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Soil moisture patterns and hydraulic properties associated with alternative biomass cropping systems across a landscape gradient

by

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ABSTRACT

Predicting the hydrologic consequences of biomass cropping systems requires an understanding of how different crops and management practices affect soil hydraulic properties across space and time. To inform such predictions, I investigated the impacts of five biomass cropping systems on the hydraulic properties of soils across a landscape gradient in wet, dry, and average rainfall years. I used data from 2010 – 2012 on monthly volumetric soil moisture content and data from 2009 – 2013 on changes in saturated hydraulic conductivity to measure significant differences in mean soil moisture content among five cropping systems across five landscape positions. My results suggest moisture content was most broadly controlled by the amount of rainfall within a year, but there were also significant differences with landscape positions, cropping systems, cropping system by landscape position, and soil clay content; biomass yield was not a significant predictor of soil moisture. I also found a significant change in saturated hydraulic conductivity among cropping systems from 2009 to 2013, and different saturated conductivity among cropping systems at different landscape positions in 2013. Differences in hydraulic conductivity among cropping systems were commonly found at floodplain and footslope positions; there were very few significant differences among cropping systems at the summit, shoulder, and backslope positions. Changes over time within cropping systems are attributed to conversion to either perennial cropping systems or to no-till soil management in annual systems. My results support the hypothesis that different biomass cropping systems will have different hydrological impacts depending on landscape position. This knowledge can be used to parameterize or improve physically-based hydrologic models of biomass production and understand the potential environmental impacts bioenergy crop production.

CHAPTER 1

INTRODUCTION

Bioenergy has the potential to meet a significant portion of present and future global renewable energy demand. Presently, bioenergy *production* is near 50 EJ (exajoules) yr^{-1} and experts expect future global bioenergy potentials to range from 293 to 1550 EJ yr^{-1} by 2050 (Smeets et al. 2007, Offermann et al. 2011). In comparison, 2008 global primary energy *demand* (i.e., energy before conversion or transformation) is estimated near 500 EJ yr^{-1} (in 2008), with future primary energy demand in 2050 projected to be 600-1000 EJ yr^{-1} (IEA Bioenergy 2009). These findings suggest bioenergy could meet 15-25% of the world's future primary energy demand. Perennial bioenergy crops are expected to represent the largest proportion of total future bioenergy production (Haberl et al. 2010, Beringer et al. 2011).

Estimates of bioenergy production potential vary widely depending on factors such as water and land availability, land suitability, potential increases in future yield of food and energy crops, market demands, biodiversity and conservation, and environmental impacts and emissions. Expanding biomass cultivation may threaten food production and conservation efforts (Robertson et al. 2008, Tilman et al. 2009). To avoid land-use conflicts, biomass might be produced on abandoned or marginal agricultural land. In 2006, previously abandoned agricultural lands had the estimated potential to provide ~27 EJ yr^{-}1 of bioenergy, or 5%, of global primary energy consumption (Field et al. 2008). In comparison, total global primary bioenergy potential, when considering environmental factors and constraints such as land use, food production, biodiversity, and sustainability criteria, ranges from 130-270 EJ yr^{-1}, (Haberl et al. 2010, Beringer et al. 2011). Sustainable development of dedicated bioenergy crop production depends on identification of environmentally acceptable land use and management strategies (Robertson et al. 2008). As cropping system performance varies over space and time, identifying alternative systems will be critical to the development of sustainable bioenergy systems.

Perennial energy crops require fewer inputs and resources and may offer an environmentally-acceptable alternative to annual cropping systems (Robertson et al. 2011). Because integrated cropping systems produce environmental benefits such as reduced runoff and erosion, improved water quality, and increased habitat for wildlife, bioenergy systems can be made more sustainable by incorporating perennial biomass systems with annual food crops (Robertson et al. 2008, Tilman et al. 2009, Blanco-Canqui 2010). In this respect, perennial bioenergy crops are likely to have the greatest potential when grown on marginally productive or vulnerable lands, limiting competition with food production and mitigating negative environmental impacts (Gopalakrishnan et al. 2009, Dale et al. 2011). Conversely, if such considerations are neglected, biomass systems may exacerbate existing environmental quality problems (Robertson et al. 2008).

Effectively navigating of tradeoffs between annual and perennial cropping systems requires explicit consideration of where, when, what, and how perennial energy crops are established and produced (Robertson 2008, Williams et al. 2009, Dale et al. 2011, Heaton et al. 2013). Benefits derived from alternate cropping systems are unlikely to be expressed equally across all agroecosystems and agricultural landscapes (Schulte et al. 2006, Dale et al. 2011). The agronomic, environmental, and economic performance of perennial cropping systems depends on linking bioenergy feedstock management strategies to appropriate locations within and across landscapes. To optimize environmental and economic benefits, land managers and researchers must understand how integrated biomass systems affect hydraulic functions across diverse landscapes.

Research also suggests that widespread cultivation of biomass crops may affect local and regional hydrology, specifically the availability and distribution of water (Williams et al. 2009, Dale et al. 2010). Expanding cultivation of annual maize and soybean crops in the US Midwest is associated with large-scale alteration of hydrologic processes and water balances (Schilling and Libra 2003). Future changes to the water balance will depend on the type of land-use and land-cover change, with greater perennialization leading to greater evapotranspiration and declining water yield (Schilling et. al. 2008). For example, short-rotation woody crops (SRWC) are expected to have greater evapotranspiration (ET) demand than annual crops (Schilling et al. 2008). While some studies have attempted to model the potential hydrologic impacts of biomass production (Wu et al. 2012), data on the in-field performance of hydraulic properties of biomass cropping systems are scarce.

This thesis is a part of the Landscape Biomass Project, which seeks to investigate the agronomic, environmental, and economic performance of alternative biomass cropping systems. Specifically, it investigates the soil hydraulic properties (saturated conductivity) and moisture patterns associated with alternative cropping systems across a landscape gradient. My goal was to discover and understand significant differences in hydraulic properties among alternative biomass cropping systems through an experimental comparison, such comparison may be used to understand potential hydrologic consequences of such cropping systems should they be more widely deployed across agricultural landscapes. I collected and analyzed two datasets to support this goal. I monitored in-field soil moisture patterns were monitored across three growing seasons (2010, 2011, and 2012), and saturated hydraulic conductivity in 2009 and 2013. I analyzed these data for differences among cropping system treatments across a topographic gradient.

This thesis is divided into five chapters: this general introduction, a literature review of relevant biogeochemical and hydrologic processes and related factors, a paper on soil moisture patterns of cropping systems across a topographic gradient, a paper on hydraulic properties of soils associated with alternative cropping systems across a topographic gradient, and a general conclusion that includes potential future directions for research.

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CHAPTER 2

REVIEW OF CROP AND WATER DYNAMICS AND BIOGEOCHEMISTRY OF POTENTIAL BIOENERGY CROPPING SYSTEMS

Introduction

The objective of this chapter is to review the literature regarding biogeochemical and hydrologic processes that influence and are influenced by crop production. The purpose of this review is to provide relevant background information required for the interpretation and analysis of the subsequent chapters in this thesis.

The first section outlines general environmental impacts of current and potential future feedstock production. Second, I explore catchment scale hydrologic and water quality impacts. Third, I discuss the influence of topographic factors on the prevalence and evolution of soil properties and processes. Fourth, I explain topographic control of water availability for crops. Fifth, I expand upon crop water use dynamics. Last, I examine the spatial and temporal interactions among soil properties, soil moisture, and biogeochemical processes.

The Environmental Impacts of Bioenergy Feedstock Production

Widespread bioenergy feedstock cultivation is likely to be associated with several environmental impacts. Current bioenergy systems for biofuels rely on feedstocks such as maize, soybean, and sugarcane, which require high inputs of fertilizer and pesticide and are associated with negative environmental impacts including soil erosion, nitrate-nitrogen (NO_3-N) and phosphorous (P) loss, eutrophication, impairment of surface and groundwater quality, air pollution, biodiversity and habitat loss, and decline of other ecosystem services (Robertson et al. 2008, Zimmerman et al. 2008, Landis et al. 2008, Williams et al. 2009, Fargione et al. 2009, Delucchi 2010). Further studies suggest that the production of these bioenergy feedstocks may actually exacerbate greenhouse (GHG) emissions, as the carbon dioxide (CO_2) released from direct and indirect land-use changes is greater than the GHGs displaced from reduced fossil fuel consumption and carbon sequestration (Fargione et al. 2008, Searchinger et al. 2008). The expansion of maize production for biofuels, for example, is expected to further exacerbate soil, nutrient, and pesticide losses and have significant negative impacts on water quality (Thomas et al. 2009, Secchi et al. 2011). Up to 25 million additional acres may be converted from rotational cropping to continuous maize by 2020 (Mehaffey et al. 2012), exacerbating these impacts.

Sustainable bioenergy systems depend on the extent to which environmental impacts from feedstock production can be minimized (Robertson et al. 2008, Blanco-Canqui 2010). Second-generation perennial lignocellulosic feedstocks for bioenergy may provide several advantages over annual crops for biofuels. Lignocellulosic feedstocks can be derived from perennial sources, reducing the need for tillage and fertilization (Robertson et al. 2011). Perennial systems provide additional benefits such as GHG sequestration and biodiversity-based services, including pest suppression and crop pollination (Landis et al. 2008), and can mitigate negative impacts on surface and groundwater quality by minimizing the loss of mineral nutrients and soil (Youngs et al. 2012). Because perennial crops have a significantly lower nitrogen demand and contribute to a more closed nitrogen cycle by immobilizing nitrogen (Robertson et al. 2011), perennial systems mitigate nitrogen exports to streams and lakes. For example, transitioning from maize to switchgrass could result in a 20% reduction in comparative NO_3-N output from the Mississippi and Atchafalaya Basin in 2022, while meeting the U.S. Energy Independence and Security Act (EISA) 2007 biofuel production target (Costello et al. 2009). Perennial grasses such as switchgrass can reduce N and P leakage to the environment by eliminating the need for tillage, slowing runoff, and increasing infiltration (Parrish and Fike 2005, Nelson et al. 2006, Williams et al. 2009). Further, perennial biomass crops grown as buffers adjacent to annual crops may improve water quality, regulate water flow, and reduce sediment and nutrient transport to surface water (Sloots and van der Vlies 2007, Williams et al. 2009, Gopalakrishnan 2012).

Hydrologic and Water Quality Impacts of Biomass Production

Large-scale bioenergy feedstock production may significantly affect freshwater appropriation, potentially intensifying regional competition for water resources (Postel et al. 2000, Robertson et al. 2008, Gerbens-Leenes et al. 2009). Biomass production for food and fiber currently accounts for 86% of global freshwater consumption (Hoekstra and Chapagain 2007). The combined pressures of increasing demand, water degradation, and climate change will place additional pressure on regional freshwater resources in the coming decades and compromise the ecological function of freshwater ecosystems (Postel et al. 2000). Competing uses for water are likely to limit the potential of biomass production. Resolving competition between food and fuel production among other uses of water will require careful allocation of freshwater resources among food and fuel production and greater efficiency in land and water use.

Crop production has been associated with large-scale alteration of hydrological processes in the US Corn Belt (Schilling and Libra 2003, Zhang and Schilling 2006). Cropping systems primarily affect hydrological water balances through changes in evapotranspirative demand and through secondary impacts on soil water storage, surface runoff, and irrigation (Robertson et al. 2011). Historical changes to land use and land cover (LULC) are characterized by the expansion of annual crops, which have replaced perennial crops, grassland, and forest (Schilling et al. 2010). These changes have significantly affected watershed-scale water balances in Iowa (Schilling et al. 2008). The emergence of biofuels in the past decade has led to a further expansion of maize production, which has offset the production of soybean and other crops (Larson et al. 2010). Further expansion of annual crops will likely lead to exacerbation of observed hydrologic trends (Schilling et al. 2005, Schilling et al. 2008).

Rivers and streams in the Corn Belt region currently experience greater annual stream- and base-flow, minimum stream-flow, and annual ratio of base-flow to stream-flow than was normal in the 1800s (Schilling and Libra 2003, Zhang and Schilling 2006). Altered stream-flow patterns are significantly related to the expansion of annual row crop agriculture. For example, Schilling et al. (2010) determined that LULC change in the form of increasing soybean acreage accounts for a 30% increase in water flux in the Upper Mississippi River Basin (UMRB). The observed increases in stream-flow and base-flow are likely caused by lower evapotranspiration (ET) loss from annual crops compared to perennial crops and vegetation. Seasonal cultivation of annual crop fields also increases groundwater recharge during the spring and contributes to greater baseflow and streamflow (Zhang and Schilling 2006).

Conversion of annual cropland to perennial energy crops may result in the reversal of historically observed hydrologic and water quality trends resulting from the expansion of annual crops (Schilling et al. 2008). Nelson et al. (2006) predict that converting maize-soybean fields to perennial switchgrass results in an estimated 55% reduction in surface runoff. Schilling et al. (2008) predict significantly greater annual ET and a 50% reduction in surface runoff when cropland is converted to perennial grasses. Their results also predict a decline in annual streamflow and water yield. Similarly, Wu et al. (2012) predict lower water yield for the Iowa River basin when perennial switchgrass or miscanthus replaces native grassland or annual crops. Under limited conversion scenarios (e.g., 10% of annual crops converted to perennial grass), the total watershed-scale water balance may not differ significantly from baseline annual cropping systems (Wu et al. 2012). However, such land use conversion may still reduce sediment yield and surface runoff (Nelson et al. 2006, Wu et al. 2012).

Altered flow patterns also have significant implications for water quality because NO_3-N reaches streams primarily via baseflow and tile drainage (Schilling and Libra 2003, Simpson et al. 2009). Annual NO_3-N concentration in the Cedar River in Iowa increased from 2 mg/l to 6 mg/l from 1945 to 1998, concurrent with an increase in stream discharge over the same period. Similarly, the NO_3-N concentration in the Des Moines River in Iowa has also doubled over the same time period. An increase in maize cultivation to meet renewable fuel goals for 2022 would result in a 10-34% greater average annual flux of dissolved inorganic nitrogen export to the Mississippi - Atchafalaya River Basin (Donner and Kucharik 2008). Secchi et al. (2011) combined an economics-driven land-use model with a water quality simulation model to determine the potential impacts of increased maize acreage on water quality for the Upper Mississippi River Basin. They concluded that a 14.4% increase in maize acreage would result in a 5.4% increase in nitrogen loads. Increased tillage, higher total fertilizer and chemical loads, soil erosion and sedimentation associated with continuous maize systems can all contribute to lower water quality (Gerbens-Leenes et al.

2009, Thomas et al. 2009, Larson et al. 2010). In contrast, Thomas et al. (2009) used the GLEAM model to predict that higher levels of annual surface runoff may not necessarily be associated with shifting soybean acreage to maize production. Their results suggest that a shift to continuous maize production may produce significantly smaller annual percolation below the root zone compared to a maize-soybean rotation, which may be due to greater ET losses associated with maize production as opposed to soybean production.

In conclusion, historical riverine water balance could be at least partially restored as larger areas of annual cropland are converted to perennial production systems. Expansion of annual crop production is likely to exacerbate historically observed hydrologic trends. In contrast, replacing annual cropping systems with perennial bioenergy crops may result in a reversal of these hydrologic trends. Perennial bioenergy crops can be integrated with other land uses to mitigate environmental consequences. For example, targeting perennial crop production on environmentally-sensitive marginal land or riparian areas may have positive or negative implications for water quantity or quality, depending on local land and management characteristics (Schulte et al. 2006, Robertson et al. 2011).

Topographic Control of Water Flow and Soil Moisture

Soil moisture patterns can be influenced by topographic variability in the landscape (Hall and Olson 1991, Famiglietti et al. 1998, Nyberg 1996, Western et al. 1999). Moore et al. (1988) correlated several topographic attributes with soil water content along a hillslope to understand the degree and significance of topographic effects on spatial soil moisture variability. Further, soil hydraulic properties are related to soil properties such as texture, organic matter content, and bulk density, which can be correlated with topographic position

(Halvorson and Doll 1991, Pachepsky et al. 1999). Water flow, retention, and spatial patterns are likely influenced by both positional effects and the associated soil properties, though this effect may not necessarily be mutual (Pachepsky et al. 2001).

As soil moisture content increases, saturation excess and lateral flow are more likely to occur. Surface flow may also occur when the precipitation rate is greater than the infiltration rate. In all cases, water will flow to and collect in topographically convergent areas and be distributed along divergent areas. These patterns of water flow determine the availability of water that enters the soil moisture store in a given area. As a result, certain parts of the landscape will be replenished or saturated before others, while other parts may deplete. Lateral subsurface and groundwater flow are similarly influenced by topographic factors. However, these patterns depend on the prevailing wetness conditions, the topographic context, and the particular landscape. By influencing the movement of water, landscape morphology also plays a further role in geomorphic landscape evolution and pedologic processes (Hall and Olson 1991).

Western et al. (1999) analyzed the degree of spatial soil moisture organization (i.e., presence of areas with much lower variability than surrounding areas) and the ability off terrain indices to predict that organization. They discovered four major patterns of soil moisture organization caused by differences in prevailing wetness conditions. Soil moisture exhibits a lower degree of organization in dry conditions, and the highest degree of organization under moderately wet conditions. In wet conditions, the spatial organization of soil moisture is strongly controlled by topography. For example, the wetness index, which considers specific contributing area and slope, is a significant predictor of spatial soil moisture pattern. Nyberg (1996) found a significant correlation between slope angle and soil water content, however, the size of the upslope contributing area was a more significant factor. The aspect, or geographic orientation, of a hillslope determines potential solar irradiance, which influences evapotranspiration and soil moisture. Reid (1973) and Western et al. (1999) also found correlations between aspect and soil moisture.

Water flow is also influenced by the curvature of a hillslope. Hillslopes with concave contours exhibit convergent runoff and throughflow, convex contours exhibit divergent flow (Hall and Olson 1991). The curvature of the slope alters the erosive and infiltration potential of the water flow. Concave slopes are more likely to become saturated and display seepage at the summit and footslope positions. Convex slopes exhibit divergent flow at the shoulder and backslope positions, which are therefore drier. As a result of influencing water flow, curvature can also be directly linked to the variability of soil properties on a hillslope (Hall and Olson 1991).

Water flow at a point can be significantly influenced by the specific contributing area (Nyberg 1996). The specific contributing area is the size of the upslope area, which directly contributes water to a specific point or area. Both runoff and subsurface flow are influenced by the specific contributing area. Over geologically-relevant time periods, specific contributing area may increase or decrease depending on change in the landscape morphology. However, for practical purposes, it is usually considered a static quantity. At any given point, the specific contributing area is determined solely by the morphology of the landscape. Areas or points with a larger specific contributing area receive greater amounts of water from upslope areas. More generally, soil moisture variability is caused by water routing and redistribution processes.

Relative elevation is also correlated with water content, soil properties, and other topographic attributes (Famiglietti et al. 1998). Generally, areas at a lower elevation receive water from upslope, or areas at a higher elevation. Soil moisture variability can therefore be inversely correlated with relative elevation (Hawley et al. 1983, Nyberg 1996). However, the increase in soil moisture from higher to lower elevations may display a non-linear trend. For example, Henninger et al. (1976) measured surface soil moisture along transects perpendicular to the slope contour. They found that soil moisture increases in a non-linear fashion and is greatest near the convergent zone or stream of the watershed. For this reason, areas of lower elevation not only contain larger amounts of water, but also contribute a disproportionate amount of saturated excess runoff to downslope areas (Henninger et al. 1976, Anderson and Burt 1978).

Spatial variability in soil moisture is correlated with mean moisture content (Famiglietti et al. 1998). Henninger et al. (1976) note that spatial variability declines with decreasing mean moisture content. Lateral flow to convergent areas is greater in high moisture conditions (Western et al. 2002). With increasing soil moisture content, hydraulic conductivity rapidly increases, allowing for lateral flow. Thus, moisture is distributed or organized based on topographic variables. Under drier conditions, hydraulic conductivity is low and tension forces dominate, which are not conducive to lateral flow.

In sum, patterns of soil moisture are determined by relative conditions and processes (Western et al. 1999). Topographic heterogeneity determines which conditions and processes are predominantly expressed within a location or landscape. These processes may also be temporally dependent. Further, variability in the distribution and flow of water as a result of topographic heterogeneity and spatial heterogeneity in soil properties also has important implications for the productivity of ecosystems and agricultural crops (Kravchenko and Bullock 2000, Jiang and Thelen 2004, Meerveld and McDonnell 2006).

Topographic Effects on Water Availability and Crop Productivity

Crop productivity is affected by water availability (Mederski and Jeffers 1973, Cakir 2004). For example, maize productivity is related to plant-available stored soil moisture (Leeper et al. 1974). Fox and Piekielek (1998) observed a linear relationship between precipitation and maize yield. Similarly, Schmidt et al. (2007) observe a linear relationship between soil water content and maize yield. Topographic heterogeneity results in differential water flow across a landscape as a result of the variability in flow processes and soil properties. As landscapes exhibit diverse chemical, biological, physical, and hydrological properties, the predominant processes or group of processes which influence crop yield can vary spatially across a landscape. Crop productivity at a specific location is therefore always determined by the particular processes that dominate at that location. This has important implications for determining management practices such as crop selection, planting time and density, and nitrogen-application rate (Jones et al. 1989, Schmidt et al. 2007). However, these key factors are also involved in dynamic interactions that together influence or determine spatial patterns of soil moisture content and water availability (Hall and Olson 1991, Grayson et al. 1997, Famiglietti et al. 1998). Spatial variability in crop yield is then simultaneously related to landscape heterogeneity and the resulting spatial variability in water availability (Malo and Worcester 1975, Green and Erskine 200).

Stone et al. (1985) conducted a study to investigate relationships among maize productivity, soil erosion, and landscape position. They established plots of maize on all landscape positions and erosion classes at five sites with Piedmont soils. The results show consistent differences in maize yield among landscape positions. Specifically, the headslope and footslope positions (in this study, these are both convergent and low-lying areas, the headslope in other studies may be associated with the summit) had the highest yields compared to other landscape positions, likely due to the water these positions receive from surface and subsurface flows from higher landscape positions (Hanna et al. 1982, Daniels et al. 1985, Ayfuni et al. 1993).

Jones et al. (1989) linked landscape position and soil property effects to crop yields of maize, soybean, and sorghum. The results show significant differences in yields for each crop among seven different hillslope landscape positions. Generally, the lowest and highest landscape positions (with low slope angle) were associated with higher crop yield among all crops, followed by the shoulder position and the higher slope linear positions (i.e., backslope). Maize yield was significantly influenced by position and slope length, sorghum yield was influenced by position and slope gradient (angle), and soybean yield was influenced by position. Maize and sorghum performed best on the upper interfluve positions, soybean performed best at the shoulder. All three systems performed well at the footslope position. The authors suggest that the improved maize yield may be explained by slope angles and longer slope lengths that allow for sustained infiltration of overland flow, improving water availability.

Similarly, in an analysis of spatial variability in crop yield, Kravchenko et al. (2000) show that, under dry conditions, greater maize and soybean yields are correlated with sites that have low slopes and locations, while moderate and high slope locations exhibit high variability in yield. In wet conditions, low slope locations exhibit relatively lower yields. The authors suggest this was due to low drainage and the presence of excess water. Kravchenko and Bullock (2000) also show that elevation most significantly influences yield, with higher yields at lower landscape positions. Curvature and slope showed less significant effects on crop yield. Relationships between topography and yield are affected by the accumulation and storage of water from previous conditions, as well as by different rates of water consumption by crops at different locations (McConkey et al. 1997). While spatial soil moisture patterns are in a constant state of flux, predominant states of soil moisture organization do arise as a result of prevailing moisture conditions (Grayson et al. 1997). As a result of these fluctuations, spatial variability in crop yield is not necessarily congruent with spatial patterns of water distribution (Kravchenko 2000).

Afyuni et al. (1993) observe concurrent relationships among landscape position, plant-available water content, and maize silage yield. Generally, footslopes have the highest amount of plant-available water and linear slopes the lowest amount. The shoulder position may frequently have similar plant-available water content as the footslope. The footslope generally produced the highest silage yields. These trends can vary due to precipitation conditions, topographic context, and soil properties. Lower amounts of precipitation may create differences in hydraulic properties among soils that can be expressed in terms of variability in plant-available water. For example, yield variability among landscape positions was greater in the dry year (Ayfuni et al. 1993). Crop yield is more homogenous across landscape positions in years with above average rainfall (Stone et al. 1985, Daniels et al. 1985, Ayfuni et al. 1993).

