926 spot elevations. When combined, the returns form a cloud of points covering the experimental area (Fig. 2.2). Once clipped to the AOIs, the dataset was reduced to 518,084 points. Point density decreased with distance from scanner location. The average AOI contained 14,388 points (304.5 points m⁻²). The NT plots had the lowest point density amongst treatments (52.8 points m⁻²), which we considered an adequate number of points to generate mean elevations for analysis.

Lidar data indicated a range in elevation at the experimental site of 5.75 m. A hillshaded triangulated irregular network (TIN) demonstrates the large- and small-scale variability in
elevation at the site (Fig. 2.3). Large-scale variability (slope) is evident by the contours in the map, while the hillshading details the small-scale variability present throughout the experimental site. Some of this microtopography is visible as linear features, and is related to the direction of tillage, traffic, and planted rows. Other features are non-linear in shape, and reflect patches of weeds, plots where residue cover is greater, and plot alleys where tillage passes began and ended, no crops were planted, and weed growth occurred.

2.3.2 Trend Removal

Detrending produced models with $R^2 > 0.99$ for all four polynomials. Every term in all four models was highly significant ($p < 0.0001$). The trend surfaces were increasingly complex as the order of the polynomial increased (Fig. 2.4). The polynomial order indicates the number of times the fit surface can bend in a different direction. A first-order model (Fig. 2.4a) fit a flat surface as the slope. A surface fitted by a second-order polynomial (Fig. 2.4b) had a single bend; third- and fourth-order surfaces were notably more complex (Fig. 2.4c-d). Residuals from each modeled surface represented relative deviations in elevation from that surface and were used in the subsequent analyses.

Hillshaded TINs of these detrended data (Fig. 2.5) showed elevation patterns different from that of the raw data (Fig. 2.3). The original slope was no longer apparent. Elevation changes were localized within plot areas indicating the removal of the trend. The visible pattern of local elevation differed somewhat with increasing order of the polynomial trend removal. Elevation features related to tillage, traffic, weed growth, etc., remained after detrending and
showed a similar level of detail evident in the raw data (Fig. 2.3). Differences in plot-to-plot elevation possibly related to weed growth and surface residue represented a potential source of error for calculating relative plot-surface elevations.

### 2.3.3 Analysis of Variance

The analyses of variance testing block and treatment effects on relative elevation of the four detrended surfaces yielded residuals that were normally distributed and homoscedastic. Depending on the detrending model, 46 to 66% of the variability in relative elevation was accounted for by block and tillage treatment (Table 2.1).

For the raw data, tillage treatment effects were not significant (p = 0.99), while the block effect was highly significant, consistent with the position of the blocks relative to the hillslope. Since these data were not detrended, the mean elevation of 2.2 m was relative to the lowest elevation point in the dataset.

When the hillslope trend was removed with the first-order model, the tillage treatment p value decreased markedly to ~0.1, while the block effect remained highly significant. The strength of the model ($R^2 = 0.65$) was greater than that of the raw dataset ($R^2 = 0.54$), and the coefficient of variation (CV) decreased from 39.3 to 15.0%. The mean elevation (-0.02 m) reflected the average elevation of all AOI surfaces relative to the trend. Detrending with the second-order polynomial improved the ANOVA $R^2$ slightly, lowered the CV, and revealed a highly significant (p = 0.002) tillage treatment effect. The block effect remained significant, albeit with a two order of magnitude increase in p value. Mean elevation was -0.03 m.
While still exhibiting highly significant treatment effects ($p = 0.006$) and a CV comparable to that of the second-order dataset, the third-order dataset saw a drop in the proportion of variability attributable to block and treatment effects ($R^2 = 0.55$). The block effect, which was notably significant in the lower-order datasets, was highly non-significant ($p = 0.97$). This implies that effect of slope, which was used to arrange blocks, had been removed. The fourth-order dataset produced a CV and block and treatment effect significance similar to that of the third-order model, but with the lowest $R^2 (0.42)$ of any of the datasets.

We did not examine higher-order polynomials based on the highly significant treatment effects detected with the second- and third-order datasets, the disappearance of the block effect in the third-order dataset, and the decreased significance of treatment effects and lowest $R^2$ in the fourth-order dataset. Visual analysis of the hillslope suggested that either the second- or third-order surface (Fig. 2.4) best represented the landscape at the site, lending support to the decision to stop at the fourth-order polynomial. Based on these results, and those from subsequent analyses, we think the second-order polynomial was best-suited for analysis of elevation change and soil loss or gain.

### 2.3.4 Treatment Effects on Soil Elevation

Mean treatment elevations relative to the trend surface are shown in Fig 2.6. The order of treatments ranked from highest to lowest elevation was not consistent across datasets. Depending on the detrending polynomial, three to five treatments had elevations greater than the trend surface. Treatment elevation relative to the trend surface ranged from +4.32 cm (CHfa, first-order) to -13.28 cm (MPfaD, second-order). These values are well within 30-yr soil
profile-truncation measurements of 25.4 cm in Piedmont areas (Bennet and Chapline, 1928). Across all datasets, higher-intensity tillage methods had the lowest elevations relative to the trend. For all datasets, CHspD and CHfaD had the sixth- and seventh-lowest elevations, respectively, with MPspD and MPfaD consistently ranked 8th and 9th, respectively, except in the fourth-order dataset, where the rank of these two treatments was reversed. Lower-intensity tillage methods such as NT and IRS had some of the higher elevations. In most cases, CHfa or CHsp also ranked among the highest elevations. For our chosen model (second-order), elevations ranged from +3.20 (CHfa) to -13.28 cm (MPfaD), and no elevation differences were detected among the highest group: CHfa, CHsp, NT, IRS, and Disk, nor among the lowest group: CHfaD, MPspD, and MPfaD.

Higher elevations might be explained by lesser soil loss, greater soil deposition, a lower bulk density, or any combination of these. Attributing elevation differences among treatments to soil moving into plots from a higher elevation would be difficult and somewhat unlikely given the randomized pattern of treatments at the site and the alleys between blocks. Weighted bulk density in the top 5 to 15 cm of soil did vary significantly amongst treatments (Table 2.2). The three highest bulk density treatments (MPspD, NT, CHspD) were different from the lowest bulk density treatment (MPfaD). However, NT was among the highest elevation treatments and MPfaD was the lowest, countering the hypothesis that differences in bulk density observed here contributed to elevation differences. That said, bulk density samples were taken before spring tillage, while lidar scanning occurred 78 days later in the year, post-tillage. Soil-loosening effects may have persisted at the time of the scan, causing
some treatments to have a lower bulk density in the tillage zone, and thus a higher elevation, which was not apparent at the time of the bulk density data collection.

Apparent differences in elevation might also have been due to error in estimation due to weeds and crop residue. Treatments of lower tillage intensity (NT, IRS, CHfa, and CHsp) appeared to have a greater population of weeds than other treatments, though this was not specifically quantified. Lidar returns from weeds would result in artificially high estimates of soil elevation. To use aerial lidar to develop high resolution digital elevation models, numerous filters have been developed to exclude returns presumed to be from interfering vegetation and other objects in order to estimate the “bare-earth” surface (Meng, et al., 2010). Similar techniques might be developed and applied when using ground-based scanning lidar as described here.

2.3.5 Treatment Effects on Soil Loss

Ideally, soil loss and deposition would be measured relative to the original surface, which we do not know in this case. Therefore, a reference elevation was chosen. The simplest method was to use the trend itself as the reference, but it was an estimate based on current topography. Referencing the treatment with the highest elevation was another approach considered. In that scenario, CHfa would be the reference surface for three of four datasets, including the second-order dataset. Instead, considering which treatment likely eroded the least due to soil protection from crop residue led us to set NT as our reference surface, which was also consistent with previous short-term observations at the same site (Myers and Wagger, 1996).
With NT as the reference surface, we used the resultant relative elevations along with the shallow bulk density measurements to estimate soil loss. Tillage treatments affected soil loss and 64% of its variability was explained by treatment and block (Table 2.3). Soil loss or gain by tillage treatment for the second-order dataset is shown in Fig 2.7. Assuming zero soil loss in the NT system, soil gains ranged from 326.4 (CHfa) and 39.5 Mt ha⁻¹ (CHsp) while soil losses ranged from 75.8 (IRS) to 1890.5 Mt ha⁻¹ (MPfaD). Positive elevation values (discussed above) resulted in positive values in the soil loss calculation, thus reflecting a soil gain. Since we suspect the positive elevations to be artifacts due to weed growth in plots where tillage was less intense, it is likely that these values for change in soil mass were due to the same issues.

Worldwide data compiled (n = 448) by Montgomery (2007) showed that conservation tillage averaged 0.1 mm yr⁻¹ soil loss, measured by soil profile truncation, compared to 4 mm yr⁻¹ in conventional systems. Setting their conservation tillage erosion figure to zero and adjusting the other data accordingly puts their 28-year conventional tillage system soil losses equal to 4 mm annually, and 11 cm in total. This number also corresponds with the range of values we found with our more intensely-tilled plots.

2.4 Summary and Conclusions

Ground-based lidar was used to measure differences in surface elevation associated with nine tillage treatments in a long-term (28-year) study. Lidar scans of the study site revealed relief of 5.75 m (large-scale variability), as well as microtopography (small-scale variability) indicative of traffic, row patterns, and plant growth (soybeans and weeds). Modeling the
slope trend with polynomial regression produced residuals representative of the small-scale variability related to tillage treatments. The ANOVA of these residuals from the first- and second-order models had significant block effects which likely accounted partially for slope. Treatment effects were significant in the second- through fourth-order models. A highly significant treatment effect (p=0.002), high $R^2$ (0.66), and a low CV (11.1%) in the second-order model, along with the fact that the block effect became highly insignificant in the third-order model, indicated that the second-order model was best suited for removing trend and calculating elevation change.

The two moldboard plow plus disk treatments had the lowest relative elevation and greatest estimated soil loss, which was consistent with results from prior tillage studies. Soil-loss estimates for these treatments were consistent with those reported on similar soils and ranged up to 1891 Mt ha$^{-1}$, depending on the order of the polynomial used for trend removal.

Accuracy and precision of elevation measurements might be improved by using more scan locations across the site to provide a more consistent lidar point density, by decreasing weed and residue cover as consistently as possible, and/or by filtering out their lidar returns. Accuracy and precision of soil elevation change estimates and resulting comparisons of tillage treatments would likely be greatly improved by lidar scanning to determine the topography of the experimental area prior to applying treatments, which was not possible here. This would allow direct comparison of before and after surfaces to determine soil loss or accumulation due to treatments and eliminate the need for slope trend removal. Despite the lack of information regarding the original surface in this study, soil loss estimated using
ground-based lidar was similar to that reported in other studies. Thus, we conclude that ground-based lidar can be an effective tool to monitor soil loss in agricultural landscapes.
2.5 References


Nagihara, S., 2006. Use of Ground-Based LIDAR in Geomorphic and Surface Stratigraphic Studies. GCAGS/GCSSEPM, September, 25-27


Table 2.1 Results of ANOVA for the effect of block and tillage treatment on elevation for raw and detrended data. Model column indicates which model was used to detrend the data.

<table>
<thead>
<tr>
<th>Model</th>
<th>Source</th>
<th>df</th>
<th>Pr &gt; F</th>
<th>Mean elevation (m)</th>
<th>C.V.</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw</td>
<td>block</td>
<td>3</td>
<td>0.0004</td>
<td>2.18</td>
<td>39.3</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>tillage</td>
<td>8</td>
<td>0.99</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First Order</td>
<td>block</td>
<td>3</td>
<td>0.0003</td>
<td>-0.02</td>
<td>15.0</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>tillage</td>
<td>8</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Second Order</td>
<td>block</td>
<td>3</td>
<td>0.03</td>
<td>-0.03</td>
<td>11.1</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>tillage</td>
<td>8</td>
<td>0.002</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Third Order</td>
<td>block</td>
<td>3</td>
<td>0.97</td>
<td>-0.03</td>
<td>13.4</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>tillage</td>
<td>8</td>
<td>0.006</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fourth Order</td>
<td>block</td>
<td>3</td>
<td>0.97</td>
<td>-0.03</td>
<td>13.5</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>tillage</td>
<td>8</td>
<td>0.04</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2.2 Mean treatment values for bulk density, weighted by row position. P-value: 0.007. Least square means adjustment method for multiple comparisons: Tukey. NT, no-till; IRS, in-row subsoiling; CHfa, fall chisel; CHsp, spring chisel; D, disk; CHfaD, fall chisel plus disk; CHspD, spring chisel plus disk; MPfaD, fall moldboard plow plus disk; MPspD, spring moldboard plow plus disk.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mean bulk density (g cm$^{-3}$)</th>
<th>Letter Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPspD</td>
<td>1.52</td>
<td>a</td>
</tr>
<tr>
<td>NT</td>
<td>1.50</td>
<td>a</td>
</tr>
<tr>
<td>CHspD</td>
<td>1.50</td>
<td>a</td>
</tr>
<tr>
<td>IRS</td>
<td>1.46</td>
<td>ab</td>
</tr>
<tr>
<td>CHsp</td>
<td>1.44</td>
<td>ab</td>
</tr>
<tr>
<td>CHfa</td>
<td>1.40</td>
<td>ab</td>
</tr>
<tr>
<td>CHfaD</td>
<td>1.39</td>
<td>ab</td>
</tr>
<tr>
<td>D</td>
<td>1.39</td>
<td>ab</td>
</tr>
<tr>
<td>MPfaD</td>
<td>1.34</td>
<td>b</td>
</tr>
</tbody>
</table>
Table 2.3 Results of ANOVA for effect of tillage on soil loss or gain for the second-order dataset assuming zero soil loss in the no-till system. Treatment means are shown in Fig. 2.7.

