ABSTRACT

STEPHENSON, THOMAS DALTON. Water Use and Soil Physical Property Changes Following Land Conversion to Bioenergy Cropping Systems in the North Carolina Piedmont. (Under the Direction of Dr. Joshua L. Heitman).

An increased demand for non-fossil fuels has led to a significant interest in sustainable bioenergy though the production of lignocellulosic bioenergy crops. While these crops have shown potential in other regions of the USA, their productivity and sustainability for the marginal soils of the Southeastern Piedmont are unknown. The overall goal of this research is to inform prospective growers on the potential water consumption and long-term soil impacts of bioenergy crop production in the Southeastern Piedmont. We evaluated potential bioenergy crops including perennial rhizomatous grasses switchgrass (*Panicum virgatum L.*) and giant miscanthus (*Miscanthus* × *giganteus*) and annual biomass sorghum (*Sorghum bicolor spp.*). Our specific objectives were to 1) evaluate the water use of bioenergy cropping systems by developing crop coefficients to predict water use from reference evapotranspiration; and 2) evaluate changes in soil physical properties following six years after land conversion from fescue hay (*Festuca arundiainacea Schreb.*) to bioenergy cropping systems. Research was conducted on a Mecklenburg clay loam in the piedmont of NC. Cropping systems at this site included switchgrass, giant miscanthus, biomass sorghum, corn silage (*Zea mays*) (traditional crop), and fescue hay (previous management). The perennial systems were established in 2012 while annuals were planted each spring using no-till practices. Crop water use was evaluated for the 2016 and 2017 growing season using a water balance approach. Crop coefficients were developed from water balance data, and then used to predict season long water use from weather data. Giant miscanthus had the highest two-year average biomass yield (29.1 Mg ha^{-1}) followed by corn silage (23.6 Mg ha^{-1}) and biomass sorghum (21.8 Mg ha^{-1}). Fescue hay had the highest season-long water use in both years of the study. Perennial grasses giant miscanthus and switchgrass had similar seasonal water use, but giant miscanthus had a higher water use efficiency than switchgrass. The annual crops corn and sorghum both used less total water than the perennial systems because of their shorter growing season, and both also had higher water use efficiencies. Soil aggregate stability was evaluated following the 2016 and 2017 growing seasons using wet sieving and dispersion techniques. Soil bulk density, saturated hydraulic conductivity, and water retention was measured using intact soil cores collected following harvest in 2017. Six years after land conversion, switchgrass was the only cropping system with surface layer physical properties that differed from fescue hay, which likely occurred because of management practices during re-establishment. In the subsurface layer, miscanthus, sorghum, and switchgrass had fewer stable aggregates than fescue. Miscanthus had a higher volume of micropores than fescue, which likely resulted in greater water retention and a lower saturated hydraulic conductivity. Overall, production of bioenergy cropping systems in the NC piedmont appears feasible based on results from this study. All cropping systems considered consumed less water while producing similar to higher amounts of biomass than the previous land management (fescue hay). While perennial bioenergy cropping systems did slightly alter some soil physical properties in comparison to the previous land management, changes were modest when using no-till management practices for establishment.

Water Use and Soil Physical Property Changes Following Land Conversion to Bioenergy Cropping Systems in the North Carolina Piedmont

by
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DEDICATION

To my family.

BIOGRAPHY

Tommy was born and raised in Willow Spring, NC, where he grew up on a farm. After graduating from Fuquay-Varina High School, Tommy attended Wake Technical Community College where he received an Associate's degree in Art. Following his time at Wake Tech, he attended NCSU, earning a Bachelor's degree in Agricultural and Environmental Technology. Tommy was then offered an opportunity by Dr. Josh Heitman to pursue a Masters Degree in Soil Science at the NCSU Crop and Soil Sciences department.

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Chapter 1. General Introduction

Increasing world population and industrialization have increased demand for alternative energy sources. The most commonly used energy sources are fossil fuels which are non-renewable fuel sources. Fossil fuels have been noted to increase environmental pollution and CO_2 emissions. Emissions from fossil fuels and industrial processes have contributed 78% of the total greenhouse gas emissions increase from 1970-2011 (Pachauri and Meyers., 2014). Along with the negative environmental impacts of fossil fuels, oil reserves are being depleted at such a rate that fuel security will become an issue in the coming years (Shafiee and Topal, 2009). An alternative energy source being considered at the global scale is bioenergy. Bioenergy is defined as a renewable fuel source derived from biological sources (Capehart and Vasavada, 2017). Many government initiatives have led to increased development and understanding about environmental impacts of bioenergy production and use.

Currently there are two main sources of biofuel; first and second generation bioenergy crops. First generation bioenergy crops are made into ethanol by fermentation of sugars and starches from plant products such as grain (Solomon et al., 2007; Ho et al., 2014). These first generation crops are typically food crops such as corn, sugarcane, and wheat. While more than two-thirds of bioenergy comes from first generation bioenergy crops, the use of these crops as a fuel source also creates competition between the fuel and food industries (Gasparatos et al., 2013; Ho et al., 2014). Increased biofuel production from these sources may impact food prices and security if alternative sources of bioenergy are not implemented. Another potentially negative impact of bioenergy production from first-generation crops is soil erosion as a result of management practices such as native vegetation removal and fallow periods which can leave the soil bare and vulnerable to erosion (Gasparatos et al., 2013).

Biofuel is derived from second generation bioenergy crops through the cellulosic biomass from woody parts of trees, plants, grasses, and residues and where sugar from these materials are fermented into ethanol (Solomon et al., 2007). Second generation bioenergy crops consist of grasses such as switchgrass and miscanthus as well as short rotation woody crops such as poplars and willows (Solomon et al., 2007; Ho et al., 2014). Cellulosic biomass is currently the most promising form of sustainable ethanol production because it is produced from non-food crops that have shown potential to be grown on poor and degraded soils while providing a high energy yield (Ho et al., 2014). These crops have also shown benefits to improving soil structure though carbon sequestration and soil stabilization, thus helping to reduce erosion and improve water quality relative to cultivated farmland (Lewandowski et al., 2003; Blanco-Canqui, 2010; Ho et al., 2014). Development of sustainable bioenergy cropping systems must take into consideration the systems' effects on both the environmental and economic sectors.

North Carolina has shown an increased interest in research and development of second generation bioenergy crops through the North Carolina Bioenergy Research Initiative. Although corn is the primary source of ethanol in the US, corn is a challenging crop for some areas of NC because of its susceptibility to drought periods. In the Piedmont region of NC, marginal land, or land not currently used for row crop production, dominate the landscape. These field sites are often moderately eroded and are unirrigated due to their soil type and landscape features. These locations are typically not used for row crop production because of their degraded soil structure and lack of irrigation which first generation bioenergy crops such as corn are highly dependent upon. Instead these field sites are often used for hay production given the high volume of cattle produced in this region of the state. Second generation bioenergy crops such as perennial bioenergy grasses miscanthus and switchgrass have shown potential to be productive in other areas of the US with little inputs of water and nutrients, making these crops a low maintenance alternative for growers in these regions.