Conflicting results have also been reported. Simmons et al. (1989) show that topography has the largest influence on crop yield in dry years. Malo and Worcester (1975) report low yields at the footslope and the highest yields at the backslope position. Yield differences were related to landscape position through differences in soil properties caused by variable erosion among positions. Kaspar et al. (2003) show that maize yield is negatively correlated with relative elevation, slope, and curvature in dry years, and is positively correlated with relative elevation and slope in wet years. Erosion potential is thought to more significantly affect yield than landscape position, although a close relationship between landscape position and erosion potential has been suggested (Daniels et al. 1985, Hall and Olson 1991).Stone et al. (1985) found differences were less closely correlated with erosion class than with landscape position. The results indicate landscape position effects may be equally or more important than the degree of erosion for maize yield (Stone et al. 1985). Hydrologic processes such as water flow between landscape positions could account for such yield differences, for example, with lower landscape positions receiving surface and subsurface water from higher elevations. While erosion of topsoil may reduce nutrient availability and potential rooting depth at steeper locations, water availability may be the predominant factor influencing yield. Frye et al. (1982) attributed reduced maize yields from soil erosion primarily to the soil's decreased water holding capacity and high clay content.

Crop and Soil Water Dynamics

Vegetation can affect soil moisture content through transpiration. Differences in water-use characteristics of plants and crops can produce differences in soil moisture patterns over time and space (Meerveld and McDonnell 2006). Crop yield is strongly correlated with cumulative transpiration, and potential transpiration is related to plant-available water and soil water content (Denmead and Shaw 1962). Consequent variability in plant-available water may affect future crop potential (Afyuni et al. 1993). Hupet and Vanclooster (2002) showed how spatial variability in early season maize growth induced spatial variability in ET rates and soil moisture patterns.

Zeri et al. (2013) investigated the water use efficiency of perennial and annual bioenergy crops. They observe greater total transpiration for switchgrass, miscanthus, and prairie compared to a maize-soybean rotation. Three years after establishment, harvestable biomass water-use efficiency (HWUE: harvestable biomass over total water used) was greatest for miscanthus grass, followed by maize-soybean, switchgrass, and prairie, respectively. Biome water-use efficiency (BWUE: (net ecosystem productivity – harvestable biomass)/total water used)) for biomass crops was higher for the perennial crops than the annual maize-soybean rotation.

Hattendorf et al. (1988) determined the water-use characteristics of six agricultural row crops including maize, soybean, and grain sorghum. Water use was characterized based on several measurements including seasonal water use, mean daily water use rate, seed yield water use efficiency (WUE), and dry matter yield WUE. Mean seasonal water use for maize was greater than for soybean, while sorghum had intermediate seasonal water use values. Maize and sorghum had the highest dry matter yield water use efficiency values, soybean dry matter yield WUE values were approximately half of maize and sorghum. Daily ET rate varied over the growing season. Maximal ET rate for maize and sorghum was reached half way through the growing season, while maximal soybean ET rate was reached 60-65% of the way through the season. Maize ET rates reached a minimum at the very end of the growing season, sorghum and soybean ET rates reach a minimum at 71% and 75% of the growing season, respectively (Hattendorf et al. 1988).

Hattendorf et al. (1988) further calculated the soil water depletion by depth for each crop from 0.3m depth to 3.1 m depth. Sunflower depleted significantly more soil water than other crops at the 0.99-1.6 m depth. In 1981, maize depleted significantly more water than sorghum from the 0.38-0.69 m depth. In 1982, maize depleted more soil water than sorghum from the 0.69-0.99 m depth, but there were no other significant differences. However, maize depleted 10mm more than soybean at the 0.38-0.69 m depth in 1981. The authors also note that measured crop water-use values are relative and can be determined by variety selection, management (i.e., planting dates, planting density), and weather conditions.

To determine reliance of crop growth on profile water storage, Russell and Danielson (1956) investigated time and depth patterns of water use by maize. The results suggest up to 50% or more of the transpiration demand is met by soil water depletion. The depletion curve shows similar moisture content patterns across depth between the beginning and end of the season, while the absolute moisture content declined. Depletion occurred along the entire 150 cm profile. In covered plots, the major zone of depletion moved downward through the profile across the season, almost all the water near the end of the season was depleted from below 120 cm depth. The results from the rainfed plots were more variable due to greater water flux in the upper 60 cm. Soil moisture profiles were also monitored for fallow plots. Differences between fallow and maize moisture profiles were also limited to the upper 60 cm.

Water-use patterns may be different in crops grown in rotation. Crop rotations have a positive effect on yield, even when controlling for fertility and disease (Pierce and Rice 1988). The causes of this rotation effect are unknown. Greater soil water depletion has been observed in crops grown in rotation than in monoculture (Roder et al. 1989). This suggests the rotation effect may be linked to changes in crop water-use efficiency. Copeland et al. (1993) observe greater seasonal water depletion and yield in maize when rotated. Soybean does not show a similar effect for seasonal water use, but displays higher WUE under rotation. This effect can be more pronounced in dry years or under stress (Crookston and Kurle 1987, Copeland et al. 1993). Importantly, crop choice in a rotation can have a negative effect if one crop depletes soil water necessary for the growth of a subsequent crop (Grecu et al. 1988). Roder et al (1989) found a negative correlation between early season rainfall and soybean yield when rotated with sorghum, suggesting a water conservation response potentially caused by the presence of sorghum residues. Fahad et al. (1982) observed significantly lower infiltration rates associated with continuous soybean as compared to soybean in rotation with sorghum or fallow. Similarly, Peters and Johnson (1960) investigated soil moisture-use patterns by soybean. During the wet year, evaporation from the soil surface was responsible for over half of the total moisture loss from the soil profile. Most of the rainfall was therefore lost to surface evaporation. In the dry year, this amount was a quarter to a half of total moisture loss. Soybean also deplete a significant amount of soil water from the lower root zone during the growing season, while rainfall only affects the upper half of the rooting zone. Additionally, row spacing has a significant effect on water depletion patterns. Water use is greater within the row and significantly lower between row intervals. This suggests the majority of soybean water use is limited to an undetermined area around individual soybean plants.

Water stress at critical growth stages can significantly reduce the final dry matter yield of maize (Cakir 2004). In contrast, switchgrass shows tolerance to a wide range of soil moisture conditions (Barney et al. 2009). These observations suggest potentially significant relationships between cropping system performance and nutrient and water management. For example, field-scale results show that modifying nutrient management practices can improve crop water-use efficiency while also improving yield (Hatfield et al. 2001). Similarly, modifying soil management practices can improve water-use efficiency by 25-40%.

Relationships among Soil Properties, Soil Moisture, and Biogeochemical Processes

Soil moisture has a major influence on hydrological processes such as runoff, flooding, erosion, evapotranspiration, solute transport, infiltration, and subsurface flow. Soil moisture variability is in turn influenced by factors such as topography, soil properties, vegetation type and density, mean moisture content, depth to water table, precipitation, solar radiation, aspect, water routing processes, and other factors. Due to the spatial heterogeneity of these influential factors, soil moisture content is known to be highly variable across landscapes (Western et al. 2002). Spatial variability of soil moisture and hydraulic properties significantly influences catchment runoff (12-52 ha) (Merz and Plate 1997). Soil moisture patterns generate patterns of partial-area saturation excess runoff (i.e., partial areas of a watershed which reach saturation quicker and generate greater runoff than other areas), which can significantly influence total catchment runoff (Dunne and Black 1970, Anderson and Burt 1978). Understanding soil moisture patterns and processes is therefore necessary to predict and understand catchment scale hydrologic processes.

Water movement and flow can also be an influential factor in pedogenesis and landscape evolution (Hall and Olson 1991). Soil differences across a landscape evolve as a result of drainage conditions, differential transport and deposition of soil materials, and differential transport of mobile chemical elements. Water flow and movement is a governing factor in the transport of soluble and suspended materials. Variations in the type, direction, and quantity of water movement produce variability in chemical and physical processes, giving rise to differences in soil physical and chemical properties across a landscape (Hall and Olson 1991). The resulting variability in soil properties influences the flow and distribution of soil moisture (Famiglietti et al. 1998). Pedogenic and hydrologic processes are involved in a dynamic, yet mutual process that determines their characteristics and evolution across a landscape and over time. Specifically, soil and topographic heterogeneity cause differential patterns of water flow and movement that induce the development of further topographic variability and spatial variability in soil properties.

Spatial variability of soil properties may affect numerous processes that influence yield potential, hydrology, and transport of soil, chemicals, and nutrients. For example, Jiang and Thelen (2004) observe significant correlations between numerous soil properties and topography and crop yield. Lower elevations tend to have higher soil fertility, which is influenced by water flow and erosion processes that redistribute soil particles and chemicals. As a result, lower landscape positions receive water and materials that influence soil fertility. They also found that coarse sand content is positively correlated with slope and negatively correlated with crop yield. These differences can produce variability in crop yield across a landscape (Jones et al. 1989).

Cambardella et al. (1994) describe spatial patterns in the variability of soil parameters at a field-scale. Organic C, total N, pH, macroaggregation were shown to be strongly spatially dependent, microbial biomass C, microbial biomass N, bulk density, and denitrification were shown to be moderately spatially dependent. Soil properties also determine the soil color, which affects surface albedo and thus the potential evaporation rate from soil (Famiglietti et al. 1998). Heterogeneity in soil properties such as percent organic matter, coarse fragments, bulk density, and macroporosity can influence patterns of soil moisture distribution by affecting the fluid transmission and retention properties of soil (Saxton and Rawls 2006). For example, spatial variation of soil texture influences the vertical and lateral spatial distribution of soil moisture (Price and Bauer 1984, Crave and Gascuel-Odoux 1997). Soils with similar properties display similar soil moisture characteristics (Henninger et al. 1976). These relationships are captured by the idea of soil 'drainage class,' which reflects the water retention or wetness potential of a soil.

Soil moisture variability in the profile is influenced by precipitation, evapotranspiration, drainage, lateral subsurface flow, soil properties, and runoff (Western et al. 2002). Changes in soil moisture storage are primarily influenced by precipitation, soil evaporation, and plant transpiration. Soil moisture increases primarily due to infiltration, it decreases primarily due to ET. Fluxes between the atmosphere and the active root zone dominate in the upper 50 cm of the soil profile, consequently, moisture content and patterns are more variable in this area over time and space than at greater depths. The moisture at lower depths is buffered by the upper soil layers, and is therefore less responsive to changes in water flux.

The relative influence of precipitation and evapotranspiration depends on plant composition and density. Transpiration is likely to dominate in densely vegetated landscapes, while soil evaporation will dominate in sparsely vegetated landscapes. The mechanisms by which vegetation influences soil moisture content and distribution include: the pattern of throughfall produced by the canopy, variable shading of the land surface which causes variable evaporation rates, plant transpiration, and changes in soil hydraulic conductivity caused by root activity and organic matter cycling (Famiglietti et al. 1998). Lateral redistribution and groundwater flux also influence soil moisture content in the profile, depending on the context. Percolation from the soil profile is the primary mechanism of groundwater recharge. In contrast, capillary flow from groundwater may replenish soil moisture during dry periods.

Soil moisture can also influence biogeochemical processes such as N-mineralization, soil carbon evolution, and ammonification (Miller and Johnson 1964, Cassman and Munns 1984). In addition, it affects root growth, water use efficiency, and phosphorus (P) and nitrogen (N) uptake in maize (Mackay and Barber 1985). Low soil moisture inhibits P diffusion through the soil, limiting uptake by maize roots. Similarly, potassium (K) uptake in maize is limited by decreasing soil water content (Seiffert et al. 1995). Nitrate uptake by maize roots is also inhibited in moisture deficit conditions (Buljovcic and Engels 2001). Mederski and Wilson (1960) found greater total uptake of P, K, and Mg in maize at higher soil moisture levels. Mechanisms for lowered mineral and nutrient uptake caused by a soil moisture deficit include decreased mineralization of organically-bound nutrients, decreased soil transport and diffusion of nutrients, lowered nutrient availability at the root surface, decreased root growth, lower uptake ability of stressed roots, and root shrinkage. Additionally, soil moisture content can influence soil respiration (Wildung et al. 1975, Bloem et al. 1992). The soil respiration rate is primarily a function of soil microbial activity, which decomposes plant roots by oxidizing carbon constituents to CO_2. Water influences soil microbial activity, and hence the respiration rate.

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CHAPTER 3

SOIL MOISTURE DYNAMICS OF FIVE BIOMASS CROPPING SYSTEMS ACROSS A TOPOGRAPHIC GRADIENT

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Abstract

Soil moisture is an important component of a watershed's water balance and influences hydrologic processes such as infiltration and runoff. Soil moisture is also critical factor in crop performance and yield. Here we investigate soil moisture patterns associated with five biomass cropping systems across a toposequence considering combined moisture data from the 2010, 2011, and 2012 growing seasons; respectively, high, average, and low rainfall years. Cropping systems included continuous maize, triticale/soybean-maize-soybean,maize-switchgrass, triticale/sorghum, and triticale-aspen. We randomly assigned three plots of each treatment to landscape positions at the summit, shoulder, backslope, footslope, and floodplain of the toposequence and analyzed soil moisture data from a 20-120 cm depth range. Across the three years of study, landscape position, cropping system, the cropping system by landscape position interaction, and soil clay content were all significant predictors of soil moisture; biomass yield was not significant. We found that the summit and shoulder positions generally had lower moisture contents than other position for the continuous maize and triticale-aspen system. Maize-switchgrass and triticale/sorghum generally had lower moisture content at the summit. The modified rotation had lower moisture content at the footslope and floodplain positions as compared to the upper three positions. The summit and floodplain generally had the lowest moisture contents. While the effects of landscape and topographic heterogeneity and cropping systems on soil moisture dynamics have been explored elsewhere, this is the first study to have addressed the combined influence of landscape factors and cropping systems on soil moisture profile patterns. This knowledge can be used to parameterize or improve physically-based hydrologic models of biomass production and understand the potential environmental impacts bioenergy crop production.

Keywords: bioenergy, biomass crops, hydrology, landscape. Landscape Biomass Project, soil moisture

Introduction

Widespread row crop production has altered landscape-scale hydrologic processes and patterns in the US Corn belt. The shift from perennial land covers to seasonal row crops may have reduced total annual evapotranspiration (ET) leading to increased groundwater inflow and, consequently, increased baseflow and streamflow (Schilling and Libra 2003, Zhang and Schilling 2006). Land-use change accounts for a 32% increase in discharge from the Upper Mississippi River Basin between 1890 and 2003 (Schilling et al. 2010). The Raccoon River watershed in Iowa showed a significant increase in streamflow and baseflow from 1917 to 2004 associated with increasing row crop production (Schilling et al. 2010). Further row crop expansion, especially as a result of higher demand from ethanol production, is expected to result in increased water yield and nutrient export (Schilling et al. 2010, Secchi et al. 2011).

Perennial crops may present an opportunity to mitigate the hydrologic and other environmental consequences of increasing annual row crop production (Schilling et al. 2010, Robertson et al. 2011). Annual ET can differ among perennial crops as well as between annual and perennial systems. For example, tree plantations are likely to have higher water demand than either grasslands or annual cropping systems. If adopted over widespread areas, tree plantations may lead to reduced streamflow and groundwater recharge (Anderson et al. 2009, Robertson et al. 2011). However, mature tree stands can also reduce evaporation at the soil surface and are associated with higher steady-state infiltration rates than grassland or cultivated crops (Guevara-Escobar et al. 2000, Eldridge and Freudenberger 2005), attributable to more shade at the soil surface and a greater proportion of soil macropores under tree canopies. Similarly, herbaceous perennial bioenergy crops like miscanthus (*Miscanthus* x *giganteus*) and switchgrass (*Panicum virgatum*) are also likely to have greater annual ET demand than maize (*Zea mays*) and soybean (*Glycine max*) systems (Zeri et al. 2013). Hickman et al. (2010) found that miscanthus and switchgrass respectively have 55% and 25% greater cumulative ET demand than a maize system. Annual ET is greater for miscanthus because it has a longer growing season and higher water demands. Miscanthus had 18% greater ET than maize considering the time period when both crop canopies were closed. The relatively higher ET from switchgrass is primarily due to a longer growing season. The overall impact of perennial biomass crops on the watershed-scale water balance will depend on vegetation type and the degree and scale of land-use conversion. A modeling study of biomass production in the Iowa River Basin shows a 4.6% decrease in watershed water yield based on 100% conversion of maize fields to miscanthus (Wu et al. 2012).

Topographic and soil heterogeneity also influence soil moisture variability at multiple spatial scales (Price and Bauer 1984, Western et al. 1999). Soil components such as sand, silt, clay, and organic matter and soil properties such as pH and structure are known to vary with landscape position (Brubaker et al. 1993, Cambardella et al. 1994). Topographic variation in soil properties is linked to variation in hydraulic properties and soil water retention (Pachepsky et al. 2001, Jiang et al. 2007). Spatial soil moisture patterns also are correlated directly with topographic variables such as specific upslope area, slope, curvature, and relative elevation (Nyberg et al. 1996, Famiglietti et al. 1998). Soil moisture exhibits temporally-dependent preferred states of spatial organization as a result of changing meteorological and vegetation conditions (Grayson et al. 1997). Spatial variability in soil moisture can significantly influence runoff at different scales (12-54 ha) (Merz and Plate 1997).

While the effects of landscape and topographic heterogeneity and cropping systems on soil moisture dynamics have been explored, no studies have addressed the combined influence of landscape factors and cropping systems on soil moisture profile patterns. Landscape position effects on crop productivity have been observed (Stone et al. 1985, Jones et al. 1989), and water availability has been posited as a potential explanatory mechanism (Hanna et al. 1982). Afyuni et al. (1993) observed variability in plant-available water by landscape position and correlate it to variability in maize silage yields. Daniels et al. (1987) argue that variability in soil moisture by landscape position most likely affects crop yield. As different crops show variable soil moisture response profiles across the growing season and variable productivity across landscape positions (Jones et al. 1989, McIsaac et al. 2010), it is possible that bioenergy crops will exhibit variable soil moisture response profiles across landscape position over the course of a growing season.

Here we focus on soil moisture dynamics at the plot and hillslope scale, as landscapes may be considered mosaics of individual hillslopes (Bronstert and Plate 1997).

Understanding soil moisture patterns of alternative biomass crops over space and time at the hillslope scale can be used to predict the potential impact on moisture-dependent hydrological processes when deployed at catchment scales through the use of hydrologic models that account for variable cropping system and topographic impacts on soil moisture, and hence baseflow. While previous studies have modeled the potential hydrologic impacts of biomass cultivation (Schilling et al. 2010, Wu et al. 2012), empirical data on hydrologic impacts of biomass cultivation are less prevalent (McIsaac et al. 2010). Data from such investigations may be used to parameterize or improve physically-based hydrologic models of biomass production, as well as understanding of the potential environmental impacts bioenergy crop production.

Our study addresses this research gap by investigating the soil moisture dynamics of five biomass cropping systems across five landscape positions over time. We hypothesized that (a) in terms of landscape positions, summit and shoulder positions would generally have the lowest and floodplain and footslope positions have the highest moisture contents, (b) in terms of cropping systems, perennial systems would have lower mean seasonal soil moisture content due to greater ET demand, and (c) continuous maize, maize-switchgrass, and triticale (*Triticosecale* x)-aspen (*Populus alba* x *P. grandidentata*) systems would have a greater number of significant differences in mean moisture content among landscape positions than the modified rotation and triticale/sorghum (*Sorghum bicolor*) systems. Specifically, there is a general downward flow of water from upper to lower landscape positions (Hanna et al. 1982). In addition, due to the length of their growing season, perennial crops are likely to exhibit greater total soil moisture depletion than annual crops (Robertson et al. 2011). Lastly, crops generally exhibit improved water-use efficiency and performance in rotation (Copeland et al. 1993). This will likely reduce differences in crop performance among landscape positions within these systems, leading to similar impacts on soil moisture among landscape positions. Here we address these hypotheses in the context of the Landscape Biomass Project. The project was established to improve scientific understanding of how biomass systems are likely to perform within and across landscapes. This specific study investigates the influence of topographic factors on the soil moisture dynamics of five biomass cropping systems. We discuss the potential hydrological implications of differences in soil moisture dynamics among cropping systems across a topographic gradient during the 2010, 2011, and 2012 growing seasons.

Materials and Methods

Experiment Design and Site Description

In fall 2008, the Landscape Biomass Project was established as a randomized, replicated block design experiment at the Uthe Farm, an Iowa State University Research and Demonstration Farm located 20 km southwest of Ames, Iowa. This site provided the optimal landscape context and hillslope properties for the design and development of the experiment. The experiment was established on an eastward facing hillslope. Two treatment factors were applied to a total of 75 0.20 ha plots. Each treatment factor includes five treatment levels. The landscape position treatments include (1) summit, (2) shoulder, (3) backslope, (4) footslope, and (5) floodplain. The biomass cropping system treatments include (1) continuous maize, (2) a modified rotation that includes soybean-triticale/soybean-maize, (3) maize-switchgrass, (4) triticale/sorghum, and (5) triticale-aspen. Each cropping system is randomly assigned within each landscape position, producing a total of 25 unique treatment levels. The treatments are replicated in three blocks. Prior to establishment, the land use of the upslope landscape positions was agriculture in a maize-soybean rotation, while approximately one-half of the riparian floodplain plots were in mixed grasses.

Each plot is surrounded by a grass buffer at least 6 m in width, which is used to isolate plots and reduce cross-plot effects. The buffer around the tree plots is 18.3-m wide to mitigate potentially more significant cross-plot effects. The plots in the upper four landscape positions (summit, shoulder, backslope, footslope) have slope lengths of 24.4 m and widths of 18.3 m, the floodplain plots have slope lengths of 18.3 m and widths of 24.4 m. The average slope across the entire site is 6%, with an elevation difference of 20 m between the floodplain and summit. Soil properties also vary across the site by landscape position (Table 1). Table 2 shows which crops were grown in the 2010, 2011, and 2012 growing seasons, the years for which soil moisture data were collected for this specific study. See Wilson et al. (2014) for a full description of the experimental site, cropping systems, and landscape positions.

Data Collection

Two soil moisture access tubes were installed in each of the 75 plots in 2009. The dimensions of the tubes measures 52 mm diameter by 120 mm in length. In 2010, soil moisture measurements were taken on June 3-4, 7-9, July 13-14, August 25-26, and September 25-26. In 2011, Soil moisture measurements were taken on April 10-11, May 7-8, June 7-8, July 8-9, August 8-9, and September 8-9, and October 13-14. In 2012, measurements were taken on April 26, July 24, August 26, and September 28. We measured the soil moisture content at 20 cm depth intervals from 20-120 cm at each access tube using the TRIME-FM time domain reflectometer (TDR) with a TRIME-T3 access probe. Moisture content was measured in 20 cm intervals at 20 cm to 120 cm depth. Two readings were taken at each depth interval. We were unable to take surface soil moisture measurements were during the 2012 growing season due to drought conditions. In addition, the surface moisture data for 2010 and 2011 showed very high variability, with no observed differences among treatments in a preliminary analysis. Those data were therefore not analyzed in this study. Precipitation data were collected using a rain gauged located 1.5 km southeast of the project site (Table 3).

Data Analyses

Here we present analyses of soil moisture using a 20-120 cm depth interval; additional analysis using a 20-40 cm depth interval conducted for comparison purposes is presented in Appendix B. We assessed significant differences in mean soil moisture content among cropping system and landscape position treatments both across the three years of study (2010-2012) and within each year individually (2010, 2011, 2012). Data were analyzed using SAS statistics software (SAS Institute, 2001). We used the GLIMMIX procedure to perform analysis of covariance (ANCOVA) and calculate treatment means across all three years of study and within each year. The ANCOVA model we used included cropping system, landscape position, the interaction between cropping system and landscape position, month of data collection, soil clay content, depth, and crop yield. Cropping system, landscape position, and their interaction were treated as fixed effects, the data collection period (or month) as a random blocking effect, soil clay content, depth and biomass yield were treated as linear covariates. Denominator degrees of freedom were determined using the Kenward-

Rogers method. Data analysis was subsequently conducted by each individual year of study to determine significant treatment effects within each growing season. Clay was included as a covariate; biomass yield was not included in these analyses. Treatment means and multiple comparisons were output by the GLIMMIX procedure using the *slice* statement, which applies the Tukey adjustment for multiple comparisons.