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Mean Soil Loss (Mt ha(^{-1}))</th>
<th>C.V.</th>
<th>Pr &gt; F</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>block</td>
<td>3</td>
<td>-442.85</td>
<td>32.46</td>
<td>0.03</td>
<td>0.64</td>
</tr>
<tr>
<td>tillage</td>
<td>8</td>
<td></td>
<td></td>
<td>0.005</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 2.1 Aerial image, trial boundary, and airborne lidar-derived 0.6-m elevation contours for the Nine Tillage Study. Slope decreases from the east to the west. This image was made approximately 3 weeks after lidar scanning. Location of blocks and many individual tillage plots are visible. Image date: 7 July 2010. Source: Google Inc. Elevation contours source: NC Floodplain Mapping Program. Date: 2007.
Fig. 2.2 Location of lidar returns from four scans in the Nine-Tillage Study. Each black dot represents one return (data point) of a laser pulse to the scanner head. Four circular areas indicate location of scanner in the alleys (between blocks) of the experiment. Linear WSW to ENE features with no returns (white) indicates areas not visible to the scanner behind a ridge of soil.
Fig. 2.3 A hillshaded Triangulated Irregular Network (TIN) created from raw elevation values (trend intact). Hillslope indicated by 0.5-m contours.
Fig. 2.4 Oblique representation of trend surfaces modeled using (a) first-, (b) second-, (c) third-, and (d) fourth-order polynomials. Vertical elevations were exaggerated 20x to better show effect of higher-order models on trend-surface complexity. Elevation contours represent 0.25 m of elevation change. Grayscale gradient illustrates high (dark gray) to low (light gray) elevations. Surfaces have been tilted to effectively show shape of surface.
Fig. 2.5 Hillshaded TINs created from data detrended using a (a) first-, (b) second-, (c) third-, and (d) fourth-order polynomial. Data were classified to illustrate areas above (> 0) and below (< 0) the trend. White polygons indicate location of AOIs.
Fig. 2.6 Mean elevations of tillage treatments relative to the trend for data detrended with first- through fourth-order polynomials. Treatment columns within one panel differ significantly when labeled with different letters (LSD, $p \leq 0.05$). Error bars are standard errors. NT, no-till; IRS, in-row subsoiling; CHfa, fall chisel; CHsp, spring chisel; D, disk; CHfaD, fall chisel plus disk; CHspD, spring chisel plus disk; MPfaD, fall moldboard plow plus disk; MPspD, spring moldboard plow plus disk.
Fig. 2.7 Soil loss or gain by treatment in the Nine Tillage Study for the second-order dataset. Loss or gain was estimated from elevation differences using NT elevation as a baseline (zero soil loss or gain) and bulk density. Least square means separation adjustment method: Tukey. NT, no-till; IRS, in-row subsoiling; CHfa, fall chisel; CHsp, spring chisel; D, disk; CHfaD, fall chisel plus disk; CHspD, spring chisel plus disk; MPfaD, fall moldboard plow plus disk; MPspD, spring moldboard plow plus disk.
3. **Tillage, depth, and traffic effects on soil physical properties and yield in a long-term tillage study in the North Carolina Piedmont.**

**Abstract**

Understanding the long-term effects of tillage on soil physical properties and yield is critical to providing accurate recommendations to growers regarding optimizing yield, soil moisture status, and reducing runoff and erosion. Conservation tillage methods have shown favorable results for yields and soil properties and processes. The objective of this study was to describe the long-term influence of nine tillage methods, row position, and depth on soil bulk density ($\rho_b$), carbon stratification ratio (CSR), volumetric water content ($\theta_v$), water retention (WR), plant-available water (PAW), and crop yield for a sandy clay soil in the North Carolina Piedmont. In a long-term (30-yr) trial in the Piedmont of North Carolina with nine tillage treatments, soil cores were extracted at three row positions centered at 2.5, 10, 20, 30, 40, 60, and 100 cm depths. Tillage treatments ranged widely in intensity of soil disturbance and included, (in order of tillage intensity, from low to high): no-till (NT), in-row subsoiling (IRS), fall chisel (CHfa), spring chisel (CHsp), disk (D), spring chisel plus disk (CHspD), fall chisel plus disk (CHfaD), spring moldboard plow plus disk (MPspD), and fall moldboard plow plus disk (MPfaD). Row positions were in-row; untrafficked interrow; and the trafficked interrow. Soil physical properties measured in all three row positions included bulk density and volumetric soil water content at time of sampling. Other soil properties measured only in the in-row position included: particle size distribution; water retention at matric pressures of 10, 30, 100, 500, and 1500 kPa; carbon content; and two carbon stratification
ratios. Bulk density was greater at the in-row position to a depth of 10 cm. Water retention differed at 30 and 100 kPa for only two tillage methods. Water retention did increase with depth within all tillage treatments, likely due to the co-local increase in clay and decrease in sand. More differences may have been detected had intact cores been used. Carbon content is considered to benefit the physical, chemical, and biological state of soils. Carbon content decreased with depth for all tillage treatments, a trend which was captured in two carbon stratification ratios: the ratios of carbon at 2.5 cm to that at 10 cm (CSR₁), and at 2.5 cm to that at 20 cm (CSR₃). CSR₁ was found to be affected by tillage with the highest mean in NT, and a general trend of decreasing CSR₁ as tillage intensity increased. The CSRs tended to follow the same trend found in long-term crop yields at this site, which for both crops, declined as tillage intensity increased. Results show that conservation tillage methods foster conditions favorable to crop growth, especially as they relate to carbon content, and that Piedmont growers should see long-term benefits in the use of these soil management practices in their corn-soybean rotations.

3.1. Introduction

Adoption of conservation tillage methods from 1990 through 2004 increased from 26.1 to 40.7% in the United States, a change from 73.2 to 112.6 million acres (Conservation Technology Information Center, 2004). This has been driven by factors including the need for more efficient use of resources such as fuel, equipment, and time; and the desire to conserve soil, organic matter, and water through erosion prevention and increased water infiltration and storage. In order to evaluate and improve the effectiveness of conservation
tillage methods, it is important to measure and understand how soil physical properties in these tillage systems compare with other commonly used tillage methods.

The amount of soil disturbance resulting from tillage affects soil physical properties and ultimately, plant growth and crop yield (Cassel et al., 1995; Hill, 1990; Hill, 2001). Over the years, tillage effects on soil physical properties have been studied in various places, on various crops, and over different time scales. Since soil physical properties may change incrementally over time, both short- and long-term (> 10 years) experiments are necessary to understand the effects of new soil management methods, and to avoid the incorrect promotion of poor methods (Dick et al., 1991; Six et al., 2004).

Results from a number of long-term tillage studies have been reported in the literature (Allmaras et al., 1996; Allmaras et al., 1988; Hill, 1990; Pikul and Allmaras, 1986; Staricka et al., 1991). Some have focused on changes in soil physical properties (Hill, 1990; Low, 1955; Rhoton, 2000), runoff and water quality (DeLaune and Sij, 2012; Freese et al., 1993; Myers and Wagger, 1996); as well as infiltration and plant-available water (Baumhardt et al., 2011). Horne et al. (1992) showed that after 10 years on a silt loam, the soil under NT was denser than that under disk-harrow. Rhoton (2000) concluded that over eight years, changes in soil physical properties were associated with changes in soil organic matter content (SOM). Increased SOM in NT was associated with greater aggregate stability and modulus of rupture, while the opposite occurred under conventional till (CT) due to steady decreases of SOM.
Franzluebbers (2002b) measured SOC at 0 to 5, 5 to 12.5, and 12.5 to 20 cm in Texas, and at 0 to 2.5, 2.5 to 7.5, and 7.5 to 15 cm in Georgia. He found that SOC was uniformly distributed in the top 15 to 20 cm under long-term CT, while there was greater SOC near the soil surface under NT. At 7.5 to 15 cm, more SOC was found in CT than NT likely due to the transport of crop residues to subsurface areas, and the lack of such transport where soil and surface residue is left undisturbed (Brown and Dickey, 1970; Ghidey and Alberts, 1993). Franzluebbers (2002b) hypothesized that the degree of C stratification could be used as an indicator of soil ecosystem functioning and subsequently developed the C stratification ratio (CSR) - the ratio of C at the surface (0-5 cm) to that at a deeper range interval in the profile (15-20 cm). Higher ratios would reflect higher C content near the surface, which can reduce crusting, promote infiltration, and improve nutrient-holding capacity. Results showed that while total C from 0 to 20 cm was equal in NT and CT systems, the CSR was almost double in NT, ranging from 2.1 to 3.4, compared to CT, with ratios of 1.1 to 1.9. Poor tillage recommendations could be made if based on total SOC without a measure of stratification (Franzluebbers et al., 1999).

Ultimately, crop yield is among the primary reasons for a change in, or adoption of, any crop- or soil management practice. Regarding this matter, Hill (1990) indicated it took three to six years for corn yield on a silt loam in Maryland under NT to match that of CT, with NT yields even surpassing CT output after that time. Blevins et al. (1983) described CT yields in Kentucky on a silt loam that equaled or surpassed that of NT at higher N rates. He suggested that the five-year duration of the study was insufficient for the accreted organic N to have increased mineralization. In an infiltration study, Freese (1993) described corn yields in 1988
at the same piedmont site as our research (described later) equaling 6.5, 4.8 and 2.5 Mg ha\(^{-1}\) for the NT, CH, and MP plots, respectively. He attributed this crop response to greater infiltration in NT than in MP plots. At the same site, Cassel et al. (1995) described corn yields in 1986 and 1987 of 4.1, 2.6, and 1.0 Mg ha\(^{-1}\) for the same treatments, respectively, the same pattern as described by Freese et al. (1993). They cited poor rainfall and abnormally high temperatures during critical growth stages as contributors to below-average yields in 1986 and 1987.

The topography and climate of the southeastern U.S.A. Piedmont have created a landscape both shaped by, and subject to, the forces of erosion. These factors, coupled with early farming soil management systems that relied on moldboard plow tillage, have left agricultural fields with a shallow topsoil, and with much less organic matter than was present originally. Bennett and Chapline (1928) estimated soil profile truncation of 25.4 cm had occurred over the course of 30 years in Piedmont areas. Erosion estimates made at a long-term tillage study in the NC Piedmont indicated soil profile truncation of up to 15.4 cm over a 30-yr period in moldboard-plowed plots (Meijer et al., 2013). Piedmont soils today are drastically different from those present at the time the land was cleared for agriculture. Tillage methods have since changed dramatically as well, with moldboard plow usage mostly a thing of the past. While tillage has had detrimental effects on the landscape, it may too be part of maintaining or improving the condition and productivity of the soil. Thus, long-term research regarding tillage and its effect on soil physical properties is important.
The Nine Tillage Study (NTS), a long-term tillage study in the North Carolina Piedmont, was initiated in 1984 to study the effects of tillage on soil physical properties. The objectives of the study were to discover tillage systems that would promote soil water storage, reduce soil erosion, and increase crop yield for regional growers (Cassel et al., 1995). At its initiation, the use of moldboard plow and disk was common in the region (Cassel et al., 1995). The site was suitable for this type of experiment due to its sandy loam soil typical of Piedmont soils used extensively for agriculture (Cassel et al., 1995). Additional site characteristics suitable for fulfilling their objectives included its susceptibility to drought-stress (Denton and Wagger, 1992), erosion, crusting (Cassel et al., 1995; Denton and Wagger, 1992), and bulk densities high enough to restrict root development (Freese et al., 1993; Myers and Wagger, 1996).

The data and analysis reported herein are both unique and important due to the 28-year duration of the experiment from which the data were generated; the number and timing of tillage treatments; the range of soil disturbance represented amongst the treatments; sampling depths down to 105 cm; the potential three-way interactions of tillage, row position, and depth; and the soil on which the study was conducted. However, the underlying objectives of this long-term experiment are virtually unchanged from those described by Cassel et al. (1995).

The objective of this study was to describe the long-term (28-year) influence of nine tillage methods, row position, and depth on soil bulk density ($\rho_b$), carbon stratification ratio (CSR),
volumetric water content ($\theta_v$), water retention (WR), plant-available water (PAW), and crop yield for a sandy clay soil in the North Carolina Piedmont.