Establishment of second generation bioenergy systems on marginal landscapes has shown potential to produce high yields while improving soil structure in other regions of the US (Blanco-Canqui, 2010). In a previous study conducted by Wang et al. (2017) five cropping systems were studied in the NC Piedmont to determine nutrient removal rates and their effects on soil structure following land conversion from fescue hay production. Crops considered in this study were second generation bioenergy crops; switchgrass, giant miscanthus, biomass sorghum, and a corn/wheat/soybean rotation (a common cropping rotation for this region), and fescue hay as a control since it was the previous land management. This study concluded that production of second generation bioenergy crops on marginal lands was feasible based on their results but other factors such as crop water use should be considered. During the final year of their study, yields of switchgrass and giant miscanthus remained constant while the yield of biomass sorghum significantly decreased which was attributed to the lack of growing season rainfall observed at the site. It was proposed that evaluation of crop water use of these systems could help to determine whether these crops could have sustainable yields based on average rainfall for the region.

Also following the conclusion of the Wang et al. (2017), it was noted that the second generation perennial bioenergy crops had influenced some soil physical properties at this site during the first few years after establishment. However, more measurements, as well as a longer experimental duration, were needed to determine the crop's ultimate effect on soil structure, especially because some perennial bioenergy crops have been observed to sustain yields for up to

14 years (Cadoux et al., 2012; Alexopoulou et al., 2015) and soil structure may change gradually over time.

This thesis aims to quantify crop water use and soil physical property changes of second generation bioenergy cropping systems (miscanthus, switchgrass, sorghum) and an alternative cropping system (corn silage) in comparison to prior land management (fescue hay) 5-6 years after initial establishment on marginal farmland in the NC Piedmont. Chapter 2 reports the yields, estimated water use, and water use efficiency of the cropping systems for two growing seasons at the experimental site. Chapter 3 focuses on evaluating soil physical property changes under the different cropping systems to determine the cropping systems' effect on soil structure in comparison to fescue. Finally, chapter 4 synthesizes conclusions from these studies and suggests ideas for future work.

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CHAPTER 2. Water Use and Biomass Yield of Bioenergy Cropping Systems in the North Carolina Piedmont

2.1. Abstract

Bioenergy crops are a potential alternative to traditional row crops and pasture/hay systems in the North Carolina Piedmont, but there is limited information available about the water requirements of these crops and their water use efficiencies. The goal of this study is to evaluate the growth, water use, and yields of three potential bioenergy crops: switchgrass (*Pancicum virgatum L.*), giant miscanthus (*Miscanthus x giganeus*), and biomass sorghum (*Sorghum bicolor spp.*), and two traditional crops: corn silage (*Zea mays L.*) and fescue hay (*Lolium arundinacea* Schreb.) Specific objectives were to evaluate season-long water use of these cropping systems by developing crop coefficients to predict crop evapotranspiration from reference evapotranspiration. Specific objectives are to quantify season-long water use of these cropping systems and to develop crop coefficients to predict water use from reference evapotranspiration. The study was conducted on a Mecklenburg clay loam in the Piedmont region of North Carolina. The perennial systems were established in 2012 while annuals were planted each spring. Crop water use was evaluated for the 2016 and 2017 growing seasons using a water balance approach. Crop coefficients developed were from water balance data, and then used to predict season-long water use of these cropping systems from weather data. Giant miscanthus had the highest two-year average biomass yield (29.1 Mg ha^{-1}) followed by corn silage (23.6 Mg ha^{-1}) and biomass sorghum (21.8 Mg ha^{-1}). Fescue hay had the highest season-long water use both years of the study. Perennial grasses, giant miscanthus, and switchgrass had similar seasonal water use but giant miscanthus had higher water use efficiency than switchgrass. The annual crops corn and sorghum both used less total water than the perennial systems because

of their shorter growing season, and both had higher water use efficiencies. This information can aid growers when making management decisions about converting land into bioenergy cropping systems and managing the systems once they are in place.

2.2. Introduction

The NC Piedmont lies within the southeastern region of the United States and is comprised of diverse agricultural systems including grain and forage crop production. Government initiatives to reduce the use of fossil fuels with bioenergy have led to an increased interest to convert traditional regional cropping systems such as corn (*Zea mays*) and fescue hay (*Lolium arundinacea* Schreb.) to potential bioenergy cropping systems. Perennial rhizomatous grasses such as giant miscanthus (*Miscanthus* × *giganteus*) (hereafter referred to as miscanthus) and switchgrass (*Panicum virgatum* L.) could be excellent choices based on the high yield potential reported in other regions of the USA and the low input requirements following initial establishment (Lewandowski et al., 2003). Biomass sorghum, an annual crop, has potential to be part of a crop rotation and has shown potential to produce high yields over short growing seasons. To evaluate the potential suitability and sustainability of these cropping systems in the Piedmont region, yield potential, crop water requirements, and water use efficiencies of these systems must be considered.

Biomass yields of potential bioenergy cropping systems have been well documented for regions of the United States and Europe. Heaton et al. (2008) reported that biomass yields of miscanthus were 33-48 Mg ha^{-1} following three years of establishment in Illinois. These yields were higher than those reported by Mantineo et al. (2009), where miscanthus yielded 15.4-27.0 Mg ha^{-1} following years 2-5 of consistent management in an irrigated Mediterranean environment. In a review of US lowland and upland switchgrass yields from 17 states, Wullschleger et al. (2010) reported that across all cultivars the most commonly observed yields were 10-14 Mg ha^{-1}. For the North Carolina Mountains, yields of 18.4 and 20.9 Mg ha^{-1} were observed for miscanthus and switchgrass, respectively, following three years of establishment (Palmer et al., 2014). In the North Carolina Piedmont, Wang et al. (2017a) observed significantly higher yields for miscanthus than switchgrass for years 2-4 of management. Miscanthus also outperformed switchgrass in the North Carolina Coastal Plain during four years of consistent management (Wang et al., 2017b). While it typically requires approximately 3 years to achieve maximum yields of perennial bioenergy grasses (Heaton et al. 2008; Palmer et al. 2014; Alexopoulou et al. 2015), miscanthus and switchgrass have been observed to maintain yields for up to 14 years following establishment (Alexopoulou et al., 2015).