Results and Discussion

Multi-year analysis

Cropping system, landscape position, and the cropping system by landscape position interaction were all significant effects. Clay was a significant covariate. Biomass yield was insignificant (Table 4). Significant treatment effects differed by landscape position and cropping system (Table 5, Figure 1). There are fewer landscape position differences among cropping systems. Specifically, the backslope, footslope, and floodplain appear to have similar moisture contents, while the summit and shoulder have lower soil moisture. This again suggests downslope movement of water. However, since water depletion is more likely to occur nearer the surface (Peters and Johnson 1960), high water levels at lower depths may prevent the detection of any treatment effects at these positions. Hanna et al. (1982) observe higher moisture contents at the backslope and footslope positions relative to other positions, due to runoff and subsurface flow of water from upslope positions. They also observed higher moisture content at the backslope relative to the footslope, due to greater crop productivity and weed growth at the footslope position during the growing season, which lead to increased water consumption and lower soil moisture content. Similarly, Afyuni et al. (1993) predicted highest total soil moisture content at the footslope position, but observed the lowest moisture content at this position, with soil moisture increasing upslope. This was due to the coarse soil texture at the footslope position and finer soil textures upslope.

The modified rotation system had lower moisture content at the footslope and floodplain positions (Table 6, Figure 1). The continuous corn and triticale-aspen systems show lower mean moisture content at the summit and shoulder positions. Maize-switchgrass and triticale/sorghum show higher mean moisture at the shoulder and backslope positions as compared to the other three positions.

2010

All treatment effects were highly significant at the $P <= 0.05$ level, except depth (Table 7). High and repeated precipitation events would prevent the establishment of a moisture gradient with depth. In a wet year like 2010, topography or landscape position has a larger influence than vegetation on moisture distribution (Western et al. 1999, Meerveld and McDonell 2006). Within the summit position, there were no significant cropping system effects. Within the shoulder position, there were four significant pairwise cropping system differences. Within the backslope position, there were two significant differences. The shoulder position had four significant pairwise cropping system differences; while the floodplain position only had two (Table 7, Figures 2a and 3a).

There were seven significant pairwise landscape position differences for continuous maize, two for triticale/soybean, six for maize-switchgrass, two for triticale/sorghum, and six for triticale/aspen (Table 7, Figures 2a and 3a). The triticale/soybean and triticale/sorghum systems were relatively less affected by landscape position, suggesting that landscape position will not be a significant contributing factor in overall hydrologic impacts.

Continuous maize and the two perennial systems (switchgrass and aspen) had a higher number of significant landscape position effects.

2011

Mean soil moisture content declined significantly at all landscape positions over the growing season (Figure 4). The largest decline in mean moisture occurred at the floodplain position; while the footslope had a slightly lower change over the season. The shoulder position displayed the lowest change in mean moisture content; the summit and backslope showed a slightly greater seasonal difference. Generally, the summit had the lowest soil moisture through the growing season (Figure 4). The floodplain, which started out with very high moisture content in April, had significantly lower moisture content than the shoulder, footslope, and backslope from July-September (Figure 4). The backslope position always had higher moisture content than the shoulder and summit. The floodplain and footslope positions start out with higher moisture content in April than the backslope, but generally had lower soil moisture after June.

Significant differences in mean moisture among landscape positions varied by cropping system (Table 7, Figures 2b and 3b). For the continuous maize system, the summit and shoulder generally had lower moisture content than the footslope. The shoulder position also had significantly lower moisture than the backslope and floodplain. The maize crop within the maize-soybean-triticale/soybean rotation displayed significantly higher soil moisture content at the summit than the footslope and the floodplain positions. In the maize-switchgrass system, the summit was generally drier than the shoulder and backslope positions. The shoulder position was drier than the floodplain. The backslope position had higher moisture content than either the footslope or floodplain positions. In the triticale/sorghum system, the summit position had less moisture than the backslope position. In the triticale-aspen system, the summit and shoulder positions were significantly drier than the backslope and footslope positions; whereas the shoulder was also drier than the floodplain. The backslope and footslope positions had significantly greater moisture content than the floodplain (Table 7, Figures 2b and 3b).

2012

2012 was a very dry year (Table 7, Figures 2c and 3c). In such cases, topographic redistribution as a result of lateral flow is likely to be minimal. Soil moisture would largely be controlled by soil and vegetation factors rather than topographic factors (Grayson et al 1997). Mean moisture content showed significant variation among cropping systems over the growing season (Figure 4). Generally, the continuous maize system had the lowest moisture content at all points during the growing season. In April, continuous maize had lower mean soil moisture than the other four cropping systems, which did not significantly differ in their mean moisture contents. In July, all systems, except maize-switchgrass and triticale-aspen, have significantly different mean moisture contents. Triticale/sorghum had significantly higher moisture than all other systems from July through September. Soybean had higher moisture contents than the maize-switchgrass and aspen systems from July through September, though this difference wasn’t significant in August. All systems exhibit a declining trend in mean moisture content from the beginning to the end of the season. Hattendorf et al. (1988) observed that maize and soybean may have greater total seasonal soil moisture depletion than sorghum, though these differences vary by season and are not always significant. Crop growth and yield is highly correlated with cumulative transpiration (Hanks 1983). Up to 50% or more of the seasonal water requirements of maize and soybean are met by soil moisture stored in the soil profile (Russell and Danielson 1956, Peters and Johnson 1960).

Previous studies comparing water use among crops show varying impacts on soil moisture depletion at varying depths (Hattendorf et al. 1988). For example, over the course of the growing season, maize depletes water from the soil profile in a downward pattern to a depth below 150 cm (Russell and Danielson 1956). In the final part of the season (late August – early September), almost all the moisture depletion occurs below the 122 cm depth. This depletion pattern may vary by crop and cultivar. Soybean extracts more water from a depth below 80 cm as growth progresses, regardless of water availability at the surface (Peters and Johnson 1960). A drought-resistant soybean cultivar was shown to deplete more soil moisture from the soil horizon above 68 cm compared to a non-drought variety, as a result of the greater lateral spread and fibrosity of its roots (Hudak and Patterson 1996).

Mean moisture content differed significantly among landscape positions over the growing season (Table 7, Figures 2c and 3c). In April, moisture is highest at the footslope position and lowest at the summit position. From July to September, moisture content is highest at the backslope and lowest at the summit and floodplain positions. The shoulder position always has higher moisture content than the summit position and lower moisture content than the backslope position.

Conclusion

Our research shows that different biomass cropping systems have variable impacts on soil moisture content across a topographic gradient over time. Specifically, soil moisture under cropping systems is a function of numerous factors that may include topography, soil type, and cropping system. Our research identified differences in mean seasonal soil moisture among cropping systems as a function of landscape position. This indicates differences in soil moisture loss or availability among these systems. Differences among cropping systems are likely related to differences in ET, soil moisture loss, infiltration, runoff, and subsurface flow. Future research should be directed toward monitoring and understanding these other processes and how they influence the spatiotemporal evolution and organization of soil moisture under alternative cropping regimes.

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TABLES

Table 1. Mean values for selected soil properties across landscape positions. Modified from Ontl et al. (2013).

Landscape position	SOC (g kg-1)		Depth A horizon		Bulk density (g cm-3)		Geometric mean diameter		POM (g kg-1)		Sand (%)	
Summit	15.8 ± 1.8	b	33.0 ± 6.2	b	1.58 ± 0.04	b	0.249 ± 0.008	c	0.230 ± 0.017	b	54.1 ± 5.7	a
Shoulder	16.6 ± 0.7	ab	40.2 ± 3.8	b	1.55 ± 0.03	b	0.239 ± 0.007	c	0.204 ± 0.007	b	49.0 ± 3.1	a
Backslope	17.9 ± 1.3	ab	37.8 ± 6.5	b	1.54 ± 0.05	b	0.262 ± 0.011	c	0.199 ± 0.003	b	45.5 ± 1.5	a
Footslope	17.8 ± 1.1	b	46.5 ± 9.7	b	1.58 ± 0.03	b	0.318 ± 0.013	b	0.226 ± 0.018	b	52.3 ± 2.3	a
Floodplain	31.0 ± 1.4	a	85 ± 9.8	a	1.28 ± 0.03	a	0.481 ± 0.042	a	0.345 ± 0.042	a	29.5 ± 2.6	b

Table 2. Crop grown in each year for each cropping system.

Cropping system	2010	2011	2012
Continuous maize	Maize	Maize	Maize
Modified rotation	Triticale and Soybean	Maize	Soybean
Maize-switchgrass	Switchgrass	Switchgrass	Switchgrass
Triticale/Sorghum	Triticale and Sorghum	Triticale and Sorghum	Triticale and Sorghum
Triticale-Aspen	Triticale and Aspen	Triticale and Aspen	Aspen

Table 3. Total monthly precipitation (cm) by year. (Data from nearby Comparison of Biofuel Systems research site, Iowa State University.)

	2010	**2011**	**2012**
January	2.00	0.43	0.43
February	0.38	1.34	1.67
March	4.80	2.13	5.89
April	11.88	11.20	10.36
May	11.15	14.47	5.76
June	30.53	17.01	7.79
July	19.07	5.41	6.35
August	28.09	8.94	5.53
September	25.98	5.02	2.71
October	2.20	1.29	6.04
November	5.15	8.00	2.31
December	0.73	5.13	1.70

Table 4. Multi-year ANCOVA results at depth 20-120 cm. P <= 0.05 is considered significant.

Source of Variation	Num df	Den df	F	P
Landscape Position	4	5346	90.08	< 0.0001
Cropping System	4	5346	17.95	< 0.0001
Landscape Position * Cropping System	16	5346	22.5	< 0.0001
Clay	1	5346	404.33	< 0.0001
Depth	4	5346	60.61	< 0.0001
Biomass yield	1	5346	1.44	0.2300

Table 5. Individual year ANCOVA results at depth 20-120 cm. P <= 0.05 is considered significant.

Year	Source of Variation	Num df	Den df	F	P
2010	Landscape Position	4	1400	32.55	0.0008
	Cropping System	4	1400	4.75	< 0.0001
	Landscape Position * Cropping System	16	1400	5.01	< 0.0001
	Clay	1	1400	120.56	< 0.0001
	Depth	1	1400	1.31	0.2530
2011	Landscape Position	4	1400	32.20	< 0.0001
	Cropping System	4	1400	12.36	< 0.0001
	Landscape Position * Cropping System	16	1400	18.25	< 0.0001
	Clay	1	1400	177.95	< 0.0001
	Depth	1	1400	1.47	0.2250
2012	Landscape Position	4	1400	40.89	< 0.0001
	Cropping System	4	1400	16.82	< 0.0001
	Landscape Position * Cropping System	16	1400	5.59	< 0.0001
	Clay	1	1400	129.62	< 0.0001
	Depth	1	1400	201.45	< 0.0001

Table 6. Landscape position and cropping system means for multi-year analysis at 20-120 cm depth. Letters indicate significant differences among cropping systems within landscape positions at the P <= 0.05 level.

Landscape Position	Continuous maize	Modified rotation	Maize-switchgrass	Triticale/Sorghum	Triticale-Aspen
Summit	31.3 ± 3.72 c	35.6 ± 3.72 a	32.7 ± 3.72 b	33.0 ± 3.72 b	32.8 ± 3.72 b
Shoulder	32.0 ± 3.72 c	35.3 ± 3.72 b	36.8 ± 3.72 a	35.8 ± 3.72 b	32.4 ± 3.72 c
Backslope	35.4 ± 3.72 b	35.6 ± 3.72 b	37.0 ± 3.72 a	36.1 ± 3.72 b	37.5 ± 3.72 a
Footslope	35.9 ± 3.72 b	34.1 ± 3.72 c	35.4 ± 3.72 b	35.7 ± 3.72 b	37.6 ± 3.72 a
Floodplain	33.9 ± 3.72 b	34.6 ± 3.72 b	32.4 ± 3.72 c	33.9 ± 3.72 b	35.5 ± 3.72 a

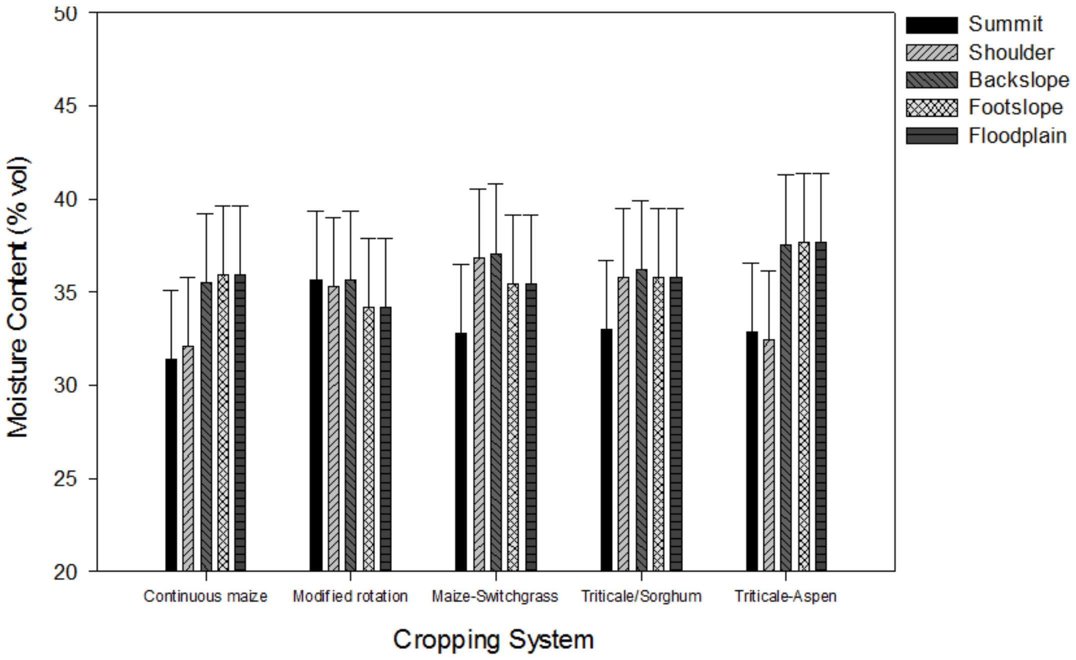
Table 7. Cropping system and landscape position means by year at depth = 20-120 cm. Letters indicate significant differences among cropping systems within landscape positions at the P <= 0.05 level.

Year	Landscape Position	Continuous maize	Modified rotation	Maize-switchgrass	Triticale/Sorghum	Triticale-Aspen
2010	Summit	34.8 ± 2.78 a	36.6 ± 2.82 a	34.9 ± 2.82 a	34.5 ± 2.78 a	34.7 ± 2.79 a
	Shoulder	35.2 ± 2.78 b	38.7 ± 2.79 a	37.4 ± 2.82 a	35.3 ± 2.78 b	35.3 ± 2.83 b
	Backslope	39.4 ± 2.79 a	37.7 ± 2.78 c	40.5 ± 2.78 a	38.4 ± 2.79 bc	39.0 ± 2.79 bc
	Footslope	38.7 ± 2.78 a	36.4 ± 2.78 b	38.5 ± 2.78 a	37.6 ± 2.78 b	39.4 ± 2.78 a
	Floodplain	38.6 ± 2.79 a	37.4 ± 2.79 ab	37.5 ± 2.79 c	37.2 ± 2.79 bc	37.8 ± 2.79 a
2011	Summit	37.2 ± 1.41 a	43.0 ± 1.54 bc	37.9 ± 1.41 b	38.7 ± 1.41 b	35.8 ± 1.41 c
	Shoulder	36.1 ± 1.41 d	39.9 ± 1.41 c	41.6 ± 1.43 a	40.4 ± 1.41 b	36.1 ± 1.41 d
	Backslope	39.6 ± 1.41 d	40.0 ± 1.41 cd	42.7 ± 1.41 ab	41.2 ± 1.41 bc	42.3 ± 1.41 a
	Footslope	40.5 ± 1.41 b	38.6 ± 1.43 c	39.2 ± 1.41 cb	40.3 ± 1.41 cb	42.1 ± 1.41 a
	Floodplain	39.5 ± 1.41 b	38.9 ± 1.41 b	38.3 ± 1.41 c	39.1 ± 1.41 b	38.1 ± 1.41 a
2012	Summit	24.4 ± 2.80 c	28.4 ± 2.88 a	25.4 ± 2.80 b	26.2 ± 2.81 ab	25.0 ± 2.80 ab
	Shoulder	24.9 ± 2.80 b	26.4 ± 2.81 b	27.6 ± 2.80 a	28.4 ± 2.80 a	25.2 ± 2.80 b
	Backslope	27.0 ± 2.80 b	29.2 ± 2.80 a	29.4 ± 2.81 a	29.6 ± 2.80 a	29.3 ± 2.80 a
	Footslope	29.3 ± 2.80 bc	27.3 ± 2.80 c	28.3 ± 2.80 c	31.1 ± 2.80 a	29.1 ± 2.80 ab
	Floodplain	26.0 ± 2.80 b	26.9 ± 2.80 a	25.8 ± 2.81 b	27.3 ± 2.80 a	26.5 ± 2.81 a

Figures

Figure 1. Means in soil moisture by cropping system and landscape position in multi-year analysis (2010–2012): (a) by cropping system at 20-120 cm depth, and (b) by landscape position at 20-120 cm depth.

a.



b.

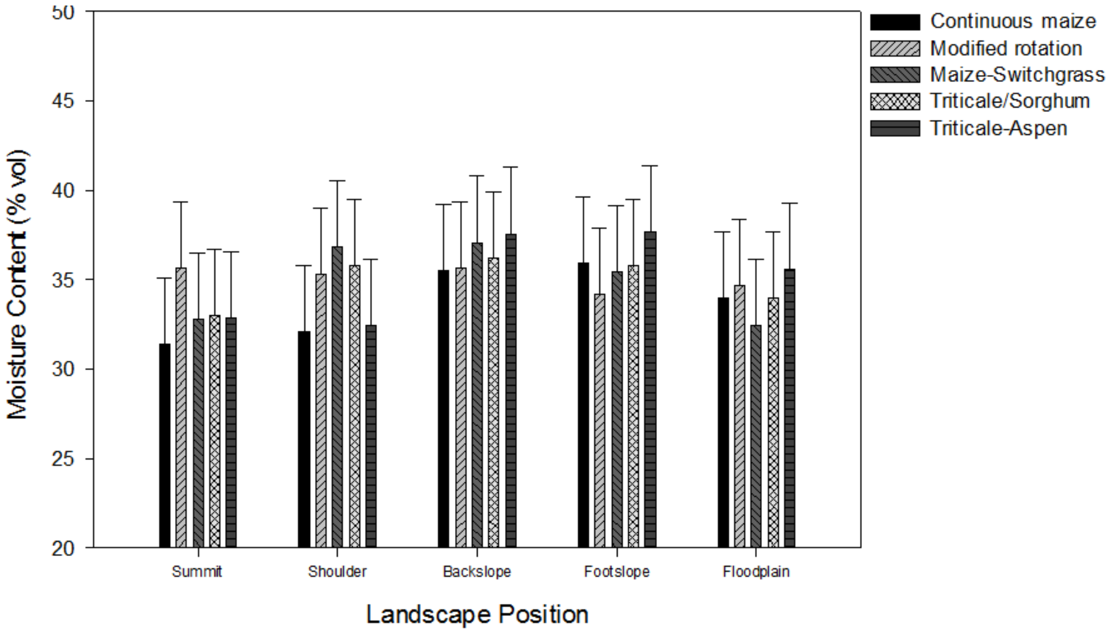
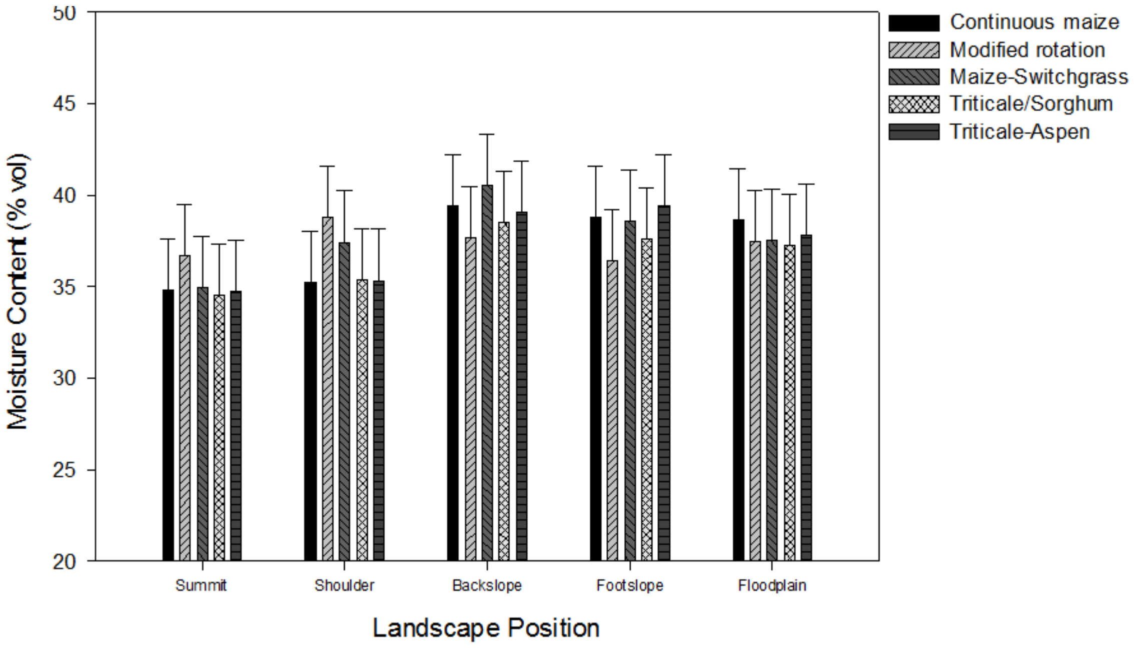
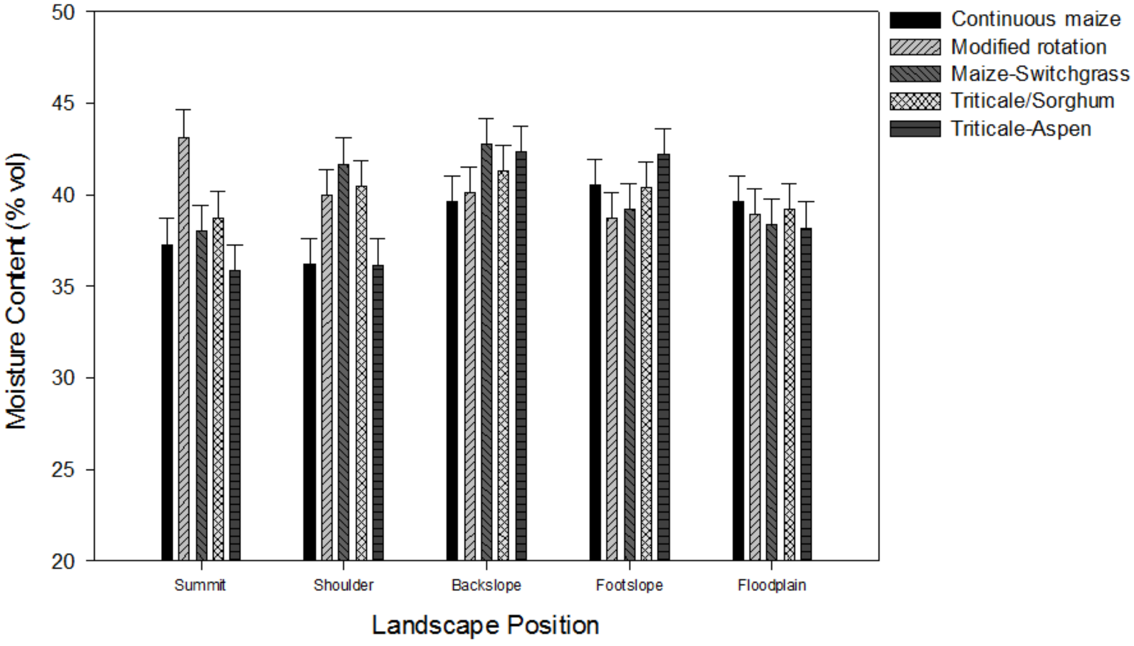


Figure 2. Means in soil moisture by landscape position at 20-120 cm depth in (a) 2010, (b) 2011, and (c) 2012.

a.



b.



c.