3.2. Materials and Methods

3.2.1. Location, Soils, and Cropping System

Field sampling was conducted in 2009 at the Upper Piedmont Research Station near Reidsville, NC (36.383883 N, -79.701895 W) on a long-term (28-yr) tillage study, referred to as the “Nine Tillage Study” (NTS). Soil type is mapped as a Casville sandy loam (fine, mixed, semiactive, mesic, Typic Kanhapludult). Corn (Zea mays, L.) was cropped continuously from 1984 through 1989. Since that time, corn and soybean (Glycine max, L. Merr.) have been rotated annually.

3.2.2. Experimental Design & Treatments

The treatment structure was a three-way ($9 \times 3 \times 6$) factorial, Tillage $\times$ Row Position $\times$ Sampling Depth. The tillage treatments were no-till (NT), in-row subsoiling (IRS), fall chisel (CHfa), spring chisel (CHsp), disk (D), fall chisel plus disk (CHfaD), spring chisel plus disk (CHspD), fall moldboard plow plus disk (MPfaD), and spring moldboard plow plus disk (MPspD). The row positions were in-row and the trafficked and untrafficked interrows. The depths were 5 to 15, 15 to 25, 25 to 35, 35 to 45, 55 to 65, and 95 to 105 cm. For CSR, an additional core was taken from 0 to 5 cm. The treatments were arranged in a strip-split plot design in a RCBD with four replications. Tillage was the main plot factor, row position the split plot factor, and sampling depth the split-split factor. Traffic was considered stripped due
to its constraint to every other interrow for the duration of the experiment. Main-plot and whole-experiment dimensions were 15.5 x 5.5 and 80 x 49.5 m, respectively. Tillage was performed annually along the length of the plots parallel to the 0.92-m crop rows, with controlled traffic in every other interrow throughout the 28-yr duration of the study. All disking was performed in the spring prior to planting.

3.2.3. Cultural practices

Cultural practices including weed and insect control have been carried out in a manner consistent with regional practices over the life of the study. For corn, some N was applied as starter, with the rest following 4 to 5 weeks after emergence. Lime, P, and K were applied based on soil-testing recommendations from the North Carolina Department of Agriculture and Consumer Services. Crops were harvested using a two-row combine, with its traffic pattern matching that of all other equipment passes in the field.

3.2.4. Soil physical and properties

Soil cores, 7.6 cm in diameter and 115 cm deep, were extracted using a Giddings probe (Giddings Machine Co., Windsor, CO), in March of 2009 from all the NTS plots. The cores were sectioned to 10-cm lengths, and those corresponding to depths of 5 to 15, 15 to 25, 25 to 35, 35 to 45, 55 to 65, and 95 to 105 cm were kept for analysis. In 2012, additional cores were extracted at 0 to 5 cm from the in-row position for the C analysis described below in Section 3.5. These depth increments are hereafter referred to by their mean depth: 2.5, 10, 20, 30, 40, 60, and 100 cm, respectively. These depths were chosen to match the depths at which
volumetric water content was being monitored on a weekly basis for other work occurring at the test site. These non-intact cores were bagged and immediately weighed to obtain a wet mass. Bulk density was calculated using the core method (Klute, 1986). Gravimetric water content ($\theta_g$) was derived from mass lost upon oven drying for 24 h at 105°C. Volumetric water content ($\theta_v$) was calculated by multiplying $\theta_g$ by $\rho_b$, and dividing by the density of water. The cores from the in-row position were saved for further analysis as described below. The dried soil was ground to pass a 2-mm sieve. Approximately one half of each in-row sample was sent for standard analysis at the soil testing lab of the North Carolina Department of Agriculture and Consumer Service Agronomic Division in Raleigh, NC. Particle size analysis (PSA) was determined using the hydrometer method (Klute, 1986). Water retention was determined with methods described by Klute (1986) using a pressure cell apparatus at pressures of 10, 30, 100, 500, and 1500 kPa. Permanent wilting point was estimated using $\theta_v$ at 1500 kPa, and plant available water (PAW) was calculated using $\theta_v$ at both 10- and 30-kPa pressures as estimates of field capacity (FC): PAW$_{10}$ and PAW$_{30}$. Based on literature describing comparisons between lab and in situ measurements, Cassel and Nielsen (1986) recommended that lower pressures (5 to 10 kPa) be used for coarser-textured soils, and values around 33 kPa used for medium-textured soils. They also stated that the in situ FC value for a particular coarse-textured soil may correlate better with the 33-kPa water content from the lab.
3.2.5. Carbon and Carbon Stratification

Total C, from the in-row position only, was determined on weight:weight basis using a Perkin-Elmer CHN Elemental Analyzer (PE 2400, Perkin-Elmer Corp., Norwalk, CT). Carbon content was determined for all treatments except those with fall tillage (CHfa, CHfaD, and MPfaD). Two CSRs were determined. Ratios used were C at 2.5 cm relative to that at 10 cm (CSR₁) and to that at 20 cm (CSR₂). The CSR₁ is comparable to that used by Moreno et al. (2006), who used a ratio of 0 to 5 cm relative to 5 to 10 cm. The CSR₂ is comparable to the depth increments used by Franzluebbers (2002a). Others have used larger depth ranges, such as 0 to 15 cm relative to 15 to 30 cm (Akala and Lal, 2001).

3.2.6. Statistical Analyses

Mixed models analysis was performed using PROC MIXED in SAS v.9.2 (SAS Institute, Cary, NC) for $\rho_b$; $\theta_v$ at sampling; PSA; $\theta_v$ at 10, 30, 100, 500, and 1500 kPa; and C with block, block x tillage, and block x row positions as random factors. REPEATED measures were used in SAS for sampling depth as the effect of depth was constrained within a sampling location. Residuals were tested and found to be normally distributed and homoscedastic. In each case, several covariance structures were evaluated. These were: unstructured; compound symmetry (with and without heterogeneity of variances), spatial power law, and spherical (Littel et al., 2002). The covariance structure that provided the lowest AIC value was selected, provided that model convergence and positive Hessian definite criteria were met. Certain covariance structures, such as Autoregressive and Toeplitz, were not appropriate here due to the uneven spacing of the sampling depths (Littel et al.,...
2002). The lowest AIC covariance structures specified for analysis parameters were: unstructured for \( \rho_b \) and \( \theta_v \); compound symmetry for \( C \); and spherical (power) for all other variables.

For CSR, ANOVA was performed using general linear models in PROC GLM (SAS). Tukey-adjusted least square means separation was performed using the macro “pdmix800” contained in the macro collection “danda” (Design and Analysis Collection Version 1.29) (Saxton, 1998). An alpha value of 0.05 was used to test main effects. It is wise to examine simple effects within interactions with p-values up to, and even greater than 0.20, particularly where F-values are large (Snedecor and Cochran, 1989; Littel et al., 2006). Interactions were thus investigated even if their p-value exceeded 0.05. Correlation analysis was performed in SAS using PROC CORR to gauge the relationships among: CSR; residue reported by White et al. (2009); and yield metrics, which included the 5-yr relative yield mean, the long-term corn and soybean yields, as well as the overall long-term relative yield from 1988 to 2012. Relative yields were calculated as a treatment’s yield as a proportion of the highest-yielding treatment that year, which allowed for multi-year, multi-crop comparisons.

3.3. Results and Discussion

3.3.1. Bulk density

The position \( \times \) depth interaction was highly significant (\( p = 0.001 \)), and there was evidence for interactions of tillage \( \times \) position (\( p = 0.07 \)) and tillage \( \times \) depth (\( p = 0.09 \)) (Table 3.1). Position effects were evident within depth, and vice versa. The effect of depth was detected
within tillage but not the effect of tillage within depth. Finally, although the p-value was smaller for the tillage × position interaction, effects of neither factor were detected within the other.

Across all row positions and depths, mean bulk density ranged from 1.37 g cm\(^{-3}\) (row position, 10 cm) to 1.57 g cm\(^{-3}\) (UT, 100 cm). The simple effects of row position on \(\rho_b\) by depth, averaged over tillage treatments, are shown in Fig. 3.2. Bulk density differed with row position for only the uppermost sampling depth. Bulk density in the trafficked interrow at 10 cm (1.52 g cm\(^{-3}\)) was greater than that of both the in-row and untrafficked interrow positions, which measured 1.37 and 1.39 g cm\(^{-3}\), respectively. These results are consistent with those reported by Balbuena et al. (2000) who found that traffic-induced \(\rho_b\) increases were greater in the top 15 cm of soil.

The simple effects of depth on \(\rho_b\) by row position, averaged over tillage treatment, are shown in Fig. 3.1. Bulk density increased with depth for both the in-row and untrafficked interrow positions but not for the trafficked interrow. For both the in-row and untrafficked interrow positions, \(\rho_b\) at 10 cm was lower than at all depths below 20 cm. Tire traffic is unavoidable in agriculture, so related compaction effects are to be expected, since research has shown that tire traffic results in increased bulk density. In the NTS, Frees et al. (1993) showed that bulk density was higher in trafficked vs. non-trafficked interrows.

Across all tillage treatments and depths, simple effect mean treatment \(\rho_b\) ranged from a minimum of 1.35 g cm\(^{-3}\) (MPfaD, 10 cm) to a maximum of 1.60 g cm\(^{-3}\) (MPfaD, 100 cm) (Table 3.2). Cassel et al. (1995) examined \(\rho_b\) at the same site only at 0 to 10 cm and 10 to 20
cm. At 10 to 20 cm, when averaged across row positions, he found $\rho_b$ for NT, CH, and MP, was 1.59, 1.50, and 1.49 g cm$^{-3}$, respectively. While our sampling intervals were 5 cm deeper than those of Cassel et al. (1995), our values at the same depth for the same treatments, averaged across all row positions and the 10 and 20 cm depths, were consistently about 0.05 to 0.1 g cm$^{-3}$ lower: 1.48, 1.48, and 1.45 g cm$^{-3}$, respectively. The difference in bulk density may have been due to the timing of samples with ours being taken in spring and theirs later in the growing season, or an effect of slight change over time since their previous sampling.

Bulk density varied with depth for only CHfa and MPfaD (Table 3.2), while differences were not detected when examining the effect of tillage within depth. In the case of MPfaD, $\rho_b$ at 10 cm (1.35 g cm$^{-3}$) was lower than at all other depths (Table 3.1), indicating a persisting near-surface effect of soil loosening. For CHfa plots, $\rho_b$ at 10 cm (1.39 g cm$^{-3}$) was lower than that of the 100-cm depth (1.58 g cm$^{-3}$) only, most likely indicating an effect of soil texture rather than a tillage effect. These results may be explained by both the timing of tillage and sampling. At the time of sampling in March, the elapsed time since plots were last tilled was 12 months for spring-tilled and only five months for fall-tilled plots. Thus, spring-tilled soils had had a longer time to settle, while the soil-loosening effects of tillage were more noticeable in some of the fall-tilled treatments. Tillage of fall-tilled treatments would possibly create better conditions, such as increased oxygen supply in the plow layer for organic matter breakdown, and allow a longer period of time for such action prior to new crop growth. The amount of decay in surface residue would also vary with respect to tillage timing, potentially affecting $\rho_b$ and other properties.
Though a tillage × row position interaction was detected (p=0.07), neither the simple effects of tillage nor position were evident when examined by the levels of the other (Table 3.1). This stands in contrast to Cassel et al. (1995), who found a tillage × position interaction in 1986 and 1987 in the NTS. Soil cores in Cassel’s study were extracted at the onset of tasseling, i.e., a few months after spring-tillage. However, our sampling took place in spring, just prior to spring tillage, i.e., 11 mo. after the previous spring tillage, which may help explain this difference between the two studies. With trafficked soil immediately adjacent to a crop row, potential lateral shifts in row positions of even 15 to 30 cm from year to year since the start of the NTS could mute the tillage x position effects.

### 3.3.2 Volumetric Water Content

Water content ($\theta_v$) at time of sampling was affected by two-way interactions of tillage and depth (p=0.004), as well as position and depth (p=0.0003) (Table 3.1). Averaged over row position, tillage had no effect on $\theta_v$ within depth. Averaged over row position, depth affected $\theta_v$ within each tillage treatment, increasing from the 10- to either the 20- or 30-cm depths (Table 3.3). In all tillage treatments but CHfaD, $\theta_v$ at 10 cm was less than at 30 through 100 cm. In the case of CHfaD, $\theta_v$ at 100 cm was not different than that of any other depth. In all cases, the lowest water content occurred in the upper sampling depths. Also, no differences were detected among depths from 30 to 100 cm. Higher infiltration of winter precipitation was thought to occur in fall-tilled treatments during at least a portion of the winter, given the soil loosening and soil roughness found in those plots after tillage. This would potentially lead to higher water contents in those treatments. However, our measurements contradicted
this. At this site in 1986, soil water content varied with tillage only at the 0- to 20-cm depth (Cassel et al., 1995). In Cassel’s study, 19.5 cm of rain fell the week prior to sampling and increased soil water content in NT, CP, and IRS in the upper 20 cm to levels greater than MP. The differences between these two studies regarding the timing of sampling and the amount of precipitation preceding sampling preclude us from drawing extensive comparisons.

