Project title: Quantifying Evaporation, Crop Evapotranspiration, and the Water Balance for Tilled and Untilled Fields

Final Report

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I. ACKNOWLEDGEMENTS

On behalf of the project team, I would like to express my sincere appreciation to the Nebraska Environmental Trust for providing financial support and to the Nebraska Department of Natural Resources for their support and contributions on this project.

Respectfully submitted,

Suat Irmak

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SUMMARY

There are over 8 million acres of irrigated land in Nebraska and many of these are managed under no-till practices. The impact of no-till field versus tilled fields on agricultural water use under Nebraska's climate, soils, and irrigation management practices have not been evaluated and some misconceptions exist today that no-till practices can harm the water resources. Thus, the impact of no-till practices on Nebraska's water supplies has become a key question that needs to be clarified to water and land managers in the state. The goals of this project is to quantify the effect of no-till versus disk-till practices on the water use, soil hydraulic properties, water balance components, and crop growth and yield. The project findings and knowledge will be transferred to clientele through appropriate means to help growers and their advisors to enhance irrigated and dryland agricultural productivity in Nebraska and enhance the environmental benefits.

The study was conducted at two sites, one in southeast Nebraska and the other in south central Nebraska. The site in south east Nebraska is near Geneva in Fillmore County and the site in south central Nebraska is near Holdrege in Phelps County. Two producers, one with no-till fields and the other with tilled were identified at each site and recruited to collaborate in the project. Each collaborator had about 130-acre center pivot-irrigated field. The no-till fields had been in continuous no-till for at least 8 years. At each site, two fields were close to each other (within 1/2 mile), had similar soil texture, slope, and other soil characteristics, similar center pivot irrigation systems that have similar sprinkler package and water delivery capacity and application efficiency, planted the same corn hybrids and soybean variety, same planting row direction and planting population, and used the same pesticide, herbicide, and insecticide applications when applicable. The same irrigation management practices were applied in both fields. The only difference between the two fields were the tillage practice (no-till vs. disk-till), which was the treatment effect. In both fields, the fertilizer applications were similar as much as possible and were based on University of Nebraska-Lincoln Extension recommendations. Irrigation date and amounts were recorded. In addition,

the collaborator kept a record of all other soil and crop management practices. The assistance of the collaborators were compensated annually and included in the budget.

A Bowen ratio energy balance system (BREBS) was installed in each field to measure crop evapotranspiration and other surface energy balance components such as net radiation, sensible heat, soil heat flux, incoming shortwave radiation, air temperature, relative humidity, soil temperature, wind speed and direction, and precipitation on an hourly basis. Soil water content (SWC) in each field was measured at 1 ft increments up to 6 ft on an hourly basis. The *SWC* measurements were used to quantify the amount of soil water depletion from each tillage practice at the end of the growing season and calendar year. It was assumed that the effective crop root zone for both corn and soybean is 4 ft. The soil water measurements in the two additional layers (5 and 6 ft) were used to quantify deep percolation below the crop root zone. Quantifying deep percolation is very important because ultimately precipitation that deep percolates recharges the ground water reservoir. The BREBS was operated on an annual basis and sampled all variables every 60 sec and averaged and recorded each variable on an hourly basis. Thus, all variables wee measured for growing season as well as non-growing (dormant) season in each field.

The Geoprobe sampling was conducted in the 10-20 ft layer beneath the sites to document the rate of water transfer in the intermediate vadose zone and how it is influenced by tillage practices. The soil infiltration rate was quantified with ring infiltrometers. Runoff, bulk density, hydraulic conductivity, aggregate stability, particle size distribution, wetting front suction, and organic matter content were measured. The infiltration rate and other soil physical properties were measured on selected dates. Soil samples were taken to determine the particle size distribution in each field. Runoff from selected catchments in each field was measured with flumes equipped with electronic transducers and loggers. The soil physical properties and other data collection on selected variables were also repeated at UNL long-term tillage research site at Rogers Memorial Farm near Lincoln for comparing the data to that collected at the selected field sites for this project. During the duration of the study (2008-2011), we studied two

soybean years and one corn year. The study is continuing using project director's (Dr. Suat Irmak) other resources to obtain one more year of data for corn so that we can have two years of data for both corn and soybean.

The differences in total evaporation (*E*) from the soil surface between the no-till and conventional till fields were quantified as a residual of the water balance equation. Crop height and leaf area index measurements were made every 7-10 days in each field. These data are used in remote sensing/satellite algorithm model to adjust the surface roughness for heat transfer and to develop vegetation indices which takes into account the effects of background soil and soil wetness. Crop residue cover was measured with frequent intervals on selected days. Crop yield was measured from each field at the end of the growing season using the combine yield monitor data from the collaborators.

This report presents some preliminary data on the differences in climatic variables and evapotranspiration measured above no-till and disk-till fields. The average daily air temperature, relative humidity, and evapotranspiration were higher over disk-till fields especially during the crop growing season. The difference in cumulative evapotranspiration in no-till and disk-till fields measured from July 9, 2008 to April 30, 2011 was 1,161 mm. The greatest differences in actual crop evapotranspiration between the no-till and disk-tilled fields occurred during early growing season when the canopy was partially closed due to greater soil evaporation in the disk-tilled fields. No-till systems influenced the hydraulic properties of soils and the soil surface conditions. The result of long-term use of no-till could be higher infiltration and lower runoff from rainfall and irrigation. This potential was investigated in the study. Cumulative runoff data showed more runoff on tilled fields, which aligns with findings from the hydraulic conductivity from these fields. Surface satiated hydraulic conductivity was significantly higher for no-till at the center pivot irrigated sites with 6.2 cm h^{-1} and 8.2 cm h^{-1} measured for no-till and 3.9 cm h^{-1} and 2.8 cm h^{-1} for tilled. However, the dryland corn had significantly higher hydraulic conductivity on the tilled plot (46.3 cm h^{-1}) compared to the no-till (8.3 cm h^{-1}) plot. This discrepancy may be due to soil shrinkage causing surface cracks. Overall, no-till fields had higher hydraulic

conductivity and lower runoff. No consistent differences in plant growth and yield appear in the observed data. More in-detail data analyses and interpretation of the project findings will be published in a series of refereed journal articles with the acknowledgements to the Nebraska Environmental Trust and the copies of the journal articles will be provided to the Trust leadership.

1. INTRODUCTION

1.1 Background

The water managers of Nebraska are currently working very hard to reduce the consumptive use of water in agriculture so that the use of the state's streams and aquifers can be sustained for many years into the future. If these efforts are to be effective, the causes of increased consumptive use must be accurately identified. Many allege that the decrease in flow rates seen in many of the state's streams are as a result of conservation tillage practices such as no-till farming. There are over eight million irrigated acres in the state and many of these are managed under no-till practices. Thus, the impact of conservation tillage practices on Nebraska's water supplies has become a key question that needs to be clarified to water and land managers in the state. The seasonal and annual evaporation from a no-till field versus tilled fields and the differences in water use efficiency under these different tillage practices have not been evaluated for Nebraska's climate, soils, and irrigation management practices.

Evaporation from agricultural fields is energy and aerodynamically-driven process. The loosening of surface soil by tillage causes changes in the energy reflection and water transmission properties and water storage capacity of the soil. Therefore, the rate of evaporation from tilled soil will be different from that of untilled soil. Loosening of the soil surface increases surface roughness which reduces albedo (surface reflectance) and increases potential evapotranspiration by concentrating heat in the surface soil layers. The roughness also increases the surface area of soil exposed to the surrounding microclimate and will result in greater wind penetration into the soil,

increasing evaporation and creating a suitable environment for wind erosion. Soil physical and hydraulic properties are also altered by tillage. Bulk density and pore size distribution associated with loosening cause soil suction (matric potential) to change at any given volumetric water content and, thus, will change hydraulic conductivity. Limited studies have been conducted on the tillage effect on the infiltration rate dynamics of soil. Higher infiltration rates have been reported for untilled soils compared to tilled soils. The infiltration rate is extremely variable in space and time. It also varies within the same tillage practice between the dry conditions versus wet soil surface conditions. The presence of cracks in the dry surface soil can increase the infiltration rate as compared to the wet soil surface. There may be conditions where the infiltration rate can be higher in tilled soil under dry conditions versus untilled soil with wet surface soil. Soil evaporation from residue-covered soils and bare soils are also influenced differently by climate and soil texture.

In addition, time-dependency of evaporation from tilled versus untilled soils is critical and must be taken into account when assessing water savings (differences in evaporation) between tilled and untilled soils. Unfortunately, time-dependency of evaporation is often neglected by researchers when quantifying evaporation rate differences between tillage practices. Measurement of the evaporation rate at a given time and a single location in the field will result in false conclusions in terms of evaporation rate differences between the tilled and untilled soils. For example, when soil is tilled, the initial rate of evaporation will increase as a result of decreased albedo (surface reflectance), increased surface area exposed to the microclimate, and greater penetration of wind into the loose and rough surface layer of tilled soils. Following this, water is rapidly lost from the upper soil layer and is replenished more slowly in the tilled than in the untilled soil because of the decreased unsaturated hydraulic conductivity of the loosened soil layer. Therefore, the top few inches of the tilled layer will dry out more rapidly than the corresponding layer of the untilled soil. This dry layer acts as a barrier to both liquid and water vapor flow to the surface and reduces further evaporation. This decrease in evaporation is greater in tilled than untilled soil

because the untilled soil permits liquid flow from the interior of the soil to the surface for a longer period due to the intact soil structure. The breaking of capillaries by tillage reduces the rate of water transfer in the soil profile. Thus, for a period of time the evaporation rate from untilled soil will be greater than from the tilled soil.

With time, the surface layer of the untilled soil also dries out and the depth to liquid water moves to deeper soil layers. The dry layer that develops at the surface of the untilled soil is less conductive to water than that created by tillage. When the drying front penetrates into the deeper untilled soil layers, the less porous dry surface layer permits less vapor flow compared with an equal depth of the more porous tilled layer. Consequently, after a period of time, the evaporation rate from the tilled soil begins to exceed that from the untilled soil. This process is schematically shown in Figure 1. For a short time after tillage, the evaporation rate from tilled soil exceeds that from the untilled soil. Later, with the rapid formation of a dry layer by the accelerated drying of the tilled surface, evaporation from tilled soil lags behind that from the untilled. Eventually, when a dry layer also forms at the surface of untilled soil, the evaporation rate from tilled soil again exceeds that from untilled.

Similar physical dynamics and characteristics exist in evaporation rate differences between bare versus residue-covered soil. Initially, the evaporation rate from residue-covered soil is lower than that from bare soil. This is because residue cover (i) reduces energy reaching the soil surface and the vapor pressure at the soil surface by reflecting or intercepting solar radiation, and (ii) reduces vapor diffusion from the site of evaporation to the surrounding atmosphere by increasing the thickness of the non-turbulent air layer above the soil surface. However, the higher initial evaporation rate from bare soil compared with that from residue-covered soil lowers the water content of the surface layer, with a concomitant decrease in unsaturated hydraulic conductivity and hence evaporation rate. As evaporation continues for a period of time, at some point the evaporation rate from bare soil equals that from residue-covered soil and/or becomes lower as shown in Figure 1. As the surface drying of bare soil continues, a dry layer in the form of natural soil mulch is formed at the

surface. The evaporation rate from the bare soil falls below that from the residue-covered soil because the surface soil remains wetter under the residue and water is supplied from lower layers to the surface for a longer period of time. Thus, the dynamics of the relative evaporation rates from residue-covered and bare soil determines the time course of evaporation reduction with residue mulches.

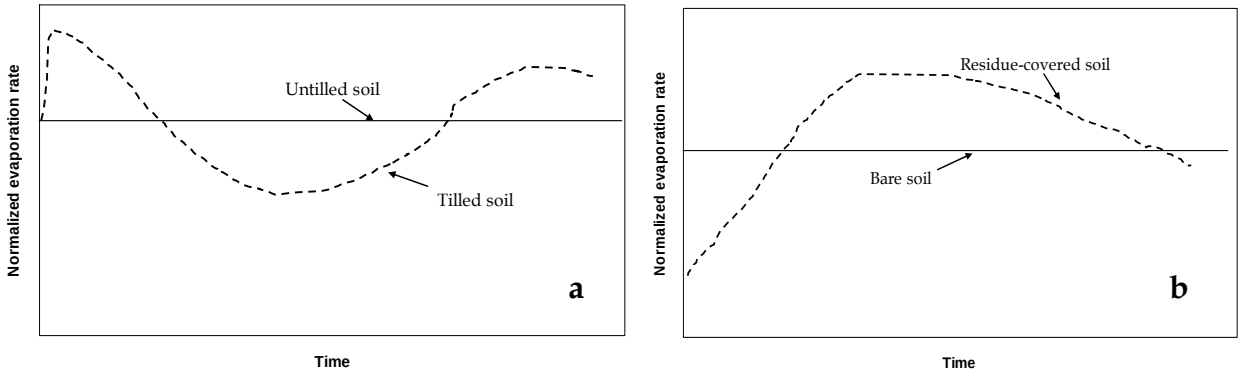


Figure 1. Schematic representation of evaporation from tilled versus untilled soil (a), and evaporation from residue-covered soil relative to that from bare soil.

The aforementioned findings suggest that the duration and magnitude of the fluctuation in evaporation between the tilled versus untilled and bare versus residue-covered soil, which determines the course of evaporation reduction with no till and residue cover, will strongly depend upon the soil texture, time, frequency of wetting by rainfall and irrigation and type of tillage, initial soil water content, amount and type of residue cover, irrigation amount and frequency, climatic conditions and their interactions. Therefore, it is extremely crucial to conduct field experiments that are sufficiently long (e.g., monthly seasonal or annual with multiple years) to measure key components of soil-water-crop-atmosphere dynamics and variables to quantify differences in evaporation between tilled and untilled crop fields. Furthermore, since there are many internal and external factors that drive the evaporation process, it may not be feasible or even acceptable to measure the evaporation rate for a short period of time at a few locations in tilled and untilled soils. The main components of water

balance in tilled and untilled fields will be measured to quantify evaporation difference as residuals of the water and energy balance.

1.2 Project Goals and Objectives

The goals of this project is to quantify the effect of one of the most important soil management practices (tillage) on the water availability, soil hydraulic properties (infiltration, bulk density and organic matter content), water balance components (run-off, deep percolation), ET_c and crop parameters and yield. The project also aims quantify the water use differences between the no-till and conventional tillage (disk till) for the state's most commonly used cropping pattern, corn and soybeans in rotation. The **specific objectives** were as follows**:**

- Measure ET_c from untilled and tilled crop fields with a corn-soybean rotation.
- Quantify growing and non-growing (dormant) season evaporation from tilled and untilled crop fields.
- Measure soil physical properties and hydrologic balance components such as soil hydraulic properties and infiltration rate, bulk density, organic matter content, deep percolation, soil water status and runoff from selected subsections of two fields.
- Develop methodologies to estimate ET_c from tilled and untilled corn and soybean fields using airborne and satellite remote sensing data.
- Measure crop growth parameters such as leaf area index, crop height, biomass production and crop yield for tilled and untilled cropping systems.
- Use the experiment sites as demonstration sites for public education and enable information transfer to Nebraskans. Utilize the data, experience, and knowledge in community education and outreach to enable citizens to be aware of the differences in tilled and untilled crop management and their interactions, and their impact on agricultural water management.

- Develop Extension, educational and outreach materials to disseminate project progress and outcomes and publish project findings in scientific refereed journals.

1.3 Rationale and Significance

The benefits of no-till practices, such as energy savings due to reduced field traffic, reduced dust emission from agricultural fields, reduced wind and water erosion, enhanced soil quality (structure, macroporosity, infiltration) and organic matter accumulation, and soil temperature moderation have been documented for many years. However, there are fundamental gaps in knowledge of the impacts no-till practices on crop water use. The effect of different tillage practices on soil hydraulic properties and infiltration, runoff, deep percolation and other water balance components have not been sufficiently documented for Nebraska soil, climate and crop management conditions. Until we have this understanding we cannot be sure that we are focusing our management efforts in the right direction. In this project, the annual, seasonal, monthly and weekly crop evapotranspiration (ET_c) losses from the no-till and conventional tilled fields were quantified and the amount of surface evaporation difference between the two tillage practices determined. Differences in soil physical properties and hydrologic balance components of the two tillage practices for a center pivot-irrigated corn-soybean rotation were measured. Methodologies were developed to estimate ET_c from both fields using airborne and satellite remote sensing data. The project findings and knowledge will be transferred to clientele through appropriate means to help growers and their advisors to enhance irrigated and dryland agricultural productivity.

2. METHODOLOGY

2.1. Study Locations

The project was conducted at two sites in Nebraska using producer's fields. The first site was in southeast Nebraska near Geneva in Fillmore County and located about

30 miles east of Clay Center. Two producers from this site (Rick Hughes and Kim Becker) were recruited to collaborate in the study at the beginning of the 2008 crop season. They agreed to stay in the project and let us conduct experiments in their fields for a period of 3 years. Rick Hughes' field was a no-till field that had been on no-till practice for more than five years. Kim Becker's field had been on disk-till for more than five years. The soil at this site is classified as Crete silty clay loam soil (USDA NRCS, 2010) and the slope is about 1.0%. The two fields are about a half a mile away from each other as shown in Figure 2a. The second site was in south central Nebraska was near Holdrege in Phelps County and located about 60 miles west of Clay Center. Two producers from the Holdrege site (Steve Frisells and Bob & Mark Wells) were recruited to collaborate in the study at the beginning of the 2009 crop season. They agreed to stay in the project and let us conduct experiments in their fields for a period of 3 years. Steve Frisells's field was a no-till field that had been on no-till practice for more than 5 years. Bob Wells's field had been on disk-till for more than 5 years. The soil in this area is classified as Holdrege silt loam soil (USDA NRCS, 2010) and the slope is about 0.4%. The two fields are about ½ mile away from each other as shown in Figure 2b.

2.2. Field Management Operations

The cropping system on the fields under this project is corn/soybean rotations. Planting operations during all cropping seasons were coordinated such that the two producers at each site planted their crops on the same day, with the same hybrid, same planting depth, same planting direction (east-west), and all other management practices were made similar as much as possible. The only major difference between the two fields being compared at each site was the tillage practice. Table 1 shows the field management operations during the three years of study.

2.3 Measurements of Microclimate Variables and Soil Water

The goal of these measurements is to quantify growing and non-growing (dormant) season evapotranspiration from no-till and tilled crop fields. Measurements of microclimate variables were made using a deluxe version of a BREBS (Radiation and Energy Balance Systems, REBS, Inc., Bellevue, WA) installed at the four selected producers' fields in Fillmore County and Phelps County as shown in Figure 2a-b.

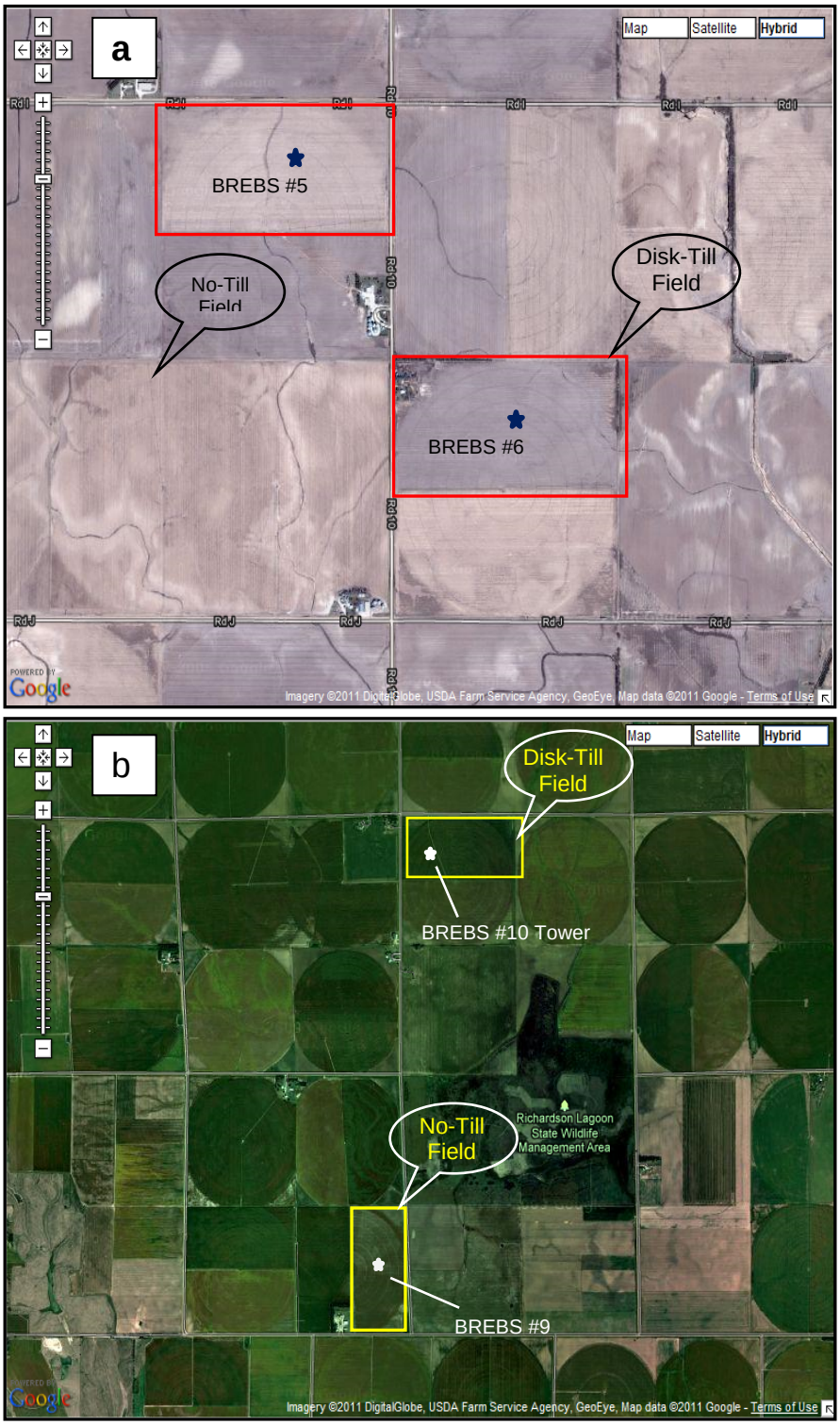


Figure 2. Location of study sites. (a) fields at Geneva in Fillmore County and (b) fields at Holdrege in Phelps County.

Table1. Crop management practices, irrigation amounts, and yields at Geneva and Holdrege research sites, 2008 -2010

Parameter	2008 Crop Season (Geneva)		2009 Crop Season (Geneva)	
	Disk-Till	No-Till	Disk-Till	No-Till
Planting date	5/20/2008	5/20/2008	5/03/09	5/04/09
Planting population	180,000	180,000	31,000	31,000
Planting depth	1 in	1 in	1.75 in	1.75 in
Emergence date	5/27-30/2008	5/27-30/2008	5/9-12/09	5/11-15/09
Harvest date	10/03/2008	09/27/2008	11/25/09	11/12/09
Soybean variety	Pioneer 93M11	Pioneer 93M11	-	-
Corn variety	-	-	Hybrid 33D49	Hybrid 33D49
Row spacing	30 in	30 in	30 in	30 in
Plant spacing	9-10 seeds/ft	9-10 seeds/ft		
Total Irrigation	2.4 in	2.6 in	7.5 in	7.5 in
Total Fertilizer	None	None	32% N before planting & N through irrigation	Anhydrous ammonia in fall
Pesticide application	None	Extreme 5/14/08 Roundup 7/2/08		
Average yield	64.4 bu/ac	64.4 bu/ac	232 bu/ac	216 bu/ac
Parameter	2010 Crop Season (Geneva)		2010 Crop Season (Holdrege)	
	Disk-Till	No-Till	Disk-Till	No-Till
Planting date	5/6/2010	5/6/2010	5/8/10	5/8/10
Planting population	170,000	170,000	189,000	189,000
Planting depth	1.75 in	1.75 in	1.25 in	0.75 in
Emergence date	5/11-14/2010	5/11-14/2010	5/14-17/08	5/14-17/08
Harvest date	9/28/2010	9/28/2010	9/30/10	9/26/10
Soybean variety	93Y13 Pioneer	93Y13 Pioneer	93Y12 Pioneer	93Y12 Pioneer
Corn variety	-	-	-	-
Row spacing	30 in	30 in	30 in	30 in
Plant spacing	9-10 seeds/ft.	9-10 seeds/ft.	9-10 seeds/ft.	9-10 seeds/ft.
Total Irrigation		3.0 in	4.3 in	3.0 in
Total Fertilizer		VRT on 2/24/2010	60 lb Ph 1lb Zinc	Dry 11-52 0 MESZ
Pesticide application		Envive+Durango on 5/18/10; Sychrony XP and Durango on 6/30/10		Exreme applied 6/4/10
Average yield		70.6 bu/ac	72 bu/ac	65.0 bu/ac

All measurements of microclimate variables were sampled every 30 seconds and recorded on an hourly basis. The following microclimate variables were measured from the BREBS:

1. Actual evapotranspiration
2. Sensible heat
3. Net radiation
4. Incoming and outgoing shortwave radiation at the crop/soil surface
5. Incoming and outgoing long wave radiation at the crop/soil surface
6. Soil temperature
7. Soil heat flux
8. Soil water content and available water every foot up to six ft
9. Rainfall
10. Air temperature
11. Relative humidity
12. Wind speed and direction
13. Actual vapor pressure
14. Barometric pressure

All four Bowen ratio energy balance systems (BREBS) that are used in this project are part of the *Nebraska Water and Energy Flux Measurement, Modeling, and Research Network* (NEBFLUX) (Irmak, 2010). NEBFLUX) is a comprehensive network that is designed to measure surface energy and water vapor fluxes, microclimatic variables, plant physiological parameters, soil water content, surface characteristics, and their interactions for various vegetation surfaces. The NEBFLUX is a network of micrometeorological tower sites that uses mainly the Bowen ratio energy balance systems (BREBS) to measure surface water vapor and energy fluxes between terrestrial agro-ecosystems and microclimate. At present, ten BREBSs and one eddy covariance system are operating on a long-term and continuous basis for vegetation surfaces ranging from tilled and untilled irrigated and rainfed croplands, irrigated and rainfed grasslands, to Phragmites (Phragmites australis)-dominated cottonwood (Populus

deltiodes var. occidentalis) and willow stand (Willow salix) plant communities. The NEBFLUX project will provide good quality flux and other extensive supportive data on plant physiology [leaf area index, stomatal resistance, within-canopy radiation parameters, productivity (yield and/or biomass), and plant height], soil characteristics, soil water content, and surface characteristics to the micrometeorology, water resources engineering, and science community on broad spectrum of agro-ecosystems. The fundamental premise of the NEBFLUX project is to make continuous and long-term (at least ten complete annual cycles for each surface) exchange of water vapor and energy fluxes. In addition to the scientific and research objectives, information dissemination to educate the general public and youth is another important objective and output of the network. This paper describes basic principles and operational characteristics of the NEBFLUX.

The BREBS towers for the NET tillage projects were installed in the middle of the experimental fields with a fetch distance of more than 200 m in all directions (Figures 3-7). In addition, the experimental fields were surrounded with other large irrigated fields in four directions. The BREBS measurements were made throughout the year covering both the growing and non-growing (dormant) season. The Chromel-constantan thermocouple air temperature (Temp) and humidity (RH) probes (Model THP04015 for temp, and THP04016 for RH; REBS, Inc., Bellevue, WA) with a resolution of 0.0055^{o}C for Temp and 0.033% for RH were used to measure Temp and RH gradients. Temperature and RH sensors were located at the center of coaxial anodized aluminum radiation shields and continuously aspirated by brushless 12 volt DC fans at approximately 2.6 m s^{-1} constant air velocity. The temperature sensors for determining RH cavity temperatures are platinum resistance temperature detectors. Each RH sensor is contained in a housing protected by an appropriate filter to prevent contamination. Temperature sensor sensitivities are crucial in the BREB method due to the nature of the method that the gradients of both Temp and RH must be measured with a great accuracy. Small biases between Temp sensors can result in incorrectly determined gradients causing significant errors in crop evapotranspiration. Consequently, it is

desirable to frequently exchange temp and RH sensor locations to remove these biases. Thus, the deluxe BREBS used an automatic exchange mechanism that physically exchanged the Temp and RH sensors at two heights above the canopy. The Temp and RH sensors were exchanged during the last two minutes of each 15 minute interval. The upper exchanger tube that houses the Temp and RH probes is driven down for the last 1st and 3rd 15 minute periods of each hour, and the bottom tube is driven down for the 2nd and 4th 15 minute periods of each hour (Irmak et al., 2007b).

