EFFECT OF TILLAGE ON THE HYDROLOGY OF CLAYPAN SOILS IN KANSAS

by

MEGHAN ELIZABETH BUCKLEY

B.S., Iowa State University, 2002
M.S., Kansas State University, 2004

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

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Abstract

The Parsons soil has a sharp increase in clay content from the upper teens in the A horizon to the mid fifties in the Bt horizon. The high clay content continues to the parent material resulting in 1.5 m of dense, slowly permeable subsoil over shale residuum. This project was designed to better understand soil-water management needs of this soil. The main objective was to determine a comprehensive hydrologic balance for the claypan soil. Specific objectives were a) to determine effect of tillage management on select water balance components including water storage and evaporation, b) to quantify relationship between soil water status and crop variables such as emergence and yield, and c) to verify balance findings with predictions from a mechanistic model, specifically HYDRUS 1-D. The study utilized three replicates of an ongoing project in Labette County, Kansas in which till and no-till plots had been maintained in a sorghum [*Sorghum bicolor* (L.) Moench] – soybean [*Glycine max* (L.) Merr.] rotation since 1995. Both crops are grown each year in a randomized complete block design. The sorghum plots were equipped with Time Domain Reflectometry (TDR) probes to measure A horizon water content and neutron access tubes for measurement of water throughout the profile. Precipitation, evaporation, and perched water depth were determined at the field scale. Drainage was estimated as negligible after performing hydraulic conductivity measurements on the clayey subsoil. Runoff was determined as the residual in this water balance. Cumulative differences in the hydrologic balances as a result of tillage management were found to be minimal over an entire growing season. However, tillage treatment differences were seen in early season evaporation, surface water content, and the resulting residual runoff values. The chisel-disk treatments had greater evaporation leading to reduced runoff when compared with no-till. There was interaction between tillage treatment and time for surface water content measurements. No effect of tillage treatment was found for whole-profile water content. Crop variables were unaffected by tillage other than the first days emergence, and first days tillering being greater for chisel-disk treatments. No correlation between stored water and crop variables could be found. All aspects of field measurement were well supported by the predictions of the HYDRUS 1-D model.

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CHAPTER 1 - Introduction

Claypan soils are those that have a sharp increase in clay content over an abrupt or clear boundary (SSSA, 2006). The Parsons soil has roughly 18% clay in the A horizon and 55% clay in the Bt horizon. This subsoil is dense, slowly permeable, and typically results in reduced infiltration and drainage. There are approximately 4 million hectares of claypan soils in the Midwestern USA. Kansas State University Extension has recognized these soils and others of the southeast Kansas region to have reduced drainage through the clay layer, which contributes to soil wetness problems, increases surface runoff, and decreases the success of no-till farming (Whitney et al., 1999). Working wet soil can increase the likelihood of damaging soil physical properties through compaction. Also wet and/or cool early spring conditions have been reported to reduce seedling vigor and crop stands. Furthermore, moist soils are more habitable to crop diseases.

Few comprehensive hydrologic balances have been completed to understand a cropping system's effect on soil water. More frequently, studies have made comparisons between crop management and/or tillage systems for one part of the hydrologic cycle. A common comparison is runoff volume. Some studies show increased runoff from tilled treatments citing compaction or crusting in the tilled treatment and improved macropore flow in no-till. Other studies have found greater runoff from no-till treatments presuming greater antecedent moisture conditions in the no-till. Studies conducted on claypan soils have often found the no-till treatment to have greater runoff volume; however these studies have not directly linked soil water content to runoff water loss.

Besides runoff, tillage also affects infiltration into the soil, evaporation from the soil surface, and drainage through the soil by altering the amount of surface residue as well as physical properties such as structure, compaction, pore connectivity, and surface roughness. Furthermore, it is important to keep in mind the interrelation of water balance components. For example, reduced drainage likely leads to reduced infiltration and increased runoff.

While many of the components of a hydrologic balance are easy to measure (i.e. precipitation, soil water), some components are not as easily identified. Studies frequently assume lateral flow to be a minor component. However, this claypan soil has restricted drainage and a high potential for lateral flow. Subsoil drainage is also an area where direct quantification methods are limited. It is possible to use field data in a mechanistic (process-based) model to provide insight on the importance of some of these components. This is achieved iteratively by modifying the mechanistic description of the components and comparing simulated results with field data. Governing equations for such a process are well established and a number of models are available. With input parameters including unsaturated hydraulic conductivity and a water retention curve, Richards' equation can be used to predict soil water content and validate a water balance study.

Objectives

In light of the aforementioned moisture problems and the desirability of no-till adoption from an environmental perspective, this study was designed with the principal objective of determining a comprehensive hydrologic balance for these claypan soils. Specific objectives include:

- Determine effect of tillage on select components of hydrologic balance including water storage and evaporation from the soil surface.
- Quantify relationship between stored soil water and crop production variables including emergence rate, stand, and yield.
- Verify hydrologic balance findings with predictions from a mechanistic model.

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CHAPTER 2 - Literature Review

Background of Claypan Soils

Claypan soils are defined as having a sharp increase in clay content between the A and B horizons over an abrupt or clear boundary (SSSA, 2006). The clay subsoil has restricted water movement and requires special management for engineering and agricultural uses. For example, use of subsurface drainage has been shown to increase corn (*Zea mays* L.) yields up to 1.8 t ha^{-1} (Sipp et al., 1986). Previous work on claypan soils has shown that the response to cropland management practices including crop rotation, irrigation, and tillage is often different from more typical soils. Despite the large amount of water held within the claypan, availability of that water to crops is low and use of deep rooted crops to increase aggregation has been shown to deplete the subsoil of available water supplies (Grecu et al., 1988) while irrigation has improved yields up to 3.9 t ha^{-1} for corn (Sipp et al., 1986). Also, no-till practices used to conserve soil have been shown to increase the volume of runoff and associated pollutants on claypan soils (Ghidey and Alberts, 1998; Buckley-Zeimen et al., 2006) when normally no-till would increase infiltration because of greater macroporosity (Logsdon et al., 1990). In addition to soil conservation, no-till practices have been shown to increase soil water storage (Norwood et al., 1990). While increased water storage has improved yields in semiarid areas of the Great Plains or on well drained soils, the effect is perceived by producers as having a negative impact on crop production for claypan soils which tend to be excessively wet early in the growing season. This has resulted in limited adoption of no-till practices. As agronomists and soil scientists struggle to understand the above observations, it becomes clear that a comprehensive understanding of soil-water relations for claypan soils is needed as well as verification of tillage effects on the soil water balance.

Hydrologic Balance

A hydrologic balance accounts for the distribution of water through the earth and atmosphere. As hydrologists, we aim to quantify the amount of water in each storage pool and account for movement between pools. Storage pools include the atmosphere, surface water, groundwater, and soil water. Pathways between pools include precipitation, evaporation, transpiration, runoff, drainage, capillary rise, and seepage where groundwater intersects surface water (Linsley et al., 1975). The water balance components of concern in an agricultural soil are precipitation, stored soil water, evaporation and transpiration, drainage, and runoff where change in stored water equals the sum of the other components. Tillage practices have been shown to influence a number of these components and hence affect the entire water balance. These effects, particularly as seen in claypan soils, will be discussed in the following review.

Precipitation

Precipitation is the pathway by which water moves from the atmosphere to the earth and includes rain, snow, and dew (Linsley et al., 1975). Precipitation is the one variable not influenced by any form of crop management. Some agronomic systems receive additional inputs to the water balance in the form of irrigation. Effective precipitation refers to how much rainfall actually penetrates, or infiltrates, the soil surface and varies with intensity and duration of a storm event, soil properties such as texture, pore size distribution, and slope, as well as management effects including ground cover.

Runoff and Infiltration

Falling precipitation typically either infiltrates the soil or runs off. Sometimes water temporarily ponds on the soil surface where it may directly evaporate back to the atmosphere or enter the soil as delayed infiltration. Runoff encompasses both surface and subsurface lateral water movement. Several studies have examined management effects on infiltration and/or runoff, but few have drawn a correlation between these variables and soil water content. It is generally understood that increased antecedent moisture decreases infiltration capacity and increases runoff volume (Bundy et al., 2001; Mickelson et al., 2001a; Sauer and Daniel, 1987; Sharma et al., 1983).

Many studies have shown that crop management variables such as tillage, previous crop, residue cover, and planting date affect surface runoff volume. Most work in this area has focused on tillage differences. As with evaporation, it can be difficult to separate the effects of tillage from those of residue since reduced tillage operations typically result in greater crop residue on the soil surface, which protects the soil from raindrop impact and wind and water erosion.

Conservation tillage (i.e. chisel-, ridge-, no-till) has been found to reduce surface runoff volume over conventional methods that involve multiple deep tillage passes (Mickelson et al., 2001b; Seta et al., 1993; Blevins et al., 1990). These differences were attributed to increased surface residue and increased infiltration in no-till. Chisel and no-till practices were reported to have similar surface runoff when chisel operations are with the slope gradient (Blevins et al., 1990). Chisel plowing typically leaves more residues on the soil surface than conventional tillage which can improve infiltration (Good and Smika, 1978). No-till practices are not as disruptive to macropores which promote infiltration (Logsdon et al., 1990).

Conversely, some studies have shown that no-till increases surface runoff volume over other tillage methods (Sauer and Daniel, 1987; Mickelson et al., 2001a) and attribute the effect to increased compaction in no-till. Early season runoff events are often greater from no-till; this has been assumed to be related to greater soil moisture content allowing for less water infiltration to the soil profile than those soils that have been dried and aerated by tillage (Bundy et al., 2001). Ghidey and Alberts (1998) and Buckley-Zeimen et al. (2006) have investigated sites with claypan soils and found that no-till had increased surface runoff volume despite greater residue cover in multiyear studies. Ghidey and Alberts noted that the greatest difference in runoff volume was during early spring fallow, a time when tillage has broken the surface seal and increased micro relief and soil drying. Immediately following tillage, worked ground also generally has lower bulk density and soil water content than no-till treatments (Blanco-Canqui et al., 2002). The effect of tillage on soil properties may not be permanent as another study found that, while chisel plowing resulted in less surface runoff volume during the first event, reconsolidation and surface sealing reduced the difference from no-till in subsequent runoff events (Myers et al., 1995).

Subsurface runoff, also referred to as lateral flow or interflow, is assumed negligible in most water balance studies. However, it can have an important contribution in soils that are steeply sloped and/or have restrictions to downward water movement. This laterally moving water can also have a significant impact on nutrient transport from crop fields (Garg et al., 2005; Reuter et al., 1998). Wilkinson and Blevins' (1999) work on claypan soil showed that, while water perched above the clay during large precipitation events, the water soon moved into the clay via macropores. They also used tracers to determine the direction of water movement and concluded that, while lateral flow did occur, it was negligible compared to downward movement.

Blanco-Canqui et al. (2002) concluded that a better understanding of lateral flow is needed on claypan soils where runoff losses are being assessed. The effect of tillage on lateral flow is somewhat dependent on the depth to a restrictive layer and other water balance components. Bosch et al. (2005) showed conventional tillage to have less subsurface runoff than a reduced tillage system; however, conventional tillage had greater surface runoff, thereby reducing the amount of water entering the soil to potentially become lateral flow.

Drainage

After infiltrating the soil, water may be stored or continue moving downward, eventually draining out the bottom of the profile. The drainage process can either occur through the soil matrix or via macropore preferential flow paths. Bjornberg et al. (1996) found that the initial high rate of water drainage following a precipitation event was from preferential flow whereas the lower, steady-state rate was from matric flow. The higher preferential flow rate did not exist in drainage events through very wet soil. Tillage has little effect on overall drainage rates as practices only influence the upper 20 cm of the soil, though macropore channels running all the way to the surface can be disrupted (Bjornberg et al., 1996).

Drainage rate has been found to be a function of available water (Black et al., 1969) with greater water diffusion in wetter soils. A management comparison showed that greater surface cover reduces water reaching deeper soils depths, therefore reducing drainage, resulting in native prairie soils having much less drainage than either tilled or no-till cropping systems while the no-till drainage was less than that for chisel tillage (Brye et al., 2000). This study also only had drainage occurring during the first half of the year, when there was more available water, for all three study years.

The impact of drainage on the soil-water balance varies with soil properties and climate. Brye et al. (2000) reported 26 to 40 cm of drainage on silt loam agricultural soil in a climate with 65 cm annual precipitation while Heitman (2003) reported 5 cm of drainage during the growing season in a slightly drier climate. Van Bavel et al. (1968) showed drainage at rates of up to 3 cm a day immediately following water application. However, some of these studies also had to account for upward water movement at these deeper depths (Heitman, 2003; van Bavel et al., 1968) reducing the total amount of drainage in a water balance. A claypan soil has reduced hydraulic conductivity and water availability (Blanco-Canqui et al., 2002), therefore creating a scenario of reduced drainage through the soil matrix. Preferential flow can represent up to 35% of the draining water in claypan soils (Wilkinson and Blevins, 1999).

Evaporation and Crop Water Use

Evaporation is the conversion of soil water to atmospheric water. It is one of the most difficult components of the water balance to measure directly and is often estimated from atmospheric and soil conditions including air temperature, relative humidity, exposed surface, and available soil water. Measurements have been done with lysimeters and microlysimeters based on daily weight changes in a situation where drainage is either restricted or accounted for. These studies have found that the amount of evaporating water is related to soil properties such as available water, hydraulic conductivity, and residue cover. Steiner (1989) tested the effects of tillage and residue cover on evaporation and found that there was no direct link between evaporation and tillage, but that tillage affected the amount of residue cover. Regardless of tillage, treatments with the least cover had the greatest evaporation.

It is possible that tillage has a greater impact than its influence on residue cover. Some tillage studies have found that crusting of tilled treatments restricted evaporation because of reduced hydraulic conductivity as compared with no-till (Steiner, 1989). Hamblin (1984) discerned that treatments with greater tillage had disruption of downward water movement, increasing the amount of water available for evaporation. Meanwhile, others have credited no-till for increasing water storage through the growing season without directly measuring evaporation rates (Tolk et al., 1999; Norwood et al., 1990). They conclude that the increased residue cover of no-till reduced evaporative losses from the soil profile.

Transpiration is water that moves through the plant en route to becoming atmospheric water. Generally, evaporation and transpiration are considered together as evapotranspiration; however, evaporation is the dominant process in the early season when the soil surface is exposed and transpiration is the dominant process once a canopy is established. Transpiration rates are a reflection of root distribution (which vary with crop type and stage) and available water. Greater biomass production in reduced or no-till soils when compared with conventional tillage is an indicator of greater transpiration rates from those soil treatments (Norwood et al., 1990).

Stored Soil Water

Water stored in the soil profile is a reflection of the amount of water entering the soil profile and any water leaving the profile. In an agronomic system, inputs are driven by the amount of precipitation that infiltrated the soil. Outputs include evaporation from the soil surface, crop water uptake, and drainage. Tillage effects on infiltration and evapotranspiration were discussed above. The influence of each these processes changes over time. It is important to understand which factors are most responsible for changes in stored water at different points during the growing season. For this reason, our water balance both studies the changes in water content and quantifies the inputs and outputs.

The amount of water that can be stored in a soil profile is driven by the soil texture and structure. Smaller pores in clayey or compacted soils tend to hold water at high tensions where it is neither easily drained from the profile nor readily available to plants. Therefore, despite the ample moisture, these soils are considered low for storage of plant available water supplies and experience very small changes in total water storage (Aydin, 1994). Several studies have taken the approach of following changes in stored water during the course of the season and comparing water savings of various tillage treatments. Norwood et al. (1990) found greater profile moisture at spring planting in reduced tillage compared with conventional tillage in 10 of 14 y. Later work by Norwood (1994) supported these findings and showed greater profile water in no-till compared with reduced tillage treatments. Also, the no-till treatment led to water moving deeper into the clay loam profile, reducing evapotranspiration (ET) losses.

Water Balance Summary

Many of the previously mentioned studies have only examined one or two aspects of soil-water relations. This has led the investigators to make assumptions on what caused any phenomena they may have observed. It is important to understand all aspects of soil-water relations in order to fully comprehend the water balance. For example, a soil with increased water infiltration because of tillage may also experience greater evaporation resulting in no actual difference in plant available water as in the study of Schwartz (2006). Also, the impact of various balance components varies with soil properties and soil management. In claypan soils, the drainage and available water storage should be reduced while runoff and lateral flow are increased as compared with other soils.

Tillage Effects on Soil Physical Properties

One of the primary reasons that tillage practices influence soil-water relations is the effect tillage practices have on soil physical properties. Tillage can alter the pore size distribution and total porosity of a soil by increasing compaction and crusting, or by decreasing aggregation. Katsvairo et al. (2002) found lower penetration resistance, lower bulk density, and greater porosity on conventional and chisel till treatments as compared with strip tillage through the vegetative stage of crop growth, but differences were not significant during the later reproductive stage. Licht and Al-Kaisi (2005) confirmed that penetration resistance is lower in chisel than either strip tillage or no-till with differences in soil water storage during the vegetative stage.

Aggregation is frequently reduced by increasing tillage, with no-till having the greatest aggregate stability (Lal et al., 1994). However, Raimbault and Vyn (1991) found no difference in aggregate size between conventional and chisel plow operations. Care can be taken during tillage operations to minimize detrimental effects such as aggregate smearing and compaction. Soils are most easily compacted when wet, but shy of saturation. Hillel (1982) reports maximum compactibility at 80% saturation. However, Mosaddeghi et al. (2000) noted that increasing organic matter of the soil increases the trafficable moisture range, meaning high OM soils can be worked wetter than low OM soils. This may indicate a benefit to incorporating high residue crops into rotations. Williatt (1987) showed large aggregates to be most susceptible to compaction in wet conditions when compared to small (less than 2 mm) or mixed aggregates. There were few differences in drier conditions.

The physical state of the soil (i.e. density, aggregation, etc) can alter hydraulic properties. Water retention and hydraulic conductivity are two important measures of soil-water relations. The shape of the water retention curve is controlled by both pore size distribution and total porosity of the soil. To that end, both soil structure and texture can influence the shape of the curve, with structure playing a greater role at the wetter end. As structure is more likely to be influenced by tillage than texture, tillage effects to the water retention curve should be seen on the wetter end (Ahuja et al., 1998; McVay et al., 2006). Ahuja et al. (1998) reported similar air entry values (dry end, high tensions) for tilled and untilled soil but different slopes and different water retention at the wet end (nearing saturation, low tensions) where the tilled treatment held more water. They determined that tillage increased the volume of large pores, creating greater space available to hold water at low tensions. McVay et al. (2006) worked with five sites across Kansas that had long term tillage studies to compare conventional, reduced, and no-till methods. They showed tillage effects on the dry end of the water retention curve at two sites (including Parsons), on the wet end at one other site, and in the curve fitting parameters for these three sites on soils sampled from the 0- to 5-cm depth. No tillage effect was seen at the other two sites. In all cases, increasing tillage increased the amount of water held in the soil. Despite effects on the shape of the water retention curve at three sites, there was a significant difference in water holding capacity at only one site. That site was the only one sampled before spring planting; the other sites were fall sampled. Tillage operations create an initial increase in porosity, but the weakened aggregates are more susceptible to raindrop impact and compaction, resulting in decreased total porosity when compared with no-till later in the growing season (Ahuja et al., 1998).

The influence of tillage on porosity also plays out by creating differences in hydraulic conductivity between tillage treatments. Increasing tillage results in a reduction of stable macropores for water conduction (Ankeny et al., 1990; Buczko et al., 2006). The increased volume of macropores in reduced tillage treatments resulted in greater saturated hydraulic conductivity for a silt loam soil in Germany (Buczko et al., 2006). Ankeny et al. (1990) examined the effect of both tillage and traffic on saturated hydraulic conductivity determining that there was no significant tillage effect in non-traffic treatments but greater compaction in the chisel management resulting in reduced hydraulic conductivity as compared with no-till.

Tillage Effects on Agronomic Factors

Finding the perfect conditions for optimum seed germination and emergence as well as seedling vigor has been a mainstay of agronomic research. It is generally accepted that warmer and drier (within limits) is better. Mündel (1986) showed that each 1°C decrease in soil temperature slowed seed emergence 2 d in soybean [*Glycine max* (L.) Merr.]. Wet soils tend to warm slower than dry soils because of water's high specific heat capacity. In a later study, Mündel et al. (1995) tested safflower (*Carthamus tinctorius* L.) seedling emergence and disease at three water contents: saturation, field capacity, and the wilting point. For all soil temperatures and all soil infestation levels, the saturated soil had less than 4% emergence. The soil at field capacity and at wilting point had similar emergence rates (above 85%) at all temperature regimes in sterile soil. However, in the *Pythium* infested soil, the drier and cooler treatments faired much better than the 27% emergence in the field capacity, 25°C treatment, many of which later 'damped-off' due to the *Pythium* fungus. Licht and Al-Kaisi (2005) showed strip till and chisel till to have similar soil temperatures and seed emergence rates while no-till lagged behind in both categories. However, Chen et al. (2004) showed no significant differences in time to emergence for canola (*Brassica napus* L.) or canary grass (*Phalaris canariensis* L.) in six different tillage treatments on a heavy clay soil in a year of average moisture while no-till emerged at the fastest rate in a dry year. Sipp et al. (1986) showed that use of subsurface drainage to decrease soil moisture increased yields of both corn and soybean grown on claypan soils in Illinois.

Normally, emergence is a good indicator of yield. However, sorghum [*Sorghum bicolor* (L.) Moench] is a crop that can tiller and compensate for a poor stand (Vanderlip, 1993). Available moisture is the primary limitation to yield. In dry climates, there may not be enough precipitation at the time that plants need it. Also certain soils may not store enough water in a plant available form to grow a successful crop. Southeast Kansas has both high clay, low available water soils and low summer rainfall.

In western Kansas, where dry summers are the primary yield limiting factor, no-till has been shown to increase yields of sorghum and other crops as compared to conventional and reduced tillage cropping systems (Norwood et al., 1990; Schlegel et al., 1999). These and other studies have attributed increased crop yields in no-till to greater available soil water supply (Stone and Schlegel, 2006). A study conducted in a more humid climate with heavier soils found a yield advantage to chisel tillage in two of four corn years and all four soybean years (Vetsch et al., 2007). Vetsch et al. tested both long term and rotational tillage systems and confirmed significant yield reductions for no-till management with both systems. However, this study also applied an economic analysis and reported that the yield reductions were not enough to effect overall economic return of the no-till cropping system. A variety of reasons for reduced yield were given, but not verified, including less favorable temperature and/or moisture conditions and difficulty planting into previous crops' stubble. More work needs to be done in order to establish the reason that tillage affects crop yield.

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CHAPTER 3 - Materials and Methods

Field Plot Description

The site for this study was at the Kansas State University Southeast Agricultural Research Center in Labette County, Kansas. The soil is mapped as Parsons silt loam (fine, mixed, active, thermic Mollic Albaqualf) (Soil Survey Staff, 1990). On-site observations revealed a rather shallow topsoil overlying a claypan starting at a depth of 15 to 20 cm. A rod and transit were used to determine that the site had a 1% slope where the northeast corner was highest in elevation (Appendix A). A claypan is defined as a dense, compact, slowly permeable layer in the subsoil having a much higher clay content than the overlying material, from which it is separated by a well defined boundary (SSSA, 2006). The study site had a surface texture of silt loam (18% clay) with 2.6% organic matter and pH of 6.5 while the subsurface texture was clay (55% clay).

Labette County receives an average of 1117 mm of precipitation per year with 25% of that falling in May and June (1970-2000 average, Kansas Weather Data Library), which is enough to refill the soil profile each spring. The 2006 crop year had below average precipitation with 178 mm precipitation in the month before planting and 168 mm precipitation while sorghum was growing (19 May (DOY 139) to 25 Aug. (DOY 237)) at the field station. In contrast, the 2007 crop year had above average precipitation with 191 mm precipitation in the month before planting and 636 mm precipitation while sorghum was growing (21 May (DOY 141) to 17 Sept. (DOY 260)).

The site had a soybean [*Glycine max* (L.) Merr.] – grain sorghum [*Sorghum bicolor* (L.) Moench] crop rotation under both no-till and chisel-disk tillage systems such that each crop was grown each year in each tillage regime. The crop and tillage system was established 10 y prior to the start of this study on plot P26 at the Southeast Kansas Agricultural Research Center. The four treatments were completely randomized in one strip of each block, while the other strip had four treatments not used in this study (Appendix A). This study used only the sorghum plots in the three northern blocks, or replicates, for the 2006 and 2007 crop years for a total of six study plots per year. The dimensions of each plot were 9 m wide by 12 m long. Because of the crop rotation, the same plots were not instrumented each year. Grain sorghum (Pioneer 8500, fluxofenim treated) was planted at 148,000 seeds per hectare in 0.75 m rows on 19 May 2006 and 21 May 2007. Agronomic practices for each year are detailed in Tables 3.1 - 3.2.

Table 3.1 The 2006 growing season description of agronomic practices.

Procedure	Treatment	Details
Tillage	Chisel-Disk	Disked 7 March, Chiseled 15 March, Field Cultivated 19 May
	No-Till	None
Fertilizer	Both	Broadcasted 224 kg/ha 0-0-60 potash 15 March; knifed 134 kg/ha 28-0-0 urea ammonium nitrate and 67 kg/ha 10-34-0 ammonium poly-phosphate 17 March, 10 to 15-cm deep, 44-cm row spacing
Herbicide	Chisel-Disk	1.2 L/ha S-metolachlor and 2.3 L/ha atrazine 19 May
	No-Till	1.2 L/ha S-metolachlor, 2.3 L/ha atrazine, 1.2 L/ha 2,4-D ester, 2.3 L/ha glyphosate, and 2.3 L/ha ammonium-sulfate surfactant 12 April

Table 3.2 The 2007 growing season description of agronomic practices.

Procedure	Treatment	Details
Tillage	Chisel-Disk	Disked 30 April, Chiseled 1 May, Field Cultivated 17 May
	No-Till	None
Fertilizer	Both	Broadcasted 224 kg/ha 0-0-60 potash 17 May; knifed 134 kg/ha 28-0-0 urea ammonium nitrate and 67 kg/ha 10-34-0 ammonium poly-phosphate 17 May, 10 to 15-cm deep, 44-cm row spacing
Herbicide	Chisel-Disk	1.2 L/ha S-metolachlor and 2.3 L/ha atrazine 18 May
	No-Till	1.2 L/ha S-metolachlor, 2.3 L/ha atrazine, 1.2 L/ha 2,4-D ester, 2.3 L/ha glyphosate, and 2.3 L/ha ammonium-sulfate surfactant 30 April

Measurement of Water Balance Components

Precipitation

Precipitation at the field site was monitored with three tipping bucket rain gauges (TR-525I, 0.01 inch per tip, Texas Electronics, Dallas, TX) connected to dataloggers (HOBO Event Logger, Onset Computer Corp., Bourne, MA) set up to surround the site. Before each field season, the rain gauges were calibrated by using a syringe pump to deliver water to each gauge at a known rate. Precipitation was monitored from May to November in 2006 and April to October in 2007.

Surface Water Content and Temperature

In each plot, time domain reflectometry (TDR) was used to obtain duplicate measurements of volumetric water content at the 10- and 20-cm depths. Each replicate had a separate TDR system consisting of a main enclosure (Model ENCTDR100, Campbell Scientific, Inc., Logan, UT) containing a TDR100 Time-Domain Reflectometer, CR10X datalogger, and a SDMX50SP multiplexer. The main enclosure was linked by RG8 coaxial cable to two SDMX50 multiplexers each with four TDR probes (Model CS605-L, Campbell Scientific) so that each plot had two TDR probes at each depth. The actual cable lengths for the three TDR systems included 3.7 m of RG58 coaxial cable between probe and multiplexer and 15.2, 10.7, or 6.1 m of RG8 coaxial cable from multiplexer to TDR100 depending on replicate. The operational total cable lengths used in calculations were determined during calibration to be 25.2, 19.3, and 13.9 m for the three systems. The TDR probes were installed horizontally, between crop rows in nontraffic interrows only (Figure 3.1). A small pit was excavated to install two probes, one at 10 cm and one at 20 cm. The two probes were offset from each other to minimize the potential for interference (Figure 3.2). The faces of the excavated pits were 6 and 9 m from the north end of the plot. Calibration of TDR probes was tested in a laboratory by capturing waveforms of each probe in air, water, and moist soil.

Thermocouple probes were used to monitor soil temperature at the 5-, 10-, and 20-cm depths. The probes were made from sections of 16-guage (1.65 mm o.d., 1.19 mm i.d.) stainless steel tubing cut to a length of approximately 95 mm. Each section of tubing was filled with high-thermal-conductivity epoxy (Omegabond 101, Omega Engineering, Inc., Stamford, CT) after an insulated thermocouple junction (Type T, 36-American wire gauge thermocouple wire, Omega Engineering, Inc.) was positioned a few millimeters from one end. The wires exiting the other end were connected to extension wire (Part No. PP-T-24, Omega Engineering, Inc.), and epoxy-lined heat-shrink tubing was used to insulate the connections and provide structural support. Two sets of thermocouple probes were installed with the TDR probes while a third set had its own pit 9 m from the north end of the plot (Figure 3.1). The three probes at each depth were wired in parallel to average the signal recorded by the datalogger. Distance from sensor to wiring block was the same for all probes to eliminate any effect of unequal resistance of lead wires on measurements. The thermocouple probes were tested in a laboratory by measuring temperature of air and ice water.

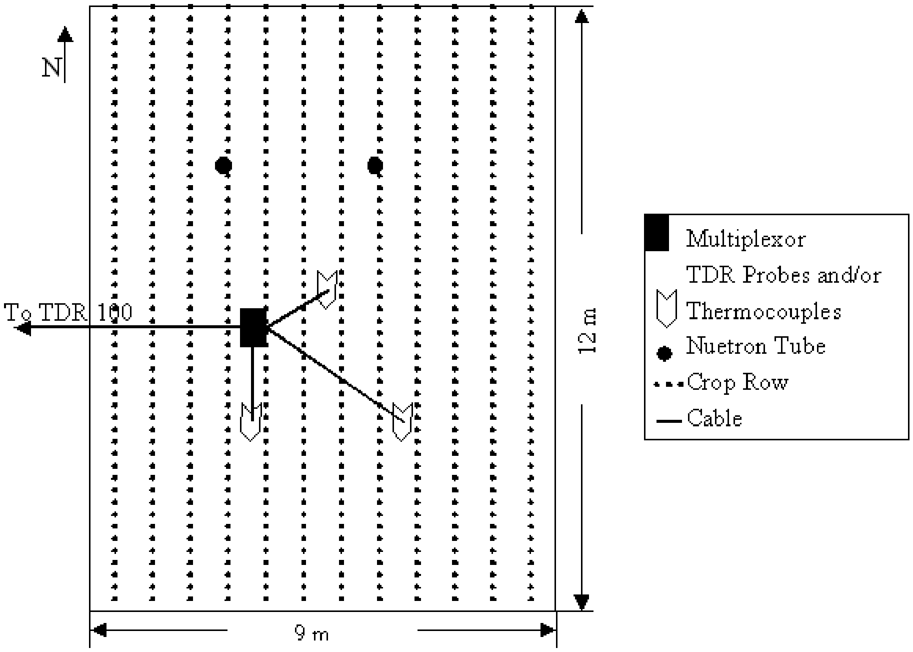

Figure 3.1 Layout of measurement equipment in field plots.

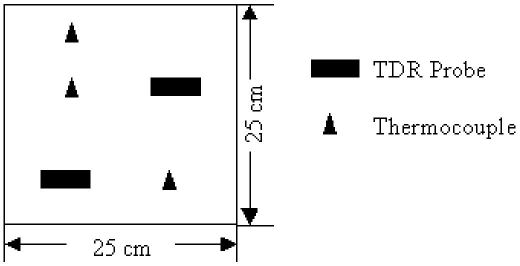

Figure 3.2 Layout of TDR and thermocouple probes in vertical face of the excavated pits.

The TDR probes and thermocouples were operated by the same CR10X Campbell datalogger. For both the 2006 and 2007 growing season, the datalogger was programmed to measure temperature every 10 min and record the hourly average, daily maximum, and daily minimum. In 2006, the datalogger was set to determine volumetric water content by comparing measured coaxial cable length of a given reading to the known operational cable length using the equation of Topp et al. (1980) every 30 min and record the hourly average, daily maximum, and daily minimum. A TDR waveform was also captured and recorded every hour. To simplify the process of matching saved waveforms with reported water contents in 2007, the datalogger program was changed to both capture a TDR waveform and determine volumetric water content on an hourly basis without averaging, as well as record daily maximum and minimum water contents.

Subsurface Water Content

Water content in the claypan was monitored with a neutron probe (503 DR Hydroprobe Moisture Gauge, CPN International, Inc., Martinez, CA) using a count duration of 16 s. Two neutron access tubes of standard type 6061-T6 aluminum tubing (o.d. 4.128 cm, wall 0.089 cm) were installed in each plot with a drop-hammer to maximize contact between the soil and tube wall. Soil was removed from the inside of the tubes with an auger and tubes were sealed at the top with a rubber stopper. There was no seal at the base of tubes. The tubes were placed in the crop row, 3 m from the north edge of the plot (Figure 3.1). Neutron readings were taken every 15 cm to a depth of 150 cm. Neutron readings were taken approximately every 2 wk from June to October. Standard counts were recorded before and after tube measurements. A mean standard count was used to calculate the count ratio (CR) from each tube-measured count (CR = measured count / mean standard count). The factory calibration equation ($\theta = 0.1733\text{CR} - 0.006923$) of this neutron probe was used to calculate volumetric water content (θ). Determination of a field calibration for this neutron probe was not attempted because the subsoil water content remained fairly constant providing only one point along a potential calibration curve.

Evapotranspiration

Two different approaches were used to quantify evapotranspiration. Early season evaporation from the soil surface was examined with microlysimeters (Boast and Robertson, 1982) every 24 h for the 2 d following substantial rainfall events. The microlysimeters were fabricated from aluminum tubing (72 mm i.d., 1.7 mm wall thickness, AMS, Inc., American Falls, ID) cut to a length of 102 mm. Microlysimeters were pushed into the soil surface either by hand or with a small slide hammer, depending on soil firmness, and then excavated, wiped clean, and sealed at bottom with plastic caps (AMS, Inc.). After weighing with a portable balance, the microlysimeters were wrapped in plastic (leaving surface exposed) and returned to original soil location for approximately 24 h after which the plastic was removed and microlysimeters (with bottom cap) were reweighed. Three microlysimeters were installed in each plot for each daily evaporation measurement in the center of non-traffic interrows.