Averaged over tillage treatments and within row positions, $\theta_v$ increased from the 10- to 20- to 30-cm depths, and even to the 40-cm depth in the case of the in-row position (Table 3.4). These results may confirm prior results showing higher infiltration rates in untrafficked areas of tillage treatments vs. trafficked areas (Freese et al., 1993). This may have been related to the increasing proportion of clay, and thus, higher water holding capacity, over those depths.

When examined by depth, $\theta_v$ varied with row position only at 10 cm, with $\theta_v$ in the row position (0.19 cm$^3$ cm$^{-3}$) being less than the trafficked position (0.21 cm$^3$ cm$^{-3}$) (Table 3.4). Since higher infiltration rates had been detected in untrafficked vs. trafficked areas (Freese et al., 1993), it was expected that higher moisture content would be found in-row, but this was not the case.

**3.3.3. Particle Size Analysis**

There was no tillage × depth interaction for sand, silt, and clay percentages, which differed by depth but not by tillage treatment (Table 3.1). Sand content ranged from 54% to 70% and decreased with depth from 10 to 30 cm and then increased from 40 to 60 cm (Fig. 3.3). The
relationship of clay content to depth was the inverse of that observed with sand content, increasing with depth through 30 cm, and decreasing from 40 to 60 cm. Silt content changed little with depth, with a range of 10 to 12%. Soil survey data (Soil Survey Staff, Natural Resources Conservation Services, 2013) for the Casville sandy loam map unit describes sand content ranging from 32 to 68%, clay content ranging from 14 to 50%, and silt content fixed at 18% throughout the profile. While the numbers differ slightly, the patterns of changing sand and clay content with depth, along with no change in silt content are a clear match. We had expected a tillage by depth interaction, due to the mixing of soil resulting from moldboard plowing versus the lack of disturbance resulting from NT. Drees et al. (1994) showed that there was more sand in the top 5 cm of a Maury silt loam in NT than in CT. Sand content in NT at 0-5, 10-15 and 20-25 cm was 14.5, 9.9, and 8.9 %, respectively, but remained consistent with depth at 8.3% in CT. Tollner et al. (1984) also showed that moldboard plowing created a uniform texture in the upper 30 cm while no-till preserved the stratification of soil separates. We hypothesized that land use prior to 1984 may have involved moldboard plowing, and as such, may have caused a thorough mixing of the soil in the upper 20 cm. Our results indicate, however, that both sand and clay percentages were different even between the 10- and 20-cm sampling depths, a sign that any tillage prior to 1984 did not create a homogeneous plow layer.

3.3.4. Water Retention

There was no tillage treatment × depth interaction for water retention. Only depth affected water retention (WR) at all matric pressures, while tillage was affected it only at 30- and 100-
kPa (Table 3.1). A main effect of tillage on WR was detected only for the 30- and 100-kPa pressures (Table 3.5). It is likely that more differences were not detected due to the fact that the soil was ground prior to analysis, which disrupts soils structure and narrows pore-size distribution by eliminating macropores. At lower pressures (10 and 30 kPa), WR increased at each depth from 10 to 40 cm (Table 3.6) ranging from 0.17 to 0.24 cm$^3$ cm$^{-3}$ and 0.12 to 0.19 cm$^3$ cm$^{-3}$, respectively. At greater depths at these matric potentials, WR was not significantly greater than either the 30- or 40-cm depths. At matric potentials of 100 and 500 kPa, WR increased through 30 cm, with no significant differences at depths greater than 30 cm, other than at 500 kPa, where WR was slightly less at 100 cm than it was at 40 and 60 cm. At 1500 kPa, WR increased with depth through 40 cm, with no difference between 20 and 30 cm.

Water release curves for the nine tillage treatments at the matric potentials measured are shown in Fig. 3.4. As described earlier, there was little mean separation among treatments within matric potentials, but NT had the lowest mean $\theta_v$ at each matric pressure. The fact that the lines are nearly parallel indicates that PAW should be roughly equal for each tillage treatment.

3.3.5. Plant Available Water

The range of $\text{PAW}_{10}$ was 0.104 to 0.147 cm$^3$ cm$^{-3}$, while $\text{PAW}_{30}$ ranged from 0.056 to 0.094 cm$^3$ cm$^{-3}$ (Table 3.8). There was no tillage × depth interaction for either PAW metric (Table 3.1). The main effect of depth was significant for both, but tillage affected only $\text{PAW}_{30}$ (Table 3.1). The IRS had greater $\text{PAW}_{30}$ (0.095 cm$^3$ cm$^{-3}$) than both NT and MPfaD (0.068 and 0.067 cm$^3$ cm$^{-3}$, respectively) (Table 3.7). The $\text{PAW}_{30}$ difference between NT and IRS is
striking, as they are very similar treatments with respect to residue left on the surface and minimal soil disturbance. The treatments are quite different though, with respect to the in-row position, due to the subsoiling action in IRS. Because our PAW determinations used ground soil samples, the potential effect of pore-size distribution and soil structure among tillage methods may have been eliminated. Subsoiling is likely to affect these properties below the surface, and would not have been detected given the procedures we used. This same issue may explain the similarity in values for NT and MPfaD. These two treatments are the two extremes when it comes to: soil disturbance and residue; the presence of crusting; yield; and most of the other factors we examined, yet they were not different here. There were gradual increases in both \( \text{PAW}_{10} \) and \( \text{PAW}_{30} \) with depth (Table 3.8), which may reflect the increase in clay content. There were no significant differences between any adjacent sampling depths.

### 3.3.6. Carbon and Carbon Stratification Ratio

Carbon content varied among tillage methods at different depths (Table 3.1 and Fig. 3.5). In all tillage treatments, \( C \) decreased with depth (Fig. 3.5), although the depth at which \( C \) changed varied by tillage treatments. A difference in \( C \) between 2.5 and 10 cm was detected only in NT, an indicator of little soil- and residue-disturbance in that treatment. In fact, \( C \) in NT at 2.5 cm was nearly three times that at 10 cm. Soil \( C \) tended to be greater at 2.5 cm than at 10 cm for the next four treatments of increasing disturbance: IRS, CHsp, CHfa, and D. Within depths, differences among treatments were detected only in the surface increment, where NT had more \( C \) than both MP tillage treatments; while IRS, D, and all CH treatments
differed only from MPfaD (Fig. 3.6). We had expected that treatment differences in C would also be detected at 10 cm due to the lack of soil mixing in NT vs. the deep mixing caused by MP, but this was not the case.

Tillage affected CSR$_1$ (Table 3.1), although it should be noted that CSR$_2$ just missed the cutoff of $\alpha = 0.05$ ($p = 0.06$). The CSR$_1$ ranged from 3.1 in NT, to 0.7 in MPfaD. The ratio for NT was greater than that of all CHD and MPD treatments. The CSR$_1$ for MPfaD was only lower than that of NT and CHsp. Crop residue in these plots plays a large role in determining this ratio, so it was not surprising that NT and other conservation tillage methods had higher ratios. Where residue is left undisturbed (e.g., NT), high C content would likely be present in the uppermost portion of the soil profile, increasing the chance of a higher stratification ratio.

3.3.7 Crop Yield

Crop yields at this site were summarized by Meijer et al. (2012), who found them to range widely depending primarily on seasonal precipitation. Insufficient rainfall resulted in total soybean crop failure in 1998 and 2002. Long-term tillage-treatment mean yields for corn and soybean ranged from 3.4 to 6.3 and from 1.9 to 2.7 Mg ha$^{-1}$, respectively (Fig. 3.8). The trend from high to low tillage treatment yield means corresponded to an increase in tillage intensity, with NT on the high end of the yield range and MPfaD on the low end.

The depth at which soil physical properties change from a level conducive to plant growth to one that hinders such growth can affect yield by the influence on rooting; water content and movement; and organic matter content with depth. Bulk density, $\theta_v$, and C were the only
three variables for which there was an interaction of tillage and depth. Bulk density differed among depths in only the CHfa and MPfaD treatments. To say that the reduced $\rho_b$ in CHfa or MPfaD was indicative of better rooting conditions in the upcoming season vs. that of CHsp or MPspD would be erroneous, as the bulk density of the latter two treatments would have been reduced upon spring tillage. We expected differing levels of soil moisture amongst tillage methods for the depths affected by tillage, yet $\theta_v$ did not vary by tillage within depth, although there were significant differences by depth within tillage method.

Freese et al. (1993), working at the same site, measured cumulative infiltration after applying 2.6 cm of water over a 30-minute duration shortly after spring tillage and prior to crop emergence. They showed that cumulative infiltration in NT at early post-emerge was double that of MP (2.01 vs. 0.96 cm) in non-trafficked areas, and almost 3.5 times greater in trafficked areas. This may have been the result of crusting that occurs in the intensely-tilled treatments in this trial, likely resulting from having little to no residue cover. Freese (1993) noted that drought-stress conditions were observed frequently in MP plots, less so in CH plots, and rarely in NT. Freese suggested that these soil moisture conditions likely affected yields of NT, CH, and MP treatments in 1988, which were 6.56, 4.8, and 2.5 Mg ha$^{-1}$, respectively. Organic matter, in terms of residue and soil carbon content, likely played a role in crop development and yield in this trial.

3.4. Summary and Conclusions
Soil physical properties, including bulk density; volumetric water content; percent sand, silt, and clay; water retention; plant-available water; and carbon were measured in a long-term (28-yr) tillage study in the North Carolina Piedmont on a sandy loam soil.

Higher bulk density was detected in the trafficked interrow position than either the in-row or untrafficked interrow positions. This effect, likely due to the pressure of tire traffic over the duration of the experiment, was only detected in the uppermost (10 cm) sampling depth. While some tire traffic is unavoidable in production agriculture, the control of such traffic to as few interrows as possible will limit the percentage of field area compacted by such action.

There was little difference amongst tillage methods for water retention tested at 10, 30, 100, 500, and 1500 kPa. Water retention at 30 and 100 kPa did increase with depth most likely due to the co-local decreases in sand and increases in clay. While tillage did affect plant-available water, the use of disturbed cores may have negated any differences between NT and IRS that might have existed in situ.

Carbon content decreased with depth for all tillage treatments, although the depth intervals at which they changed differed amongst treatments. The most dramatic decrease of C with depth was found in conservation tillage, which was reflected in the CSR. The stratification ratio of carbon at 2.5 cm to that at 10 cm (CSR$_1$) decreased with increased tillage intensity, with the highest values in NT and the lowest in the MP treatments (Fig. 3.7).

Mean long-term tillage treatment yields at this site indicated that NT, IRS and other less-intensive tillage treatments systems outperformed treatments with greater tillage intensity.
such as MP. Tillage effects on the parameters measured here tended to follow a similar pattern, with conditions more conducive to plant growth being inversely correlated to tillage intensity. However, no single parameter seemed to provide a clear explanation of yield performance. Tillage effects on these parameters, coupled with the variation in time and magnitude of environmental factors such as precipitation and temperature, may influence other factors such as runoff, infiltration, and water storage, all of which likely influenced crop growth at this site.

Further research and analysis of available soil profile moisture and precipitation data is being carried out to help explain the effects of tillage on yield in this experiment. Meijer et al. (2013) estimated long-term erosion trends using ground-based lidar and spatial analysis techniques; they found that erosion tended to increase with increasing tillage intensity. The continued trend of low-intensity tillage methods resulting in the greatest yields makes a very strong case for piedmont farmers to employ tillage methods with little to no soil disturbance and greatest crop yields.
3.5 References


Table 3.1 Analysis of variance $p$ values for the effects of tillage, depth, and position on bulk density ($\rho_b$) and volumetric soil water content at sampling ($\theta_v$), and the effects of tillage and depth on all other parameters (where positions were not sampled). T, tillage; P, position; D, depth; $\theta_{10}$, $\theta_{30}$, $\theta_{100}$, $\theta_{500}$, $\theta_{1500}$, volumetric water retention at matric pressures of 10, 30, 100, 500, and 1500 kPa, respectively; PAW$_{10}$, PAW$_{30}$, plant-available water using 10-kPa and 30-kPa field capacity, respectively; C, carbon; CSR$_1$, stratification ratio of carbon at 0-5 cm to that of 5-15 cm; CSR$_2$, carbon stratification ratio of carbon at 0-5 cm to that of 15-25 cm.

<table>
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<th>Effect</th>
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<th>Si</th>
<th>Cl</th>
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<th>$\theta_{30}$</th>
<th>$\theta_{100}$</th>
<th>$\theta_{500}$</th>
<th>$\theta_{1500}$</th>
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Table 3.2 Simple effects of depth on bulk density by tillage method, averaged over row position. Within bolded columns, means followed by different letters indicate Tukey-adjusted means separation (α = 0.05). There were no significant differences among tillage treatments by depth. NT, no-till; IRS, in-row subsoiling, D, spring disk; CHfa, fall chisel plow; CHsp, spring chisel plow; CHfaD, fall chisel plow plus spring disk; CHspD, spring chisel plow plus spring disk; MPfaD, fall moldboard plow plus spring disk; MPspD, spring moldboard plow plus spring disk.