Barometric pressure was measured using a Model 276 Barometric Pressure Sensor (Setra Systems, Inc., Boxborough, MA). Soil heat flux was measured using three REBS HFT-3.1 heat flux plates and three soil thermocouples. Each soil heat flux plate was placed at a depth of 0.08 m below the soil surface. The REBS STP-1 soil thermocouple probes were installed in close proximity to each soil heat flux plate at depths of 0.02, 0.04, 0.06, 0.08, and 0.10 m below the soil surface. Measured soil heat flux values were adjusted to soil temperatures and soil water content as measured using three REBS SMP1R soil moisture probes. One soil moisture probe was installed in close proximity of each soil heat flux plate. Net radiation was measured using a REBS Q*7.1 net radiometer that was installed approximately 4.5 m above the soil surface. The radiometer is sensitive to wavelengths from 0.25 to 60 nμm. The net radiometer was attached to a 5-m long metal arm to extend the radiometer away from the tripod (horizontally to the crop canopy) so that only the net radiation at the canopy surface is measured. Thus, the reflection of heat and radiation from any other instruments that are installed on the tripod is minimized. The radiometer consists of two chromel-constantan (Type E) differential thermocouple junctions that are installed to monitor temperature differences between the core and upper and lower windshields (domes). The net radiometer was supplied with a constant air blown with a fan through a desiccant tube to keep air space inside the dome dry.

Incoming and outgoing shortwave radiation were measured simultaneously using a model REBS THRDS7.1 double sided total hemispherical radiometer that was sensitive to wavelengths from 0.25 to 60 μm. From these measurements, the surface

albedo was calculated. The THRDS7.1 was attached to a 3.5-m long metal arm to extend the radiometer away from the tripod so that only the incoming and outgoing radiation and albedo at the canopy surface were measured. Rainfall was recorded using a Model TR-525 rainfall sensor (Texas Electronics, Inc., Dallas, TX). Wind speed and direction at 3-m height were monitored using a Model 034B cup anemometer (Met One Instruments, Grant Pass, OR) that had a wind speed range of 0-44.7 m s^{-1} with a starting threshold of 0.28 m s^{-1}. All variables were sampled at 30 sec interval and averaged and recorded every hour for energy balance calculations using a Model CR10X datalogger and AM416 Relay Multiplexer (Campbell Scientific, Inc., Logan, UT). All system components were powered by a solar panel and a 12 volt, 140 amp marine battery. The BREBS was closely supervised and general maintenance was provided at least once a week. Maintenance included cleaning the thermocouples and housing units (exchanger tubes), servicing radiometers by cleaning domes, checking/replacing the desiccant tubes and making sure that the radiometers were properly leveled. The radiometer domes were replaced every 3-4 months. In addition, the upper and lower exchanger arms were adjusted as needed as the crop height increased during the season. The lower exchanger tube was kept 0.70 to 0.80 m above the canopy throughout the growing season. The distance between the lower and upper exchanger tubes was kept at 0.90 m throughout the season. The BREBS data were downloaded from the datalogger every week and carefully screened.

Watermark sensors were installed at 12, 24, 36, and 48 inches to supplement the measurements of soil moisture by the BREBS as shown in Figure 8.

No-till

No-till

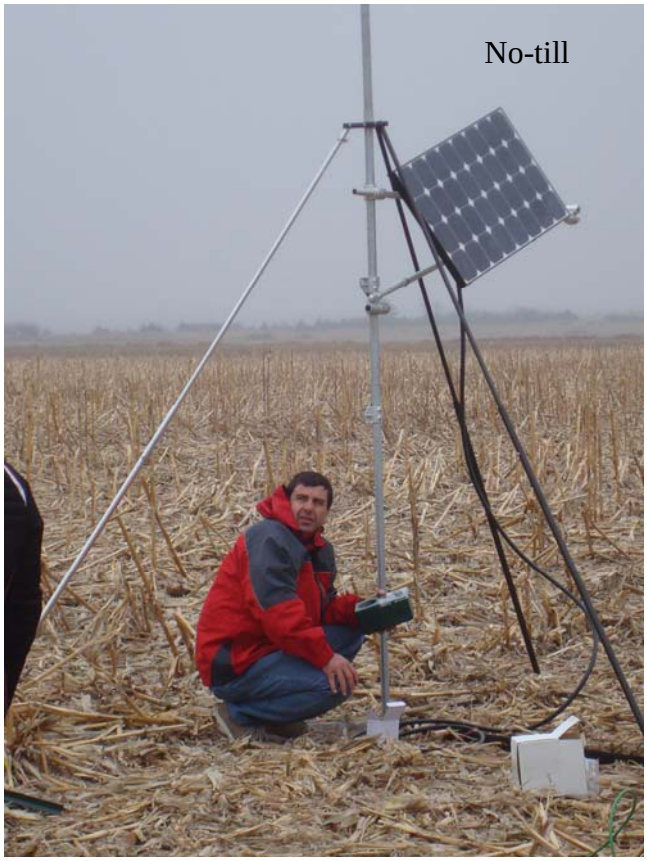


Figure 3. Project team installing a new BREBS in one of the experimental fields

Figure 4. View of BREBS tower installed in a disk-till corn field

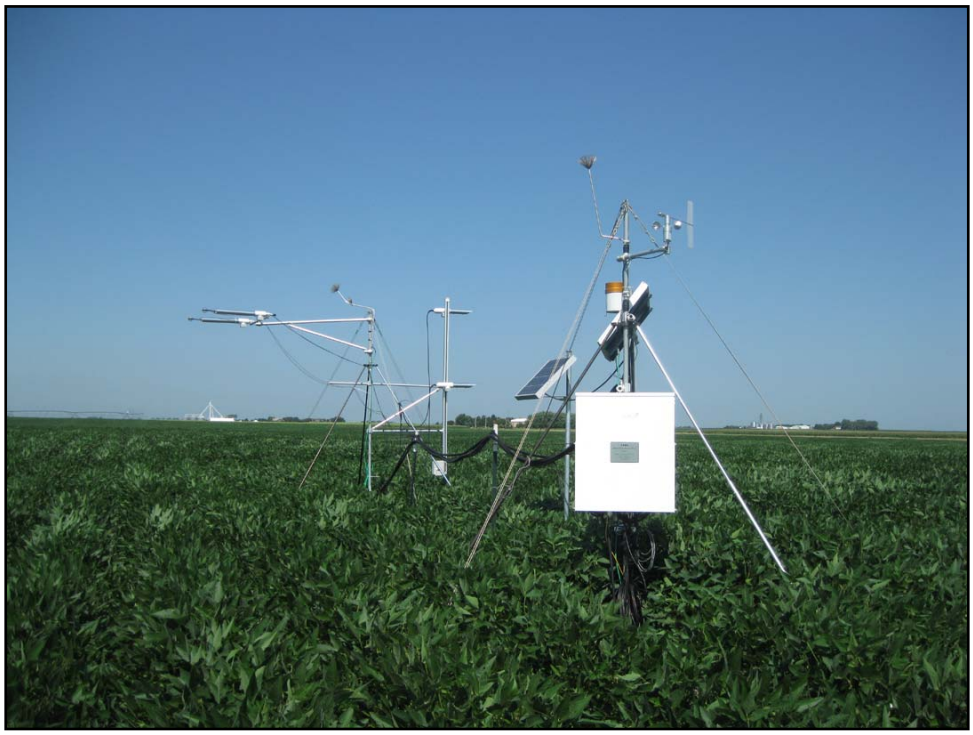


Figure 5. View of BREBS tower installed in a soybean field

Figure 6. View of BREBS tower in the field after crop harvest

Figure 7. View of BREBS tower in the field during winter

Figure 8. View of watermark sensors installed in the field to supplement soil moisture measurements from the BREBS.

2.4 Measurements of Plant Height and Leaf Area Index

In addition to microclimate variables, plant heights and leaf area index (LAI) were measured in all the experimental fields every 7 to 10 days during the entire crop growing period. Both plant height and LAI were measured at 30 sampling points taken randomly about 30 feet radius around the BREBS towers. The LAI was measured using the Plant Canopy Analyzer LAI-2000 (LI-COR, Inc, Lincoln, NE). Figure 9 show plant LAI measurements.

Figure 9. Using the Plant Canopy Analyzer LAI-2000 to measure LAI

2.5 Measurements of Infiltration and Surface Runoff Components

The goal of these measurements is to quantify and compare the effects of no-till and tillage on infiltration, percolation, and surface runoff of rainfall and irrigation water under center-pivot irrigation. Field measurements of infiltration, percolation, and surface runoff and other related variables were taken at the no-till and disk-till experimental fields at both Geneva and Holdrege sites.

2.5.1 Infiltration Tests

The purpose of the infiltration tests was to determine the field saturated hydraulic conductivity at the soil surface and immediately below the depth of the tillage layer (subtillage). Two different methods were used to measure infiltration at the soil surface and subtillage. One is the single ring infitrometer method and the other is a rainfall infiltrometer method. Using the two methods gave us a way to separate the

effect of water flow in macropores because water does not flow in macropores during rainfall until the surface is becomes saturated.

The single ring infiltration measurements were made close to the three micro runoff plots in each field. The infiltrometers were installed 1.5 m upslope of the micro runoff frames, in three consecutive rows, and at places where there had been minimal foot traffic. Before installing the ring infiltrometers for surface infiltration measurements, the measurement areas were prepared by removing loose residue while being cautious not to disturb the surface. Surface residue partially buried in the soil within the perimeter of the ring was left in place. Residue extending beyond the border of the test area was cut before the ring was driven into the soil so as not to create a gap between the metal rim and soil where water could penetrate. For subtillage infiltration measurement, the loose cultivated layer, approximately 15 cm, was removed from the tilled field. The depth of the soil layer removed on the no-till fields was 80% of that removed on the corresponding tilled field to account for a higher bulk density in the no-till surface layer. The test areas with the surface layer removed were vacuumed to avoid obstruction to water pathways by removing loose dirt that may have been displaced from digging.

Installation of the infiltrometer consisted of driving a 14.88 cm diameter ring 15 cm into the ground. A coffee filter was then set in the infiltration ring before water was added to minimize surface disturbance. For each plot, the temperature of water was documented to account for changes in viscosity, then 285 mL of tap water, equivalent to 1.64 cm of depth, was added into the ring and the filter was gently removed. The time was recorded for half the surface to be free from water. If time exceeded three minutes, water was removed with a syringe until half the soil was free from water ponding. Both time and the volume of water removed were recorded. The infiltration measurements at each field were performed in two consecutive days on dry soil without any rain or irrigation between days. Eight measurements were performed at each runoff plot making a total of twenty-four measurements per field.

The inverse form of the Green and Ampt infiltration equation (Green and Ampt, 1911) was used to calculate field satiated hydraulic conductivity, K_s, and is given by:

$$K_s = 1/t\ [F - h_f \Delta\theta \ln (1+F/\ (h_f \Delta\ \theta))]$$

where t = time for water to infiltrate; F = cumulative infiltration; h_f = wetting front pressure head; Δè = change in moisture content. At the time of the field infiltration test, a 136 cm^3 soil sample next to the ring was taken to determine bulk density and initial water content. The length of the bulk density core was 6 cm.

2.5.2 *Satiated Hydraulic Conductivity*

Satiated hydraulic conductivity was measured in the lab using the falling head method (Klute, 1986). Tests were performed on undisturbed samples collected from the matching layer where the corresponding field conductivity test was performed. The location of collection was immediately upslope from the field test. The samples were used to verify field methods. To collect lab samples, a core sampler was driven into the ground 7 cm. The sample ring was 3 cm in length. The soil was left in the ring during the test to keep the core intact. A 25 cm acrylic tube was fastened to the metal ring sample using a rubber seal. However, the soil/ring seam was occasionally loose, increasing the conductivity erroneously. Samples were soaked in tap water for 12 hours to satiate the core and eliminate most of the air in the pores. After the conductivity test was performed, the samples were dried to obtain bulk density. Subsamples of the core were used for lab analysis of percent sand, clay, and organic matter.

2.5.2 *Sampling of Sediments in the Vadose Zone*

Samples of the sediments in the intermediate vadose zone to a depth of 25 feet were collected using a Geo-Probe hydraulic sampler. The samples were retained in 5-foot long plastic liners and stored at 55 degrees until analysis is complete.

2.5.3 *Measurements of Surface Runoff*

Surface runoff measurements using micro runoff plots installed in the experimental fields. Each field contained three micro runoff plots, which included a rain gage, runoff frame, gutter, sump, and pressure transducer. At the Fillmore site, the plots were located in spans 3, 5, and 7. At the Phelps site, all of the plots were installed in span 7. Runoff plot placement avoided unrepresentative rows, such as varying spacing on the end rows of the planter and wheel tracks. The galvanized steel frames, measuring 0.76 m wide by 1.83 m long and driven into the soil 15 cm, captured a representative sample of field runoff. Runoff was caught by a 0.10 m wide gutter covering the down slope width of the frame. The gutter routed the runoff into a sump extending six feet into the ground. The gutter was exposed to the rainfall and the depth of rain received directly onto the gutter area was subtracted from the amount of runoff measured in the sump to acquire an accurate runoff from the micro runoff frame.

Figures 10-11 shows the shows the equipment and setup for measurements of infiltration and surface runoff components

Figure 10. Collection of vadose zone samples with Geo-probe

Figure 11. Vadose samples in 5-foot liners.

Figure 12. Micro-runoff plot installed in the field

Figure 13. Ring used for infiltration measurements.

Figure 14. Cornell rainfall infiltrometer used for rainfall infiltration measurements.

Monitoring runoff began in 2008 at Fillmore County in soybean. Instrumentation was installed in August and removed in late September. In 2009 and 2010, runoff events in late-May through September were monitored at the Fillmore County and Phelps County sites

2.5.4 Depressional Storage, Surface Seal, and Aggregates

Random roughness is a measure of the variation in height of the surface depressions due to soil relief and surface residue and relates to the depth of water that can be stored on the surface. Random roughness was determined using the Saleh chain method. A 1.0 m roller chain (ANSI 35 riv.type) was carefully positioned on the ground, parallel to the row, following residue and surface contours. The reduced length was measured. The roughness of the field was determined using Saleh's chain method equation for random roughness.

$$RR = (1 - L_2 / L_1)100$$

where RR = random roughness, L_1 = the length of the chain, L_2 = the adjusted length of the chain when draped over depressions and residue on the ground. Once ponding occurs, the water begins to pool in depressions on the surface and is referred to as the depressional storage. From the random roughness, depressional storage was calculated by the following equation:

$$DS = 0.112 \cdot RR + 0.031 \cdot RR^2 - 0.012 \cdot RR \cdot S$$

where DS = depressional storage in centimeters, RR = random roughness in centimeters, and S = percent slope.

2.5.5 Aggregate stability

Aggregate stability was investigated at the center pivot sites. Approximately forty grams of soil was taken from the soil surface. Twelve samples were taken from each center pivot irrigated field and eight samples from each clay center subplot. The samples were air dried for twelve hours. The soil was then sieved through a 2 mm and then 1 mm sieve. The aggregates were the portion of the soil that went through the 2 mm sieve, but not the 1 mm sieve. The sample was misted with water so air pockets would not form when placed into water. Then the soil was placed on a 250 µm sieve, immersed into water, and then removed from water. The pulsing of inundation took place for three minutes at a rate of 35 submerges per minute. Samples were dried and weighed and the process is repeated with a dispersing solution, hexameta-phosphate. The dispersing solution broke apart all aggregates so the sand and residue can be weighed and subtracted from the stable aggregates.

2.5.5 Measurement of Macropores

Macropores were quantified in each field through image analysis. An 8.6 cm diameter soil sampler was used to collect soil cores directly below the tillage layer, to a depth of approximately 6.5 cm, for both sites. The core was flipped over and the picture was taken on the underside of the excavated core at each infiltration test area. Pores greater than 1.0 mm were considered macropores. The pores at the bottom of the tillage layer were assumed to be connected with surface. Using the picture, pores were counted within each sample and the diameter was measured. Each pore was assumed circular. The total area of macropores was found and compared to the area sampled.

2.6 Surface residue measurements

Residue measurements were made on the tilled and no-till fields on several dates Mass samples and other measurements were taken close to the Bowen Ratio tower: within a radius of ~ 200 ft. On each field, eight samples were taken around the Bowen Ratio tower. Below is the protocol that was followed.

The eight sample locations were selected randomly. Each sample area was one row wide and 20 inches long. Row width was 30 inch for both fields in Fillmore County and 36 inch for both fields in Phelps County. Before collecting residue, a picture was taken of each sample area. Minimum, maximum, and average residue thickness was measured inside each sample area. The average thickness was area-weighted and was an estimate rather than a measurement. Heights of standing stems inside each sample area were measured. Residue was then cut on the boundaries of the sample area and collected by hand. If a piece of residue was partially buried, the entire piece was collected, unless it broke off easily at the soil surface.

All collected residue was dried in an oven for 24 hours at 60 ^{o}C. Subsamples were ground through a 1-mm sieve using a grinder (Udy Corporation Cyclone Mill, Model 3010-030). The resulting fine material was mixed and three subsamples were collected, weighed, and then ashed at 500 ^{o}C for six hours. Samples were then weighed again to determine the soil-free mass of each residue component.

Percent residue cover was measured with the line-transect method using a 15.2-m (50-ft) measuring tape. Residue hits or misses were evaluated at each of the 50 footmarks. This measurement was made immediately to the north-east of each mass sampling location (eight locations per field).

Using GPS, the coordinates of the mass sample locations were recorded. With the 50-ft cover measurements, the beginning and end point of the 50-ft tape were recorded. This information will be used to compare the ground-based residue measurements with estimates of residue mass and cover made from sensors mounted on satellites.

2.7. Remote sensing and satellite imagery

The goal of this component is develop methodologies to estimate ET_c from tilled and untilled corn and soybean fields using airborne and satellite remote sensing data.

Calculation of evapotranspiration is possible using remotely sensed surface temperatures from sensors aboard air or space platforms that provide instantaneous

data at frequencies of days to weeks, so that instantaneous ET_c can be computed from energy balance algorithms. Both aerial and satellite/remote sensing methods will be a part of this project. The ET_c will be mapped with selected intervals to assess the progression of ET_c with time during the growing season. The application of remote sensing (i.e., calibration/validation) in this project will be supplemented/supported by our ongoing research projects using ground-based instrumentation and related to the applications of these methods.

Remote sensing/satellite algorithm (RSSA) was applied to quantify individual surface energy fluxes and ET_c at different spatial and temporal resolutions using both airborne and Landsat satellite data. Currently, RSSA does not have capability to differentiate the rate of evaporative losses between tilled and untilled soils. Methodologies were developed to modify RSSA to account for the difference in evaporative losses due to tillage based on measured ET_c data. The calibration procedure used included implementing aerodynamic parameters such as excess resistance term in the sensible heat flux equation for tillage conditions, multiple temperature differential (dT) functions and calibrating soil heat flux parameters to account for the impact of tillage on soil heat flux and ET_c.

The key remotely sensed data used were from an airborne-based platform with a 3-ft or 7-ft spatial resolution and will consist of 62 hyper-spectral bands (62@10 nm) between 400-1000 nm. The images were taken on selected dates depending on clear sky conditions. The RSSA parameters were calibrated using ground truth data. The spectral signatures of the system were identified using different combinations of hyper-spectral bands. In addition, thermal signatures of tillage systems used as an indication of the amount of evaporative cooling or soil heating, including evaporation from wet soil or the understructure.

The LANDSAT Enhanced Thematic Mapper (ETM) with 30-m spatial resolution with a thermal IR channel with 60-m spatial resolution were also be used to scale up estimates to compute the water budget for larger areas. The **r**epeat coverage interval for LANDSAT ETM is 16 days**.** We continue to take calibrated RSSA parameters obtained

with airborne images and utilize them with LANDSAT data**.** We continue to **c**ompare the ability of the RSSA (using both airborne and satellite remote sensing data) to predict daily and seasonal ET_c with the measured data. Geo-processed LANDSAT ETM scenes were purchased for at least seven dates for each year during the growing season. The AISA Imager and Thermal Infrared Camera at CHAMP (CALMIT Hyperspectral Aerial Monitoring Program) were used to acquire images on scheduled mission dates.

3. RESULTS AND DISCUSSION

3.1 Measurements of microclimatic variables and soil water

Results are presented in Figures 15-33

3.2 Measurements of plant height and leaf area index

Results are presented in Figures 34-37

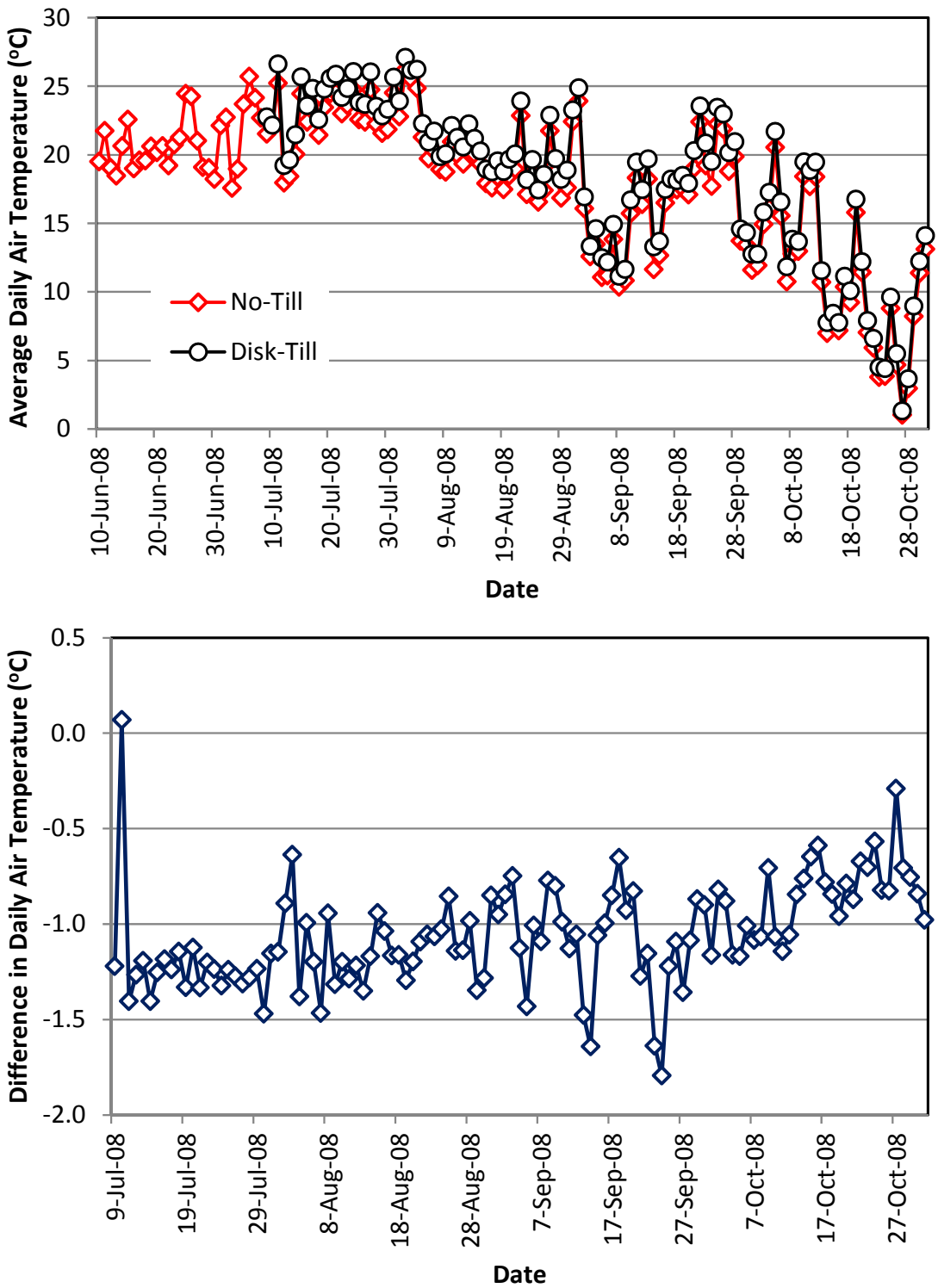


Figure 15. Growing season 2008 (a) average daily air temperature above no-till and disk-till fields, and (b) difference in air temperature between no-till field and disk-till fields at the Geneva site (soybean).

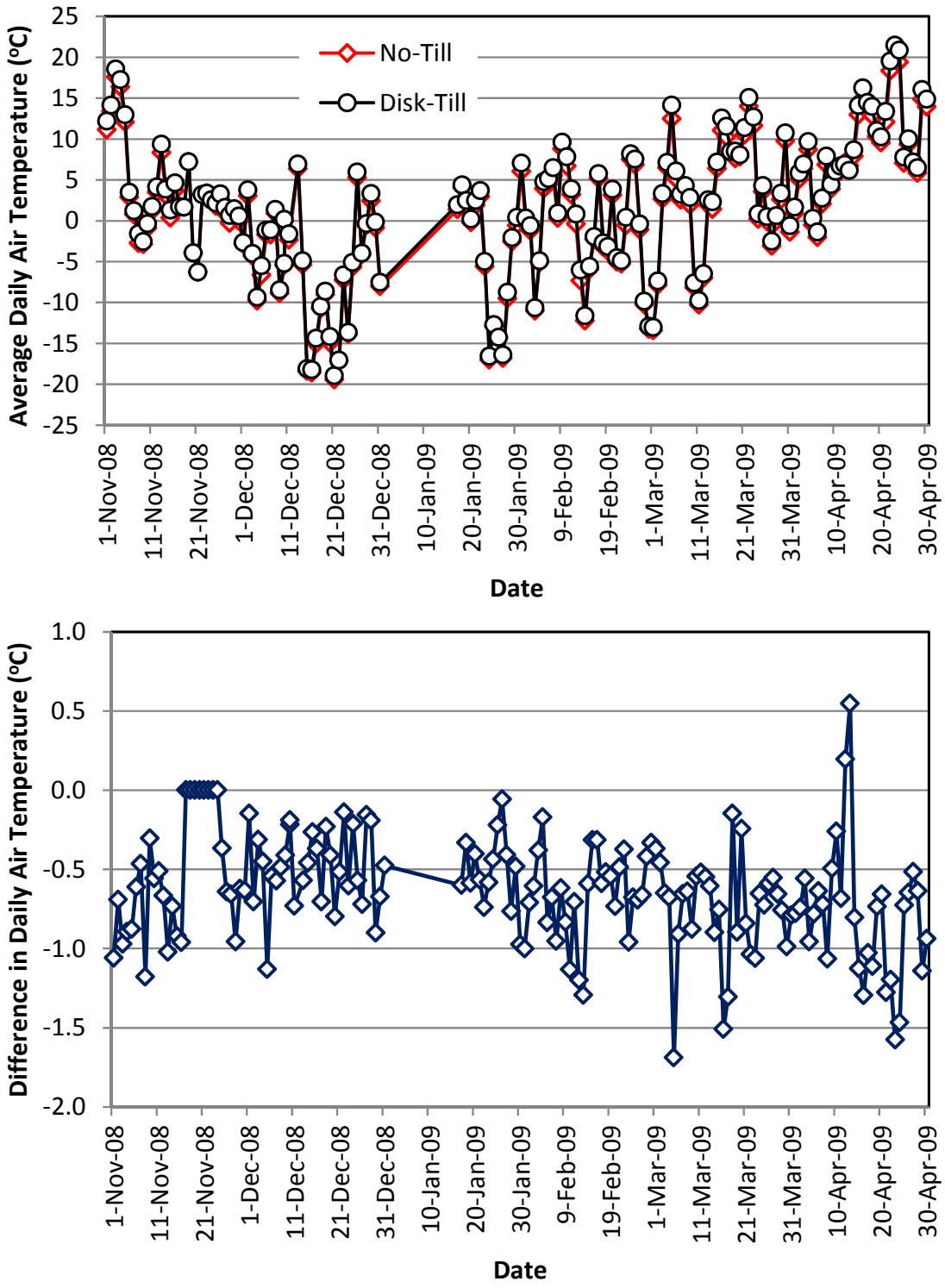


Figure 16. Non-growing season 2008-2009 (a) average daily air temperature above no-till and disk-till fields, and (b) difference in air temperature between no-till field and disk-till fields at the Geneva site (No crop).