Annual crops such as corn and sorghum usually have higher yields than perennial grass systems during the first year of establishment since perennial systems take multiple seasons to establish their deep rooting systems. Once established, perennial systems tend to be less susceptible to water stress than annuals because of these deep rooting systems (Ferchaud et al., 2014). Recent yield reports of biomass sorghum indicate that it has potential to produce similar yields to perennial bioenergy grasses in the Midwestern region of the US. Yimam et al. (2015) reported that yields for biomass sorghum were similar to or higher than switchgrass for a three-year study in Oklahoma. Sorghum yields between 14.6 and 23.5 Mg ha^{-1} were observed by Hao et al. (2014) for an irrigated system in Texas. The same authors also noticed that yields decreased to 12.1 to 18.2 Mg ha^{-1} for dryland sorghum, signifying that sorghum yields were influenced by water availability. Biomass sorghum yields of 10.1-26.1 Mg ha^{-1} were reported by Wang et al. (2017a) for the NC Piedmont, while (Heitman et al., 2017) reported yields a yield of 15.7 ± 5.1

Mg ha^{-1} in the NC Coastal Plains, suggesting that biomass sorghum grown in North Carolina could produce high biomass yields as seen in other areas of the US.

Seasonal crop water use and total water resources available for crop growth are important considerations when establishing a crop into a new landscape or region. In the Piedmont region of NC, most field sites are unirrigated, therefore understanding how water availability affects the yields of these bioenergy systems is important when determining their potential productivity. Seasonal crop water use and effect of water availability on bioenergy crop yields have been assessed in other regions of the US. Yimam et al. (2015) reported that the yields of rainfed biomass sorghum were strongly influenced by seasonal water supply when comparing growing seasons with drought to growing seasons with adequate rainfall. These findings were consistent with Hao et al. (2014) who reported significantly higher amounts of seasonal crop evapotranspiration (ET_c) and biomass yields for a full irrigation system than in dryland conditions in Texas. Yimam et al. (2015) reported that ET_c of switchgrass was similar to biomass sorghum but the yields of switchgrass were less sensitive to water availability (although season precipitation totals <600 mm did appear to limit maximum potential yield). This was consistent with Wullschleger et al. (2010) where they found no strong correlation between yields and precipitation totals for both upland and lowland switchgrass ecotypes. In Illinois, giant miscanthus yields were reported to be more strongly influenced by water than were those of switchgrass (Heaton et al., 2004). Contrary to that study, giant miscanthus yields reported by Dohleman et al. (2012) did not decrease during two growing seasons that experienced below average rainfall. Overall, studies from the US Midwest have suggested that yields of perennial biofuel candidates are not as effected by drought as biomass sorghum, and no long term drought effect was reported between growing seasons.

Water use efficiency of a cropping system is another important consideration when determining sustainability of a cropping system for a rainfed landscape. Water use efficiency is useful for comparing between cropping systems since the comparisons are based on crop yield per unit of water consumed. Annual crops such as corn and biomass sorghum typically have more variable water use efficiencies than perennial systems because biomass yield for annuals are more dependent on available water than are those of perennials (Hao et al., 2014; Yimam et al., 2015). Water use efficiencies for biomass sorghum were 9-49 kg ha^{-1} mm^{-1} in Oklahoma (Yimam et al., 2015) and 30-47 kg ha^{-1} mm^{-1} in Texas (Hao et al., 2014). Water use efficiencies reported for biomass sorghum in these studies are similar to the water use efficiency of corn silage (29.7 kg ha^{-1} mm^{-1}) reported by Hickman et al. (2010). Similar water use efficiencies between corn silage and biomass sorghum implies that biomass sorghum will produce a similar amount of biomass to corn silage if given the same amount of available water. Water use efficiencies of perennial grass crops tend to be lower than annual row crops because the perennial crops have a longer growing season, in which higher amounts of cumulative ET_c are observed. Hickman et al. (2010) reported water use efficiencies of miscanthus and switchgrass to be 19.1 and 9.7 kg ha^{-1} mm^{-1}, respectively. Yimam et al. (2015) reported similar water use efficiencies for switchgrass of 8 to 21 kg ha^{-1} mm^{-1}. Although annual crops have a higher water use efficiency than perennials in the Midwest region, region-specific research is needed to better understand how the different climatic conditions and soil types of the southeastern region could influence water availability and water use efficiency for these cropping systems.

The performance of five cropping systems was studied in the NC Piedmont to determine their potential productivity and water use. Our objectives were to:

1) Evaluate the water use and yields of three alternative bioenergy crops (switchgrass, miscanthus, and sorghum) and two traditional crops (corn and fescue) in the Piedmont of North Carolina; and
2) Determine crop coefficients for these crops that could be used to predict evapotranspiration from reference crop evapotranspiration and thereby estimate and compare season-long water use.

2.3. Materials and Methods

2.3.1. Site Description and Establishment

The study was conducted using an existing bioenergy field experiment located at the Piedmont Research Station in Salisbury, NC (35°41'N, 80°37'W). The soil type was a Mecklenburg clay loam (fine, kaolinitic, thermic, Ultic Hapludalf). The site was previously managed for tall fescue hay production with consistent management for more than five years prior to establishment of the experiment in 2012. Five cropping systems were included: three perennials; giant miscanthus ‘Freedom’, switchgrass ‘Colony’, tall fescue hay (traditional system), and two annuals; corn ‘Pioneer 31G71’ and sorghum ‘Blade ES5200’. The crops were arranged in a randomized complete block design with four replications. Each plot was 9 m x 12 m.

The perennial systems (switchgrass, miscanthus) were established in 2012 using no till practices as described in Wang et al. (2017a). Switchgrass seeds were planted using a no-till drill at a population of 11.2 kg seed ha^{-1}. Giant miscanthus plugs were established using a no till transplanter with an in-row spacing of 80 cm and between row spacing of 100 cm. Due to intense weed pressure following initial establishment, switchgrass treatments were tilled to a depth of 30 cm and then replanted by hand with plugs at an in-row spacing of 46 cm and between row spacing of 60 cm in the summer of 2012. Following applications of pre and post-emergent herbicides in the summer of 2012, no herbicides or insecticides were applied to the miscanthus and switchgrass. The fescue hay treatment consisted of experimental units which was predominantly tall fescue with some mixed grasses that was established more than 5 years prior to 2012. This treatment was sprayed with glyphosate following the first harvest in May 2017 due to intense weed pressure and was not reseeded. The plots naturally reestablished with mixed grasses for the remainder of the growing season.

Annual cropping systems corn silage and biomass sorghum were established each spring using no till practices. Prior to the 2016 growing season the continuous corn silage treatment was a corn/wheat/soybean rotation. The corn/wheat/soybean rotation was replaced with a continuous corn silage treatment to allow for comparison of corn biomass to biomass harvest collected from other cropping systems. Corn was planted in April or May each year with a no till planter at a rate of 74,000 seed ha^{-1} and a row spacing of 80 cm. Biomass sorghum was established in June each year using the same no till planter and row spacing with a population of 247,000 seed ha^{-1}. For both continuous corn and biomass sorghum a mixture of glyphosate and S-metolachlor plus atrazine was applied as a pre-emergent herbicide at a rate of 2.32 L ha^{-1}, on the same day as planting. Post emergent herbicide glyphosate was applied to corn while S-metolachlor plus atrazine was applied to biomass sorghum, both at a rate of 2.32 L ha^{-1}, two weeks following planting. Corn and sorghum received fertilizer before and after planting each year while fescue hay only received fertilizer once a year. Switchgrass and miscanthus were only fertilized at establishment in 2012. Specific fertilizer management is listed in Table 2.1. Harvest of the miscanthus and switchgrass occurred after winter senescence where the center swath of the plot was harvested with a mechanical forage plot harvester (Wintersteiger Inc., Salt Lake City, UT, USA). Sorghum and corn were harvested by hand cutting two 1.52-m lengths of row from two random locations within the center four rows of each plot and weighing the biomass. Biomass remaining on the plots was removed with a silage cutter and disposed of offsite. The fescue hay was hand harvested twice in 2016 and three times in 2017 by harvesting all biomass from the plots and recording the mass. For each harvesting operation, subsamples were taken from each plot and were dried at 65 ^{o}C until consistent moisture content was reached to determine dry biomass yield.