Daily evapotranspiration was calculated on a field scale basis beginning DOY 131 (day of assumed full profile) in each year following procedures in the FAO-56 handbook for Crop Evapotranspiration (Allen et al., 1998). This method uses the Penman-Monteith equation and coefficients for basal crop transpiration ($K\text{cb}$), soil evaporation ($K\text{e}$), and water stress conditions ($K\text{s}$). Actual evapotranspiration ($ET\text{a}$) is calculated using the expression

$$ET\text{a} = (K\text{s}K\text{cb} + K\text{e})ET\text{o}\,. \tag{3.1}$$

Relative humidity, wind speed, and reference grass evapotranspiration ($ET\text{o}$) for the Parsons field station were downloaded from the Kansas Weather Data Library. Calculations for $ET\text{a}$ were completed for each plot using field measured details of ground cover and available water holding capacity. Complete details of ET calculations are described in Appendix C. The FAO-56 method has been reported to correlate well with evapotranspiration measured with lysimeters, though it has a tendency to slightly overestimate ET in dry conditions (Allen et al., 2005; Howell et al., 2004).

Runoff

Neither surface nor subsurface (lateral flow) runoff was measured directly. This component of the water balance was calculated as the residual from precipitation, evapotranspiration and change in whole profile water storage (as determined with neutron probe readings). The site was protected from run-on by soil berms on the north and east sides but water was free to move from plot to plot within the site.

Potential for lateral flow was determined by checking for presence and measuring the depth of perched water in shallow (20-28 cm) observation wells. The observation wells consisted of a 2-in Schedule 40 PVC well casing with screening over a 15.2-cm interval at one end (Environmental Manufacturing, Inc., Manhattan, KS). A hollow, sand-filled, well point was attached to the well casing immediately below the screened interval. Observation wells were installed by augering a 10-cm-diameter hole and then standing the well in the hole. Fine sand was placed around the screened portion and bentonite was used to fill the hole to soil surface. The removed soil was then mounded around the observation well, above the bentonite, to minimize downward water movement around the well. The depth of wells varied as each well was placed so that the bottom of the screened interval was flush with the surface of the claypan. Six observation wells were installed around the field site where no well was in a treatment plot. A diagram of the placement of observation wells at the field site is available in Appendix E.

In 2007 only, the wells were equipped with pressure transducers (WL400-003-025 Water Level Sensor, Global Water Instrumentation, Inc., Gold River, CA) to report both presence and depth of standing water. The pressure transducers were positioned in the observation wells so that the measured depth of water was equal to the positive pressure from overlying saturated soil at the interface of the claypan. The lead wires of each pressure transducer were connected to extension wire in a waterproof enclosure containing desiccant, placed near the monitoring well. To prevent condensation of water in the vent tubes of the pressure transducers, the end of each vent tube entered the waterproof enclosure and was connected to the barrel of a syringe that had been filled with desiccant. The extension wire continued to a CR10X datalogger (Campbell Scientific, Inc., Logan, UT) and was attached to the wiring panel via a 125-Ohm resistor (S102K, Texas Components Corporation, Houston, TX) to convert the pressure transducer output from current to voltage. One lead from the resistor and the negative lead from the pressure transducer were wired to the “high” side of a differential channel. The other resistor lead was wired to the “low” side of the differential channel, and a short length of wire was used to connect the “low” side of the channel to ground. The positive lead of the pressure transducer was wired to the 12-V power supply. The datalogger registered output voltage and calculated depth of water using the factory supplied calibration equation for each pressure transducer. The datalogger recorded the depth of water for every half hour as well as daily maximum and minimum values.

Soil Physical Properties

Bulk Density

Bulk density measurements were taken from the soil surface before and after each growing season. Soil samples of known volume were extracted, dried at 105 °C for 72 h, and then weighed in order to calculate bulk density. The sampling procedure varied with sampling date and is reported with results.

Particle Size Analysis and Organic Carbon and Nitrogen

Particle size analysis was completed using a modification of the pipette method of Kilmer and Alexander (1949) for soil samples collected in October of 2007 from the six plots used in the 2007 growing season. Samples were collected from depth intervals of 0-5, 5-10, 10-15, 15-20, 20-25, and 25-30 cm using a push corer. Samples from depth intervals of 30-45, 45-60, 60-90, 90-120, and 120-150 cm were collected with a Giddings probe. The soil samples from the upper 30 cm were also tested for total carbon and nitrogen using a LECO (CN-2000, St. Joseph, MI) dry combustion method where total carbon was assumed equal to organic carbon.

Water Retention

Intact soil cores, 8 cm in diameter and 3 cm tall, centered at the 5- and 15-cm depths, were used in Tempe pressure cells (Model 1405, with Model 1405B1M3 0.1-MPa, high flow ceramic plate, Soilmoisture Equipment Corp. (SEC), Santa Barbara, CA) for water retention analysis at 5, 10, 15, 20, 30, 50, and 100 kPa. The soil cores were collected in October 2007 from the six plots used in the 2007 growing season. Brass rings designed to fit into the pressure cells were pushed into the soil to the appropriate depth, excavated, and trimmed in the field. Cores were stored at 4 °C between sampling and pressure runs. Initial saturation of the cores was accomplished by wetting the cells from below with 5 mM $CaSO_4$ solution delivered via mariott bottle where the water level was set equal to the bottom of the core for 12 h and then raised to the top of the core for an additional 24 h. The mariott bottle was then detached, and the cores were covered and allowed to drain for 24 h. Initial weight of Tempe cells was determined immediately following the 24 h drainage. A 2 d equilibration time was used for pressures of 5, 10, and 15 kPa, 3 d was used for pressures of 20, 30, and 50 kPa, and 5 d was used for the 100-kPa pressure. The exact pressure at which samples were equilibrated was determined with a water or mercury manometer (depending on pressure range). After cycling through all pressure steps, cores (still in brass rings) were removed from Tempe cells, dried at 105 °C for 48 h, and reweighed to determine bulk density and final water content.

Water retention at pressures of 100, 200, and 500 kPa, as well as 1.0 and 1.5 MPa was measured with ceramic plates and a high-pressure apparatus (Klute, 1986) using sieved, air-dry soil samples collected at the same time (October 2007) from the same locations and depths (5 and 15 cm) as the intact cores. Samples were packed into rubber retaining rings about 1 cm tall and 5 cm in diameter that had been set on the ceramic plates. Samples were saturated with 5 mM $CaSO_4$ solution by placing plates into sufficient solution so that the plates, but not the rings, were completely submerged for 24 h. A 1-bar ceramic plate (SEC, Santa Barbara, CA) was used for the 100-kPa measurement and a 5-bar ceramic plate (SEC) was used for the 200-kPa measurement. Both plates were pressurized in a 5-bar extractor (SEC) with equilibrium times of 5 d for 100 kPa and 6 d for 200 kPa. The 5-bar ceramic plate was also used for the 500-kPa measurement, while a 15-bar ceramic plate (SEC) was used for the 1.0-MPa measurement. Both plates were pressurized in a 15-bar extractor (SEC) with a 7 d equilibration period. After removal from pressure apparatus, samples were weighed, dried at 105 °C for 24 h and re-weighed to determine gravimetric water content. A subsample of the sieved, air-dry soil samples used for the above water retention measurements was sent to the NRCS National Soil Survey Laboratory in Lincoln, NE for determination of water retention at 1.5 MPa in a pressure-membrane extractor (Soil Survey Staff, 2004). All values were converted to volumetric water content using the bulk density determined from the intact core taken at the same location.

The van Genuchten (1980) water retention function, $\theta(\psi)$, with no hysteresis is

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha\psi|^n]^m} \qquad [3.2]$$

where

$$m = 1 - 1/n. \qquad [3.3]$$

Here, ψ is pressure head (less than zero), θ_r and θ_s are residual and saturated water contents, respectively, and α and n are curve fitting parameters. The water retention function was fit to data from each treatment and depth using a non-linear optimization method in the Solver function of Microsoft Excel (Wraith and Or, 1998). Constraints on the potential range of values for α, n, θ_r, and θ_s were taken from Schaap et al. (1998).

Hydraulic Conductivity

Saturated hydraulic conductivity (K_s) was measured on 4 Oct. 2007 using the constant-head well permeameter method (Amoozegar and Warrick, 1986). Measurements were made in boreholes (5.3 cm diameter) that were hand-augered to a depth of 140 cm. Compact constant head permeameters (Ksat, Inc., Raleigh, NC) were used to maintain a constant head of water (0.01 M $CaCl_2$ solution) in the boreholes and measure rate of discharge. Water was ponded to a depth of approximately 15 cm in the boreholes, thereby measuring average K_s over the 125- to 140-cm soil depth interval. Saturated hydraulic conductivity was calculated using the Glover solution for a borehole far above an impermeable layer (Eq. [12] of Amoozegar and Warrick (1986)). Boreholes were placed in nontraffic interrows 5 m from the north end of each plot. Care was taken to be at least two crop rows west of the neutron access tubes.

Measurement of Agronomic Effects

Percent residue cover was determined in early spring and again after planting with the line-transect method (Hickman and Schoenberger, 1989). Stand counts were taken for several days after planting and once after sorghum tillering. The total number of plants (with plumule above soil surface) in the center two rows of each plot were counted and then converted to population per hectare. Biomass sampling occurred 8 wk after planting (during flowering in 2006 and during boot in 2007). Whole plants were taken from 1 m of row (neither middle nor edge of plot) and separated into leaves, stems, and heads. The separated samples were oven dried at 60 °C for 48 h with dry weights recorded. Head counts were taken before harvest. The total number of heads (exposed from stem) in the center two rows of each plot were counted and then converted to heads per hectare. Yield, as kg of grain per hectare, was recorded at harvest by weighing grain from all plants in the center two rows of each plot and converting to 13% moisture.

Statistical Analysis

The field experimental design was a randomized complete block with three replications. Single factor tillage treatment comparisons for variables with repeated measures over time such as emergence, stored water content, evapotranspiration, time between precipitation and maximum water content, evaporation, and temperature were analyzed using a Satterthwaite analysis with the PROC MIXED procedure of SAS 9.1 (SAS Institute, Cary, IN). Analyses where we examined both an entire soil profile and individual depths such as stored water content, particle size analysis, and organic carbon and nitrogen contents also used the Satterthwaite analysis in PROC MIXED. Tillage treatment comparisons for variables such as bulk density, water retention curve fitting parameters, biomass, and yield used PROC GLM where treatment effect means were compared using Fisher's LSD. Comparisons across years were not made because of large weather differences.

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CHAPTER 4 - Soil Properties

This chapter covers an overview of soil physical properties. These properties were examined to gain insight on how tillage treatments may have created soil differences that contribute to hydrologic differences.

Bulk Density

Bulk density was measured in spring and fall of both crop years (Table 4.1). The only time a significant difference was seen was on the 20 Apr. 2006 measurement from the 0- to 5.2-cm depth where no-till was 21% denser than chisel. No significant difference was seen in the fall of either year as the tilled soil had had ample time to settle. The spring 2007 measurement occurred in May. The lack of significant difference on that date may be because of the longer time between tillage and measurement or because a greater depth of soil was sampled. Bulk density differences appear to decrease over the course of the growing season as a result of soil reconsolidation during large precipitation events. However, inconsistencies in sampling depth reduce the accuracy of the reported trend. On 20 Apr. 2006, a bulk density measurement was also taken from the 15- to 20.2-cm depth; no significant difference was seen between tillage treatments (CH = 1.16 g cm^{-3}, NT = 1.28 g cm^{-3}, $p = 0.111$). Another Kansas study reported greater bulk density for no-till in five locations as compared with reduced or conventional tillage practices; however, the only location that was significant at the $p = 0.05$ level was also the only location sampled in spring (McVay et al., 2006). The other sites in that study were fall sampled. In contrast to this work and the work of McVay et al., Lal et al. (1994) reported lower bulk density in no-till treatments as compared to either chisel or moldboard plowing, citing increased earthworm activity under the increased residue cover. The soil and climatic conditions at the Parsons field site are quite different from that of the Lal et al. study.

Table 4.1 Bulk density at the Parsons field site.

Date	Sampling Depth	Chisel	No-till	p-value
	-- cm --	------ g cm^{-3}	-------	
Spring 2006	0-5.2	1.01	1.22	0.021
Fall 2006	0-6.0	1.28	1.27	0.361
Spring 2007	0-10.2	1.15	1.18	0.601
Fall 2007	3.5-6.5	1.25	1.32	0.173

Organic Carbon Content

The organic carbon analysis revealed a decrease in carbon from the surface to the 30-cm depth for both tillage treatments (Figure 4.1). This decrease is typical in cropping systems because most of the soil organic material is from above-ground biomass. The effect is expected to be greater in no-till systems that do not incorporate the biomass (Blanco-Canqui and Lal, 2008). The 0- to 5-cm depth had a significant difference between the two tillage treatments with no-till have 27% greater organic carbon than chisel. At all other depths, there was no difference at the p = 0.05 level. When comparing across depths, the two treatments had p = 0.09 significance with no-till having greater carbon content than chisel. For four of five sites in Kansas, McVay et al. (2006) reported greater mass of organic carbon in the surface layer (0- to 5-cm depth) for no-till than for reduced and conventional tillage practices.

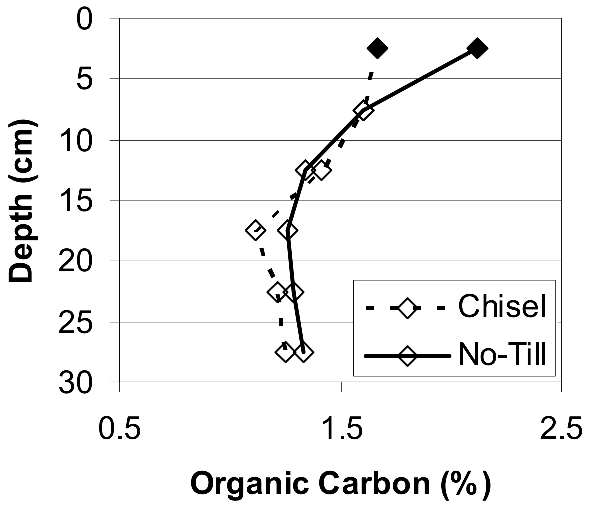


Figure 4.1 Soil carbon content by depth. Closed points are significantly different.

Particle Size

The texture of the surface soil was silt loam, with approximately 18% clay, while the subsoil was in the silty clay textural class with clay contents around 55% (Figure 4.2a). Texture analysis was performed on samples from 5-cm depth increments in each plot to determine the depth to claypan (Figure 4.2b). There was not a significant tillage effect on the depth interval at which clay content begins to increase. Rather, the detailed textural analysis showed there to be spatial differences in depth to clay content increase across the field site (Appendix A) where the three plots in the southwestern portion of the field had significant increases in clay content at a depth approximately 5 cm shallower than in the three northeastern field plots. The portion of the field that is shallower to clay includes the entire southern block and the western portion of the middle block. In 2006 the plots that were shallower to clay included two of the three chisel plots and one of the two no-till plots. In 2007 the plots that were shallower to clay included one of three chisel plots and two of three no-till plots. The spatial variation in depth to claypan created a confounding of effects due to tillage and texture-dependent physical properties (e.g., water retention and soil water storage) in the 15- to 25-cm depth interval.

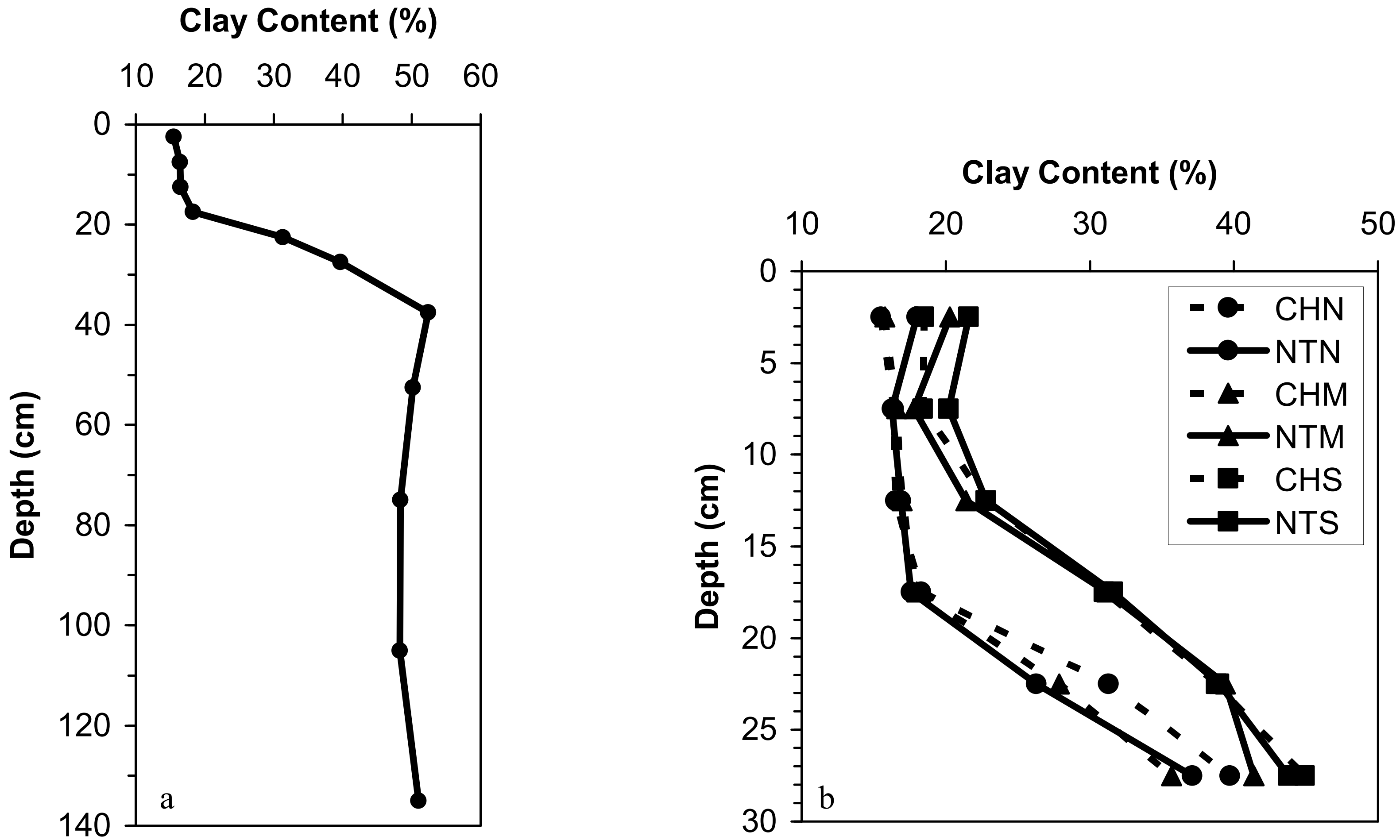


Figure 4.2 (a) Typical texture profile for the P26 field location. (b) Depth of clay increase for each plot. Legend codes: CH – Chisel tillage, NT – No-till; N, M, and S indicate north, middle, and south block, respectively.

Water Retention

Water retention was characterized at pressures between 5 kPa and 1.5 MPa at the 5-cm (Figure 4.3) and 15-cm (Figure 4.4) depths. Both figures show curves fitted to the mean of water retention data from the six field plots while error bars show the range of curves fit to individual plots. Treatment means of fitting parameters from each individual plot are reported in Table 4.2 with expanded results in Appendix B. The measured water retention points between 5 kPa and 1.5 MPa were used to fit the water retention model of van Genuchten (1980). Before setting Tempe cell soil cores under pressure, they were saturated from below and then allowed to freely drain for 24 h. The weight at this point was recorded to give an initial water content (θ_i) that was near saturation. The θ_i values were not used in curve fitting. For all water retention curves, the θ_i point was not in alignment with the other measured points, possibly because of a bimodal water retention curve with multiple inflection points (Durner, 1992). Multimodal water retention curves are common in soils with fine texture and good aggregation (Durner, 1992). It is unfortunate that data were not obtained in the wettest range (0 to 5 kPa) to allow fit of a bimodal curve, which would have allowed for examination of treatment effects under near saturated conditions and determination of pore size distribution. The initial water content is numerically greater for the chisel tillage treatment.

For water retention at the 5-cm depth, the chisel and no-till curves appear close together on the dry end with some separation at the wet end (Figure 4.3). There is a significant difference in the curve fitting parameter θ_s (saturated water content) at the 5-cm depth (Table 4.2). The parameter θ_s does not represent true saturation but is a convenient parameter to compare treatment effects at the wet end of the curves. Effects at the wet end are typically caused by differences in porosity or structure and are indicative of treatment effects. In this case the no-till has a greater θ_s. While the data do not indicate a significant difference in total porosity, ϕ, between tillage treatments at the 5-cm depth, there is no determination or comparison of pore size distribution so it was not possible to determine if there is difference in pore size between tillage treatments causing differences in θ_s values. Field observations revealed a system of large macropores in no-till which are likely responsible for storing greater soil water under low pressure (near saturated) conditions. No significant difference is seen at the dry end of the water retention curves (θ_r, residual water content) or in the curve shape parameters α and n.

The tillage treatment effect resulting in significant differences for θ_s but not θ_r matches the findings of Ahuja et al. (1998). However, those workers reported greater saturated water content and porosity in the tilled treatment while our no-till has greater water retention at θ_s. Though not statistically significant, this work shows numerically greater ϕ and θ_i in the chisel treatment. These opposing effects further emphasize the lack of curve fit to θ_i and the suggestion of a multimodal curve.

There are no significant differences in water retention curve fitting parameters due to tillage treatment at the 15-cm depth (Table 4.2). At this depth, the water retention curves were more strongly influenced by soil texture. The three plots that were shallower to clay held more water at the 15-cm depth than those plots where clay started deeper. The slight treatment separation at the dry end of the water retention curves (Figure 4.4) is likely a result of the fact that two of the three no-till plots are shallower to clay while only one of the three chisel plot is in the shallow-to-clay part of the field site. The dry end of water retention curves and the θ_r parameter are typically texture driven with treatments effects rarely seen.

The water retention data can be used to estimate available water capacity (AWC) by subtracting the 1.5-MPa water content from the 30-kPa water content. The AWC can be used in interpreting evapotranspiration and yield results from each plot. The AWC was significantly greater in no-till at the 5-cm depth whereas there was no treatment effect at the 15-cm depth. At the 5-cm depth, the greater AWC in no-till is related to no-till also having greater θ_s than chisel, while there is no difference in θ_r. If a treatment effect was seen on both ends of the water retention curves, the effects could offset each other and result in no difference in AWC. A greater AWC would indicate more water available for use by plants; however, since the effect is only significant at the shallowest depth and roots are using water form much deeper depths under dry conditions, this tillage effect will likely not result in a yield difference between the treatments.

Table 4.2 Water retention curve-fitting parameters (α, n, θ_r, and θ_s), initial water content (θ_i), porosity (ϕ), and available water capacity (AWC). All values are treatment means. Expanded results are provided in Appendix B.

Treatment	α	n	θ_r	θ_s	θ_i	ϕ	AWC†
			----------------------		$cm^3\ cm^{-3}$		------------------------
5 cm							
Chisel	0.068	1.37	0.046	0.377	0.477	0.529	0.178
No-Till	0.048	1.43	0.061	0.393	0.458	0.502	0.198
p-value	0.09	0.85	0.16	0.03	0.33	0.17	0.01
15 cm							
Chisel	0.054	1.29	0.029	0.378	0.425	0.468	0.180
No-Till	0.044	1.31	0.047	0.376	0.427	0.472	0.177
p-value	0.64	0.58	0.24	0.82	0.79	0.53	0.41

† Available water capacity determined from measured water retention values at 30 kPa and 1.5 MPa.

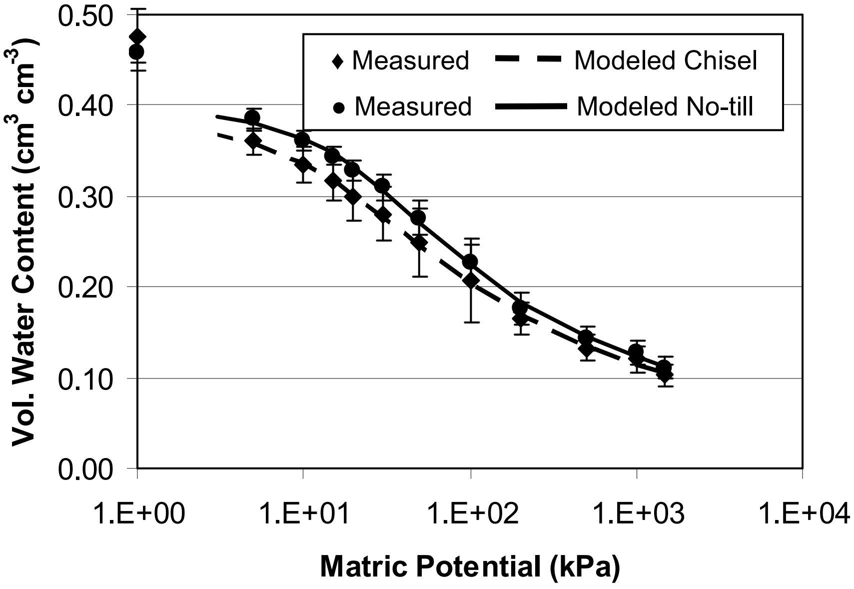


Figure 4.3 Water retention curves from the 5-cm depth.

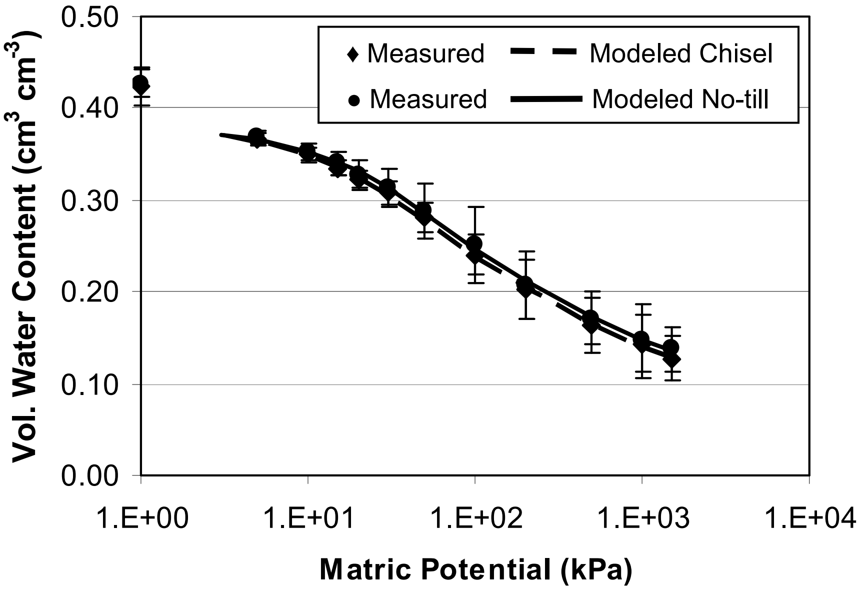


Figure 4.4 Water retention curves from the 15-cm depth.

Saturated Hydraulic Conductivity

The saturated hydraulic conductivity, K_s, was measured in the clay subsoil with the constant-head well permeameter method. With this method, K_s is calculated using the rate of discharge from the borehole after steady-state flow has been achieved. For many of the permeameter measurements at the Parsons field site, steady-state was not achieved with discharge rates decreasing until water stopped entering the soil. This may have been caused by dispersion of clay, or may indicate that the K_s of this soil is too small to be quantified with the constant-head well permeameter method. Although steady state was not achieved, the results are still useful for estimating the upper bound of K_s for the 125- to 140-cm depth interval. The average estimated upper bound for K_s was 0.2 cm d^{-1}, with a maximum value of 0.4 cm d^{-1}. As expected at this depth, there was no significant difference in the upper bound K_s due to tillage treatment. Blanco-Canqui et al. (2002) reported a value of 0.2 cm d^{-1} for the saturated hydraulic conductivity at depth in the central Missouri claypan region.

Soil Temperature

Thermocouple probes were used to monitor soil temperature on an hourly basis at depths of 5, 10, and 20 cm. The hourly data were used to calculate daily average soil temperature (Figures 4.5 - 4.6). In 2006 a wiring error occurred such that the outputs from one probe at the 10-cm depth and two probes at the 5-cm depth were averaged to generate the 5-cm reading from the south chisel plot. Also, the outputs from one probe at the 5-cm depth and two probes at the 10-cm depth were averaged to generate the 10-cm reading in that plot. For both the 5- and 10-cm depths, this error affected one of nine values averaged to characterize the temperature of the chisel treatment. It was not possible to extract or unaverage this data but the influence appears negligible in the final data. The error was corrected overwinter and not an issue for the 2007 growing season.

Daily mean temperature at the 5-cm depth had no overall significant differences due to tillage treatment in either year. In 2006 there was a significant treatment by time interaction and some differences due to tillage early in the season. No-till was cooler than the chisel treatment on 15 of the first 25 d that measurements were taken (DOY 147-150, 152-157, 162-163, 168, 171-172). In 2007, there were no days that had significantly different daily temperature means. Licht and Al-Kaisi (2004) reported greater soil temperatures in the top 5 cm of soil for strip and chisel tillage as compared with no-till. The reduced temperature of no-till correlated to a reduced rate of emergence in their work.

The daily mean temperature at the 10-cm depth in 2006 was significantly different over time because the no-till was cooler ($p = 0.040$). In 2006, a tillage treatment by time interaction existed because soil temperatures were not different at $p = 0.05$ on all dates. The dates with no difference generally were those immediately following large precipitation events. In 2007, daily mean soil temperatures at the 10-cm depth did not show a tillage effect overall or on any specific days.

The daily mean temperature at the 20-cm depth in 2006 was significantly different over time because the no-till was cooler ($p = 0.031$). In 2006, a tillage treatment by time interaction existed because soil temperatures were not different at $p = 0.05$ on all dates. In 2007, daily mean soil temperatures at the 20-cm depth did not show a tillage effect overall or on any specific days.

Daily maximum and minimum temperatures were subtracted to obtain the amplitude of daily temperature fluctuations. This provides insight to heat transfer in the soil, which is frequently influenced by soil physical properties such as bulk density and water content. In general, the amplitude of the temperature fluctuations were greater in no-till than in the chisel treatment. At all measured depths, no-till had greater maximum and smaller minimum temperatures nearly every day of measurement in the 2-yr field investigation (sample data in Figure 4.7).

In summary, a treatment effect in daily mean temperature at the 5-cm depth was seen only during the early 2006 season and likely was caused by treatment differences in residue cover (Horton et al., 1996). Increasing residue cover has been shown to decrease soil temperature; however, Horton et al. (1996) also reported that increasing residue cover generally decreases the amplitude of temperature fluctuations, a finding opposite that observed in this study. At the 5-cm depth, the cooling effect of residue did not persist into late season because, at that time, both treatments had a closed canopy and were shaded from direct sunlight. There was a stronger treatment effect for daily mean temperature at deeper depths (10 and 20 cm), indicating that the physical nature of the soil was different in the two treatments and affected the way that heat moves through the soil. Azooz and Arshad (1995) reported that soil thermal conductivity is closely correlated with both soil water content and bulk density, both of which were greater in the no-till treatment during the early part of the 2006 growing season. In the study of Azooz and Arshad (1995), the no-till treatment also had greater water content and greater thermal conductivity than that in conventional tillage. Tillage treatment effects were not seen during the 2007 growing season, which was generally cooler and wetter for both treatments. The drier 2006 crop year had greater separation of soil temperatures between the tillage treatments.

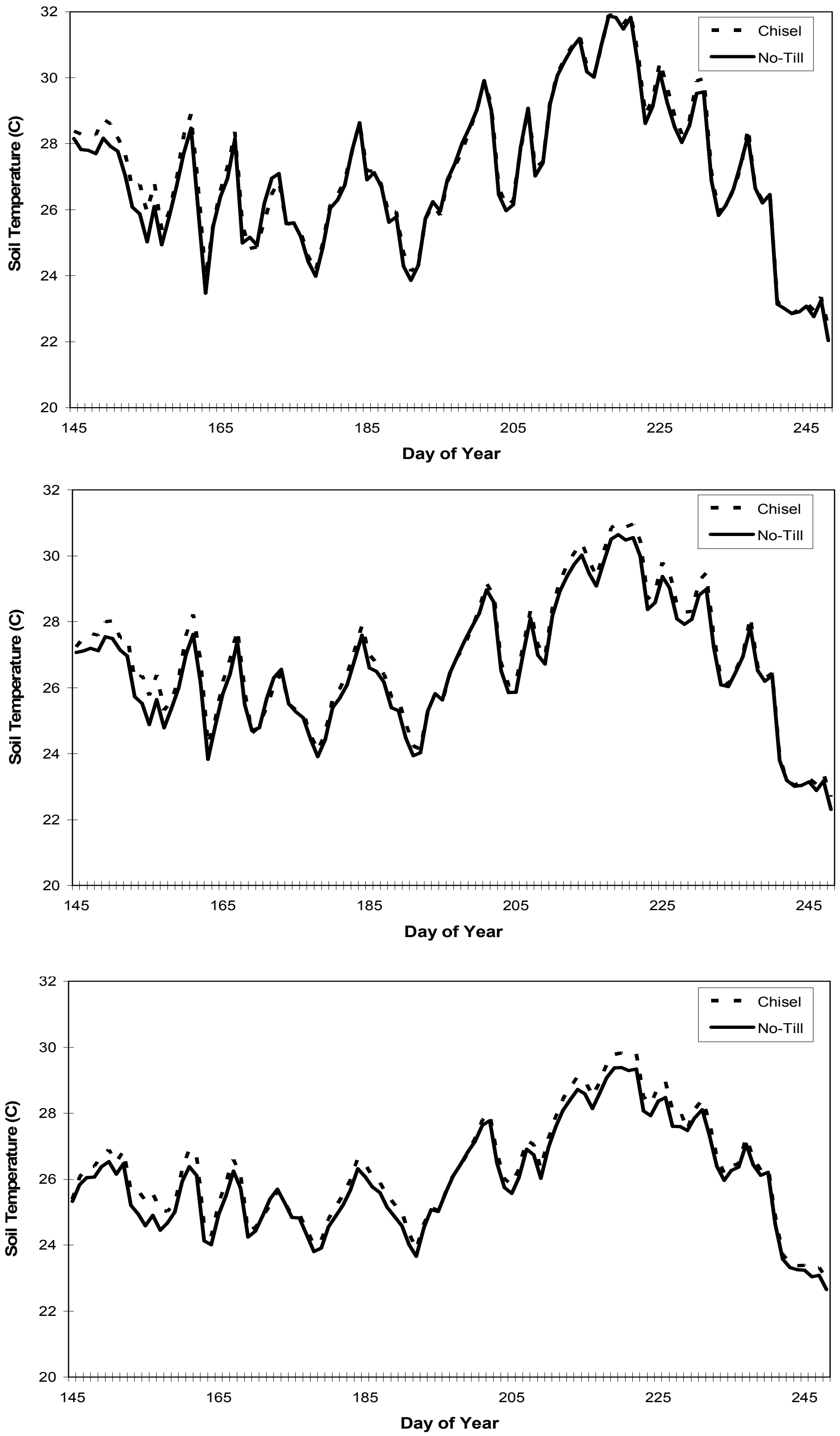


Figure 4.5 Daily mean soil temperature at 5- (top), 10- (middle), and 20-cm (bottom) depth in 2006.