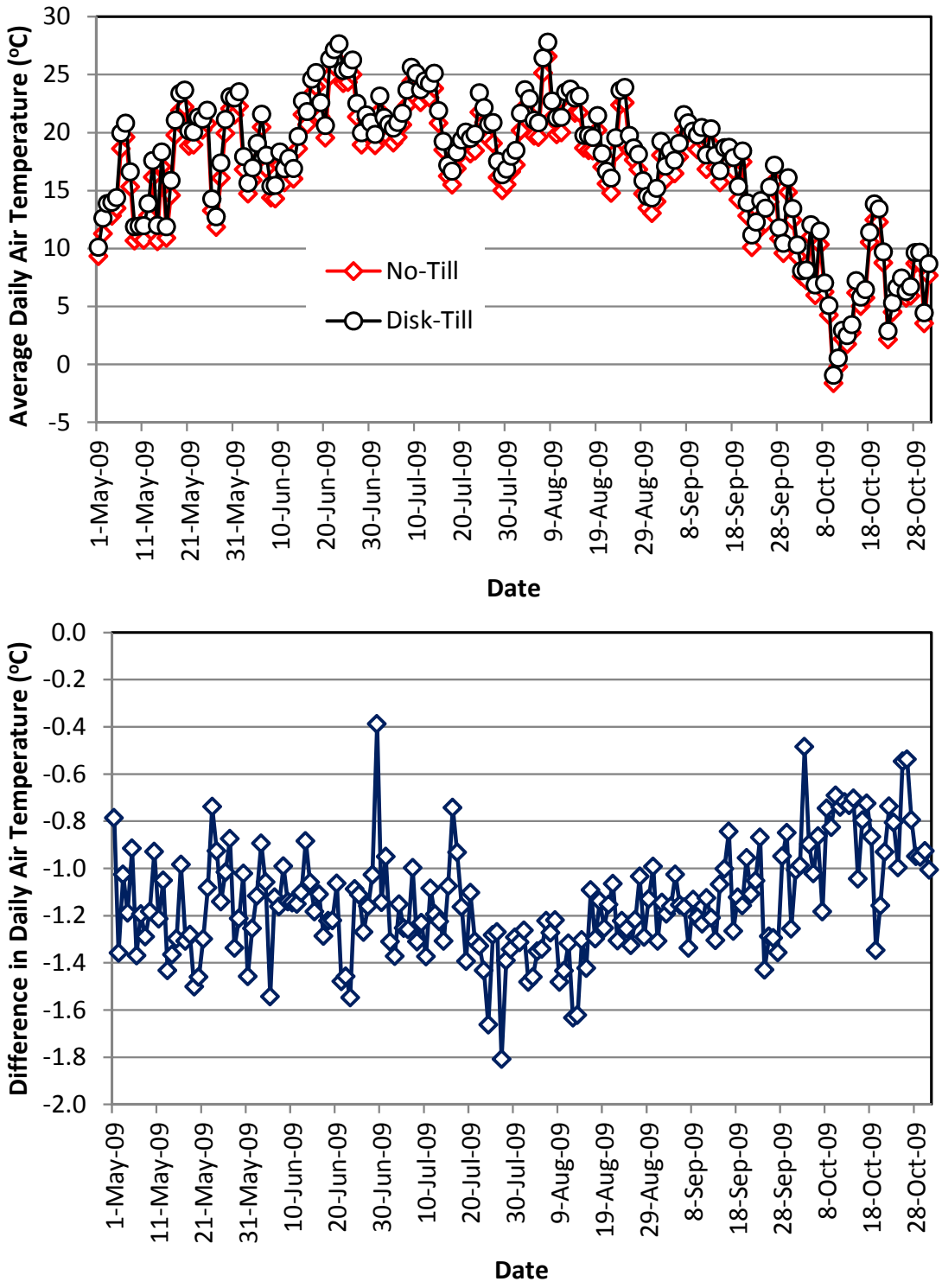


Figure 17. Growing season 2009 (a) average daily air temperature above no-till and disk-till fields, and (b) difference in air temperature between no-till and disk-till fields at the Geneva site (corn).

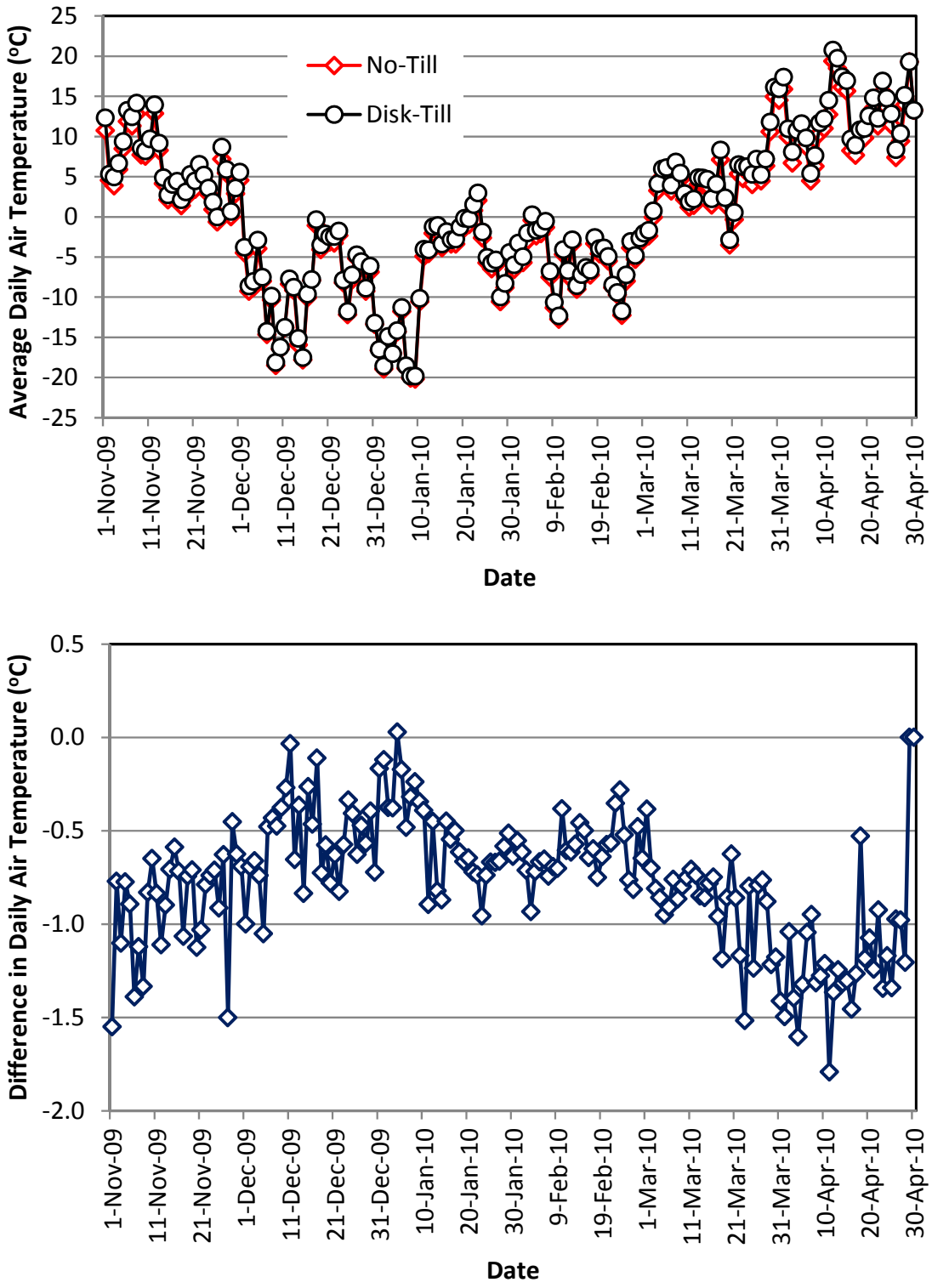


Figure 18. Non-growing season 2009-2010 (a) average daily air temperature above no-till and disk-till fields, and (b) difference in air temperature between no-till and disk-till fields at the Geneva site (No crop).

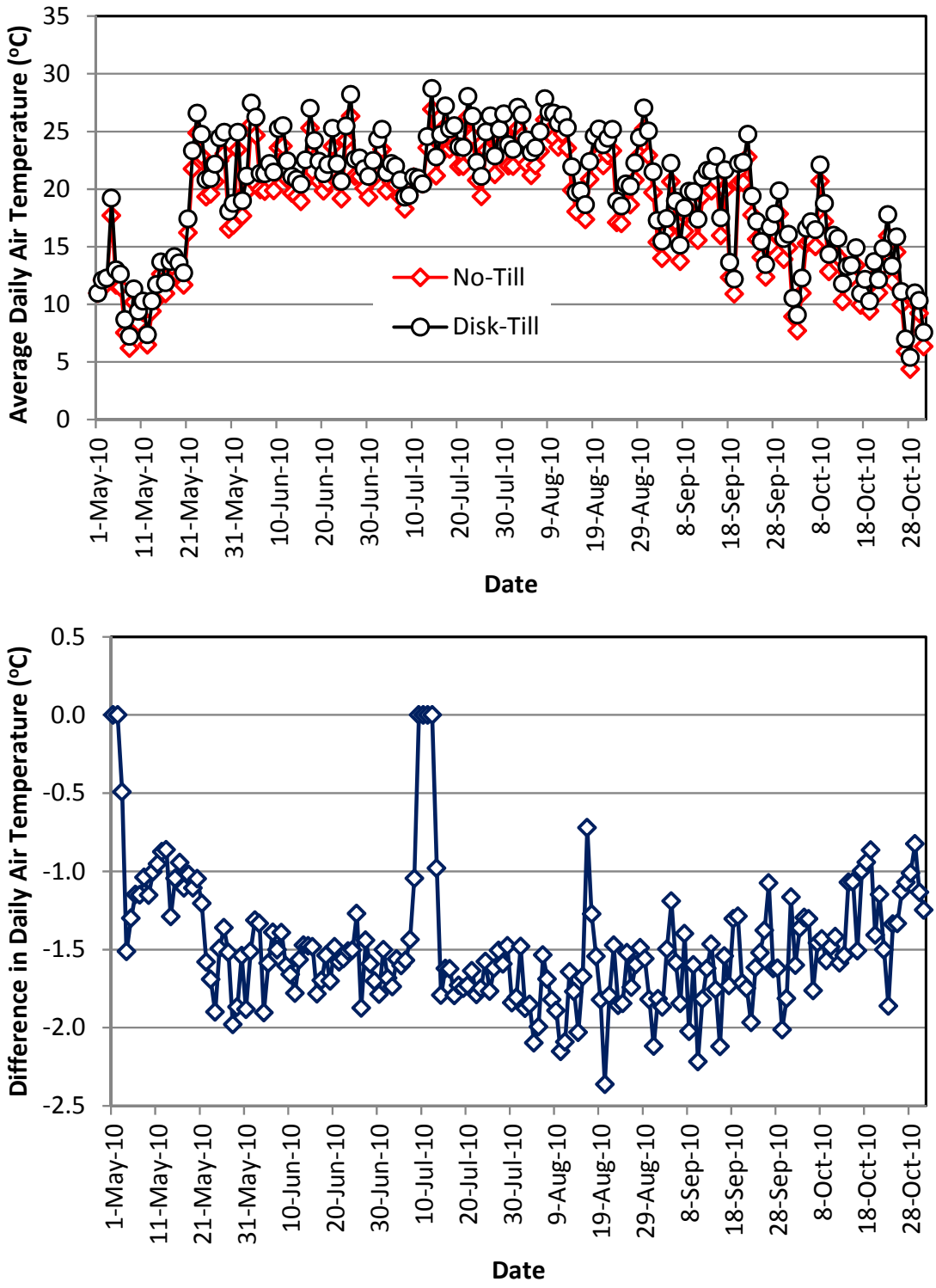


Figure 19. Growing season 2010 (a) average daily air temperature above no-till and disk-till fields, and (b) difference in air temperature between no-till and disk-till fields at the Geneva site (soybean).

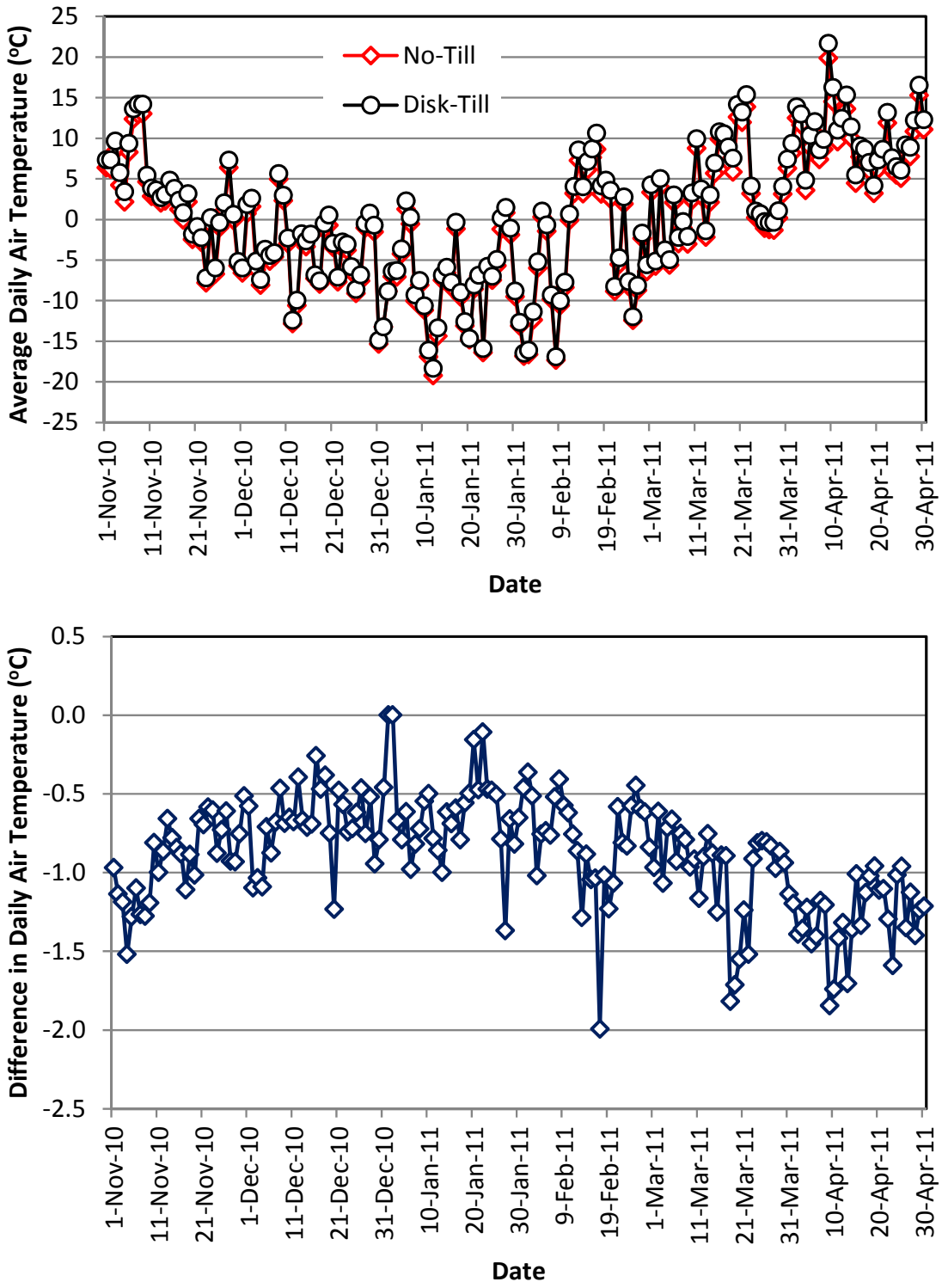


Figure 20. Non-growing season 2010-2011 (a) average daily air temperature above no-till and disk-till fields, and (b) difference in air temperature between no-till and disk-till fields at the Geneva site (No crop).

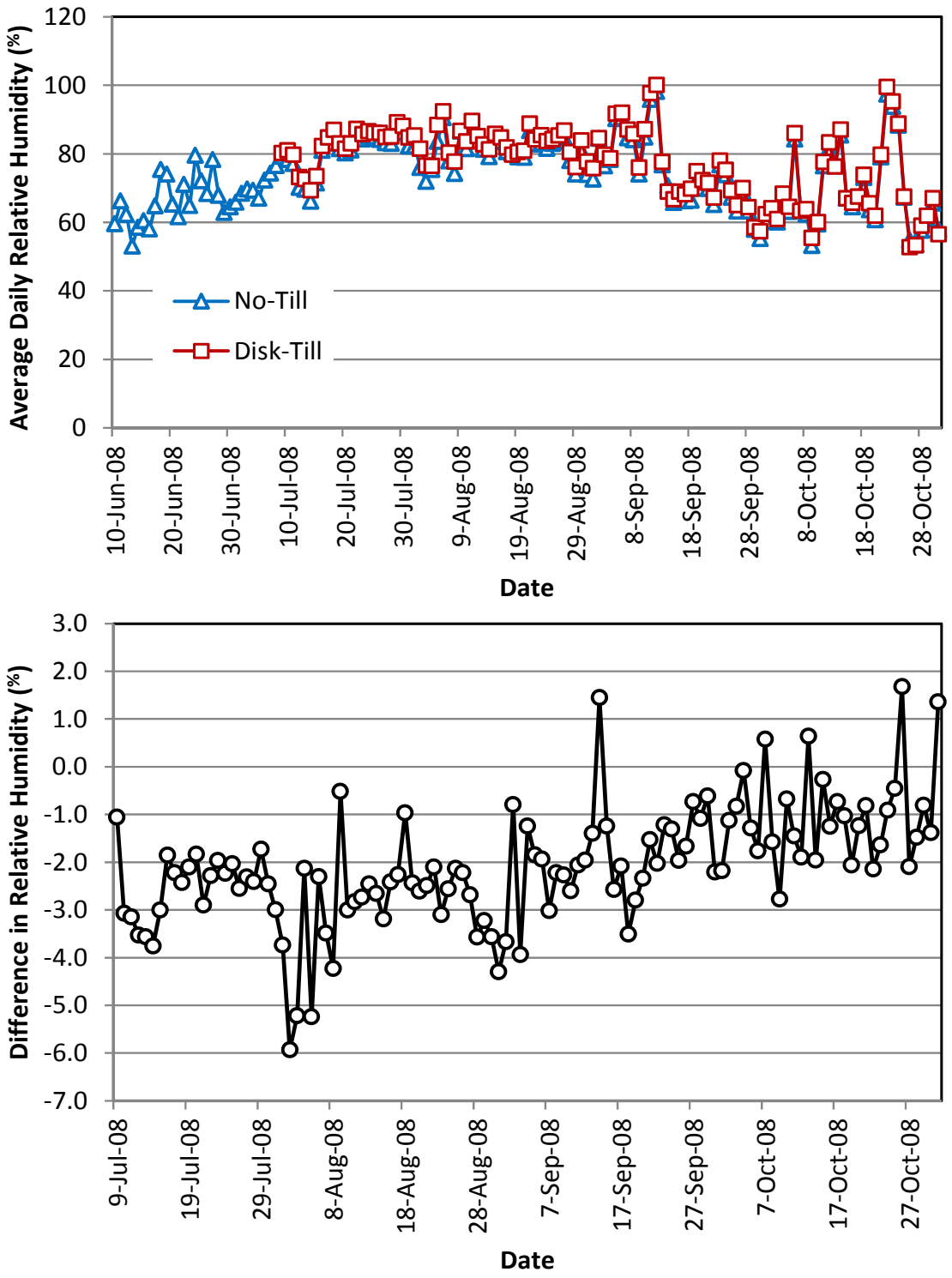


Figure 21. Growing season 2008 (a) average daily relative humidity above no-till and disk-till fields, and (b) difference in relative humidity between no-till and disk-till fields at the Geneva site (soybean).

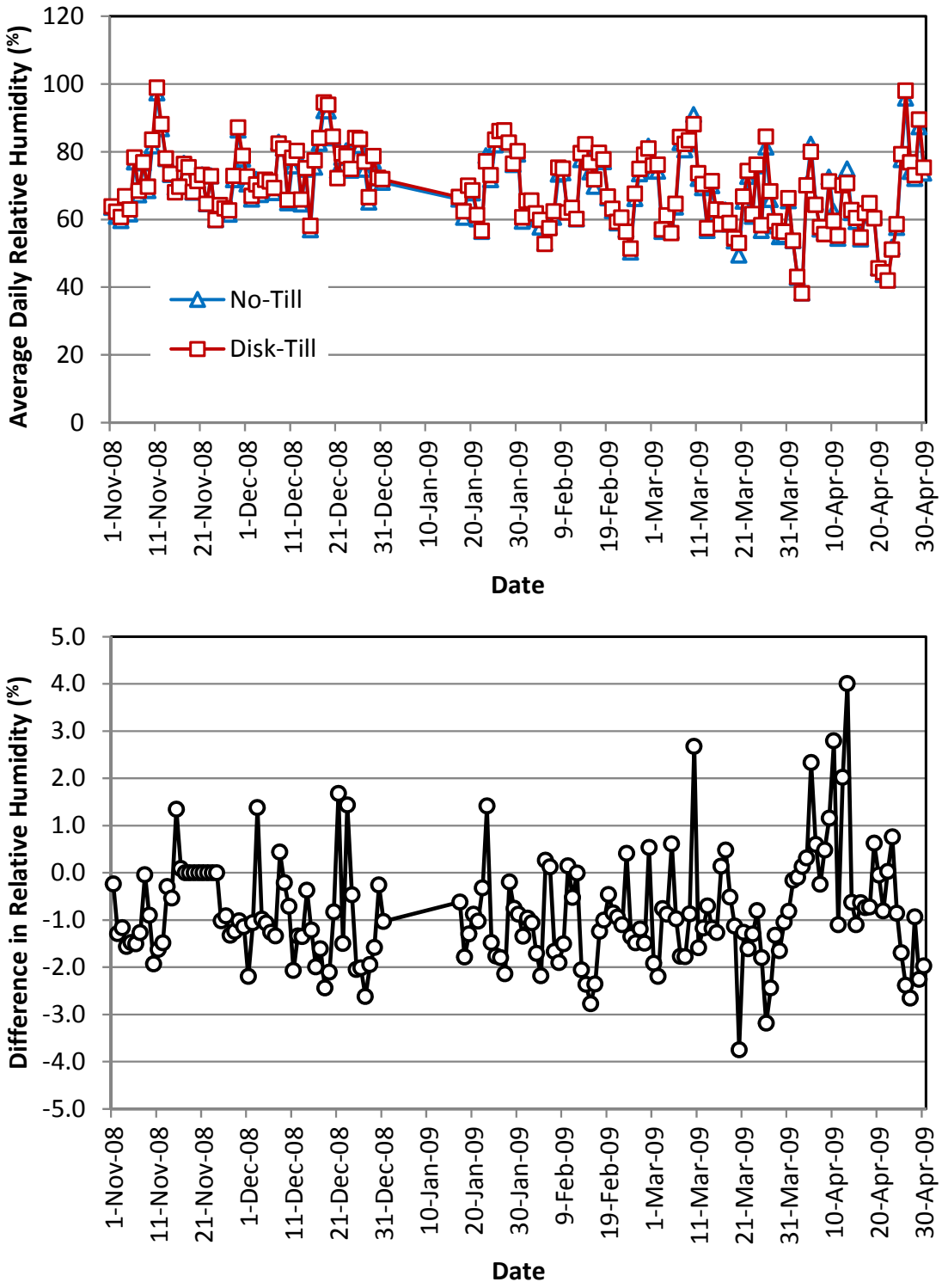


Figure 22. Non-growing season 2008-2009 (a) average daily relative humidity above no-till and disk-till fields, and (b) difference in relative humidity between no-till and disk-till fields at the Geneva site (No crop).

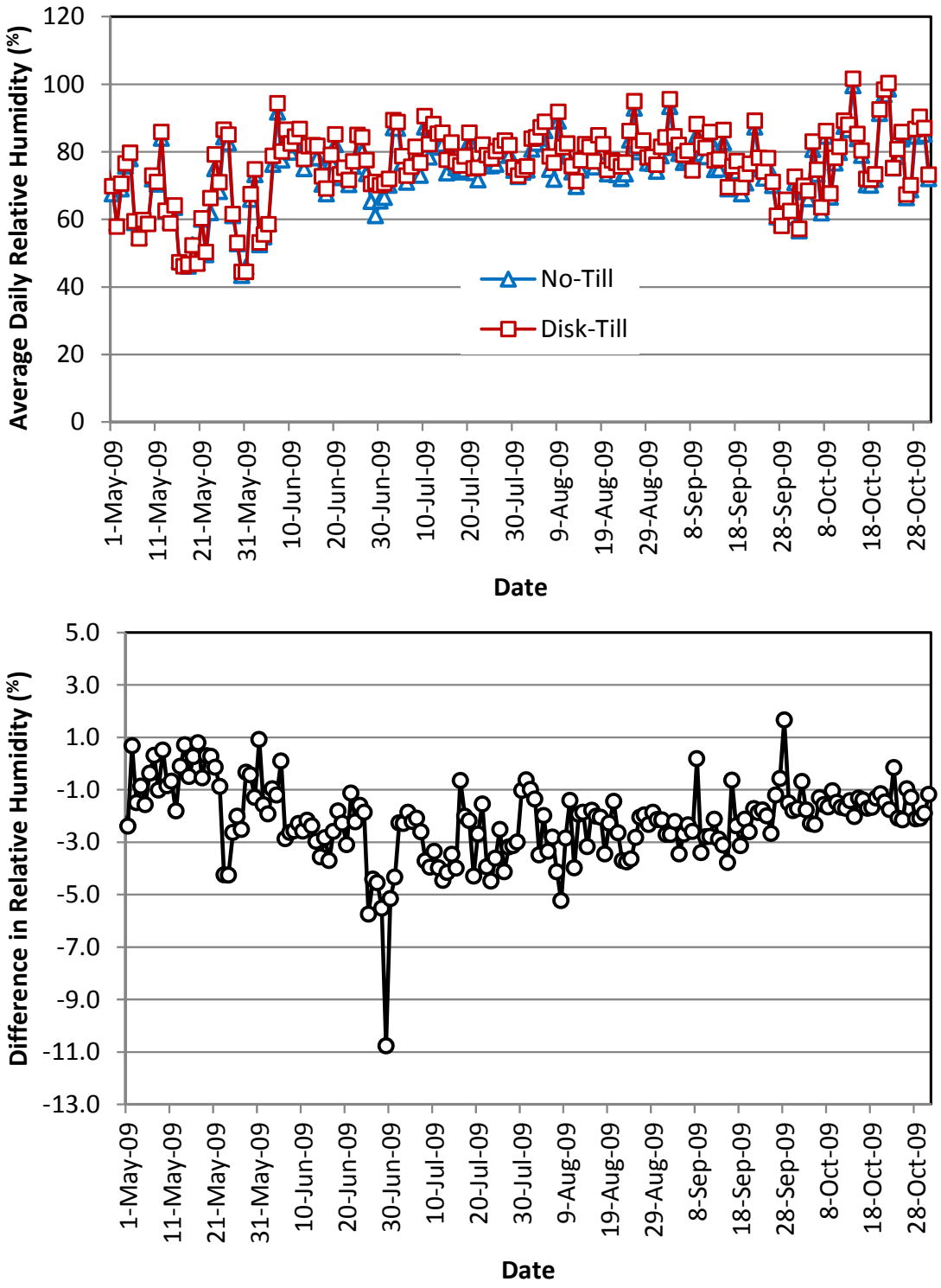


Figure 23. Growing season 2009 (a) average daily relative humidity above no-till and disk-till fields, and (b) difference in relative humidity between no-till and disk-till fields at the Geneva site (corn).

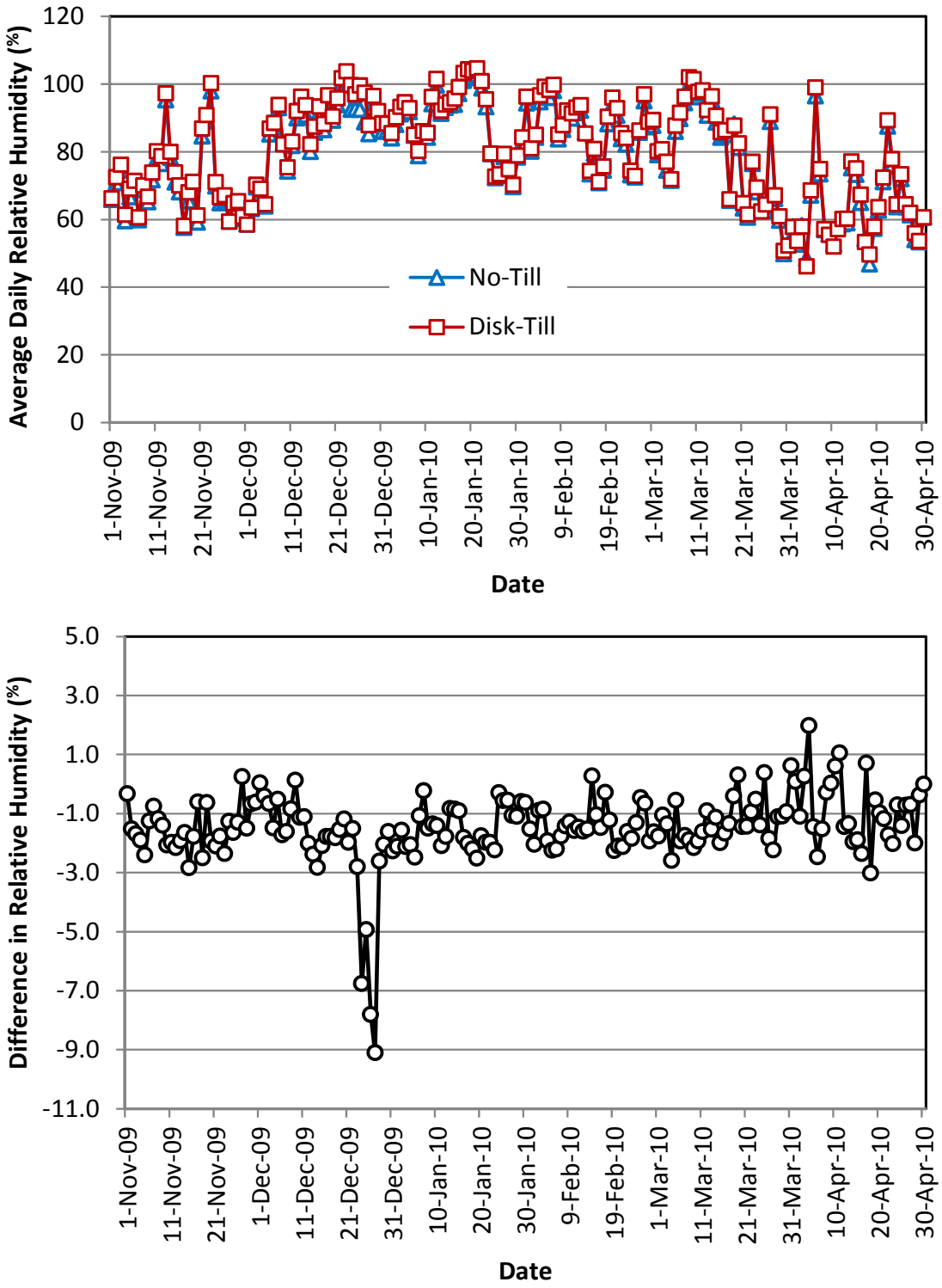


Figure 24. Non-growing season 2009-2010 (a) average daily relative humidity above no-till and disk-till fields, and (b) difference in relative humidity between no-till and disk-till fields at the Geneva site (No crop).