2.3.2. Crop Evapotranspiration

Crop evapotranspiration (ET_c) was calculated using a bi-weekly water balance for multiple intervals during the 2016 and 2017 growing seasons to quantify and compare the rate of water use from the cropping systems. The water balance was:

$$ET_c = P - \Delta S - R - D \quad (1)$$

where P is precipitation, ΔS is change in soil profile water storage, R is runoff, and D is drainage. P was measured using an on-site tipping bucket rain gauge maintained by the North Carolina State Climate Office.

The term ΔS represents the change in water storage within the soil profile and here was considered as the change in soil water content for the top 100 cm of the soil profile between two consecutive measurements of volumetric water content. Bi-weekly measurements of volumetric soil water content were collected using a PR2/6 dielectric soil moisture probe (Dynamax Inc, Houston, TX) at depths of 10, 20, 30, 40, 60, and 100 cm via an access tube located in the center of each experimental unit. Each moisture content measurement consisted of an average of three readings within each access tube. Field calibration of the soil moisture probe took place during the 2017 growing season with an access tube located beside the research plots. Soil moisture contents were collected via the access tube and were paired with volumetric water contents calculated from known bulk densities and gravimetric water contents from soil augured near the access tube to create a simple linear calibration equation for the sensor. Since there were two PR2/6 sensors used over the duration of the trials, separate calibration curves were established for each sensor. Volumetric water contents at all depths were corrected using the calibration equations. The field calibration reduced the output root mean squared error (RMSE) of one sensor from 0.077 to 0.018 cm^3 cm^{-3}. The other sensor output was not improved by calibration and had a RMSE value of 0.077 cm^3 cm^{-3}. No improvement was observed likely due to the limited range of water contents observed during the calibration of that particular sensor.

Runoff was not directly measured in this study. Instead, criteria were established based on storm intensity to calculate ET_c from the water budget only when the rainfall intensity did not exceed 1.24 cm hr^{-1}. This value was selected because it was below the surface saturated hydraulic conductivity at the site (Wang et al., 2017a). Some investigators who have studied bioenergy crop water use via a water balance approach have neglected runoff based on the average annual runoff estimated from the Water Erosion Prediction Project (Yimam et al., 2015). In our study, weeks with rainfall intensities above this threshold was assumed to result in some surface runoff that would lead to overestimation of the actual ET_c of these systems, given the slope of the landscape (approx. 8%) and clay loam soil type. These measurement periods were therefore excluded. This was similar to the approach used by Wilson et al. (2001) and Roygard et al. (2002).

D was evaluated by calculating a drainage flux:

$$Drainage\ Flux = K(\frac{\Delta H}{\Delta Z}) \quad (2)$$

where *K* is the unsaturated hydraulic conductivity (mm day^{-1}), ΔH is the change in hydraulic head (cm), and ΔZ is the change in soil depth (cm). Average field volumetric water contents between a depth of 60 and 100 cm, tensiometers installed at 60 and 90 cm depths, and saturated hydraulic conductivity measurements for the 90-100 cm depth were used to estimate the parameters for the unsaturated hydraulic conductivity function using the van Genuchten-Mualem model (Genuchten, 1980). Unsaturated hydraulic conductivity was thereafter predicted for each measurement period using the hydraulic conductivity function established from the van Genuchten- Mualem model, and average field volumetric water contents at 50-70 and 80-100 cm. The unsaturated hydraulic conductivity was multiplied by the hydraulic gradient obtained from the tensiometers for each bi-weekly measurement period throughout each season to estimate *D* (i.e., Eq. [2]). The drainage flux was considered negligible for all measurement intervals given that drainage was less than 1% of calculated ET_c during those same measurement periods.

2.3.3. Reference ET

Daily reference crop evapotranspiration (ET_o) was calculated using the FAO-56 Penman Monteith equation (Allen et al., 1998):

$$ET_o = \left[\frac{0.408\Delta\,(R_n - G) + \gamma\,\frac{900}{T+273}\,u_2\,(e_s - e_a)}{\Delta + \gamma(1 + 0.34\,u_2)}\right] \quad (3)$$

where ET_o is the reference evapotranspiration (mm d $^{-1}$), Δ is the slope of the saturation vapor pressure curve (kPa ^{o}C^{-1}), R_n is the net radiation from the crop surface (MJ m^{-2} d^{-1}), *G* is the soil heat flux (MJ m^{-2} d^{-1}); *T* is mean daily air temperature at 2 m height (^{o}C); u_2 is wind speed at 2 m height (m s^{-1}), e_s is saturation vapor pressure of the air (kPa), e_a is the actual vapor pressure of the air (kPa), (e_s - e_a) represents the saturation vapor pressure deficit of the air (kPa), and γ is the psychrometric constant (kPa $^{o}C^{-1}$]. Parameters used to calculate ET_o were measured by a weather station located onsite (Model ET107, Campbell Scientific Inc, Logan UT).

2.3.4. Crop Coefficients

Crop coefficients (K_c) were developed for each cropping system using field measured values of ET_c and ET_o for the 2016 and 2017 growing seasons. Crop coefficients were defined according to:

$$K_c = \frac{ETc}{ETo} \tag{4}$$

and were calculated for measurement intervals available from the water balance, as described above. Since this resulted in non-continuous K_c data, measurement period K_c values were averaged for each growing season.

2.3.5. Total Predicted ET_c and Water Use Efficiency

Once K_c values were determined, $ET_{c,p}$ (where subscript *p* indicates predicted) was estimated using daily estimated ET_o and K_c values for the appropriate crop. Daily estimated values of $ET_{c,p}$ were calculated as:

$$ET_{c,p} = K_c \times ET_o \tag{5}$$

The summation of daily estimated values of $ET_{c,p}$ was considered the total estimated $ET_{c,p}$ for the growing season.