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<th>CHfaD</th>
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<th>MPspD</th>
<th>MPfaD</th>
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Table 3.3 Simple effects of depth on volumetric water content by tillage method. Within columns, means followed by different letters indicate Tukey-adjusted means separation ($\alpha = 0.05$). NT, no-till; IRS, in-row subsoiling; D, spring disk; CHfa, fall chisel plow; CHsp, spring chisel plow; CHfaD, fall chisel plow plus spring disk; CHspD, spring chisel plow plus spring disk; MPfaD, fall moldboard plow plus spring disk; MPspD, spring moldboard plow plus spring disk. Simple effects of tillage method within depth were not detected.

<table>
<thead>
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<td>0.37 c</td>
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Table 3.4 Simple effects on volumetric water content of depth by row position, and row position by depth, both averaged across tillage method. Within columns, means followed by different letters indicate Tukey-adjusted means separation ($\alpha = 0.05$) for the simple effect of depth by row position. Uppercase letters within rows, where present, indicate Tukey-adjusted means separation ($\alpha = 0.05$) for the simple effects of row position by depth. R, in-row; T, trafficked interrow; U, untrafficked interrow.

<table>
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<th>Depth cm</th>
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<td>30</td>
<td>R</td>
<td>0.32 c -</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>0.34 c -</td>
</tr>
<tr>
<td></td>
<td>U</td>
<td>0.33 c -</td>
</tr>
<tr>
<td>40</td>
<td>R</td>
<td>0.35 d -</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>0.35 c -</td>
</tr>
<tr>
<td></td>
<td>U</td>
<td>0.35 cd -</td>
</tr>
<tr>
<td>60</td>
<td>R</td>
<td>0.36 d -</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>0.35 c -</td>
</tr>
<tr>
<td></td>
<td>U</td>
<td>0.36 cd -</td>
</tr>
<tr>
<td>100</td>
<td>R</td>
<td>0.35 cd -</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>0.34 c -</td>
</tr>
<tr>
<td></td>
<td>U</td>
<td>0.37 d -</td>
</tr>
</tbody>
</table>
Table 3.5 Main effect of tillage method on water retention for matric potentials tested, averaged over depth. Tukey-adjusted means separation ($\alpha = 0.05$). NT, no-till; IRS, in-row subsoiling; D, spring disk; CHfa, fall chisel plow; CHsp, spring chisel plow; CHfaD, fall chisel plow plus spring disk; CHspD, spring chisel plow plus spring disk; MPfaD, fall moldboard plow plus spring disk; MPspD, spring moldboard plow plus spring disk.

<table>
<thead>
<tr>
<th>Tillage Method</th>
<th>Matric Potential (kPa)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>30</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>NT</td>
<td>0.20</td>
<td>0.14 a</td>
<td>0.11 a</td>
<td>0.09</td>
<td>0.08</td>
</tr>
<tr>
<td>IRS</td>
<td>0.23</td>
<td>0.19 b</td>
<td>0.15 ab</td>
<td>0.11</td>
<td>0.10</td>
</tr>
<tr>
<td>CHsp</td>
<td>0.24</td>
<td>0.20 b</td>
<td>0.15 ab</td>
<td>0.11</td>
<td>0.10</td>
</tr>
<tr>
<td>CHfa</td>
<td>0.20</td>
<td>0.16 ab</td>
<td>0.14 ab</td>
<td>0.1</td>
<td>0.08</td>
</tr>
<tr>
<td>D</td>
<td>0.23</td>
<td>0.18 ab</td>
<td>0.16 b</td>
<td>0.11</td>
<td>0.10</td>
</tr>
<tr>
<td>CHspD</td>
<td>0.21</td>
<td>0.17 ab</td>
<td>0.13 ab</td>
<td>0.10</td>
<td>0.09</td>
</tr>
<tr>
<td>CHfaD</td>
<td>0.22</td>
<td>0.16 ab</td>
<td>0.13 ab</td>
<td>0.10</td>
<td>0.09</td>
</tr>
<tr>
<td>MPspD</td>
<td>0.21</td>
<td>0.16 ab</td>
<td>0.12 ab</td>
<td>0.10</td>
<td>0.09</td>
</tr>
<tr>
<td>MPfaD</td>
<td>0.21</td>
<td>0.16 ab</td>
<td>0.13 ab</td>
<td>0.10</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Table 3.6 Main effect of depth on water retention for matric potentials tested, averaged over tillage treatments. Within columns, means followed by different letters indicate Tukey-adjusted means separation ($\alpha = 0.05$).

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Matric Pressure (kPa)</th>
<th>Volumetric Water Content (cm$^3$ cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>10</td>
<td>0.170 a</td>
<td>0.122 a</td>
</tr>
<tr>
<td>20</td>
<td>0.195 b</td>
<td>0.154 b</td>
</tr>
<tr>
<td>30</td>
<td>0.218 c</td>
<td>0.172 c</td>
</tr>
<tr>
<td>40</td>
<td>0.239 d</td>
<td>0.192 d</td>
</tr>
<tr>
<td>60</td>
<td>0.233 cd</td>
<td>0.182 cd</td>
</tr>
<tr>
<td>100</td>
<td>0.238 cd</td>
<td>0.185 cd</td>
</tr>
</tbody>
</table>
Table 3.7 Main effect of tillage method on plant-available water using field capacity estimated at both 10 and 30 kPa. Letters within columns denote significant differences ($\alpha = 0.05$). NT, no-till; IRS, in-row subsoiling; D, spring disk; CHfa, fall chisel plow; CHsp, spring chisel plow; CHfaD, fall chisel plow plus spring disk; CHspD, spring chisel plow plus spring disk; MPfaD, fall moldboard plow plus spring disk; MPspD, spring moldboard plow plus spring disk.

<table>
<thead>
<tr>
<th>Tillage Method</th>
<th>Field Capacity Matric Potential (kPa)</th>
<th>Volumetric Water Content (cm$^3$ cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>NT</td>
<td>0.121 a</td>
<td>0.068 b</td>
</tr>
<tr>
<td>IRS</td>
<td>0.129 a</td>
<td>0.095 a</td>
</tr>
<tr>
<td>CHsp</td>
<td>0.139 a</td>
<td>0.090 ab</td>
</tr>
<tr>
<td>CHfa</td>
<td>0.120 a</td>
<td>0.079 ab</td>
</tr>
<tr>
<td>D</td>
<td>0.130 a</td>
<td>0.081 ab</td>
</tr>
<tr>
<td>CHspD</td>
<td>0.118 a</td>
<td>0.075 ab</td>
</tr>
<tr>
<td>CHfaD</td>
<td>0.127 a</td>
<td>0.071 ab</td>
</tr>
<tr>
<td>MPspD</td>
<td>0.119 a</td>
<td>0.069 ab</td>
</tr>
<tr>
<td>MPfaD</td>
<td>0.123 a</td>
<td>0.067 b</td>
</tr>
</tbody>
</table>
Table 3.8 Main effect of depth on plant-available water calculated using field capacity at both 10- and 30-kPa (PAW$_{10}$ and PAW$_{30}$). Letters within columns denote significant differences ($\alpha = 0.05$).

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Field Capacity (kPa)</th>
<th>Volumetric Water Content (cm$^3$ cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.104 a</td>
<td>0.056 a</td>
</tr>
<tr>
<td>20</td>
<td>0.111 ab</td>
<td>0.069 ab</td>
</tr>
<tr>
<td>30</td>
<td>0.122 bc</td>
<td>0.076 bc</td>
</tr>
<tr>
<td>40</td>
<td>0.132 cd</td>
<td>0.085 bc</td>
</tr>
<tr>
<td>60</td>
<td>0.135 cd</td>
<td>0.085 bc</td>
</tr>
<tr>
<td>100</td>
<td>0.147 d</td>
<td>0.094 c</td>
</tr>
</tbody>
</table>
Fig. 3.1 Simple effects of depth on bulk density by row position. Within row positions, means followed by different letters indicate Tukey-adjusted means separation ($\alpha = 0.05$). R, in-row; T, trafficked interrow; U, untrafficked interrow.
Fig. 3.2 Simple effects of row position on bulk density by depth. Within depths, means followed by different letters indicate Tukey-adjusted means separation ($\alpha = 0.05$).
Fig. 3.3 Effects of depth on percent sand, silt, and clay. Within column segments, different letters indicate Tukey-adjusted means separation (α = 0.05).
Fig. 3.4 Water release curves by tillage method. Significant differences between treatments at 33 and 100 kPa are denoted by larger symbols.
Fig. 3.5 Simple effects of depth on percent C by tillage method. Within tillage treatments, means followed by different letters indicate Tukey-adjusted means separation ($\alpha = 0.05$). NT, no-till; IRS, in-row subsoiling; D, disk; CHfa fall chisel plow; CHfaD, fall chisel plow plus disk; MPfaD, fall moldboard plow plus disk.
Fig. 3.6 Simple effects of tillage method on percent C by depth. Within depths, means followed by different letters indicate Tukey-adjusted means separation ($\alpha = 0.05$). NT, no-till; IRS, in-row subsoiling; D, disk; CHfa fall chisel plow; CHfaD, fall chisel plow plus disk; MPfaD, fall moldboard plow plus disk.
Fig. 3.7 Main effect of tillage on the ratio of C at 0 to 5 cm to 5 to 15 cm (CSR). Means followed by different letters indicate Tukey-adjusted means separation ($\alpha = 0.05$). NT, no-till; IRS, in-row subsoiling, D, spring disk; CHfa, fall chisel plow; CHsp, spring chisel plow; CHfaD, fall chisel plow plus spring disk; CHspD, spring chisel plow plus spring disk; MPfaD, fall moldboard plow plus spring disk; MPspD, spring moldboard plow plus spring disk.
Fig. 3.8 Tillage treatment effects on long-term (1988-2011) corn and soybean yield means. Means within crop followed by different letters indicate Tukey-adjusted means separation ($\alpha = 0.05$). NT, no-till; IRS, in-row subsoiling, D, spring disk; CHfa, fall chisel plow; CHsp, spring chisel plow; CHfaD, fall chisel plow plus spring disk; CHspD, spring chisel plow plus spring disk; MPfaD, fall moldboard plow plus spring disk; MPspD, spring moldboard plow plus spring disk.
4. Effects of nine long-term tillage systems on soil moisture in the North Carolina Piedmont

Abstract

Lack of sufficient rainfall during the growing season in the Piedmont region of the southeastern USA limits corn and soybean from reaching their yield potential, even causing crop failure in some years. Capturing and storing rainfall in the soil is critical to minimizing drought stress. Conservation tillage practices have been shown to improve soil moisture storage and yield. Extensive measurements of soil moisture at depths of 10, 20, 30, 40, 60, and 100 cm were made in six tillage treatments in a long-term tillage trial in North Carolina from 2008 through 2012. Precipitation was frequently less than reference crop evapotranspiration in three of the five years studied, providing an opportunity to examine tillage effects on soil moisture during periods of limited moisture availability. Analysis of variance indicated the presence of a tillage x depth x date interaction in 2010, 2011, and 2012; the presence of all three possible two-way interactions of tillage, depth, and date in all years; and the main effect of tillage in both 2009 and 2011. Mean soil moisture content during a critical period in corn, 60 to 90 days after planting, was higher in tillage treatments of lesser tillage intensity. However, the disk treatment with relatively high levels of soil disturbance had the highest mean soil moisture for this period, which could not be explained. Water use efficiency (WUE) was inversely related to tillage intensity, with no-till and in-row subsoiling having the highest WUE in all five years, and both spring chisel plus disk and spring moldboard plow plus disk having the lowest in those years. Periods of near-zero
rainfall were studied to examine the relative differences in soil water depletion. Subsequent replenishment, or recharge, was calculated as well. Again, tillage methods of lower tillage intensity tended to have higher soil moisture contents at the onset of the dry period, had the greatest loss of soil moisture during that dry period, and had the most soil moisture regained after rainfall. Results indicate the ability of soils under conservation tillage to withstand sporadic rainfall shortages in the summer, allowing crops to maintain healthy growth during those times.

4.1 Introduction

The sporadic distribution of rainfall in the southeastern Piedmont of the USA is a key factor in limiting corn and soybean production. At times throughout the growing season, evapotranspiration (ET) may exceed rainfall. Since irrigation is usually unfeasible here due to cost and the sometimes steep, undulating terrain, optimizing rainfall capture and soil moisture availability is imperative to successful crop production. Conservation soil management techniques have been shown to improve infiltration (Freese et al., 1993) and reduce water loss from the soil surface early in the season (Cassel et al., 1995). Corn and soybean yields from conservation-tillage systems, such as no-till (NT), are often greater than yields in conventional-tillage systems (Meijer et al., 2012).

Research has suggested a number of factors that may increase crop yield with conservation tillage. Most cite soil management (tillage) effects on various soil physical properties that influence crop yields. Cassel (1995) showed improved yields with reduced tillage, citing surface residue in preventing crusting, promoting infiltration, and reducing evaporative losses
in NT, in-row subsoiling (IRS) and chisel plow (CH) treatments. Improved yields can result when chisel plowing allows rooting to reach below restrictive layers (Reicosky et al., 1976), especially in years of low rainfall (Cassel et al., 1995).