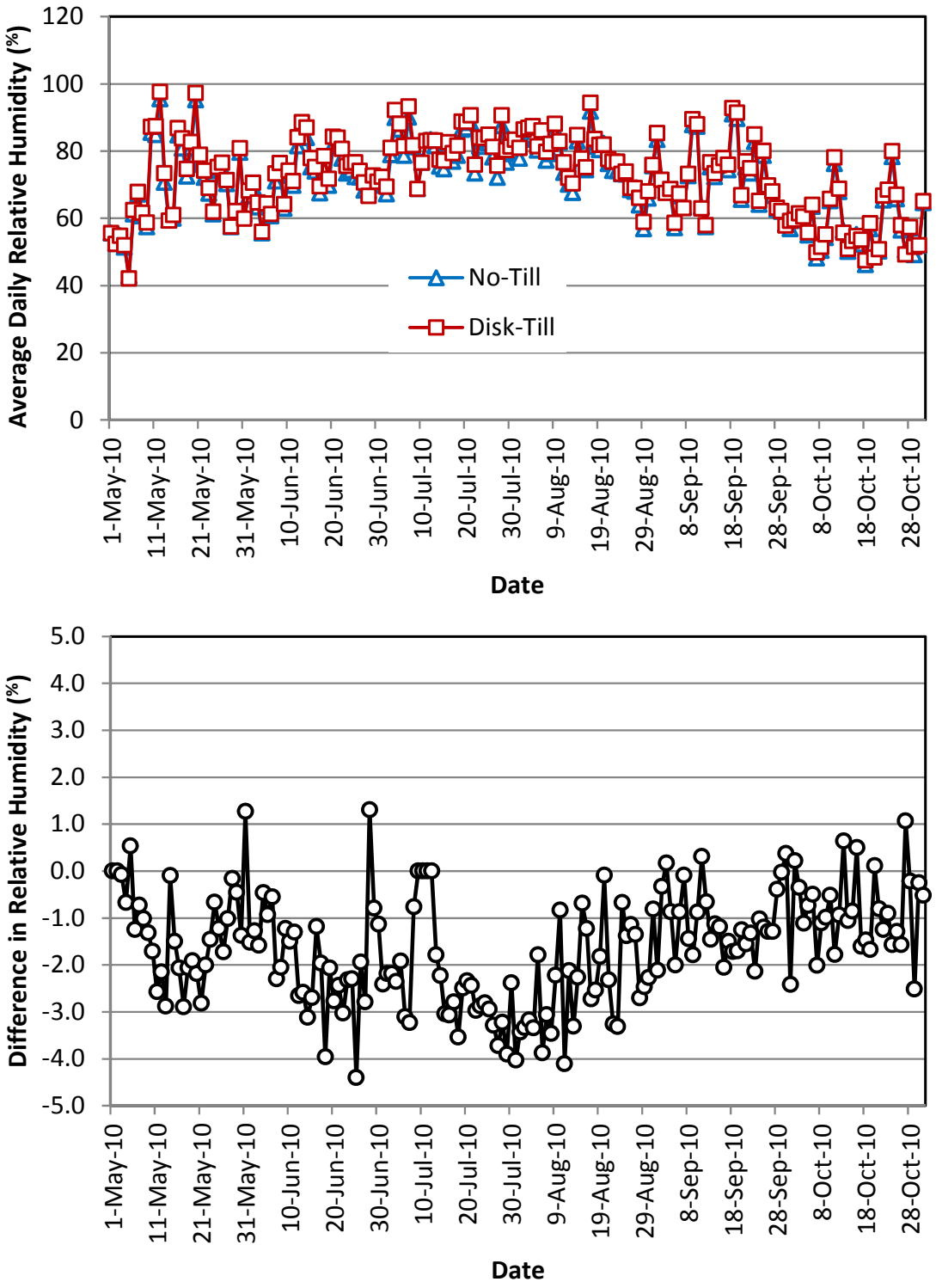


Figure 25. Growing season 2010 (a) average daily relative humidity above no-till and disk-till fields, and (b) difference in relative humidity between no-till and disk-till fields at the Geneva site (soybean).

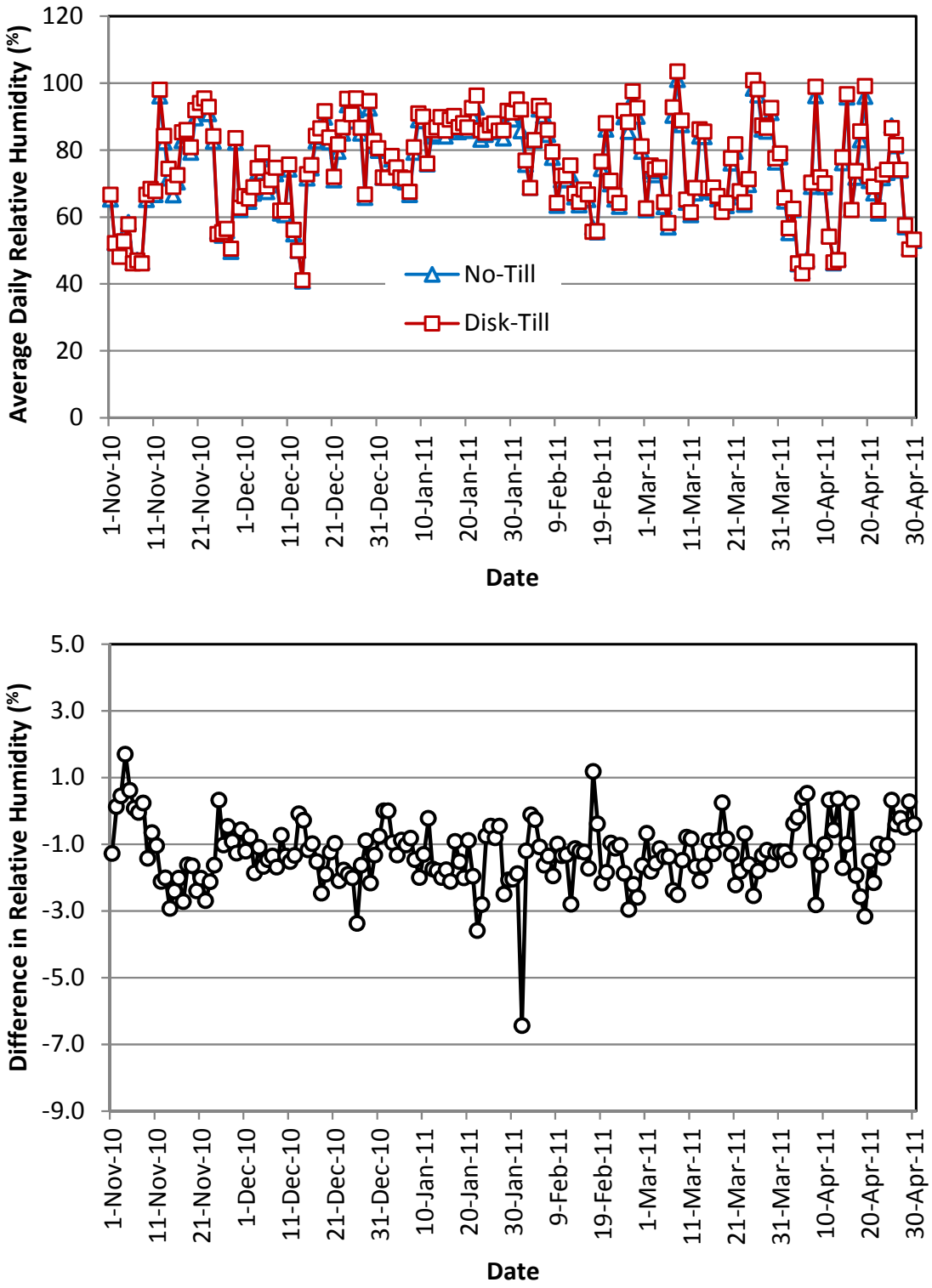


Figure 26. Non-growing season 2010-2011 (a) average daily relative humidity above no-till and disk-till fields, and (b) difference in relative humidity between no-till and disk-till fields at the Geneva site (No crop).

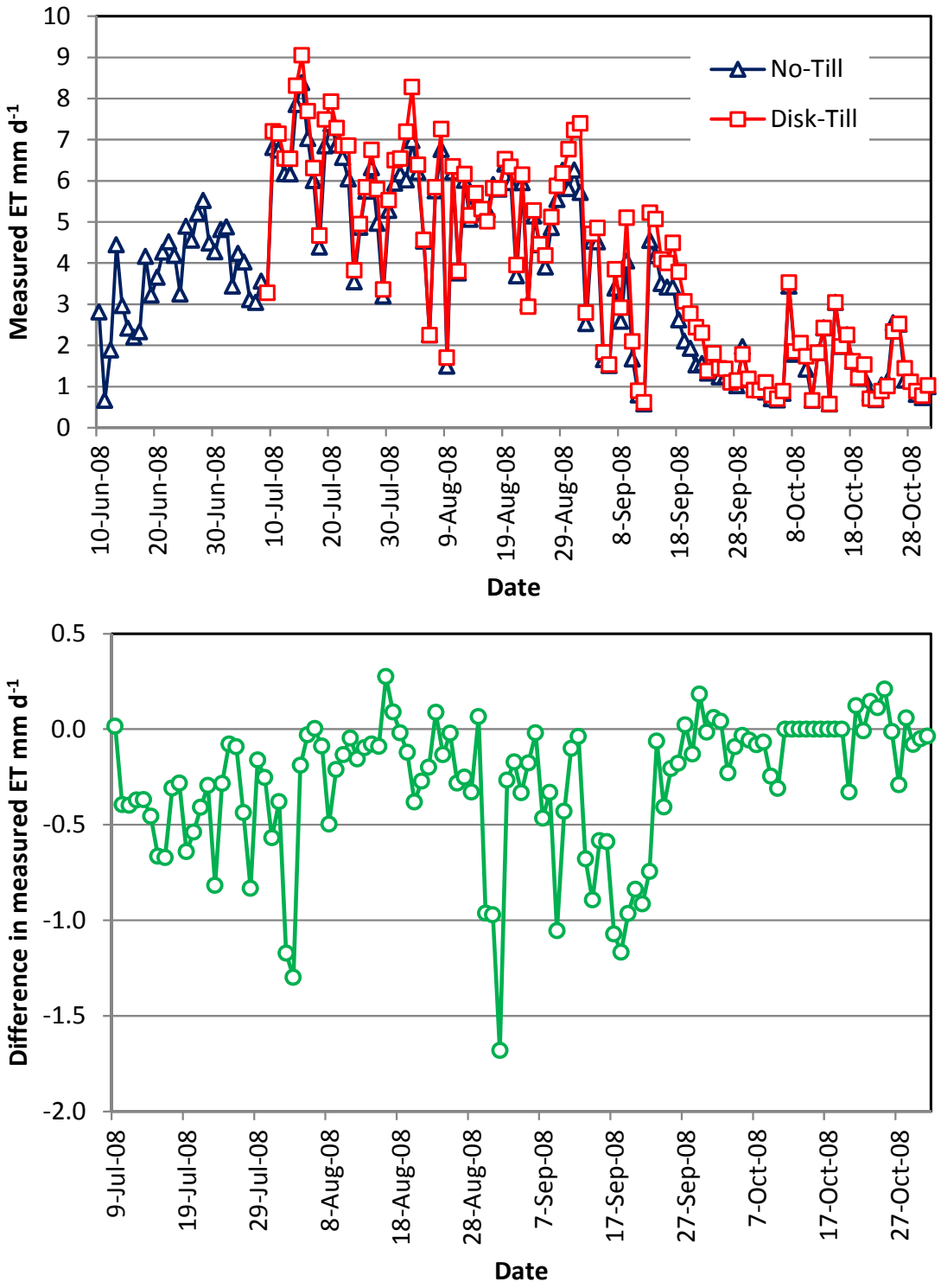


Figure 27. Growing season 2008 (a) daily evapotranspiration (ET) measured above crops in no-till and disk-till fields, and (b) difference in ET between crops in no-till and disk-till fields at the Geneva site (soybean).

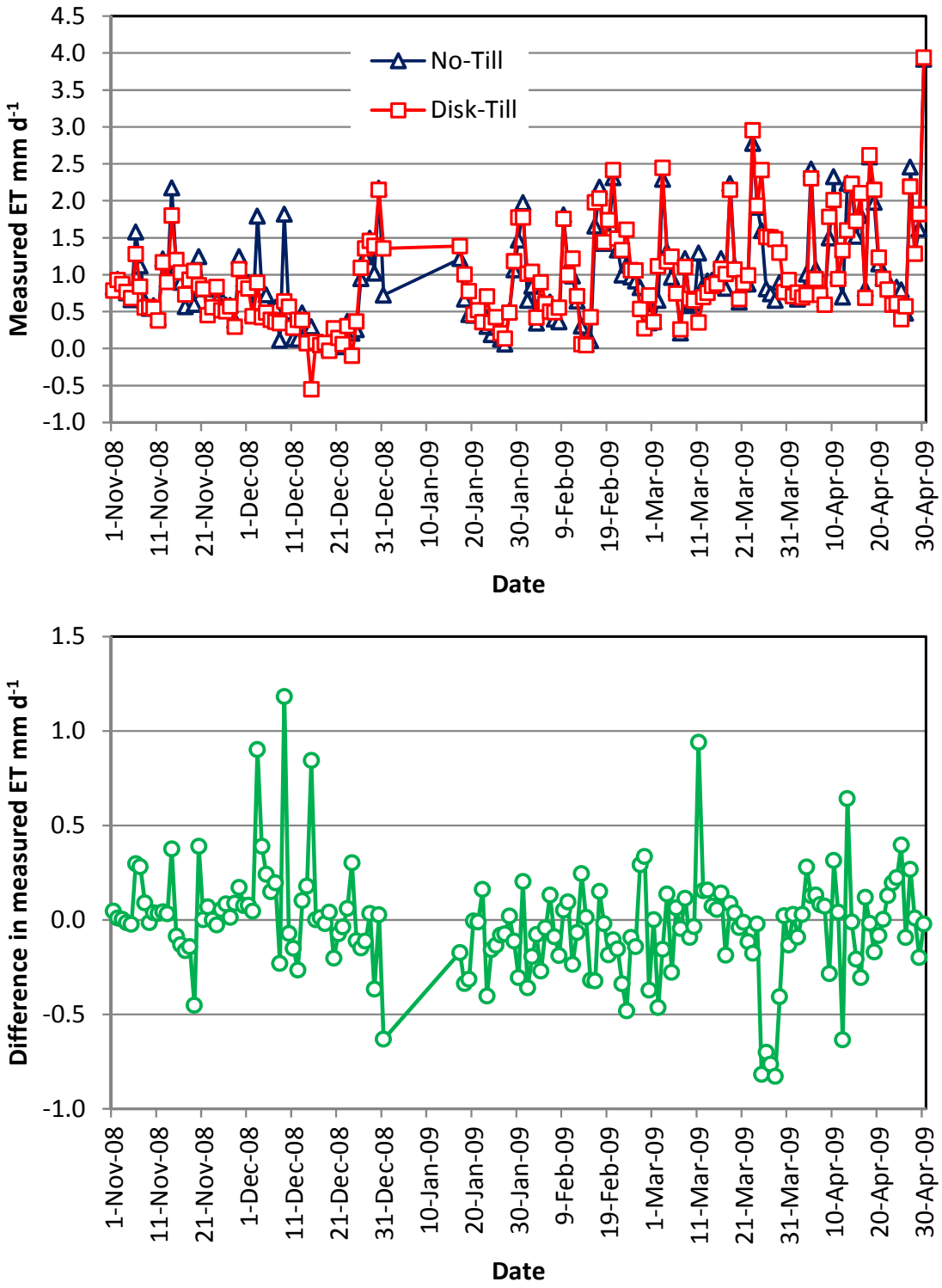


Figure 28. Non growing season 2008-2009 (a) daily evapotranspiration (ET) measured above no-till and disk-till fields, and (b) difference in ET between no-till and disk-till fields at the Geneva site (No crop).

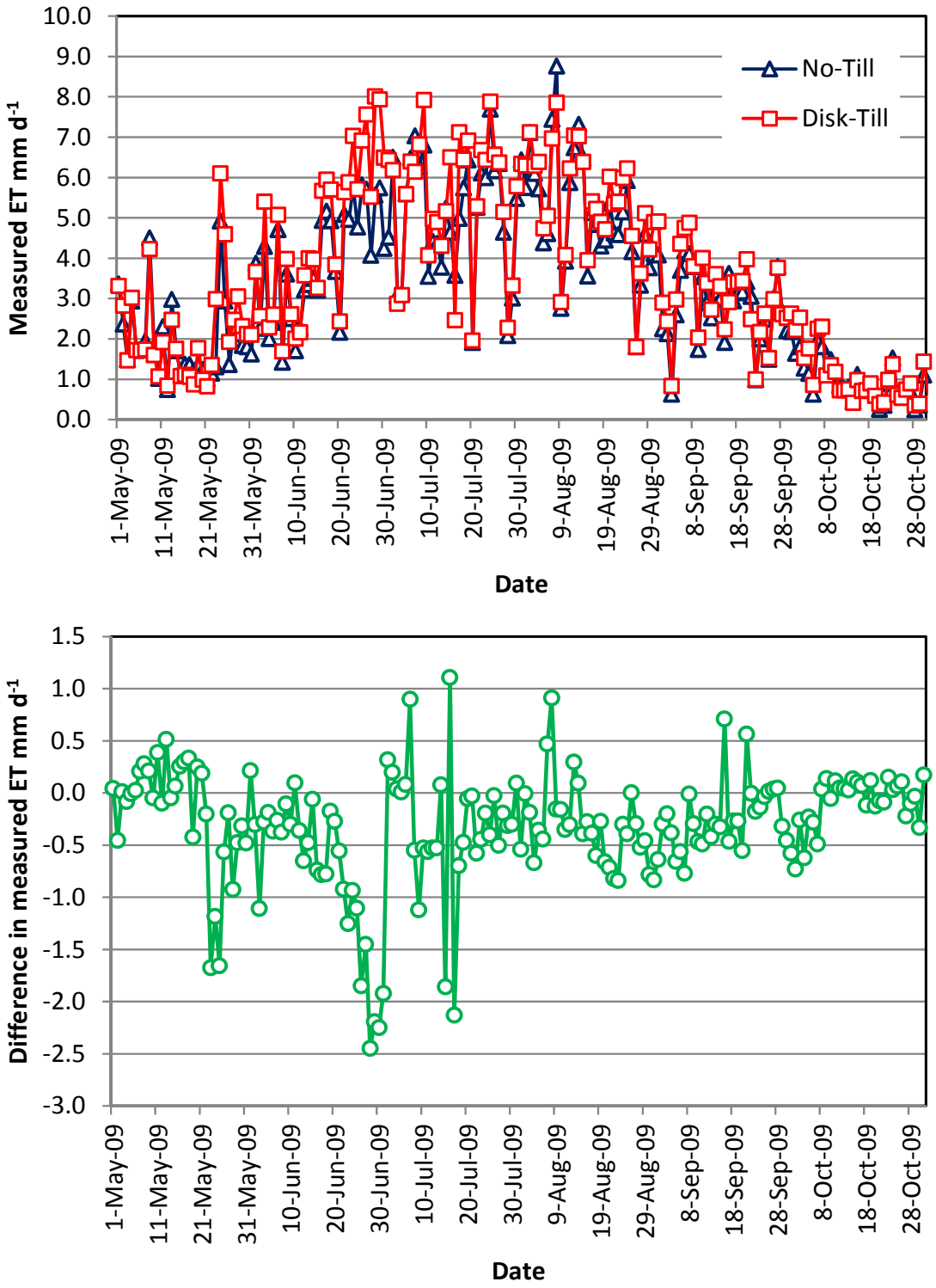


Figure 29. Growing season 2009 (a) daily evapotranspiration (ET) measured above crops in no-till and disk-till fields, and (b) difference in ET between crops in no-till and disk-till fields at the Geneva site (corn).

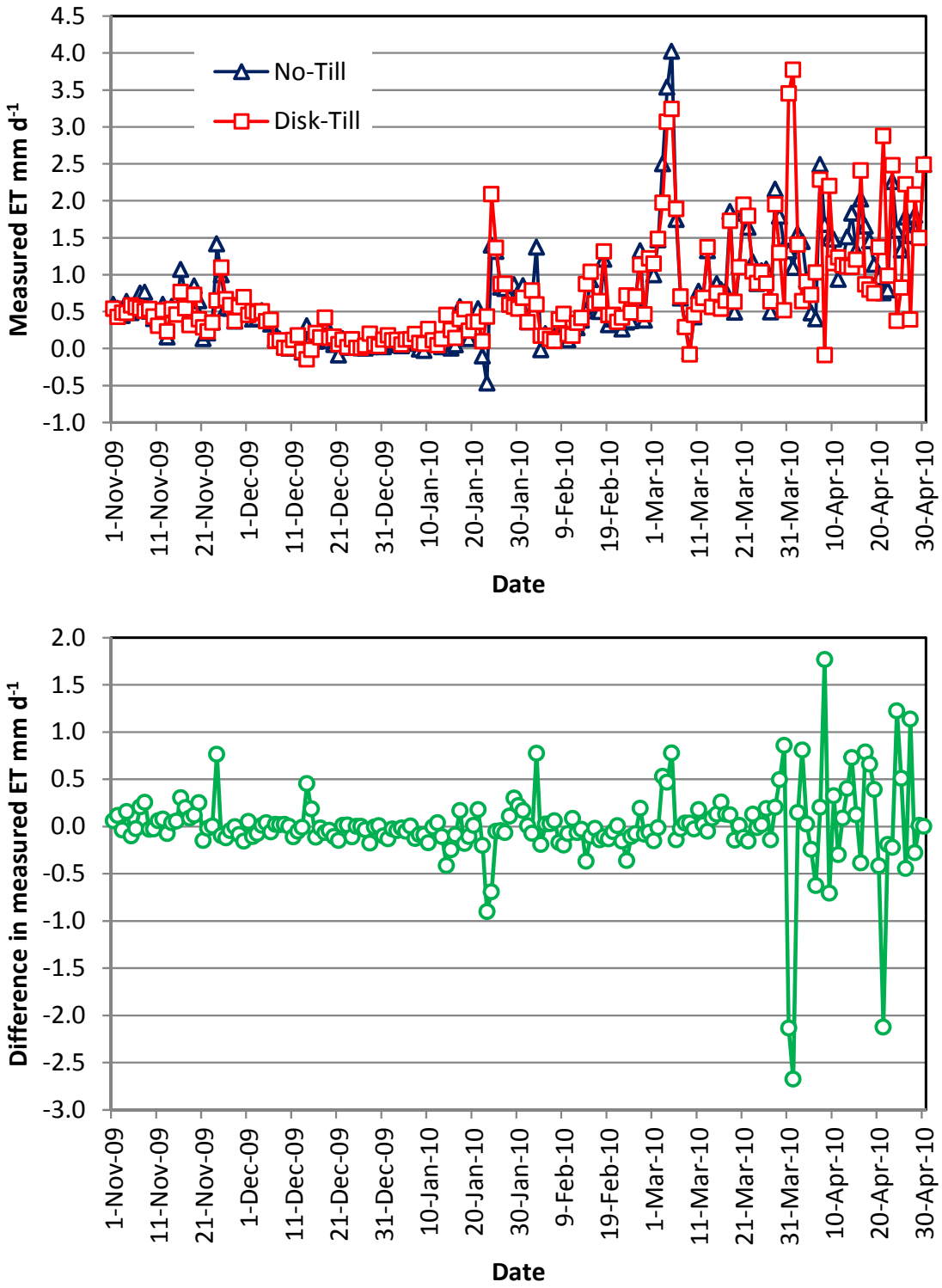


Figure 30. Non growing season 2009-2010 (a) daily evapotranspiration (ET) measured above no-till and disk-till fields, and (b) difference in ET between no-till and disk-till fields at the Geneva site (No crop).