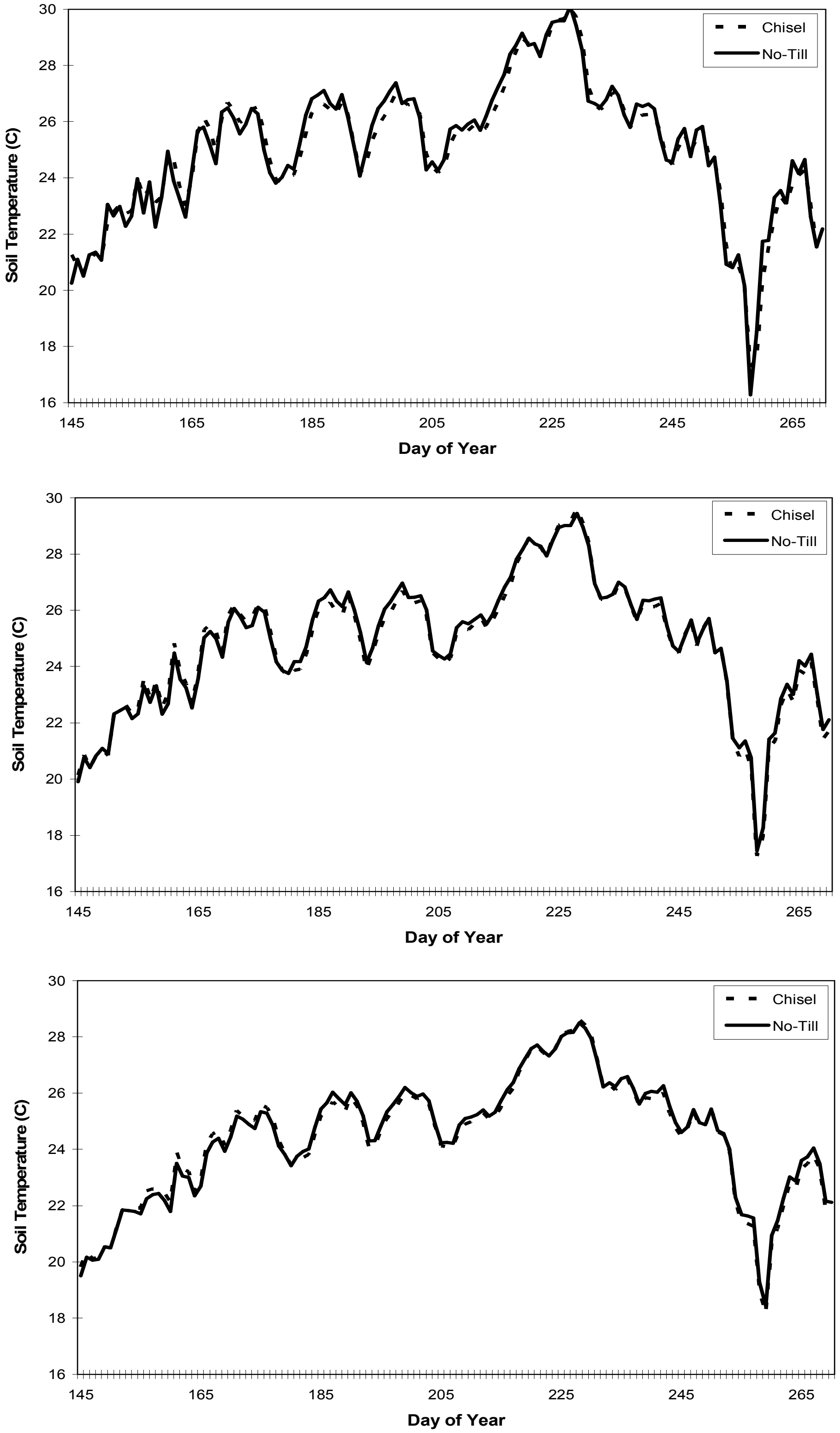
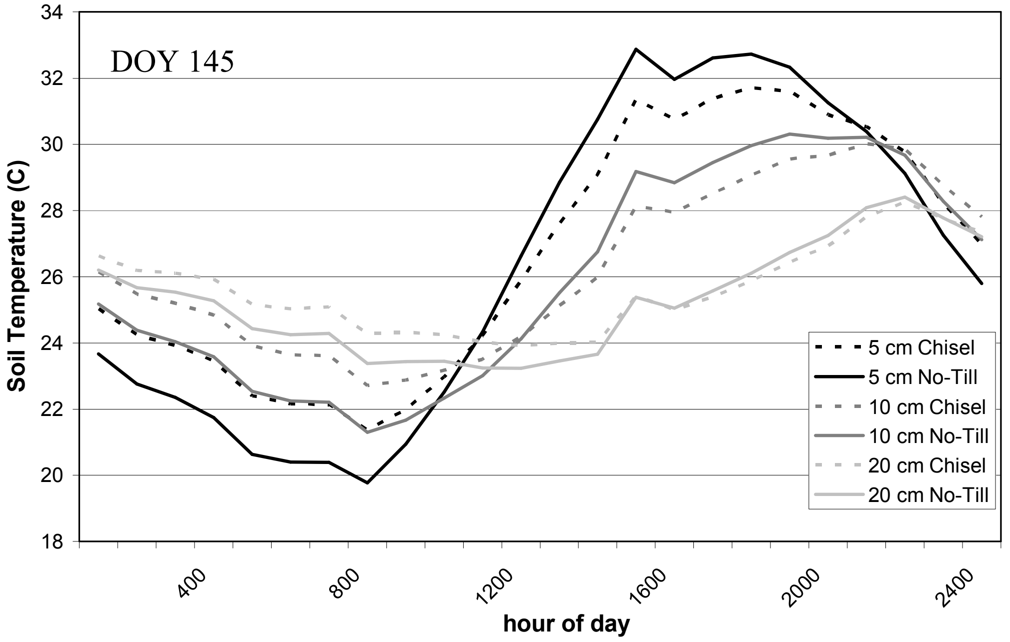


Figure 4.6 Daily mean soil temperature at 5- (top), 10- (middle), and 20-cm (bottom) depth in 2007.



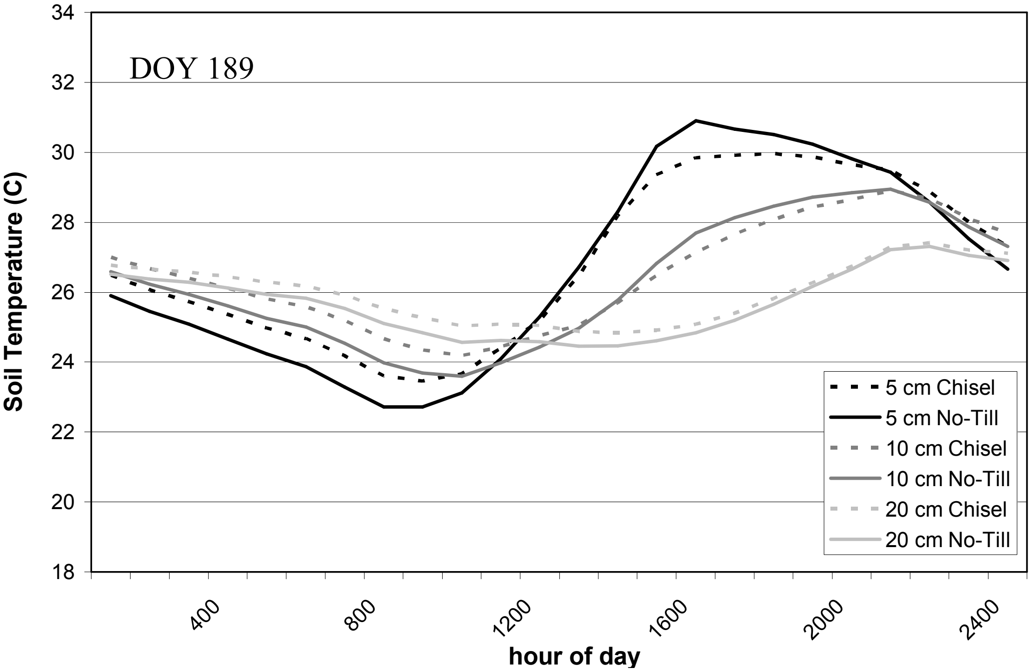


Figure 4.7 Typical daily temperature fluctuation curves. Top shows soil temperature at three depths on a day with moist soil (DOY 145) while bottom shows a day with dry soil conditions (DOY 189). Weather was very similar for both dates.

Conclusions

The effects of tillage can be seen in several soil physical properties as discussed above. The tilled soil does not seem to have a shallower surface horizon as compared with the no-till treatment though it was the opinion of a professional soil scientist that the whole site had been eroded in the past. The soil under no-till did have significantly greater bulk density than chisel in early spring, and significantly greater organic carbon in the 0- to 5- cm depth interval. The organic carbon was not different at any other depths or overall. There were differences in water retention at the 5-cm depth, with greater measured available water and model-fit saturated water content in no-till than chisel likely because of differences between treatments for bulk density or aggregation and pore size distribution (which were not measured).

Though differences in physical and hydrologic properties between the two tillage treatments were found to be minimal, we were able to identify some treatment effect where others have not. Several works have reported minimal effects from tillage and crop management on soil physical properties in long term studies. Carter (1996) reported greater porosity for the conventionally tilled treatment at the 0- to 10-cm depth immediately following tillage. However, the tillage depth was 25 cm and no difference was seen at deeper depths or later in the growing season as compared with reduced tillage practices. Brye (2003) found decreased water retention with increasing length of time since a site was broke from prairie and began being used in cultivation. However, the length of time also increased the amount of clay in the surface horizon (presumably due to erosion). Once this confounding factor was removed, there was no effect on water retention. Mielke and Wilhelm (1998) were able to show that tillage reduced hydraulic conductivity and porosity in the 0- to 76-mm depth but found no differences at deeper depths. Subbian et al. (2000) worked with various cropping systems and showed no effect on aggregate stability or size and only a water retention effect at 0.1 MPa, which they suggest was caused by different root patterns of the different cropping systems.

The amplitude of daily soil temperature fluctuations was greater in no-till than in the chisel tillage treatment at each depth. When comparing daily mean soil temperatures, there were no differences at the 5-cm depth while the soil under chisel tillage was warmer at the 10-and 20-cm depths in 2006. There was no significant difference at any depth in the cooler, wetter 2007 growing season.

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CHAPTER 5 - Water Balance

The objectives of this chapter are to examine tillage treatment effects on some individual components of the soil water balance, quantify estimated components, and report the final water balance of each crop growth season. This hydrologic balance will examine the precipitation, evapotranspiration, changes in stored soil water, drainage, and runoff.

Precipitation

Differences in weather between the two crop years had a pronounced effect on the results of this study. The first year, 2006, was hot and dry. The water content of the surface soil fell below the permanent wilting point on five occasions, with dry conditions persisting upwards of 3 wk at a time. The sorghum crop was harvested 98 d after planting and had below average yield. On the other hand, 2007 was a rather wet and cool year during which the southeastern Kansas region experienced occasional flooding. Crop emergence and tillering were delayed and the average yielding crop was in the field for 119 d.

Southeastern Kansas typically receives enough spring precipitation to assume a water filled soil profile. For each hydrologic balance, the start date was figured from the last day of heavy rainfall before planting. For example, in 2006, 82 mm of rain fell between 3 and 10 May. There was no precipitation between then and planting on 19 May. For this reason, 11 May (DOY 131) was used as the start of our water balance. Coincidentally, 11 May was also the date of full profile in 2007, though planting did not occur until 21 May.

Any instrumentation placed in the field plots was not installed until after crop planting. The installation dates encompassed 22 to 24 May (DOY 142 to 144) in both years. As such, the water content value for a full profile could not be measured on the date for which full profile conditions were assumed. Full profile water contents were taken from the neutron probe measurement of profile water content on 2 July 2007. This measurement followed 196 mm of rain over a 6-d span.

There is no treatment effect on precipitation. The 2006 crop year had 169 mm precipitation while sorghum was growing (19 May (DOY 139) to 25 Aug. (DOY 237)) as compared to 636 mm of precipitation while sorghum was growing in 2007 (21 May (DOY 141) to 17 Sept. (DOY 260)).

Evapotranspiration

Early season evaporation was examined with microlysimeters for tillage treatment effects. Evaporation in the first few days after precipitation was as great as 6.5 mm d^{-1} (Tables 5.1-5.2). The measured water loss from the chisel treatment was consistently greater than that from no-till in both years with the greatest differences typically seen closer to the date of the precipitation event. No direct evaporation measurements were made during drier soil conditions, and there was one event in each year where faulty weather forecasts prevented measurements directly after precipitation. The absence of a significant difference in evaporation two days after the 17 June 2006 is an example of not getting to the field site in time to capture evaporative differences.

Residue cover measured in 2007 averaged 37% for chisel and 95% for no-till; residue cover in 2006 was assumed to be similar. This difference in residue cover seems to be the primary reason for differences in evaporation rate between tillage treatments. Steiner (1989) found that increasing residue cover decreased evaporation regardless of underlying tillage treatment.

Some of the soil water measurements made at the Parsons field site were influenced by depth to clay. However, the microlysimeters sampled the upper 10.5 cm of soil, which is well above the depth at which clay content begins to increase. Thus, any spatial differences in depth to clay across the field site do not influence our interpretation of the evaporation data.

Table 5.1 Evaporative water loss as measured early in the 2006 growing season.

	Precipitation date	Microlysimeter water loss - first day after rain -	Microlysimeter water loss - second day after rain -
		--------------- mm	----------------
Chisel		6.1	5.3
No-Till	10 May	5.0	4.2
p value		0.059	0.062
Chisel		5.7	4.7
No-Till	6 June	5.1	3.0
p value		0.009	0.004
Chisel		ND†	1.3
No-Till	17 June	ND	1.9
p value			0.334

† - No data available.

Table 5.2 Evaporative water losses as measured early in the 2007 growing season.

	Precipitation date	Microlysimeter water loss - first day after rain -	Microlysimeter water loss - second day after rain -
		-------------- mm	--------------
Chisel		5.2	5.3
No-Till	10 May	3.6	4.1
p value		< 0.0001	0.003
Chisel		4.7	ND†
No-Till	15 May	3.7	ND
p value		0.013	
Chisel		6.4	6.5
No-Till	2 June	5.5	5.5
p value		0.036	0.015

† - No data available.

Daily evapotranspiration was calculated with the FAO-56 method on a field scale basis beginning 11 May (DOY 131) of each year (Figures 5.1 - 5.2). Inputs such as ground cover and available water varied with tillage treatment resulting in different evapotranspiration rates by treatment. Not all days of the year had significant differences. In both years, evapotranspiration early in the growing season was greater in chisel than no-till, a finding similar to microlysimetry results. After canopy establishment, there were few daily treatment effects with evapotranspiration being similar for both tillage treatments. However, there were some days during the driest part of each year when no-till had greater evaporation due to greater available water. Because of this, there was a significant treatment by time interaction for both years.

The overall growing season evapotranspiration was greater for chisel than no-till in both years. Total losses from DOY 131 to harvest for the chisel and no-till treatments were 242 and 231 mm in 2006 ($p = 0.0009$), and 352 and 319 mm in 2007 ($p = 0.0040$), respectively (Figures 5.1b and 5.2b). The differences in total evapotranspiration between tillage treatments were driven by treatment differences in residue cover and evaporation rate early in the season. Evapotranspiration was greater in 2007 because weather conditions created a longer period of crop growth and greater available moisture. The base water requirement to produce a sorghum crop has been reported as 175 mm (Hattendorf et al., 1988). The water use in 2006 was approximately 62 mm greater than base with low yields resulting. The water use in 2007 was approximately 160 mm greater than base with average yields resulting. This data indicates than the FAO-56 calculated cumulative evapotranspiration values were reasonable.

Previous research has established that no-till generally has less evaporative losses than worked soil (Brye et al., 2000; Steiner, 1989); however, the mechanism causing differences was not always clear. In this study, the difference in early season residue cover seems to be the primary factor influence differences in evapotranspiration. In mid season, when a crop canopy protected most of the surface and transpiration accounted for a majority of the water loss, there were few significant differences in daily evapotranspiration. Differences in bulk density and stored water were not always significant between treatments and therefore are assumed to have made less of a contribution to significant differences in evaporation losses.

The two methods of measuring evaporation in early spring did not always yield equal results. In general, the microlysimeters measured greater daily evaporation than that calculated with the FAO-56 method. However, the magnitude and sign of differences between treatments were the same for both methods. It is possible that the microlysimeters overpredicted evaporation because of damage (i.e., cracking) that occurred to the soil surface during insertion of the microlysimeter, creating a greater evaporative surface area. It is also possible that the FAO-56 method underestimated evaporation. This method requires adjustment from the reference evapotranspiration of a grass stand to actual evapotranspiration of current conditions. Since the conditions in early season have no growing plants, the method likely has greater error than at mid-season.

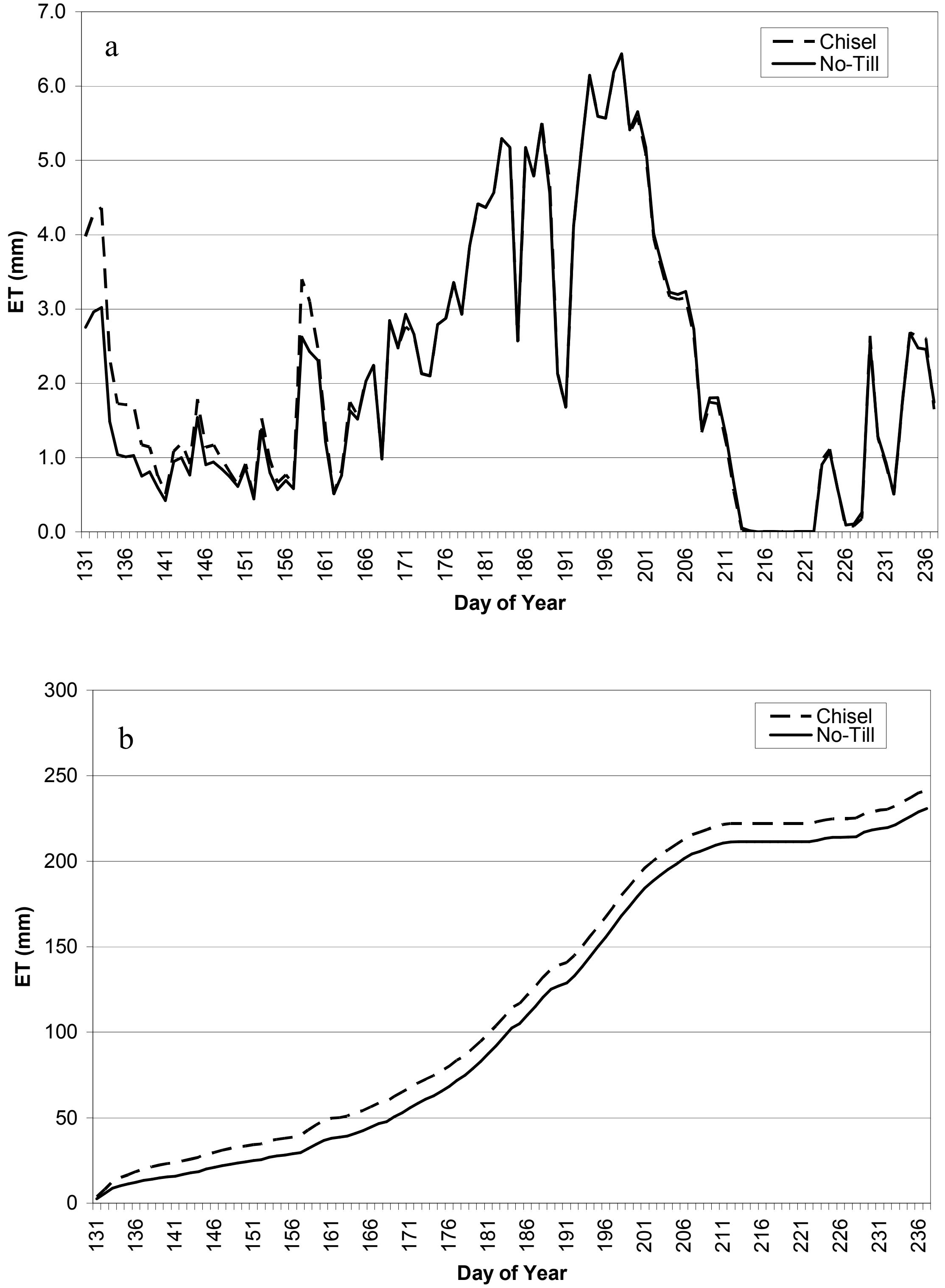
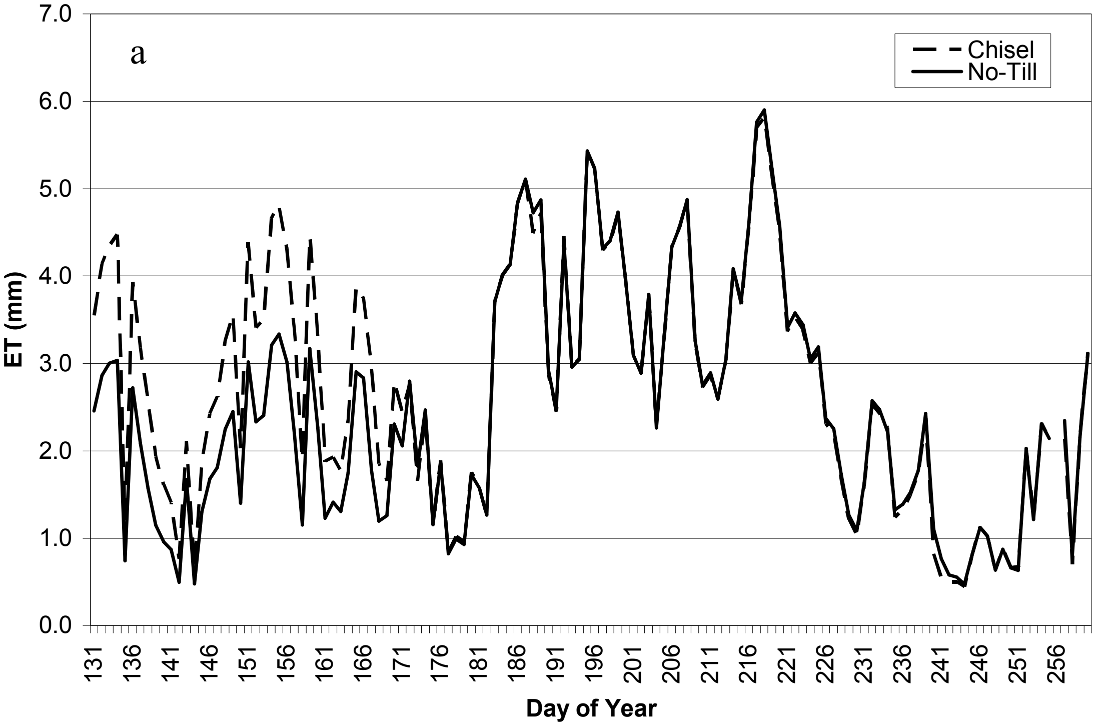


Figure 5.1 Evapotranspiration during the 2006 growing season. (a) Daily evapotranspiration (chisel > no-till at $p = 0.05$ on days 131-148, 153-154, and 158-161; no-till > chisel at $p = 0.05$ on day 171). (b) Cumulative evapotranspiration (chisel > no-till at $p = 0.0009$).



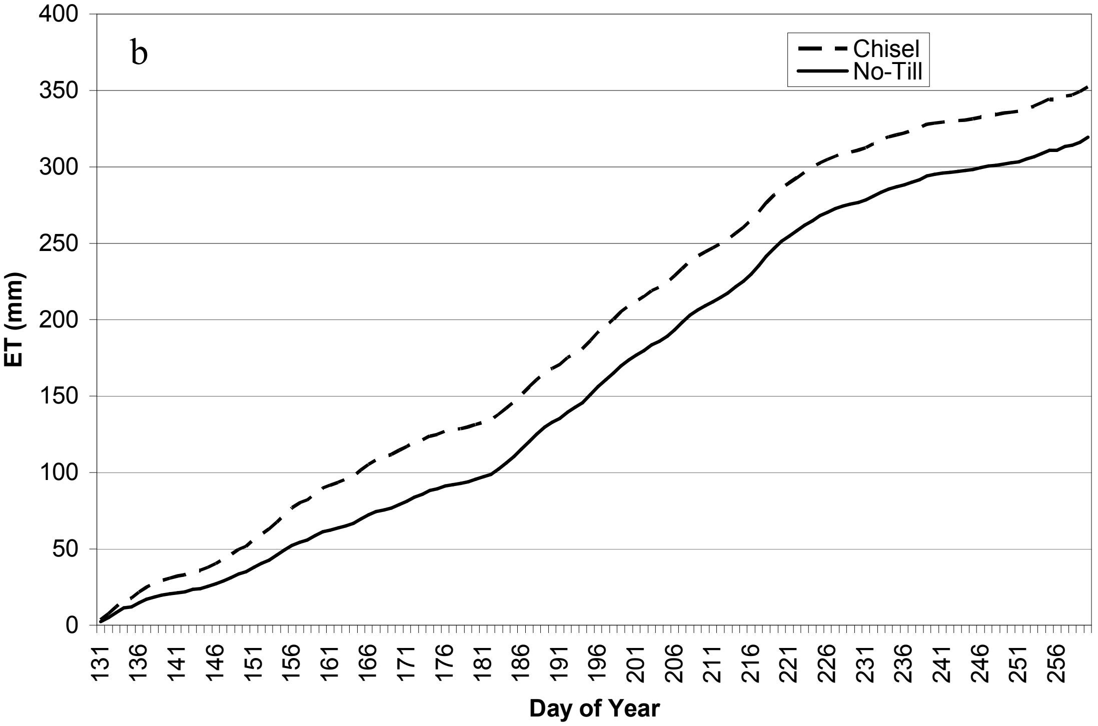


Figure 5.2 Evapotranspiration during the 2007 growing season. (a) Daily evapotranspiration (chisel > no-till at p = 0.05 on days 131-171, no-till > chisel at p = 0.05 on days 173, 188-189, 240-241, 257, 263-267, 275). (b) Cumulative evapotranspiration (chisel > no-till at p = 0.0040).

Change in Stored Water

The water content of the entire soil profile was determined from neutron probe measurements. Because the neutron probe method samples a relatively large volume of soil and does not provide continuous measurement, Time Domain Reflectometry (TDR) was also used to track the water content of the surface horizon. These measurements of water content allowed determination of depth of water in the profile, changes in water content over time, and changes in layer-depth of water extraction over time.

Surface Water Content

Analysis of Change Over Time

The water content of the A horizon varied over time in response to precipitation, evaporation, and crop water uptake. Water contents were monitored at the 10- and 20- cm depths in both crop years (Figures 5.3 - 5.6). In 2006, the TDR data indicate that, over time, the water content at the 10-cm depth was not significantly affected by tillage treatment (Figure 5.3). Furthermore, the two treatments were not significantly different at $p=0.05$ on any days. Part of the reason for the lack of seasonal tillage effect is a significant treatment by time interaction where neither treatment had consistently greater water content. It appears that the no-till treatment was wetter immediately following significant precipitation events, while a few days after these precipitation events, the no-till became the drier of the two treatments.

For the 2007 crop year, water content at the 10-cm depth was not significantly affected by tillage treatments overall (Figure 5.4), but there was a significant treatment by time interaction, and there were days during the wet early season when no-till had significantly greater water content than the chisel tillage system (DOY 145 to 149 and 161 to 178) at $p = 0.05$. The 10-cm water content results for the two crop years are similar in that the water content of no-till was greater during wet conditions, but not significantly different from chisel over the entire growing season because of significant treatment by time interaction. This interaction may be driven by a better macropore network moving water into and through no-till and/or differences in the water retention properties of the two treatments. Soil from the no-till treatment has been shown to hold more water under saturated conditions than that from chisel tillage (Table 4.2).

The water content results at the 20-cm depth do not mirror the nearer surface results. In 2006, the water content at the 20-cm depth was significantly different ($p = 0.08$) over time, with chisel greater than no-till (Figure 5.5) and no treatment by time interaction. There were also several dates where the water content was significantly different at $p = 0.05$. These include the entire time period of 17 June to 25 Aug. 2006 (DOY 168 to 237), or the height of summer drought, where the chisel retained more water at the 20-cm depth. Nearer the beginning and end of the growing season, when the soil was generally wetter, significant differences in water content were not detected. The moist 2007 crop year had no significant effects for water content at the 20-cm depth (Figure 5.6).

In both growing seasons, the depth to clay content increase had greater influence than tillage treatment on the soil water content at the 20-cm depth. Plots that were shallower to clay had greater water content than those that were deeper, particularly during dry periods. The water retention curves for the 15-cm depth also showed no effect from tillage, and samples from the plots that were shallower to clay content increase had greater residual water content. The three plots with shallower clay included two no-till and one chisel replicate in 2007 (Figure 4.2b). Particle size analysis was not performed in the plots used for the 2006 growing season but we can estimate that two chisel and one no-till treatment were in the shallower to clay portion of the field (Appendix A). The shallower depth to clay in two chisel plots is the primary reason for the significant difference where chisel was wetter than no-till at the 20-cm depth in 2006. Though the shallower-to-clay plots were holding more water during the dry part of the year, the amount of water available to plants was not increased. Clay soils generally hold water at greater tensions than silty soil and perhaps at too great a tension for plant uptake.

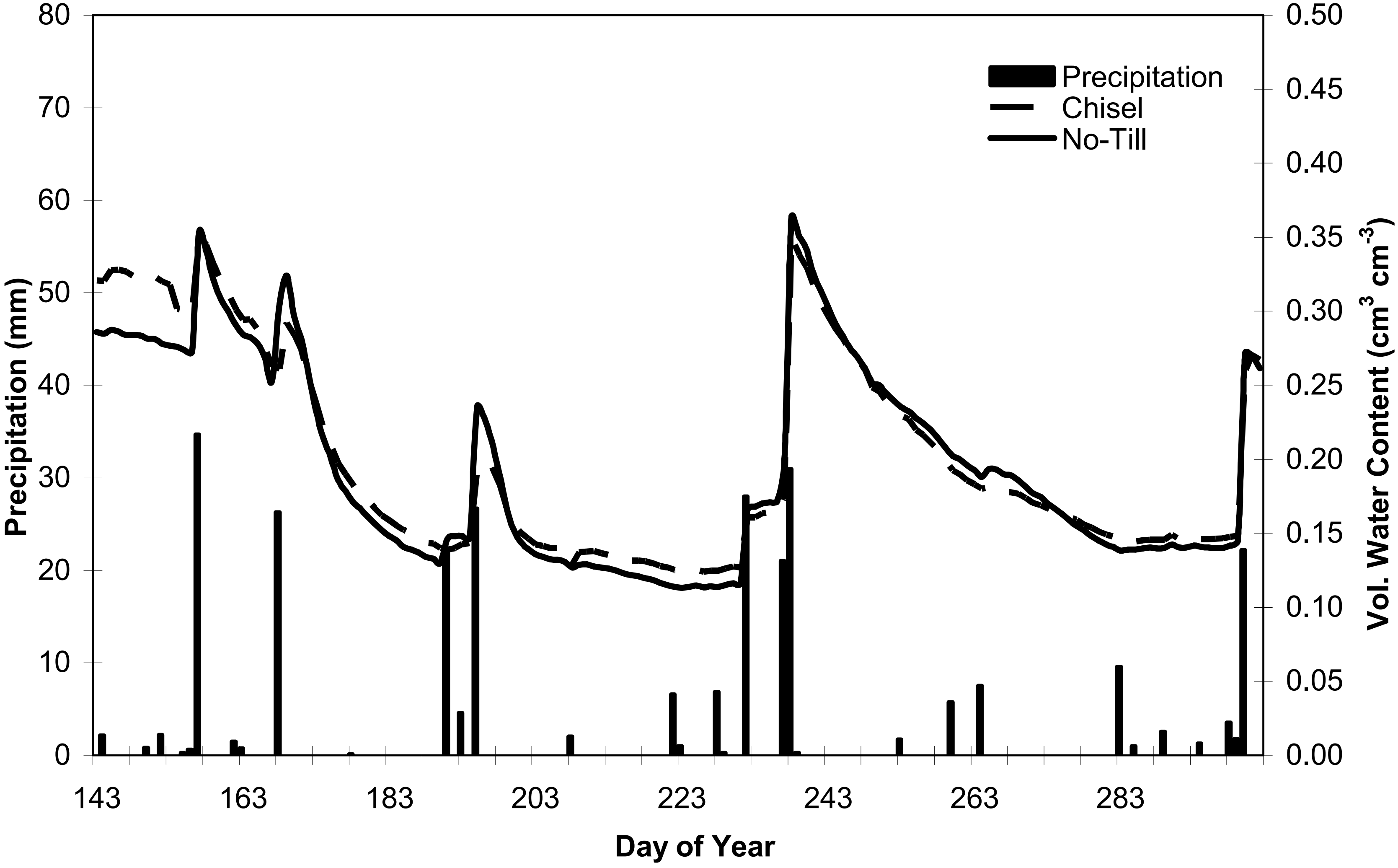


Figure 5.3 Precipitation and soil water content (10-cm depth, TDR data) during the 2006 growing season. Tillage did not cause a significant difference in water content over the entire season or on any particular days. There was a significant treatment by time interaction.