The estimated water use efficiency was calculated for the observed growing season of each crop. For the perennial systems the growing season was considered April - October each year, similar to that used in Dohleman et al. (2012). While fescue hay can actively grow year-round in this region, this observed growing season allows for comparison of the perennials while they were all actively growing. The growing season for the annual systems was the day of planting until the day of harvest each year. Water use efficiency (WUE) was calculated as (Yimam et al., 2015)

$$WUE = \frac{Biomass\ yield}{Cumulative\ ETc,p} \qquad (6)$$

where Biomass yield reflects above-ground dry biomass harvested (kg ha^{-1}) per cumulative $ET_{c,p}$ (mm).

2.3.6 Statistical Analysis

Since data from both growing seasons were collected from the same experimental unit, year was treated as a repeated measure. Crop species and year were considered to be fixed effects while replications were considered random effects. Biomass yields and maximum rate of ET_c were analyzed using the Glimmix procedure in SAS ver. 9.3 (SAS institute Cary, NC) to determine main effects and interactions between crop and years. Means for crop yields and maximum rate of ET_c were compared by Tukey's honest significant difference test (HSD). Significance was determined at the 5% probability level. For both yields and maximum rates of ET_c the crop × year interaction was not significant ($p < 0.05$) so crop yields and ET_c were averaged for the two growing seasons. Average ET_c rates and K_c values were not compared statistically because of the imbalanced observations between the annual and perennial cropping systems due to the difference in growing season length. Estimated cumulative $ET_{c,p}$ and water use efficiency were also not compared statistically because these values were calculated from crop coefficients that were not replicated by block, but rather an average of the cropping system.

2.4. Results and Discussion

2.4.1. Growing Conditions

Onsite precipitation and ET_o are presented in Table 2.2. Across both years ET_o was similar with a narrow range of 1169 and 1187 mm. While precipitation varied considerably between 2017 (1257 mm) and 2016 (890 mm), both years were above the 30 year normal average for the site of 839 mm yr^{-1}. The 2016 growing season (April to October) had a precipitation deficit (i.e., total precipitation – total ET_o) of 334 mm, while in 2017 there was a surplus of 20 mm

2.4.2. Biomass Yields

Biomass yields are presented in Table 2.3. Since the crop species × year interaction was not significant ($p < 0.05$), the two-year average biomass yield was reported for each cropping system. Miscanthus yielded significantly more biomass than the other cropping systems with an average yield of 29.1 Mg ha^{-1}. Yields for these two growing seasons were greater than previous years at the site; Wang et al. (2017a) reported yields of 16.5-21.2 Mg ha^{-1} in years 2 through 4 after establishment. Taken together these results suggest that yields had not yet reached their plateau in the first four years after establishment. This differs from the reports of Heaton et al. (2008), Palmer et al., (2014), and Alexopoulou et al. (2015) where maximum yields of miscanthus were achieved within three years following establishment. Miscanthus at this site may have been delayed in reaching ceiling yields due to a drought period during the 2015 growing season which resulted in similar yields as the previous season (Wang et al., 2017a). Miscanthus yields was similar to those observed in Italy by Angelini et al. (2009) but higher than those reported in the mountains of NC where it was stated that water availability was most likely limiting maximum growth of these crops at this site (Palmer et al., 2014). However yields observed at our site were less than yields reported by Heaton et al. (2008), where peak yields of miscanthus reached 33-48 Mg ha^{-1}.

The other perennial bioenergy grass, switchgrass, yielded similar to the fescue hay treatment, but significantly less than the corn and sorghum annual cropping systems, with an average yield of 14.2 Mg ha^{-1}. Switchgrass yields were similar to previous yields reported at the site and to yields of lowland type switchgrass in other areas of the US (Wullschleger et al., 2010; Wang et al., 2017a). Unlike miscanthus, switchgrass at the site yielded less than that observed in the NC mountains potentially due to differences in plant variety where 'Alamo' was established at that site (Palmer et al., 2014). It is noteworthy that these perennial crops (miscanthus and switchgrass) have maintained or improved their yield in years 5-6 following establishment without any agronomic inputs (Table 2.1) since establishment. Results from the North Carolina Soil Testing lab for samples collected in December 2017 (data not shown), did indicate that the phosphorus levels of miscanthus were low. Average phosphorus levels for this cropping system were 30.5 kg ha^{-1} which is below the critical level of 60 kg ha^{-1} recommended by Hardy et al. (2014). Even though phosphorus was below the critical value, yields were likely not limited given that Haines et al. (2015) reported that miscanthus had little yield response to phosphorus fertilization in the Mountains and Piedmont of NC, with phosphorus values below the critical value.

Biomass sorghum had an average yield of 22 Mg ha^{-1} for the two growing seasons. Biomass yields for sorghum were within the range previously reported at this site and other locations in the US (Hao et al., 2014; Yimam et al., 2015; Wang et al., 2017a). The other annual system, corn silage had an average biomass yield of 23.5 Mg ha^{-1} which was similar to sorghum. While there is no previous corn biomass yield data for this site, Wagger and Cassel (1993) reported similar corn silage yields under limited irrigation and dryland management at this same research station in 1989. Corn biomass yields at the site are within the range reported by Karlen et al. (1994) for the Southern USA. These data indicate that biomass sorghum yields similarly to corn silage over multiple growing seasons with comparable annual fertilizer inputs, which could be useful when considering the potential of this system for regional production.

2.4.3. Crop Evapotranspiration

The rate of ET_c is an important consideration when assessing water requirements of a crop, especially when considering crops for potentially water-limited rainfed systems. Crops that have a high rate of ET_c will deplete soil water storage at a faster rate than a crop with a low rate of ET_c, thereby increasing the potential for the crop to become drought stressed.

Daily ET_c rates were estimated throughout the growing season using a bi-weekly soil water balance approach. Since runoff was not measured, only observational periods of net soil dry down were used to calculate ET_c. This resulted in non-continuous measurement of ET_c within the growing season. Nevertheless daily ET_c rates for observational periods of soil dry down were compared during the growing seasons to assess the range and maximum rates of ET_c for each cropping system. All cropping systems exhibited a typical pattern of ET_c, with the rate of ET_c increasing as crop growth increased and the maximum ET_c rates observed during peak growth (Figs. 2.1.-2.5). ET_c rates decreased during late season growth as the crops began to senesce. For all cropping systems the maximum rate of ET_c was significantly higher than the rate observed during early and late season growth ($p < 0.05$).