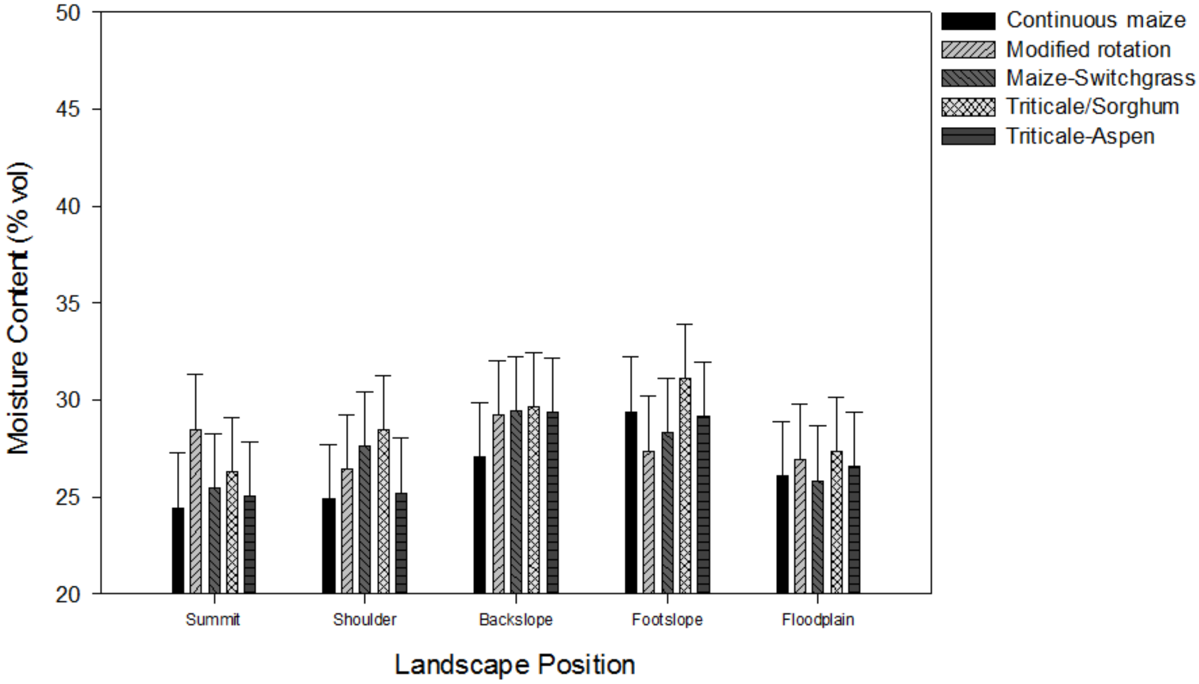
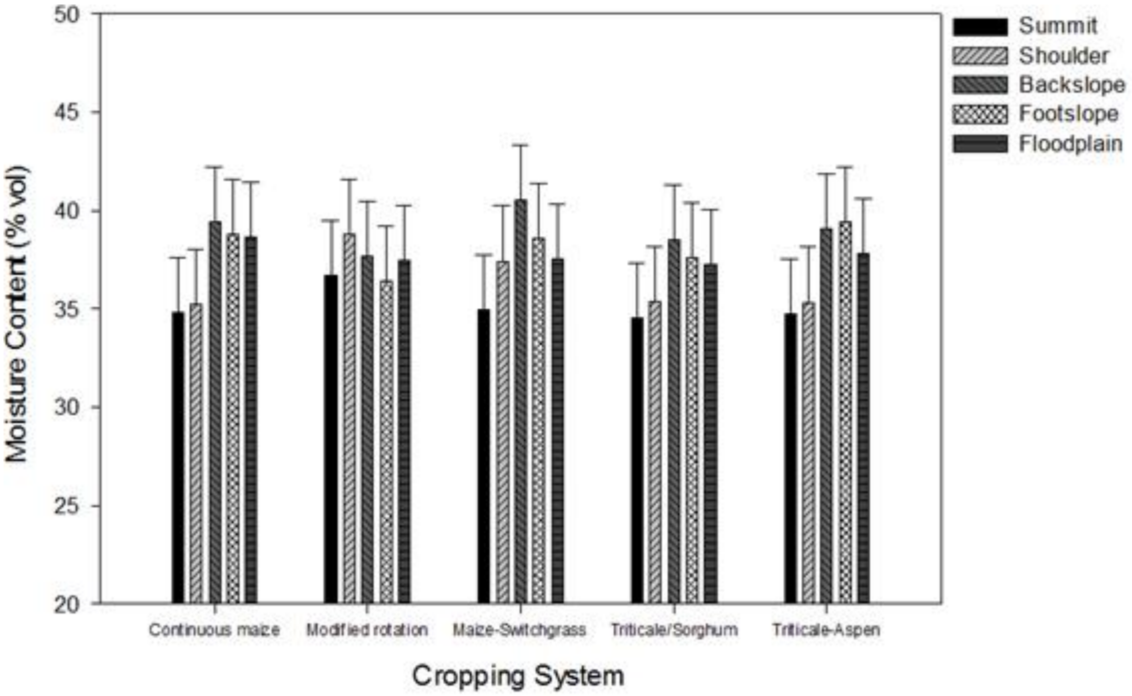
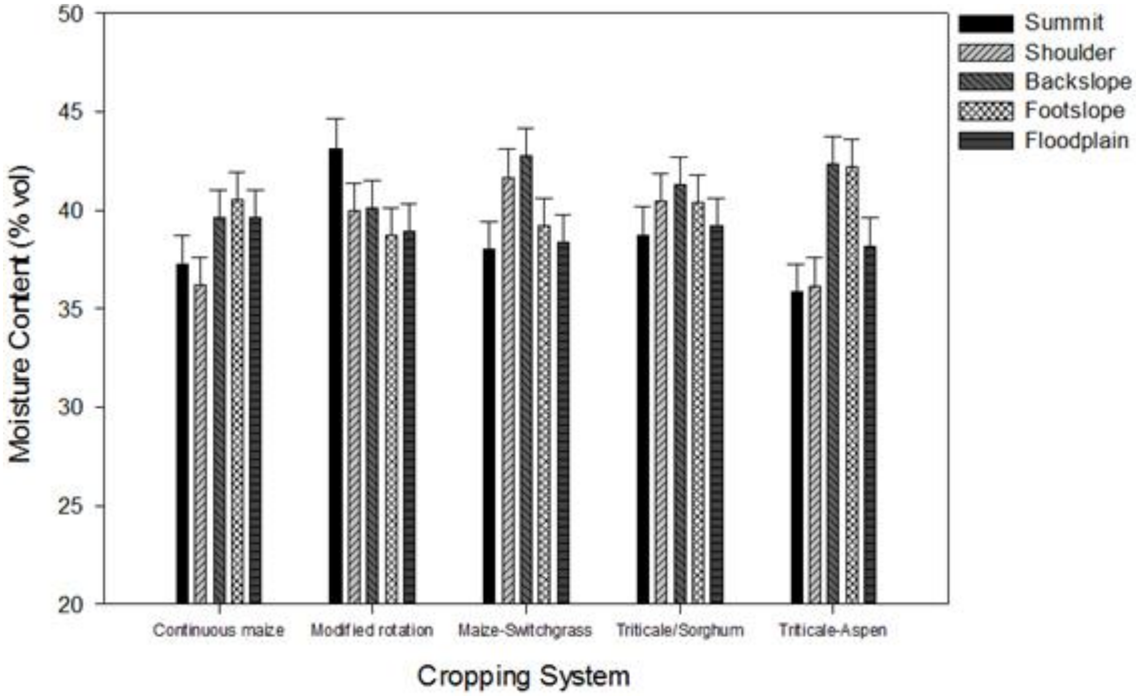

50
45
40
35
30
25
20
Moisture Content (% vol)
Summit
Shoulder
Backslope
Footslope
Floodplain
Landscape Position
Continuous maize
Modified rotation
Maize-Switchgrass
Triticale/Sorghum
Triticale-Aspen

Figure 3. Means in soil moisture by cropping system at 20-120 cm depth in (a) 2010, (b) 2011, and (c) 2012.

a.



b.



c.

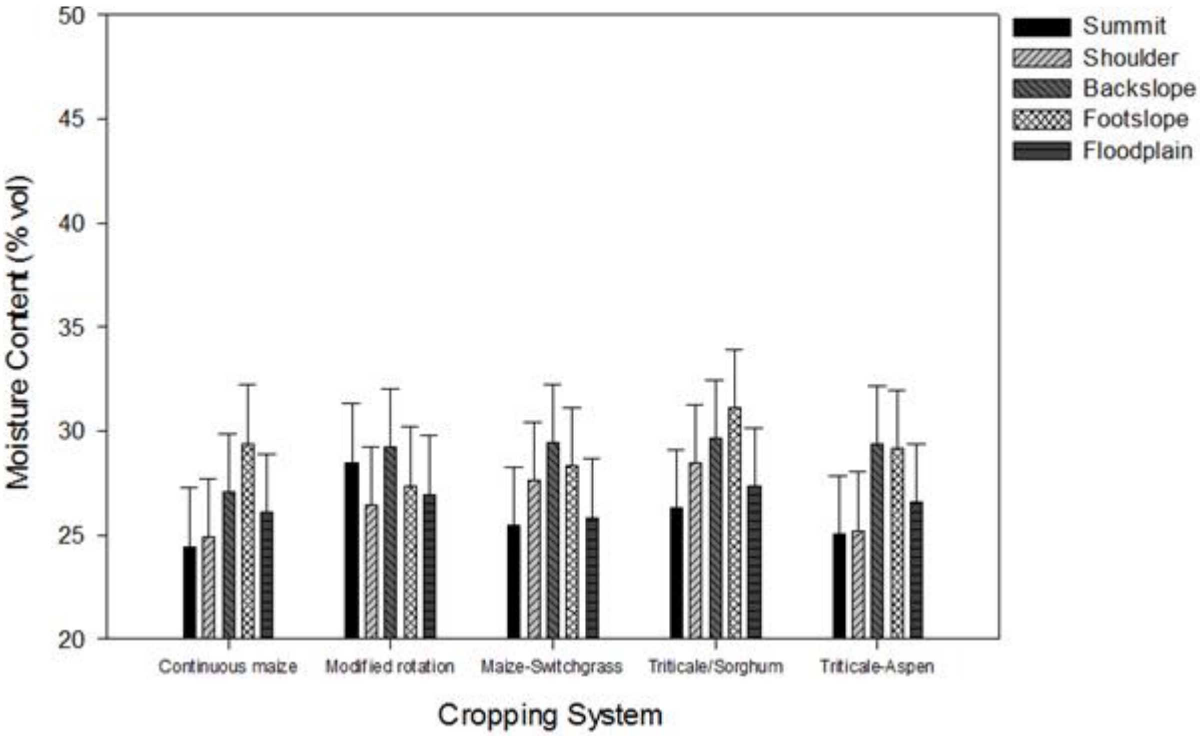
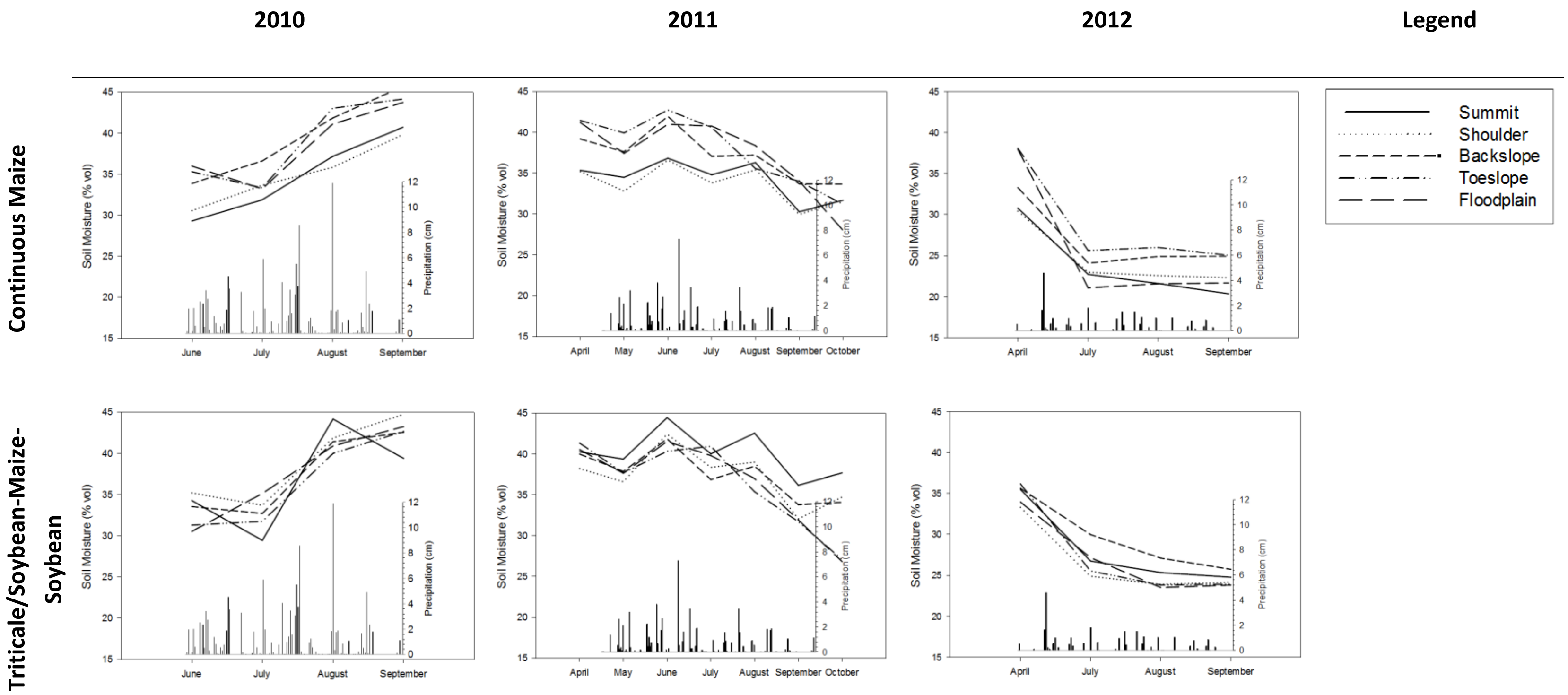
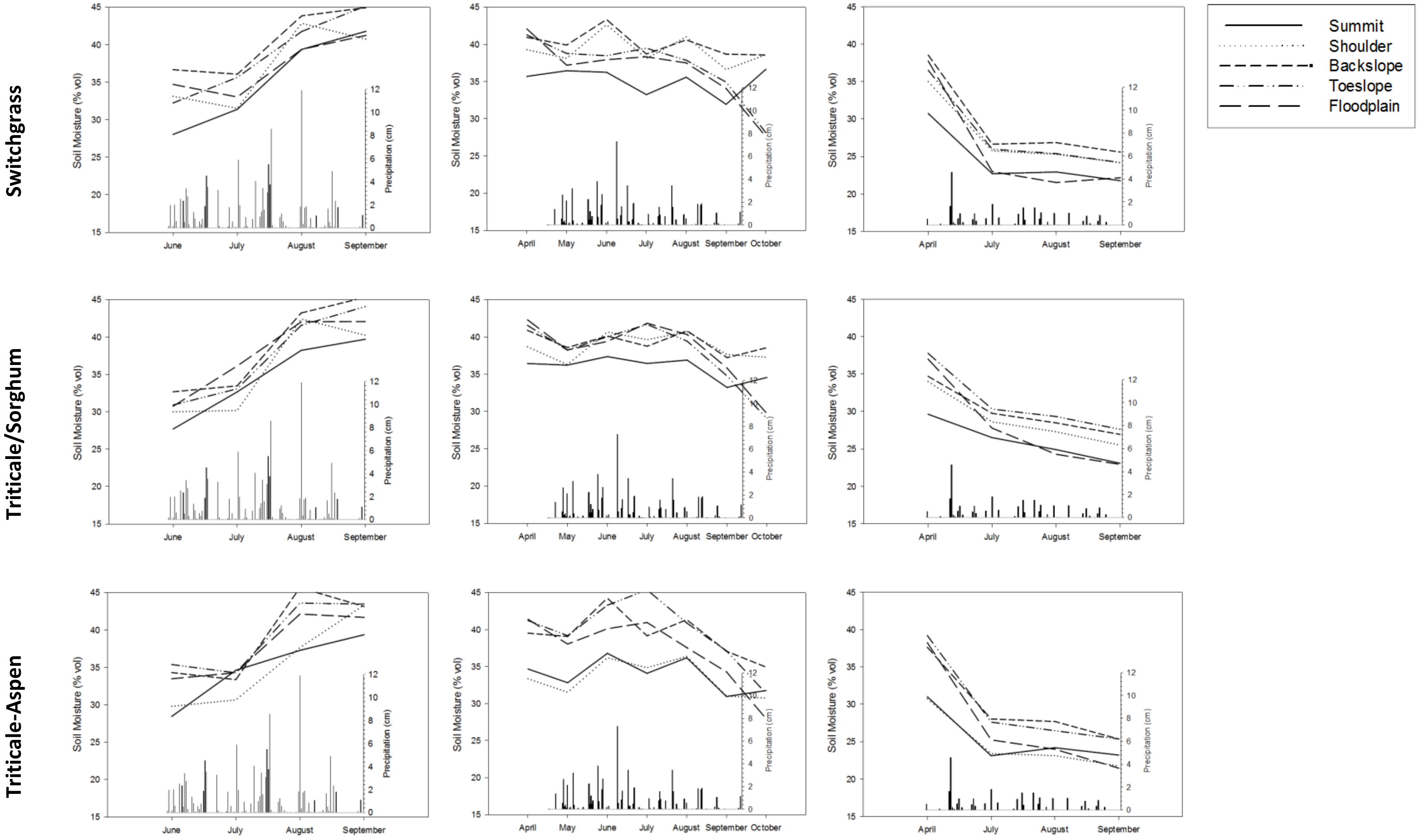

50
45
40
35
30
25
20
Moisture Content (% vol)
Summit
Shoulder
Backslope
Footslope
Floodplain
Continuous maize
Modified rotation
Maize-Switchgrass
Triticale/Sorghum
Triticale-Aspen
Cropping System

Figure 4. Mean soil moisture of five cropping systems over five landscape positions across the 2010, 2011, and 2012 growing seasons (continued on next page). Precipitation is also displayed. 45% is field capacity.




Switchgrass
Triticale/Sorghum
Triticale-Aspen
Summit
Shoulder
Backslope
Toeslope
Floodplain
Soil Moisture (% vol)
Precipitation (cm)
45
40
35
30
25
20
15
12
10
8
6
4
2
0
June
July
August
September
April
May
October

CHAPTER 4

THE EFFECT OF FIVE BIOMASS CROPPING SYSTEMS ON THE HYDRAULIC PROPERTIES OF SOILS ACROSS A TOPOGRAPHIC GRADIENT

Usman Anwar, Lisa A. Schulte, Randall K. Kolka, and Matthew Helmers

A paper prepared for submission to *Biomass and Bioenergy*

Abstract

Because bioenergy cropping systems have potential field- and watershed-scale impacts on hydrology, understanding their in-field performance and impacts is needed to inform both bioenergy policy development and farmer adoption of alternative crops. We determined the effects of five biomass systems (continuous maize, soybean-triticale/soybean-maize, maize-switchgrass, triticale/sorghum, triticale-aspen) across five landscape positions on the saturated hydraulic conductivity (K_S) of soils. We compared data from the time of cropping system establishment (2009) to four-years post-establishment (2013). Both our 2009 and 2013 data confirmed that cropping system impacts on K_S vary by landscape position. We found that differences impacts were more likely to occur at lower landscape positions, specifically, within footslope and floodplain positions. Previous research on cropping system impacts suggested grass and woody systems were associated with a general increase in K_S over time, with greater changes likely occurring at landscape positions with a higher erosive potential or lower SOC content. Our results confirmed that the triticale-aspen tree system was associated with a significant increase in K_S across all landscape positions over a four year period (2009-2013). In contrast, we did not observe an increase in K_S under switchgrass, which we attributed to the high density of switchgrass roots during the 4 years of study; we expect an increase in Ks under switchgrass under longer measurement periods.

We also found a significant increase in Ks in the annual systems over the 4-year period of investigation, likely due to the conversion to no-till soil management with cropping-system establishment. We expect such differences to become more apparent over longer timescales as ecological processes continue to impact soil and hydraulic properties.

Keywords: bioenergy, biomass crops, hydraulic conductivity, hydrology, infiltration rate, landscape, Landscape Biomass Project

Introduction

The development of sustainable bioenergy systems will require the development and use of alternative biomass feedstocks with varying environmental impacts and benefits. Globally, the conversion of native perennial vegetation to annual crops has led to declining water quality, freshwater habitat, and biodiversity (Foley et al. 2005). Increased cultivation of annual crops such as maize (*Zea mays*) has led to an increase in runoff, erosion, and nutrient losses (Thomas et al. 2009). In contrast, perennial bioenergy crops are expected to provide improved environmental performance relative to their annual counterparts, such as reduced nutrient pollution, improved soil quality, lower nitrous oxide (N_2O) and carbon dioxide (CO_2) emissions, and lower runoff and subsequent soil erosion (Blanco-Canqui 2010, Robertson et al. 2008).

To better understand the potential environmental impacts of alternative energy crops, we investigated steady-state infiltration rates (K_S) associated with five different cropping systems. The steady-state infiltration rate, or saturated hydraulic conductivity (K_S) is a measure of hydraulic conductivity under saturated conditions, or when the hydraulic gradient is at unity, and depends only on the intrinsic permeability of the soil (Raoof et al 2011). Ks can significantly influence numerous hydrological processes such as infiltration, runoff generation, soil moisture content, and plant-available water, which can in turn influence soil properties and crop performance (Collis-George 1977, Hall and Olson 1991, Bronstert and Plate 1997).

Differences in physiological characteristics and management among alternative biomass systems can have variable impacts on soil hydraulic properties (Jiang et al. 2007). As a result, the water balance of these systems is also likely to be different. The infiltration rate is a key factor influencing the partitioning of precipitation to the different components of the water balance. An understanding of how this factor differs among biomass cropping systems will improve our understanding of their potential environmental and hydrologic impacts. From a hydrology perspective, variability in soil organic matter content associated with different cropping systems can affect soil water retention, especially in sandy and silty soils (Rawls et al. 2003).

Perennial crops may contribute to greater soil organic carbon (SOC) due to increased input of root biomass and also because once established, perennial systems do not require ongoing tillage (Robertson et al. 2008, Robertson et al. 2011). Higher SOC content can impact hydraulic conductivity by influencing the production of stable soil aggregates, which affect pore size distribution and soil structure (Boyle et al. 1989). Greater total SOC content is significantly correlated with higher water infiltration rate (Franzluebbers 2002). Soil under dense perennial vegetation, as in a natural prairie, can have nearly double the organic matter content of crop fields, and the K_S of such fields can be nearly 10 times higher than in crop fields (Fuentes et al. 2004). Conversion from conventional till to no till can increase the rate of SOC accumulation, which may lead to an increase in aggregate formation and soil structure (Bouma 1991, Elliott and Efetha 1999, West et al. 2002). Six et al. (1999) suggest tillage reduces aggregate formation and concentrations of fine intra-aggregate particulate organic matter (53-250 µm) in macroaggregates. In addition, perennial vegetation can influence soil hydraulic properties by preventing the formation of a soil crust. Folorunso et al. (1992) observed reduced soil surface strength under bromegrass and clover. This was associated with a 37-41% increase in K_S. Compared to annual crop fields which are typically bare during the spring, perennial cover can intercept and reduce the impact energy of rainfall, which disrupts soil aggregates and causes consolidation of soil particles at the soil surface. SOC accumulation under switchgrass (*Panicum virgatum*), which has an extensive root system, can range from 1.7 to 10.1 Mg C ha^{-1} yr^{-1} (Schmer et al. 2011). This effect is likely to differ among soil types and soils with lower carbon stocks are most likely to experience greater change in soil organic matter over time (Garten and Wullschleger 2000).