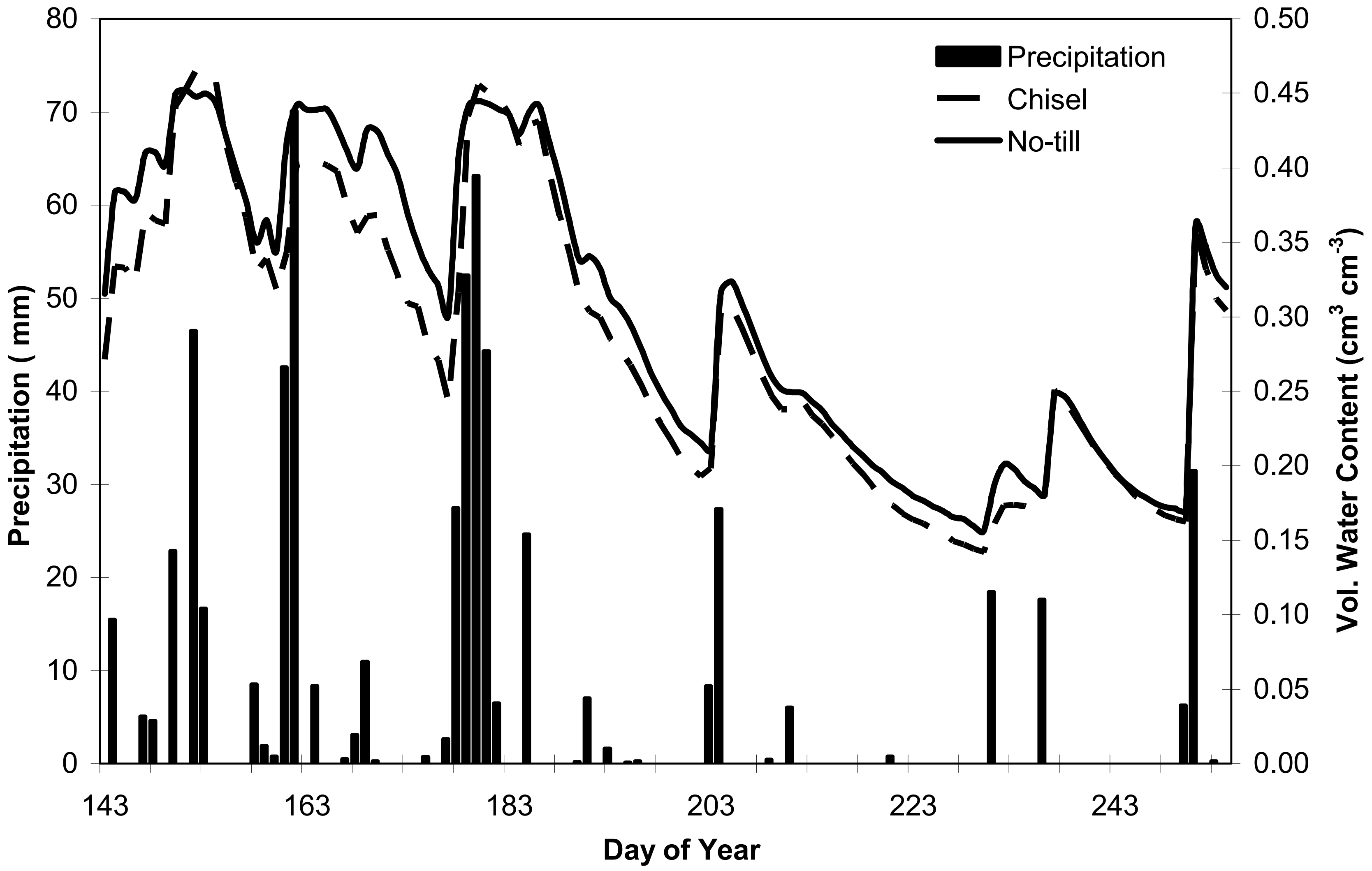


Figure 5.4 Precipitation and soil water content (10-cm depth, TDR data) during the 2007 growing season. Tillage did not cause a significant difference in water content over the entire season but there were differences on days (145-149 and 161-178). There was also a significant treatment by time interaction.

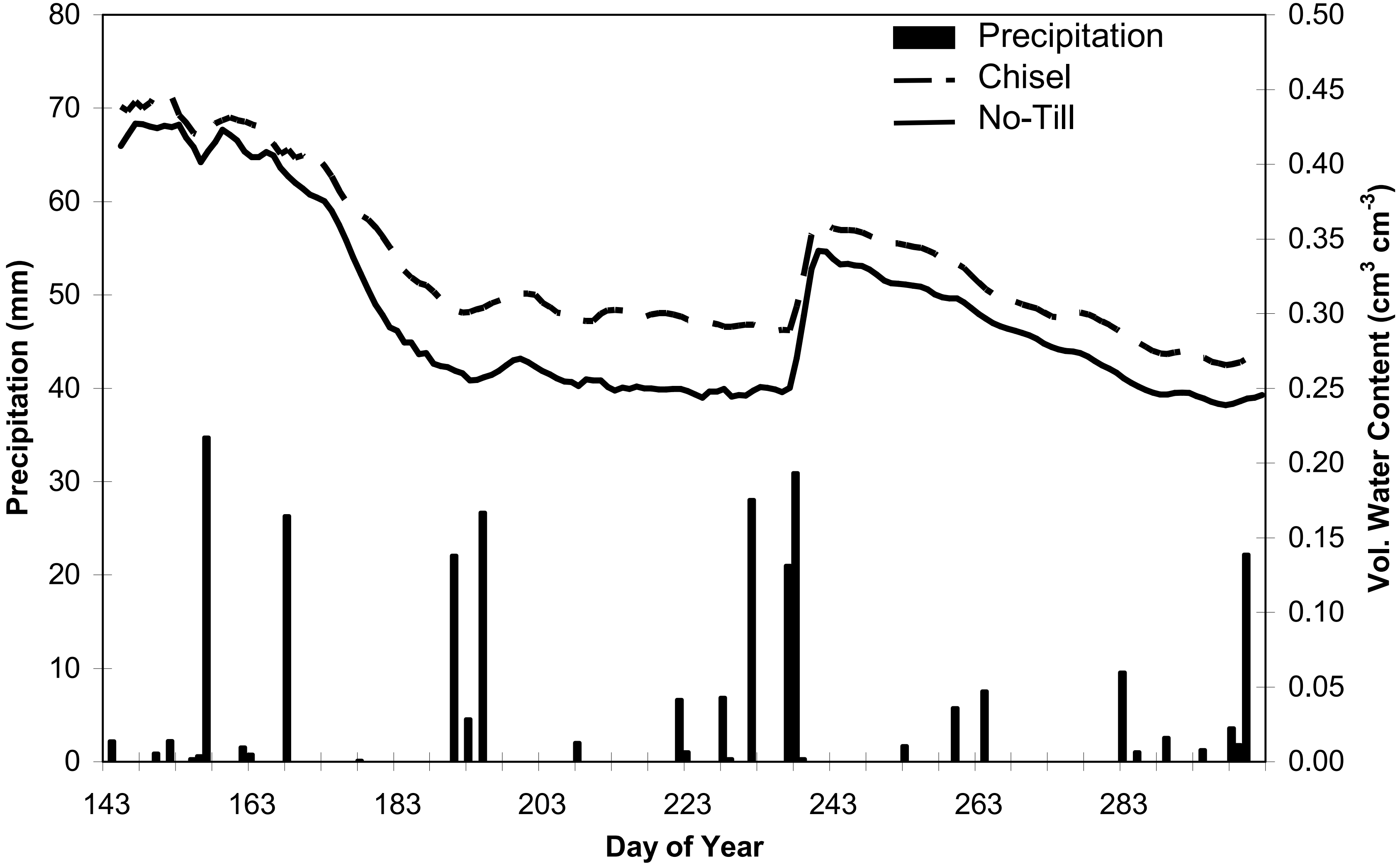


Figure 5.5 Precipitation and soil water content (20-cm depth, TDR data) during the 2006 growing season. Tillage did cause a water content difference at $p = 0.08$ over the entire season and at $p = 0.05$ for days 168 to 237 (driest part of year).

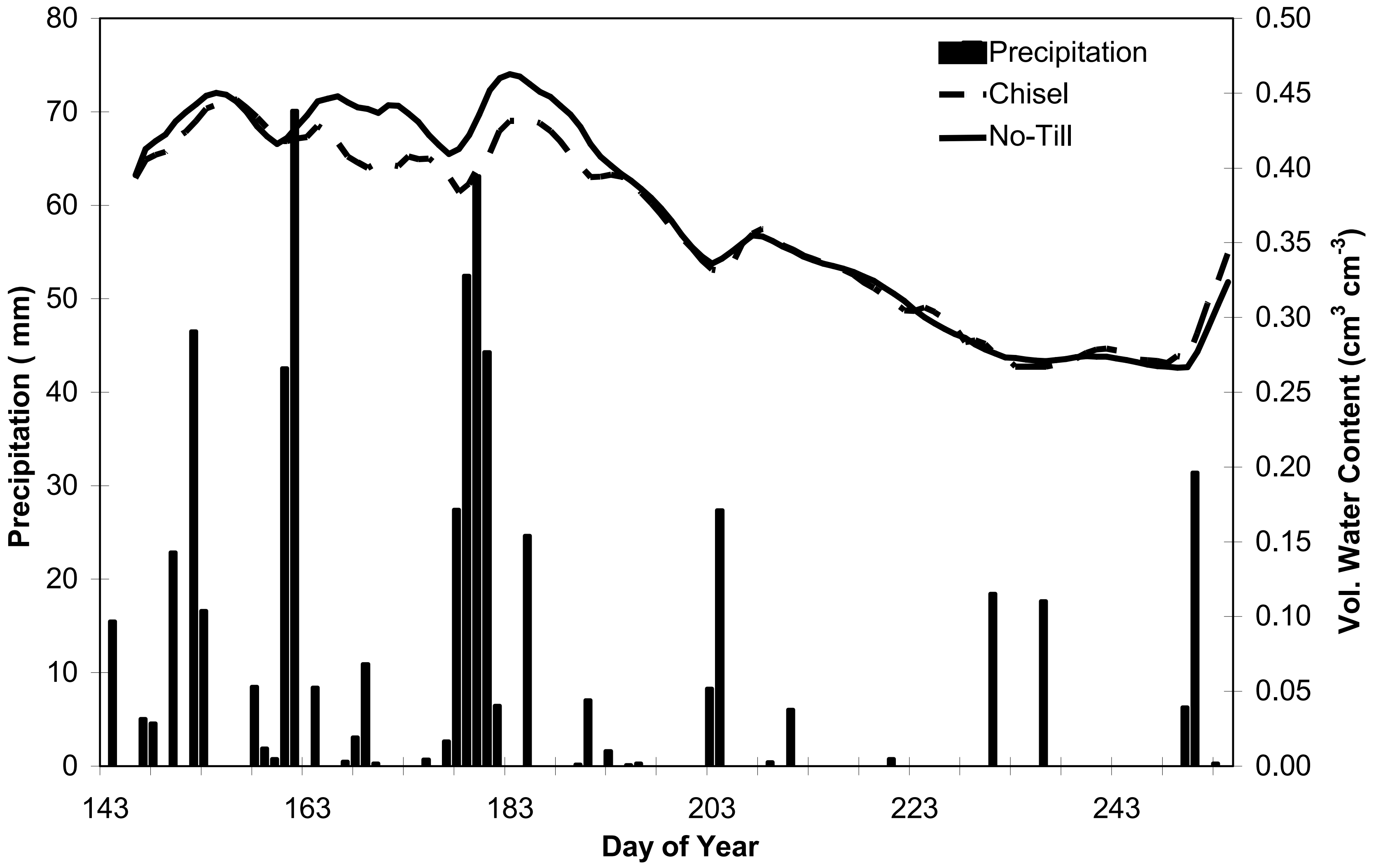


Figure 5.6 Precipitation and soil water content (20-cm depth, TDR data) during the 2007 growing season. Tillage did not cause a significant difference in water content over the entire season or on any particular days.

Analysis of Storm Events

To better understand the significant treatment by time interaction, the soil water content at the 10-cm depth following large precipitation events was analyzed to determine time to peak water content and total change in water content (Tables 5.3 - 5.4). Of the four events in 2006 (Table 5.3), there was one with a significant ($p = 0.07$) difference in time to peak water content (shorter for no-till) and another with a significant ($p = 0.09$) difference in amount of water content increase (greater for no-till). The two mid-June events had a general trend of no-till increasing in water content at a greater rate and with greater overall increase than chisel. The late June 2007 event (Table 5.4) matched the trend from 2006 where time to peak water content was shorter for no-till. The soil of the no-till treatment was probably able to take on greater amounts of water at a greater rate due a better developed macropore network than in the chisel treatment.

Events during wet soil conditions (early 2007 growing season) showed a smaller change in water content for the no-till treatment because the no-till had greater antecedent water content and reached complete saturation sooner than chisel. The two dates (30 May and 27 June 2007) with significantly ($p =$ 0.03 and 0.06, respectively) smaller changes in water content for no-till as compared with chisel were dates where there was sufficient precipitation to completely saturate the soil surface and no-till had less available space for infiltrating water. It is likely that the no-till plots experienced greater runoff than chisel on these two dates. Events later in the growing season (significant on 19 and 24 August 2007) showed the opposite trend, where time to peak water content was significantly shorter for the chisel treatment. At this point of the season, both treatments were drier than during the May and June events and the antecedent water content of chisel was less than no-till, so it likely had more surface cracks promoting rapid water infiltration to the 10-cm depth.

These findings support earlier results of a significant treatment by time interaction at the 10-cm depth. The interaction occurs because there is frequently one treatment taking on water faster so that the difference between treatments is not the same (parallel) at all times and because no-till takes on water faster in early season and chisel takes on water faster in the mid to late season.

Table 5.3 Storm events in 2006. Table shows amount of time between precipitation start and peak water content as well as total change in water content (10-cm depth, TDR data).

		Time to peak water cont.			Water cont. increase		
Day of precip.	Precip. total	Chisel	No-Till	p-value	Chisel	No-Till	p-value
	mm	----- h -----			---- cm^3cm^{-3}----		
6 June	35	9.0	9.3	0.999	0.07	0.07	0.786
17 June	26	21.5	17.5	0.066	0.06	0.08	0.271
14 July	27	21.7	12.0	0.972	0.05	0.09	0.087
25 Aug.	52	12.2	14.8	0.992	0.18	0.18	0.958
Overall Tillage Effect				0.342			0.373
Tillage * Time Interaction				0.422			0.142

Table 5.4 Storm events in 2007. Table shows amount of time between precipitation start and peak water content as well as total change in water content (10-cm depth, TDR data).

		Time to peak water cont.			Water cont. increase		
Day of precip.	Precip. total	Chisel	No-Till	p-value	Chisel	No-Till	p-value
	mm	----- h -----			---- cm^3cm^{-3} ----		
24 May	15	11.5	14.5	0.604	0.06	0.07	0.517
30 May	23	9.0	10.0	0.863	0.10	0.06	0.030
1 June	19	6.7	9.3	0.645	0.03	0.02	0.353
10 June	113	11.8	14.8	0.604	0.11	0.12	0.738
27-30 June	187	47.0	31.7	0.011	0.18	0.14	0.064
4 July	25	4.3	8.0	0.526	0.05	0.05	0.704
23 July	27	13.5	14.8	0.817	0.12	0.11	0.918
19 Aug.	18	25.3	35.3	0.089	0.03	0.05	0.417
24 Aug.	18	24.5	36.5	0.043	0.08	0.07	0.500
8 Sept.	31	10.7	13.0	0.686	0.20	0.19	0.670
Overall Tillage Effect				0.200			0.412
Tillage * Time Interaction				0.154			0.292

Whole Profile Water Content

Analysis of Treatment Effect

Pairwise comparisons of chisel versus no-till were possible for every depth, every date, and across all dates and/or depths of measurement to determine treatment effect on water content. There was no overall tillage treatment effect in either year (Table 5.5). Of all measurements, there was a significant effect in only one pairwise comparisons (Appendix D); the 19 June 2007 water content at the 15-cm depth was significantly greater for no-till as compared with chisel tillage. The behavior of soil water within the claypan seems to be driven by the high clay content, which resists changes in water content and restricts plant root growth thereby minimizing treatment effects.

Table 5.5 P values for fixed effects and interactions of profile water content data.

	2006	2007
	--------- p-values ----------	
Treatment	0.9073	0.4559
Time	< 0.0001	< 0.0001
Depth	< 0.0001	< 0.0001
Treatment*Time	0.1375	0.8564
Treatment*Depth	0.0935	0.0477
Time*Depth	< 0.0001	< 0.0001
3 way interaction	0.9979	1.0000

Analysis of Change Over Time

In the absence of treatment effects, all measurements from a particular date can be averaged to view changes over time (Figures 5.7 - 5.8). The depth at which significant changes in water content occurred was deeper in the dry 2006 growing season than in 2007. Within the claypan, the decrease in water content over time occurred primarily due to water uptake by plant roots (transpiration). The potential rate of water flux for this soil is small enough that water redistribution alone cannot account for the observed changes in water content. Water content nearer the soil surface (15-, 30-, and 45-cm depths) seemed to be influenced by precipitation and evaporation as well as transpiration. The late season rewetting of upper claypan soil indicates that water is able to move into the clay from the surface horizon. This downward movement is likely through macropores, root channels, and/or soil cracks that would not transport water upward under unsaturated conditions.

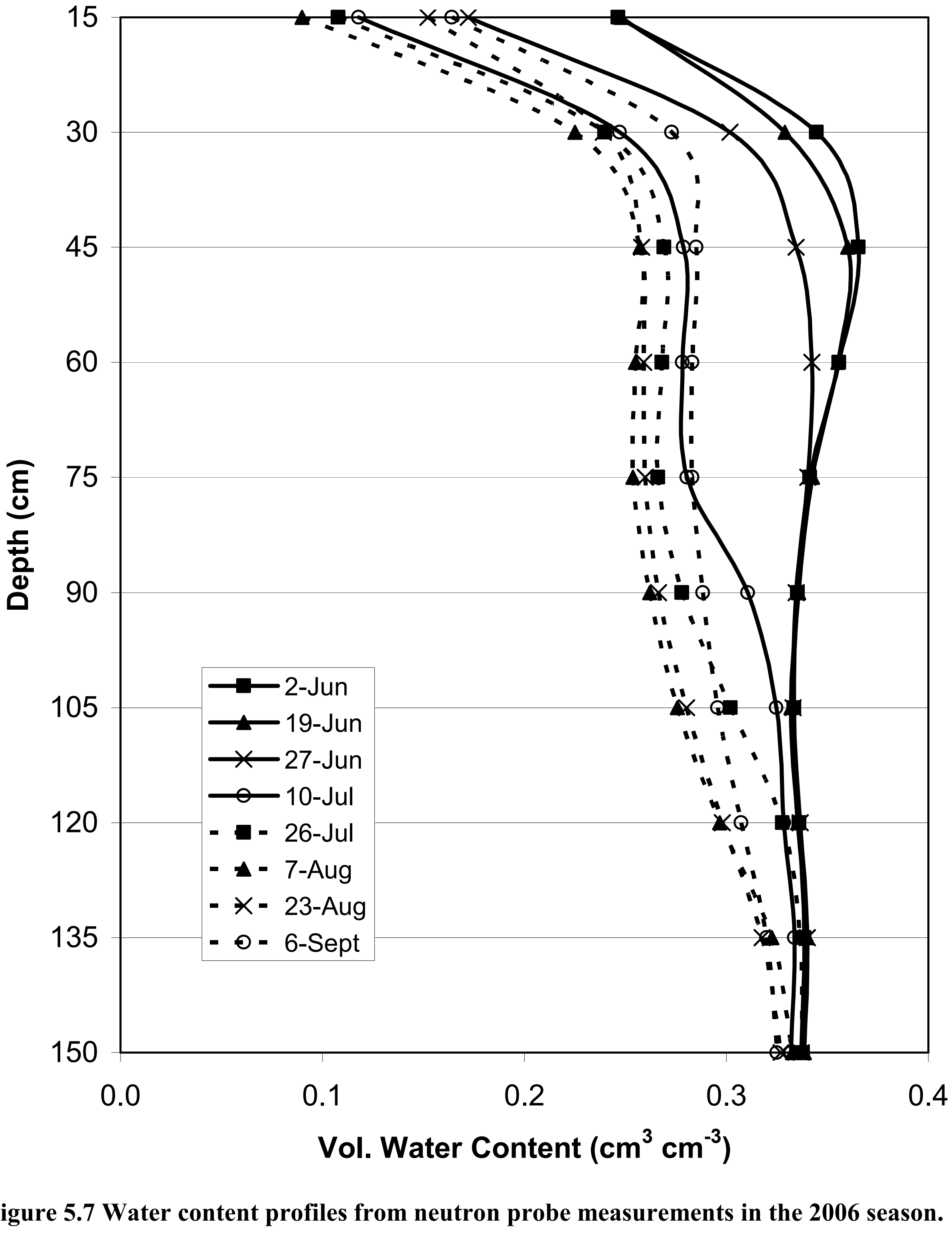


Figure 5.7 Water content profiles from neutron probe measurements in the 2006 season.

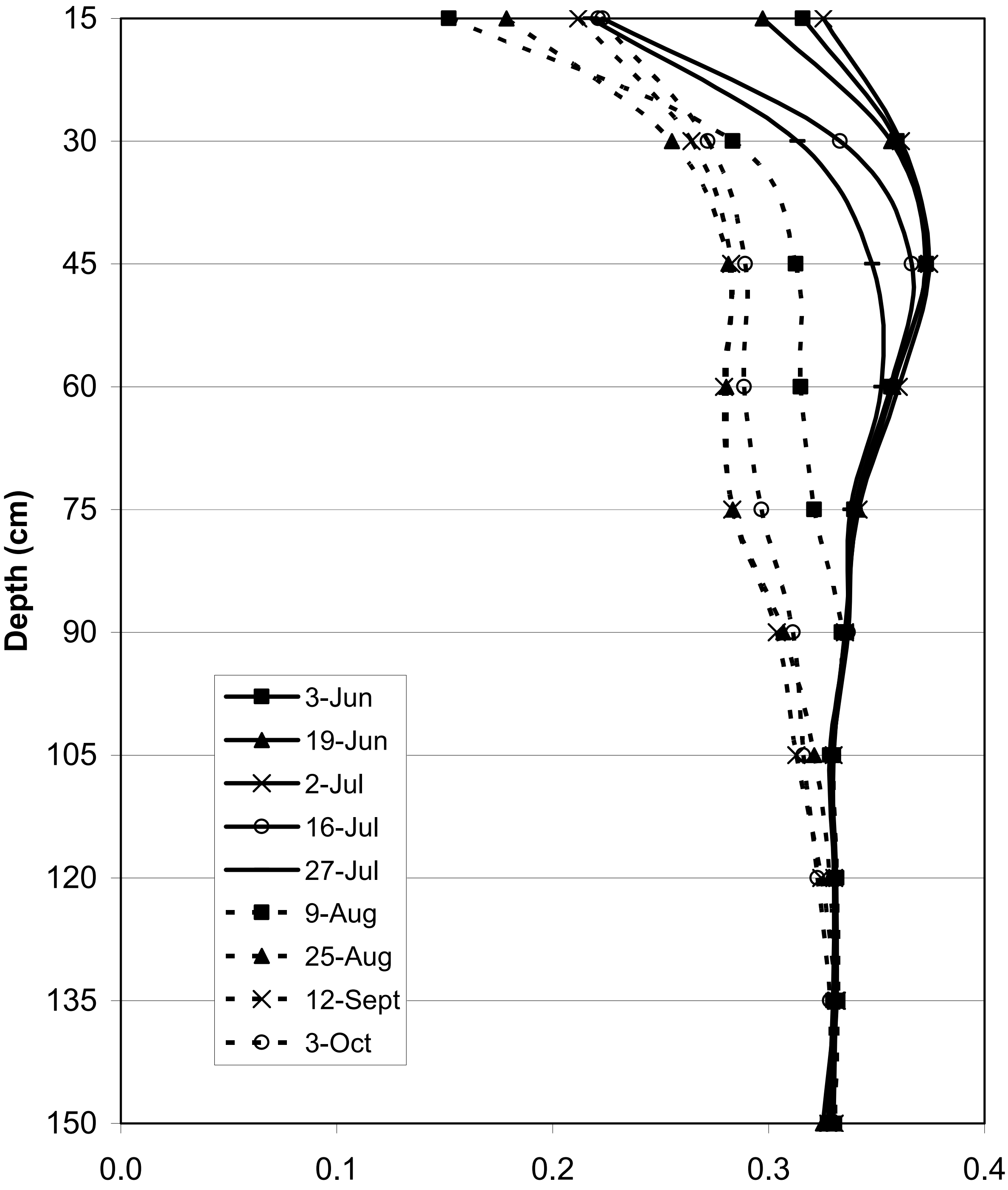


Figure 5.8 Water content profiles from neutron probe measurements in the 2007 season.

The date that the water content at a particular depth became significantly different from the season's first water content reading at that depth (Table 5.6 - 5.7) indicates when water was first withdrawn from that depth. This data allows us to estimate the root penetration patterns. The date of first withdrawal occurred at increasingly deeper depth as the season progressed, while water content at the deepest depths (150 cm in 2006; 105, 120, 135, and 150 cm in 2007) did not change during a growing season. The water content at the 150-cm depth remained constant throughout the 2-yr study despite both drought and flooding conditions at the soil surface. The water content at this depth (~0.33 cm^3 cm^{-3}) appears to be between the 33-kPa and 1.5-MPa water content predicted by NRCS water retention studies on similar soils (Soil Survey Staff, 2008) and between the water retention parameters for saturated and residual water content used in the HYDRUS 1-D Hydraulic Properties Catalog, adapted from Carsel and Parrish (1988), for a silty clay soil.

The study of water withdrawal also allowed determination of the amount of water that was extracted from the claypan. An examination of the withdrawal pattern by depth over time periods with no precipitation indicated that up to 20% of the water in the claypan was used during crop growth. During periods of particularly dry soil conditions, up to 90% of root water uptake came from the subsoil horizons.

Table 5.6 Date when water content became significantly different (p = 0.05) from 2 June 2006.

Depth	Chisel	No-Till
cm	------- date -------	
15	6/7	6/7
30	6/27	6/27
45	6/27	6/27
60	7/10	7/10
75	7/10	7/10
90*	7/10	7/26
105	7/26	7/26
120	8/7	8/7
135	8/7	8/7
150	never	never

* Indicates a depth with significant treatment by date interaction.

Table 5.7 Date when water content became significantly different (p = 0.05) from 26 May 2007.

Depth	Chisel	No-Till
cm	-------- date --------	
15*	6/3	7/2
30*	7/27	7/16
45	7/27	7/27
60	8/9	8/9
75*	8/9	8/25
90	8/25	8/25
105	never	never
120	never	never
135	never	never
150	never	never

* Indicates a depth with significant treatment by date interaction.

Deep Drainage

The water contents at the 135- and 150-cm depths were statistically equivalent to each other during the entire 2-yr study and averaged 0.33 cm^3 cm^{-3}. This finding allowed the assumption of a unit gradient condition where any drainage was equal to the unsaturated hydraulic conductivity, K(θ), which must be less than saturated hydraulic conductivity (K_s). As reported in Chapter 4, the maximum value of K_s in the claypan was measured at 0.4 cm d^{-1}. From this, K(θ) can be calculated with the van Genuchten (1980) function:

$$K(\theta) = K_s S_e^l [1 - (1 - S_e^{1/m})^m]^2 \quad [5.1]$$

where *l* is the pore connectivity parameter (typically estimated as 0.5), *m* is a shape parameter from the water retention curve, and S_e is effective saturation, calculated with:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad [5.2]$$

Parameters of $m = 0.08$, $\theta_r = 0.07$, and $\theta_s = 0.36$ are representative silty clay values, and were obtained from the Hydraulic Properties Catalog in HYDRUS 1-D (adapted from Carsel and Parrish, 1988). For a water content of $\theta = 0.33$ cm^3 cm^{-3}, evaluation of equation [5.1] yields K(θ) = 2.1×10^{-4} cm d^{-1}. For a unit gradient situation, the Darcy-Buckingham equation simplifies to:

$$q = |K(\theta)| \quad [5.3]$$

which results in a total flux of 2.3 x 10^{-2} cm when summed over a 108-d growing season. Therefore, drainage was assumed to be negligible in this water balance. This assumption is verified in Chapter 7.

Hydrologic Balance

This research project explores a number of ways of looking at the water balance including the distribution of each precipitation event, the quantity of water accounted for by each balance component over the growing season, and comparing water storage changes between each neutron reading date. This allows examination of both short and long term differences in the water balance and if there are differences in the water balance by time of year. Individual precipitation events were examined with surface water content (Table 5.3 - 5.4).

Seasonal Water Balance

The tillage treatments resulted in minimal significant differences in the various components of the seasonal water balance (Tables 5.8 - 5.9). Stored water in the soil profile and precipitation were measured in field. Drainage and evapotranspiration were calculated from field measured inputs. Runoff was calculated as the residual of the other water balance components. The hydrology of this soil appears to have been heavily influenced by the restrictive clay layer, so that tillage treatments had a small impact. There was no tillage treatment effect on either initial or final profile water storage. Though the near surface water content was different at times (primarily early season), tillage by time interactions erased any seasonal effect. Precipitation and drainage were assumed the same for each treatment. There was a significant difference in seasonal evapotranspiration and crop water use. This difference was driven by the early season effect where soil evaporation from chisel was greater than no-till by up to 1 mm d^{-1} (Figures 5.1 - 5.2) because of differences in ground cover. These differences in evapotranspiration caused some numerical separation in the residually determined runoff values but, interestingly, did not create a statistically significant difference in the runoff component of the water balance due to tillage treatment.

Table 5.8 Seasonal water balance for the 2006 growing season (11 May to 25 Aug.).

Treatment	Initial profile water	Precipitation	Drainage	ET	Runoff	Final profile water
	-------------------------------	-------------------------------	cm	-------------------------------	-------------------------------	
Chisel	50.6	16.9	0.0	24.2	3.2	40.1
No-till	52.0	16.9	0.0	23.1	6.1	39.7
p-value	0.373	NA	NA	0.003	0.406	0.826

Table 5.9 Seasonal water balance for the 2007 growing season (11 May to 17 Sept.).

Treatment	Initial profile water	Precipitation	Drainage	ET	Runoff	Final profile water
	-------------------------------	-------------------------------	cm	-------------------------------	-------------------------------	
Chisel	50.6	63.6	0.0	35.2	35.8	43.2
No-till	52.0	63.6	0.0	31.9	39.2	44.5
p-value	0.373	NA	NA	0.004	0.121	0.620

The difference in the seasonal water balance between the two crop years demonstrates the influence of weather conditions. The 2007 growing season had much greater precipitation. As this clay soil has limited storage and no drainage, that excess precipitation was forced to become runoff. The evapotranspiration was greater in 2007 than in 2006 because of the longer growing season and increased available moisture. The increased precipitation of 2007 came early enough that storage till peak plant water use was not an option and crop water use could not make up enough of the difference in precipitation to reduce runoff volume. The change in soil water storage (Initial profile water – Final profile water) was greater during the drier 2006 crop year (10.5 cm for chisel, 12.3 cm for no-till) than in 2007 (7.4 cm for chisel, 7.5 cm for no-till). However, the 2006 water balance ended during a dry summer month (August) while the 2007 growing season extended into September. Fall precipitation was shown to increase profile water in both growing seasons (Figures 5.7 - 5.8).

Water Balance Component Changes Over Time

The water balance was broken down over time to analyze treatment effects on change in water content, evapotranspiration, and runoff for shorter time periods (Table 5.10 - 5.11). The time periods of analysis were determined by dates of neutron probe reading. Depth of water in the 150-cm soil profile was determined for each date of measurement. Subtracting the previous measurement from the current showed the change in water storage for that time period. A similar procedure was followed to determine change in water storage for just the 20-cm surface layer; depth of water was determined from the 10- and 20-cm depth TDR measurements. Daily evapotranspiration was summed for each time period with runoff calculated as the residual of precipitation, evapotranspiration, and change in water storage for the whole profile.

There was not a significant tillage effect for change in water storage of either the whole profile or the surface layer when viewing the sum of all biweekly events for both growing seasons (Tables 5.10 - 5.11). However, there were tillage effects at the beginning of both growing seasons. In 2006, the whole profile experienced a greater increase in water storage for no-till as compared to chisel during the first time period. There was no difference for the surface layer. This effect was likely caused by water moving through the surface into the subsurface via macropores only found in the no-till treatment. Also, the soil under chisel tillage experienced greater evaporative losses during this time period, so precipitation would not have increased stored water content as much as in no-till. During the rest of the 2006 season there were no tillage effects for change in water storage, evapotranspiration, or runoff.

In 2007, the change in water storage for the early growing season was of greater magnitude for the chisel tillage treatment in both the surface layer and whole profile as compared to no-till. In the first time period, both treatments increased in water storage, with the soil under chisel tillage gaining more water. In the second time period, chisel soil decreased in stored water while the no-till soil experienced little change. Evaporative losses were greater for the chiseled soil in both time periods. The results for the second time period were as expected. Since chisel had greater evaporation, it also had a greater decrease in stored water. The third time period (ending July 2) also showed a significant treatment effect of greater increase in surface layer water storage for the chisel tillage treatment. At first glance, the results for the first and third time periods seem counterintuitive, but this is similar to what was seen in the storm basis analysis of Table 5.4; because the no-till was already near saturation, it had reduced capacity for increasing water storage during precipitation. Much of the precipitation that fell during these time periods became runoff. A significant difference was seen in runoff results for these time periods, with no-till having greater runoff than chisel. During the remainder of the 2007 season there were no tillage effects for change in water storage, evapotranspiration, or runoff.

Residually determined runoff seems to work on the scale of an entire growing season (Tables 5.8 - 5.9), but was not as useful when examining treatment effects over time (Tables 5.10 - 5.11). The most obvious example of the method failing occurred during the time period ending 7 Aug. 2006. There was no precipitation during this time period, yet calculations indicate 16 to 19 mm of runoff. There were also a few time periods for which the residually calculated runoff resulted in a negative value. Most of the dates of suspect runoff determinations occur during the dry portions of the growing season. The reason for the faulty determinations of runoff may have been that the FAO-56 calculations were not sufficiently capturing evapotranspiration during the dry time periods, or there may be other aspects of the water balance that we do not understand. For example, there may be a time lag in the change of certain balance components as compared to other balance components, such as the amount of time it takes for subsurface runoff to move offsite, or the amount of evaporation required before water contents fall below saturation in extremely wet or ponded conditions.