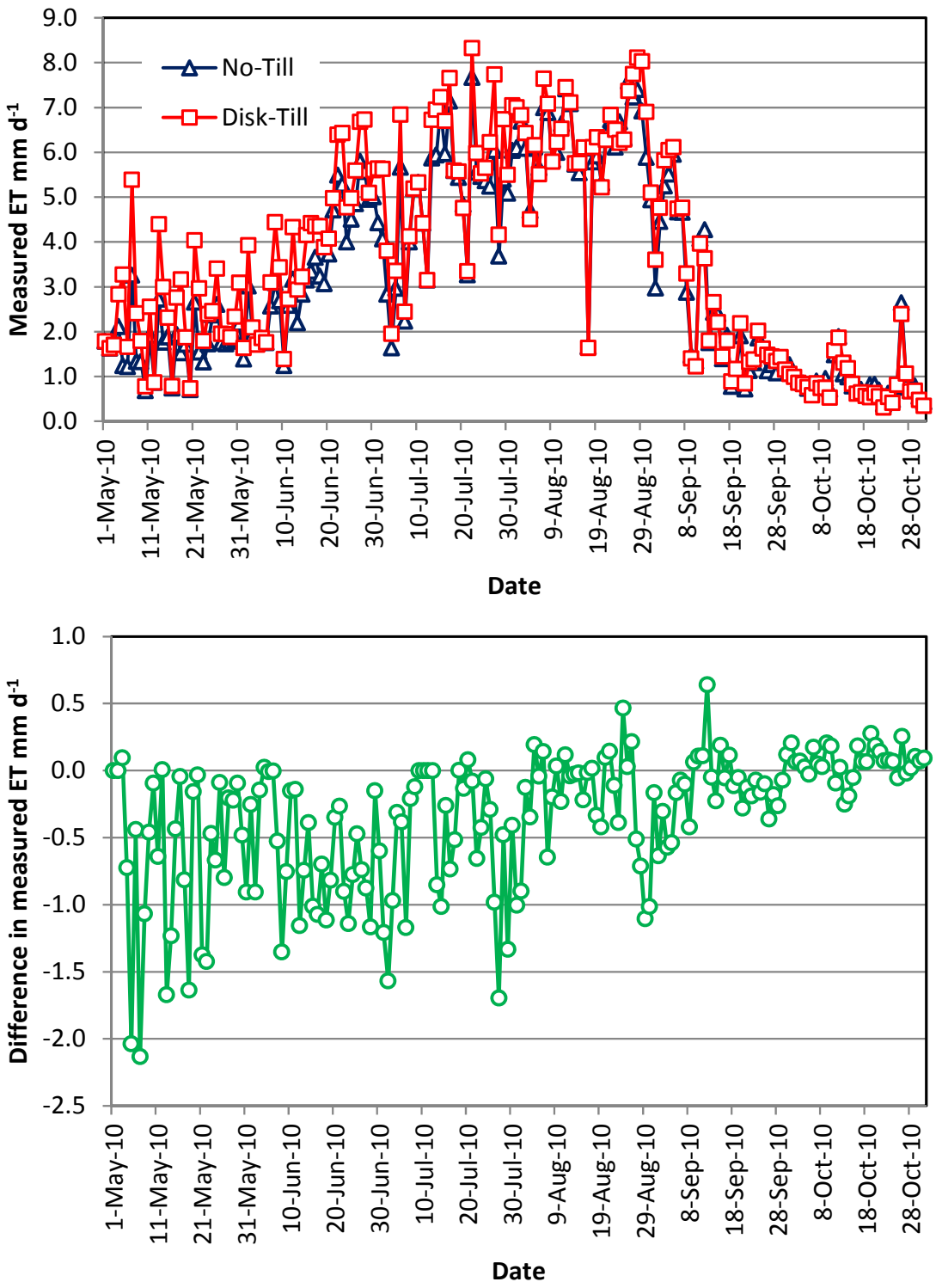


Figure 31. Growing season 2010 (a) daily evapotranspiration (ET) measured above crops in no-till and disk-till fields, and (b) difference in ET between crops in no-till and disk-till fields at the Geneva site (soybean)

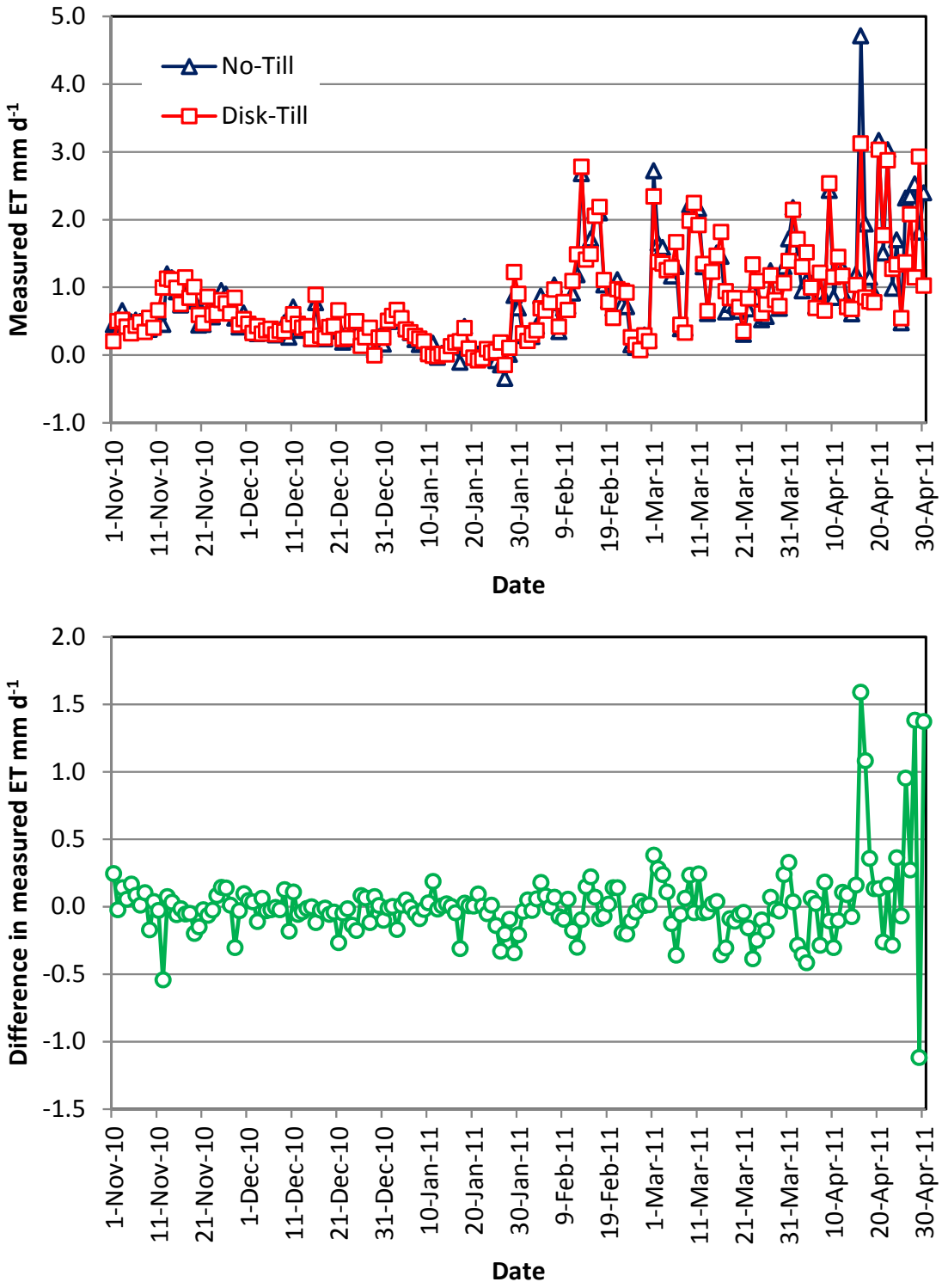


Figure 32. Non growing season 2010-2011 (a) daily evapotranspiration (ET) measured above no-till and disk-till fields, and (b) difference in ET between no-till and disk-till fields at the Geneva site (No crop).

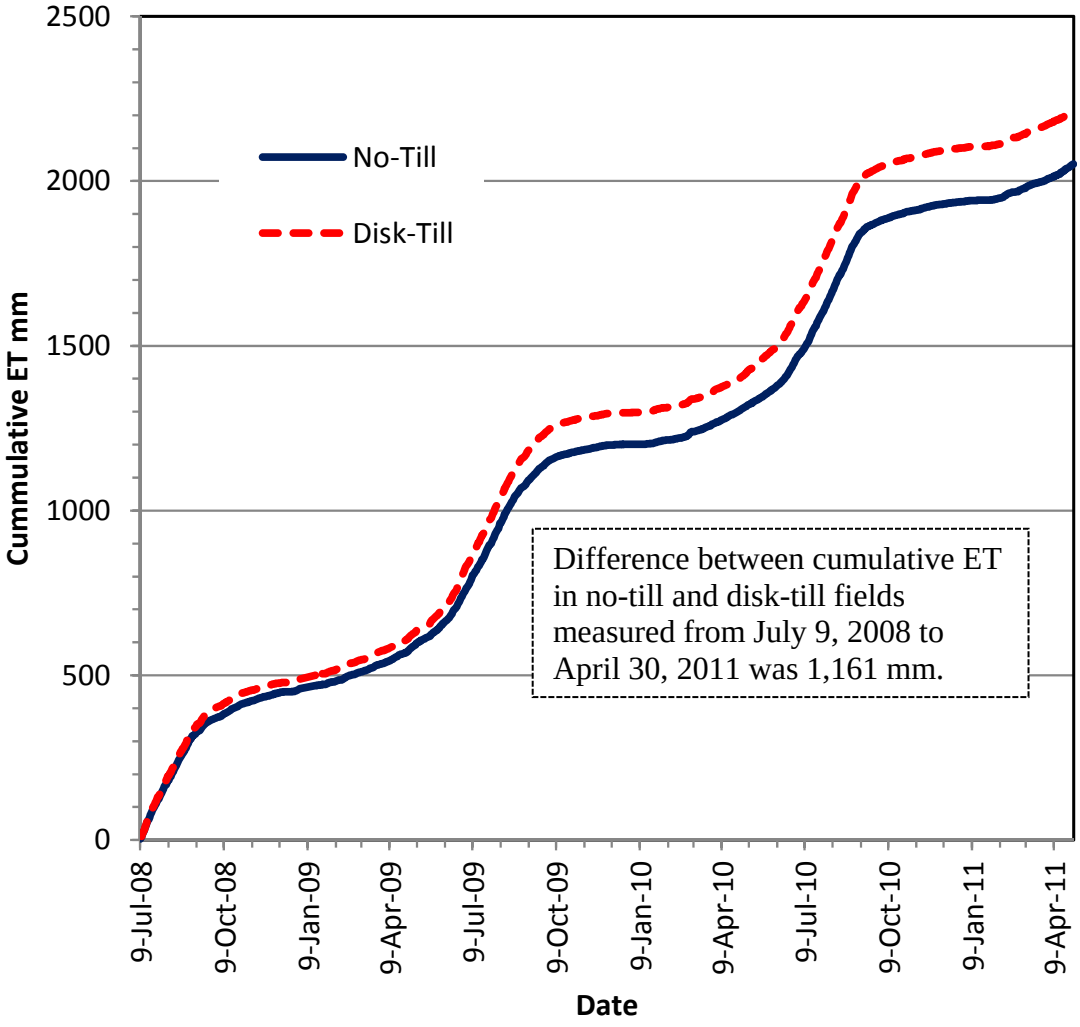


Figure 33. Measured cumulative evapotranspiration in no-till and disk-till fields at Geneva from July 9, 2008 to April 30, 2011.

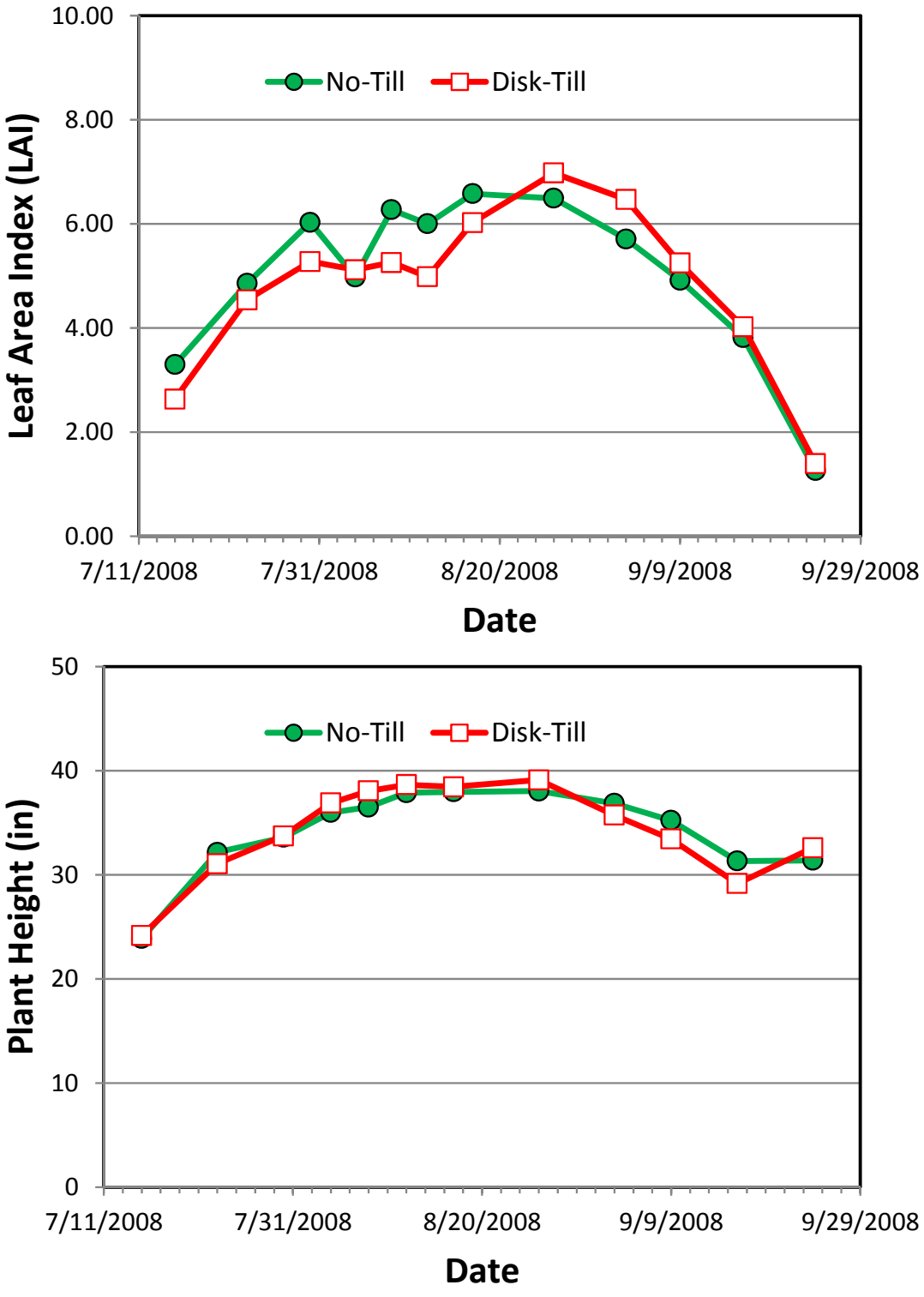
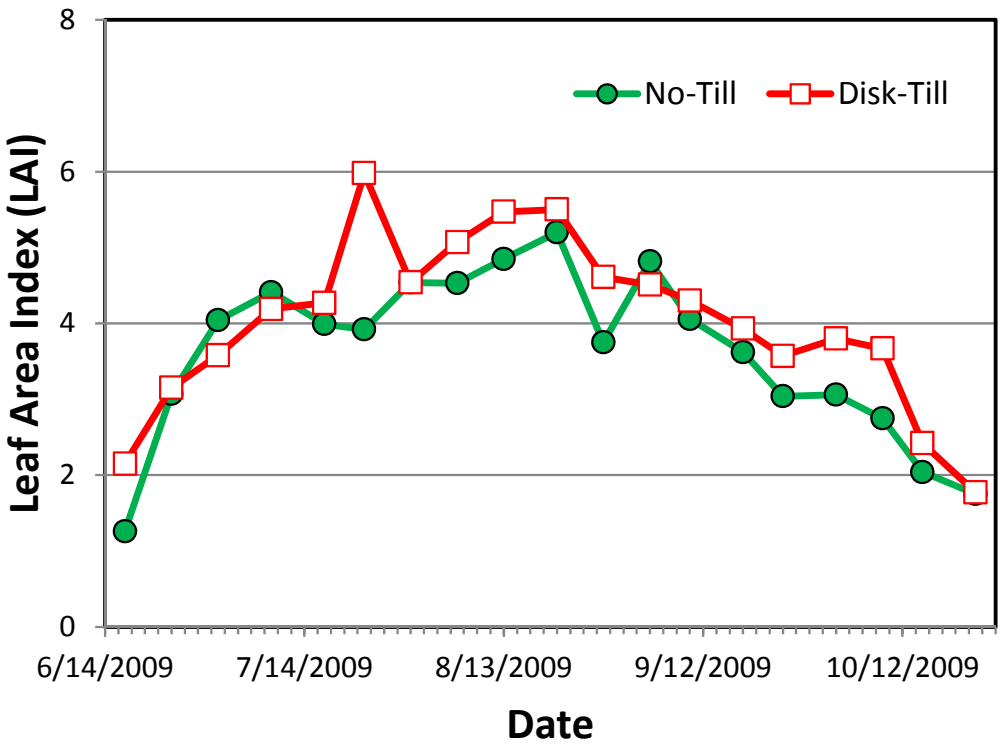


Figure 34. Measured leaf area index (LAI) and plant height in no-till and disk-till fields at Geneva during the 2008 crop season (soybean)



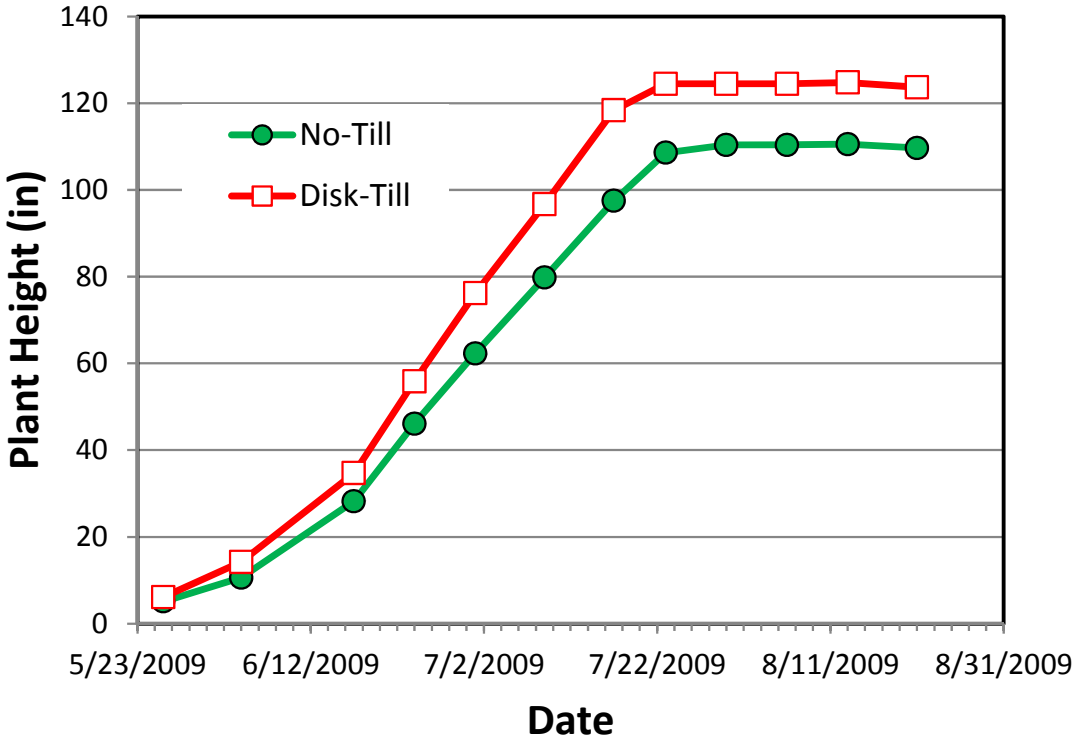


Figure 35. Measured leaf area index (LAI) and plant height in no-till and disk-till fields at Geneva during the 2009 crop season (corn)

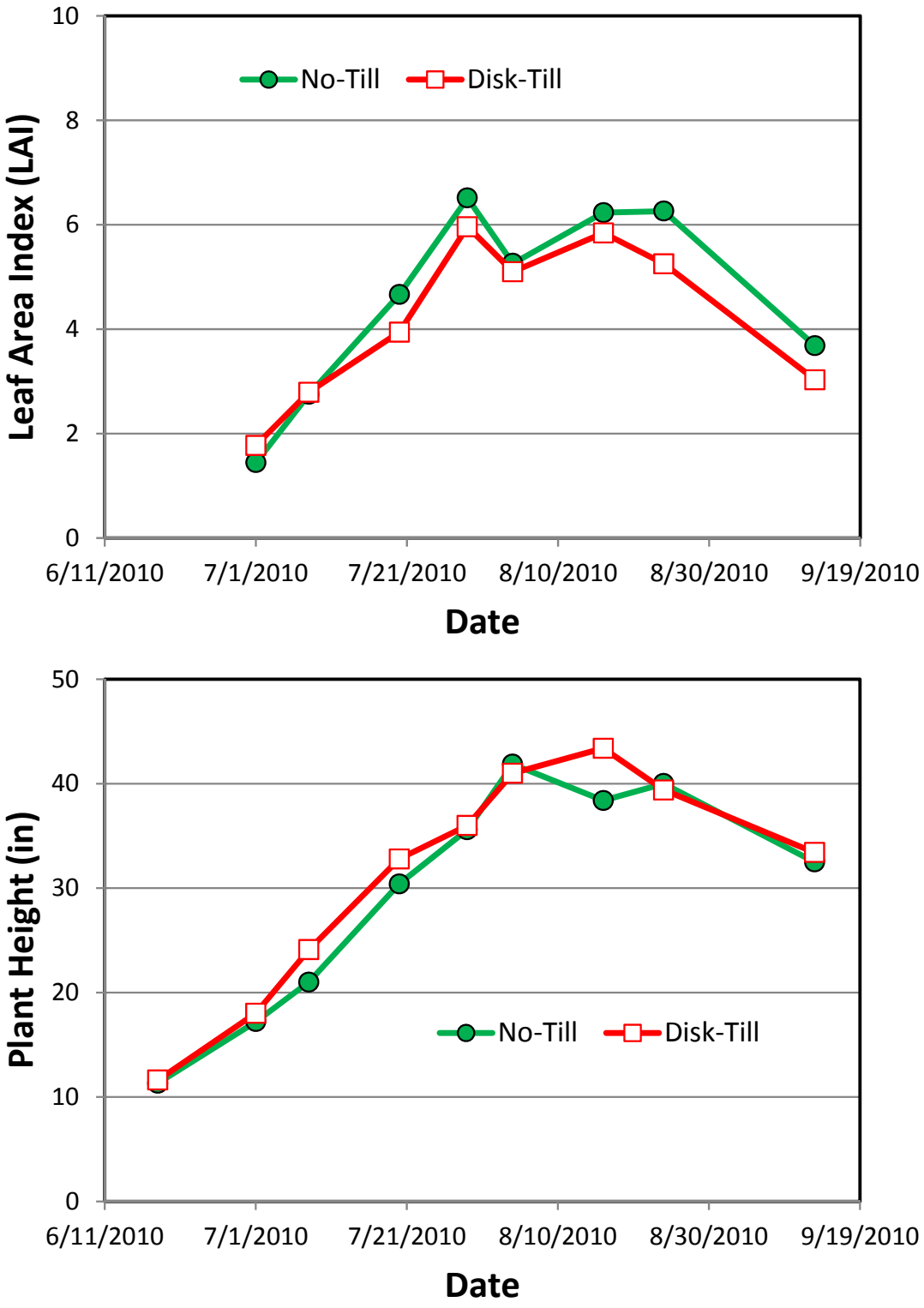


Figure 36. Measured leaf area index (LAI) and plant height in no-till and disk-till fields at Geneva during the 2010 crop season (soybean)

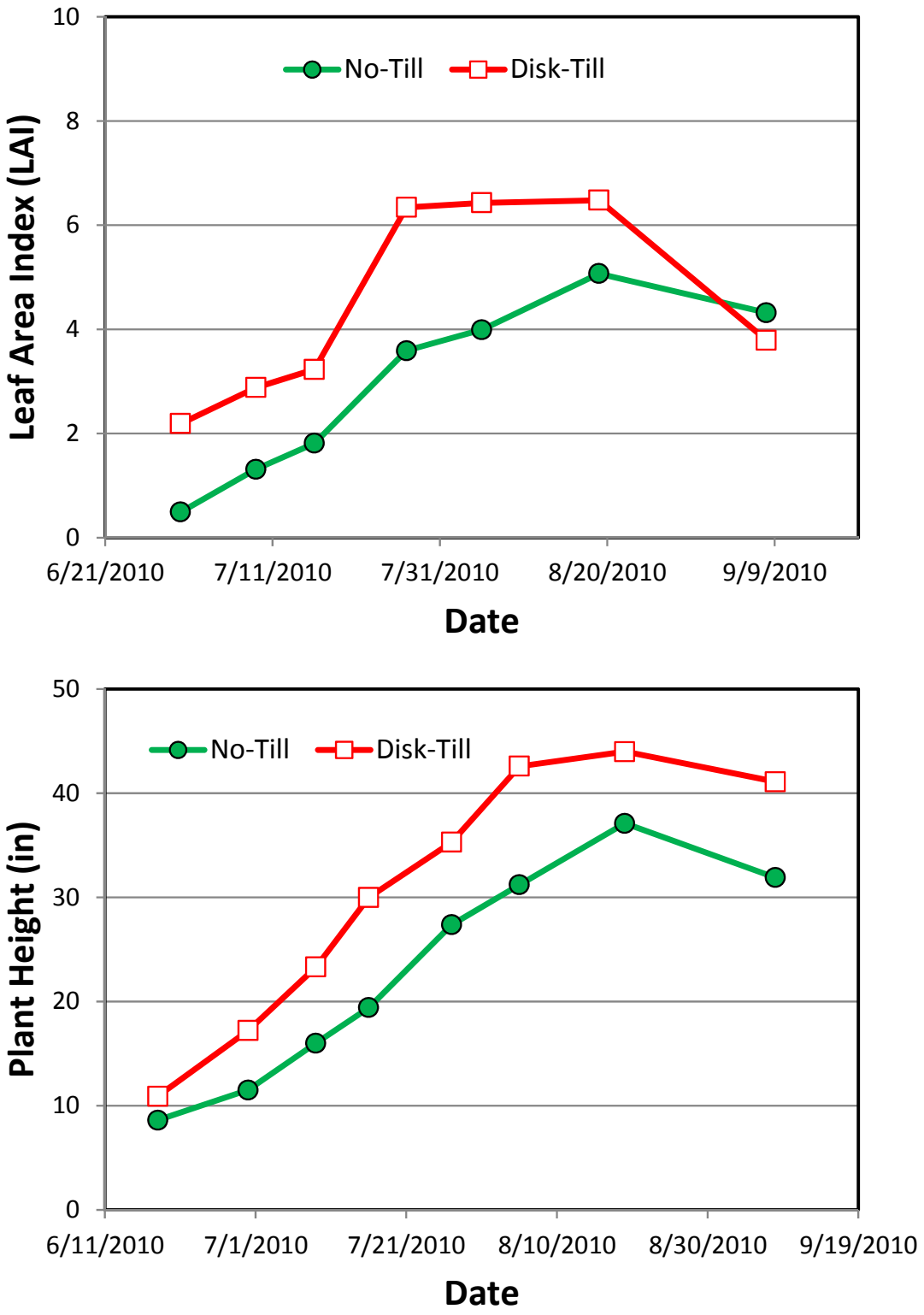


Figure 37. Measured leaf area index (LAI) and plant height in no-till and disk-till fields at Holdrege during the 2010 crop season (soybean)

3.3 Hydraulic conductivity and runoff components

Measured Hydraulic Conductivity

Hydraulic conductivity data are presented in Table 2 and displayed in Figure 38. Fillmore County, Phelps County, and SCAL have a texture of silt loam. Surface and subtillage hydraulic conductivity values fall in line with values reported in other references for silt loam. However, the rotational disk plot in SCAL was in the upper range provided. The Rogers Farm site, which has a texture of silty clay loam, had high surface and subtillage hydraulic conductivity values when compared to those reported by Rawls et al., 1993 for silty clay loam. At Fillmore County, the no-till field had a geometric mean surface hydraulic conductivity of 6.18 cm $h^{-1}$and the tilled field had a value of 3.89 cm h^{-1}. Phelps County followed the same trend as Fillmore County with a no-till hydraulic conductivity geometric mean of 8.21 cm h^{-1} and the tilled hydraulic conductivity geometric mean of 2.82 cm h^{-1}. Rogers Farm corn had higher hydraulic conductivity in the tilled plot (46.29 cm h^{-1}) than the no-till (8.25 cm h^{-1}). Rogers Farm soybean measured a hydraulic conductivity of 16.35 cm h^{-1} for no-till and 11.3 cm h^{-1} for the tilled. SCAL slot, ridge, and disk treatments were found to have surface conductivities of 8.89 cm h^{-1}, 4.64 cm h^{-1}, and 22.13 cm h^{-1}, respectively, for the rotational corn and 4.48 cm h^{-1}, 2.81 cm h^{-1}, and 8.74 cm h^{-1} for the slot, ridge, and disk treatments in continuous corn.

The high field hydraulic conductivity tests were also present in the lab tests as shown in the plot of lab versus field graph in Figure 39. The lab test had higher hydraulic conductivity values. The lab data illustrated the field methods were sufficient. The geometric mean of field measured satiated hydraulic conductivity over the geometric mean of the lab satiated hydraulic conductivity was 0.29 for surface measurements and 0.54 for the values in the subtillage layer, indicating field values were slightly higher.

Table 2. Geometric means of saturated conductivity of no-tillage and tillage on corn/soybean rotation for field tests. Twelve tests were conducted per plot for Fillmore County, Phelps County, and SCAL. Six replications were run for Rogers Farm.