Soil management effects on soil moisture have also been the focus of numerous studies. Surface residue in NT systems reduces soil moisture loss via evaporation (E) until canopy closure, after which evaporative loss from NT and conventional tillage (CT) becomes equal (Hill and Blevins, 1973). Prior to canopy closure, each centimeter of water protected from evaporation in NT over that of CT, resulted in a corn yield gain of almost 0.56 Mg ha\(^{-1}\). Soil water content in clay loam soils in Minnesota was also greater under NT vs. CT (Gantzer and Blake, 1978).

Water use by corn and soybean increases dramatically as their biomass and leaf area increase and during the reproductive part of their life cycles (Kranz et al., 2008). A plant is highly susceptible to water stress during this critical period, which can result in poor pollination and grain fill. Under NT management, decreased evaporation and improved water storage can aid crop survival for short-term periods of drought with minimal negative effects (Blevins et al., 1971, Al-Darby et al., 1987). Water use efficiency (WUE) can be expressed as the unit of yield (or biomass) produced per unit volume of infiltrated water. In many cases, NT and other conservation tillage methods had higher WUE than their tilled counterparts (Lal et al., 1978; Osuji, 1984). Water use efficiency improved from 200 to 224 kg ha\(^{-1}\) cm\(^{-1}\) in a corn and silage study by Wagger and Cassel (1993), and was up to 30% greater in conservation vs. conventional tillage in a study with double-cropped corn-wheat rotation in the North China
Plain (Jin et al., 2009). Some other studies have shown no effect of tillage on WUE (Olson and Schoeberl, 1970).

The timing, duration, and severity of drought conditions can lead to poor crop performance, and even crop failure. Short-term periods of drought can decrease crop yield, especially when they coincide with critical stages of a plant’s life cycle. To optimize irrigation practices, some growers mitigate these short-term dry periods through continuous soil moisture monitoring, as correctly timed irrigations are needed for precise application of water to a growing plant (Bausch, 1995). Sandy, coastal plain soils in North Carolina, for example, might only store from six to eight days of plant-available water, and require irrigation every two to four days, depending on evaporative demand (Cassel et al., 1985). Individual grain weight in barley was reduced by 20% when treatments of drought and high temperature were applied for 5 to 10 days during grain fill (Savin and Nicolas, 1996). This justifies consideration of the effects of short-term periods of low rainfall and subsequent increases in soil moisture upon precipitation after these periods.

In 1984, the Nine Tillage Study was initiated in the North Carolina Piedmont to study the effects of nine different tillage methods ranging from NT to MPD on yield, soil water storage, soil physical properties, and erosion (Cassel et al., 1995). In the NTS, runoff after 30 minutes of simulated rainfall was up to 4.5 times greater in conventional tillage than in NT (Afunyi et al., 1997). Cumulative infiltration over a 30-min period, measured pre-tillage, in similar experimental conditions at this site averaged 84, 77, and 68% for NT, CH, and moldboard plow (MP) treatments, respectively (Freese et al., 1993). Immediately following
tillage, infiltration was 77, 88, and 83% for the same treatments, showing an increase for both CH and MP, due to the soil loosening that had just occurred. However, one to two weeks later, measured infiltration was 62, 54, and 26%. The severe reduction in infiltration for MP appeared to be related to surface sealing caused by raindrop impact in the MP treatment. No explanation was given for the reduced infiltration in NT and CH. Additionally, symptoms of drought stress were observed frequently in MP, less so in CH, and rarely in NT (Freese et al., 1993). These results provided evidence for tillage-related effects on soil water status in this environment.

The objectives of this study were to determine how tillage method influenced (i) soil profile moisture at a critical period of the growing season, (ii) WUE, and (iii) soil moisture depletion and recharge during short-term periods of drought at a long-term tillage experiment in the North Carolina Piedmont.

4.2. Materials and Methods

4.2.1. Location, Soils, and Cropping System

Soil moisture was monitored from 2008-2012 in a long-term (28-yr) tillage study at the Upper Piedmont Research Station near Reidsville, NC (36.383883 N, -79.701895 W). The soil is mapped as a Casville sandy loam (fine, mixed, semiactive, mesic, Typic Kanhapludult). In some plots, soil coring indicated the presence of saprolite, usually at a depth of 90 cm or greater. Corn (Zea mays, L.) was cropped continuously from 1984 through 1989. Since that time, corn and soybean (Glycine max, L. Merr.) have been rotated annually.
4.2.2. Experimental Design & Treatments

The experimental design was a split plot with tillage as the main plot factor arranged in a randomized complete block in four blocks with depth as split plot factor. Plot- and whole-experiment dimensions were 15.5 x 5.5 m and 80 x 49.5 m, respectively. Tillage was performed annually along the length of the plots parallel to the 0.92-m crop rows. Wheel traffic has been controlled throughout the 28-yr duration of the study so that traffic occurred in every other interrow. Nine tillage treatments were tested, including NT, IRS, fall chisel (CHfa), spring chisel (CHsp), disk (D), fall chisel plus disk (CHfaD), spring chisel plus disk (CHspD), fall moldboard plow plus disk (MPfaD), and spring moldboard plow plus disk (MPspD). A subset of these treatments was used for this study, including all but the fall-tilled treatments. All disking was performed in the spring prior to planting. Residue cover, described by White et al. (2009), was 92, 70, 45, 22, 18, and 6 % in NT, IRS, CH, D, chisel plus disk (CHD), and MPD, respectively. We ranked tillage intensity by these numbers, with higher residue cover indicating lower tillage intensity.

4.2.3. Cultural practices

The study site was planted to soybeans in 2008, 2010, and 2012; and to corn in 2009 and 2011. Planting and harvest dates are shown in Table 4.1. Cultural practices including weed- and insect control have been carried out in a manner consistent with regional practices over the life of the study. For corn, some N was applied as starter, with the rest following 4 to 5 weeks after emergence. Lime, phosphorus, and potassium were applied based on North Carolina Department of Agriculture and Consumer Sciences soil-testing recommendations.
Crops were harvested using a two-row combine, with its traffic pattern matching that of all other equipment passes in the field.

4.2.4 Soil Profile Moisture Monitoring

Soil profile moisture was measured in six of the nine tillage treatments (NT, IRS, CHsp, D, CHspD, and MPspD) using a PR2/6 Profile probe (Delta-T Devices, Cambridge, UK). The PR2/6 is a multisensor capacitance probe which measures soil permittivity; data were recorded with a HH2 logger (Delta-T Devices). The probe consists of a scaled polycarbonate rod with six pairs of sensors located 10, 20, 30, 40, 60, and 100 cm from the top of the probe. Access tubes, with a diameter and length of 2.7 120 cm long, respectively, were installed in the crop row after planting each season using proprietary installation equipment designed to bore a hole of precise diameter and depth to minimize air gaps between the tube and the soil.

To record soil moisture data, the access tube was uncapped and checked for water accumulation which would indicate the presence of condensation or failure of the sidewall of the tube. The probe was inserted into the tube and three readings were made, with the second and third readings taken with the probe rotated 120 and 240°, respectively, from the initial position. Data were downloaded as a comma separated value file and organized in a spreadsheet. Soil moisture readings were made weekly, when possible, between planting and harvest. Soil moisture data were checked for missing values. On 29 July 2010, only two blocks were sampled. On 28 October, 2010, only 2 of 3 subsamples were collected. At harvest in 2011, three access tubes were damaged and not used until being replaced the following spring. Since this work focused on in-season moisture, this presented no problem.
with our analyses. The data were examined for anomalies resulting from potential sensor malfunctions. Evidence of sensor-related problems associated with these missing data were not found, resulting in no data being removed from the dataset. Qi and Helmers (2010) described a procedure for field-specific calibration of the PR2/6 soil moisture readings; in the present study we used the generalized calibration provided by Delta-T Devices. A similar approach was taken by Kargas et al. (2012). Based on analysis of variance for the complete data set (see 4.2.9 on statistical analysis), several additional soil moisture parameters were considered: moisture storage during critical growth periods (4.2.6), WUE (4.2.7), and depletion and recharge events (4.2.8).

### 4.2.5 Precipitation and Evapotranspiration

Precipitation data were obtained for 2008-2012, as recorded daily by staff at the Upper Piedmont Research Station, while reference crop evapotranspiration ($ET_0$) data were obtained from the NC Climate Retrieval and Observations Network of the Southeast Database (State Climate Office of North Carolina, [http://www.nc-climate.ncsu.edu/cronos/](http://www.nc-climate.ncsu.edu/cronos/)) based on calculations with the Penman-Monteith method.

### 4.2.6 Critical Growth Periods

The time for a plant to reach a certain growth stage will vary amongst cultivars, and even within hybrids due to environmental conditions including temperature and soil moisture. Critical growth periods (CGP) were defined to approximate a period of peak water use by corn and are shown in Fig. 4.1. The CGP was set at 60 to 90 d after planting per Duley and
Miller (1921) and Heiniger (1998). Duley and Miller (1921) stated that stress treatments applied to corn during that time frame reduced yields by 43%. As soil moisture fluctuation was much less pronounced at 60 and 100 cm depths, mean $\theta_v$ from measurements at 10, 20, 30 and 40 cm depths was calculated for the period of time 60-90 days after planting.

### 4.2.7 Water Use Efficiency

Water use efficiency can be defined by the economic yield divided by crop water use (Evett et al., 2012). Water use was defined for each plot and year as the sum of precipitation and mean net change of $\theta_v$ averaged between 10-, 20-, 30-, and 40-cm depths (hereafter “through 40 cm”) during the first 120 d from planting. Drainage losses were not included in the water balance. WUE represented kg grain yield per cm of water used (kg ha$^{-1}$ cm$^{-1}$).

### 4.2.8 Depletion and Recharge Events

Periods of profile soil moisture depletion (DP) and the subsequent recharge (RC) following rainfall were targeted for analysis (Fig. 4.1). Criteria for selecting DP and RC events were: a minimum of 10 days with up to 0.5 cm of rainfall followed by a rain of greater than 1.0 cm. Four DP and RC events were selected (Table 4.2). Soil moisture readings closest to the beginning and end of both the depletion (DP) and recharge (RC) period were used to calculate the net gain/loss of soil moisture for each treatment through 40 cm depth.
4.2.9 Statistical Analysis

A three-way analysis of variance (AOV) was performed using PROC MIXED in SAS ver. 9.2 (SAS Institute, Cary, NC) to study the annual effect of tillage, depth, and sampling date on soil profile moisture at six depths for each year. Repeated measures were used on model residuals, due to the temporal dependence of readings throughout the year. The effects of tillage and year on CGP volumetric water content ($\theta_v$) were tested using two-way analysis of variance in PROC GLM. The net change in $\theta_v$ through 40 cm depth during DP and RC events was calculated for each plot and tested for tillage effects in PROC GLM. The effect of tillage on crop yields was analyzed using PROC-GLM independently within years.

4.3. Results

4.3.1 Precipitation

Precipitation data are summarized in Table 4.3. Mean annual precipitation was 111.7 cm from 2008-2012, ranging from 92 cm in 2012 to 130 cm in 2010. March was consistently a wet month, averaging almost 14 cm, while April was relatively dry, averaging only 5.4 cm (2009-2012).

Daily precipitation events are shown in Fig. 4.1, along with cumulative rainfall commencing at the planting date for each year, ending at harvest. The temporal distribution of precipitation events was somewhat uniform, but many events totaled less than 1 cm. Cumulative ET$_o$ exceeded cumulative precipitation for much of the growing season in 2008, 2009, and 2011, while rainfall kept pace, or exceeded ET$_o$ in 2010 and 2012 (Fig. 4.1).
4.3.2 Crop Yield

Soybean and corn yields responded to tillage in each year of our study (Fig. 4.2). No-till was among the top yielders in each year. Mean treatment corn yields ranged from 3.1 to 5.0 Mg ha\(^{-1}\) in 2009 and from 2.9 to 7.9 Mg ha\(^{-1}\) in 2011. Note that NT, IRS, and CHsp corn yields were approximately 60% greater in 2011 than 2009, while MPspD yields were not different, which was likely due to the extended dry period during grain fill in 2009. The most distinct differences amongst treatments occurred for corn in 2011, evidenced by declining yields with increasing tillage intensity across the range of tillage intensity in the study. NT was greater than all but IRS, which yielded no differently than CHsp. Although 2011 was drier than other years, corn yields were higher than in 2009. This may have been related to the timing of precipitation in those years. More rainfall fell in the CGP of 2011 than in 2009 (Fig. 4.1). Yield differences amongst treatments were expressed most clearly in 2011, evidence of the advantage of conservation tillage to conventional methods when precipitation is scarce. The most intensely tilled treatments, MPspD and CHspD, were the lowest yielding of all treatments each year.