Additional analysis of the individual water balance components was conducted to determine if the water inputs during each time period could be accounted for with water losses such as evapotranspiration and runoff (Tables 5.12 - 5.13). For each time period, the inputs were calculated by summing the precipitation and change in water storage values given in Tables 5.10 and 5.11. For a given time period, if the amount of water stored in the profile decreased, then the inputs were larger than the amount of precipitation received during that time period. Evapotranspiration during each time period was the same as presented in Tables 5.10 and 5.11. Rather than determine runoff as the residual of each biweekly water balance, it was determined from the amount precipitation received in excess of water storage capacity for the surface soil layer. The available storage capacity of the surface layer was calculated as the difference between the depth of water in the surface layer at the time a precipitation event begins and the depth of water the 20-cm deep surface layer can store at saturation (90 mm). By assuming that water will not evaporate or move into the clay subsoil during a precipitation event, runoff can be predicted as the depth of precipitation exceeding the depth of available storage. This method allows us to compare the sum of evapotranspiration and runoff to the sum of precipitation and change in storage for each time period while residually determined runoff would not. Statistically, the water input for either the whole profile or just the surface layer was compared with the sum of evapotranspiration and predicted runoff as water outputs.

The water inputs and outputs were in agreement overall for the 2006 growing season with a difference between inputs and outputs occurring for the whole profile in four of the nine time periods (outputs were overpredicted on 10 July and underpredicted on 19 June, 7 Aug. and 23 Aug). Agreement between water inputs and outputs was poorer for the 2007 growing season where a difference between inputs and outputs for the whole profile occurs in five of the nine time periods (outputs were over predicted on 3 June, 16 July, 27 July, and 9 Aug. and underpredicted on 25 Aug.). The poor agreement between inputs and outputs during the high precipitation growing season of 2007 was likely due to inaccuracies in the method for predicting runoff from available water storage capacity. The method does not consider rate of precipitation.

For both 2006 and 2007, agreement between surface water inputs and total profile water inputs were good in the early season (time periods prior to mid-June in 2006 and prior to mid-July in 2007) when all activity for the water balance was occurring in the surface soil. During this period, water input was frequently larger than calculated evapotranspiration, but similar to the sum of evapotranspiration and estimated runoff, providing evidence that runoff did occur at this site. In 2006, the first time period showed no difference between inputs and outputs for chisel (Table 5.12), but a difference in no-till, where inputs were smaller than predicted outputs because little change in water storage occurred as discussed above. In 2007, it was more common for the inputs and outputs to be different in the early season. This was likely because of the large quantity of precipitation and difficulty in predicting runoff.

Comparisons during the mid season show the input of water to the surface to be smaller than that of the whole profile. This indicates a period of water use (root extraction) from the subsoil. During the late July time period of both years, the whole profile water inputs match up well with evapotranspiration losses. It is reasonable to assume that little runoff or drainage occurred during this period. However, during the dry August month, the differences between inputs and outputs are significant. This was attributed to difficulty in calculating evapotranspiration during drought periods.

Agreement between water inputs and outputs was best in the latter portion of the growing season. However, during the time periods ending on 6 Sept. 2006 and 3 Oct. 2007, the input of water to the surface was greater than that to the entire profile (indicating that the increase in stored water was smaller in the surface layer than in the whole profile) and both exhibit a poor relationship to water outputs. This seems to indicate that water was moving from the surface into the subsurface during these time periods. Previous drainage calculations have shown that there is no water moving out the bottom of the profile during any time periods. However, water could move into the upper part of the subsoil via cracks formed during the driest part of the year.

Table 5.10 Component water balance over time for 2006. Start date was 2 June.

			Change in Water Storage			
End date	Treatment	Precip.	Whole Profile	Surface Layer	ET	Residual Runoff
			mm			
7 June	Chisel	35.6	0.8	4.7	6.4	28.4
	No-Till		9.2	6.1	5.3	21.6
	p-value		0.065	0.531	0.020	0.100
19 June	Chisel	28.6	-8.6	-8.8	22.1	15.1
	No-Till		-6.6	-8.6	20.9	14.3
	p-value		0.658	0.950	0.017	0.860
27 June	Chisel	0.0	-21.7	-15.7	21.6	0.2
	No-Till		-21.5	-18.8	21.8	-0.3
	p-value		0.951	0.097	0.721	0.918
10 July	Chisel	0.0	-40.0	-10.7	54.2	-14.3
	No-Till		-46.2	-8.5	54.1	-7.8
	p-value		0.257	0.236	0.746	0.226
26 July	Chisel	55.4	-17.6	0.3	74.9	-2.3
	No-Till		-25.9	-1.0	75.5	5.9
	p-value		0.129	0.513	0.203	0.126
7 Aug.	Chisel	0.0	-22.8	-1.0	6.6	16.2
	No-Till		-26.0	-1.0	7.0	19.0
	p-value		0.474	0.986	0.388	0.522
23 Aug.	Chisel	42.8	14.2	2.5	15.3	13.4
	No-Till		11.8	3.8	15.1	15.9
	p-value		0.596	0.479	0.757	0.561
6 Sept.	Chisel	52.2	23.5	14.1	25.3	3.5
	No-Till		26.6	15.1	25.6	0.0
	p-value		0.478	0.584	0.488	0.420
25 Sept.	Chisel	15.0	-10.5	-11.2	22.8	2.7
	No-Till		-15.3	-9.4	22.7	7.6
	p-value		0.340	0.339	0.752	0.312
Overall Tillage Effect			0.436	0.636	<.0001	0.352
Tillage * Time Interaction			0.323	0.129	<.0001	0.367

Change in water storage determined as current depth of water minus previous.
(ET) Evapotranspiration calculated following FAO-56 method.
Residual runoff is difference of other balance components.

Table 5.11 Component water balance over time for 2007. Start date was 26 May.

			Change in Water Storage			
End date	Treatment	Precip.	Whole Profile	Surface Layer	ET	Residual Runoff
		----------------------------------	mm	----------------------------------		
3 June	Chisel	95.6	10.0	18.0	27.4	58.2
	No-Till		3.0	11.0	18.9	73.7
	p-value		0.042	0.054	<.0001	<.0001
19 June	Chisel	146.7	-6.2	-10.3	42.2	110.7
	No-Till		0.4	-2.9	29.8	116.5
	p-value		0.055	0.041	<.0001	0.089
2 July	Chisel	197.4	8.9	10.0	23.4	165.1
	No-Till		3.4	2.5	23.2	170.8
	p-value		0.108	0.040	0.635	0.094
16 July	Chisel	33.8	-22.3	-29.9	58.0	-1.9
	No-Till		-19.7	-26.5	58.4	-4.9
	p-value		0.443	0.341	0.407	0.376
27 July	Chisel	35.6	-7.5	0.5	42.2	0.9
	No-Till		-7.8	-0.5	42.2	1.2
	p-value		0.914	0.781	0.922	0.925
9 Aug.	Chisel	7.2	-26.4	-13.6	51.3	-17.7
	No-Till		-29.2	-13.0	51.8	-15.4
	p-value		0.405	0.869	0.259	0.501
25 Aug.	Chisel	36.1	-20.7	4.7	34.3	22.5
	No-Till		-23.0	2.5	35.1	24.0
	p-value		0.509	0.541	0.098	0.673
12 Sept.	Chisel	37.9	3.0	10.8	20.4	14.4
	No-Till		5.3	11.2	21.1	11.5
	p-value		0.506	0.902	0.151	0.383
3 Oct.	Chisel	43.9	7.5	-2.0	31.0	5.5
	No-Till		7.7	0.0	32.0	4.2
	p-value		0.937	0.566	0.036	0.697
Overall Tillage Effect			0.983	0.826	0.004	0.068
Tillage * Time Interaction			0.071	0.069	<.0001	0.008

Change in water storage determined as current depth of water minus previous.
(ET) Evapotranspiration calculated following FAO-56 method.
Residual runoff is difference of other balance components.

Table 5.12 Comparison of water balance inputs and outputs for 2006. Start date was 2 June.

		Water Inputs		Water Outputs		P-value	
End date	Treatment	Whole Profile	Surface Layer	ET	Predicted Runoff	Whole Profile	Surface Layer
		mm					
7 June	Chisel	34.8	32.5	6.4	28.2	0.9428	0.1723
	No-Till	26.4	29.8	5.4	30.2	0.0122	0.0289
19 June	Chisel	37.2	36.9	22.1	0.0	<.0001	<.0001
	No-Till	35.2	37.6	20.9	0.0	0.0003	<.0001
27 June	Chisel	21.7	14.8	21.6	0.0	0.8881	0.0613
	No-Till	21.5	18.8	21.8	0.0	0.9143	0.0867
10 July	Chisel	40.0	10.7	54.2	0.0	0.0087	<.0001
	No-Till	46.2	8.5	54.0	0.0	0.0028	<.0001
26 July	Chisel	78.0	55.1	74.9	0.0	0.1966	<.0001
	No-Till	79.3	56.9	75.5	0.0	0.2154	<.0001
7 Aug.	Chisel	22.8	1.0	6.6	0.0	<.0001	0.0220
	No-Till	26.0	1.7	7.0	0.0	<.0001	0.0164
23 Aug.	Chisel	28.6	40.3	15.3	0.0	0.0003	<.0001
	No-Till	30.9	37.6	15.1	0.0	<.0001	<.0001
6 Sept.	Chisel	28.7	38.0	25.2	5.3	0.0490	0.2278
	No-Till	25.5	37.0	25.6	12.1	0.0528	0.0002
25 Sept.	Chisel	25.5	26.2	22.8	0.0	0.2986	0.1708
	No-Till	28.4	24.4	22.7	0.0	0.1580	0.4679

Water inputs determined from precipitation minus change in water storage.
(ET) Evapotranspiration calculated following FAO-56 method.
Predicted runoff estimated from available water storage capacity of surface layer at time of precipitation event.
P-value compares water input for either whole profile of surface layer to the sum of water outputs (evapotranspiration and runoff).

Table 5.13 Comparison of water balance inputs and outputs for 2007. Start date was 26 May.

		Water Inputs		Water Outputs		P-value	
End date	Treatment	Whole Profile	Surface Layer	ET	Predicted Runoff	Whole Profile	Surface Layer
		-------------------------------- mm --------------------------------					
3 June	Chisel	85.5	77.8	27.4	79.0	0.0023	<.0001
	No-Till	92.7	84.8	18.9	84.6	0.1052	0.0043
19 June	Chisel	151.8	156.7	42.2	97.4	0.0302	0.0021
	No-Till	146.3	149.9	29.8	120.6	0.4299	0.5641
2 July	Chisel	189.8	188.8	23.4	159.9	0.8791	0.5516
	No-Till	194.0	194.3	23.2	183.1	0.3627	0.5814
16 July	Chisel	61.3	60.4	58.0	20.9	0.0005	0.0198
	No-Till	59.0	60.3	58.4	22.5	0.0002	0.0018
27 July	Chisel	37.8	35.2	42.2	5.2	0.8402	0.3581
	No-Till	38.0	36.1	42.2	4.5	0.1771	0.0100
9 Aug.	Chisel	33.4	20.8	51.3	0.0	0.0196	<.0001
	No-Till	36.4	20.2	51.3	0.0	0.0102	<.0001
25 Aug.	Chisel	56.9	31.4	34.3	0.0	0.0004	0.6036
	No-Till	59.0	33.6	35.1	0.0	0.0014	0.8592
12 Sept.	Chisel	35.0	27.2	20.4	10.8	0.2477	0.8715
	No-Till	32.7	26.7	21.1	8.4	0.8842	0.2173
3 Oct.	Chisel	36.6	45.9	31.0	1.9	0.8520	0.0529
	No-Till	36.2	43.9	32.0	0.3	0.3387	0.0606

Water inputs determined from precipitation minus change in water storage.
(ET) Evapotranspiration calculated following FAO-56 method.
Predicted runoff estimated from available water storage capacity of surface layer at time of precipitation event.
P-value compares water input for either whole profile of surface layer to the sum of water outputs (evapotranspiration and runoff).

A graphical analysis of the above allocations of water loss from the surface gives a better view of changes in water use over the 2007 growing season (Figure 5.9). Early in the season (wettest time of year) surface water losses were accounted for with both evapotranspiration and runoff. The particularly wet spring of 2007 had above average runoff. In mid-season, during the period of active plant growth, evapotranspiration accounted for nearly all of the water loss from the surface layer. After the sorghum crop began to senesce (late season), the contribution of evapotranspiration was reduced while contributions of runoff and redistribution within the soil profile were increased. This redistribution represents water able to move through the surface soil and into upper layers of the subsoil, probably through cracks and macropores.

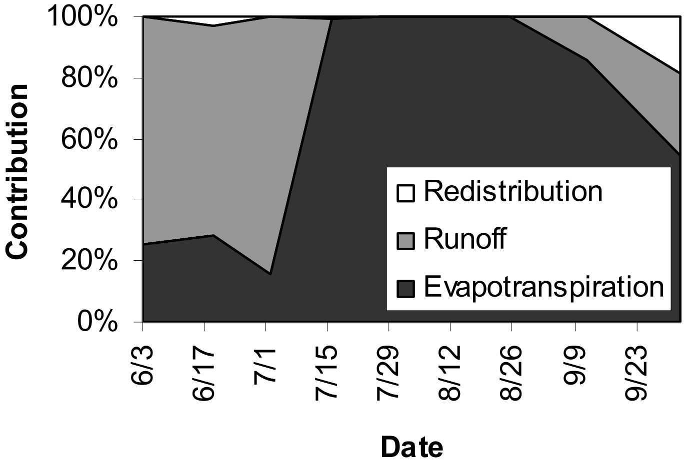


Figure 5.9 Allocation of surface water losses in 2007. Figure shows contribution of water that can be accounted for by runoff, evapotranspiration, or redistribution to subsoil in each time period. The tillage treatments were averaged since tillage did not significantly affect water allocation for most of the year.

Runoff

Total runoff was taken as the residual of the other measured water balance components and totaled 32 and 61 mm in 2006 and 358 and 392 mm in 2007 for chisel and no-till, respectively (Tables 5.8 - 5.9). There was not a significant treatment effect on runoff at the seasonal scale. Visual evidence of surface runoff was observed following precipitation events on 6 June 2006 and on 2, 11, and 30 June 2007. Surface runoff from a particular precipitation event was estimated from the amount of precipitation that exceeded the water storage capacity of the surface horizon (Tables 5.12 - 5.13). Using this method, the total surface runoff losses for chisel and no-till treatments were estimated at 34 and 42 mm in 2006, and 375 and 424 mm in 2007, respectively (Tables 5.12 - 5.13). These values are comparable to the residually determined runoff but are more likely to have error as they do not consider evapotranspiration, drainage, or changes in water content that may occur during the storm or the rate at which precipitation occurred.

In general, studies on the effect of tillage on surface runoff volume have had varied results with conventional-, conservation-, and no-tillage practices each being reported as having the least runoff in certain settings. Studies using claypan soils have reported increased runoff volume from no-till practices (Ghidey and Alberts, 1998). Our work agrees with that and suggests that differences in early season water content created by differences in evaporation rate and water holding capacity are the driving factor for treatment effects on runoff volume. The greater early season bulk density in no-till may also contribute to reduced water intake.

In addition to quantifying the amount of precipitation that became runoff, this study was also interested in determining the potential for subsurface runoff. Measurements with pressure transducers in shallow monitoring wells during the 2007 growing season looked for the presence and depth of saturated soil conditions (Table 5.14). Data indicate that precipitation events greater than 10 mm could result in positive pressure in the wells during wet soil conditions, events greater than 20 mm had some water during dry soil conditions, and near full saturation of surface layer was seen in events greater than 45 mm. There were no events where the measured water level was greater than the well depth. Such a condition would indicate complete saturation of soil and surface ponding. This result is interesting because there were frequently surface runoff events concurrent with the perched water events. The wells were placed around the entire site rather than measure perched water depth in any particular plot or attempt to make treatment comparisons.

Table 5.14 Perched water events during the 2007 growing season. Maximum depth of water during each event is reported for the six wells. The observation well in the northwest corner of plot (NW) was 28.4 cm deep while, NC was 26.0, NE was 22.0, SW was 20.5, SC was 20.0, and SE was 24.5. Well locations are shown in Appendix E.

		Peak Water Level					
Date	Precip.	NW	NC	NE	SW	SC	SE
	mm	cm					
4 Apr.	53	25.4	21.1	ND†	17.4	17.0	ND
1 May	43	25.2	19.8	9.6	16.5	17.3	21.6
3 May*	21	26.5	21.3	11.4	17.3	16.9	20.0
7 May	74	25.1	21.7	11.2	17.5	18.1	21.0
30 May	23	24.2	0	6.8	16.2	17.1	15.5
1 June	46	24.5	17.2	18.5	17.1	17.5	19.6
2 June*	17	25.2	20.7	20.7	17.4	16.8	23.1
11 June	113	24.3	7.9	10.5	15.9	18.8	21.1
13 June	8	22.1	0	0	10.9	15.6	17.9
18 June	11	2.5	0	0	0	3.7	12.8
1 July	194	25.4	21.3	21.7	17.8	17.5	22.5
4 July	25	21.0	10.1	1.3	1.4	11.8	17.5

† - No data available

Asterisks indicate dates on which observation wells had not yet completely emptied from previous event.

Peak pressure head during storm events generally occurred 2 to 10 h after precipitation began (sample data in Figure 5.10). Typically, the pressure head registered in wells increased from zero to values between 17 and 24 cm in 1 to 2 h, and then decreased slowly over the next 24 to 72 h. Model verification of perched water is discussed in Chapter 7. Graphical representations of depth and duration of positive pressure conditions in observation wells can be seen in Appendix E.

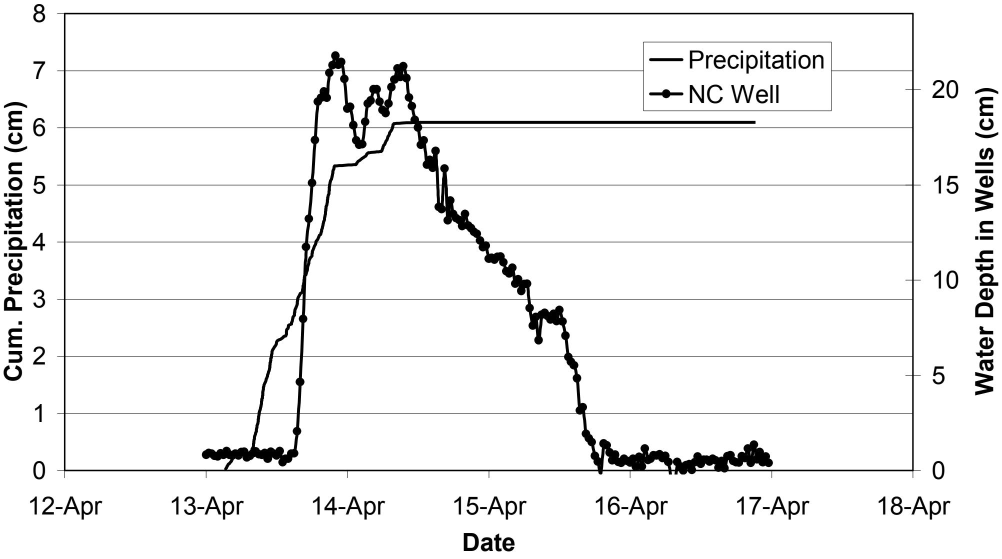


Figure 5.10 Depth and duration of saturated conditions near the north central (NC) monitoring well during the 53 mm precipitation event on 13 Apr. 2007.

The amount of precipitation that became laterally moving water over an entire growing season was difficult to quantify because much of the water that moved laterally later become evapotranspiration or vertical redistribution to subsoil. Perhaps it is best to conclude that lateral flow does exist in significant volumes but is not a key contributor to the vertical water balance. The observation well results did not show longer periods of saturation in downslope positions or other indicators that water was moving off site in large volumes. The assumption was that the quantity of lateral movement from a location is matched by lateral movement to the location, maintaining mass balance.

Wilkinson and Blevins' (1999) work on claypan soil showed that, while water perched above the clay during large precipitation events, the water soon moved into the clay via macropores. They also used tracers to determine direction of water movement and concluded that, while lateral flow did occur, it was negligible compared to downward movement. The effect of tillage on lateral flow is somewhat dependent on depth to restrictive layer and other water balance components. Bosch et al. (2005) showed conventional tillage to have less subsurface runoff than a reduced tillage system; however, the conventional tillage had greater surface runoff thereby reducing the amount of water entering the soil to potentially become lateral flow. Our study did not examine the effect of tillage on perched water levels but rather aimed to quantify the influence of lateral water movement on a hydrologic balance finding that while lateral flow does occur, it may not be a major contributor to the overall vertical water balance. However, the laterally moving water can have significant impacts on nutrient transformations and transport in crop fields (Garg et al., 2005). Estimates of potential treatment effects on perched water are difficult to make but as the no-till treatment generally had greater water content during wet soil conditions, it may experience a shorter time to perched water.

Summary and Conclusions

This examination of water balance components resulted in interesting findings of whether each component varied with time and/or tillage treatment. The amount of precipitation received was quite different between the two crop years with 2007 being the wetter year. Despite these differences, the following summary of water balance findings is applicable to both growing seasons.

Evaporation was the balance component most influenced by tillage treatment. Microlysimetry measurements and FAO-56 calculations both indicated greater rates of evaporation for chisel tillage early in the growing season. As the season progressed, both tillage treatments were equally shaded from direct sunlight by the growing crop and transpiration became the dominant process in the evapotranspiration component. For these reasons, little difference in evapotranspiration was seen between tillage treatments in mid and late season. The greater evaporation in chisel was directly related to the decreased residue cover of the chisel treatment.

The amount of water stored in the soil surface (10-cm depth) was greater for no-till, though only significantly so in the early 2007 season. This tillage effect was driven both by the greater evaporative loss in chisel and the greater water retention near saturation for no-till (Chapter 4). The near-surface water storage was affected by a tillage by time interaction and was not significantly different over the entire growing season in either year. Closer examination of time to peak water content and total change in water content following large precipitation events revealed that no-till generally increased in water content at a greater rate and, when storage capacity allowed, had a greater total change in water content. There were dates where precipitation caused both treatments to reach saturation and no-till generally did so faster than chisel. Treatment effects on water content at the 20-cm depth were difficult to interpret due to confounding issues with depth to increasing clay content.

Though the near-surface water contents exhibited interesting phenomena, there was no tillage effect on the amount of water stored in the whole profile. Tillage frequently has little effect on hydraulic properties within the subsoil. There were water content changes over time to a depth of 120 cm in 2006 and a depth of 90 cm in 2007 due to precipitation, evaporation, and water extraction by plant roots. Water content was affected by root extraction at greater depths than anticipated, suggesting that roots must have penetrated the clay subsoil, possibly through cracks, earthworm channels, or old root paths. Withdrawal patterns indicate that up to 20% of the water stored in the clay subsoil was used by crops during periods of high soil water content and low precipitation. Late season precipitation also had a greater than expected influence on water content in the clay subsoil. This rewetting likely occurred through cracks that developed during dry August conditions of each year. Though water entered the upper part of the clay subsoil, it was accounted for as increased water storage. There appears to be minimal water redistribution to the lower depths of the clay subsoil and drainage from the profile was assumed to be negligible.

As there were no differences between tillage treatments in profile water storage throughout the entire growing season, the full water balance at the scale of an entire growing season also had few tillage effects. The only difference was cumulative evapotranspiration and it appeared to be driven by the early season differences in evaporation. In the early season, when evaporation created a difference in the near-surface water storage, there was also greater residually determined runoff for the wetter no-till treatment. When runoff was accumulated over an entire growing season, the treatment effect became insignificant.

The residually determined runoff appeared valid over an entire growing season but inaccurate when used over shorter time periods (~ 2 wk). The primary explanation is that FAO-56 calculated evapotranspiration values were also inaccurate during these time frames. The largest discrepancies seem to occur during the time periods with the least precipitation. Though others have reported that the FAO-56 method overestimates evapotranspiration (Allen et al., 2005; Howell et al., 2004), this work indicates underestimation during dry conditions. Another method of estimating runoff from precipitation and available soil-water storage capacity was introduced that reduced the likelihood of predicting excessive runoff during dry conditions. The cumulative values from this method agreed with residually determined runoff values for the entire growing season.

This study showed that a perched water table develops above the claypan during large precipitation events, creating the potential for lateral water movement (subsurface runoff). However, the contribution of lateral water movement to the vertical water balance was difficult to determine as a horizontal mass balance of perched water was maintained and much of the vertical loss of water was accounted for as evapotranspiration or redistribution throughout the profile.

The study of the whole season water balance resulted in few differences between tillage treatments. Most of the differences found in this study occur in the early season and future work should place greater emphasis on that portion of the growing season. These early season differences seem to be driven by differences in residue cover though there are some tillage effects on soil physical properties such as bulk density and water retention. Steiner et al. (1989) examined the effect of tillage and residue on soil evaporation and found that residue cover had a greater impact than tillage. In that study the chisel tillage had greater evaporation than no-till; however, when residue was removed there were no significant differences between no-till and chisel. This is an important consideration as we look for broader implications of the work. A crop that produces less residue, such as soybean, may not have as great of differences between tillage treatments as found here. Also, these findings could be presented during consideration for use of biomass for secondary income from crop fields.

By mid season, the crop canopy has closed and precipitation has reconsolidated tilled soil. At this time, the difference between treatments becomes minimal. A better understanding of tillage differences and the influence of residue cover would come from refocusing this study on the early part of the season. Our work before crop planting was limited to evaporation measurements and estimation of evapotranspiration. As these proved significant, it would be useful to know if there are differences in soil water content at this time as well. The experimental design did not allow for water monitoring equipment in the field before planting without increased manual labor.

In addition to refocusing on early season, future work should also include efforts to quantify subsurface runoff and partition the total runoff into surface and subsurface components. Management can be used to reduce water losses to surface runoff, but if this shallow to clay soil has greater subsurface runoff there may be little that management can do. As water scarcity and flooding became more prevalent issues, keeping water in crop fields is more desirable. Though the southeast Kansas claypan soils have more issues from too much water than from not enough, they can still be managed for flood mitigation.

Overall, the high clay content and depth to clay were the driving factors of this soil water balance. There was little difference between tillage treatments indicating equal results with either management method. Other factors, such as economics, should have greater influence on crop management decisions than available water.

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CHAPTER 6 - Plant Results

Crop variables including emergence, biomass, and yield were sampled from the sorghum plots where the water balance study was carried out. Objectives of this portion of the analysis were to determine differences between tillage treatments and quantify any relationship between the crop variables and soil water status.

Ground Cover

Percent residue cover was measured on 12 May 2007 and 26 May 2007. The first date was after the majority of spring precipitation while the second date was after planting. Residue cover was not determined in 2006. There was minimal variability in residue cover between replicates. On the first date, no-till averaged 95% ground cover as compared to 37% cover on the chisel treatments. After planting, cover was reduced to 88 and 23%, respectively. Results from 12 May 2007 were used in the FAO-56 evapotranspiration calculations to determine early season evaporation for both growing seasons.

Emergence and Stand

Stand counts were taken regularly after planting (19 May 2006, 21 May 2007) in order to determine differences in emergence by tillage (Figures 6.1 - 6.2). In both growing seasons, the sorghum emerged and tillered 1 d earlier in chisel treatments as compared with no-till. However, the stand values after both treatments had emerged and after both treatments had tillered (data not shown) were not significantly different, indicating that sorghum grown in no-till was able to develop as strong a stand as that grown in chiseled ground. The significant differences ($p = 0.10$) between stand seen 4 and 19 d after planting in 2006 and 29 d after planting in 2007 represent the dates where chisel emerged or tillered the day before no-till. The initial emergence effect was likely not seen in 2007 because travel and weather limited days that counts were performed. All other count dates showed no difference between treatments. Emergence and tillering were delayed in the cooler, wetter 2007 crop season as compared to 2006. Both crop years had similar final stands though further cropping analysis indicated not all tillers were effective. Because sorghum has great ability to tiller and compensate for reduced stands, little work has been done on emergence or stand and minimal tillage effect on final stand was expected. Norwood et al. (1990) did report a reduced sorghum stand in an exposed soil that had become crusted by precipitation between planting and emergence as compared with a treatment having greater residue cover. Other workers have reported reduced stands in corn (TeKrony et al., 1989) and soybean (Helms et al., 1996; Mündel, 1986) grown in no-till because of cooler, wetter conditions as compared with chisel tillage systems. Chen et al. (2004) reported greater emergence in no-till as compared with five other tillage methods for canola and canary grass in a climate that receives little precipitation around planting.

Correlation analysis was performed to examine the relationship between emergence and soil moisture (Figure 6.3). The correlation was not significant for either year. Studies in western Kansas (Stone and Schlegel, 2006; Norwood et al., 1990) have reported sorghum yields to be well correlated with available water at planting, but did not mention stand.

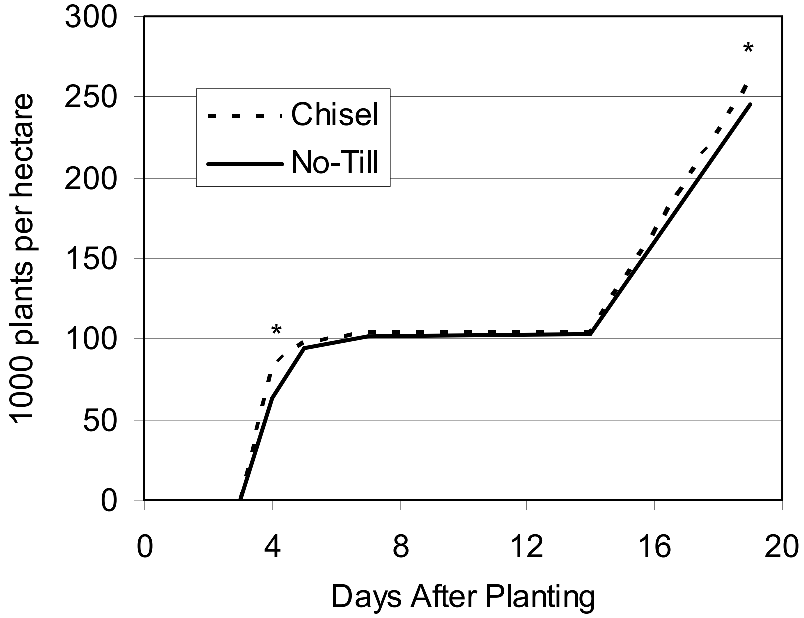

Figure 6.1 Stand count data from 2006. Asterisks indicate dates with significant differences. (Chisel > no-till on day 4 and 19 at p = 0.038 and 0.092, respectively.)

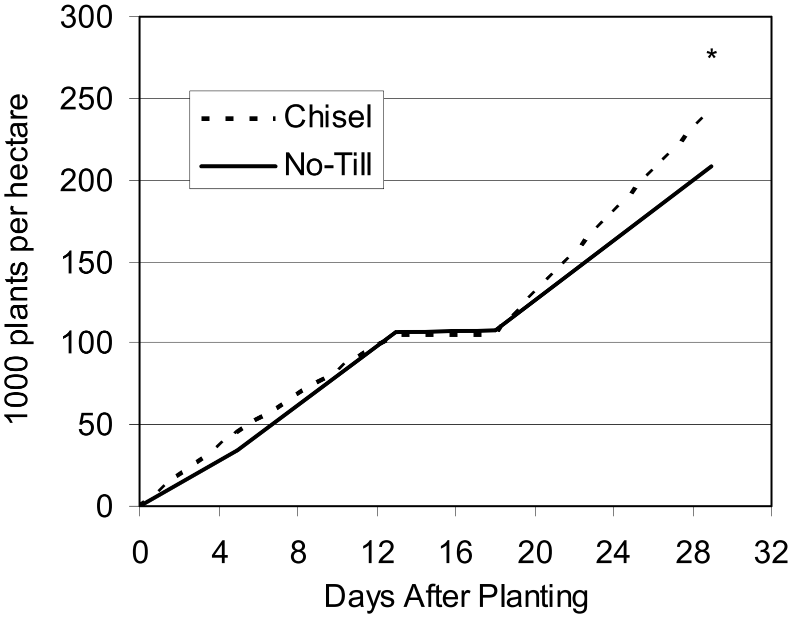

Figure 6.2 Stand count data from 2007. Asterisk indicates date with significant difference. (Chisel > no-till on day 29 at p = 0.002.)

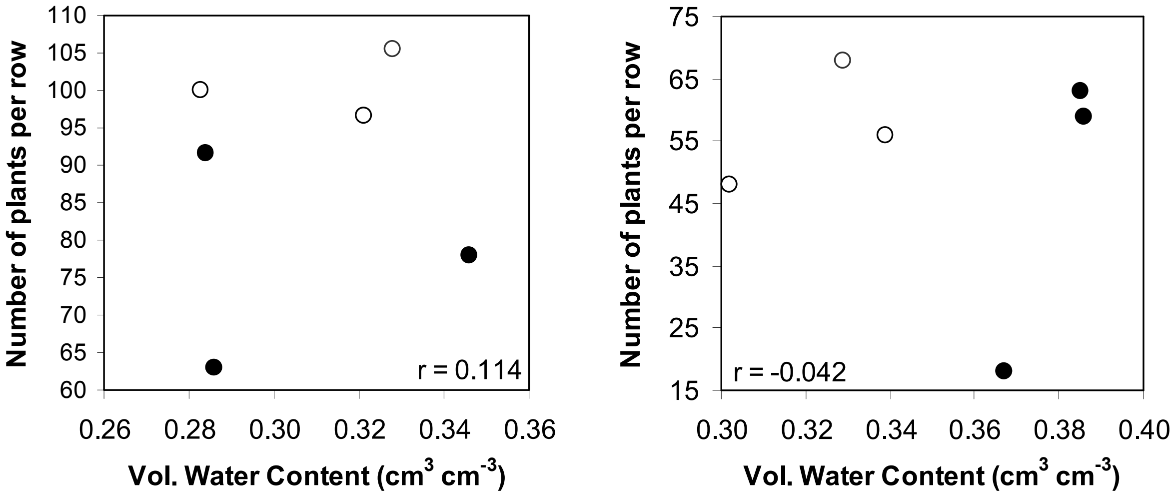

Figure 6.3 Relationship between stand and soil moisture at emergence (23 May 2006 (left) and 26 May 2007 (right)). Soil moisture determined from 10 cm TDR data on that date. Open circles represent chisel treatments while closed circles represent no-till.

Plant Biomass

All plant material in 1 m of crop row was collected exactly 8 wk after planting in both 2006 and 2007 (Table 6.1). In 2006 the crop was in bloom stage with a majority of heads exposed while in the cooler, wetter 2007 season, the crop had only reached boot stage with less than half the heads exposed. No significant difference was seen between tillage treatments for whole plant biomass or the biomass of stems, leaves, and heads. Sweeney (1993) showed a significant tillage effect at the 9-leaf stage with reduced dry matter in no-till treatments as compared with reduced- and ridge-tillage methods. However, the difference was no longer present by boot stage, similar to these results.

Table 6.1 Biomass results.