In addition to the greater accumulation of organic matter under perennial systems, the higher rate of root growth and decay may contribute to higher soil macroporosity (Chan and Mead 1989, Jiang et al. 2007). Macropores significantly influences water flow through soils (Beven and Germann 2013). Edwards et al. (1988) attributed reduced surface runoff in a no-till watershed to greater infiltration and number of macropores compared to conventional tillage. Udawatta et al. (2006) found significantly greater numbers of macropores and macroporosity in soils from tree and grass systems compared to row-crop areas, which was correlated with higher K_S in those treatments. The number of macropores accounted for as much as 64% of the variation in K_S.

Evidence for differences in the hydraulic properties of soils under alternative crops and management regimes can be conflicting. Eldridge and Freudenberger (2005) found significantly higher K_S values under eucalyptus trees compared to pasture or cultivated cropland, though this effect was only observed on fine-textured soil. Anderson et al. (2009) found no significant differences in K_S among crop, grass, and forest treatment plots, although they observed greater recharge in forest plots after rainfall events at the end of the growing season, caused by lower antecedent soil moisture conditions due to greater seasonal evapotranspiration (ET) in those plots. Bharati et al. (2002) observed that cumulative infiltration (i.e., the amount of water infiltrated as a function of hydraulic conductivity and time) was highest in silver maple plots, followed by grass filter strips, and then switchgrass treatments. All three of these perennial treatments had higher cumulative infiltration than crop fields and pasture, which did not vary significantly among each other. These differences were attributed to improved soil quality and significantly greater SOC under the perennial treatments. Dosskey et al. (2007) found that newly established grass filter strips experienced a positive trend in infiltration over a period of 10 years, with most of the change occurring in the first three years. The newly established grass strips had greater infiltration than crop fields, though there were not any significant differences between grass and forest plots. The lack of differences between grass and forest plots was attributed to herbaceous undergrowth in the tree plots, which may have minimized differences in ground cover and soil properties between tree and grass plots. While differences in infiltration may have been observed, it might be difficult to explain these observed treatment effects in terms of differences in soil hydraulic properties without some idea of the antecedent moisture conditions. The observed differences may simply have been due to lower moisture status due to greater ET in the perennial treatment plots, as observed by Anderson et al. (2009).

Comparing infiltration rates under saturated conditions may help reduce the influence of antecedent moisture conditions on observed hydraulic conductivity. However, since infiltration in a field largely occurs under unsaturated conditions, the importance of antecedent moisture conditions on the infiltration properties of soils associated with different cropping systems cannot be entirely overlooked (Zhou et al. 2008). Saturated hydraulic conductivity largely describes water flow through macropores under saturated water conditions (Messing 1989). Saturated flow is influenced to a large degree by processes that contribute to soil structure and macropore formation, such as root growth and decay or burrowing earthworms (Beven and Germann 2013, Edwards et al. 1993). Further, macropore flow, or preferential flow is a significant factor determining flow even in unsaturated soils, and can take place regardless of antecedent moisture conditions (Beven and Germann 2013).

Jung et al. (2009) observed significantly lower K_S in three annual cropping systems (two with a maize-soybean [*Glycine max*] rotation at different fertilization rates and one with a winter cover crop) compared to three perennial cropping systems (multi-species perennial systems), and no significant differences among individual annual cropping systems. Similarly, Jiang et al. (2007) observed K_S was significantly higher in Conservation Reserve Program (CRP) plots compared to a mulch-till maize-soybean system, at the backslope position of a hillslope. They suggested that perennial systems are more likely to improve soil hydraulic properties at slope positions with greater vulnerability to soil degradation.

In comparison, Schwartz and Unger (2003) did not find a significant difference between cropland (wheat [*Triticum aestivum*]/sorghum [*Sorghum bicolor*]) and native grassland, but did observe that cropland converted to grassland had significantly lower K_S, suggesting that even after 10 years, conversion of cropland to grasses did not ameliorate changes in soil structure related to previous land use history. They did observe a temporal effect where hydraulic conductivity decreased over the course of the growing season from

May to August, indicating that measurement period had a greater influence than land use on observed hydraulic conductivities.

Perennial crops furthermore do not require repeated tillage, which may further influence hydraulic properties of the soil (Strudley et al. 2008, Robertson et al. 2011). Recently tilled soil typically has a high infiltration rate due to the presence of large macropores, but this effect diminishes as rainfall causes the soil surface to consolidate (Cassel and Nelson 1985). However, at the same time, tillage can reduce hydraulic conductivity between soil layers due to the disruption of pore continuity (Bouma 1991, Logsdon et al. 1990). Tillage also contributes to the loss of soil organic carbon, which can prevent the formation of stable soil aggregates and inhibit the development of a soil structure conducive to high infiltration rates (Boyle et al. 1989, Chan et al. 2002, Guzman and Al-Kaisi 2011).

Reports on the potential impact of reduced tillage alone (i.e., excluding any effects of perennial vegetation) on the hydraulic properties of previously cultivated soils are conflicting. Fuentes et al. (2004) observed no significant difference in near-saturated hydraulic conductivity between continuously tilled soils and soils that had not been tilled for 27 years. In comparison, Logsdon et al. (1993) show that minimum tillage and no tillage had significantly higher K_S values than tillage systems (though this effect was significant only on some measurement dates and not others, and temporal differences were greater than tillage or crop effects). Similarly, Elliott and Efetha (1999) observed significantly higher infiltration rates in no-till fields compared to conventionally tilled ones. No-till systems showed higher infiltration rates at the shoulder position compared to other positions in the spring, while the conventional till plots had lower rates at this position. Infiltration rates were relatively equally distributed among landscape positions for both systems in the fall. In addition, no-till plots had significantly higher soil organic carbon and aggregate stability, though these were weakly correlated with infiltration rate.

Soil properties exhibit heterogeneity at different spatial scales (Cambardella et al. 1994). Soil heterogeneity across a landscape develops as a consequence of drainage conditions, differential transport and deposition of soil materials, and differential transport of chemical elements (Hall and Olson 1991). Variations in the type, direction, and quantity of water movement produce variability in chemical and physical processes which gives rise to differences in soil physical and chemical properties across a landscape. Pedogenic and hydrologic processes are involved in a dynamic, yet mutual process that determines their characteristics and evolution across a landscape and over time. Specifically, soil and topographic heterogeneity cause differential patterns of water flow and movement, which contribute to the development of further spatial variability in topography and soil properties.

Spatial variability in soil properties is related to variability in soil hydraulic properties (Unlu et al. 1990, Famiglietti et al. 1998, Pachepsky et al. 2001). Infiltration rate can vary by landscape position, typically with lower elevation (footslope) areas exhibiting greater infiltration than higher elevations (summit) (Dunne et al. 1991, Sauer et al. 2005). Similarly, Jiang et al. (2007) found that K_S and bulk density were significantly related to landscape position, with the midslope having significantly lower K_S than summit or footslope positions. Spatial variability in infiltration rate also exhibits some degree of autocorrelation over distances from 0 – 40 m (Vieira et al. 1981, Mohanty and Mousli 2000).

Sauer et al. (2005) found lower infiltration rates at upland, higher elevation areas compared to the floodplain or bottom areas in a forest/pasture watershed. Guzman and Al-

Kaisi (2011) observed lower root biomass, SOC, and water stable aggregates and higher bulk density at the midslope position with increasing prairie age after establishment. This was associated with lower infiltration rate compared to the summit and footslope positions. The footslope position had higher SOC concentrations and lower bulk density than the summit, which was correlated with a significantly higher infiltration rate at this position. Elliott and Efetha (1999) observed that infiltration rate was positively correlated with aggregate stability and negatively correlated with bulk density, which are both soil properties that can vary with landscape position (Guzman and Al-Kaisi et al. 2011).

Experimental Goals and Hypotheses

Numerous factors may be involved in the development of hydraulic properties of soils under different cropping and management regimes. Specifically, the question of whether or not perennial systems alter the hydraulic properties of soils after conversion from annual cropping systems remains inconclusive. Hydraulic properties of soils significantly influence infiltration, which can determine partitioning of rainfall into water balance components. A better understanding of the impacts of contrasting land uses on hydraulic properties of soils is critical for understanding the potential environmental and hydrological impacts of alternative biomass cropping systems.

Towards this end, we sought to compare K_S among alternative biomass cropping systems across a landscape gradient. The experiment in which this research was conducted arrayed cropping systems across a toposequence to account for the potential influence of soil properties and landscape factors on hydraulic properties relative to crop or management effects. Previous research indicated that landscape position can interact with cropping and management treatments to influence hydraulic properties (Jiang et al. 2007, Elliott and Efetha 1999). We investigated the hydraulic properties of five biomass cropping systems across five landscape positions over a period of four years.

Based on the above literature review, we hypothesized the following:

- the footslope and floodplain landscape positions have higher associated K_S values than summit, shoulder, and backslope positions;
- a temporal (inter-annual) effect on saturated hydraulic conductivity and that this effect differs among cropping system treatments, with perennial systems exhibiting larger changes in hydraulic conductivity over time;
- perennial tree systems have the highest observed K_S, followed by switchgrass, and then annual cropping systems; and,
- an interaction between landscape position and cropping system treatment effects.

Materials and Methods

Site Description and Experiment Design

In fall 2008, the Landscape Biomass experiment was established at the Uthe Farm, an Iowa State University Research and Demonstration Farm located 20 km southwest of Ames, Iowa. The Uthe Farm provided the optimal landscape context and hillslope properties, which sought to understand soil-water-crop relationships over a topographic gradient. The experiment was established on an eastward facing hillslope in a randomized, replicate block design. Two treatment factors (landscape position and cropping system) were applied to a total of 75 0.2 ha plots. Prior to establishment, the land use of the majority of the site was agriculture in a maize-soybean rotation, while approximately one-half of the riparian floodplain plots were in mixed grasses. A full description of the experiment can be found in Wilson et al. (2014).

Landscape Positions

We considered five landscape positions as blocks in this experiment. Within each position, plots were randomly assigned to a cropping treatment. The point of highest elevation along the hillslope was designated the summit. The position at the lowest elevation was designated the floodplain. The shoulder, backslope, and footslope positions are intervening positions with progressively lower elevation between the summit and floodplain, their delineation was also based on slope angle. The average slope across the entire site is 6%, with an elevation difference of 20 m between the summit and floodplain. Soils vary across the site by landscape position and replicate (Ontl et al. 2013).

Cropping Systems

Five biomass cropping systems were investigated in this study. All treatments were under no-till soil management and included: (1) continuous maize, (2) a modified rotation that included soybean-triticale (*Triticosecale* x)/soybean-maize, (3) maize-switchgrass, (4) triticale/sorghum, and (5) triticale-aspen (*Populus alba* x *P. grandidentata*). Fertilization of treatments was based on soil nutrient tests. More detailed information on cropping system establishment and crop management can be found in Wilson et al. (2014). It should be clarified that in the maize-switchgrass system, maize was double cropped with switchgrass in 2009. From 2010-2013, only switchgrass was grown in those plots.

Sampling Procedure

We measured K_S of soils under alternative management regimes. K_S is a measure of the ability of a soil to transmit water and is a measure of hydraulic conductivity under saturated conditions, or when the hydraulic gradient is at unity (Raoof et al 2011). Ks is typically reported as a rate. Under steady state conditions, the infiltration rate is equivalent to K_S near the surface. Ks is further related to unsaturated hydraulic conductivity (K_H), which is a measure of hydraulic conductivity under unsaturated conditions, with a hydraulic gradient greater than one. Due to the dynamic relationship between conductivity and water content, flow under unsaturated conditions is transient, i.e., the amount of water flowing through the soil and the infiltration decrease with time. As a result, K_H depends on both the intrinsic permeability of the soil and the degree of saturation. Generally, K_H is a positive, non-linear function of K_S (Raoof et al. 2011).

Measurements were taken using a calibrated permeameter (Precision Permeameter, Johnson Permeameter LLC, Fairfax, VA, USA). The precision permeameter measures hydraulic conductivity under saturated, static-head conditions by maintaining the head of water within a borehole at a constant, pre-determined level. The saturated hydraulic conductivity is estimated by an appropriate analytical solution that incorporates the steady-state flow rate of water into the soil, height of water in the borehole, and borehole geometry, known as the Glover solution (Zangar 1953):

$$K_S = Q_S \left[\sin h^{-1} (H/r) - (r^2/H^2+1)^{.5} + r/H\right] / (2\pi H^2) \qquad \text{(Glover Solution)}$$

where Ks = saturated hydraulic conductivity, Q_S = steady-state flow rate of water into the soil, H = constant height of water in the borehole, and r = radius of the borehole.

Our sampling procedure used a pre-determined borehole dimension with a 4.5 cm radius and 19 cm depth. The constant height of water in this borehole measured 15 cm. The steady-state flow rate, Q, was determined by observing the changing volume of water in a graduated cylinder at an interval of 1 minute, until steady-state flow equilibrium was established. For each measurement, the Glover solution was applied to estimate K_S. Using this procedure, K_S is taken as the average K_S of the entire wetted region (Amoozegar 1989). Measurements of Ks were taken between May and July in each of 2009 and 2013. Three measurements were taken in each of the 75 treatment plots, for a total of 225 measurements in each year.

Data Analyses

The observed measurements were analyzed using analysis of variance. Landscape position, cropping system, and year were treated as fixed effects. Interaction effects included landscape by cropping system, year by cropping system, and year by landscape position. A random effect was included to account for repeated measures within a plot. Comparison of individual treatments was achieved using the Holm-Tukey adjustment for multiple comparisons. Additionally, due to the high variability associated with the floodplain, the data were analyzed with and without floodplain measurements. Significance of model parameters was determined at $P < 0.05$.

Results

2009

There were no significant cropping system effects observed in 2009, whether or not floodplain data were included (Table 1, Tables 4 and 5). There was a significant landscape position effect, but the interaction between landscape position and cropping system was insignificant. When the floodplain measurements were included, the triticale-aspen system was significantly affected by landscape position (Table 5). Specifically, the summit, backslope, and footslope positions had significantly lower K_S values than the floodplain position. When floodplain measurements were excluded from the analysis, these comparisons were not significant (Table 4). This comparison also revealed that the maize-switchgrass treatment had significantly higher K_S at the shoulder as compared to the backslope (Table 4, Figure 1).

2013

Both cropping system and landscape position treatment effects were significant in 2013 (Table 2). When the floodplain data were excluded, the overall interaction between landscape position and cropping system was not significant. Cropping system differences were limited to the footslope position (Table 4). Specifically, continuous maize, the modified rotation, triticale/sorghum, and triticale-aspen each had significantly higher K_S values than maize-switchgrass at this position. There were no differences among cropping systems at any other landscape position. The contrasts, which compare cropping systems treatments across all landscape positions, showed that maize, maize-switchgrass, and triticale/sorghum have significantly lower K_S than triticale-aspen (Table 4). All cropping systems except switchgrass were significantly affected by landscape position (Table 4). Continuous maize and triticale-aspen had significantly lower K_S values at the summit, shoulder, and backslope compared to the footslope. The modified rotation had a significantly lower K_S at the summit compared to the footslope. Triticale/sorghum had significantly lower K_S at the summit and shoulder compared to the footslope.

When the floodplain data were included in the analyses, the interaction between cropping system and landscape position was significant (Table 2). Contrasts showed that continuous maize, maize-switchgrass, and triticale/sorghum each had significantly lower K_S than triticale-aspen when averaged across all positions. Analysis of multiple comparisons showed that cropping system treatment effects were limited to the floodplain position. At this position, continuous maize, the modified rotation, and triticale/sorghum all had lower K_S values than triticale-aspen (Table 5). Continuous maize and the modified rotation had significantly higher K_S values than maize-switchgrass. All cropping systems except maize-switchgrass were significantly affected by landscape position. Continuous maize, triticale/sorghum, and triticale-aspen all had significantly lower K_S values at the summit, shoulder, backslope, and footslope compared to the floodplain (Table 5, Figure 1). There were no significant differences among the upper four landscape positions for any cropping system.

Change in K_S between 2009 and 2013

In the cross-year analysis, measurement year was treated as a fixed effect. When excluding floodplain measurements from the analysis, we found significant year, year by landscape position, and year by cropping system effects (Table 3). Multiple comparisons revealed that the summit, backslope, and footslope had significantly higher K_S in 2013 (Table 4, Figure 2). All cropping system treatments, except switchgrass, had higher K_S in 2013 than in 2009 (Table 4, Figure 2).

When floodplain data were included, we found significant effects for year, year by landscape position, and year by cropping system (Table 5). This indicates that K_S changed significantly over time by both landscape position and cropping system. Multiple comparisons showed that the footslope and floodplain landscape positions had significantly higher K_S in 2013 (Figure 2a). All cropping system treatments, except switchgrass, had significantly higher K_S in 2013 than in 2009 (Figure 2b).

Discussion

Saturated hydraulic conductivity primarily describes saturated water flow through macropores, as much as 64% of the variability in K_S measurements can be explained by the number of macropores (Messing 1989, Udawatta et al. 2006). Macropore formation is significantly influenced by cropping effects and tillage (Schwartz and Unger 2003, Shipitalo et al. 2000). No-till or minimum tillage systems generally exhibit greater soil infiltration rates than tilled systems (Lindstrom et al 1981, Meek et al. 1990, Logsdon et al. 1993). Tillage can form large, unstable fractures and macropores, while lowering macropore connectivity, but may initially lead to significantly higher infiltration rates. The general trend for no-till is an increase in macropore connectivity and saturated hydraulic conductivity over time (Strudley et al. 2008).

The broad, site-wide increase in K_S across four of five cropping systems and four of five landscape positions over a four year period (2009 – 2013) is consistent with the adoption of site-wide no-till management during the establishment phase of the experiment in 2008 (Strudley et al. 2008). Similarly, in a long-term (11 year) cropping system and tillage experiment, Elliott and Efetha (1999) observed significantly higher K_S in no-till plots compared to conventionally tilled plots at all landscape positions and sampling dates. In the conventionally tilled plots, the backslope and shoulder positions had lower higher K_S than other positions, suggesting that lower K_S is correlated with landscape positions that have greater slopes and erosion potential.

We observed that summit, backslope, footslope, and floodplain landscape positions had significantly higher K_S values in 2013. Higher K_S values at the footslope may be caused by SOC accumulation (Guzman and Al-Kaisi 2011). The summit and backslope are more likely to suffer erosion and losses of SOC, which can accumulate at lower elevations at the footslope and floodplain positions (Gregorich et al. 1998). We observed a broad increase in SOC across all landscape positions, but did not observe any differences in SOC accumulation among landscape positions (Ontl et al. 2013). All cropping systems, except switchgrass, had significantly higher K_S at the footslope and floodplain positions. This may be the result of greater crop productivity at these locations, resulting in greater cropping impacts on soil and hydraulic properties.

While we did not observe any other cropping system differences at specific landscape positions, we did find that the continuous maize, switchgrass, and sorghum/triticale treatments had significantly lower K_S than triticale-aspen when considered across all landscape positions. Eldridge and Freudenberger (2005) also observed significantly higher K_S under woodland trees compared to pasture or cultivated areas. This was attributed to a greater proportion of soil macropores under trees. Similarly, Bharati et al. (2003) observed greater infiltration (i.e., the amount of water infiltrated as a function of hydraulic conductivity and time) of water at silver maple sites as compared to switchgrass, maize, and soybean treatment sites. In a meta-analysis of water infiltration studies in the tropics, Ilstedt et al. (2007) concluded that afforestation of agricultural fields led to an average three-fold increase in K_S.

Our results also indicate that switchgrass had the lowest associated K_S compared to other cropping treatments. Switchgrass measurements were conducted in late May and early June. The low saturated hydraulic conductivity below switchgrass may partly be explained by the high density of living roots. Living roots may initially reduce hydraulic conductivity by compacting soil and filling macropore channels. Gish and Jury (1983) observed that infiltration was highest following crop removal, due to the presence of root channels left behind by decomposed roots. Preferential flow paths or macropores are produced upon root decay. Mitchell et al. (1995) found that it was the decaying roots of alfalfa that produced stable macropores leading to an increase in final infiltration rate. Active switchgrass rhizomes can essentially be sod forming and 68.2 –90.4% of switchgrass root weight density occurs in the upper 15 cm of planted soil (Parrish and Fike 2005, Ma et al. 2000). Although density of living switchgrass roots reaches a peak in August (Tufekcioglu et al. 1999), we noted a high density of living roots in the boreholes when conducting field measurements during the spring, when switchgrass infiltration is typically thought to be at its peak (Bharati et al. 2003). The high density of switchgrass roots may therefore have resulted in the relatively low observed K_S during this period. In contrast, Rachman et al. (2004) observed significantly greater hydraulic conductivities under stiff-stemmed grass hedge systems as compared to maize and soybean systems. However, these measurements were taken 10 years after hedge establishment.

While we observed some significant cropping system and landscape effects in this study, it is likely that more than four years may be required to observe additional treatment effects that can be linked to changes in soil physical and hydraulic properties. Schwartz and Unger (2003) suggest than conversion of cropland to perennial grasses had little impact on soil hydraulic properties over a period of 10 years. Similarly, Rachman et al. (2004) observed an increase in K_S under switchgrass hedges 10 years after establishment.

Conclusion

Our results demonstrate that alternative cropping systems have variable impacts on soil hydraulic properties across space and time. The widespread adoption of perennial biomass crops and associated land-use changes may have beneficial or adverse impacts on the environment. Our research fulfills a key knowledge gap by revealing how alternative biomass cropping systems impact saturated hydraulic conductivity across landscape positions. We also observed a broad site-wide increase in K_S, consistent with the adoption of side-wide no-till management. This knowledge can potentially inform decision-making about when and where alternative biomass crops can realistically be grown. For example, areas within a biomass landscape prone to generating excessive overland flow might best be suited for the triticale-aspen system described here due to its relatively greater associated hydraulic conductivity. Ultimately, such decisions are likely to vary as a result of numerous site and production-specific goals and factors.

We also expect that cropping system impacts and differences will become more apparent over longer timescales, as the ecological processes that contribute to changes in soil and hydraulic properties evolve over extended periods. While we observed significant changes in soil hydraulic conductivity over a very short period, some systems did not complete a harvest cycle (triticale-aspen) or reach their full production potential (switchgrass). Due to the establishment time associated with perennial systems, total impacts may not be clear for some time.

Acknowledgements

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Tables

Table 1. ANOVA model results for 2009 analysis.

Source of Variation	Num df	Den df	F	P
Landscape Position	4	195	6.08	0.0001
Cropping System	4	195	2.06	0.0873
Landscape Position * Cropping System	16	195	1.47	0.1152

Table 2. ANOVA model results for 2013.

Source of Variation	Num df	Den df	F	P
Landscape Position	4	198	31.12	< 0.0001
Cropping System	4	198	6.34	0.0002
Landscape Position * Cropping System	16	198	2.4	0.0125

Table 3. ANOVA model results for cross-year analysis.

Source of Variation	Num df	Den df	F	P
Landscape Position	4	409	31.12	< 0.0001
Cropping System	4	409	6.34	< 0.0001
Landscape Position * Cropping System	16	409	2.4	0.0019
Year	1	409	404.33	< 0.0001
Year * Landscape Position	4	409	60.61	< 0.0001
Year * Cropping System	4	409	1.44	0.0006

Table 4. Mean saturated hydraulic conductivity (Ks, cm/d) of cropping systems and landscape positions, excluding the floodplain position, in 2009 and 2013.