Daily ET_c rates of corn ranged from 2.1 to 9.5 and 3.0 to 11.0 mm day^{-1} during the 2016 and 2017 growing seasons, respectively (Fig. 2.1). ET_c rates of corn at this site are similar to the rates observed in Texas (Howell et al., 1998; Piccinni et al., 2009). Daily ET_c rates of sorghum ranged from 3.0 to 10.3 mm day^{-1} in 2016 and 3.8 to 11.1 mm day^{-1} in 2017 (Fig. 2.2). These rates are similar to the rates observed for corn silage at this site implying that the two cropping systems have similar water use. The maximum rate of ET_c observed at this site for sorghum (11.1

mm day^{-1}) was higher than the maximum weekly average rate of 6.7 mm day^{-1} reported in Oklahoma (Wagle et al., 2016). Since biomass sorghum is a relatively new crop, there are fewer reports of observed ET_c rates. Differences in observed ET_c between this site and Oklahoma could be a result of regional differences or methodology, as they collected data using an eddy covariance system. Growing season ET_c rates of miscanthus ranged from 1.8 to 6.3 mm day^{-1} in 2016 and 1.9 to 8.8 mm day^{-1} in 2017 (Fig. 2.3). ET_c rates observed at this site were within the range reported for a study in Italy (Triana et al., 2015). Switchgrass had a similar range of daily ET_c rates to miscanthus. Switchgrass ET_c rates observed at the site were 0.8-8.2 and 2.3-9.2 for the 2016 and 2017 growing seasons, respectively (Fig. 2.4). Reports of ET_c rates of switchgrass are limited much like biomass sorghum. The maximum rate of ET_c for switchgrass of 9.2 mm day^{-1} is higher than that reported by Wagle et al. (2016). As above, the higher maximum rate of ET_c observed at this site could again be a result of differences in measurement approach. Daily ET_c rates of fescue hay were 2.0-7.1 and 2.2-7.9 mm day^{-1} for the 2016 and 2017 growing seasons, respectively (Fig. 2.5). The maximum ET_c rate of fescue hay is higher than ET_c rates of tall fescue turf reported in Carrow (1995). The maximum ET_c rate at this site is likely greater than reported for turf grass, because fescue grown for hay has a greater leaf area index, resulting in greater transpiration. Reports of daily water use for fescue managed as hay were not readily available in the literature.

Average ET_c rates were not statistically evaluated for a cropping system effect because crops had different growing season lengths, resulting in varying numbers of ET_c observations per crop. The maximum rate of ET_c each year was averaged for the two seasons and compared amongst the cropping systems (Fig. 2.6). Sorghum and corn had a higher maximum rate of ET_c than miscanthus and fescue hay at this site. This result indicates that the different growth habits (i.e. perennial vs. annual) of these crops could influence the rate at which they use water during peak midseason growth. Annual crops which have a shorter growing season than the perennials, used a higher rate of water than miscanthus and fescue hay during mid-season growth likely due to rapid biomass accumulation. Differing rates of ET_c indicate that these crops are depleting soil water storage at different rates during their maximum growth stage which could potentially have a greater influence on crop yields during times of insufficient rainfall events.

2.4.4. Crop Coefficients

Crop coefficients were developed to predict daily ET_c from weather parameters (ET_o) over the growing season. These estimates were used to calculate seasonal water use and water use efficiencies of the systems. K_c values were calculated for each crop using measured values of ET_c and ET_o. In some cases, crops are assigned multiple K_c values that change over the growing season since K_c values follow the same pattern as ET_c. K_c values are assigned to growth stages that represent a period where ET_c rates are similar. For these crops we attempted to assign K_c values to growth stages based on canopy light interception. Justification of using this method required that ET_c values would be significantly different before and after canopy closure for these systems. However, after statistical analysis, there were no significant differences in the K_c values for before and after canopy closure, therefore values were averaged to report a single season-long K_c value. This was a similar approach to that used by Beale et al. (1999) where a single crop coefficient was used to describe the seasonal water dynamics of giant miscanthus. K_c values reported in Table 2.3 are an average of the 2016 and 2017 growing seasons. Incorporating ET_c data for both growing seasons into one average K_c value allowed for a greater distribution of observations to represent the whole growing season. The average K_c values were not analyzed statistically between cropping systems given the varying number of ET_c observations for each crop.

Crop coefficients at this site were generally similar to those reported in other regions (Table 2.3). The K_c value of 1.27 for sorghum was similar to values reported in a Mediterranean environment (Garofalo et al., 2011). The K_c value for sorghum was higher than an irrigated study in Spain likely because of differences in experimental approach (López-Urrea et al., 2016). The corn K_c value of 1.12 was within the range of values suggested by Allen et al. (1998) and Piccinni et al. (2009). Sufficient precipitation at this site could have resulted in K_c values similar to irrigated corn systems. In a rainfed study that experienced below average rainfall in the Virginia coastal plain, midseason corn K_c values of 0.65-0.91 were reported (Roygard et al.,2002), which are considerably lower than the season long K_c value observed at our site with sufficient rainfall. K_c values for rainfed systems are typically lower than irrigated systems due to drought stress during the growing season, which can decrease the rate of ET_c. Fescue hay had a season long K_c value of 1.13. The K_c value for fescue hay at this site was within the range of values reported for a tall fescue turf study (Carrow, 1995). Miscanthus and switchgrass had season long K_c values of 0.97 and 0.93, respectively. Miscanthus K_c values for this site are within range of some studies conducted in Europe (Beale et al., 1999; Triana et al., 2015). We are currently unaware of any published reports of switchgrass K_c values. Overall, crops at this field site have comparable K_c values to other areas where these crops have been studied.

2.4.5. Estimated Crop Evapotranspiration

Estimation of $ET_{c,p}$ allows for comparison of the cropping systems based on the total amount of water used during the observed growing season. To compare cumulative $\mathrm{ET}_{c,p}$ of the cropping systems, given that field observations of ET_c were non-continuous, cumulative $\mathrm{ET}_{c,p}$

was calculated by estimating daily $ET_{c,p}$ from daily values of ET_o and K_c for each cropping systems over the two growing seasons. It is acknowledged that since K_c values of these cropping systems are season long averages, daily $ET_{c,p}$ during early and late season growth are likely to be overestimated, while midseason daily $ET_{c,p}$ is likely to be underestimated. Cumulative $ET_{c,p}$ is reported as an average of both growing seasons (Table 2.3).

Cumulative $ET_{c,p}$ was calculated for an observational period when the crops were actively growing. Since the perennial cropping systems had a longer observed growing season (April-October), cumulative $ET_{c,p}$ for these systems was higher than the annual cropping systems as seen in Figs. 2.7 – 2.8. Differences between the cumulative $ET_{c,p}$ of the perennial crops are a result of differences in K_c values since the observed growing seasons were the same length.