		Stem	Leaf	Head	Total
		kg/ha			
2006					
	Chisel	3900	2300	650	6200
	No-Till	3700	2400	640	6000
	p-value	0.32	0.55	0.91	0.26
2007					
	Chisel	2300	2000	380	4700
	No-Till	2200	1900	220	4300
	p-value	0.65	0.36	0.29	0.28

Head Count

Head counts were performed approximately 1 wk before harvest in both the 2006 and 2007 growing season. All exposed heads were counted regardless of degree of grain development. In 2006 there were 103,000 and 104,000 heads per hectare for chisel and no-till treatments, respectively. In 2007, there were 106,000 and 105,000 heads per hectare for chisel and no-till treatments, respectively. No significant effect of tillage treatment was seen on head count in either year. In both years the standard deviation for the no-till treatment was greater than that for chisel.

Yield

Yields were determined from grain weight in the center two rows of each plot. In 2006, the drier of the two crop years, yields were 3430 and 3260 kg ha^{-1} for chisel and no-till, respectively. In 2007, the wetter of the two crop years, yields were 5240 and 5100 kg ha^{-1} for chisel and no-till, respectively. No significant effect of tillage treatment was seen for yield in either year. In both years the standard deviation for the no-till treatment was greater than that for chisel. Use of no-till has been shown to increase sorghum yields in dry summer climates (Norwood et al., 1990; Schlegel et al., 1999) but literature from climates more similar to eastern Kansas was hard to find. Progress reports from the Parsons field site indicate that sorghum grown in no-till generally had productivity that was less than or equal to tilled treatments (Sweeney, 2004).

Correlation analysis was performed to examine the relationship between yield and soil moisture at flowering (Figure 6.4). The correlation was not significant in 2006, but showed a significant relationship of reduced yields in the wettest treatments for the wetter 2007 crop year. Soil moisture was at or above field capacity for much of the 2007 growing season. A 30-yr study of sorghum crops has shown strong correlation between yield and the combination of available moisture at planting and in season precipitation, finding that no-till was able to store more water and increase crop yields in dry climates (Stone and Schlegel, 2006). Sorghum is not generally grown in wetter climates, but studies with corn have shown both positive and negative correlation between tillage and yield. A Nebraska study showed that increased spring precipitation decreased yield of no-till corn while increased midseason precipitation increased yield (Wilhelm and Wortmann, 2004).

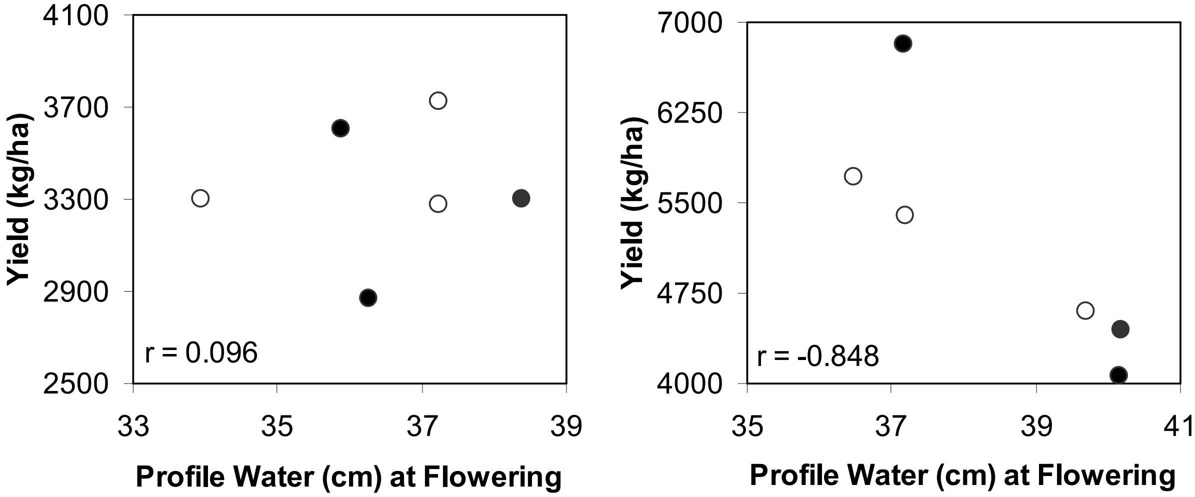

Figure 6.4 Relationship of yield and depth of water in soil profile at flowering, determined from neutron probe measurements to 120 cm on 14 July 2006 (left) or 27 July 2007 (right). Open circles represent chisel treatments while closed circles represent no-till.

Conclusions

The tillage treatment resulted in few differences in crop performance in this 2-yr study. The only significant tillage effect was that chisel emerged and tillered earlier than no-till. This difference was compensated for during tillering and later plant growth so that no difference was seen in dry matter production, head count, or yield. This finding reinforces previous statements that the main differences between the tillage treatments occurred in the early spring.

No relationship was found between emergence and soil water status or the 2006 yield and soil water status. However, a negative relationship existed between yield and soil water in 2007 with the wettest soils producing the lowest yields. Yields were below average in the drier 2006 growing season but approximately average in 2007.

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CHAPTER 7 - Modeling to Verify Field Observations

A mechanistic model can be used to verify field measured observations and investigate the various processes that govern the flow and distribution of water in soil. Variably saturated, one-dimensional water flow was simulated using the HYDRUS 1-D modeling software (version 3.0, available at http://www.pc-progress.cz), which was developed by J. Šimůnek, M.Th. van Genuchten, and M. Šejna at the University of California Riverside and the G.E. Brown Jr. Salinity Lab in Riverside, California. The HYDRUS 1-D program uses a Galerkin finite element method to numerically solve Richards' equation. Richards' equation for one dimensional flow is

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} K(\psi)[\frac{\partial \psi}{\partial x} + 1] - S \qquad [7.1]$$

where θ is the volumetric water content, ψ is the water pressure head, t is time, x is depth (positive upward), $K(\psi)$ is the unsaturated hydraulic conductivity, and S is a sink term.

Various analytical models for characterizing hydraulic properties are available in HYDRUS 1-D. All simulation results presented in this chapter were obtained by using the van Genuchten – Mualem single porosity model with no hysteresis. The water retention function, $\theta(\psi)$, and hydraulic conductivity function, $K(\psi)$, for that model (van Genuchten, 1980) are

$$\theta(\psi) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{[1 + |\alpha\psi|^n]^m} & \psi < 0 \\ \theta_s & \psi > 0 \end{cases} \qquad [7.2]$$

$$K(\psi) = K_s S_e^l [1 - (1 - S_e^{1/m})^m]^2 , \qquad [7.3]$$

where,

$$m = 1 - 1/n \qquad [7.4]$$

and S_e is effective saturation,

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} . \qquad [7.5]$$

Values of ψ greater than zero represent saturated conditions while values less than zero represent unsaturated conditions. The parameters θ_r and θ_s are the residual and saturated water contents, respectively, while α and n are curve fitting parameters. In addition to the parameters θ_r, θ_s, α, and n, the hydraulic conductivity function also utilizes saturated hydraulic conductivity, K_s. The values for the parameters θ_r, θ_s, α, n, and K_s are constant for a given soil and typical values can be set in HYDRUS 1-D simply by choosing a soil textural class in the hydraulic properties catalog (adapted from Carsel and Parrish, 1988). The typical parameter values for silt loam and silty clay (Table 7.1) were used for many of the simulations; however, measured values of θ_r, θ_s, α, n, and K_s from Chapter 4 were used as well.

Table 7.1 Hydraulic parameters for silt loam and silty clay soil materials as reported in the hydraulic properties catalog in HYDRUS 1-D.

Hydraulic Property	Silt Loam	Silty Clay
θ_r (cm^3 cm^{-3})	0.067	0.07
θ_s (cm^3 cm^{-3})	0.45	0.36
α	0.02	0.005
n	1.41	1.09
K_s (cm h^{-1})	0.45	0.02

Several of the simulations that were conducted cover a brief time frame during which root water uptake is assumed negligible (S = 0 in Eq. [7.1]). However, for the whole season water balance verification, root water uptake and root growth processes were used to model soil water content changes over time. The uptake of water by plant roots is taken into account in the sink term (S) in equation [7.1]. In HYDRUS 1-D, a water stress response function is used to characterize the reduction in root water uptake that occurs when soil water pressure head falls outside the range for optimal extraction. For simulations involving root water uptake, the Feddes et al. (1978) root water stress response function (which assumes negligible osmotic stress) was used (Figure 7.1). In the Feddes function, root water uptake does not occur near saturation, but begins increasing at a pressure head, Po, below which anaerobic conditions no longer exists. The stress coefficient is one (no restrictions to water uptake) between optimal high and low pressure heads, Ph and Pl, respectively. As pressure head approaches the permanent wilting point, Pw, water uptake decreases, returning to zero at pressure heads below Pw. To simulate water uptake for sorghum, the pressure head values for Po, Ph, Pl, and Pw were set at -15, -30, -500, and -24,000 cm, respectively. These values were adapted from the corn water uptake settings in HYDRUS 1-D.

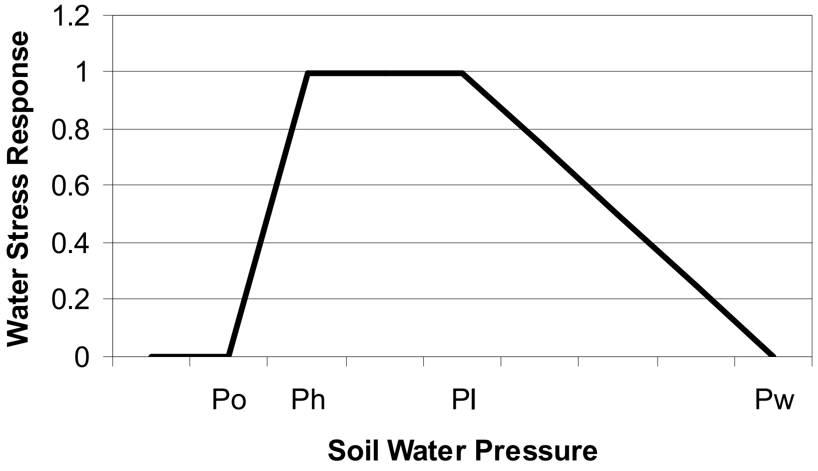

Figure 7.1 The Feddes root water uptake stress response to soil water pressure. A stress response of 1 represents maximum rates of water uptake during optimal pressure head conditions.

Root growth was modeled by selecting initial (L_o) and maximum (L_m) rooting depths and length of growing season (t) for use in Šimůnek and Suarez's (1993) adaptation of the classical Verhulst-Pearl logistic growth function

$$L_R(t) = L_m \frac{L_o}{L_o + (L_m - L_o)e^{-rt}} \qquad [7.6]$$

where L_R is rooting depth and r represents the rate of root growth and is calculated by using the assumption that 50% of maximum depth will be reached when the growing season is 50% over. Length and start date of growing season as well as maximum rooting depth were set from actual field conditions for each year. The initial root depth on the day of planting was zero. In 2006, the growing season extended 98 d from planting on 19 May to harvest on 25 Aug. with roots reaching a depth of 120 cm (based on water content data) while the 2007 growing season extended 119 d from planting on 21 May to harvest on 17 Sept. with roots reaching a depth of 105 cm. Root penetration was shallower in 2007 because of greater precipitation and available water supplies near the soil surface.

When root growth is allowed, the root water uptake distribution, $b(x)$, is determined by the trapezoidal function of Hoffman and van Genuchten (1983), originally proposed by Gardner (1983),

$$b(x) = \begin{cases} \dfrac{1.66667}{L_R} & x > L - 0.2L_R \\ \dfrac{2.0833}{L_R}\left(1 - \dfrac{L - x}{L_R}\right) & L - 0.2L_R \geq x \geq L - L_R \\ 0 & x < L - L_R \end{cases} \qquad [7.7]$$

where L is profile depth and $x = 0$ is the bottom of the soil profile while $x = L$ is the soil surface. The value of L_R increases with time as seen in equation [7.6]. An example of this root water uptake distribution when $L_R = 120$ cm and $L = 150$ cm is graphically represented in Figure 7.2.

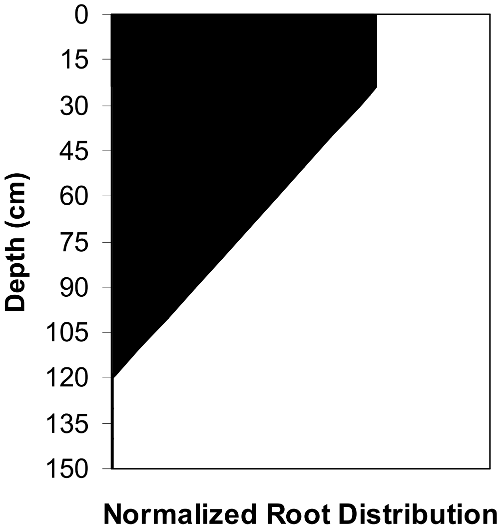

Figure 7.2 Distribution of root water uptake used in the HYDRUS 1-D model.

The following results are from relatively simple simulations designed to verify findings for surface evaporation, surface water content changes during precipitation, potential for a perched water table, and the whole cropping season mass water balance. While running simulations it was determined necessary to increase the number of iterations (from the default value) and to increase the density of computational nodes in the vicinity of the silt loam - silty clay interface in order to reduce likelihood that the model would fail to converge at the transition.

Suitability of Microlysimeter for Measuring Surface Evaporation

These simulations were conducted with the objective of verifying that the microlysimeters were able to capture all evaporation from the soil surface. The primary concern was whether microlysimeters underestimated daily evaporation because the hydraulic break at the base of the lysimeter significantly impeded upward water movement. When using microlysimetry, the bottom is sealed and not able to draw moisture from below. Thus, the microlysimeters are not drawing from the total pool of available water and measured evaporation may underestimate true water loss.

To check for this error, two models were developed with the same boundary and initial conditions but different profile depths. The models both had a one-layer system of silt loam material with the hydraulic parameters listed in Table 7.1. For the initial condition, a pressure head of -300 cm was specified throughout the profile. One model had a 10.5-cm deep profile to represent the available evaporative pool in a microlysimeter while the other model had a 50-cm deep profile to represent a larger pool of available water. For both models, the upward flux at the soil surface (evaporation) was set from actual microlysimeter data at 0.02 cm h^{-1} between 6 am and 6 pm each day. If the simulated soil system was unable to sustain evaporation at the rate of 0.02 cm h^{-1}, the boundary condition would internally change from the constant flux to a prescribed pressure head of -100,000 cm. A zero flux condition (no evaporation) was set for the remaining 12 h of each day. No fluxes were allowed at the bottom of either modeled system, effectively creating a zero drainage situation.

Analysis of the differences in volumetric water content over time between the two profile depths was performed (Figure 7.3). Over a 48-h time period, the water content at the surface was the same for both the 10.5- and 50-cm deep profile. Water content varied over time as evaporation dried the soil during the day and upward fluxes within the soil rewet the surface overnight. Although water content at the soil surface was unaffected by profile during the first 48 h, the shallow profile was slightly drier than the deep profile after 2 d had elapsed. As anticipated, the greatest difference occurred at the 10.5-cm depth, where the shallower profile had a water content 0.0038 cm^3 cm^{-3} lower than that in the deep profile at a time of 48 h. At this time, there was 0.02 cm less total water in the shallow profile than in the surface 10.5 cm of the deep profile. These results illustrate the effect of the hydraulic break at the base of the microlysimeter. Relative to the deep profile, the water status of the shallow profile was reduced due to the lack of upward water movement from depths below 10.5 cm. Despite this reduction in soil water status, cumulative evaporation from the shallow profile was nearly identical to that from the deep profile. Over the first 48 h, cumulative evaporation from the shallow profile was only 2 x 10^{-5} cm lower than from the deep profile. This difference, which amounts to less than 0.01 % of the cumulative evaporation from the deep profile, is insignificant. As differences in water content between the shallow and deep profiles continue to increase, later days show greater differences in evaporative rate and are less suitable for measurement with the microlysimeter. Boast and Robertson (1982) reported on the influence of length of microlysimeter and found that columns as short as 70 mm are suitable for use over a 1- or 2-d period, having a measurement error value less than 0.5 mm d^{-1}. Our model findings support this conclusion and verify that microlysimeters were able to adequately quantify evaporation and detect treatment differences over a 1- or 2-d period with minimal error due to availability of water.

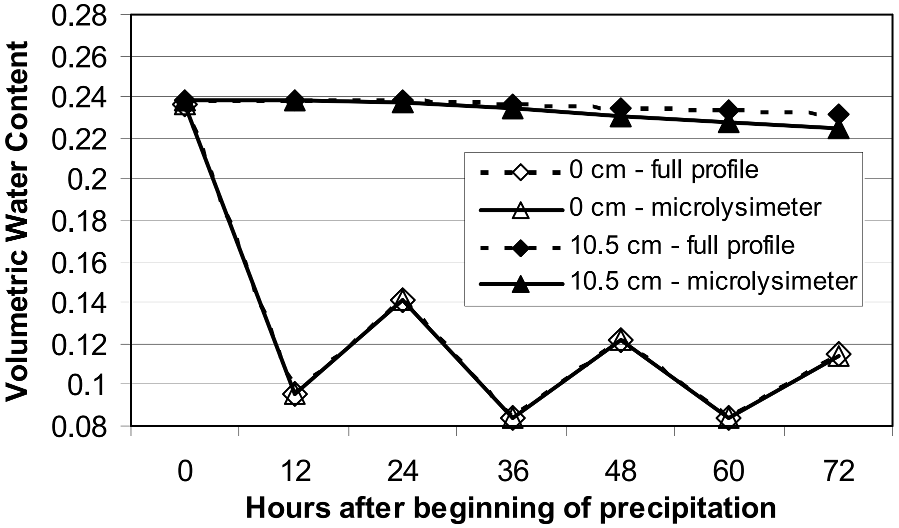

Figure 7.3 Simulated soil water content during evaporation from a full 50-cm deep silt loam profile as compared to a shallower 10.5-cm profile. Water contents are from the 0- or 10.5-cm soil depth of each system.

Verification of Observed Surface Water Behavior

Results of the water retention measurements and curve fitting exercise were used to simulate the wetting and drying behavior of the surface soil in order to verify observed changes in soil water content, and the differences and interactions between tillage treatments. Separate models were developed for no-till and chisel field conditions. These models both used a two-layer system with the soil hydraulic properties over the 0- to 20-cm depth determined from the water retention curve fitting parameters measured for each treatment in the north block of the Parsons field site (except K_s, which was taken from the hydraulic properties catalog for silt loam). The 20- to 150-cm layer used the silty clay hydraulic parameters (except K_s, which was field measured at 0.008 cm h^{-1} for the silty clay subsoil). Water flow was simulated for 144 h (starting at 6 am, day 1) where the first 18 h were wetting (downward flux of 0.2 cm h^{-1}) after which drying (upward flux of 0.005 cm h^{-1}) occurred from 6 am to 9 pm each subsequent day. A zero flux condition was set during the other hours of the day (overnight). For the initial condition, a pressure head of -300 cm was used for the entire 150-cm profile. Free drainage was specified as the bottom boundary condition. The free drainage option imposes a unit hydraulic gradient where water movement is driven by gravity alone. This situation is appropriate in deep soil profiles well above a water table.

The two models were used to simulate changes in water content over time at the 10-cm depth for systems with no-till and chisel hydraulic properties (Figure 7.4). Under these conditions, no-till was consistently wetter (greater water content) than chisel; however, there does appear to be some treatment by time interaction as the curves are not parallel over time. Specifically, in the hours after precipitation stops, the water content for no-till continues to increase while chisel begins to decrease in water content. The differences between treatments in Figure 7.4 are due to differences in water retention. Note that the initial condition of -300 cm pressure head results in different volumetric water contents for the two treatments at time zero.

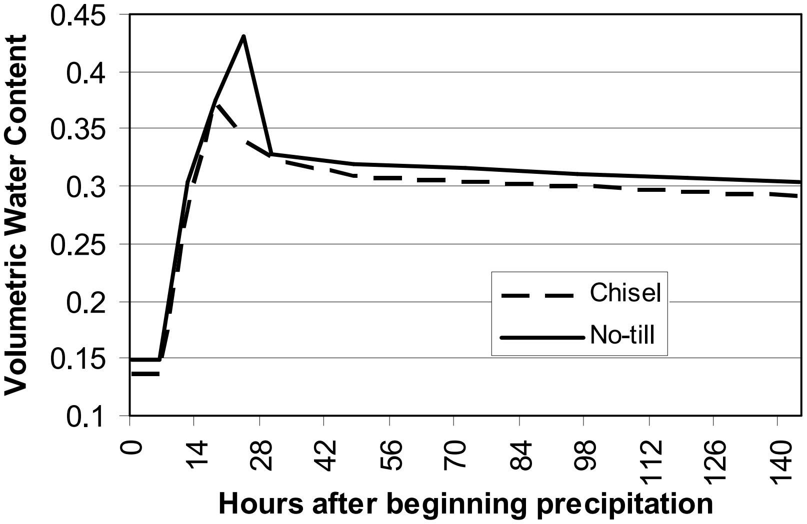

Figure 7.4 Simulated change in chisel and no-till surface water content during 18 h wetting and subsequent drying from the 10 cm depth. Soil conditions set from van Genuchten curve fitting of measured water retention values.

The results of the chisel and no-till model simulations were similar to field measured conditions in that the water content for the two tillage treatments was similar except during near saturated conditions. The observed interaction between tillage treatment and time was also supported by model simulations. Overall, there were few significant differences in the water retention data or field-measured near-surface water content and the simulations support this finding, being unable to model different conditions for each tillage treatment. Further work in this area should expand the characterization of hydraulic properties (i.e., field measured $K(\psi)$) before modeling of water behavior differences can be improved.

Verification of Perched Water Conditions

A model was developed with the objective of tracking a high rainfall event on this shallow soil to determine potential for development of a perched water table. The model used a two-layer system with the hydraulic parameters (Table 7.1) for silt loam in the 0- to 20-cm layer and for silty clay in the 20- to 150-cm layer (except K_s, which was field measured at 0.02 cm d^{-1} for the silty clay subsoil). Precipitation was simulated by imposing a continuous surface flux of 0.3 cm h^{-1}, a typical rate at the Parsons field site. Free drainage was specified at the bottom boundary. For the initial condition, a pressure head of -300 cm was specified for the entire 150-cm profile. This simulation was designed after a precipitation event on 13 April 2007.

Results obtained with this model showed that a perched water table (positive pressure head) occurred near the boundary of the clay subsoil. Simulated pressure became positive about 13 h after precipitation began while field measured data from the six observation wells indicated perched water conditions between 10 and 20 h after precipitation began. Also, the rate and depth of water rise were similar for modeled and field observed conditions, with water level going from zero to approximately 20-cm pressure head in less than 1 h. Overall, the results of this HYDRUS 1-D simulation verify our field measured findings of potential for perched water during heavy rainfall conditions due to restrictions of water movement into and through the clay subsoil.

While conducting this simulation, it became evident that HYDRUS will crash if the preset surface boundary conditions cannot be maintained. The model was set up with a 0.3 cm h^{-1} downward flux but crashed when the surface layer became wetted to the extent that it could no longer sustain the 0.3 cm h^{-1} infiltration rate. Because of this, simulating an entire perched water event proved difficult. To circumvent this problem, a second model was designed to start with saturated conditions and simulate the decline in perched water level. This model had the same soil hydraulic properties, but different initial conditions. The initial pressure head increased linearly from 0 cm at the surface to +20-cm at a depth of 20 cm, then decreased linearly to a pressure head of -300 cm at a depth of 30 cm. Below 30 cm, the initial pressure head was fixed at -300 cm. A constant evaporative flux condition of 0.015 cm h^{-1} was set at the surface while free drainage remained the specified bottom boundary condition.

Positive pressure heads continued at the 10-cm depth for 4 h and at the 20-cm depth for about 10 h in the drying model. Even after 48 h, these two depths were wetter than field capacity. Pressure heads during wetting and drying for both field monitored and modeled conditions are compared in Figure 7.5. The positive field monitored pressure heads reported here were measured with the pressure transducer in the north central (NC) shallow observation well, though all wells had similar trends (Appendix E). Negative values of field measured pressure head were estimated from soil water content data. There is reasonable agreement between the shape and magnitude of changes in measured and modeled pressure head. However, the simulated results show water level to decline at a greater rate than field observations.

Agreement in the rate of decline could be improved by reducing the surface boundary flux (evaporation rate) in the second model.

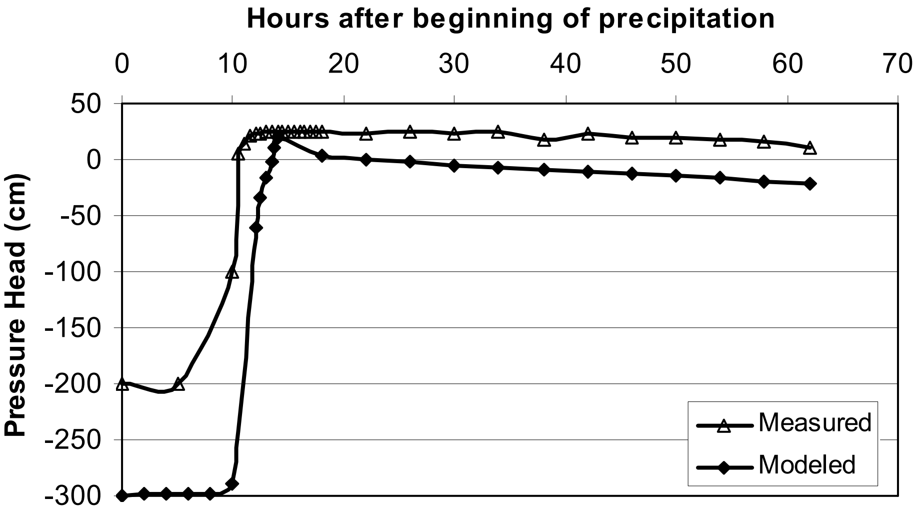

Figure 7.5 Simulated and measured pressure head conditions at the 20 cm depth during a precipitation event on 13 Apr. 2007.

Verification of Seasonal Full Profile Water Balance

Stored Water

This model was developed with the objective of simulating changes in water content over an entire growing season. The model used a two-layer system with the hydraulic parameters (Table 7.1) for silt loam in the 0- to 20-cm layer and for silty clay in the 20- to 150-cm layer (except K_s, which was field measured at 0.02 cm d^{-1} for the silty clay subsoil). Water flow was simulated for periods of 138 and 145 d to obtain results corresponding to the 2006 and 2007 growing seasons, respectively. In each year, the start of simulated conditions corresponded to 11 May, the date on which a full profile was assumed and water monitoring began. For each season, the initial condition was a pressure head of -300 cm throughout the profile. The surface flux conditions were variable over time and used the precipitation and evapotranspiration values determined at the Parsons field site. The set precipitation values used effective precipitation; precipitation greater than available storage capacity of the surface layer was considered runoff that did not contribute to changes of water storage in the profile. The set evapotranspiration values used reference evapotranspiration values calculated with the FAO-56 method on a daily basis. The model determined actual evapotranspiration internally. Free drainage was specified as the bottom condition. Root growth was allowed as described previously.

Simulated and measured water content were compared for days on which neutron probe readings were taken. For both 2006 and 2007, comparisons were made over time at depths of 15, 60, and 135 cm (Figure 7.6 - 7.11). In addition, profiles of simulated and measured water contents were compared for selected dates in the 2006 and 2007 growing seasons (Figures 7.12 - 7.17). Agreement between simulated and measured values was assessed by using coefficient of determination (R^2), mean error (ME), and root mean square error (RMSE). Mean error and RMSE were calculated using the expressions

$$\mathrm{ME} = \frac{1}{N}\sum_{i=1}^{N}(\theta'_i - \theta_i) \qquad [7.9]$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\theta'_i - \theta_i)^2} \qquad [7.10]$$

where θ' is the modeled volumetric water content and θ is the measured value.

The correlation between simulated and neutron probe measured water content over all dates and depths of field measurement can be seen in Figure 7.18. In general the correlation between simulated and measured values was good with a slight over prediction in the dry 2006 crop growth year (ME = 0.012) and a slight under prediction in the wet 2007 crop growth year (ME = -0.004). In both crop years, the model was more apt to under predict water content during the early dates and at the shallower depths. The near surface depths had similar trends in the shape of water content change over time between simulated and measured but were actually the least similar of all depth comparisons in terms of actual water content values (Figures 7.6 and 7.9). This is most likely due to slight inaccuracies of the specified initial conditions. In 2006 there were some differences between simulated and measured water contents at depth later in the season (Figure 7.14). This seemed to be caused by the model inaccurately predicting how roots would compensate with deep extraction during the periods of drought. In the wetter 2007 crop year, there was less root water use within the clay subsoil and better agreement between simulated and measured water contents. The maximum root depth (120 cm in 2006 and 105 cm in 2007) specified in the model was estimated from field measurements of water loss at those depths. While using the model to verify field observations, multiple rooting depths were tested. Simulation attempts with shallower rooting depths, including a scenario with all roots in the surface horizon, failed to simulate the observed rates of water loss from the clay subsoil. This finding reinforces the hypothesis presented in Chapter 5, that roots are extracting water from within the clay subsoil.

An interesting phenomenon of field measured water contents was water moving down into the clay subsoil late in the crop season, particularly in 2006, which experienced greater root water extraction in the clay subsoil. The 2006 simulation did not result in as great a decrease in subsoil water content as was measured in the field. Because of this, there was less water movement into the clay subsoil late in the season. During simulations, the late season precipitation significantly increased the water content of the 15- and 30-cm depths only (Figure 7.14 and 7.17). The model assumed uniform water movement through the profile. However, field observations indicate that surface cracks formed during the droughty late season. Precipitation could have moved through these cracks directly into the clay subsoil. This phenomenon would not be captured by the model, which explains the discrepancy between measured and modeled water content profiles on 6 Sept. 2006 (Figure 7.14).

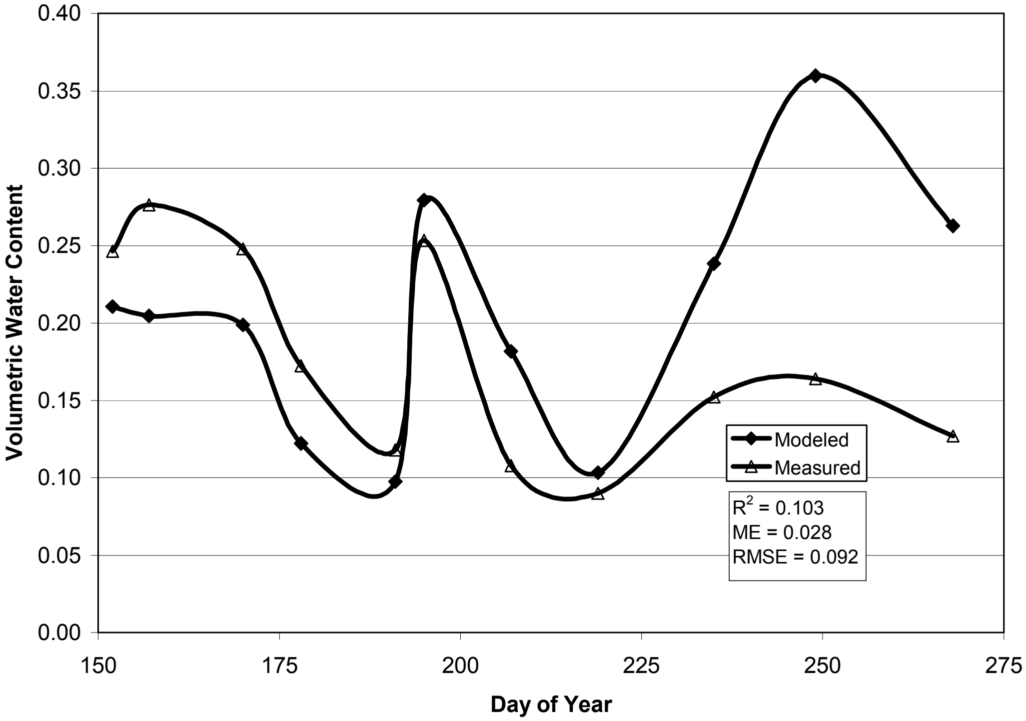

Figure 7.6 Simulated and measured water content at 15-cm depth in 2006.

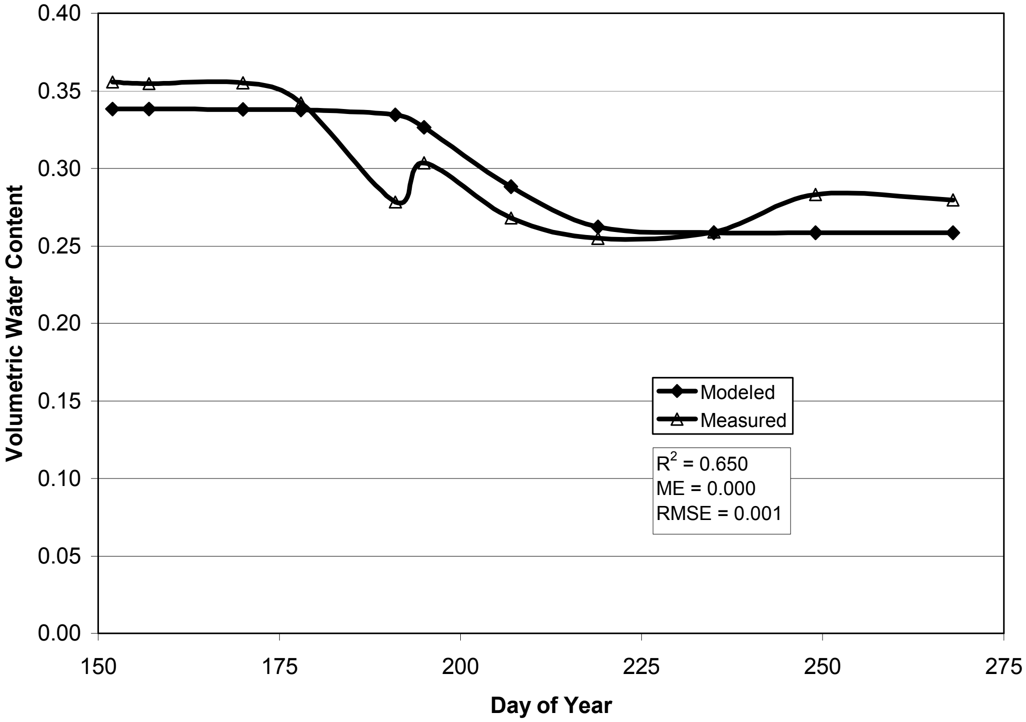

Figure 7.7 Simulated and measured water content at 60-cm depth in 2006.