Landscape Position	Cropping System	2009[#]			2013[#]		
Summit	Continuous maize	48.3	A	a	51.3	A	a
	Soybean-triticale/soybean-maize	38.1	A	a	54.0	A	a
	Maize-Switchgrass	32.0	AB	a	50.1	A	a
	Sorghum/Triticale	29.5	A	a	43.0	A	a
	Triticale-Aspen	26.9	A	a	80.0	AB	a
Shoulder	Continuous maize	25.9	A	a	42.9	A	a
	Soybean-triticale/soybean-maize	33.3	A	a	68.7	AB	a
	Maize-Switchgrass	56.6	A	a	46.3	A	a
	Sorghum/Triticale	35.3	A	a	34.4	A	a
	Triticale-Aspen	42.1	A	a	66.9	AB	a
Backslope	Continuous maize	27.4	A	a	43.1	A	a
	Soybean-triticale/soybean-maize	26.3	A	a	65.9	AB	a
	Maize-Switchgrass	23.0	B	a	31.7	A	a
	Sorghum/Triticale	18.9	A	a	54.9	AB	a
	Triticale-Aspen*	15.3	A	a	81.2	AB	a
Footslope	Continuous maize*	21.7	A	a	117.0	B	a
	Soybean-triticale/soybean-maize *	23.9	A	a	121.4	B	a
	Maize-Switchgrass	30.5	AB	a	23.3	A	b
	Sorghum/Triticale*	17.5	A	a	105.0	B	a
	Triticale-Aspen*	37.8	A	a	162.2	C	a

[#] Uppercase letters indicate significant differences between landscape positions within a cropping system. Lowercase letters indicate cropping system differences within a landscape position. $P < 0.05$.

* indicates significant difference between years. $P < 0.05$.

Table 5. Mean saturated hydraulic conductivity (Ks, cm/d) of cropping systems and landscape positions including floodplain analysis in 2009 and 2013.

Landscape Position	**Cropping System**	**2009**[#]			**2013**[#]		
Summit	Continuous maize	48.3	A	a	51.3	A	a
	Soybean-triticale/soybean-maize	38.1	A	a	54.0	A	a
	Maize-Switchgrass	32.0	AB	a	50.1	A	a
	Sorghum/Triticale	29.5	A	a	43.0	A	a
	Triticale-Aspen	26.9	A	a	80.0	AB	a
Shoulder	Continuous maize	25.9	A	a	42.9	A	a
	Soybean-triticale/soybean-maize	33.3	A	a	68.7	AB	a
	Maize-Switchgrass	56.6	A	a	46.3	A	a
	Sorghum/Triticale	35.3	A	a	34.4	A	a
	Triticale-Aspen	42.1	A	a	66.9	AB	a
Backslope	Continuous maize	27.4	A	a	43.1	A	a
	Soybean-triticale/soybean-maize	26.3	A	a	65.9	AB	a
	Maize-Switchgrass	23.0	B	a	31.7	A	a
	Sorghum/Triticale	18.9	A	a	54.9	AB	a
	Triticale-Aspen*	15.3	A	a	81.2	AB	a
Footslope	Continuous maize*	21.7	A	a	117.0	B	a
	Soybean-triticale/soybean-maize *	23.9	A	a	121.4	B	a
	Maize-Switchgrass	30.5	AB	a	23.3	A	b
	Sorghum/Triticale*	17.5	A	a	105.0	B	a
	Triticale-Aspen*	37.8	A	a	162.2	C	a
Floodplain	Continuous maize*	48.3	A	a	312.9	C	a
	Soybean-triticale/soybean-maize *	41.7	A	a	400.0	C	ad
	Maize-Switchgrass	48.3	A	a	111.9	A	be
	Sorghum/Triticale*	22.7	A	a	220.9	C	ae
	Triticale-Aspen*	79.1	B	a	533.2	D	cd

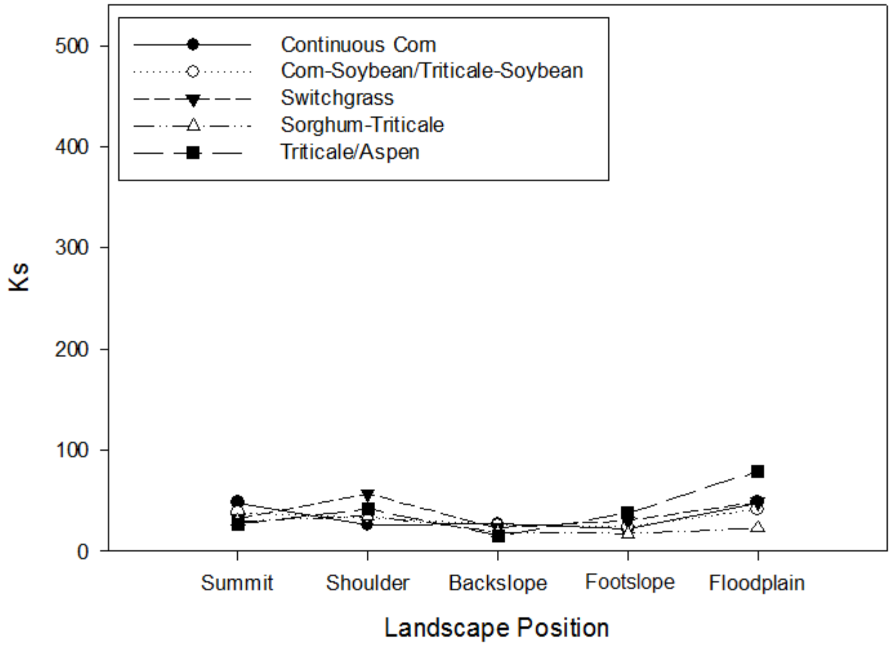
[#] Uppercase letters indicate significant differences between landscape positions within a cropping system. Lowercase letters indicate cropping system differences within a landscape position. $P < 0.05$.

* indicates significant difference between years. $P < 0.05$.

Figures

Figure 1. Saturated hydraulic conductivity (Ks) of five biomass cropping systems (continuous maize, soybean-triticale/soybean-maize, maize-switchgrass, triticale/sorghum, triticale-aspen) across five landscape positions (summit, shoulder, backslope, footslope, floodplain) in (a) 2009 and (b) 2013.

a.



b.

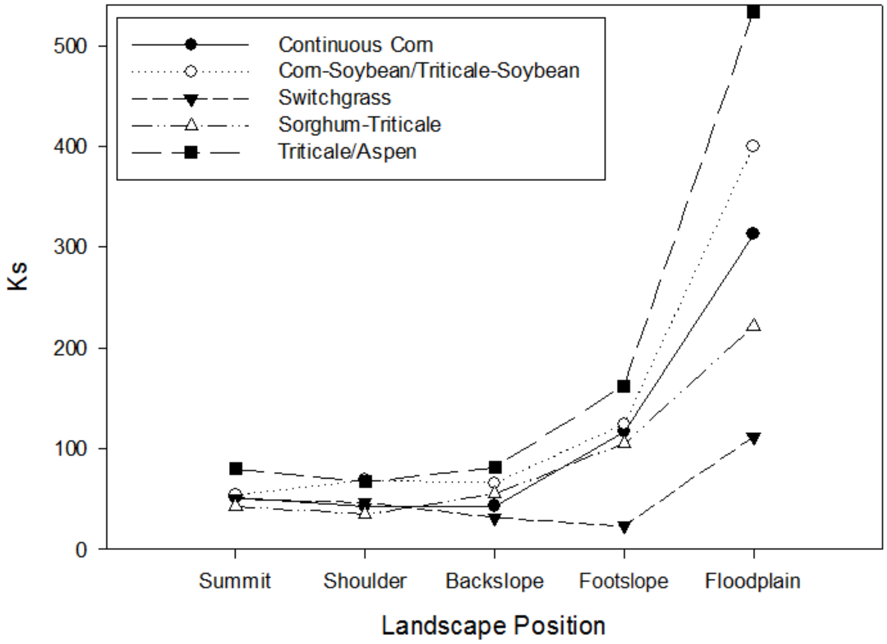
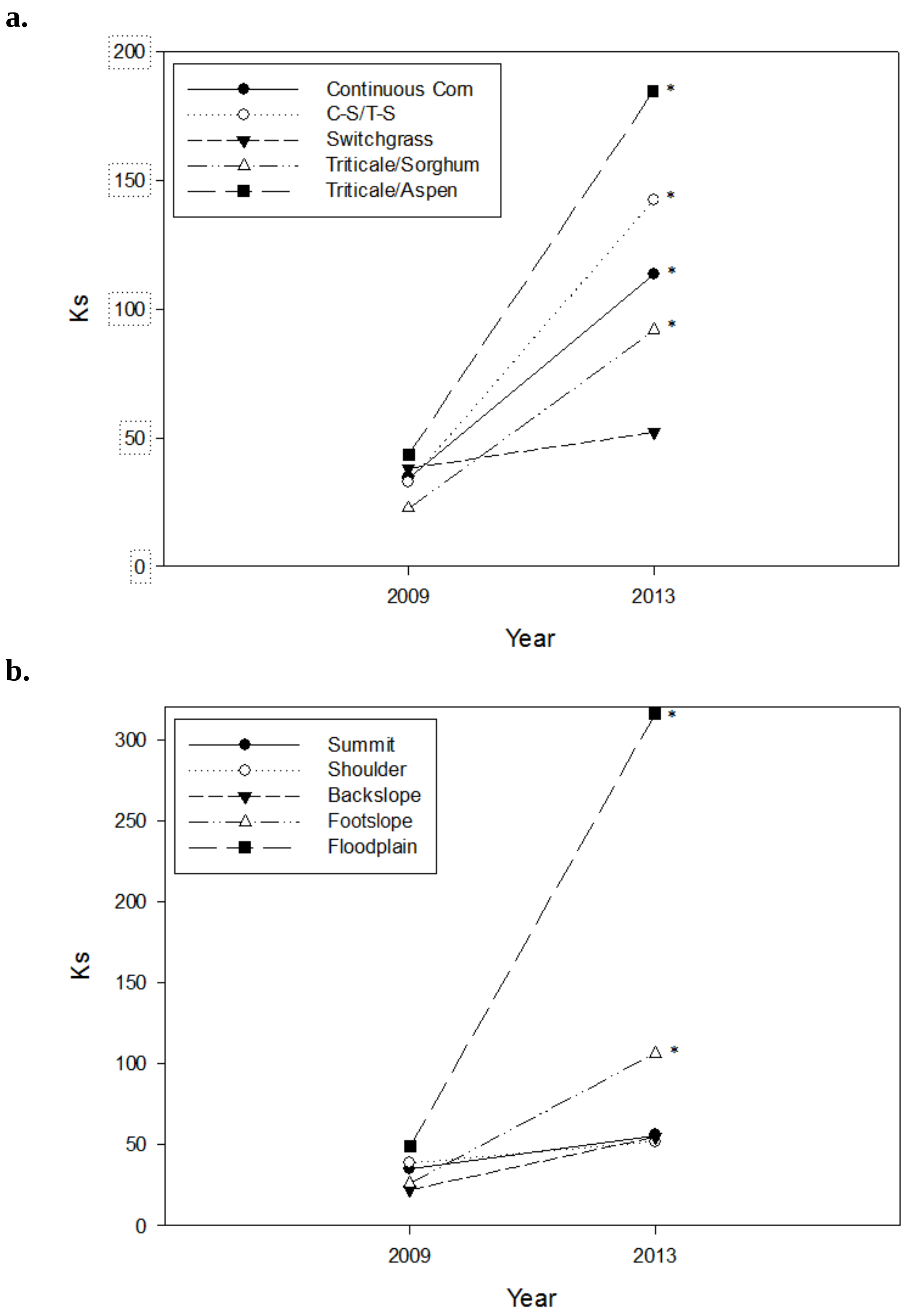


Figure 2. Change in saturated hydraulic conductivity (Ks) from 2009 to 2013 for (a) five landscape positions (summit, shoulder, backslope, footslope, floodplain) and (b) five biomass cropping systems (continuous maize, soybean-triticale/soybean-maize, maize-switchgrass, triticale/sorghum, triticale-aspen).



CHAPTER 5

GENERAL CONCLUSION

My research reveals the variable impacts of alternative biomass cropping systems on soil moisture patterns and hydraulic properties across a topographic gradient. Soil moisture patterns are a complex phenomenon influenced by cropping, landscape, and soil factors that coevolve over space and time. Variability in soil moisture patterns among cropping systems and topographic positions has significant implications in terms of predicting hydrologic consequences of widespread biomass cropping production. Soil moisture typically exhibits significant variability in spatial organization over time (Western et al. 1999), which has consequences for surface runoff (Henninger et al. 1976), vegetation growth and crop yield (Hupet and Vanclooster 2002, Meerveld and McDonnell 2006), and crop response to fertilization (Schmidt et al. 2007).

In this study, soil moisture patterns associated with alternative cropping systems were monitored across wet, average, and dry rainfall years. Results indicate significant differences in mean seasonal soil moisture content among biomass cropping systems across landscape positions, suggesting variable spatial and temporal organization of soil moisture and associated impacts under different cropping regimes. In addition, I discovered significant differences in saturated conductivity of soils associated with different cropping systems, primarily at the footslope and floodplain positions. The triticale-aspen system had the highest Ks and the switchgrass had the lowest.

These results may be used to develop more accurate hydrologic models of biomass production and cultivation. Specifically, such models may alter or calibrate parameters among land covers and topographic classes to more accurately reflect hydraulic relationships.

In some hydrologic models, saturated conductivity values can be assigned to hydrologic units. While the saturated conductivities presented in Chapter 4 are only associated with the specific soils at the experiment site used in this study, relative differences in hydraulic properties among cropping systems along a topographic gradient may be used to inform model development.

This research may have benefited from the collection of additional water balance data, such as evapotranspiration, soil water loss, runoff, or interception. Without such data, variability in soil moisture patterns cannot be directly attributable to cropping system effects. Differences among treatments may result from variability in any of these processes. Due to the scale and complexity of the experimental design, however, such comprehensive data may be quite costly or impractical to collect. Therefore, a subset of the cropping and/or position treatments could be used for additional measurements, posing a difficult tradeoff between experimental breadth and depth.

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APPENDIX A

This appendix describes additional statistical methods that may be useful in analyzing the soil moisture data. It also includes a discussion of these methods.

Two-Stage Polynomial Regression

This fits a two stage polynomial regression model to the observed moisture data. The first stage model assumes that the data for each subject or plot can be described by the general polynomial regression:

Stage 1:

$Yij = B_x(dep^2) + B_y(dep) + B_z + e$

In the second stage model, the subject-specific intercepts and parameters are related to the class of the subject (cropping system, landscape position), where C and L are indicator variables with a value of 1 or 0, describing whether or not a subject belongs to a class:

$$B_x = B_{21}C_1 + B_{22}C_2 + B_{23}C_3 + B_{24}C_4 + B_{25}C_5 + B_{26}L_1 + B_{27}L_2 + B_{28}L_3 + B_{29}L_4 + B_{30}L_5 + b_3$$

$$B_y = B_{11}C_1 + B12C2 + B_{13}C_3 + B_{14}C_4 + B_{15}C_5 + B_{16}L_1 + B_{17}L_2 + B_{18}L_3 + B_{19}L_4 + B_{20}L_5 + b_2$$

$$B_z = B_1C_1 + B_2C_2 + B_3C_3 + B_4C_4 + B_5C_5 + B_6L_1 + B_7L_2 + B_8L_3 + B_9L_4 + B_{10}L_5 + b_1$$

where b_i is a vector of subject specific effects

At first, the models are fit sequentially. First, we fit the quadratic function for each subject separately, yielding vectors of predicted estimates Bx, By, Bz. Next, stage 2 is fit to the *estimated* vectors B_x, B_y, and B_z (the vectors of predicted slopes and intercepts from stage 1), yielding estimates for treatment-specific regression parameters B_1-B_{30}.

However, the two-stage model suffers from two problems. First, information is lost in the first stage by summarizing the vector of observed measurements by regression parameters B_x, B_y, and B_z. Second, random variability is introduced by replacing Bx, By, and Bz by their predicted estimates. These problems can be addressed by combining the two stages into a single model by substitution, giving the linear mixed effects model:

$$
\begin{aligned}
Yij = \; & B_1C_1 + B_2C_2 + B_3C_3 + B_4C_4 + B_5C_5 + \\
& B_6L_1 + B_7L_2 + B_8L_3 + B_9L_4 + B_{10}L_5 + \\
& dep^2(B_{21}C_1 + B_{22}C_2 + B_{23}C_3 + B_{24}C_4 + B_{25}C_5 + \\
& B_{26}L_1 + B_{27}L_2 + B_{28}L_3 + B_{29}L_4 + B_{30}L_5) + \\
& dep\ (B_{11}C_1 + B12C2 + B_{13}C_3 + B_{14}C_4 + B_{15}C_5 + \\
& B_{16}L_1 + B_{17}L_2 + B_{18}L_3 + B_{19}L_4 + B_{20}L_5) + \\
& b_1 + b_2dep + b_3dep^2 + e_{ijk}
\end{aligned}
$$

This is the SAS code I used to run this model with the soil moisture data presented in this thesis:

```
proc mixed data = SOIL2 covtest;
class ls_pos crop_sys plotid depclss;
model moisture = ls_pos crop_sys dep ls_pos*dep crop_sys*dep dep2 ls_pos*dep2 crop_sys*dep2  /
        ddfm=kr solution;
random intercept dep dep2 / type = un subject = plotid;
repeated depclss / type=ar(1) subject=plotid r rcorr;
run;
```

Two-Stage Linear Regression

This model is similar to the two-stage polynomial regression, except in the first stage, moisture is a linear function of depth:

$Yij = B_x(dep) + B_z + e$	Stage 1

In the second stage model, the subject-specific intercepts and parameters are related to the class of the subject (cropping system, landscape position), where C and L are indicator variables with a value of 1 or 0, describing whether or not a subject belongs to a class:

$$B_X = B_{11}C_1 + B12C2 + B_{13}C_3 + B_{14}C_4 + B_{15}C_5 + B_{16}L_1 + B_{17}L_2 + B_{18}L_3 + B_{19}L_4 + B_{20}L_5 + b_2 \qquad \text{Stage 2}$$

$$B_z = B_1C_1 + B_2C_2 + B_3C_3 + B_4C_4 + B_5C_5 + B_6L_1 + B_7L_2 + B_8L_3 + B_9L_4 + B_{10}L_5 + b_1$$

w.here b_i is a vector of subject-specific effects.
This is the SAS code I used to run the model:

```
proc glimmix data = eleven noprofile;
        class crop_sys LS_Pos time Rep;
        model moisture = dep crop_sys*dep ls_Pos*dep LS_Pos crop_sys /
                ddfm=kr solution, * makes adjustments for degress of freedom ;
        random time;
        random _residual_ /
                subject = ls_pos*rep*crop_sys*time2
                type = ar(1), *use autoregressive covariance structure for repeated measurements over depth in a
                single plot in a single month;
        nloptions tech=nrridg, *this option forces glimmix to use the same optimization method as proc mixed;
run;
```

There are several questions that need to be addressed in terms of model selection:

1. If depth is a categorical variable, is it a random or fixed effect?
    a. If depth is a random effect, how do we model correlation of repeated measures?

2. If depth is a continuous variable, is it a fixed effect or a random effect?
    a. If depth is random effect, how do we model correlation of repeated measures?
3. Does depth have a linear or quadratic relationship with soil moisture? Is one model more appropriate than the other?

Question 1:

If we say depth is a fixed effect, this means it will have the same effect at all sites or landscape positions. Conceptually, this seems unlikely due to differences in soil texture and bulk density and depth to different horizon at different locations. If the effect is different at different sites, it should be considered a random effect.

Question 1a:

If depth is a random effect, then it becomes possible to specify a covariance structure – since it is likely that the random depth effect is related to nearby random depth effects. Also, it was not proper to apply a covariance structure to a fixed effect. The main question then becomes whether to treat it as a random G-side or a random R-side effect. As it turns out, it can be treated as both – an incidental consequence of our experiment design. The question then becomes – which, if either, is preferable?

Consider a situation where patients are randomly selected from a pool of patients and are sampled over time. The patients are modeled as a G-side random effect with random intercepts. Multiple measurements are taken on a single patient (subject) over time and are correlated. In this example, patient is a G-side effect, and time is an R-side effect. By this reasoning, we would expect depth measurements to be similar to time -- individual observations are correlated.

But we can specify a covariance structure for a random G-side depth effect. This would essentially say that *levels* of depth are correlated – not individual observations. Specifying a subject in this effect determines the scale at which the random depth effect is realized. If the scale and subject is a plot, then a single depth has multiple measurements which were taken at different time points. Alternatively, the subject could be an entire landscape position, in which case, there are multiple measurements arising both from the fact that measurements were taken at a single depth at different time points, and the fact that they were taken in different plots. This also means that different landscape positions will have different random depth effects, rather than each plot having its own set of random depth effects. There are also other possibilities (for example, landscape position * cropping system). Another way of saying this is that the random depth effect is specific to that landscape position.

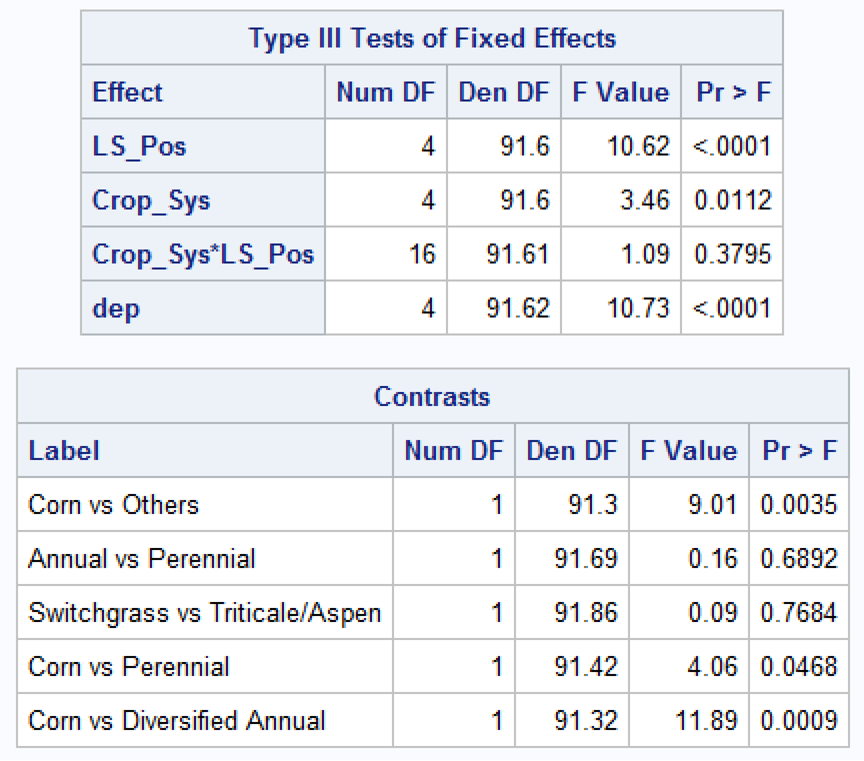
There is another way we could think of depth that would lead to it being considered an R-side random effect. We could consider multiple measurements over depth on a single plot as multiple measurements on a subject, just like when taking measurements over time. In this case, the random depth effect would be specific to a single plot *at a single point in time* (which is what makes it different from a plot level G-side effect).