			Geometric Mean (mean ± 1 standard deviation)*	
Site	Plot	Date	Surface K_s, cm h^{-1}	Subtillage K_s, cm h^{-1}
Fillmore County Rotational Corn	No-till	22-Jun-09	6.18 (2.10-18.22)	0.88 (0.15-5.37)
	Tilled**	22-Jun-09	3.89 (1.44-10.49)	1.03 (0.56-1.88)
Phelps County Rotational Corn	No-till	23-Jun-09	8.21 (3.47-19.44)	1.27 (0.61-2.62)
	Tilled	23-Jun-09	2.82 (1.26-6.30)	1.42 (0.75-2.67)
Rogers Farm Rotational Corn	No-till	7,8-July-09	8.25 (1.39-49.00)	13.08 (5.21-32.84)
	Tilled	7,8-July-09	46.29 (26.28-81.52)	19.83 (11.23-34.99)
Rogers Farm Rotational Soybean	No-till	7,8-July-09	16.35 (4.03-66.36)	4.94 (1.25-19.45)
	Tilled	7,8-July-09	11.3 (1.85-68.98)	15.26 (1.90-122.57)
SCAL Rotational Corn	Slot	10-Jun-10	8.89 (1.26-18.55)	1.94 (1.08-2.49)
	Ridge	10-Jun-10	4.64 (2.57-8.39)	1.39 (0.74-2.64)
	Disk	11-Jun-10	22.13 (11.08-44.20)	1.04 (0.44-2.50)
SCAL Continuous Corn	Slot	10-Jun-10	4.48 (1.26-18.55)	0.94 (0.57-1.53)
	Ridge	10-Jun-10	2.81 (0.90-8.77)	0.84 (0.47-1.49
	Disk	11-Jun-10	8.74 (2.31-33.04)	0.54 (0.21-1.40)

* mean ± standard deviation = $10^{[\log_{10}(\bar{y} \pm s_y)]}$

** Only eight tests are included for Fillmore County tilled

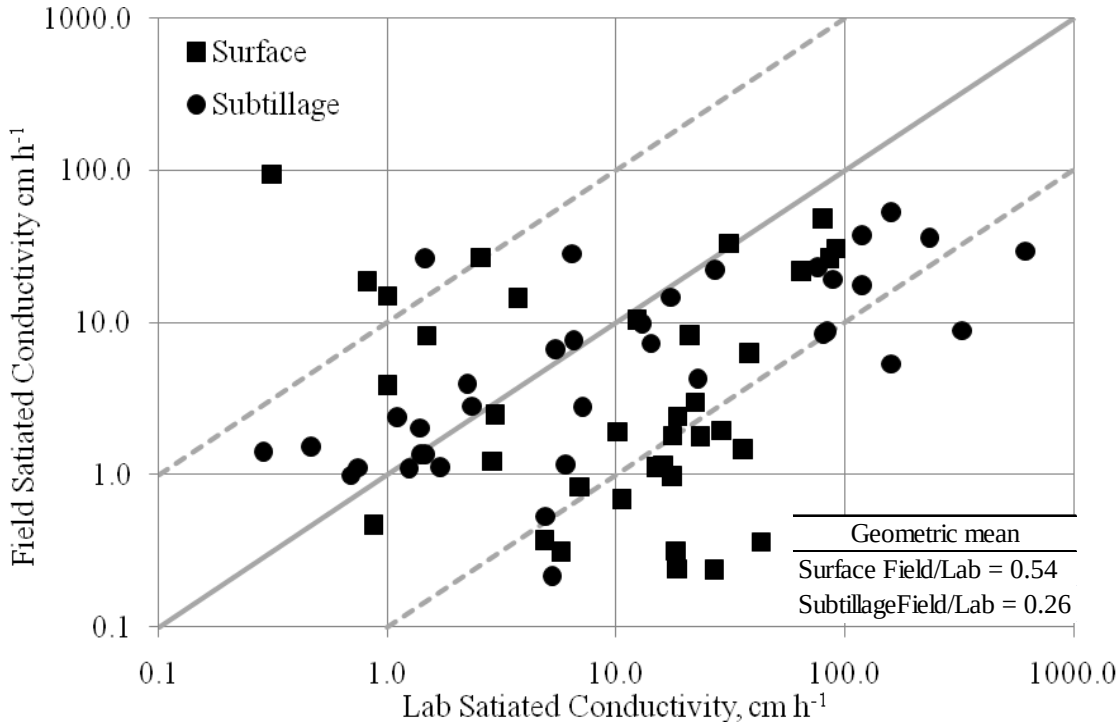


Figure 38. Field vs. lab satiated hydraulic conductivity for surface and subtillage layers

Analysis of variance was performed for the satiated hydraulic conductivity (Table 3). Statistical difference ($P < 0.10$) existed between surface hydraulic conductivities in Phelps County and in Fillmore County, with no-till values being higher. At the furrow irrigation site, SCAL, a significant difference was found in the rotational corn among each variation for slot, ridge, and disk treatment surface hydraulic conductivities. In continuous corn at SCAL, only ridge and disk were significantly different. Disk had the highest hydraulic conductivity. The tilled field was significantly higher in Rogers Farm corn than the no-till measurements. The Rogers Farm soybean measurements had no trend. The only subtillage measurements that were different were the disk versus slot hydraulic conductivities in SCAL, indicating differences in soil from no-till systems that affect hydraulic conductivity are within the tillage (surface) layer of the soil.

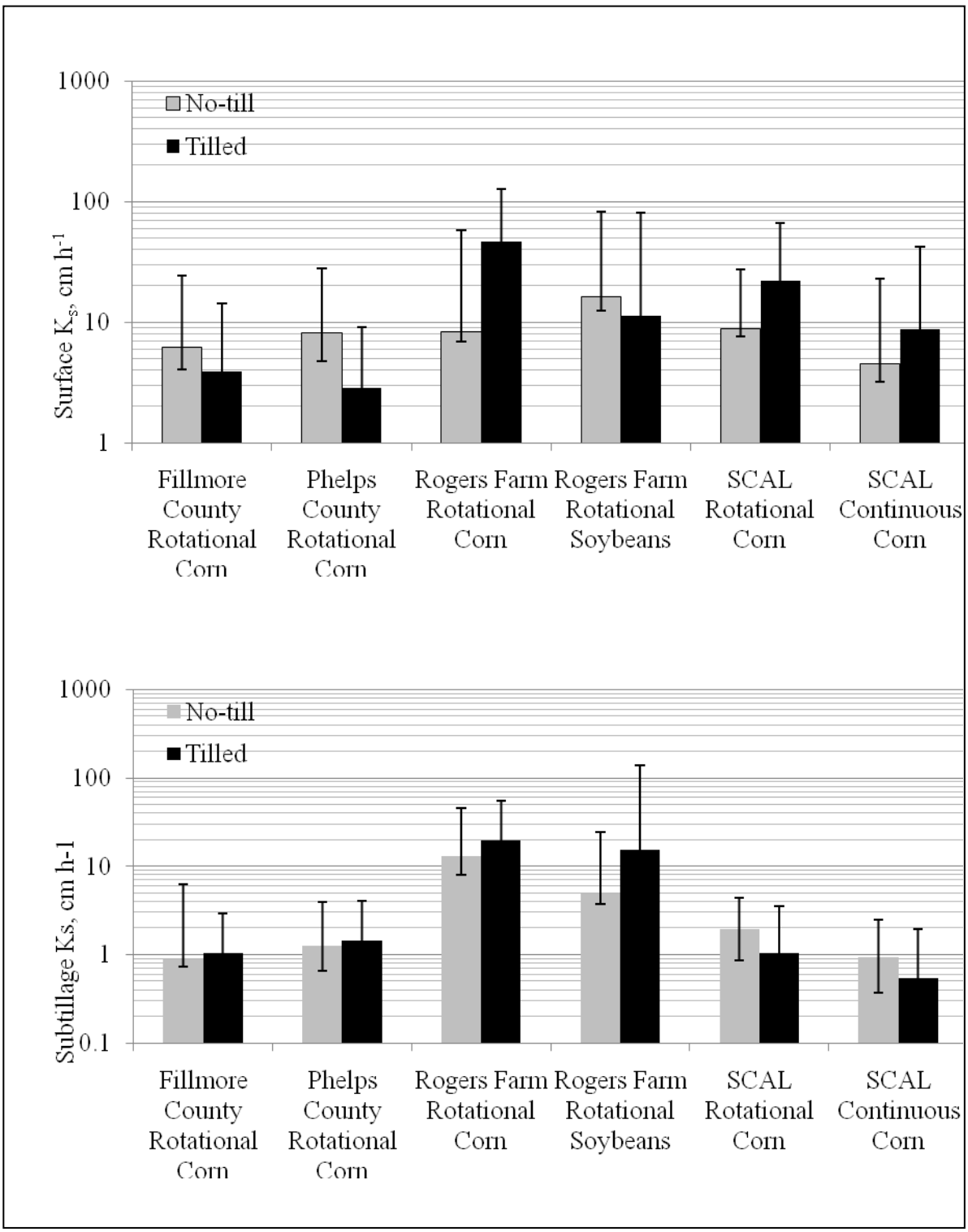


Figure 39. Surface and subtillage hydraulic conductivity for tilled and no-till plots. Error bars indicate standard deviation

Table 3. Two-way analysis of variance of satiated hydraulic conductivity (Holm-Sidak method). Statistically significant if P < 0.10.

Site	Comparisons for factor	Comparison	Unadjusted P	Different
Fillmore County	Tillage Treatment within Surface	Tilled vs. No-till	0.028	Yes
	Tillage Treatment within Subtillage	Tilled vs. No-till	0.112	No
Phelps County	Tillage Treatment within Surface	Tilled vs. No-till	0.001	Yes
	Tillage Treatment within Subtillage	Tilled vs. No-till	0.713	No
Rogers Farm Corn	Tillage Treatment within Surface	Tilled vs. No-till	0.012	Yes
	Tillage Treatment within Subtillage	Tilled vs. No-till	0.512	No
Rogers Farm Soybean	Tillage Treatment within Surface	Tilled vs. No-till	0.709	No
	Tillage Treatment within Subtillage	Tilled vs. No-till	0.262	No
SCAL Rotation	Tillage Treatment within Surface	Disk vs. Ridge	<0.001	Yes
	Tillage Treatment within Surface	Disk vs. Slot	0.001	Yes
	Tillage Treatment within Surface	Slot vs. Ridge	0.029	Yes
	Tillage Treatment within Subtillage	Disk vs. Ridge	0.115	No
	Tillage Treatment within Subtillage	Disk vs. Slot	0.023	Yes
	Tillage Treatment within Subtillage	Slot vs. Ridge	0.446	No
SCAL Continuous	Tillage Treatment within Surface	Disk vs. Ridge	0.008	Yes
	Tillage Treatment within Surface	Disk vs. Slot	0.163	No
	Tillage Treatment within Surface	Slot vs. Ridge	0.191	No
	Tillage Treatment within Subtillage	Disk vs. Ridge	0.42	No
	Tillage Treatment within Subtillage	Disk vs. Slot	0.197	No
	Tillage Treatment within Subtillage	Slot vs. Ridge	0.624	No

Texture was investigated as a possible influence on hydraulic conductivity results. The no-till field at Fillmore County had significantly higher clay content, with P = 0.035. At Phelps County, the tilled field had a significantly higher percentage of sand than no-till. Since at the other two sites the tillage treatment variations were located within the same field, no differences were found in texture. Two models were used to determined hydraulic conductivity based on the surface properties of the soil. ROSETTA is a model for predicting hydraulic conductivity with an input of percent sand, silt, and clay and bulk density. The Soil Water Characteristics tool, which is a model that uses pedotransfer functions, requires an input of percent sand, clay, and organic matter and bulk density. The results are shown in Table 4. Based on texture differences, hydraulic conductivity should be higher in the tilled fields at Phelps County and Fillmore County, confirming higher hydraulic conductivity in no-till fields was not due to the percent sand and clay.

Table 4. Texture, organic matter, and bulk density predicted satiated hydraulic conductivity using Soil Water Characteristics tool (SWC) and ROSETTA. Measured

Site	Plot	K_s, cm h^{-1}		
		Measured Subtillage (mean ± 1 standard deviation)*	SWC	ROSETTA
Fillmore County	No-till	0.88 (0.15-5.37)	1.32	1.55
	Tilled	0.67 (0.27-1.67)	1.41	7.24
Phelps County	No-till	1.27 (0.61-2.62)	1.48	1.76
	Tilled	1.42 (0.75-2.67)	1.67	2.99

* mean ± standard deviation = $10^{[\log_{10}(\bar{y} \pm s_y)]}$

Data from the tilled field in Fillmore County were collected ten days after cultivation. The ground was wet when cultivation took place, resulting in a very

cloddy surface. Only one of the spans where the experiments were conducted was cultivated because the corn was high. Minimal rainfall (<1.27 cm) occurred between the cultivation of the single plot and testing; therefore, no surface seal was expected to form. The data from this span were excluded in the above analysis, and are given below (Table 5). The excluded June cultivated plot at Fillmore County tilled had significantly higher measured hydraulic conductivity values than the other two plots in the tilled field.

Table 5. Geometric mean K_s span 3 data for tilled field in the above Fillmore County analysis; there were 4 of replications of the test. The data were not used in analysis in Tables 4-5.

		Geometric Mean (mean ± 1 standard deviation)*	
Site	Plot	Surface K_s, cm h^{-1}	Subtillage K_s, cm h^{-1}
Fillmore County	Tilled Span 3	43.9 (31.3-61.6)	0.29 (0.12-0.67)

* mean ± standard deviation = $[10]^{\uparrow}([\log_{\downarrow}10\ y^{-} + \log_{\downarrow}10\ s_{\downarrow}y)])$

The value for the surface satiated conductivity conducted in cracked soil at Fillmore County tilled resembles the magnitude of hydraulic conductivity for the Rogers Farm Corn tilled plot value. It is possible the high values observed at Rogers Farm are the result of dried soil that has cracked due to high clay content (29%). Moisture deficit was highest during the tests run at Rogers Farm (Δè = 0.30) and cracks were observed in the corn tilled field at Rogers Farm. SCAL disked plot may have been high due to the low bulk density. Measurement of hydraulic conductivity recently after tillage can increase the bulk density, and therefore the hydraulic conductivity. This study assumed satiated hydraulic conductivity was constant with time although shown in other studies to be highly variable throughout the cropping season. Tillage systems may have a positive effect on infiltration immediately after tillage, before

reconsolidation and surface sealing has taken place. Therefore, our infiltration results may be influenced by the time of measurement.

Runoff

At the center pivot sites, 55 irrigation and rainfall runoff events were captured during the crop seasons from 2008-2010. An example runoff hydrograph from one of the runoff events is shown in Figure 40.

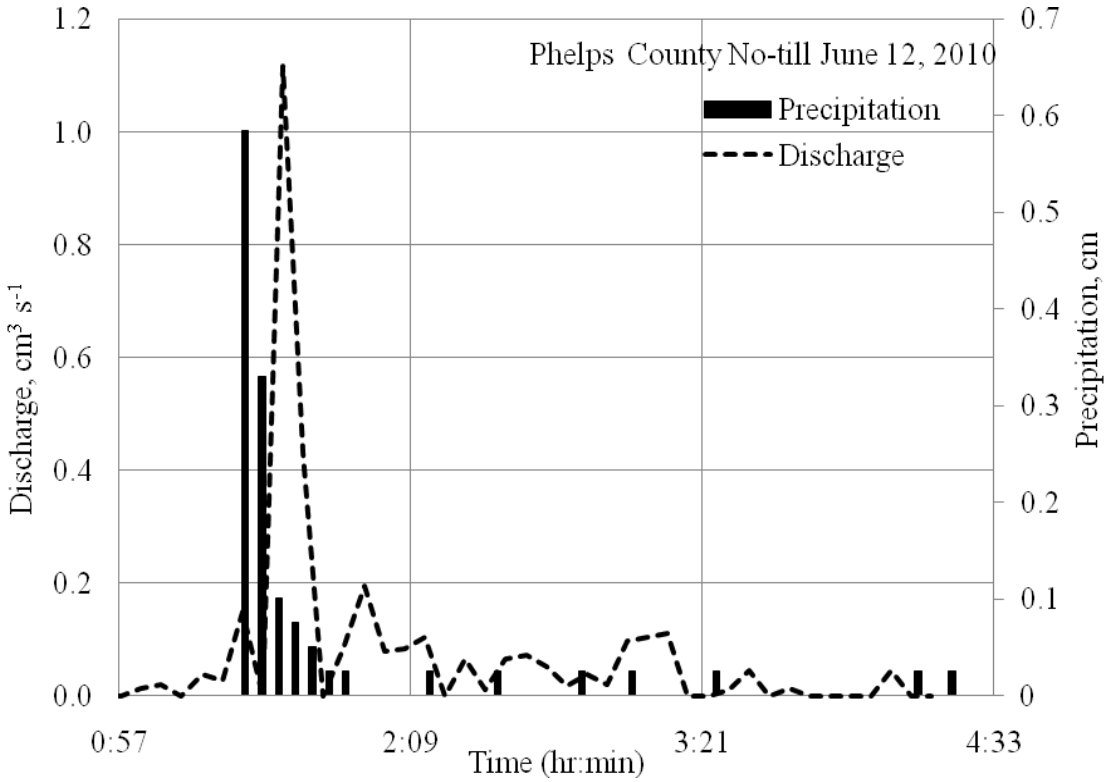


Figure 40. Example runoff hydrograph and rainfall hyetograph of an observed runoff event. Total precipitation = 1.78 cm

Forty-three pairs of the events (both tilled and no-till) were the result of rainfall and 12 individual events were monitored irrigation events. Figures 41 and 42 display cumulative rainfall runoff over the monitored seasons. Events shown do no encompass the total runoff events that occurred during the time frame. These are events with complete data from both no-till and tilled fields and ones with questionable or incomplete data were excluded.

At the sites, the two fields are located within 1.5 km, so rainfall depths were similar at both fields. For the no-till field in Fillmore County, 7.2 cm of runoff was observed. During these same events, 9.3 cm cumulative runoff was obtained from the tilled field in Fillmore County. The cumulative rainfall was 38.1 cm for no-till and 40.1 cm for tilled. Runoff vales at this site were not significantly different, so a conclusion could not be drawn. Rainfall totals for events included in the graph at Phelps County were 58.8 cm for no-till and 62.7 cm for tilled. Cumulative amounts of runoff were 6.4 cm for no-till and 14.6 cm for tilled in Phelps County. These values were significantly different.

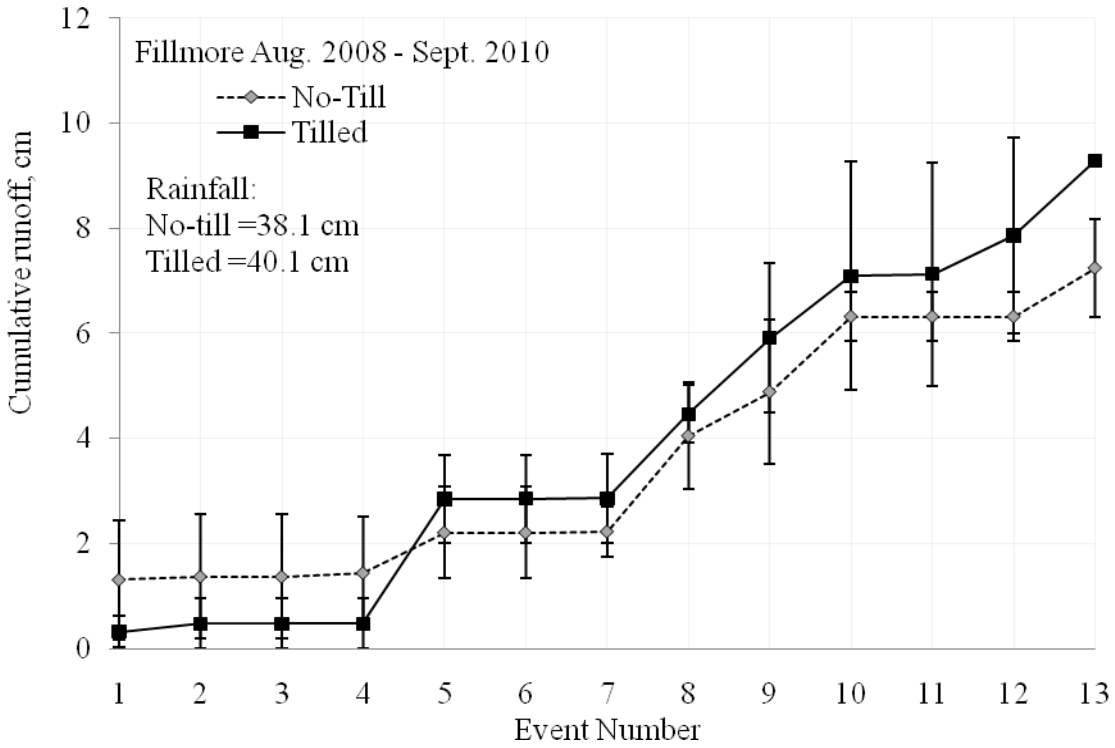


Figure 41. Growing season cumulative runoff with standard deviation error bars from rainfall events during Fillmore County cropping seasons 2008-2010

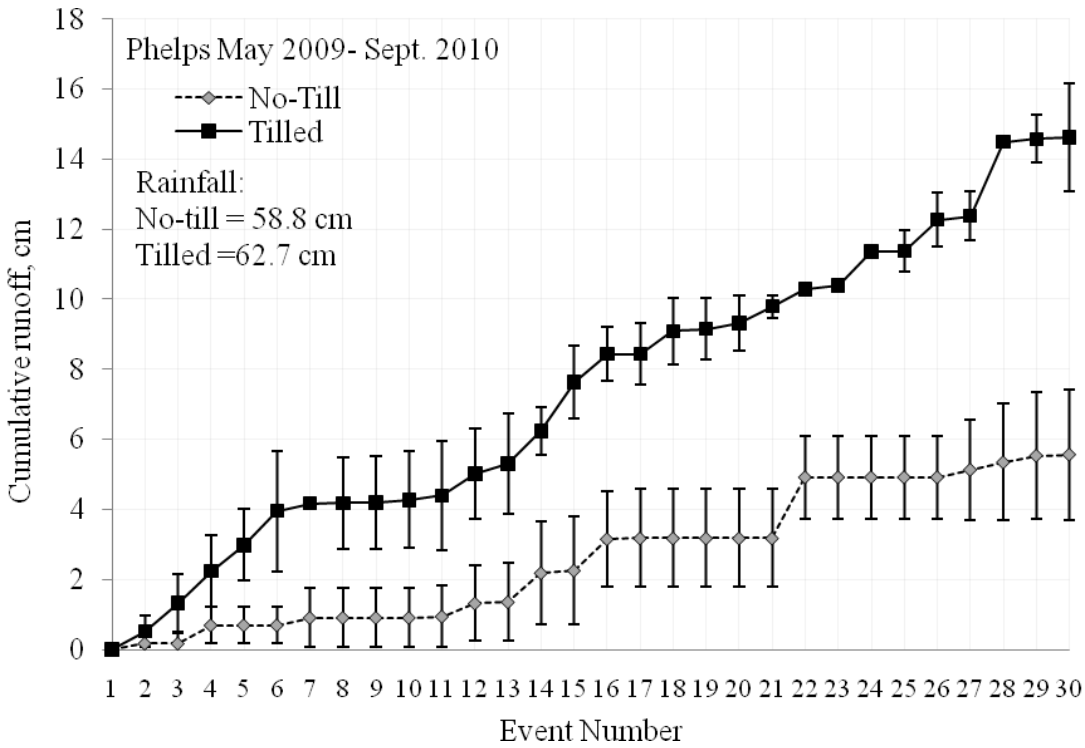


Figure 42. Growing season cumulative runoff with standard deviation error bars from rainfall events during Phelps County cropping seasons 2008-2010

Few irrigation events were captured due to incomplete rain data in 2009 since a rain gauge was not installed in the field. In Fillmore County average irrigation runoff was 14.9% for tilled and 1.7% for no-till for six and three monitored events respectively. In Phelps County tilled 52.0% of irrigation water ran off compared with 38% runoff from no-till. Two events were recorded to have runoff from no-till and one irrigation runoff event from tilled (Table 6).

Surface Seal, Storage, and Aggregates

To explore reasons for variations in hydraulic conductivity between tilled and no-till, surface sealing, depressional storage, aggregate stability, and residue were investigated. The amount of water storage per field was determined by calculating depressional storage. The results of depressional storage are shown in Table 7. Depressional storage was calculated assuming residue is a barrier that can retain pools of water from running off the field. No-tilled fields had a depressional storage of about

0.13 cm while tilled fields were in the 0.02-0.03 cm range. Depressional storage reduces runoff because soil depressions must be filled before runoff occurs. The storage is a result of soil microrelief and residue, which can retain a significant amount of water after ponding occurs. Therefore, more residue and soil depressions would decrease the amount of runoff. From a one-way analysis of variance, Fillmore County no-till depressional storage was significantly larger than tilled (P = 0.002). Phelps County no-till also had significantly more depressional storage than tilled (P = <0.001).

Table 6. Irrigation events and the corresponding runoff depths

Site	Field	Year	Day-Month	Irrigation, cm	Runoff, cm
Fillmore County	No-till	2010	4-Aug	2.74	0.02
			10-Aug	2.74	0.03
			20-Aug	3.12	0.10
	Tilled	2008	8/27-8/28	3.41	0.45
		2009	28-Jun	1.81	0.05
			7-Jul	2.08	0.34
			5-Aug	2.08	0.89
		2010	6-Aug	3.18	0.47
			12-Aug	3.33	0.17
Phelps County	No-till	2009	11-Aug	2.54	0.15
		2010	13-Jun	2.18	0.83
	Tilled	2009	21-Jul	2.29	1.20

Residue slows down the water velocity and protects the ground from rain impaction. In 2009, residue measurements constituted about 20% cover for tilled fields. No-till fields differed. Fillmore County, when the no-till field utilized strip till, had 65% residue and Phelps retained 82% of the previous year's residue. In 2010, when Fillmore County no-till switched to true no-till, both no-till fields had residue in the 90% range contrastingly the tilled fields having about 40% cover. These percentages align with values given by the Natural Resources Conservation Service for tilled and no-till

residue (USDA NRCS, 1992). Slot and ridge treatments at Clay County had about 40% residue cover while disk treatment residue was 14%.

Aggregate stability results showed no-till sites have significantly more stable aggregates (Figure 43). Forty-five percent and 33% are stable aggregates in no-till fields at Fillmore County and Phelps County, respectively. Tilled field aggregate tests resulted in 28% and 13% stable aggregates from Fillmore County and Phelps County respectively.

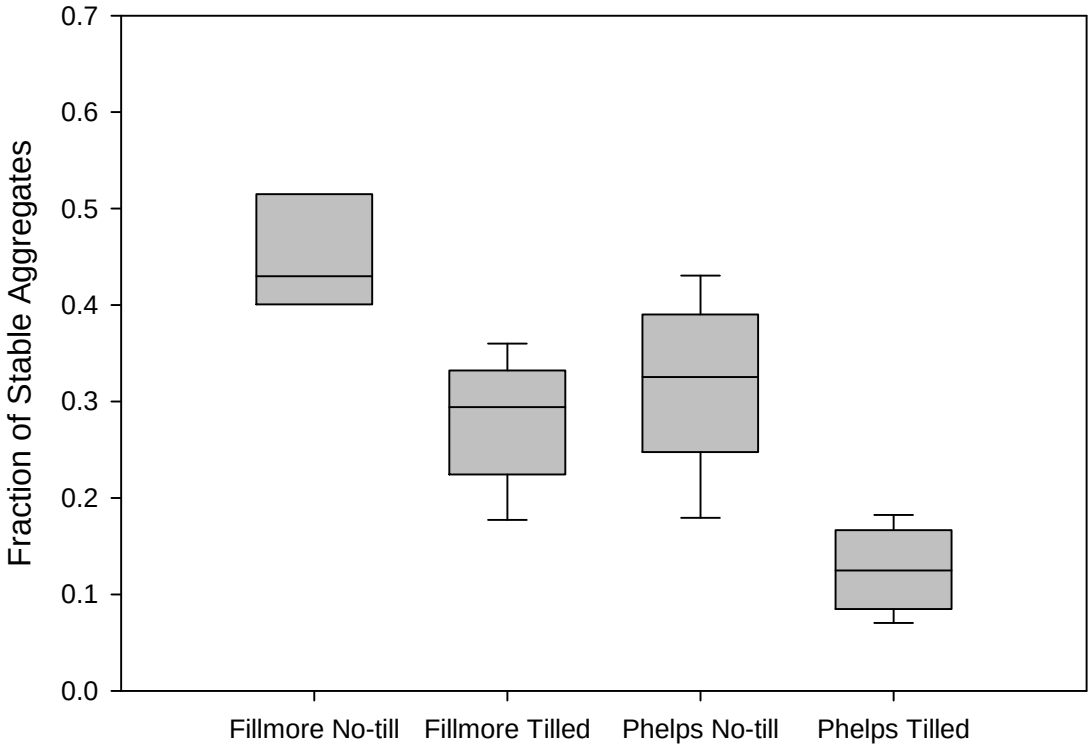


Figure 43. Fraction of stable aggregates at center pivot irrigated sites

Macropores

On average about 0.01 - 0 .15% of the area of the field was found to have macropores (Table 8), which is at the lower end of the range for pores greater in diameter than 0.04 cm (0.03-1.7% of total area). Since this study included pores larger than 0.1 cm, not 0.04 cm, it is expected that less area would be found. There was no

difference in percentage of surface area from macropores between tilled and no-till at Fillmore County or at Phelps County, or between plots at Clay County. Rogers Farm had significantly higher macropore area in the no-till field. This may be from the long term applications of no-till. Rogers Farm has had consistent tillage practices for 28 years when experiment was conducted. The other sites have been consistent for about seven years. Another factor may be the depth at which measured (6.5 cm) did not correspond to the connectivity of the surface pores. Future investigation to determine connectivity of the macropores to see how the network compares at different depths would help in understanding the effects of macropores on these fields.