Fescue hay had an average cumulative $ET_{c,p}$ of 1044 mm which was the highest of all perennial cropping systems. The average cumulative $ET_{c,p}$ for switchgrass was 856 mm which was similar of that observed in miscanthus. $ET_{c,p}$ for switchgrass was higher than reported in Oklahoma and Illinois (Hickman et al., 2010; Yimam et al., 2015). Cumulative $ET_{c,p}$ at this site was higher than in Illinois because of the longer observed growing season which resulted in a higher cumulative value of $ET_{c,p}$. The cumulative $ET_{c,p}$ for miscanthus of 889 mm was comparable to observations reported by studies in Italy and Illinois (Hickman et al., 2010; Triana et al., 2015). Both annual systems corn, and sorghum, had less cumulative $ET_{c,p}$ than the perennial systems because of their shorter observed growing seasons. This occurrence was also noted in Illinois where Hickman et al. (2010) stated that the large disparity in water use between maize and perennial species (switchgrass and miscanthus) was attributed to the length of the growing season. The cumulative $ET_{c,p}$ for biomass sorghum of 596 mm for our site was comparable to the range observed in Oklahoma and Italy (Garofalo et al., 2011; Yimam et al., 2015). Cumulative $ET_{c,p}$ of corn for our site was 691 mm which was less than that observed for corn harvested for grain in Texas (Howell et al., 1998). The lower value of cumulative $ET_{c,p}$ for our site was likely a result of the shorter growing season of corn silage. Cumulative $ET_{c,p}$ for corn was higher than reported by Roygard et al. (2002). Corn at our site likely had higher cumulative $ET_{c,p}$ due to the greater precipitation received at our field site. Cumulative $ET_{c,p}$ calculated for these cropping systems are comparable to many of the values observed in other areas where these crops are studied implying that the values estimated using this method are reasonable.

2.4.6. System Water Use Efficiency

To evaluate these crops based on their water use and yield potentials, water use efficiencies were compared between the cropping systems. Water use efficiencies were calculated using annual biomass yields of the cropping systems and the annual cumulative $ET_{c,p}$, and then averaged for the two growing seasons (Table 2.3). The annual cropping systems corn, and sorghum, had water use efficiencies of 36.6 and 35.7 kg ha^{-1} mm^{-1}, respectively. The water use efficiency of sorghum was comparable to other areas in the US. Biomass sorghum was within the range of water use efficiencies reported by Yimam et al. (2015) and Hao et al. (2014). The water use efficiency of corn silage for out site was higher than Hickman et al. (2010) who reported total maize biomass (corn silage) water use efficiency of 29.7 ± 1.1 kg ha^{-1} mm^{-1}. Interestingly, Hickman et al. (2010) found that the water use efficiency of corn decreased by one third when the crop was only harvested for grain because of the decrease in total yield. Annual systems at our site maintained a high water use efficiency over both growing seasons because of sufficient rainfall, where yields were not limited. Decreases in yields for biomass sorghum caused by limited precipitation have been reported in previous years at our field site (Wang et al., 2017a). These decreases in yields can lead to decreased water use efficiencies of biomass sorghum (Yimam et al., 2015).

The miscanthus cropping system had a water use efficiency of 33.0 kg ha^{-1} mm^{-1}. Water use efficiency of miscanthus was higher than switchgrass and fescue hay because of its significantly higher yields. The water use efficiency of miscanthus at our site was higher than reported in Illinois because of the higher yields observed during our study (Hickman et al., 2010). Switchgrass yields were significantly lower than miscanthus even with similar amounts of cumulative $ET_{c,p}$ which resulted in water use efficiency for switchgrass of 16.6 kg ha^{-1} mm^{-1}. Switchgrass has been reported in Illinois to have lower water use efficiency in comparison to miscanthus. Hickman et al. (2010) noted that the water use efficiency of switchgrass was 9.4 kg ha^{-1} mm^{-1}, which was lower than miscanthus, indicating that switchgrass was not as productive as miscanthus with similar amounts of available water. Switchgrass water use efficiency for our site was comparable to the 8-21 kg ha^{-1} mm^{-1} observed in Oklahoma (Yimam et al., 2015). Fescue hay had the lowest water use efficiency of the perennial systems, as a result of low yields and high cumulative $ET_{c,\,p}$ observed during the growing seasons. Typically plants that use the C3 photosynthetic pathway such as fescue are less water efficient than plants that use the C4 pathway such as the perennial and annual bioenergy grasses, because of their lower relative total resistance to water vapor resulting in slightly higher transpiration rates and lower assimilation rates (Hsiao and Acevedo, 1974). The ability of miscanthus to produce significantly higher amounts of biomass with similar inputs of water in comparison to the other perennial systems demonstrates that miscanthus was the most water efficient of the perennial systems at this site.

2.5. Conclusions

The amount of biomass yield produced per unit water is an important consideration in determining the sustainability of a cropping system for rainfed systems. While both switchgrass and miscanthus used similar amounts of water over the growing season, miscanthus produced a significantly higher yield, signifying that it has higher water use efficiency for the NC Piedmont region. Both annual systems, corn silage and biomass sorghum, were similar in regards to yields, K_c values, cumulative $ET_{c,p}$ and water use efficiency demonstrating that biomass sorghum has similar water requirements to corn silage, a commonly grown crop in this region. All cropping systems required less water during their individual growing seasons while producing similar or higher biomass yields than the fescue hay system, indicating that land conversion from fescue hay to bioenergy cropping systems would allow for greater biomass return on the amount of available water during a growing season. While understanding the water dynamics of these cropping systems is an important consideration before widespread establishment of bioenergy cropping systems for this region, other economic and environmental factors should be considered when determining the suitability of these systems.

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Table 2.1 Crop establishment, fertility, and harvest dates of bioenergy cropping systems in Salisbury NC

Crop	Planting Date	Fertilization	Harvest Date
Switchgrass	June 2012	112 kg ha^{-1} N as 34-0-0 [†]	December each year
Miscanthus	June 2012	112 kg ha^{-1} N as 34-0-0 [†]	December each year
Fescue hay	Pre-2012	34 kg ha^{-1} N, 30kg ha^{-1} P and 56 kg ha^{-1} K as 10-20-20[‡] 112 kg ha^{-1} N sidedressed as 30% UAN 30 kg ha^{-1} N 34 kg ha^{-1} P as 18-46-0[‡]	2-3 times per year
Corn	April 6, 2012 May 8, 2017	34 kg ha^{-1} N 30 kg ha^{-1} P 56 kg ha^{-1} K as 10-20-20[§] 112 kg ha^{-1} N sidedressed as 30% UAN 30 kg ha^{-1} N 34 kg ha^{-1} P as 18-46-0[‡]	Sept. 8, 2016 Aug. 9, 2017
Sorghum	June 3,2016 June 12, 2017	34 kg ha^{-1} N 30 kg ha^{-1} P 56 kg ha^{-1} K as 10-20-20[§] 112 kg ha^{-1} N sidedressed as 30% UAN[‡] 76 kg ha^{-1} N broadcast as 34-0-0[§]	Sept 8, 2016 Sept 7, 2017

† Only at establishment in 2012
‡ Only 2016 season
§ Only 2017 season

Table 2.2 Precipitation and reference evapotranspiration (ET_o) in 2016 and 2017 at the experimental site in Salisbury, North Carolina

Month	2016		2017	
	ET_o	Precipitation	ET_o	Precipitation
	mm			
January	36	63	40	135
February	51	87	67	16
March	97	30	92	74
April	124	44	115	174
May	133	148	138	191
June	125	85	158	184
July	180	96	179	115
August	145	81	134	65
September	115	76	112	130
October	80	98	85	87
November	49	16	37	30
December	34	66	30	56
Total	1169	890	1187	1257

Table 2.3 Two-year average biomass yield, crop coefficients (K_c), estimated cumulative cropping system evapotranspiration ($ET_{c,p}$) and cropping system water use efficiency for experimental site in Salisbury NC.