Since we are including an R-side random effect to model correlation over time, and since a generalized linear mixed model cannot have more than one R-side covariance parameter, if we want to model both the correlation over time and over depth, then depth has to be a G-side random effect. This looks like:

```
random _residual_ / subject = LS_Pos*Rep*crop_sys*dep type=sp(exp)(time), *random effect for correlation over time
random dep / subject = LS_Pos*rep*crop_sys type = ar(1), *random effect for correlation over depth
```

However, consider the following set of results using the 2012 annual dataset. In the first, depth is modeled as a G-side random effect with an ar(1) covariance structure, and correlation over time is modeled as an R-side random effect, as described above.

```
random dep / subject = LS_Pos*rep*crop_sys type = ar(1);
random _residual_ / subject = LS_Pos*Rep*crop_sys*dep type=ar(1);
```



Type III Tests of Fixed Effects

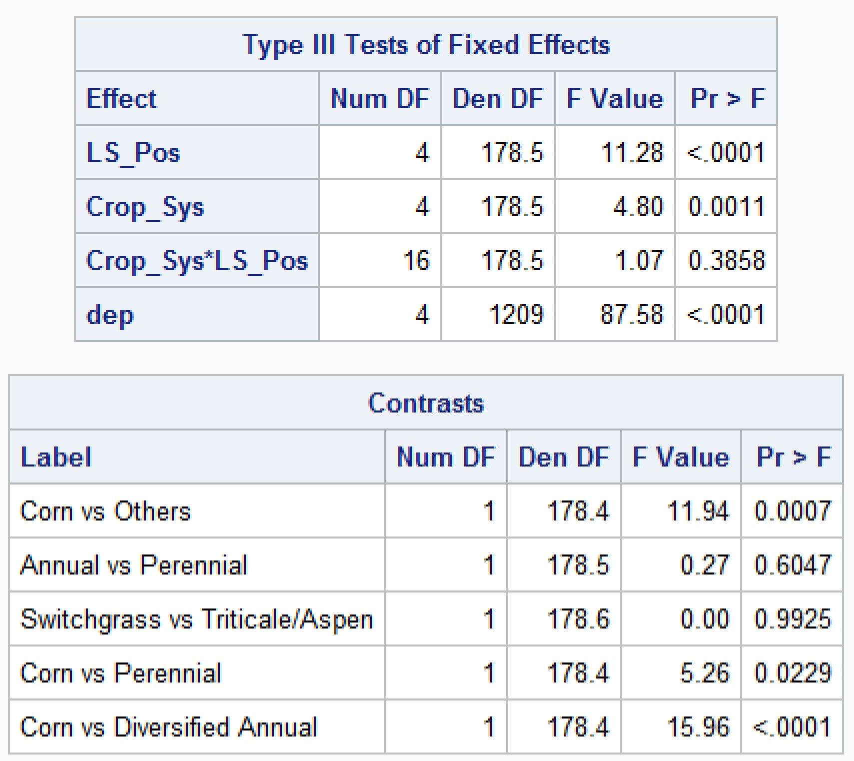
Effect	Num DF	Den DF	F Value	Pr > F
LS_Pos	4	91.6	10.62	<.0001
Crop_Sys	4	91.6	3.46	0.0112
Crop_Sys*LS_Pos	16	91.61	1.09	0.3795
dep	4	91.62	10.73	<.0001

Contrasts

Label	Num DF	Den DF	F Value	Pr > F
Corn vs Others	1	91.3	9.01	0.0035
Annual vs Perennial	1	91.69	0.16	0.6892
Switchgrass vs Triticale/Aspen	1	91.86	0.09	0.7684
Corn vs Perennial	1	91.42	4.06	0.0468
Corn vs Diversified Annual	1	91.32	11.89	0.0009

In the second, time is treated as a random blocking factor, and correlation across depth is modeled as an R-side random effect:

```
random time;
random _residual_ / subject = LS_pos*rep*crop_sys type = ar(1);
```



Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
LS_Pos	4	178.5	11.28	<.0001
Crop_Sys	4	178.5	4.80	0.0011
Crop_Sys*LS_Pos	16	178.5	1.07	0.3858
dep	4	1209	87.58	<.0001

Contrasts				
Label	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Corn vs Others	1	178.4	11.94	0.0007
Annual vs Perennial	1	178.5	0.27	0.6047
Switchgrass vs Triticale/Aspen	1	178.6	0.00	0.9925
Corn vs Perennial	1	178.4	5.26	0.0229
Corn vs Diversified Annual	1	178.4	15.96	<.0001

Both of these are models produce similar results, but the first model accounts for correlation over time as an R-side random effect, which theoretically should account for more of the variation in the model. But the results are nearly identical, indicating that the correlation effect isn't particularly significant. This is good to know, since in the combined 3-year dataset, it might not be appropriate to apply an ar(1) covariance structure for repeated measures over time since no measurements were taking between growing seasons.

As a result of these two models, we can eliminate consideration of model variations where depth is a G-side or R-side effect, because they produce similar results, as shown above. We can also avoid model variations that do or do not model correlation of time, as they produce nearly identical results, instead treating month as a random block effect.

Question 2:

The next question to answer is whether depth is better as a class variable or a continuous variable. We intuitively expect a linear relationship between soil moisture and depth, and this can be confirmed by creating a scatter plot of all the soil moisture profiles. Due to the obvious linear relationship, it would be best to consider depth as a continuous variable – there is greater statistical power (Pasta 2009, Moses 1984). A regression will always have a lower residual error than the separate means ANOVA model if there is indeed a linear relationship between the variables.

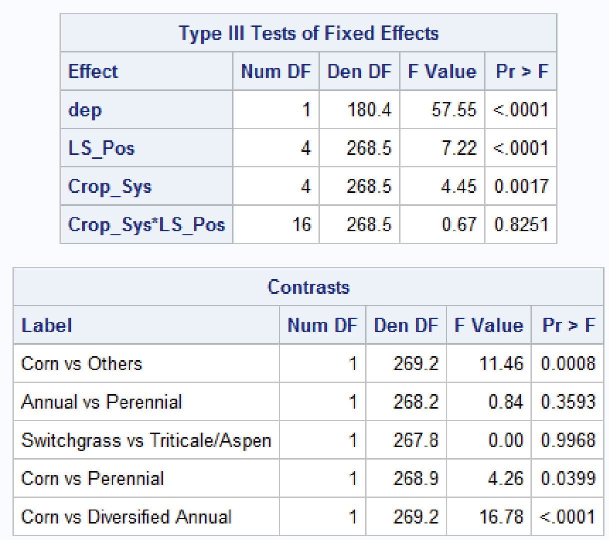
Depth can be specified as either a random and fixed effect in this model, because depth is a continuous variable. Specifying a random effect with a covariance structure would model correlated deviations from the linear trend. The fixed effect would be the linear relationship between moisture and trend, and the random effect would model how individual depths deviate from that linear relationship.

Question 2a:

Consider the following ANCOVA models to test these different assumptions:

1. Depth as random G-side depth effect**,** random effect to model autocorrelation over time

```
model moisture = dep ls_pos|crop_sys /
    ddfm=kr, * makes adjustments for degress of freedom ;
random dep / subject = LS_Pos*rep*crop_sys type = ar(1);
random month / subject = LS_pos*rep*crop_sys*dep type = ar(1) residual;
```



Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
dep	1	180.4	57.55	<.0001
LS_Pos	4	268.5	7.22	<.0001
Crop_Sys	4	268.5	4.45	0.0017
Crop_Sys*LS_Pos	16	268.5	0.67	0.8251

Contrasts

Label	Num DF	Den DF	F Value	Pr > F
Corn vs Others	1	269.2	11.46	0.0008
Annual vs Perennial	1	268.2	0.84	0.3593
Switchgrass vs Triticale/Aspen	1	267.8	0.00	0.9968
Corn vs Perennial	1	268.9	4.26	0.0399
Corn vs Diversified Annual	1	269.2	16.78	<.0001

2.

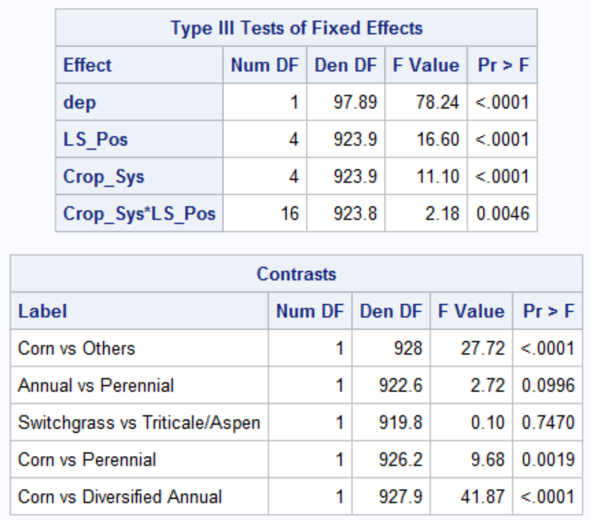
a. Depth as random G-side depth effect, time is a random block effect

model moisture = dep ls_pos|crop_sys /

*ddfm=kr, * makes adjustments for degress of freedom ;*

*random dep / subject = LS_Pos*rep*crop_sys type = ar(1);*

random month;



Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
dep	1	97.89	78.24	<.0001
LS_Pos	4	923.9	16.60	<.0001
Crop_Sys	4	923.9	11.10	<.0001
Crop_Sys*LS_Pos	16	923.8	2.18	0.0046

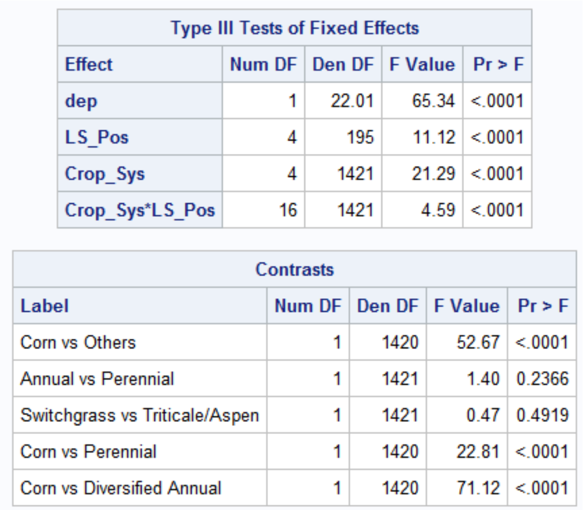
Contrasts

Label	Num DF	Den DF	F Value	Pr > F
Corn vs Others	1	928	27.72	<.0001
Annual vs Perennial	1	922.6	2.72	0.0996
Switchgrass vs Triticale/Aspen	1	919.8	0.10	0.7470
Corn vs Perennial	1	926.2	9.68	0.0019
Corn vs Diversified Annual	1	927.9	41.87	<.0001

b. Depth as random G-side effect *at the landscape position level*

*random dep / subject = LS_Pos*time type = ar(1)*

random month;

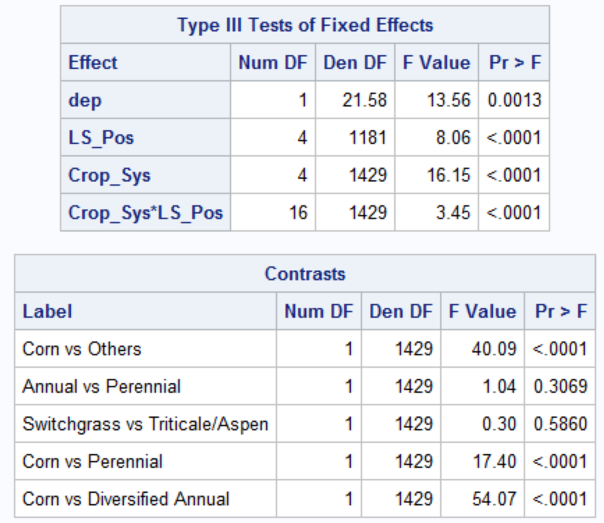


Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
dep	1	22.01	65.34	<.0001
LS_Pos	4	195	11.12	<.0001
Crop_Sys	4	1421	21.29	<.0001
Crop_Sys*LS_Pos	16	1421	4.59	<.0001

Contrasts				
Label	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Corn vs Others	1	1420	52.67	<.0001
Annual vs Perennial	1	1421	1.40	0.2366
Switchgrass vs Triticale/Aspen	1	1421	0.47	0.4919
Corn vs Perennial	1	1420	22.81	<.0001
Corn vs Diversified Annual	1	1420	71.12	<.0001

c. Same as 2 except there is an autocorrelation effect over time

```
random dep / subject = LS_Pos*rep*crop_sys type = ar(1);
random _residual_ / subject = LS_Pos*rep*crop_sys*dep type=ar(1);
```

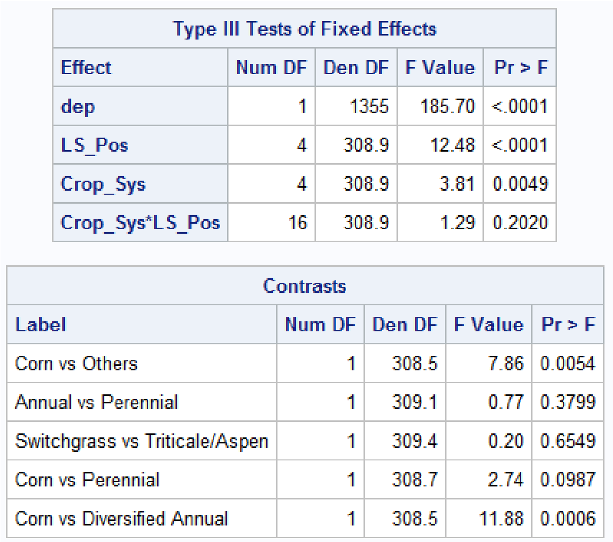


Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
dep	1	21.58	13.56	0.0013
LS_Pos	4	1181	8.06	<.0001
Crop_Sys	4	1429	16.15	<.0001
Crop_Sys*LS_Pos	16	1429	3.45	<.0001

Contrasts				
Label	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Corn vs Others	1	1429	40.09	<.0001
Annual vs Perennial	1	1429	1.04	0.3069
Switchgrass vs Triticale/Aspen	1	1429	0.30	0.5860
Corn vs Perennial	1	1429	17.40	<.0001
Corn vs Diversified Annual	1	1429	54.07	<.0001

3. Depth as a random R-side depth effect, time is a random block effect

```
model moisture = dep ls_pos|crop_sys /
                         ddfm=kr, * makes adjustments for degress of freedom ;
    random dep_factor / subject = LS_Pos*rep*crop_sys*time type = ar(1) residual;
    random time;
```



Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
dep	1	1355	185.70	<.0001
LS_Pos	4	308.9	12.48	<.0001
Crop_Sys	4	308.9	3.81	0.0049
Crop_Sys*LS_Pos	16	308.9	1.29	0.2020

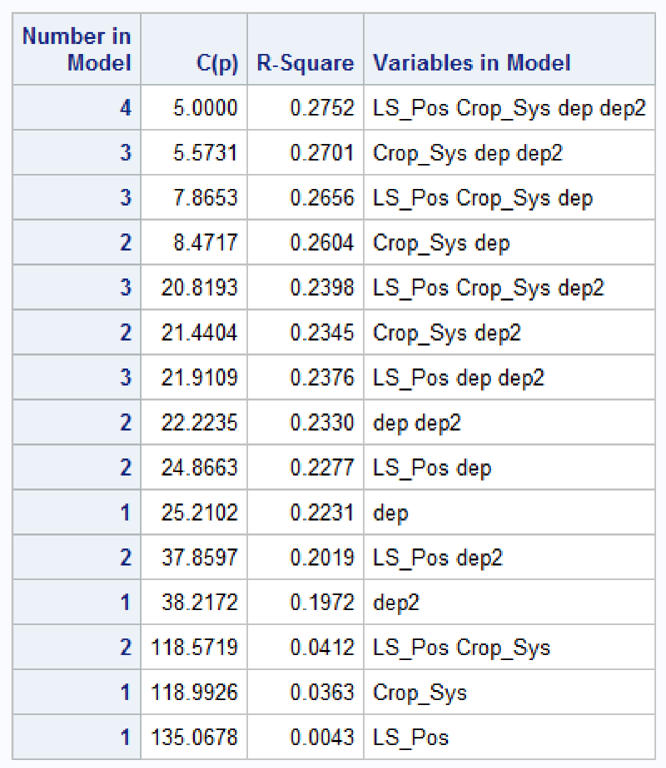
Contrasts

Label	Num DF	Den DF	F Value	Pr > F
Corn vs Others	1	308.5	7.86	0.0054
Annual vs Perennial	1	309.1	0.77	0.3799
Switchgrass vs Triticale/Aspen	1	309.4	0.20	0.6549
Corn vs Perennial	1	308.7	2.74	0.0987
Corn vs Diversified Annual	1	308.5	11.88	0.0006

Conceptually, I think it makes most sense to realize different random depth effects at different landscape positions, rather than at the plot scale. Model 2b is based on this assumption. The other models are based on random depth effects at the plot scale. Modeling correlation over time has no significant impact on the results (2a vs 2c). Month could therefore legitimately be treated as a random block effect. When depth is treated as a continuous variable, the treatment effects are highly significant. The interaction effect is also significant, where previously it was not.

Question 3:

One way to select a model is to use a model diagnostic method such as Mallow's Cp. The proc reg SAS function can be used to calculate the Cp for all possible subset models. Using this criterion, the model with the smallest Cp value is considered the best model.



Number in Model	C(p)	R-Square	Variables in Model
4	5.0000	0.2752	LS_Pos Crop_Sys dep dep2
3	5.5731	0.2701	Crop_Sys dep dep2
3	7.8653	0.2656	LS_Pos Crop_Sys dep
2	8.4717	0.2604	Crop_Sys dep
3	20.8193	0.2398	LS_Pos Crop_Sys dep2
2	21.4404	0.2345	Crop_Sys dep2
3	21.9109	0.2376	LS_Pos dep dep2
2	22.2235	0.2330	dep dep2
2	24.8663	0.2277	LS_Pos dep
1	25.2102	0.2231	dep
2	37.8597	0.2019	LS_Pos dep2
1	38.2172	0.1972	dep2
2	118.5719	0.0412	LS_Pos Crop_Sys
1	118.9926	0.0363	Crop_Sys
1	135.0678	0.0043	LS_Pos

According to this method, the best model includes all four variables. But model selection is usually inappropriate unless there is a real underlying relationship to explain the model. Bono and Alvarez (2012) suggest that soil moisture profiles are curvilinear and that statistical models should therefore account for these curvilinear tendencies. They present polynomial regression models that estimate profile water storage given surface water contents. They further show that these polynomial models are better than linear models at estimating profile storage. (Note: Bono and Alvarez are not comparing soil moisture profiles among subjects, they are only trying to estimate profile water storage.) Since moisture profiles are conceptually curvilinear as a function of depth, it makes sense to account for this. We could fit the following quadratic model, and then look for treatment effects:

$$Yij = B_1(dep^2) + B_2(dep) + B_0 + e_i$$

There are actually two ways to do this.

1. We can fit the quadratic function, and then relate the parameters (Bi) to treatment effects;
2. or, we fit the quadratic function, and then relate the treatment effects to the residual error.

The first is a two-stage approach where we look for treatment effects in terms of subject-specific profiles. The second is an ANCOVA approach where we look for treatment effects after controlling for known covariates.

If there are treatment effects in the first model, what that means is that the treatments are actually determining the shape of the subject-specific profiles (significantly different quadratic and linear slopes). In the second model, the shape of the profile is solely a function of depth and known covariates, and the treatment effects are determined after accounting for these.

In this case, one model may not necessarily be better, since they would each have different interpretations. We would be able to say that there are significant treatment effects, but in each case significant treatment effects would be interpreted differently. In the two-stage model, we would be saying something about significant differences in the parameters of a quadratic function. For example, one cropping system may have a significantly higher slope than another. This would mean that this crop tends to draw more water from the surface than the other. Similarly, if one cropping system has a significantly higher intercept than another, we would interpret that as lower interception or evapotranspiration from the surface than the other system.

The second model would allow us determine significant differences in seasonal mean soil moisture among treatments. In this case, if there were significant treatments, we would be able to say something more general about the treatment effects. For example, if one cropping system had a higher seasonal mean soil moisture than another (after controlling for other effects), we could say that generally that system has lower soil water loss than the other.

We could then look at the two-stage model for more detailed information about these differences. For example, it might be that one crop is losing significantly more water from the upper root zone than the other, and that this accounts for the overall mean difference. Or these crops may have similar slopes, but have significantly different intercepts, indicating that one system simply loses or gains more soil water than the other.

APPENDIX B

This appendix includes additional graphs and tables of the soil moisture data as well as results from analyzing the soil moisture data at a 20-40 cm depth.

Multi-year analysis

Considering only data from the 20-40 cm depth, cropping system, landscape position, and cropping system by landscape position were all significant effects. The covariates were not significant). Significant treatment effects differed by landscape position and cropping system. The backslope has the highest moisture content for all cropping systems except the modified rotation, which displays higher moisture content at the shoulder position. Higher average soil moisture content at this position suggests that it would be prone to generating greater baseflow and runoff. The summit position generally has the lowest moisture content for all cropping systems, while the floodplain has the next lowest. The increase in moisture from the summit to the backslope suggests downslope movement of water, with which we would expect higher moisture content at the floodplain position. It is possible that greater biomass yield at this position leads to greater annual ET, leading to lower than expected soil moisture, though we didn’t test biomass yield within years. Generally, the continuous corn and triticale-aspen systems have lower moisture content than the other three systems, though this effect varies by landscape position.

2010

In 2010, only the landscape position and cropping system treatment effects were significant; the interaction and clay effects were not. Considered across all landscape positions, switchgrass had significantly lower moisture content than triticale-aspen. Continuous maize and switchgrass systems had lower moisture content at the summit compared to the backslope. There were no significant cropping system differences within each landscape position.

2011

All treatments were significant at the $P <= 0.05$ level, except for clay content. Considered across all landscape positions, continuous maize had significantly higher mean seasonal moisture content than all other systems. Annual systems (continuous maize, modified rotation, and triticale/sorghum) had higher mean moisture content than the perennial systems (switchgrass, triticale-aspen). Switchgrass had significantly lower mean moisture content than triticale-aspen. Continuous maize also had higher mean moisture content than the two other annual rotations (modified rotation and triticale/sorghum).

Multiple comparisons shows that switchgrass had lower mean moisture content at the summit than the shoulder and backslope positions, which had significantly higher mean moisture content than the footslope and floodplain positions. The modified rotation system, which was in maize that year, had significantly higher moisture content at the shoulder, backslope, and footslope positions compared to the floodplain position. In the triticale-aspen system, the summit and shoulder positions had lower mean moisture content than the backslope position. The backslope and toeslope positions had significantly higher moisture content than the floodplain. Within landscape positions, the shoulder position showed the greatest number of pairwise cropping system differences; whereas the backslope and footslope showed no pairwise cropping system differences. There were two significant pairwise differences in the summit position, and four in the floodplain position.

2012

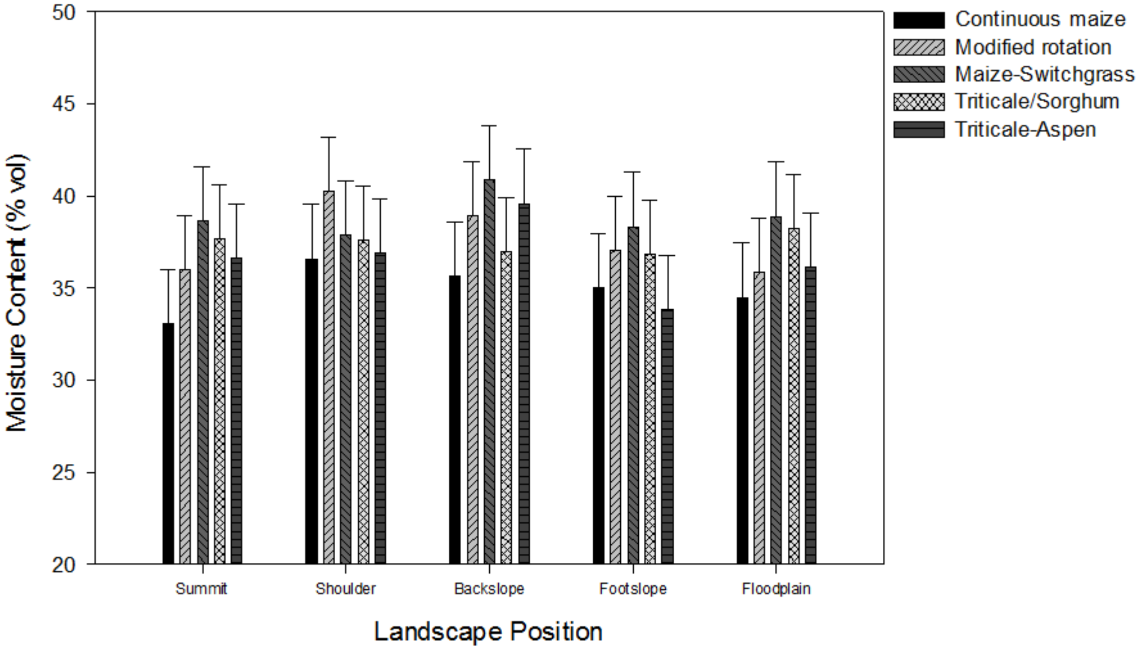
All treatment effects were significant at the $P <= 0.05$ level, except for clay content. Across all landscape positions, annual systems (continuous corn, modified rotation, triticale/sorghum) had significantly higher moisture content than the perennial systems (switchgrass, triticale-aspen). Switchgrass had significantly lower mean moisture than triticale-aspen. Continuous corn had a significantly higher moisture content than the other annual systems (modified rotation, triticale/sorghum). There was a general trend of increasing moisture content from the summit to the footslope, with a sharp decline in moisture content at the floodplain position.