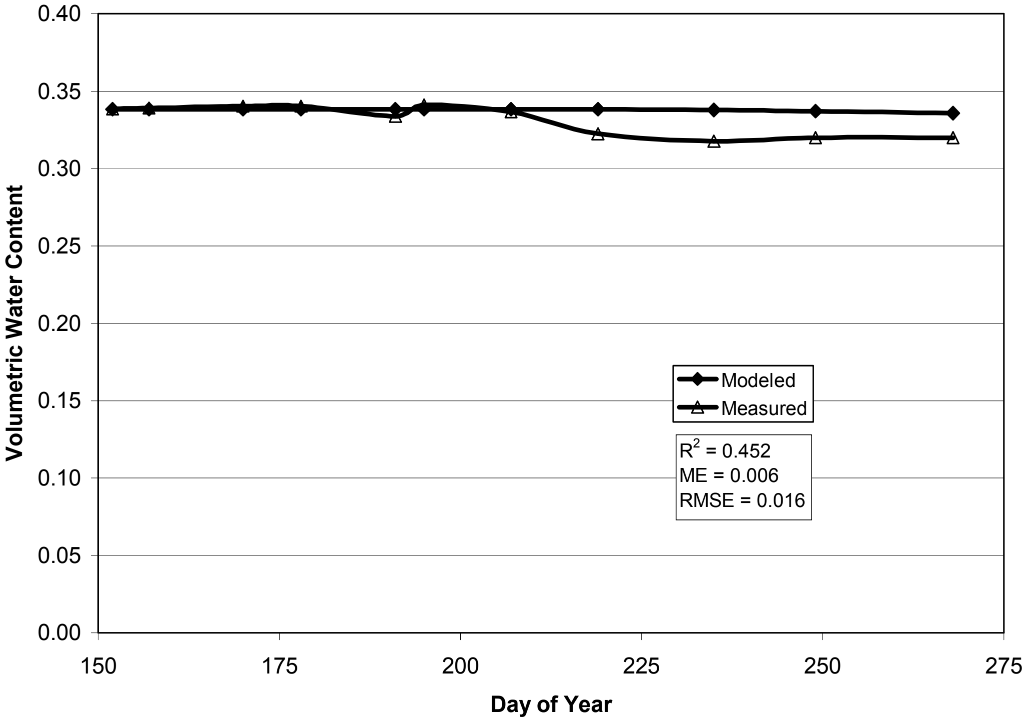

Figure 7.8 Simulated and measured water content at 135-cm depth in 2006.

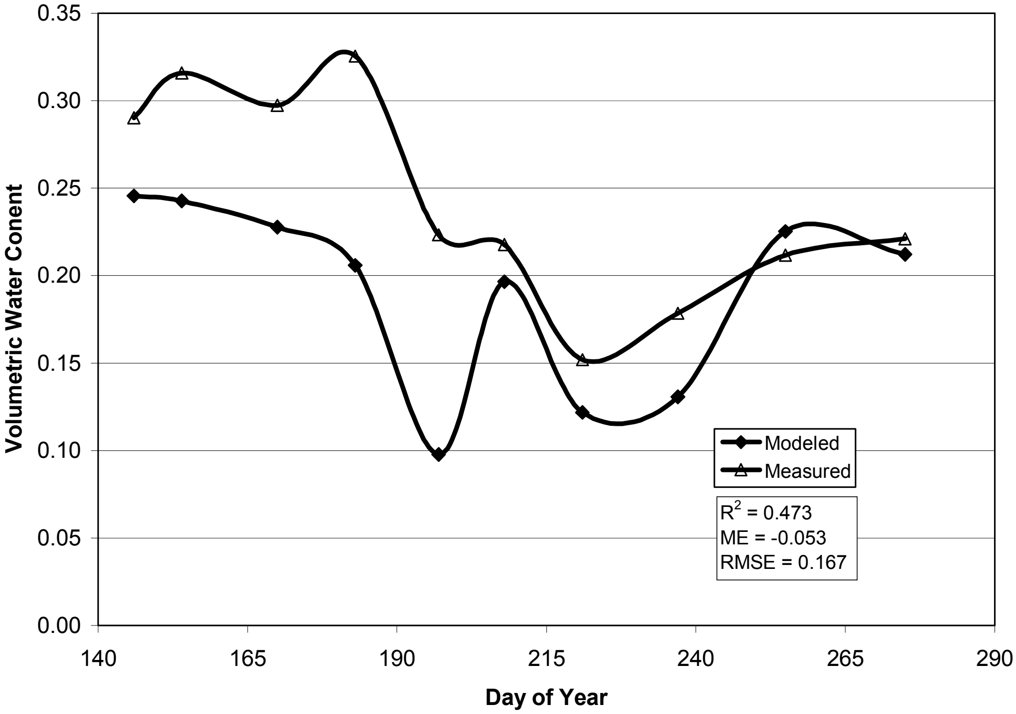

Figure 7.9 Simulated and measured water content at 15-cm depth in 2007.

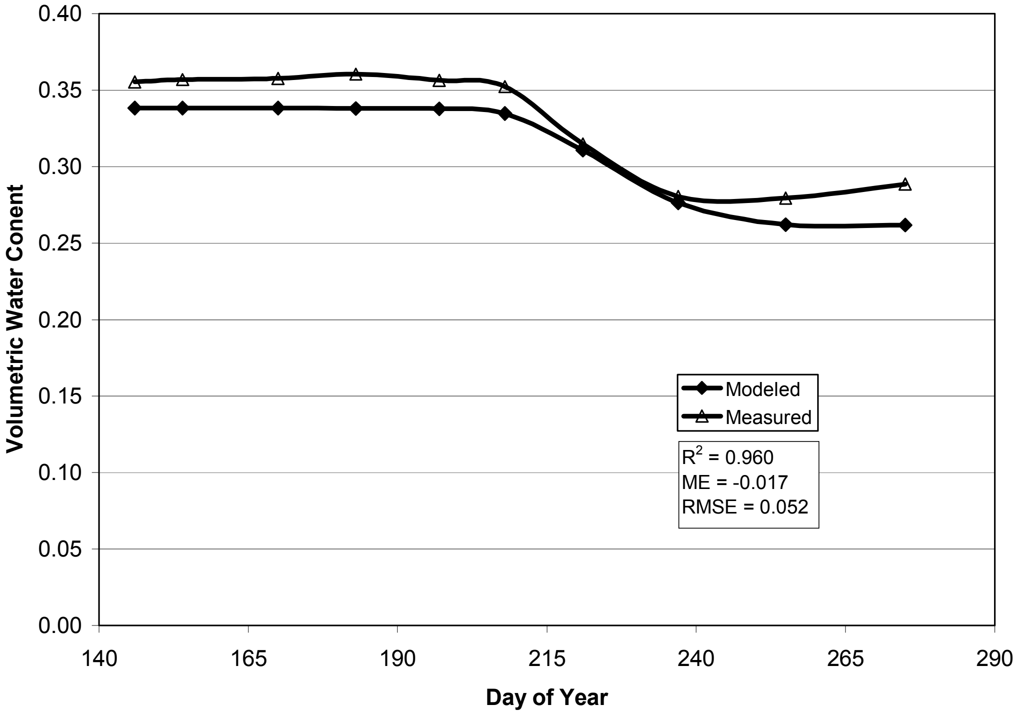

Figure 7.10 Simulated and measured water content at 60-cm depth in 2007.

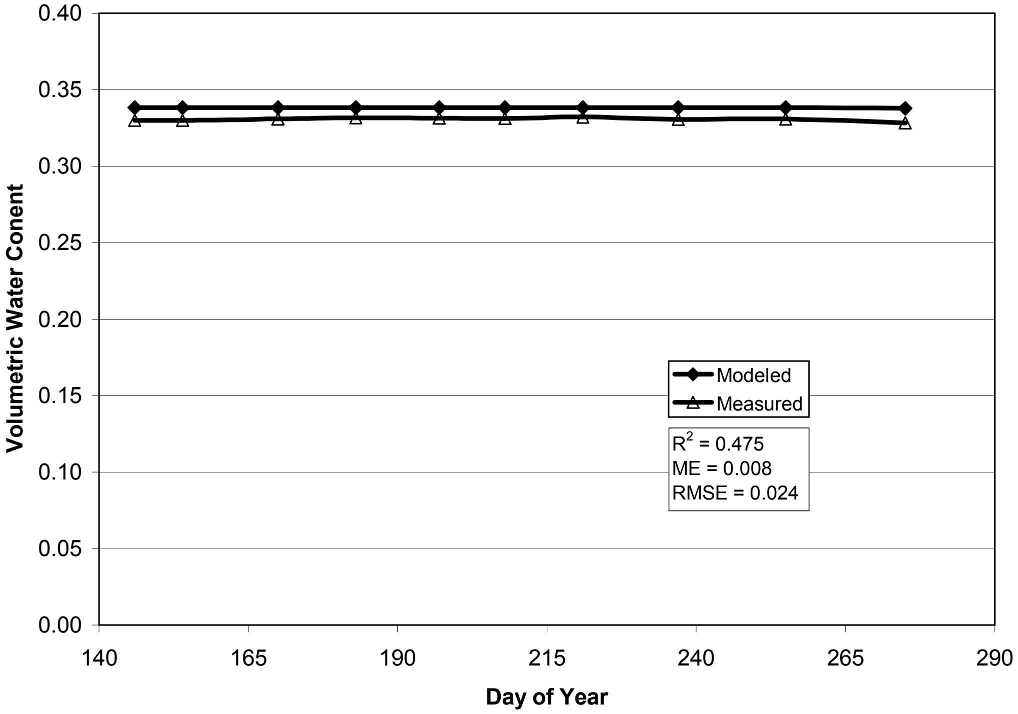

Figure 7.11 Simulated and measured water content at 135-cm depth in 2007.

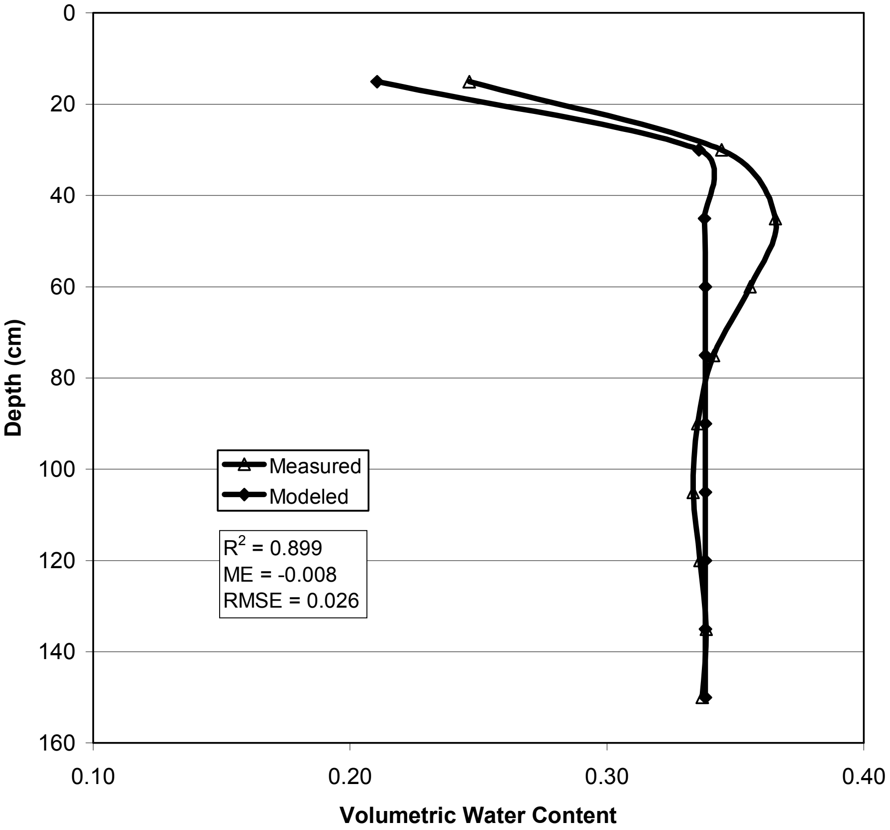

Figure 7.12 Simulated and measured water content profiles on 2 June 2006.

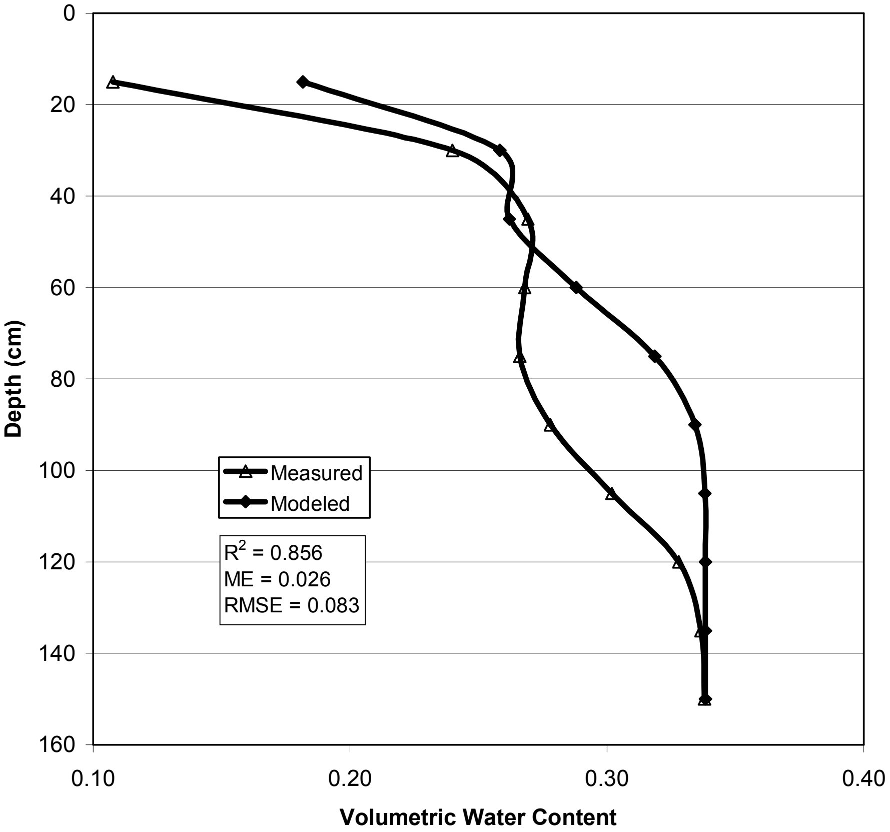

Figure 7.13 Simulated and measured water content profiles on 26 July 2006.

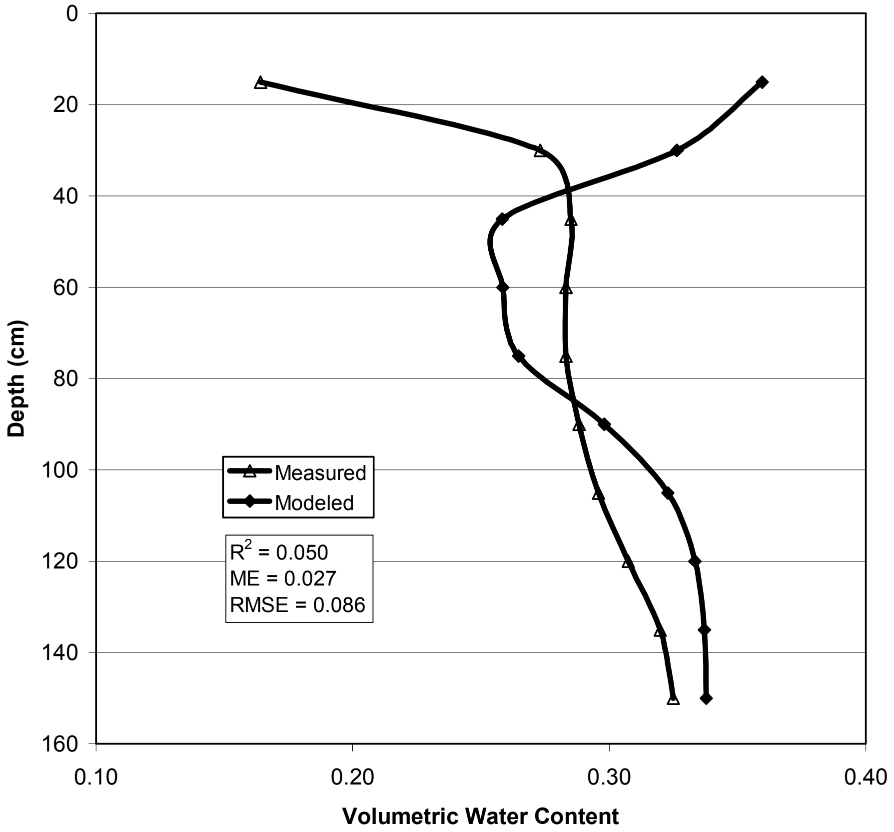

Figure 7.14 Simulated and measured water content profiles on 6 Sept. 2006.

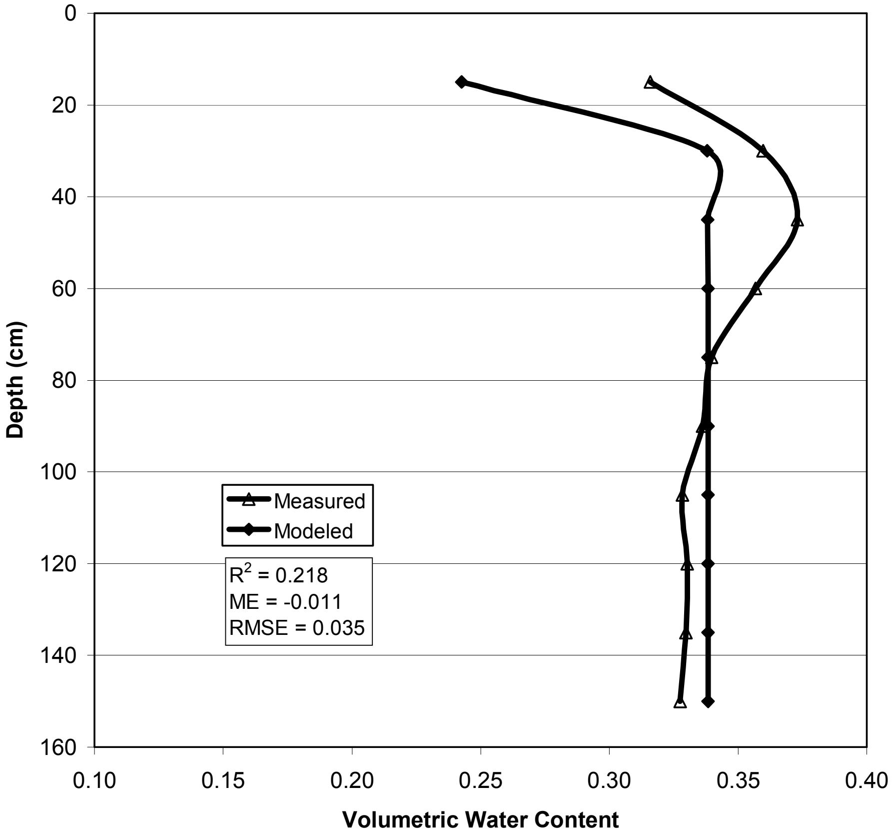

Figure 7.15 Simulated and measured water content profiles on 3 June 2007.

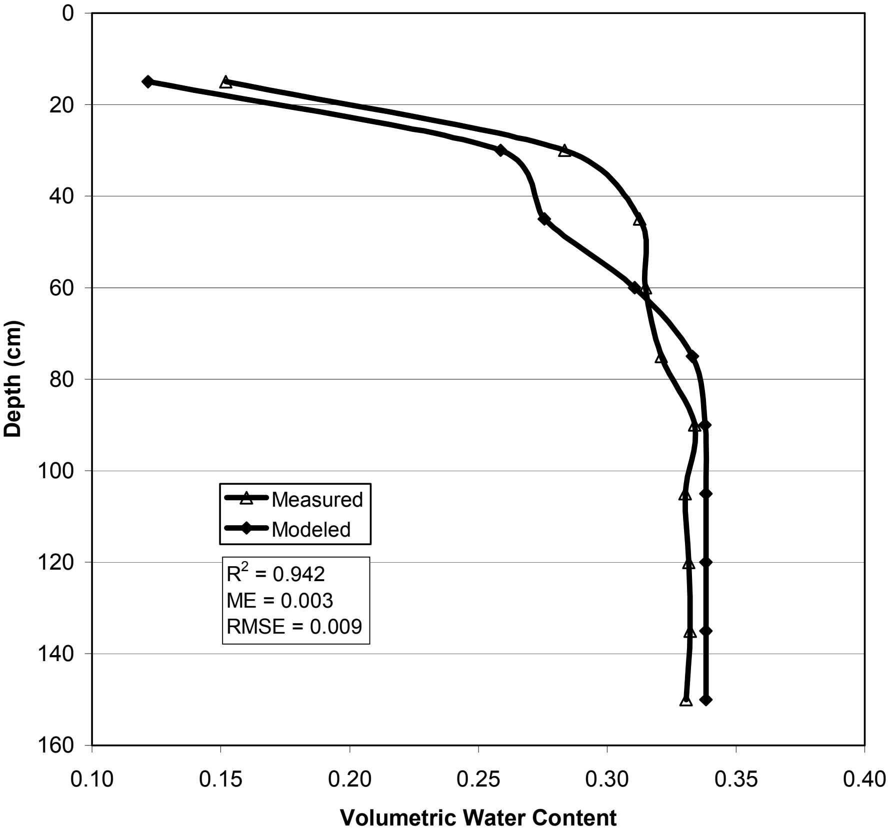

Figure 7.16 Simulated and measured water content profiles on 26 Aug. 2007.

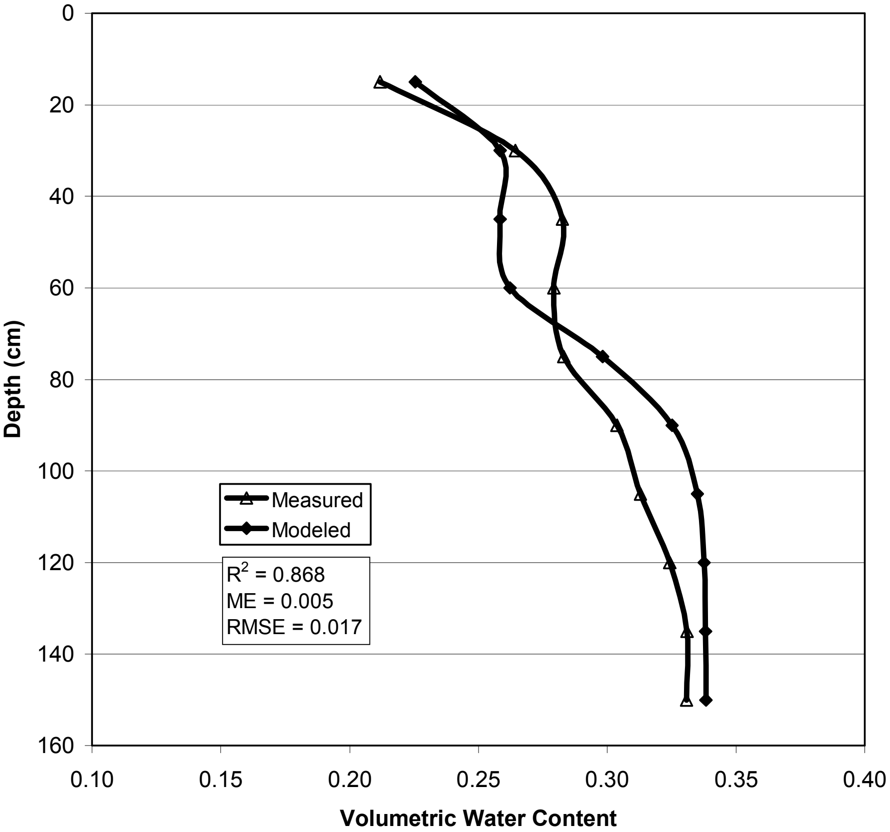

Figure 7.17 Simulated and measured water content profiles on 12 Sept. 2007.

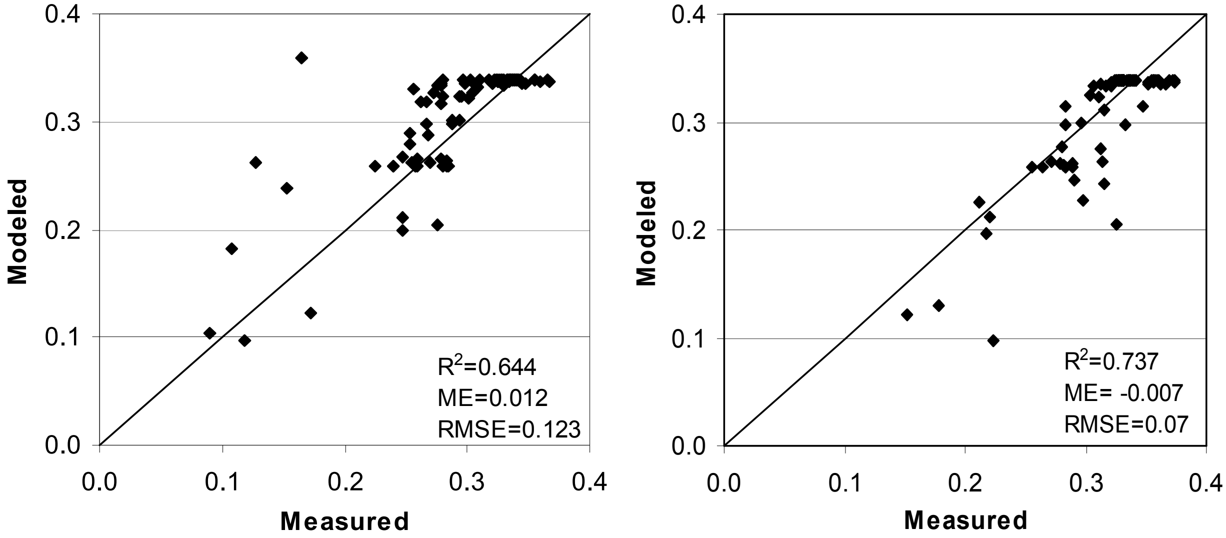

Figure 7.18 Relationship between simulated and measured water content for the 2006 (left) and 2007 (right) crop growing seasons.

Evapotranspiration

Even though the change in water content over time was more accurately modeled in the wetter 2007 crop year, the 2006 model conditions seem to allow for more accurate modeling of the combined soil evaporation and root water extraction. The cumulative evapotranspiration for the 2006 simulation was 22.75 cm of water. This value closely matched the 2006 calculated cumulative evapotranspiration (Table 5.8), which was 23 to 24 cm. However, the 2007 simulation yielded cumulative evapotranspiration of 28.28 cm while the calculated cumulative evapotranspiration (Table 5.9) was between 36 and 39 cm. The model was accurate in determining that there would be more evaporation and transpiration in the wetter 2007 crop year but did not match the magnitude. The model may not have adequately accounted for direct soil evaporation in 2007 when large precipitation events left water ponded at the soil surface. The nature of the model dictates that only effective precipitation is added as an input; ponding, runoff, or increased evapotranspiration could not be determined from total precipitation.

Drainage

While simulating a full season water balance in HYDRUS 1-D, we were able to confirm the field measured observation that water contents below the 120-cm depth do not vary significantly over the course of a season. HYDRUS was also able to predict a flux at the bottom of the soil profile. The model predicted this as a downward flux of 3.6×10^{-4} cm d^{-1} in both years. This flux was maintained until the surface reached the wilting point (9 August 2006, 18 August 2007) and then decreased in magnitude. No upward fluxes at the bottom of the profile were predicted during the modeled time periods, which covered wettest to driest soil conditions. The magnitude of the simulated flux at the bottom of the profile was similar to maximum drainage rates calculated in Chapter 5 (2.1×10^{-4} cm d^{-1}) and confirms our assumption of negligible drainage.

Conclusions

The HYDRUS 1-D model was used to show that a 10.5-cm microlysimeter can accurately measure evaporation from the soil surface over a 24 to 48 h period. The difference in cumulative surface flux between a 10.5-cm deep profile and a profile with a greater pool of water available for evaporation was simulated as only 2×10^{-5} cm over 48 h.

By using the hydraulic properties reported in Chapter 4, differences in soil water status between the chisel and no-till management were simulated. The results of these simulations reinforced the field measured findings of greater water content in no-till during wet conditions and a tillage by time interaction for soil water at the 10-cm depth. The simulation results suggest that the greater water content in no-till during wet conditions and the tillage by time interaction were caused by differences in water retention properties between the tillage treatments.

Further simulation of soil-water relations in the surface layer showed that perched water could be simulated for this two-layer soil system. Water movement into the clay subsoil is restricted such that significant precipitation events provide enough moisture to result in positive pressure head values in the surface layer. The rate and depth of water rise were similar for simulated and field observed conditions.

Simulations conducted to examine changes in water storage over an entire growing season showed good correlation between simulated and field measured water contents. However, the simulation failed to accurately capture root water extraction deep in the profile during the drought conditions of 2006. Other models (e.g., CERES, ALMANAC) have had difficulty predicting crop growth and water use in drought conditions as well (Xie et al., 2001; Kiniry and Bockholt, 1998). The simulation also failed to capture refilling of the subsoil from late season precipitation. This was partially because the simulation did not dry as much as actual conditions and partially due to the way that HYDRUS moved water through the soil. The model was set up for uniform water redistribution and the late season filling likely occurred through cracks that formed during the dry summer months. The cumulative growing season evapotranspiration was accurate for 2006 but underpredicted by simulation in 2007. The drainage flux rate simulated during each growing season was similar to calculated rates and reinforces our hypothesis of negligible drainage at the Parsons field site.

In summary, HYDRUS 1-D proved useful for verifying the soil-water conditions measured at the Parsons field site. The model seems more accurate in wetter conditions, perhaps lacking in ability to predict how roots, or other unknown factors, will dry the clay subsoil in severe drought conditions such as presented in the 2006 crop season. Simulations could have been improved with more site specific input parameters such as hydraulic properties of the clay subsoil and root growth patterns. Both these variables were assumed from catalog options within HYDRUS 1-D. There were also ways that the HYDRUS model limited our observation. For example, the root water uptake stress parameters were adapted from corn as sorghum was not a catalog option. Future work to develop these inputs could expand the applicability of both the HYDRUS model and our work.

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CHAPTER 8 - Conclusions

The overall objective of this study was to improve understanding of the hydrology of the claypan soils of southeastern Kansas and how tillage practices affect the water relations of those soils. Tillage can alter soil physical properties that affect the soil-water relations. The field site used for this investigation had chisel and no-till treatments in place for over 10 y at the time this study was initiated. The no-till treatment resulted in greater bulk density in early spring, but significant differences did not persist through the growing season. Water retention data for the A horizon revealed that the no-till treatment resulted in 7% greater water content near saturation and greater plant available water than the chisel treatment.

The differences in water retention appear to have played a role in causing the tillage effect on stored soil water. The soil under no-till had up to 20% greater water content at the 10-cm depth in early spring and following large precipitation events than that under chisel. Model simulations were used to verify that the differences in water retention properties were a likely cause for the water content differences under near-saturated conditions and the tillage by time interactions evident in near surface water content.

A second reason that no-till resulted in greater surface water content in early spring was the difference in evaporation between the two tillage treatments. The chisel treatment produced rates of evaporation up to 1 mm d^{-1} greater than that for no-till prior to canopy closure, as the chisel had less surface residue cover than the no-till treatment. As a result of these early season differences, cumulative evapotranspiration for both growing seasons was greater for the chisel treatment than for no-till. However, none of the other water balance components (stored water, precipitation, drainage, or runoff) were significantly different when summed over an entire growing season.

This 2-yr study covered both excessively dry (2006) and excessively wet (2007) growing seasons. The 2006 crop year had 169 mm precipitation during the sorghum growing season (19 May (DOY 139) to 25 Aug. (DOY 237)) as compared to 636 mm in 2007 (21 May (DOY 141) to 17 Sept. (DOY 260)). In southeastern Kansas, the soil can usually be assumed to be fully saturated by spring precipitation. The depth of stored water in the soil profile decreased during the growing season from around 51 cm in May to 40 cm at harvest in 2006 and 44 cm at harvest in 2007. The decrease in stored water was greater in 2006 because of the relatively small amounts of precipitation prior to an early harvest. During the 2006 growing season the bulk of water loss was attributable to evapotranspiration (~ 23.5 cm) while water loss for the 2007 growing season included considerable runoff in addition to evapotranspiration. In 2007, evapotranspiration accounted for approximately 33.5 cm of water loss while runoff accounted for approximately 37.5 cm. Field hydraulic conductivity measurements, flux calculations, and modeling were used to verify that drainage is a negligible component of the water balance of this claypan soil. Though quantification of the contribution of subsurface runoff to the hydrologic balance of this soil was not achieved, this study did verify the potential for subsurface runoff by detecting a perched water table following precipitation events as small as 10 mm.

Tillage primarily influenced the hydrologic balance during the early part of the growing season when the soil was more exposed and was generally wetter than at mid or late season. Tillage treatment had essentially no effect on soil water retention characteristics under drier conditions. This could explain why little difference in stored water was seen during the middle part of the growing season. The modeling work verified the finding of few differences in stored water between tillage treatments because most of the model inputs (e.g., residual water content, bulk density, and texture) were not significantly different.

As there were few differences between the water balances of the chisel and no-till treatments, this study also found few differences in crop production due to tillage treatment. The only significant tillage effect was that the sorghum emerged and tillered approximately 1 d earlier in the chisel treatment than in the no-till. The effect of this difference was minimized during tillering and plant growth at later stages, as no differences were found for dry matter production, head count, or yield. This finding reinforces previous statements that the main differences between the tillage treatments occurred in the early spring. No significant relationship was found between emergence and soil water status or the 2006 yield and soil water status. However, a negative relationship existed between yield and soil water in 2007, with the wettest soils producing the lowest yields. Field observations indicated that the plots with wet soil conditions also exhibited high amounts of weed pressure, a confounding factor to be taken into consideration. Future crop production research in the southeast Kansas region can look to this water balance study for explanation of tillage or soil-specific effects.

Better understanding of tillage effects and their influence, through residue cover or water retention properties, could be achieved by placing greater emphasis on quantification of water balance components in the early part of the season. Our work before crop planting was limited to evaporation measurements and estimation of evapotranspiration. As these proved significant, it would be beneficial to know if there are differences in soil physical properties or the soil-water status at this time. The experimental design did not allow for monitoring equipment in the field before planting. Future work could utilize increased labor and/or gravimetric sampling, hand-held vertical TDR measurements, or wireless technology to monitor soil water conditions without interrupting field operations.