In our study, mean treatment soybean yields ranged from 0.8 to 1.8 Mg ha\(^{-1}\) in 2008, 0.9 to 2.2 Mg ha\(^{-1}\) in 2010, and much higher in 2012 with yields ranging from 1.6 to 3.1 Mg ha\(^{-1}\) (Fig. 4.2). Of the three years in soybean, cumulative precipitation in 2010 and 2012 met or exceeded cumulative ET\(_{o}\), but not in 2008 (Fig. 4.1). In 2010, crusting was visible in treatments of intense tillage such as MPD, resulting in poor stands, growth, and yield in those treatments when compared to treatments where crusting was not observed. Crusting was not
observed in 2012, with plants in all treatments showing excellent growth throughout the season. While rainfall was well distributed in both years (Fig. 4.1), and kept up with demand, it is apparent that the timing of rainfall after tillage created different soil surface conditions that resulted in crusting in 2010 only.

4.3.3 Soil Profile Moisture

Mean $\theta_v$ by depth over all treatments and dates ranged from 0.03 to 0.4 cm$^3$ cm$^{-3}$. A three-way interaction of tillage, depth, and date on soil profile moisture was observed in 2010, 2011, and 2012 (Table 4.4). The two-way interactions of tillage by date, tillage by depth, and depth by date were detected in all years. These variations and interactions can be related to differential drying of surface horizons due to residue cover, crusting, or treatment effects on canopy closure; uneven water uptake by plants resulting from tillage effects on rooting patterns, or the pulse of water moving downward following precipitation, but not detected due to the depth interval between soil moisture measurements. For example, in 2010, evidence of crusting was seen in some treatments of higher tillage intensity leading to delayed and failed seedling emergence. With a potential reduction of infiltration by 20% in NT and IRS, and of 50% in MPD from pre-tillage to post-plant (Freese et al., 1993), it is apparent that time and treatment could interact to affect infiltration, possibly affecting soil moisture conditions in the profile. Furthermore, poor in-season plant growth most notably visible in 2010 in MPD and CHD plots and confirmed by yield measurements may have been due to lower water availability during that season potentially arising from the crusting-related infiltration differences described by Freese et al. (1993).
Many soil physical properties measured at this site differed by depth (Chapter 3). Changes in soil texture with depth explained much of the observed variation in other soil physical properties (e.g., water retention), as clay content increased with depth through 40 cm while sand content declined. The effects of varying particle-size distribution with depth would likely impact soil moisture as well. To best understand how tillage influenced soil moisture in our study, we sought to understand tillage effects on soil moisture at key timeframes during the growing season, such as the CGP and during DP/RC events, as well as WUE for each treatment. Since soil moisture fluctuations were muted at depths of 60 cm and deeper, influenced little by precipitation and root uptake, we chose to focus our efforts on the top 40 cm of the soil profile. For the CGP, we also chose to focus on key events during the 2009 and 2011 seasons only because: these two years had the lowest mean in-season monthly rainfall; cumulative in-season precipitation lagged behind ET₀; and yield differences between maximum and minimum yields were most prominent during these years.

### 4.3.4 Critical Growth Period Soil Moisture

Tillage affected CGP $\theta_v$ ($p < 0.0001$, data not shown), with no interaction with year ($p = 0.41$). Over all years, D had the highest mean $\theta_v$ (0.19 cm$^3$ cm$^{-3}$), along with NT, IRS, and CHspD (Fig. 4.3). MPspD had the lowest CGP $\theta_v$ (0.08 cm$^3$ cm$^{-3}$).

Yield was not correlated with CGP $\theta_v$ ($r = 0.03$, $p = 0.82$). While differences in CGP soil moisture were observed amongst treatments (Fig. 4.3), the range and ranking of $\theta_v$ amongst treatments did not match that of yields for those years. Crop water stress was not
systematically measured or observed during this study, and as such, cannot be specifically analyzed.

### 4.3.5 Water Use Efficiency

Water use efficiency was affected by tillage in all years (Fig. 4.4). Soybean WUE ranged from 32 to 85 kg ha\(^{-1}\) cm\(^{-1}\) in 2008 and 2010 and from 69 to 148 kg ha\(^{-1}\) cm\(^{-1}\) in 2012. Corn WUE ranged from 40 to 85 kg ha\(^{-1}\) cm\(^{-1}\) in 2009 and from 64 to 175 kg cm\(^{-1}\) in 2012.

No-till exhibited the highest WUE in all years, though at times not different than that of some other treatments (Fig. 4.4). Corn WUE in 2011 was at least double that of 2009 for NT, IRS, CHsp, and CHspD, but only 78% greater for D, and 60% greater for MPspD. Clearly, the advantage of conservation tillage in a drier season was exhibited in this case. In regards to rainfall, 2012 was considered a wet year, with precipitation matching that of ET\(_o\) throughout the season, and was characterized by excellent plant growth and higher yields. Conservation tillage treatments outperformed others in years of both poor (2009) and plentiful (2012) rainfall. This demonstrates the benefits of conservation soil management systems for a variety of conditions.

### 4.3.6 Soil Moisture Depletion and Recharge

The duration of DP events ranged from 12 to 28 days, followed by precipitation that ranged from 2.9 to 13 cm during the associated RC event (Fig. 4.4). Even though 2010 averaged the most in-season monthly rainfall of all years, it too had a period of soil moisture depletion
lasting 28 days. An example of rainfall patterns and mean soil $\theta_v$ through 40 cm soil depth in the 2010 DP/RC event is shown in Fig. 4.5.

Changes in soil moisture were affected by tillage during three of the four DP events, as well as three of four RC events (Table 4.5). Maximum (absolute) changes in mean profile volumetric soil water content through 40 cm soil depth ($\delta\theta_v$) for DP and recharge were -0.13 cm$^3$ cm$^{-3}$ (DP$_2$ in IRS) and 0.17 cm$^3$ cm$^{-3}$ (RC$_2$ in D), respectively (Fig. 4.6). The greatest average (absolute) $\delta\theta_v$ came in DP$_2$ and RC$_2$ with averages of -0.087 and 0.134 cm$^3$ cm$^{-3}$ depleted and regained during those two periods, respectively. Since DP$_3$ was the shortest tested (12 d), and only 2.9 cm of rain fell during the RC$_3$ period, the negative values of recharge actually indicate depletion in this case. Excessive evaporation or runoff due to crusting in these tillage treatments (CHsp, D, CHspD, and MPspD) may have caused a continued drying of the soil profile during this interval.

Results showed that water depletion decreased and recharge increased as tillage intensity increased. In events where tillage affected $\delta\theta_v$ (DP$_2$, DP$_3$, and DP$_4$), MPspD was among those treatments that lost the least water, while NT was consistently among the treatments that lost the most water (Fig. 4.6). Conversely, across all RC events where tillage effects were detected, MPspD gained the least water while NT gained the most.

These results are indicators of greater infiltration in NT and IRS vs. CHspD and MPspD, as well as the greater loss of soil water via ET from the former. Greater ET loss vs. that of E in conservation tillage systems could also be a factor (Moroke et al., 2011). These results ultimately show the effect of tillage on a soil’s ability to provide water to the plant: soils in
conservation tillage recharged the most and exhibited a greater rate of consumption which suggests greatest water availability.

4.4. Summary and Conclusions

Cumulative precipitation lagged behind cumulative potential evapotranspiration in three of five years (2008, 2009, and 2011) in this study. Soil moisture was affected by the three-way interaction of tillage x date x depth in three out of five years (2009-2012), and interactions of tillage x depth, depth x date, and tillage x date existed each year.

Mean soil moisture content through 40 cm depth during a CGP 60 to 90 days after corn planting was affected by tillage. Overlap in mean separation existed, but indicated that MPspD had less water than all but CHsp. In general, D, NT, IRS, and CHspD were among the wettest and MPspD and CHsp the driest. These results did not correlate with yield.

Water use efficiency varied with tillage in each year. In most cases, WUE was greatest where tillage intensity was lowest, with NT and IRS the highest in all 5 years. Conversely, CHspD and MPspD, the two most intensely-tilled treatments, had the lowest WUE in all years.

Declines in mean soil moisture content during extended periods of near-zero precipitation (DP) tended to be greatest in tillage plots of least intensity. These same plots also exhibited greater gain in soil moisture content after rainfall ended that dry period (RC). The effect of tillage followed a pattern of greater depletion and recharge in conservation tillage treatments when compared to more intense tillage treatments and vice versa. These results indicated the
effect of conservation tillage on a soil’s ability to provide water at times of need, likely due to increased infiltration, and increased water supply for evapotranspiration.

Tillage effects on soil moisture content; WUE; θ_v during CGP; and the net change in θ_v during periods of depletion and recharge tended to follow a pattern where tillage methods of lower intensity created conditions conducive to plant growth, although they were not always clearly defined. This is possibly due to limitations of our data collection approach. Future data collection at this site may require instrumentation that allows improved and continuous measurement of volumetric water content and matric potential, as well as systematic observation of crop growth stage and water stress.

Further analysis of this dataset might include improving the determination of critical growth periods based on cultivar and growing degree days. Future work regarding soil moisture at this site would include determining current infiltration rates in order to understand the long-term effects of tillage on this parameter, while tracing the movement of water through the soil profile to depths of 100 cm and beyond would clarify the fate of precipitation in these tillage systems. Along with soil physical property data from Chapter 3, principal component analysis may be used to identify the key factors that influence yield. Furthermore, an index of water availability such as the Least Limiting Water Range could be calculated to evaluate seasonal limitations of water by treatment, especially when coupled with simultaneous observations of crop (canopy) water stress.

These results indicated that the factors examined tended to improve conditions conducive to crop growth as tillage intensity decreased. The tendency for conservation tillage to have
higher infiltration rates gives conservation tillage the advantage when it comes to providing water during periods of little rainfall, and to allow those soils to replenish soil moisture upon rainfall. In piedmont regions of the Southeast, where summer rainfall is typically sporadic and temperatures are high, conservation tillage is a soil management practice that maximizes infiltration, soil water availability and yield in corn and soybeans.
4.5 References


Table 4.1 Planting and harvest dates for crops from 2008-2012.

<table>
<thead>
<tr>
<th>Year</th>
<th>Crop</th>
<th>Planting Date</th>
<th>Harvest Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>Soybean</td>
<td>8 May</td>
<td>Dec&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>2009</td>
<td>Corn</td>
<td>27 Apr</td>
<td>21 Oct</td>
</tr>
<tr>
<td>2010</td>
<td>Soybean</td>
<td>08 Jun</td>
<td>11 Nov</td>
</tr>
<tr>
<td>2011</td>
<td>Corn</td>
<td>21 Apr</td>
<td>6 Sep</td>
</tr>
<tr>
<td>2012</td>
<td>Soybean</td>
<td>21 May</td>
<td>14 Nov</td>
</tr>
</tbody>
</table>

<sup>a</sup>Exact day of month not recorded.
Table 4.2 Details regarding depletion periods (DP) and recharge (RC) events targeted for study. Recharge dates were chosen based on a minimum of 10 consecutive days with precipitation <0.5 cm, followed by precipitation > 1.0 cm. 2008 and 2012 had no periods meeting these criteria.

<table>
<thead>
<tr>
<th>Event</th>
<th>Year</th>
<th>DP start</th>
<th>DP end</th>
<th>DP duration</th>
<th>DP observation dates</th>
<th>RC date(s)</th>
<th>Precipitation</th>
<th>RC duration</th>
<th>RC observation date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2009</td>
<td>2 Jul</td>
<td>30 Jul</td>
<td>28</td>
<td>10, 17, 23, 30 Jul</td>
<td>31 Jul</td>
<td>3.4</td>
<td>1</td>
<td>6 Aug</td>
</tr>
<tr>
<td>3</td>
<td>2011</td>
<td>30 May</td>
<td>10 Jun</td>
<td>12</td>
<td>26 May; 2 Jun</td>
<td>11-13 Jun</td>
<td>2.9</td>
<td>3</td>
<td>17 Jun</td>
</tr>
</tbody>
</table>
Table 4.3 Precipitation for the Upper Piedmont Research Station in Reidsville, NC, from 2008 to 2012. Shaded months indicate the main months in the crop growing season for a given year; see Table 4.1 for exact dates. S, soybean; C, corn; CV, coefficient of variation.