Multiple comparisons showed that the shoulder, backslope, and footslope positions had higher moisture content than the floodplain position. Within the triticale-aspen system, the summit had significantly lower moisture content than the backslope, which had significantly higher moisture content than the floodplain position.

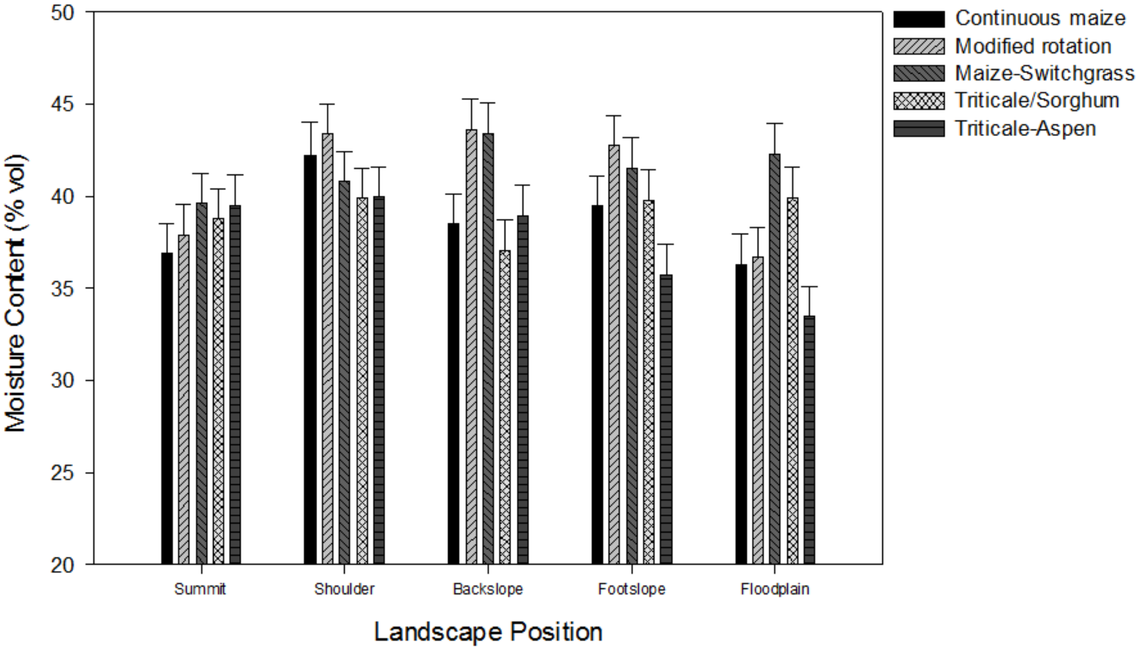
Within the summit position, the modified rotation (soybean in 2012) and triticale/sorghum had significantly higher moisture content than the triticale-aspen system. At the floodplain position, the modified rotation (soybean) and switchgrass had significantly higher moisture content than triticale-aspen.

Figure 1. Mean soil moisture (% vol.) at 20-40 cm depth of cropping systems at five landscape positions in (a) 2010, (b) 2011, and (c) 2012.

a.



b.



c.

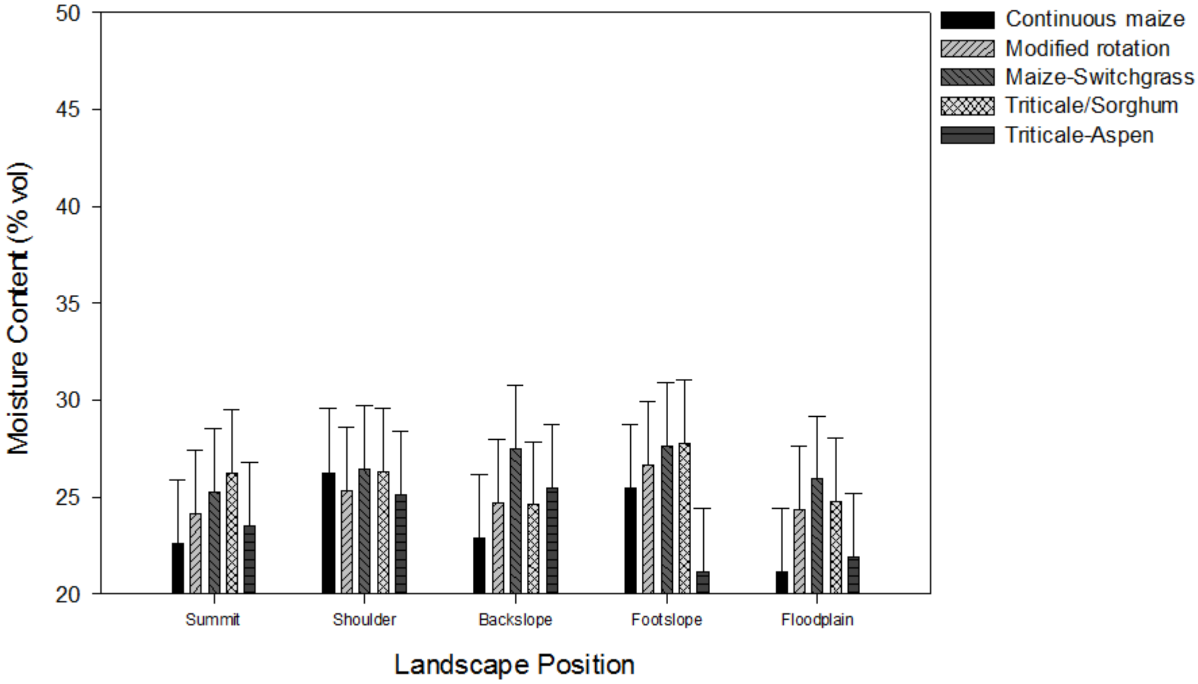
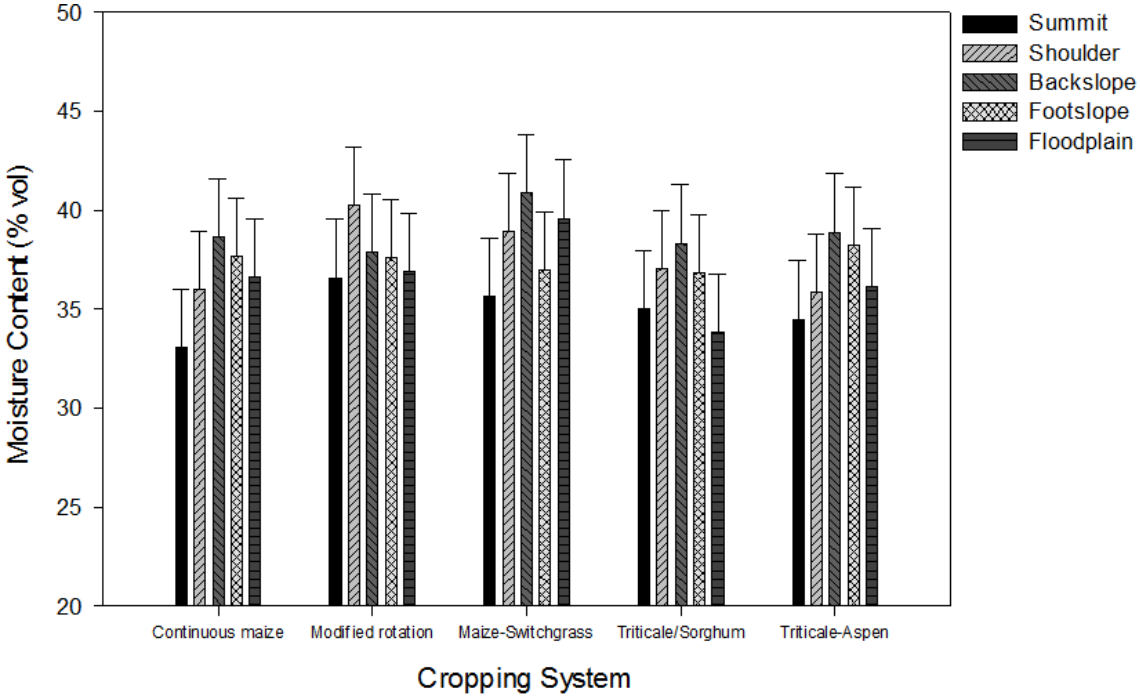
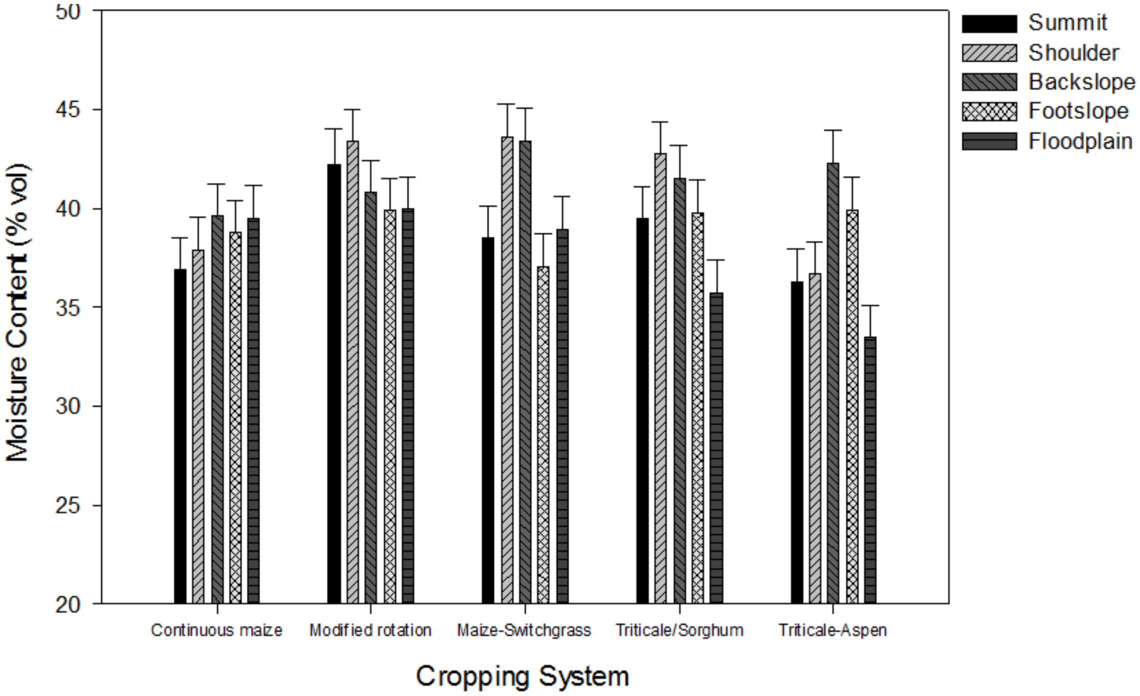

Moisture Content (% vol)
50
45
40
35
30
25
20
Summit
Shoulder
Backslope
Footslope
Floodplain
Landscape Position
Continuous maize
Modified rotation
Maize-Switchgrass
Triticale/Sorghum
Triticale-Aspen

Figure 2. Mean soil moisture (% vol.) at a 20-40 cm depth of cropping systems at five landscape positions in (a) 2010, (b) 2011, and (c) 2012.

a.



b.



c.

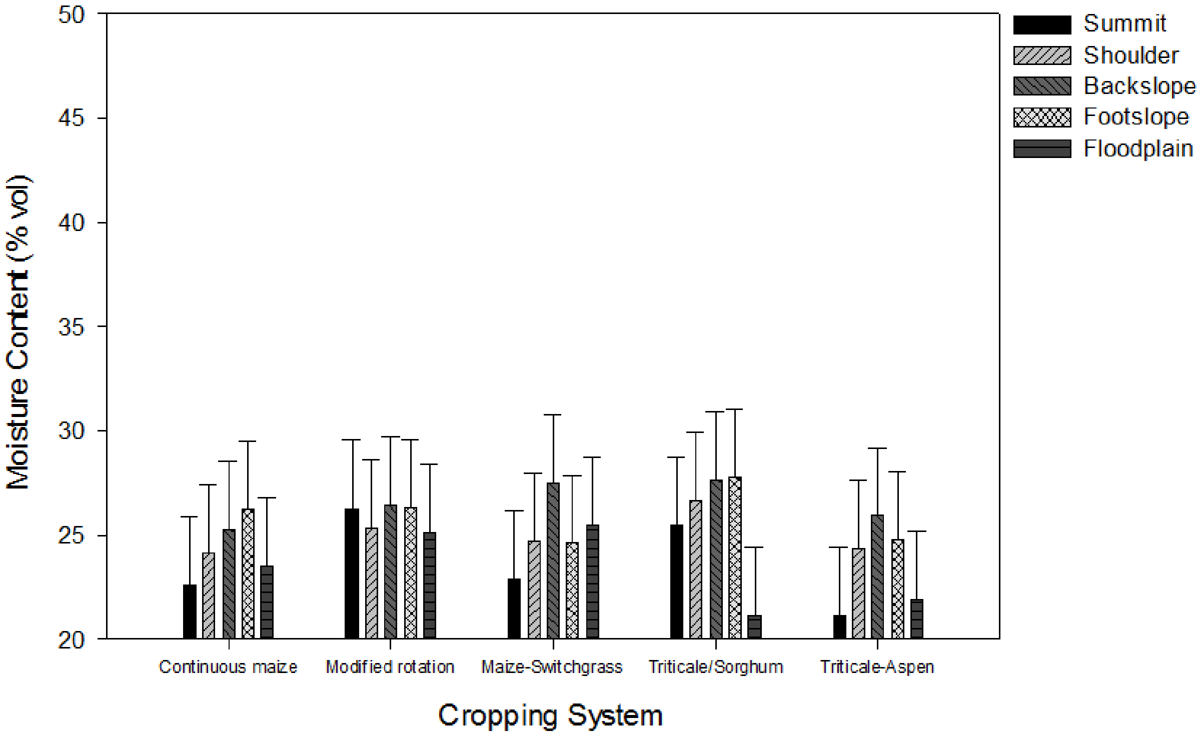

Moisture Content (% vol)
50
45
40
35
30
25
20
Continuous maize
Modified rotation
Maize-Switchgrass
Triticale/Sorghum
Triticale-Aspen
Cropping System
Summit
Shoulder
Backslope
Footslope
Floodplain

Table 1. ANCOVA results by year for soil moisture at 20-40 cm depth. P <= 0.05 is considered significant.

Year	Source of Variation	Num df	Den df	F	P
2010	Landscape Position	4	267	7.61	< 0.0001
	Cropping System	4	267	3.24	0.0134
	Landscape Position * Cropping System	16	267	1.2	0.275
	Clay	1	267	0.08	0.7791
2011	Landscape Position	4	267	13.74	< 0.0001
	Cropping System	4	267	9.88	< 0.0001
	Landscape Position * Cropping System	16	267	4.63	< 0.0001
	Clay	1	267	0.74	0.391
2012	Landscape Position	4	267	10.18	< 0.0001
	Cropping System	4	267	4.77	0.001
	Landscape Position * Cropping System	16	267	1.94	0.0172
	Clay	1	267	3.14	0.0774

Table 2. Cropping system and landscape position means by year at a depth of 20-40 cm. Letters indicate significant differences among cropping systems within landscape positions at the P <= 0.05 level.

Year	**Landscape Position**	**Continuous maize**	**Modified rotation**	**Maize-switchgrass**	**Triticale/Sorghum**	**Triticale-Aspen**
2010	Summit	33.0 ± 2.94 b	36.5 ± 2.98 a	35.6 ± 2.99 ab	35.0 ± 2.94 ab	34.4 ± 2.94 ab
	Shoulder	35.9 ± 2.93 bc	40.2 ± 2.93 a	38.9 ± 2.95 ab	37.0 ± 2.93 abc	35.8 ± 2.95 c
	Backslope	38.6 ± 2.93 a	37.8 ± 2.93 a	40.8 ± 2.93 a	38.3 ± 2.94 a	38.8 ± 2.93 a
	Footslope	37.6 ± 2.93 a	37.6 ± 2.93 a	37.0 ± 2.93 a	36.8 ± 2.93 a	38.2 ± 2.94 a
	Floodplain	36.5 ± 2.95 ab	36.8 ± 2.93 ab	39.5 ± 2.94 a	33.8 ± 2.94 b	36.1 ± 2.94 b
2011	Summit	36.8 ± 1.64 bc	42.2 ± 1.77 a	38.4 ± 1.66 bc	39.4 ± 1.64 ab	36.2 ± 1.65 c
	Shoulder	37.8 ± 1.63 b	43.3 ± 1.63 a	43.5 ± 1.66 a	42.7 ± 1.64 a	36.6 ± 1.64 b
	Backslope	39.6 ± 1.63 b	40.8 ± 1.63 a	43.4 ± 1.63 ab	41.5 ± 1.65 ab	42.2 ± 1.63 ab
	Footslope	38.7 ± 1.64 ab	39.8 ± 1.65 a	37.0 ± 1.63 b	39.7 ± 1.63 ab	39.9 ± 1.65 a
	Floodplain	39.4 ± 1.66 a	39.9 ± 1.63 a	38.9 ± 1.65 a	35.7 ± 1.64 b	33.4 ± 1.64 b
2012	Summit	22.6 ± 3.26 c	26.2 ± 3.33 a	22.8 ± 3.27 bc	25.4 ± 3.27 ab	21.1 ± 3.27 c
	Shoulder	24.1 ± 3.26 a	25.3 ± 3.26 a	24.7 ± 3.27 a	26.6 ± 3.26 a	24.3 ± 3.26 a
	Backslope	25.2 ± 3.26 a	26.4 ± 3.26 a	27.4 ± 3.26 a	27.6 ± 3.27 a	25.9 ± 3.26 a
	Footslope	26.2 ± 3.26 ab	26.3 ± 3.26 ab	24.5 ± 3.26 b	27.7 ± 3.26 a	24.7 ± 3.27 b
	Floodplain	23.5 ± 3.27 ab	25.1 ± 3.26 a	25.4 ± 3.27 a	21.1 ± 3.27 b	21.9 ± 3.27 b

Table 3. Cropping system and landscape position means by year at a depth of 20-40 cm. Letters indicate significant differences among landscape positions within cropping systems at the P <= 0.05 level.

Year	**Cropping System**	**Summit**	**Shoulder**	**Backslope**	**Footslope**	**Floodplain**
2010	Continuous maize	33.0 ± 2.94 b	35.9 ± 2.93 ab	38.6 ± 2.93 a	37.6 ± 2.93 a	36.5 ± 2.95 a
	Modified rotation	36.5 ± 2.98 b	40.2 ± 2.93 a	37.8 ± 2.93 ab	37.6 ± 2.93 ab	36.8 ± 2.93 b
	Maize-switchgrass	35.6 ± 2.99 c	38.9 ± 2.95 ab	40.8 ± 2.93 a	37.0 ± 2.93 bc	39.5 ± 2.94 ab
	Triticale/Sorghum	35.0 ± 2.94 b	37.0 ± 2.93 ab	38.3 ± 2.94 a	36.8 ± 2.93 ab	33.8 ± 2.94 b
	Triticale-Aspen	34.4 ± 2.94 c	35.8 ± 2.95 bc	38.8 ± 2.93 a	38.2 ± 2.94 ab	36.1 ± 2.94 abc
2011	Continuous maize	36.8 ± 1.64 b	37.8 ± 1.63 ab	39.6 ± 1.63 a	38.7 ± 1.64 ab	39.4 ± 1.66 ab
	Modified rotation	42.2 ± 1.77 ab	43.3 ± 1.63 ab	40.8 ± 1.63 ab	39.8 ± 1.65 b	39.9 ± 1.63 b
	Maize-switchgrass	38.4 ± 1.66 b	43.5 ± 1.66 a	43.4 ± 1.63 a	37.0 ± 1.63 b	38.9 ± 1.65 b
	Triticale/Sorghum	39.4 ± 1.64 b	42.7 ± 1.64 a	41.5 ± 1.65 ab	39.7 ± 1.63 b	35.7 ± 1.64 c
	Triticale-Aspen	36.2 ± 1.65 b	36.6 ± 1.64 b	42.2 ± 1.63 a	39.9 ± 1.65 a	33.4 ± 1.64 c
2012	Continuous maize	22.6 ± 3.26 b	24.1 ± 3.26 ab	25.2 ± 3.26 ab	26.2 ± 3.26 a	23.5 ± 3.27 b
	Modified rotation	26.2 ± 3.33 a	25.3 ± 3.26 a	26.4 ± 3.26 a	26.3 ± 3.26 a	25.1 ± 3.26 a
	Maize-switchgrass	22.8 ± 3.27 b	24.7 ± 3.27 b	27.4 ± 3.26 a	24.5 ± 3.26 b	25.4 ± 3.27 ab
	Triticale/Sorghum	25.4 ± 3.27 a	26.6 ± 3.26 a	27.6 ± 3.27 a	27.7 ± 3.26 a	21.1 ± 3.27 b
	Triticale-Aspen	21.1 ± 3.27 c	24.3 ± 3.26 ab	25.9 ± 3.26 a	24.7 ± 3.27 a	21.9 ± 3.27 bc

Table 4. Landscape position and cropping system means for multi-year analysis at the 20-40 cm depth. Letters indicate significant differences among cropping systems within landscape positions at the P <= 0.05 level.

Landscape Position	**Continuous maize**	**Modified rotation**	**Maize-switchgrass**	**Triticale/Sorghum**	**Triticale-Aspen**
Summit	31.0 ± 2.05 dc	35.3 ± 2.05 a	32.5 ± 2.05 bc	33.5 ± 2.05 ab	30.7 ± 2.06 d
Shoulder	32.7 ± 2.08 b	36.7 ± 2.05 a	37.4 ± 2.05 a	35.9 ± 2.05 a	32.1 ± 2.05 b
Backslope	34.5 ± 2.06 b	35.1 ± 2.06 b	37.4 ± 2.05 a	35.9 ± 2.05 ab	35.9 ± 2.06 ab
Footslope	34.1 ± 2.05 ab	34.6 ± 2.05 a	32.7 ± 2.06 b	34.7 ± 2.05 a	34.4 ± 2.05 ab
Floodplain	33.4 ± 2.06 a	34.1 ± 2.05 a	34.5 ± 2.05 a	30.3 ± 2.06 b	30.1 ± 2.06 b

Table 5. Landscape position and cropping system means multi-year analysis at the 20-40 cm depth. Letters indicate significant differences among cropping systems within landscape positions at the P <= 0.05 level.

Landscape Position	**Summit**	**Shoulder**	**Backslope**	**Footslope**	**Floodplain**
Continuous maize	31.0 ± 2.05 c	32.7 ± 2.08 bc	34.5 ± 2.06 a	34.1 ± 2.05 ab	33.4 ± 2.06 ab
Modified rotation	35.3 ± 2.05 ab	36.7 ± 2.05 a	35.1 ± 2.06 ab	34.6 ± 2.05 b	34.1 ± 2.05 b
Maize-switchgrass	32.5 ± 2.05 a	36.3 ± 2.05 a	37.4 ± 2.05 b	32.7 ± 2.06 c	34.5 ± 2.05 c
Triticale/Sorghum	33.5 ± 2.05 b	35.9 ± 2.05 a	35.9 ± 2.05 a	34.7 ± 2.05 ab	30.3 ± 2.06 c
Triticale-Aspen	30.7 ± 2.06 bc	32.1 ± 2.05 b	35.9 ± 2.06 a	34.4 ± 2.05 a	30.1 ± 2.06 c