Another approach to improve the understanding of the findings from this study would be to expand the measurement of soil hydraulic properties. Neither unsaturated nor saturated hydraulic conductivity was determined in the field for the surface soil. Unsaturated hydraulic conductivity was not determined for the subsoil. Also, it is important to understand how hydraulic properties change over time, particularly with increasing time since tillage occurred. Knowledge of these soil hydraulic properties, as well as how they differ with time and soil management, would improve the ability to model differences in the hydrologic balance and make management decisions.

Future work should also include additional cropping components. This study only investigated sorghum following soybean. While the study showed that sorghum was able to utilize up to 20% of the water stored in the clay subsoil, other crops have different rooting patterns and different abilities to penetrate the clay subsoil. Also, alternate crop rotations may have positive or negative effects on plant growth. Some rotations increase yield of all crops in the rotation because of improved pest management and increased soil health. There are other instances where one crop in the rotation uses more than its share of resources, which can decrease the productivity of crops in following growing seasons. In the limiting water environment of claypan soils, a deep rooting crop could deplete water at a depth that would take years to refill by downward redistribution fluxes. Knowledge of the soil-water behavior on this and other soils will be important as the diversity of crops grown in Kansas continues to increase.

In summary, the water balance of this claypan soil has special features (e.g., minimal drainage, perched water) as compared to most soil profiles. Also, the soil system is greatly affected by the shallow depth to clay, limiting the effects of tillage treatments at the seasonal scale. Differences in residue cover resulted in early season water and temperature differences that slowed emergence in no-till but did not reduce final stand or yield as compared with sorghum grown in the chisel tillage treatment. These findings can be applied to the approximately 4 million hectares of claypan soils in the Midwestern USA as few comprehensive hydrologic balances have been completed on these types of soil. This study will provide beneficial background information to explain effects seen in current research on claypan soils as well as research of various tillage methods on other soil types.

Appendix A - Plot Diagrams

Figure A.1 2006 Plot Diagram.

Alleyway			
NT Sorg.			CH Sorg.
North Block			
Alleyway			
	CH Sorg.	NT Sorg.	
Middle Block			
Alleyway			
	NT Sorg.		CH Sorg.
South Block			
Alleyway			
Unused Block			
Alleyway			

Figure A.2 2007 Plot Diagram.

Alleyway			
	CH Sorg.	NT Sorg.	
North Block			
Alleyway			
NT Sorg.			CH Sorg.
Middle Block			
Alleyway			
CH Sorg.		NT Sorg.	
South Block			
Alleyway			
Unused Block			
Alleyway			

Top of page represents north end of plot P26 at the Southeast Kansas Agricultural Research and Extension Center. Plots are 9.1 m wide from east to west to allow for a total of twelve crop rows per plot. Plots are 12.2 m long from north to south. Alleyways between blocks and between strips within blocks are 10.7 m to allow for maneuvering of equipment. Only the six plots used in a given year are labeled.

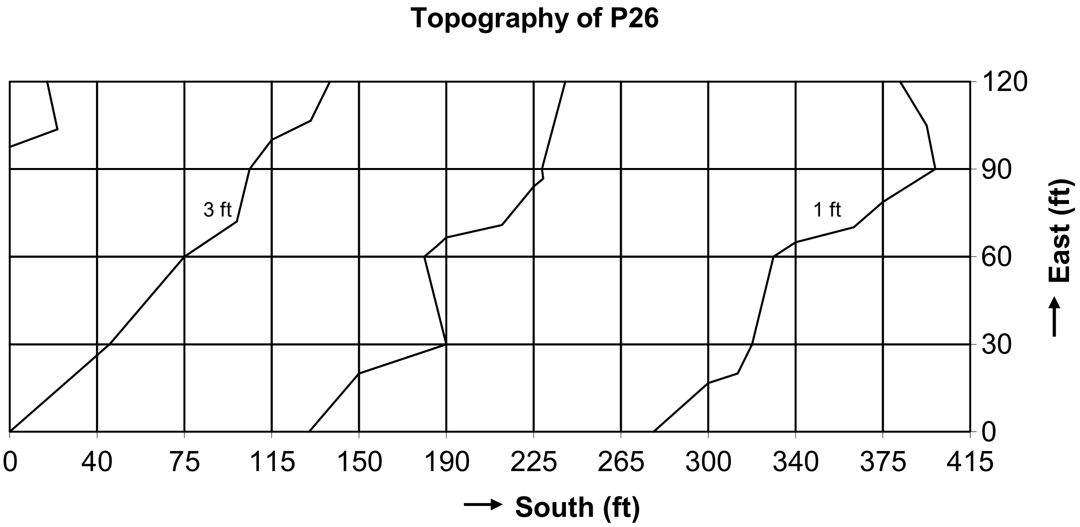


Figure A.3 Topography of field site. The lowest elevation is in the southwest corner of field site. A 0.95% slope exists toward the southwestern corner. Figure shows 3 tested blocks of P26.

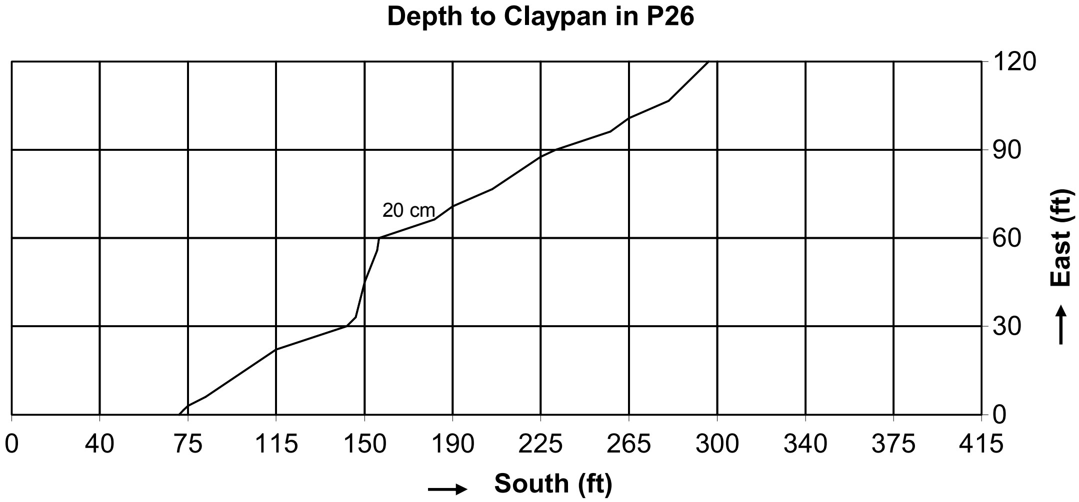


Figure A.4 Depth to clay content increase above 18%. Figure shows 3 tested blocks of P26. Clay starts around 22 cm in the northeastern portion of field site and around 17 cm in the southwestern portion.

Appendix B - Water Retention

Table B.1 Results of water retention measurement and curve fitting at the 5-cm depth: water retention curve-fitting parameters (α, n, θ_r, and θ_s), initial water content (θ_i), porosity (ϕ), and available water capacity (AWC).

Treatment	α	n	θ_r	θ_s	θ_i	ϕ	AWC
			------------------		$cm^3 cm^{-3}$		--------------------
North							
Chisel	0.066	1.466	0.055	0.387	0.470	0.526	0.186
No-Till	0.049	1.534	0.072	0.398	0.468	0.510	0.202
Middle							
Chisel	0.059	1.411	0.055	0.364	0.468	0.526	0.173
No-Till	0.047	1.474	0.066	0.386	0.462	0.515	0.195
South							
Chisel	0.084	1.242	0.000	0.377	0.492	0.534	0.174
No-Till	0.049	1.345	0.047	0.394	0.445	0.483	0.198

Significant treatment effect at $p=0.05$ for θs and AWC only.

Table B.2 Results of water retention measurement and curve fitting at the 15-cm depth: water retention curve-fitting parameters (α, n, θ_r, and θ_s), initial water content (θ_i), porosity (ϕ), and available water capacity (AWC).

Treatment	α	n	θ_r	θ_s	θ_i	ϕ	AWC
			------------------		$cm^3 cm^{-3}$		--------------------
North							
Chisel	0.058	1.302	0.017	0.376	0.445	0.489	0.182
No-Till	0.050	1.400	0.057	0.371	0.430	0.484	0.179
Middle							
Chisel	0.047	1.396	0.053	0.381	0.417	0.474	0.192
No-Till	0.064	1.297	0.047	0.390	0.436	0.478	0.171
South							
Chisel	0.047	1.193	0.000	0.373	0.412	0.442	0.165
No-Till	0.015	1.340	0.050	0.365	0.417	0.454	0.180

No significant treatment effects at $p=0.05$.

Appendix C - Evapotranspiration Calculations

Procedures given in Crop Evapotranspiration (FAO-56) (Allen et al., 1998) were followed. Weather data and reference evapotranspiration (ETo (grass)) for the Parsons field station were downloaded from the Kansas Weather Data Library (http://av.vet.ksu.edu/webwx/). The following provides details on necessary assumptions and calculations to attain actual evapotranspiration (ETa) for the sorghum crop grown. All equations from FAO-56.

$ETa = (K_sK_{cb} + K_e)ETo$
The net coefficient ranged from 0.01 under drought stress to 1.22 in optimum ET conditions.

Determination of Basal Crop Coefficient, K_{cb}

1. Measured Variables

Plant height (h): Maximum = 1.2 m
Windspeed (U)
Minimum Relative Humidity (RH_{min})

2. Table Look-Up Variables

K_{cb} for initial, mid, end stage (FAO-56: Table 17)
$K_{cb(ini)} = 0.15$, $K_{cb(mid)} = 1.0$, $K_{cb(end)} = 0.35$

3. Assumed variables

Length of growth stages (L)

2006	2007
L Initial: 20 days	L Initial: 25 days
L Developmental: 30 days	L Developmental: 30 days
L Mid Season: 25 days	L Mid Season: 35 days
L Late Season: 20 days	L Late Season: 25 days

4. Sample Equations

Climate adjusted K_{cb}, necessary for 2006 mid season hot, dry weather (avg RH_{min}=35%)
$K_{cb(adj)} = K_{cb(table)} + [0.04(U-2)-0.004(RH_{min}-45)](h/3)^{0.3}$

K_{cb} interpolation for day 27 of developmental stage, similar process for late stage
$K_{cb(27)} = K_{cb(ini)} + [(27-L_{dev})/L_{dev}] (K_{cb(mid)}-K_{cb(ini)})$

Determination of Soil Evaporation Coefficient, K_e

1. Measured Variables

Precipitation (P)

Precipitation less than 0.2ETo not considered unless part of a multiday event

Residue Cover, for determine of covered soil surface (f_c)

No-Till: 84-96%

Chisel: 20-42%

0-10 cm soil water retention properties

No-till	Chisel
Field Capacity θ: 0.31	Field Capacity θ: 0.28
Wilting Point θ: 0.11	Wilting Point θ: 0.10

2. Table Look-Up Variables

0-10 cm soil water retention properties (FAO-56: Table 19)

Readily Evaporable Water: 9.5 mm

3. Assumed variables

Maximum soil surface covered by vegetation (f_c): 0.80

4. Sample Equations

Soil Evaporation Coefficient

$$K_e = K_r (K_{cmax} - K_{cb})$$

$$K_{cmax} = 1.2 + [0.04(U-2)-0.004(RH_{min}-45)](h/3)^{0.3}$$

$$K_r = \frac{TEW - De}{TEW - REW} \qquad K_r = 1, \text{ when } De < REW \text{ (soil near saturation)}$$

Total Evaporable Water (TEW)

$TEW = (\theta_{FC} - 0.5\theta_{WP})\, Ze$ (Ze is depth of evaporation, 100 mm)

Daily Evaporation (De) (mm)

$$De_i = De_{i-1} - P_{ef} + \frac{K_e(ETo)}{1 - f_c} \qquad (De_{i-1} = 0, \text{ when } \theta \text{ is at Field Capacity})$$

Fraction of soil surface covered by vegetation (f_c):

Initial $f_c = (0.5)(\%\text{ residue cover})$

Interpolation for day 27 of developmental stage, process similar for late stage

$f_{c(27)} = f_{c\,(ini)} + [(27-L_{dev})/L_{dev}]\,(f_{c(max)}-f_{c(ini)})$

Determination of Soil Water Stress Coefficient, K_s

1. Measured Variables

Precipitation (P)
Precipitation less than 0.2ETo not considered unless part of a multiday event

0-20 cm soil water retention properties

No-till	Chisel
Field Capacity θ: 0.31	Field Capacity θ: 0.28
Wilting Point θ: 0.11	Wilting Point θ: 0.10

2. Table Look-Up Variables

20-100cm soil water retention properties (clay) (FAO-56: Table 19)
Field capacity θ: 0.34
Wilting Point θ: 0.23
Fraction of available water than can depleted before plant water stress occurs (p)
(FAO-56: Table 22)
$p_{(sorghum)} = 0.55$
This value is adjusted for special conditions (equations shown below)

3. Assumed variables

Effective plant rooting depth (Zr): Maximum = 1.2 m
Assumed decline in effective depth starting with leaf senescence in mid August.

4. Sample Equations

Soil Water Stress Coefficient

$$K_s = \frac{TAW - Dr}{TAW - RAW} \qquad K_s = 1\text{, when } Dr < RAW$$

Total Available Water (TAW)

$TAW = (\theta_{FC} - \theta_{WP})\, Zr$ (Zr varies over time. When Zr reaches subsoil, both surface and subsurface water contents must be considered)

Readily Available Water (RAW)

$RAW = p(TAW)$

$p = 0.55$ under standard conditions
$p = 0.55 + 0.04[5 - (K_{cb} + K_e)ETo]$ to consider weather conditions
$p = \{0.55 + 0.04[5 - (K_{cb} + K_e)ETo]\}0.95$ when roots in clayey soil

Daily Evapotranspiration (Dr) (mm)

$Dr_i = Dr_{i-1} - P_{ef} + (K_{cb} + K_e)ETo$ ($Dr_{i-1} = 0$, when θ is at Field Capacity)

Appendix D - Neutron Probe Expanded Results

Table D.1 Neutron probe measured water contents and pairwise treatment comparisons from the 2006 growing season.

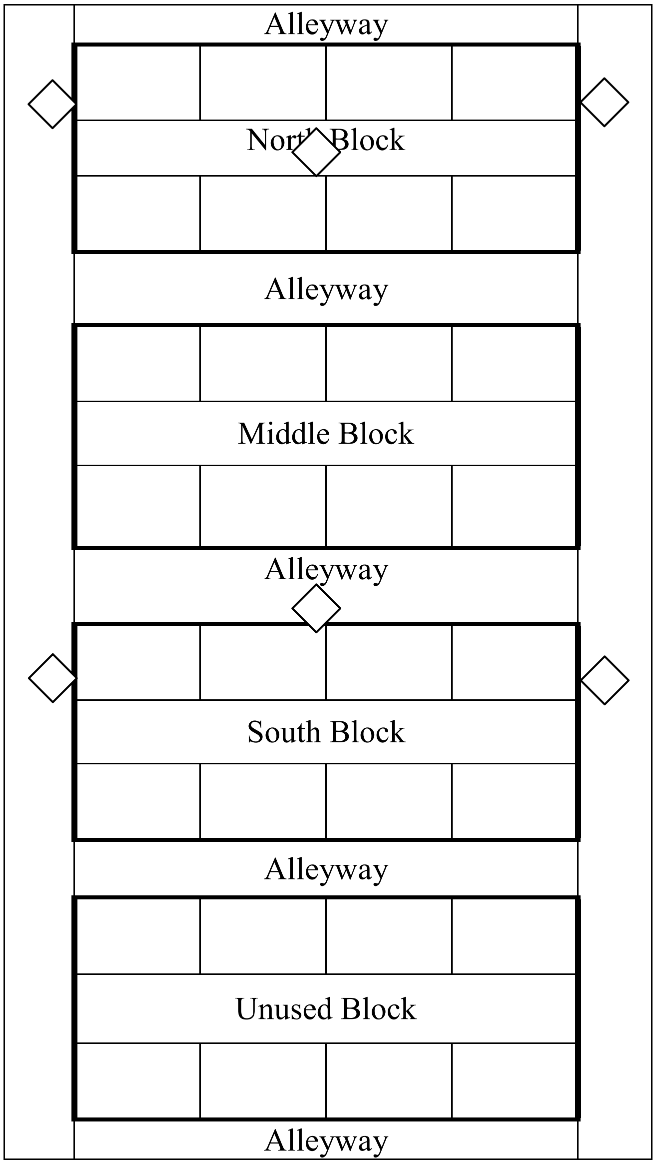
		6/02	6/07	6/19	6/27	7/10	7/14	7/26	8/07	8/23	9/06	9/25	10/27
Depth	Treatment	----------	----------	----------	----------	Volumetric Water Content (cm^3 cm^{-3})				----------	----------	----------	----------
15	Chisel	0.25	0.28	0.25	0.18	0.13	0.24	0.11	0.10	0.15	0.16	0.13	0.20
	No-Till	0.24	0.28	0.25	0.17	0.11	0.27	0.10	0.08	0.16	0.17	0.12	0.22
	p-value	0.7407	0.9470	0.9823	0.6444	0.2866	0.0839	0.5266	0.4994	0.5406	0.5692	0.6600	0.3558
30	Chisel	0.35	0.35	0.33	0.30	0.26	0.28	0.23	0.23	0.24	0.27	0.26	0.26
	No-Till	0.34	0.35	0.33	0.30	0.24	0.29	0.25	0.22	0.24	0.28	0.25	0.27
	p-value	0.6444	0.9119	0.8769	0.7407	0.2183	0.3772	0.4476	0.2702	0.7910	0.5129	0.7080	0.8004
45	Chisel	0.37	0.36	0.35	0.33	0.28	0.29	0.27	0.26	0.26	0.28	0.28	0.28
	No-Till	0.36	0.37	0.37	0.34	0.28	0.30	0.27	0.26	0.26	0.29	0.28	0.28
	p-value	0.8251	0.6600	0.4861	0.3058	0.9128	0.8251	0.7407	0.9119	0.9647	0.5406	0.9294	0.6375
60	Chisel	0.35	0.35	0.35	0.34	0.28	0.31	0.26	0.25	0.26	0.29	0.28	0.29
	No-Till	0.36	0.36	0.36	0.35	0.28	0.30	0.27	0.26	0.26	0.28	0.28	0.27
	p-value	0.7243	0.6290	0.5406	0.3452	0.6388	0.3153	0.6600	0.9294	0.6290	0.4476	0.5129	0.3301
75	Chisel	0.34	0.34	0.34	0.33	0.28	0.31	0.27	0.25	0.27	0.29	0.28	0.29
	No-Till	0.34	0.34	0.35	0.35	0.28	0.30	0.27	0.25	0.25	0.28	0.27	0.27
	p-value	0.9294	0.6600	0.4113	0.4353	0.5971	0.4602	0.9823	0.8769	0.4232	0.2966	0.4353	0.2082
90	Chisel	0.33	0.33	0.33	0.33	0.31	0.32	0.28	0.26	0.27	0.30	0.29	0.30
	No-Till	0.34	0.34	0.34	0.34	0.31	0.33	0.28	0.26	0.26	0.28	0.28	0.27
	p-value	0.9119	0.5548	0.4994	0.5406	0.5181	0.5548	1.000	0.9119	0.3997	0.3250	0.5692	0.2150
105	Chisel	0.33	0.33	0.33	0.33	0.32	0.32	0.30	0.28	0.29	0.30	0.29	0.30
	No-Till	0.33	0.34	0.34	0.34	0.33	0.34	0.30	0.27	0.27	0.29	0.29	0.29
	p-value	1.0000	0.4861	0.4113	0.5129	0.4810	0.4476	0.9470	0.8423	0.4730	0.7573	0.9823	0.6824
120	Chisel	0.34	0.33	0.33	0.33	0.32	0.33	0.33	0.30	0.30	0.31	0.31	0.32
	No-Till	0.34	0.34	0.34	0.34	0.33	0.34	0.33	0.30	0.30	0.31	0.31	0.31
	p-value	0.9119	0.7573	0.6758	0.7243	0.5568	0.6918	0.9294	0.9647	0.8079	0.8251	0.9823	0.8166
135	Chisel	0.34	0.34	0.34	0.34	0.33	0.33	0.32	0.32	0.32	0.32	0.32	0.32
	No-Till	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.33	0.32	0.32	0.33	0.32
	p-value	0.9823	0.8097	0.8423	0.6758	0.7713	0.6918	0.5839	0.5548	0.8251	0.7243	0.5987	0.8018
150	Chisel	0.34	0.33	0.34	0.33	0.33	0.34	0.33	0.33	0.32	0.32	0.32	0.33
	No-Till	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.33	0.33	0.34	0.34
	p-value	0.8351	0.7741	0.7407	0.6918	0.5373	0.6600	0.5692	0.4113	0.4476	0.4353	0.3452	0.5533

Table D.2 Neutron probe measured water contents and pairwise treatment comparisons from the 2007 growing season.

		5/26	6/03	6/19	7/02	7/16	7/27	8/09	8/25	9/12	10/03
Depth	Treatment	Volumetric Water Content ($cm^3\ cm^{-3}$)									
15	Chisel	0.28	0.31	0.28*	0.33	0.22	0.21	0.15	0.18	0.21	0.21
	No-Till	0.30	0.32	0.32*	0.33	0.22	0.22	0.15	0.17	0.22	0.23
	p-value	0.1172	0.7413	0.0280	0.9706	0.6274	0.6164	0.8218	0.5124	0.5555	0.2861
30	Chisel	0.34	0.36	0.35	0.36	0.33	0.31	0.28	0.26	0.27	0.27
	No-Till	0.36	0.36	0.36	0.37	0.34	0.32	0.28	0.25	0.26	0.27
	p-value	0.3072	0.6660	0.4208	0.4028	0.3832	0.6990	0.9102	0.9266	0.9065	0.8486
45	Chisel	0.36	0.37	0.37	0.37	0.36	0.36	0.31	0.28	0.28	0.29
	No-Till	0.38	0.37	0.37	0.38	0.37	0.34	0.31	0.28	0.28	0.29
	p-value	0.3958	0.9138	0.7396	0.6449	0.3072	0.2178	0.8111	0.9376	0.8076	0.8468
60	Chisel	0.35	0.35	0.35	0.36	0.35	0.35	0.31	0.28	0.27	0.29
	No-Till	0.36	0.36	0.36	0.36	0.36	0.36	0.32	0.28	0.28	0.29
	p-value	0.6807	0.7672	0.5467	0.7795	0.5555	0.5366	0.5585	0.7175	0.5870	0.7158
75	Chisel	0.34	0.33	0.34	0.34	0.33	0.33	0.31	0.28	0.28	0.29
	No-Till	0.34	0.35	0.35	0.35	0.34	0.34	0.33	0.29	0.29	0.30
	p-value	0.5931	0.4294	0.5096	0.4123	0.4822	0.4393	0.3461	0.3686	0.3159	0.6321
90	Chisel	0.33	0.33	0.33	0.33	0.32	0.33	0.33	0.30	0.30	0.31
	No-Till	0.34	0.34	0.34	0.34	0.33	0.34	0.34	0.31	0.31	0.32
	p-value	0.3430	0.4703	0.5251	0.3708	0.4796	0.4508	0.2604	0.3409	0.3399	0.4637
105	Chisel	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.30	0.31
	No-Till	0.34	0.34	0.34	0.34	0.33	0.34	0.34	0.33	0.32	0.33
	p-value	0.2906	0.2143	0.2730	0.3072	0.2122	0.2712	0.2997	0.2048	0.2337	0.1769
120	Chisel	0.32	0.33	0.33	0.32	0.32	0.33	0.33	0.32	0.32	0.32
	No-Till	0.34	0.34	0.34	0.34	0.33	0.34	0.34	0.34	0.33	0.33
	p-value	0.3588	0.4822	0.4650	0.4753	0.3524	0.4663	0.4559	0.3101	0.3843	0.4087
135	Chisel	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
	No-Till	0.33	0.33	0.33	0.33	0.33	0.33	0.34	0.33	0.33	0.33
	p-value	0.6465	0.6433	0.5618	0.7917	0.8847	0.7465	0.6874	0.7023	0.6401	0.7448
150	Chisel	0.32	0.32	0.33	0.32	0.33	0.33	0.33	0.33	0.33	0.32
	No-Till	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
	p-value	0.4663	0.7294	0.5342	0.5166	0.6211	0.5096	0.8486	0.7345	0.720	0.5308

Appendix E - Perched Water

Figure E.1 Location of monitoring wells.



◇ - represents one of six well locations. Wells were named by location where 'NW' is in northwest corner, NC is in center of north block and so on. The six well were located around field site rather than in any particular field plot.

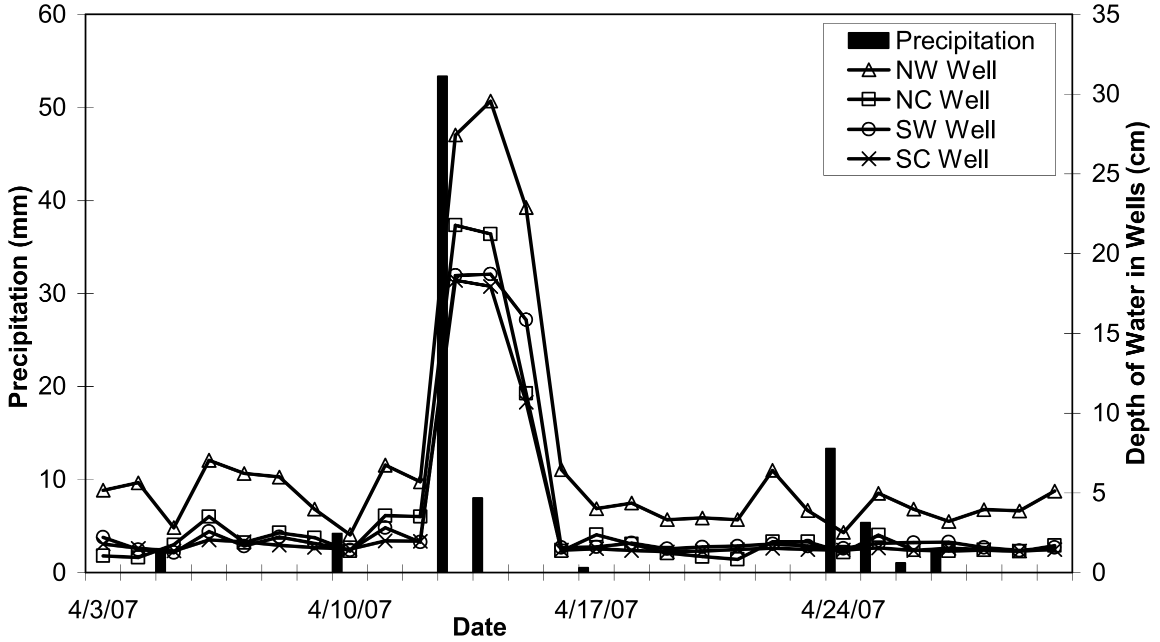


Figure E.2 Daily maximum depth of water in monitoring wells during April 2007. During April, neither the NE nor SE pressure transducers were reading properly.

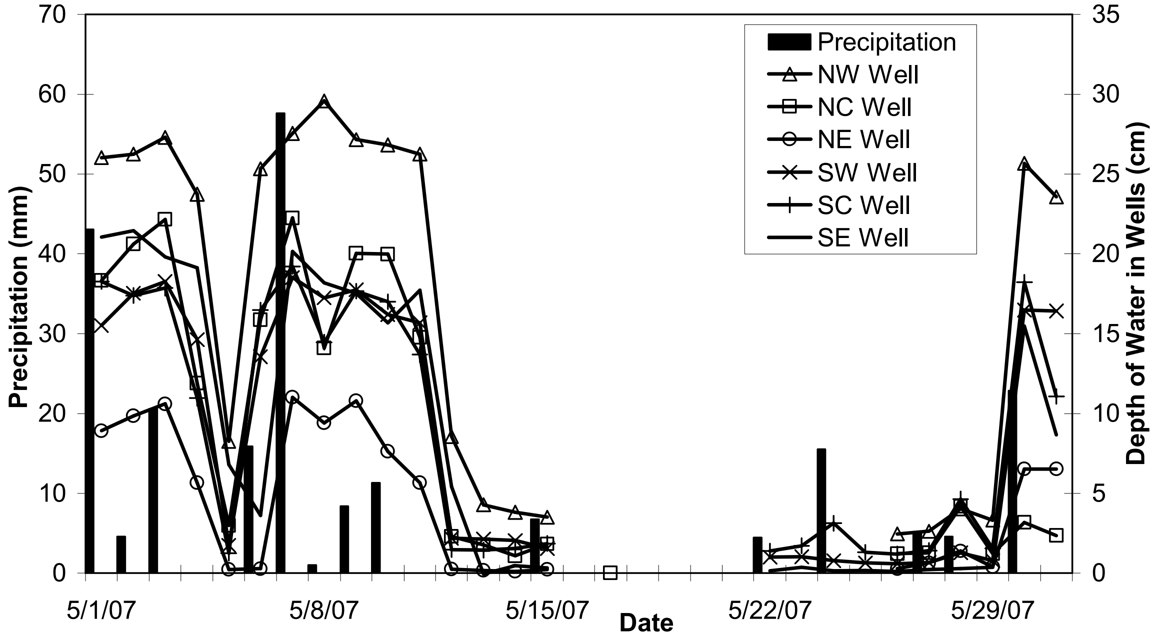


Figure E.3 Daily maximum depth of water in monitoring wells during May 2007. Pressure transducers were removed from field for week while cultivation and planting occurred.

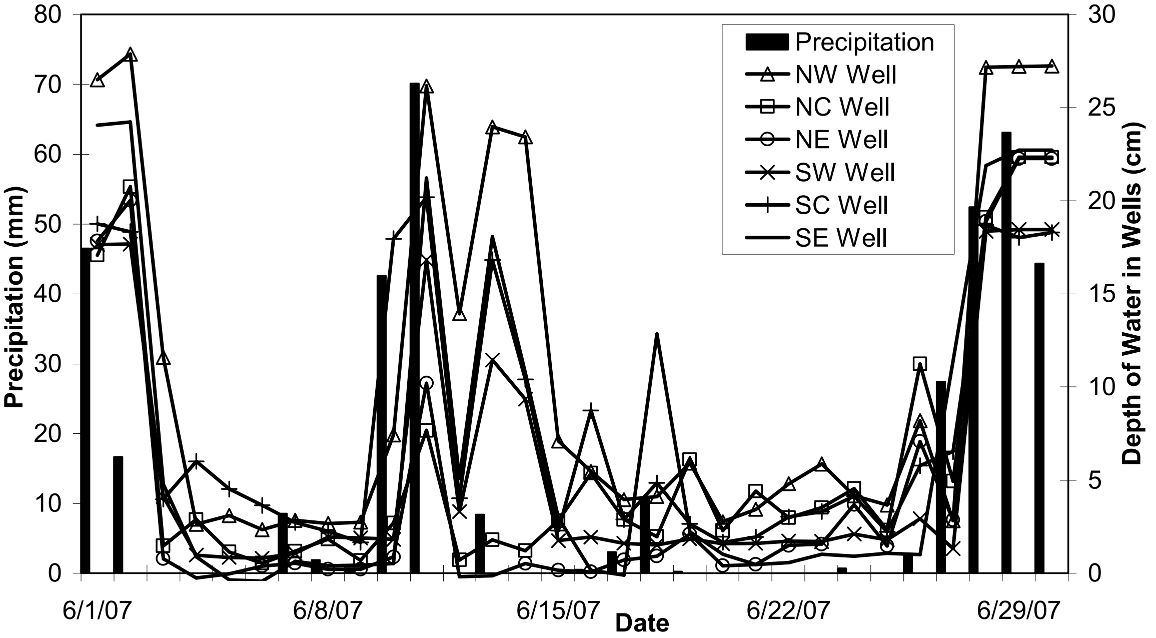


Figure E.4 Daily maximum depth of water in monitoring wells during June 2007.

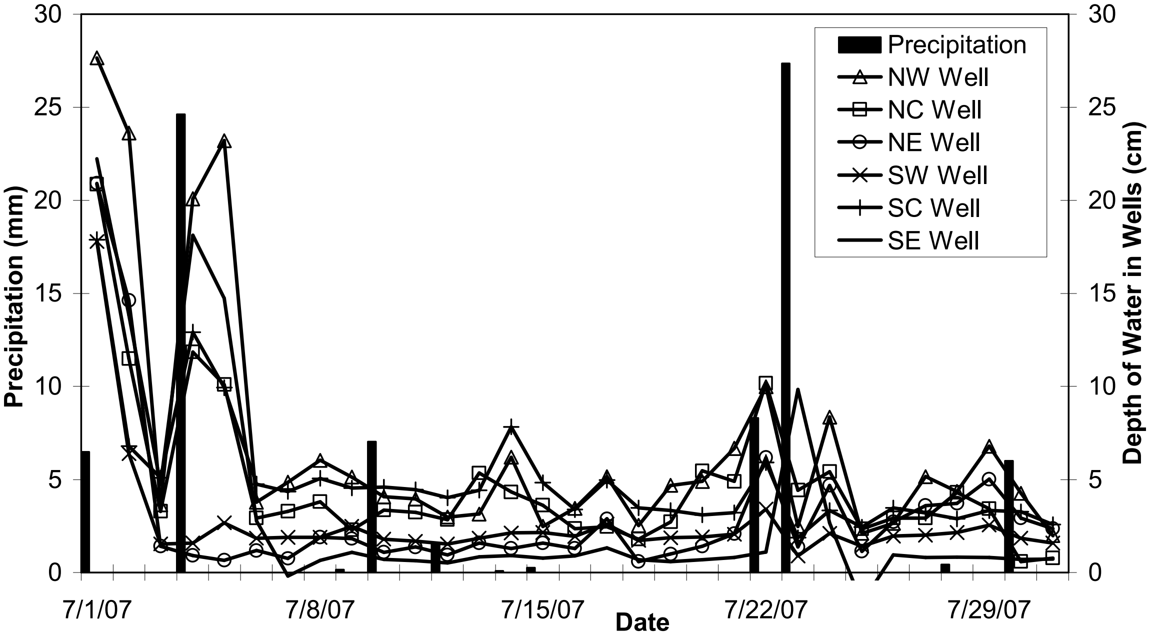


Figure E.5 Daily maximum depth of water in monitoring wells during July 2007.

Appendix F - Date to Day of Year Table

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
JAN	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
FEB	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59			
MAR	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90
APR	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	
MAY	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151
JUN	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	17	278	179	180	181	
JUL	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212
AUG	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243
SEPT	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	20	261	262	263	264	265	266	267	268	269	270	271	272	273	
OCT	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	203	304
NOV	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	
DEC	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	354	365