<table>
<thead>
<tr>
<th>Month</th>
<th>Precipitation (cm)</th>
<th>Year (Crop)</th>
<th>2008 (S)</th>
<th>2009 (C)</th>
<th>2010 (S)</th>
<th>2011 (C)</th>
<th>2012 (S)</th>
<th>Mean</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td></td>
<td></td>
<td>2.8</td>
<td>7.7</td>
<td>13.9</td>
<td>3.9</td>
<td>6.6</td>
<td>7.0</td>
<td>62.4</td>
</tr>
<tr>
<td>February</td>
<td></td>
<td></td>
<td>7.2</td>
<td>3.2</td>
<td>8.2</td>
<td>4.1</td>
<td>5.6</td>
<td>5.6</td>
<td>36.7</td>
</tr>
<tr>
<td>March</td>
<td></td>
<td></td>
<td>10.4</td>
<td>14.1</td>
<td>16.7</td>
<td>16.2</td>
<td>12.2</td>
<td>13.9</td>
<td>19.1</td>
</tr>
<tr>
<td>April</td>
<td></td>
<td></td>
<td>16.8</td>
<td>7.6</td>
<td>5.5</td>
<td>7.2</td>
<td>6.5</td>
<td>8.7</td>
<td>52.6</td>
</tr>
<tr>
<td>May</td>
<td></td>
<td></td>
<td>8.6</td>
<td>9.0</td>
<td>15.9</td>
<td>8.3</td>
<td>9.8</td>
<td>10.3</td>
<td>30.8</td>
</tr>
<tr>
<td>June</td>
<td></td>
<td></td>
<td>6.93</td>
<td>9.6</td>
<td>10.7</td>
<td>7.9</td>
<td>4.6</td>
<td>8.0</td>
<td>29.9</td>
</tr>
<tr>
<td>July</td>
<td></td>
<td></td>
<td>4.01</td>
<td>4.3</td>
<td>11.7</td>
<td>9.1</td>
<td>11.1</td>
<td>8.0</td>
<td>45.7</td>
</tr>
<tr>
<td>August</td>
<td></td>
<td></td>
<td>17.7</td>
<td>6.4</td>
<td>10.0</td>
<td>4.1</td>
<td>11.5</td>
<td>9.9</td>
<td>52.5</td>
</tr>
<tr>
<td>September</td>
<td></td>
<td></td>
<td>11.1</td>
<td>9.6</td>
<td>15.0</td>
<td>17.1</td>
<td>7.4</td>
<td>12.0</td>
<td>32.9</td>
</tr>
<tr>
<td>October</td>
<td></td>
<td></td>
<td>4.3</td>
<td>6.4</td>
<td>14.3</td>
<td>10.3</td>
<td>9.5</td>
<td>9.0</td>
<td>42.9</td>
</tr>
<tr>
<td>November</td>
<td></td>
<td></td>
<td>9.9</td>
<td>25.6</td>
<td>2.3</td>
<td>13.5</td>
<td>0.7</td>
<td>10.4</td>
<td>96.1</td>
</tr>
<tr>
<td>December</td>
<td></td>
<td></td>
<td>8.6</td>
<td>16.0</td>
<td>6.1</td>
<td>6.4</td>
<td>7.1</td>
<td>8.8</td>
<td>46.6</td>
</tr>
<tr>
<td>Growing Season Monthly Mean</td>
<td></td>
<td></td>
<td>8.9</td>
<td>7.7</td>
<td>10.7</td>
<td>7.4</td>
<td>8.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td>108.3</td>
<td>119.5</td>
<td>130.3</td>
<td>108.1</td>
<td>92.5</td>
<td>111.7</td>
<td>12.7</td>
</tr>
</tbody>
</table>
Table 4.4 P-values for the effects of tillage, depth, and sampling date on soil moisture and their interactions for all sampling dates from 2008 to 2012, by year. S, soybean; C, corn.

<table>
<thead>
<tr>
<th>Effect</th>
<th>2008 (S)</th>
<th>2009 (C)</th>
<th>2010 (S)</th>
<th>2011 (C)</th>
<th>2012 (S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tillage</td>
<td>0.57</td>
<td>0.021</td>
<td>0.14</td>
<td>0.0076</td>
<td>0.85</td>
</tr>
<tr>
<td>Depth</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Tillage x Depth</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Date</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Tillage x Date</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Depth x Date</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Tillage x Depth x Date</td>
<td>0.98</td>
<td>0.999</td>
<td>&lt;0.0001</td>
<td>0.0321</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>
Table 4.5 Effect of tillage on net change in mean soil water content through 40 cm depth for each of four depletion periods (DP) and their associated periods of recharge (RC).

<table>
<thead>
<tr>
<th>Effect</th>
<th>DP₁</th>
<th>RC₁</th>
<th>DP₂</th>
<th>RC₂</th>
<th>DP₃</th>
<th>RC₃</th>
<th>DP₄</th>
<th>RC₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tillage</td>
<td>0.27</td>
<td>0.07</td>
<td>0.02</td>
<td>0.49</td>
<td>0.03</td>
<td>0.008</td>
<td>&lt;0.0001</td>
<td>0.0007</td>
</tr>
</tbody>
</table>
Fig. 4.1 Daily precipitation, in-season cumulative precipitation, and in-season cumulative reference crop evapotranspiration (ET₀) at the Upper Piedmont Research Station in Reidsville, NC, from 2008-2012. Red dashed lines indicate critical growth periods of 60 to 90d after planting. Critical growth periods were examined in 2009 and 2011 only. Horizontal black lines indicate depletion periods (DP). No intervals meeting criteria for DP occurred in 2008 or 2012.
Fig. 4.2 Crop yields from 2008 - 2012 at the Nine Tillage Study. Columns within years followed by different letters are significantly different at $\alpha = 0.05$. NT, no-till; IRS, in-row subsoiling; CHsp, spring chisel; D, disk; CHspD, spring chisel plus disk; MPspD, spring moldboard plow plus disk.
Fig. 4.3 Main effects of tillage on soil water content during the critical growth period 60 to 90 days after corn planting averaged over 2009 and 2011. Columns marked by different letters are significantly different at $\alpha = 0.05$. NT, no-till; IRS, in-row subsoiling; CHsp, spring chisel; D, disk; CHspD, spring chisel plus disk; MPspD, spring moldboard plow plus disk.
Fig. 4.4 Effects of tillage on water use efficiency from 2008 – 2012. Columns within years followed by different letters are significantly different at $\alpha = 0.05$. NT, no-till; IRS, in-row subsoiling; CHsp, spring chisel; D, disk; CHspD, spring chisel plus disk; MPspD, spring moldboard plow plus disk; soy, soybean.
Fig. 4.5 Precipitation and mean soil profile water content of three tillage treatments during the 2010 dry-down and recharge event (DP$_2$ and RC$_2$), a year when soybeans were grown. NT, no-till; IRS, in-row subsoiling; MPspD, spring moldboard plow plus disk. Treatments shown here were selected to indicate that range of net change in soil moisture content in the data.
Fig. 4.6 Main effect of tillage on net change in soil water content through 40 cm during depletion periods (DP). Columns within group marked by same letter indicate no significant differences at $\alpha = 0.05$. NT, no-till; IRS, in-row subsoiling; CHsp, spring chisel; D, disk; CHspD, spring chisel plus disk; MPspD, spring moldboard plow plus disk.
5. Summary and Conclusions

We collected lidar, soil physical property, and soil moisture data from a long-term tillage study, known as the Nine Tillage Study (NTS) that was initiated in 1984, in the Piedmont of North Carolina. We used these data to characterize the effects of tillage, and in some cases, row position and depth, on: 1) long-term erosion; 2) soil physical properties; and 3) profile soil moisture content. Tillage methods were no-till (NT), in-row subsoiling (IRS), fall chisel (CHfa), spring chisel (CHsp), disk (D), spring chisel plus disk (CHspD), fall chisel plus disk (CHfaD), spring moldboard plow plus disk (MPspD), and fall moldboard plow plus disk (MPfaD).

A tripod-mounted laser scanner was used to measure the elevation of the soil surface. Using first-, second-, third-, and fourth order polynomial regression, we applied a series of models to estimate the underlying hillslope trend. The mean value of residuals within each plot served as the best estimator of plot surface elevations, relative to each other. The estimated elevation of each plot was determined relative to the chosen hillslope model and used in an analysis of variance to determine the effects of tillage on soil elevation.

Analyses showed that tillage had an effect on soil elevation. Assuming that NT had the least soil disruption over the history of the study and therefore was least affected by erosion, we used it as a reference elevation, to which we compared the remaining treatment elevations. Relative to the trend, treatment elevations ranged from +3.2 cm in CHfa to -13.3 cm in MPfaD, and tended to decrease with increased tillage intensity with most treatments having lower elevations than NT. The CHsp treatment had a higher elevation which was possibly
due to the lifting of soil by the chisel shanks, but also the presence of weeds, which may have caused incorrect estimates of surface elevation. The maximum estimated soil loss resulting from tillage was 1891 Mt ha\(^{-1}\) in MPfaD. These figures were similar to those estimated or measured in other erosion studies.

Soil physical properties, including: bulk density; volumetric water content; percent sand, silt, and clay; water retention; plant-available water; along with carbon contents and two carbon stratification ratios were measured. Soil samples were taken from within the row, and from the trafficked and untrafficked rows; at depths of 5-15, 15-25, 25-35, 35-45, 55-65, and 95-105 cm. Interactions of tillage and depth; tillage and position; as well as position by depth were significant for bulk density, and in the case of volumetric water content, interactions of tillage and depth; and position and depth were significant. For sand, silt, and clay content; water retention at 10, 30, 100, 500, and 1500 kPa; and plant-available water using field capacity calculated at 10 and 30 kPa, the main effect of depth was highly significant (p = <0.0001). A tillage x depth interaction was found for carbon content.

Bulk density was affected by traffic only in the uppermost sampling depth, where it was greatest in the trafficked interrow. The MPfaD treatment had a lower bulk density at 10 cm than that of subsequent depths, quite possibly an artifact of the shorter period of time (four months) since last tillage in that treatment vs. that of MPspD (eleven months).

When we compared carbon content at 0-5 cm to that at 5-15 cm, we discovered that CSR was affected by tillage. In general, the ratio decreased as tillage intensity increased, with the highest values in NT and the lowest in the moldboard plow treatments.
From 2008 through 2012, volumetric soil water content ($\theta_v$) was measured weekly at depths of 10, 20, 30, 40, 60, and 100 cm in the in-row position of all treatments except those featuring fall tillage. During these years, cumulative precipitation lagged behind cumulative potential evapotranspiration in 3 of 5 years (2008, 2009, and 2011).

A critical period of growth from 60 to 90d after corn planting (CGP) was examined in 2009 and 2011. During this period, NT, IRS, D, and CHspD had the highest $\theta_v$ while CHsp and MPspD had the lowest.

Water use efficiency (WUE) varied with tillage in each year. In most cases, WUE was greatest where tillage intensity was lowest. NT and IRS had the greatest WUE in all 5 years. Conversely, CHspD and MPspD, the two most intensely-tilled treatments, had the lowest WUE in all years.

Declines in mean soil moisture content during extended periods of near-zero precipitation tended to be greatest in tillage plots of least intensity. These same plots also exhibited greater gain in soil moisture content after rainfall ended the dry periods. The effect of tillage followed a pattern of greater depletion and recharge in conservation tillage treatments. These results indicate an effect of conservation tillage on a soil’s ability to provide water at times of need due to increased infiltration, and increased water supplied for evapotranspiration.

Long-term (since the study began) and recent (2008-2012) crop yields appeared to be inversely proportional to tillage intensity. Parameters estimated (erosion) and measured (bulk density, carbon, and carbon stratification ratio, WUE; $\theta_v$ during CGP; and the net change in
θ, during periods of depletion and recharge) all tended to show the same trend – that conditions conducive to crop growth were detected where tillage intensity was lowest. Growers of the southeast Piedmont region of the USA can use this knowledge to adopt conservation tillage practices to reduce erosion, increase yields, and optimize soil water and yield potential in their corn-soybean rotations.

5.1 Suggestions for future work

While lidar provided reasonable estimates of long-term erosion, its use could be improved in a number of ways. Our data were very dense, yet a portion of the soil surface was unmeasured, as it was shielded from the laser due to the unevenness of the soil. While it would increase the time (cost) of the process, more scans taken from more locations would reduce this concern. The presence of weeds in certain plots may have decreased our ability to accurately estimate elevations, adversely affecting the subsequent analysis of soil loss based on those measurements. Future work could include development of a method for eliminating all but soil data points. This might be accomplished through the use of a “bare-earth” algorithm, multiple-return data, and/or multispectral analysis which would permit calculation of vegetation-soil indices akin to the normalized difference vegetation index (NDVI). In addition statistical methods to determine outliers could be applied to improve results. Another improvement may be to mow any weeds or standing crop residue prior to scanning. We did not do this, because of its potential effects on treatment outcomes. However, the future of the NTS is in question; abandonment would provide the opportunity to remove all surface plant residues, e.g., through mowing and fire, and scan the resulting surface.
not possible for this site, the most effective improvement would be to conduct a baseline scan prior to implementing treatments.

The use of undisturbed soil cores would likely provide better estimates of in situ water retention and plant-available water, which might reveal treatment effects not apparent in disturbed soil. It is possible that core-sampling to a depth of 105 cm in a single tube affected the soil by compressing it. However, it was the least invasive method available. Modeling the combined effect of these parameters would be an appropriate next step, something that could be accomplished in multivariate regression analysis.

Soil profile moisture information may be greatly improved by monitoring more frequently. Another improvement may be to use a network of in situ sensors. Together, these would allow better targeting of changes resulting from rainfall events and intra-profile movement of water. Frequent observations of crop growth-stage and any crop stress related to drought would be beneficial in interpreting soil moisture data. Also, combining relevant parameters such as bulk density, soil strength, and water retention in an index such as the Least Limiting Water Range might provide insights regarding the combined effects of soil physical properties on water relations and crop yield.