Table 7. Results from percent residue, depressional storage (DS), and aggregate stability

		May 2009	Late May 2010	Early Aug 2009	
County	Plot	Residue, %	Residue, % (std dev)	DS, cm (std dev)	Stable Aggregates, % (stdev)
Fillmore	No-till	65	92.84 (6.70)	0.13 (0.06)	45 (0.08)
	Tilled	25	37.41 (15.30)	0.03 (0.02)	28 (0.06)
Phelps	No-till	82	91.42 (5.90)	0.13 (0.05)	33 (0.08)
	Tilled	21	46.74 (17.00)	0.02 (0.02)	13 (0.04)
Clay	Slot	NA	45.70 (8.50)	NA	31 (0.13)
	Ridge	NA	33.80 (10.50)	NA	36 (0.17)
	Disk	NA	14.70 (8.10)	NA	24 (0.12)

Table 8. Percentage of area contributing to macropores

Site	Plot	Macropore area, %
Fillmore County	No-till	0.028
	Tilled	0.056
Phelps County	No-till	0.009
	Tilled	0.005
Rogers Farm	No-till	0.166
	Tilled	0.025
SCAL	Slot	0.101
	Ridge	0.100
	Disk	0.147

Discussion

Even though no difference was determined in macropore quantity at three of the four sites, percent residue, depressional storage, and aggregate stability was higher in no-till, which appeared to influence hydraulic conductivity and runoff. Hydraulic conductivity was significantly higher in the no-till field at Phelps County. The hydraulic conductivity measurements corresponded to the runoff from the no-till field in Phelps County being significantly higher than the tilled field. Although this may be influenced by residue or aggregate stability, the slope of the no-till field is less than the tilled field in Phelps County, which could reduce runoff. In the no-till field at Fillmore County, the hydraulic conductivity values were significantly higher than tilled. The observed runoff, however, there was no difference found between tillage treatments. A few reasons could be increasing the runoff at the no-till field. Frequent rainfall and irrigation could result in no-till moisture content being higher, and therefore, increasing the observed runoff. As discussed previously, residue plays an important role in reducing runoff. Limited residue could lead to more surface sealing and reducing the hydraulic conductivity. Because Fillmore County no-till used strip tillage in 2009, 30% less residue covered the surface. However, no differences were visible among 2009 runoff and the other years.

Disk hydraulic conductivity measurements were significantly higher in SCAL rotational corn. This may be because of the bulk density being lower. Measurements taken in dryland corn showed tilled to have the highest hydraulic conductivity. Soil was dry and cracked which may have influence the abnormally high data from the tilled dryland corn.

Texture was found to be significantly different between the fields where the runoff plots were located. Infiltration rates are impacted by texture as shown by the Soil Water Characteristics tool, which takes percent sand, clay, and organic matter to predict hydraulic conductivity. This model predicted lower satiated conductivity in the no-till fields at Fillmore County and Phelps County, indicating the impact of no-till overshadowed the texture influence.

For future investigations, the time period between rainfall and irrigation events should be included in the analysis. No-till may remain at a higher moisture content, increasing the amount of runoff. Macropore connectivity should be quantified to better understand the impact large pores have on the field. Also, a longer time period between cultivation and hydraulic conductivity experiments should be practiced to account for surface sealing.

3.4 Determining Satiated Hydraulic Conductivity for the Green and Ampt Equation Using Natural Runoff Data

Observed runoff

Twenty-six runoff events were measured during the growing season of 2010. Six of the runoff events were due to irrigation events. The runoff data were used to create the event hydrographs to compare with the Green and Ampt modeled hydrographs. Sample hydrographs are shown in Figures 44 and 45.

Satiated hydraulic conductivity

Hydraulic conductivity was estimated using four models. Table 9 provides the hydraulic conductivity values predicted by each model. These K_s values were used in the Green and Ampt iterative equation for each monitored runoff event in 2010. The WEPP results, using the ratio derived from the tabular curve number found in the SCS handbook and the hydraulic conductivity from the curve number calculated maximum surface storage measured on the fields in this study are shown in Table 9. The hydraulic conductivity derived from the ratio was used in runoff analysis.

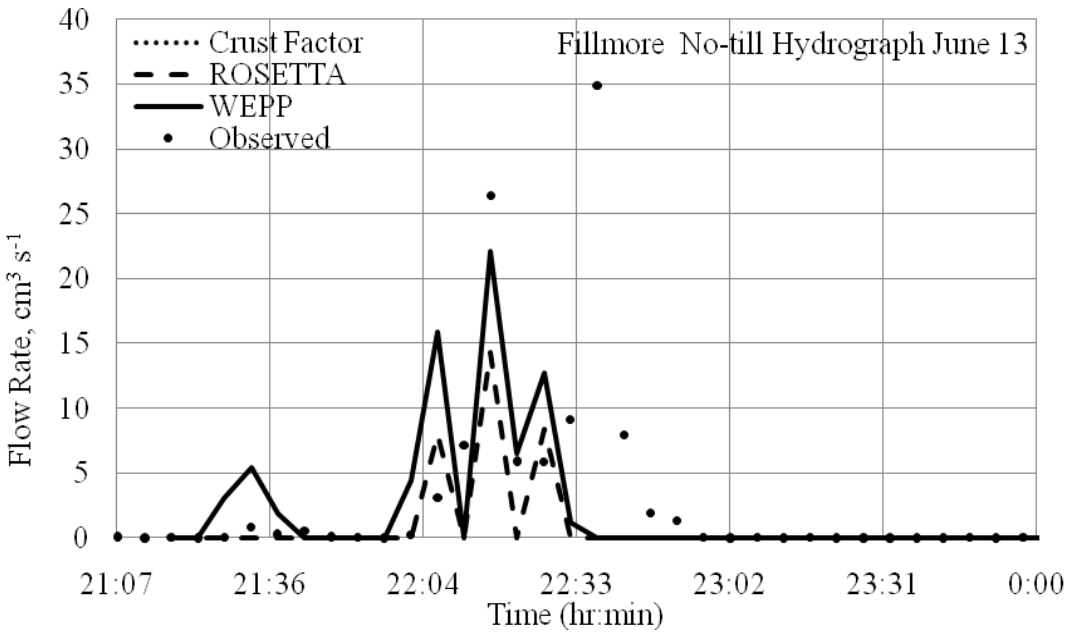


Figure 44. Observed and predicted runoff hydrographs.

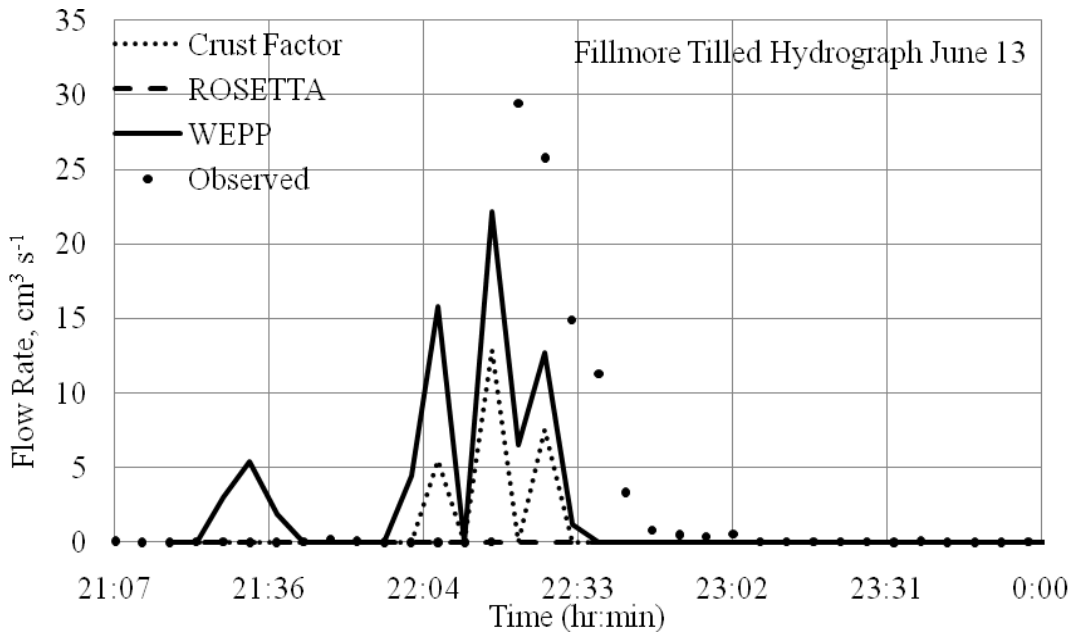


Figure 45. Observed and predicted hydrographs.

Table 9. Satiated hydraulic conductivities of the surface layer used in the Green and Ampt model

Site	Plot	Experimentally Measured	Crust Factor	ROSETTA	WEPP Tbl 2.2	WEPP Eqn 2.15	SWC
		Hydraulic conductivity, cm h^{-1}					
Fillmore County	No-till	6.18 (2.10-18.22)*	3.22	1.55	0.52	0.53	2.14
	Tilled	3.89 (1.44-10.49)	1.28	7.24	0.44	0.42	2.56
Phelps County	No-till	8.21 (3.47-19.44)	5.85	1.76	0.52	0.53	2.49
	Tilled	2.82 (1.26-6.30)	0.26	2.99	0.51	0.44	2.94

$*mean \pm standard\ deviation = 10^{[\log_{10}(\bar{y} + s_y)]}$

Depressional Storage

Depressional Storage was determined using the table from NRCS (2005) and measured values (Table 10). Comparing the modeled runoff outputs using both depressional storage numbers to the measured runoff, the measured DS resulted in higher efficiency and less percent bias. Therefore, in the analysis for model comparison, the measured DS value was used.

Table 10. Depressional Storage from NRCS and from measured

Site	% Residue	% Slope	NRCS Depressional Storage, cm	Measured Depressional Storage, cm
Fillmore No-till	93	1.0	2.00	0.13
Fillmore Tilled	37	0.9	1.42	0.02
Phelps No-till	91	0.2	2.16	0.13
Phelps Tilled	47	0.5	1.73	0.03

Rainfall Runoff

Efficiency and error values, along with the cumulative modeled and measured runoff for the season are given in Table 11. PBIAS and NSE values corresponded in all but two categories (Phelps County No-till and Phelps County Composite) for picking the optimal model for each grouping. RMSE values did not always align with the chosen PBIAS and NSE best model. NSE values were often negative, indicating poor efficiency for the model. PBIAS is therefore used in discussion to compare models.

Field measured surface hydraulic conductivity resulted in the highest K_s values for all fields except for the tilled field in Phelps County. Although high values were also observed in the lab, using the field measured hydraulic conductivity as the parameter for the Green and Ampt equation resulted in no runoff throughout the crop

season and, therefore, was not consistent with the observed runoff. Discrepancies between measured saturated hydraulic conductivities and runoff amounts may be due to testing methods or characteristics of the field at the time of measurement. Testing may have destroyed the surface seal that results from water drop impact, or created cracks in the soil. Early season measurement did not account for compaction of the seasonal soil surface after tillage or surface crusting from multiple rainfall and irrigation events .

The Crust Factor equation takes into account surface crusting. In the Crust Factor equation, experimental data were used and adjusted lower to account for the surface crust. This was the only model that predicted the Phelps County no-till field to have higher hydraulic conductivity than the tilled field. This is significant since Phelps no-till experienced significantly less runoff than the Phelps County tilled field throughout the season. Although this method did predict more runoff events than the unadjusted experiment values, this model still predicted low runoff depths. Phelps County tilled field was the only field where total runoff was over predicted by the Crust Factor model. The pooled percent bias for all fields was -36%. The composite Phelps County runoff was most accurately described by this model (PBIAS = -6%).

ROSETTA predicts hydraulic conductivity using the soil properties of percent sand, silt, and clay and bulk density. The PBIAS was -67% when all four fields were considered collectively. Modeled runoff data for most fields were lower than observed data. The exception to this was Phelps County no-till field, predicting one hundredth of a centimeter more than observed. Because ROSETTA does not include adjustments for management practices, such as residue left on the ground or the effect of rain impaction, the model did not account for the influence of tillage systems on infiltration and runoff. ROSETTA best predicted runoff from the composite no-till fields and the no-till field in Phelps County.

Table 11. Root mean squared error (RMSE), Nash-Sutcliff efficiency (NSE), percent bias (PBIAS), and cumulative runoff from rainfall based on the hydraulic conductivity derived from four models. Values are given for each field individually and the combined data (composite) and separated by tillage type and site.

	Measured	Crust Factor					ROSETTA					WEPP Tbl 2.2					SWC			
Grouping	Runoff, cm	RMSE, cm	NSE	Bias, %	Runoff, cm		RMSE, cm	NSE	Bias, %	Runoff, cm		RMSE, cm	NSE	Bias, %	Runoff, cm		RMSE, cm	NSE	Bias, %	Runoff, cm
Fillmore County No-till	4.80	1.15	-2.41	-100.00	0.00		0.84	-0.82	-75.48	1.19		0.15	0.95	-12.62	4.23	*	0.99	-1.53	-87.44	0.61
Fillmore County Tilled	5.70	0.73	-1.34	-59.08	2.33		1.04	-3.05	-86.63	0.76		0.56	-0.39	10.73	6.29	*	0.48	-5.88	16.19	1.21
Phelps County No-till	5.00	0.31	0.44	-74.99	1.04		0.34	0.39	20.49	5.01	*	0.65	-1.40	155.30	10.62		0.27	-0.07	58.79	3.42
Phelps County Tilled	9.60	0.79	-0.87	20.63	10.25		0.77	-0.69	-87.68	1.31		0.66	-0.30	6.40	12.02	*	0.59	-1.62	-38.03	1.37
No-till Composite	9.80	0.58	-0.17	-88.44	1.04		0.49	0.24	-31.13	6.20	*	0.57	-0.10	64.98	14.85		0.50	0.13	-55.30	4.02
Tilled Composite	15.30	0.80	-0.71	-7.10	12.58		0.86	-0.89	-87.31	2.07		0.66	-0.15	7.91	18.31	*	0.83	-0.84	-84.20	2.58
Fillmore County Composite	10.50	0.93	-1.87	-77.90	2.33		0.95	-1.77	-81.50	1.95		0.44	0.36	-0.01	10.52	*	0.57	-3.35	-37.25	1.82
Phelps County Composite	14.60	0.61	-0.28	-6.22	11.29	*	0.60	-0.18	-57.31	6.32		0.66	-0.51	48.20	22.64		0.53	-0.28	-55.42	4.79
Composite	25.80	0.71	-0.38	-35.99	13.62		0.70	-0.30	-67.36	8.27		0.62	-0.06	28.18	33.16	*	0.69	-0.32	-73.94	6.60

* indicates best NSE for given grouping

The WEPP model predicts satiated hydraulic conductivity for fallow conditions and adjusts the value by considering crop type and management practices through the curve number. Curve numbers were calculated using the measured runoff data from the micro runoff plots. The no-till curve number was 83, and the curve number for the tilled fields was 87. These values were higher than tabular values for curve number (Table 12). One reason for this may be the number of small rainfall depths used to predict the curve number was at the low end of the curve number versus precipitation curve so the values did not represent the curve number asymptote. Another reason is the assumed initial abstraction ratio may be too high (initial abstraction/S = 0.2). K_s values were similar, resulting in similar results for each model. The ratios based on the SCS curve numbers (WEPP) were therefore used in the analysis instead of the derived curve numbers with WEPP equation.

Table 12 Curve numbers, N, from the SCS Handbook (WEPP Tbl 2.2), 1985 and inversely measured from observed runoff events (WEPP Eqn 2.15)

	N for Hydrological Soil Group B	
Crop Type	WEPP Tbl 2.2	WEPP Eqn 2.15
Conventional soybean	81	87
Conservation soybean	80	83

Ratio values describing the cropped to fallow hydraulic conductivities are shown in Table 13. Using the curve number from the micro runoff plot data in the WEPP equation indicated a ratio close to what was described by Nearing et al., 1996. Ratios 1.70 and 1.91 were used to calculate K_s from K_{ef}, which were given in the paper by Nearing et al. (1996).

Table 13. Cropped to fallow hydraulic conductivity ratio

	K_s/K_{ef}	
Crop Type	WEPP Tbl 2.2*	WEPP Eqn 2.15
Conventional soybean	1.70	1.49
Conservation soybean	1.91	2.11

* WEPP Tbl 2.2 is the optimized ratio to describe the given soil group in Nearing et al., 1996.
** WEPP Eqn 2.15 is the ratio determined using Equation 2.15 from Nearing et al. 1996.

Runoff was over predicted at the no-till field in Phelps County with a PBIAS of 155%. Other than Phelps County no-till field, WEPP most accurately predicted all sites. The composite PBIAS = 28% and when Phelps no-till was not considered, the PBIAS was only 3.22. The Fillmore County composite PBIAS was a -0.01%.

SWC predicted hydraulic conductivity based on bulk density and percent sand, clay, and organic matter. The composite PBIAS was -74%. SWC model had low RMSE values; however it did not have the smallest PBIAS for any grouping.

Scatter plots for each model are shown in Figures 46-49. The graphs show the model predicted value for each runoff event against the observed runoff event. Each event had a different depth of rainfall. The closer the two values, the closer to the 1:1 line the points fall. Crust Factor is accurate with some scatter. ROSETTA and SWC graphs display the underestimation of the modeled runoff depths. The WEPP graph exhibits the accuracy of the model, especially at Fillmore County, which follows the regression line; however most of the Phelps County no-till field events were overestimated.

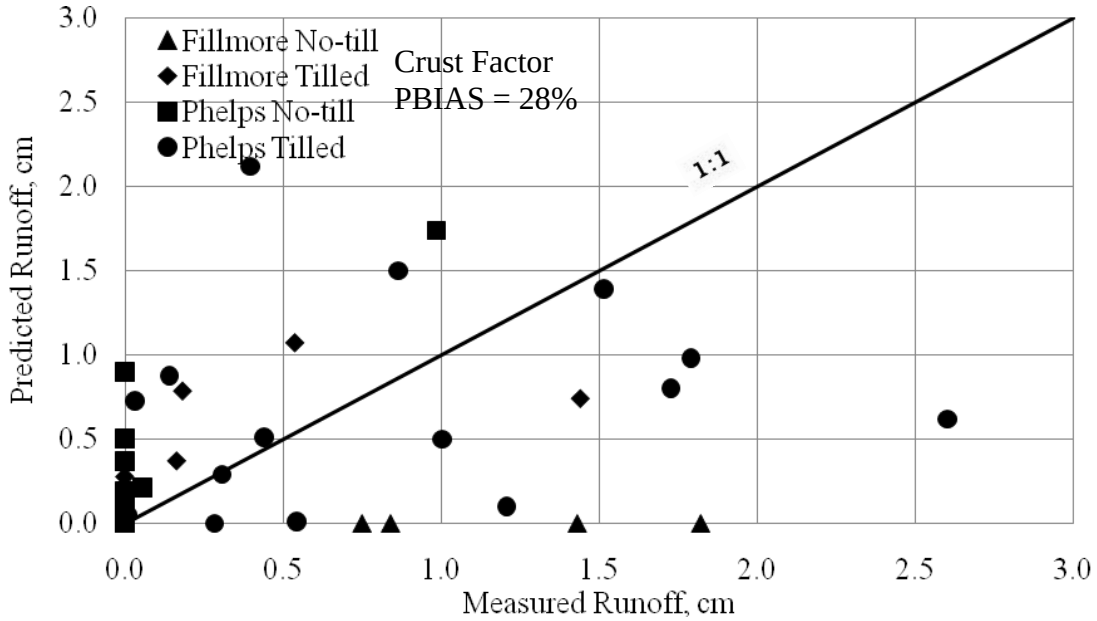


Figure 46. Observed runoff vs. Crust Factor predicted runoff in 2010

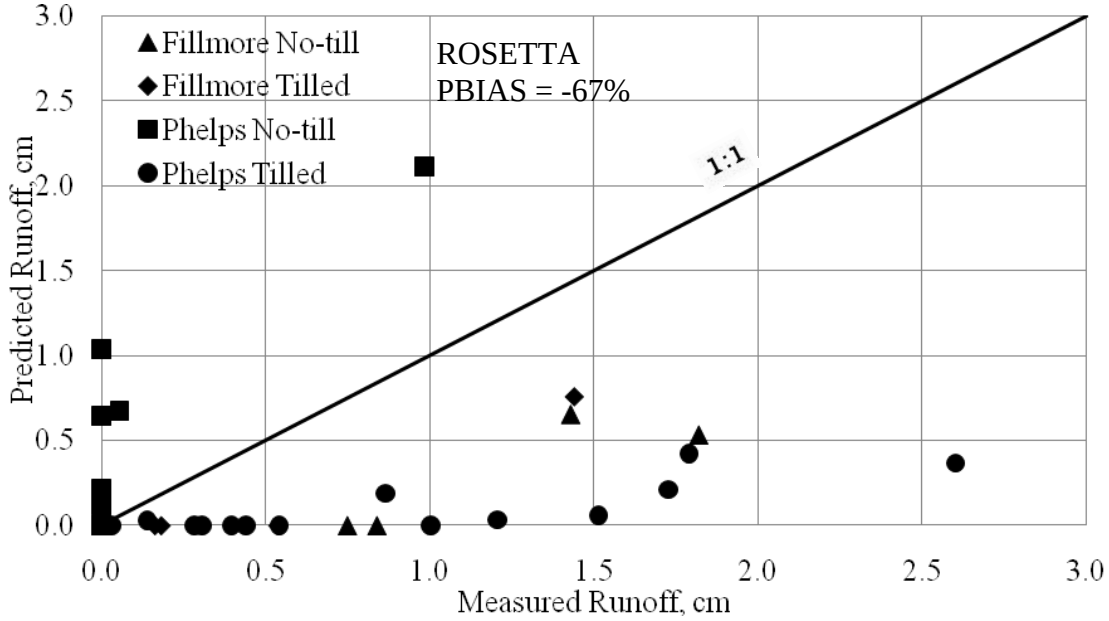


Figure 47. Observed runoff vs. ROSETTA predicted runoff in 2010

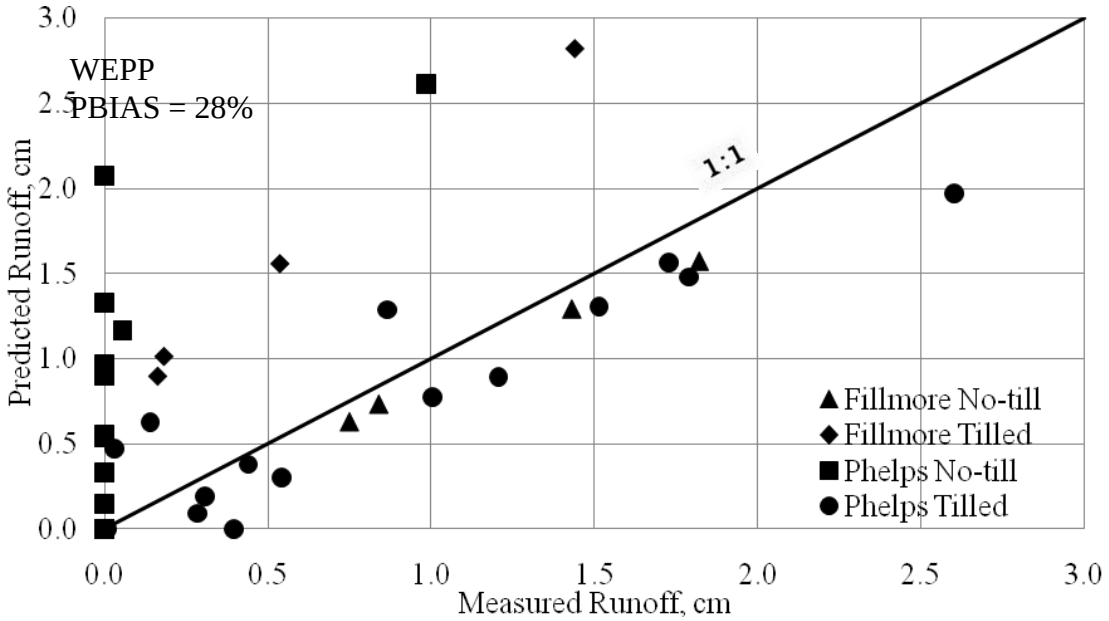


Figure 48. Observed runoff vs. WEPP predicted runoff in 2010

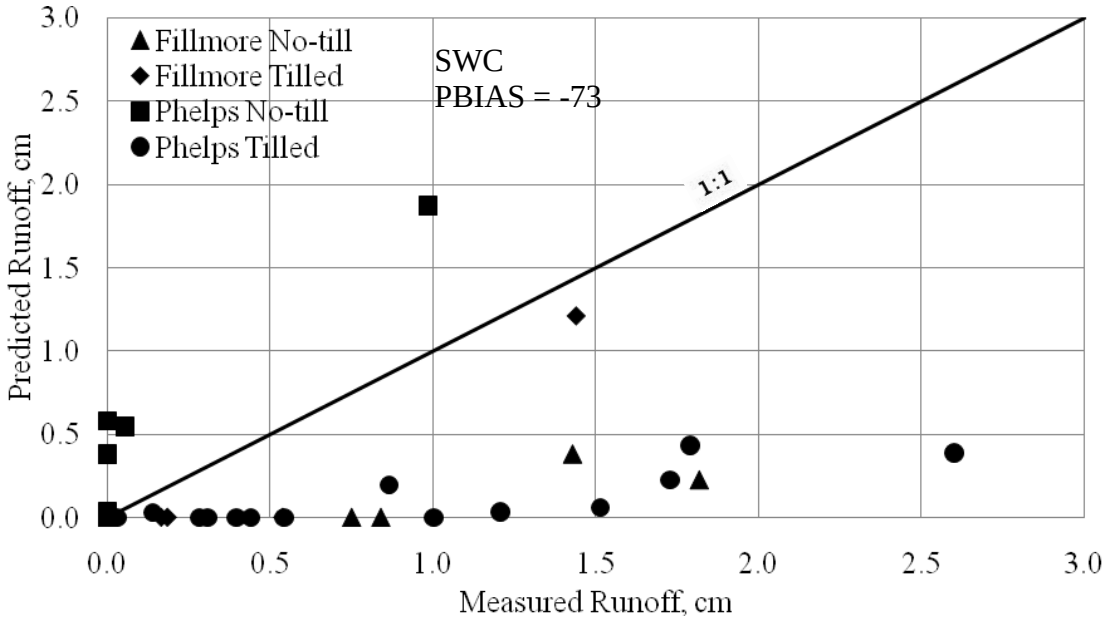


Figure 49. Observed runoff vs. SWC predicted runoff in 2010

Irrigation

From the runoff events investigated, irrigation runoff events were isolated for analysis. Irrigation rate curves for specific events were formed to illustrate the effectiveness of the tipping rain gauge and application rate relationship. Figures 50-52 show the rain gauge captured the smoothness of the application rate. All models performed poorly with the irrigation runoff prediction. ROSETTA, WEPP, and SWC overestimated runoff. Crust Factor had the best PBIAS of -46%. WEPP had a PBIAS of 282%. Table 14 shows the values for the observed irrigation runoff from 2010.

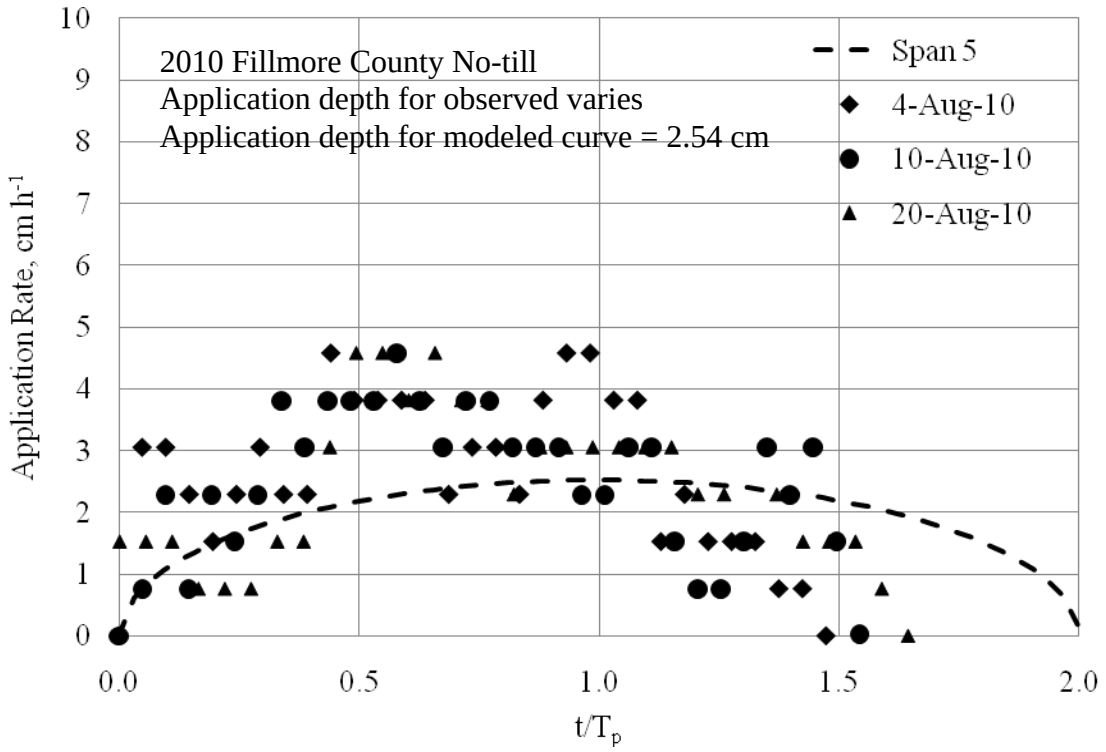


Figure 50. Fillmore County no-till modeled irrigation application rate and the observed tipping rain gauge curve from Span 5

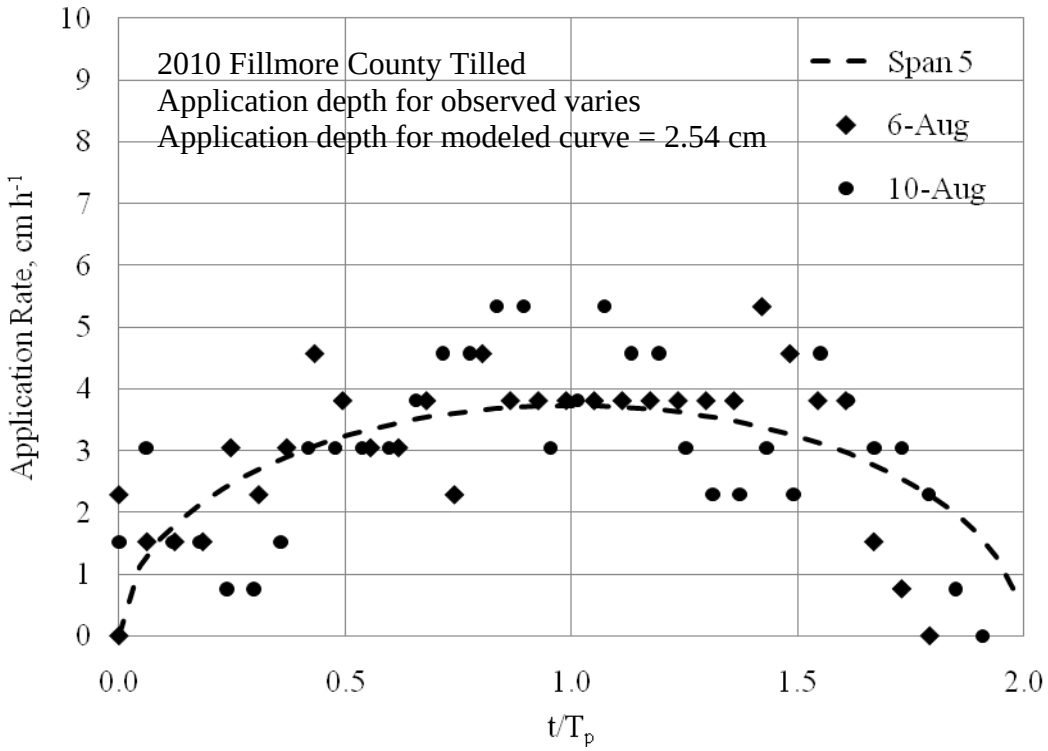


Figure 51. Fillmore County tilled modeled irrigation application rate and the observed tipping rain gauge curve from Span 5

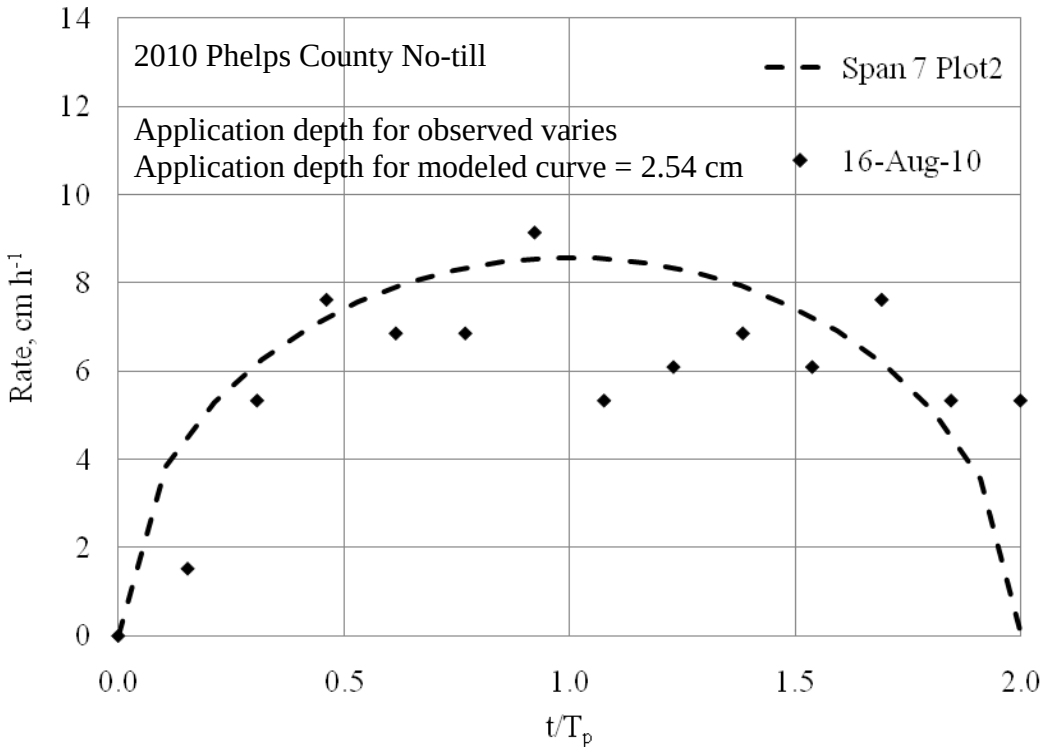


Figure 52. Phelps County no-till modeled irrigation application rate and the observed tipping rain gauge curve from Span 7

Table 14. Modeled runoff for 2010 irrigation runoff events

Site	Date	Irrigation, cm	Measured	Crust Factor	ROSETTA	WEPP	SWC
			Runoff, cm				
Fillmore County No-till	4-Aug	2.69	0.02	0.00	0.00	0.29	0.00
	10-Aug	2.74	0.03	0.00	0.00	0.26	0.00
	20-Aug	2.14	0.04	0.00	0.00	0.03	0.00
Fillmore County Tilled	6-Aug	3.33	0.47	0.00	0.00	0.74	0.00
Phelps County No-till	13-Jun	2.18	0.83	0.10	1.08	1.86	0.80

Discussion

Runoff is sensitive to the hydraulic conductivity parameter in the Green and Ampt equation. Brakensiek and Onstad (1977) found that a 10% lower K_s value over predicts the volume of runoff by 44%. This makes it difficult for one model to accurately describe any field. For example, no model could predict the low observed

runoff at Phelps County no-till field. Some condition affecting the runoff in this field was not taken into account in these models. Also the assumptions in the Green and Ampt model can influence results. The wetting front is assumed to be a piston, when in reality, the wetting front does not have a sharp boundary of saturation. The model did not account for redistribution of water during drying periods of the storm when the intensity decreased after ponding. Lastly, no head of water was assumed to be at the surface once ponding occurs. These assumptions can affect the results.

Investigating four models for predicting an accurate hydraulic conductivity for different soil types and tillage resulted in no overall optimal model. The most accurate model for determining hydraulic conductivity of the given fields was WEPP, which had a negative efficiency (NSE = -0.06) and a PBIAS of 28%. WEPP poorly predicted the no-till field at Phelps County and when that field was excluded from analysis, the NSE was a satisfactory 0.58 with a PBIAS of 3%. WEPP is the only model of the four to be derived from field measured data. The other three models were results of laboratory experiments. One drawback to WEPP was the regression equation for K_{ef} was developed using only one no-till field.

SWC and ROSETTA had the highest PBIAS values. These models did not take into account surface crusting as in the Crust Factor model or the management practices as in the curve number used in WEPP. These are important processes when considering infiltration (Blevins et al., 1983). When only irrigation runoff was considered, Crust Factor had the highest efficiency.

Pairing tilled and no-till field, the WEPP model, which accounts for tillage applications, had the lowest PBIAS for the composite tilled fields. ROSETTA was the best model for no-till fields. The curve number used in WEPP for no-till was the value for conservation soybean given in the SCS handbook. This number was derived from experiments on tilled fields with more than 30% residue cover (Rawls and Brakensiek, 1986). This does not describe the no-till soybean fields. A lower curve number would be expected, which would reduce runoff predicted from the no-till sites. With proper

descriptive curve numbers, WEPP may be able to better describe the no-till field in Phelps County.

Vadose Zone Properties

In 2009, data were collected after planting. Three holes were cored from each field using UNL's Geoprobe hydraulic sampler, which provided five 1.5 m samples to a depth of 7.5 m. The core diameter was 3.75 cm. In the lab, the 1.5 m sections were analyzed every 0.3 m for texture, bulk density, organic matter, water retention, and hydraulic conductivity. From properties gathered in the lab, water content graphs were developed for Fillmore County and Phelps County sites. Because of compression from probing, the water content equated from the lab measured high bulk density at the Fillmore County site. Pedotransfer functions from Saxton and Rawls (2006) estimated the bulk density to account for this discrepancy. From the adjusted bulk density, water content was then determined.

To illustrate the water transfer rate in the vadose zone, a nitrate analysis on the 3-4.5 m layer in the vadose zone was performed (Katupitiya et al., 1997). The nitrate levels were measured every 0.15 m. Peaks of nitrate, representing total migration for a year, exhibited the yearly movement of pore water. Darcy's velocity was obtained by using the water content in the 3 - 4.5 m core and the pore water velocity. The volumetric water content graphs paired with the percolation rates, which were derived from the nitrate samples, potentially could determine the flux beneath the root zone.

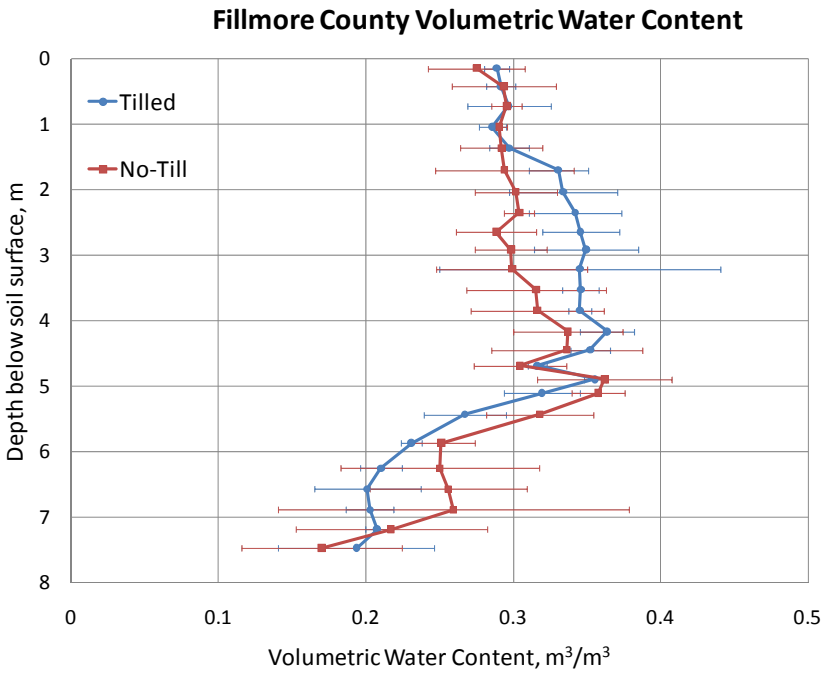
A water content difference between tilled and no-till was analyzed below the root zone to the depth of water movement since current tillage systems began, the years being estimated by v_p. Average water content values, θ_v, are listed in Table 15. Water had moved 4 m in Fillmore and 6 m in Phelps since the no-till systems were established. Based on this depth for analysis, a significant difference was found in volumetric water content at the Fillmore site, with tilled having a higher water content as shown in Figure 53. Average volumetric water contents were 0.30 and 0.29 m^3/m^3 for tilled and no-till, respectively. The second site showed a similar trend, although not significant, with 0.30

m^3/m^3 found for tilled and 0.31 m^3/m^3 for no-till as displayed in Figure 55. These results are similar to the research done by Shipitalo et al. (2000) and Katuitiya (1995) that examined the effect of preferential flow directly below the root zone and found no significant difference between tilled and no-till field water contents.

The water movement into the vadose zone is given in Table 15. The three cores from each field were used to determine an average rate of vertical water movement, v_p. Values were 0.53-0.58 m yr-1 in no-till and 0.43-0.97 m yr-1 for tilled. Katuitiya (1995) mean pore velocity values were in range of the data in this study. Even though tillage systems are long-term, percolation rates were comparable over the 7.5 m depth. Figures 54 and 56 display satiated hydraulic conductivity in the vadose zone.

Table 15. Water movement into vadose zone using nitrate analysis. θ_v is the average volumetric water content in the vadose zone. v_p denotes mean pore water velocity.

Site	Plot	θ_v, m^3/m^3	Average v_p, m/yr
Fillmore	No-till	0.29	0.53
	Tilled	0.30	0.43
Phelps	No-till	0.21	0.58
	Tilled	0.23	0.97



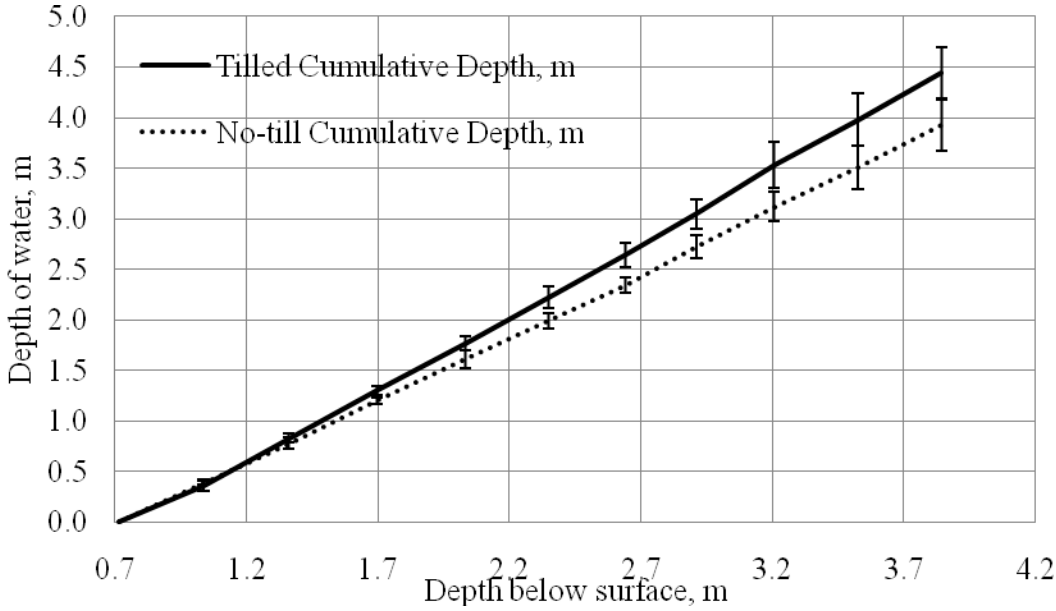


Figure 53. Fillmore County volumetric water content under tilled and no-tilled fields and Fillmore cumulative water depth in the vadose zone

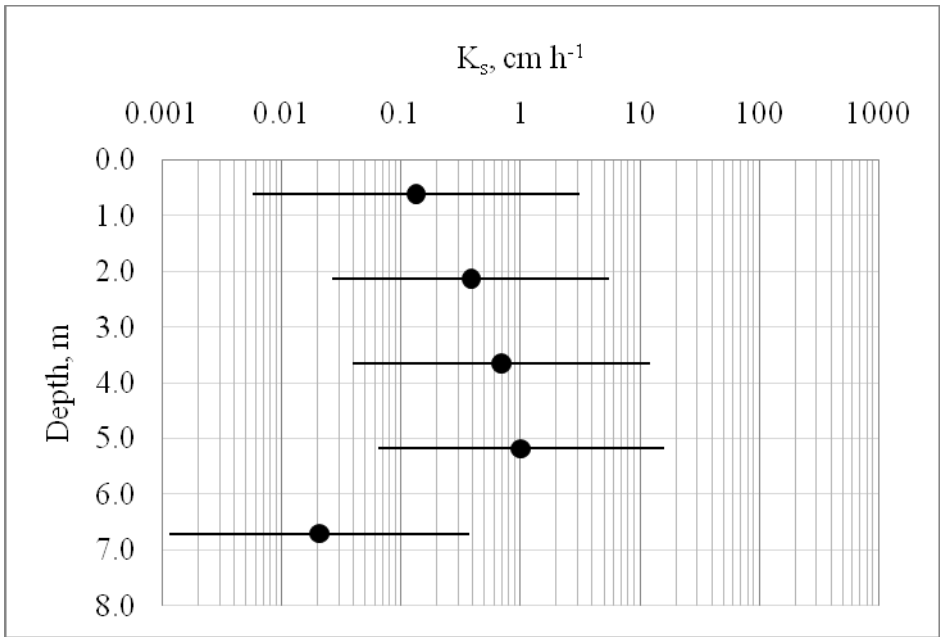
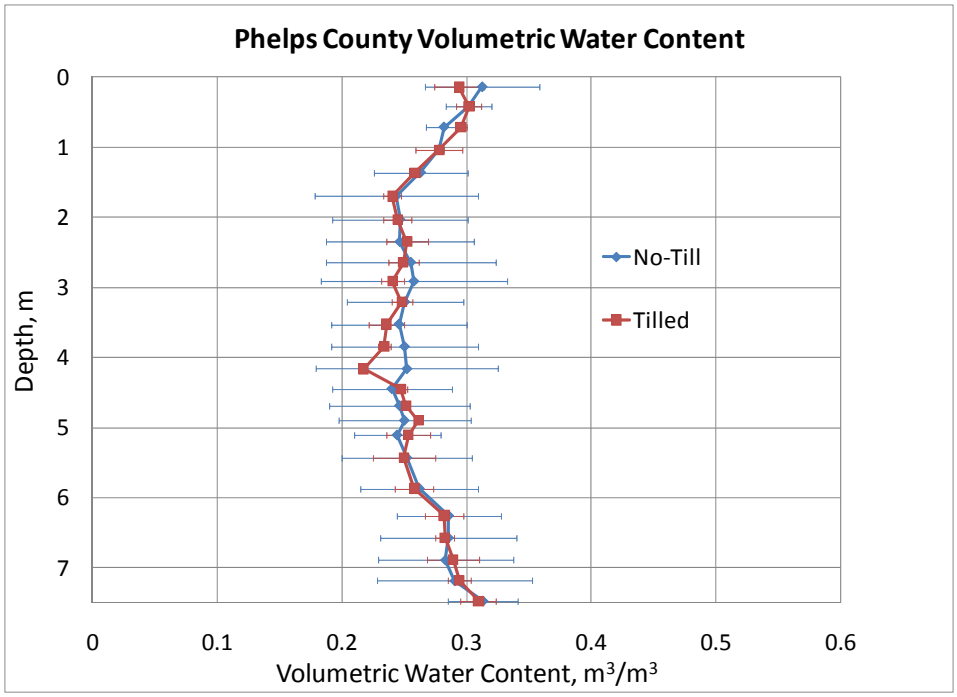


Figure 54. Satiated hydraulic conductivity in vadose zone for Fillmore County. 30 samples per geometric mean.

Error bars indicate standard deviation = $\text{abs}\left[\exp^{(\ln \bar{y} + \ln s_y)} - \text{geometric mean}\right]$



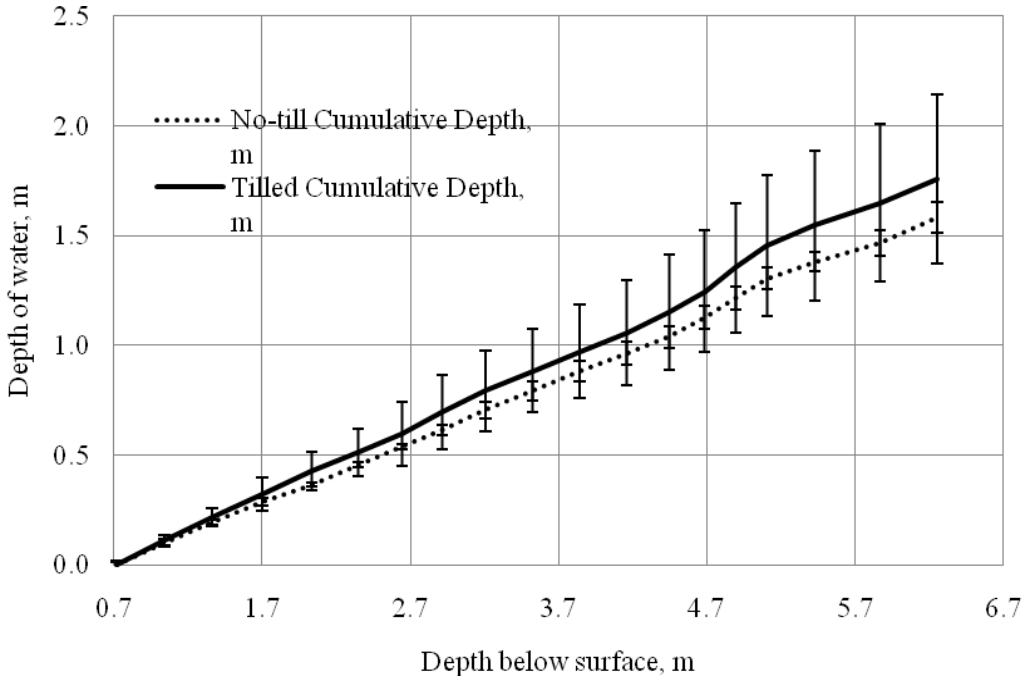


Figure 55. Phelps County volumetric water content under tilled and no-tilled fields and Phelps cumulative water depth in the vadose zone.

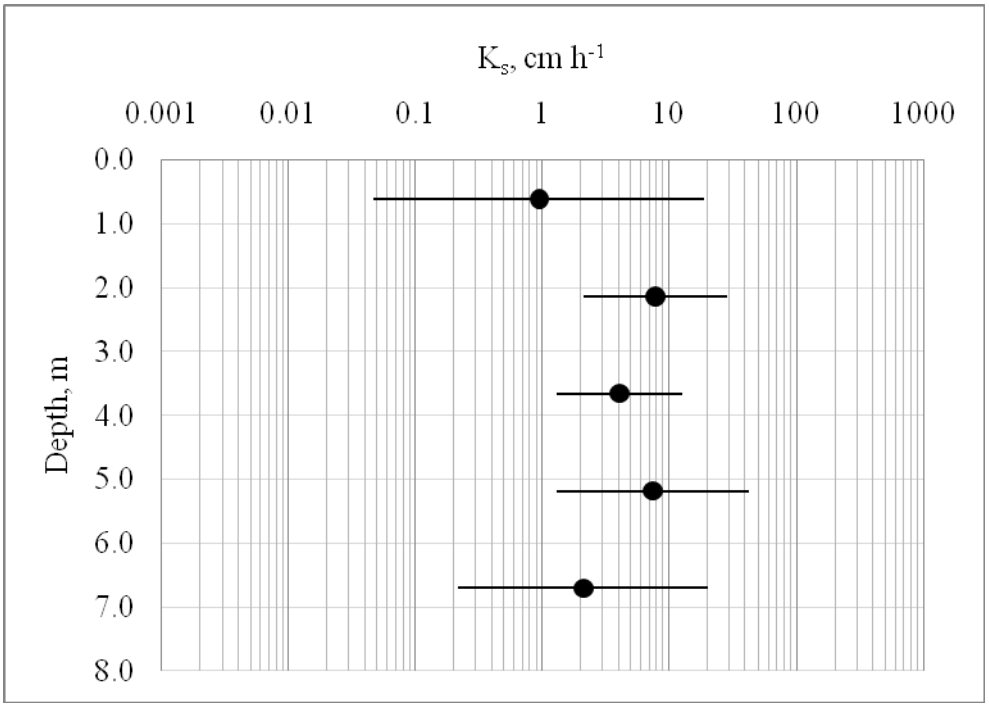


Figure 56. Phelps County satiated hydraulic conductivity in the vadose zone. 30 samples per geometric mean.
Error bars indicate standard deviation = $\text{abs}\left[\exp^{(\ln \bar{y} \pm \ln s_y)} - \text{geometric mean}\right]$

Conclusions

The effects of long-term no-till systems were not consistent among sites. The surface hydraulic conductivity was significantly higher for no-till at the two center pivot irrigated sites, concluding at these sites, no-till did increase infiltration. Runoff was significantly higher in the tilled field in Phelps County, and in Fillmore County no difference between field runoff was found. However, the rotational corn-furrow irrigated field and dryland rotational corn field had higher hydraulic conductivity in the tilled treatments. The continuous furrow irrigated corn field and the dryland rotational soybean field showed no difference among tillage treatments.

No-till fields showed greater residue, depressional storage, and higher aggregate stability indicative of no-till systems. At the center pivot irrigated sites, these qualities

point to higher amount of water to infiltrate, and therefore, less runoff during rain and irrigation events. With these qualities, runoff is reduced and farmers may be able to use lower pressure sprinkler packages on center pivots to save energy.

Realizing the amount of runoff expected on a field with a given soil type or certain management practices is important in order to quantify water savings as well as understanding the benefits of irrigation and tillage management. The Green and Ampt equation has been proven to be an accurate and useful equation for calculating infiltration into the soil. The equation is highly sensitive to the hydraulic conductivity term, a term that is difficult to accurately measure in the field or calculate due to high amount of influences, such as texture, surface cover, rainfall energy, soil structure, ect. Also, hydraulic conductivity is highly variable in a field and throughout the crop season.

Four pedotransfer functions were evaluated to find a good predictor of hydraulic conductivity that can be used when comparing tilled and no-till fields: Crust Factor, ROSETTA, WEPP and SWC. WEPP had the highest efficiency for the four fields compared in this research. WEPP used field measured data, which includes the effect of soil management practices. Although WEPP poorly described the no-till field in Phelps County, it had the lowest composite PBIAS and the lowest PBIAS for the other three fields. Consistency in a model is most important in order to use the model for any application.

3.5 Residue Measurements

Table 16 summarizes percent residue cover data for the entire project period. Tables 17 and 18 are summaries of residue mass data. In Fillmore County there was not much difference in residue cover between the tilled and the no-till fields on March 30, 2009 (Table 16), because of little difference in recent tillage history between both fields. On May 18, there was much more residue on the no-till field than on the tilled field. The tilled field was then cultivated and on July 2 residue cover was only 10% on this field

(Table 16). The no-till field was not sampled on July 2, because there had not been any residue disturbance since the previous sampling date (May 18).

In Phelps County there was much more residue on the no-till field than on the tilled field on June 4, 2009 because of … (Tables 16 and 17). The tilled field was then cultivated and on July 1 residue cover was only 7% on this field. The no-till field was not sampled on July 1, because there had not been any residue disturbance since the previous sampling date (June 4).

On March 31, 2010 we sampled residue mass and cover on the tilled and no-till fields in Fillmore County (Tables 16 and 17). Residue cover was close to 100% on both fields; neither field had been tilled since the 2009 corn harvest. On April 12, 2010 we sampled residue mass and cover on the tilled and no-till fields in Phelps County. Residue cover was close to 100% on the no-till field and a little less than 60% on the tilled field (Table 16). Later that spring, we took additional samples, in both Fillmore (May 27) and Phelps County (June 11), to capture changes in residue cover caused by tillage and planting operations.

On July 22, 2010 we measured residue cover on the tilled field in Phelps County (Table 1), to capture changes in residue cover caused by cultivation carried out since the last measurements. On the no-till field we did not take any more measurements, because there was no residue disturbance since our last measurements on June 11. In Fillmore County we did not take any more measurements, because there was no residue disturbance since our last measurements on May 27.

Residue measurements were made on all four fields shortly after the 2010 soybean harvest. On October 11 we measured residue cover on the fields in Fillmore County (Table 16). On November 10 we measured residue cover on the fields in Phelps County (Table 16).

There are not many conclusions to be drawn from the residue data by themselves. They should be very useful as supporting data for the ET measurements and should help explain differences in ET between the tilled and no-till fields.

Table 16. Average residue cover on tilled and no-till fields in Fillmore and Phelps County.

		Tilled Residue Cover	No-Till Residue Cover
County	**Date**	**%**	**%**
Fillmore	3/30/2009	85	78
	5/18/2009	25	65
	7/2/2009	10	-
	3/31/2010	97	99
	5/27/2010	58	97
	10/11/2010	91	100
Phelps	6/4/2009	21	82
	7/1/2009	7	-
	4/12/2010	58	99
	6/11/2010	31	91
	7/22/2010	8	-
	11/10/2010	85	96

Table 17. Summary of measured residue mass at Fillmore County.

		residue mass kg/ha	residue mass lb/ac	residue mass ton/ac
3/30/2009	Till	3931	3507	1.75
3/30/2009	No-till	6849	6110	3.06
5/18/2009	Till	1180	1053	0.53
5/18/2009	No-till	5299	4728	2.36
7/2/2009	Till	783	699	0.35
3/31/2010	Till	10531	9395	4.70
3/31/2010	No-till	10392	9272	4.64
5/27/2010	Till	5701	5086	2.54
5/27/2010	No-till	10234	9131	4.57

Table 18. Summary of measured residue mass at Phelps County.

		residue mass kg/ha	residue mass lb/ac	residue mass ton/ac
6/4/2009	Till	690	615	0.31
6/4/2009	No-till	5437	4851	2.43
7/1/2009	Till	284	253	0.13
4/12/2010	Till	4411	3936	1.97
4/12/2010	No-till	11110	9912	4.96
6/11/2010	Till	1365	1218	0.61
6/11/2010	No-till	11299	10081	5.05

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