Crop	Biomass Yields†	K_c	Cumulative $ET_{c,p}$	Water Use Efficiency
	——— Mg ha^{-1} ———		——— mm yr^{-1} ———	—— kg mm^{-1} ha^{-1} ——
Switchgrass	14.2C†	0.93	852	16.6
Miscanthus	29.1A	0.97	884	33.0
Fescue Hay	12.6C	1.13	1044	12.0
Corn Silage	23.6B	1.12	691	36.0
Sorghum	22.0B	1.27	596	36.8

† Letters indicate significant differences at the 0.05 probability level between cropping systems within columns.

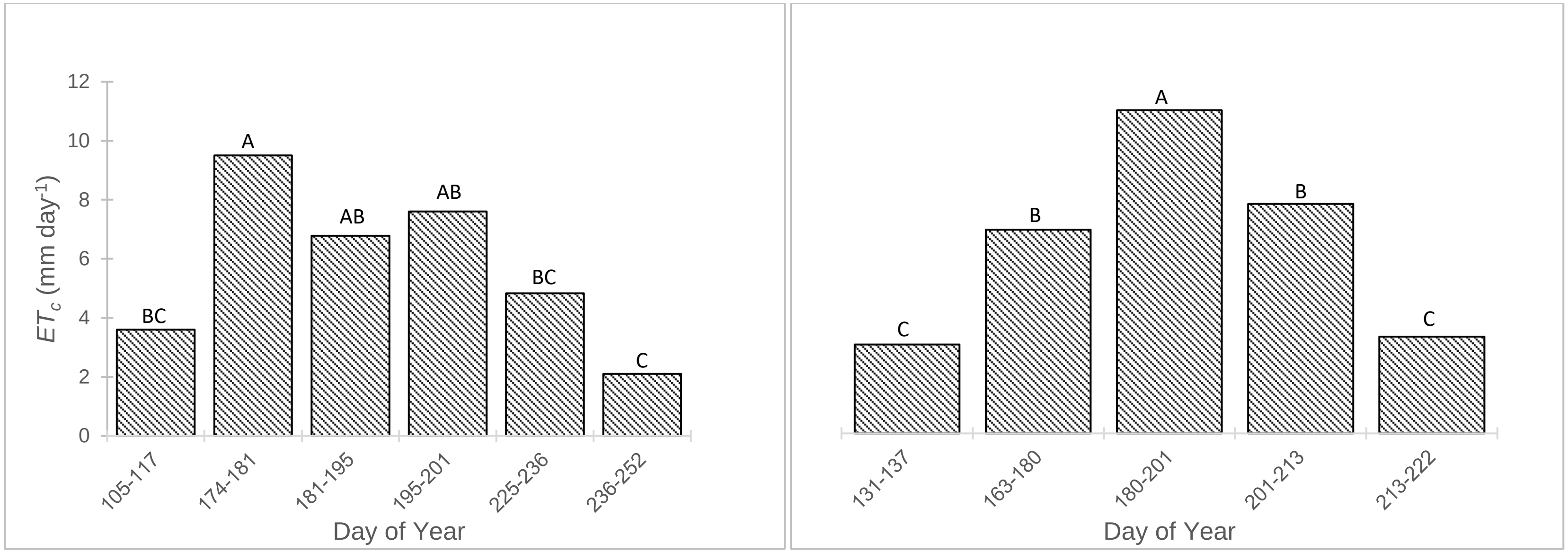

Figure 2.1 Observed corn evapotranspiration (ET_c) rate for the 2016 (Left) and 2017 (Right) growing seasons for the experimental site in Salisbury NC. Letters indicate significant differences at the 0.05 probability level within year.

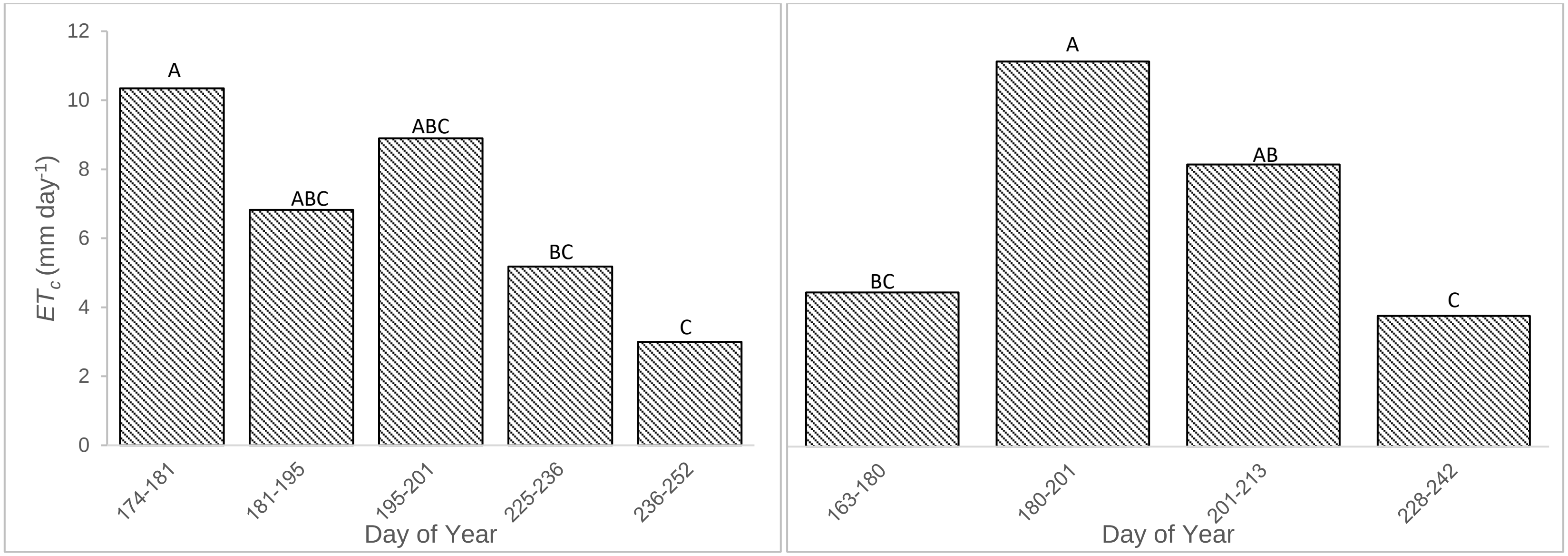

Figure 2.2 Observed sorghum evapotranspiration (ET_c) rate for the 2016 (Left) and 2017 (Right) growing seasons for the experimental site in Salisbury NC. Letters indicate significant differences at the 0.05 probability level within year.

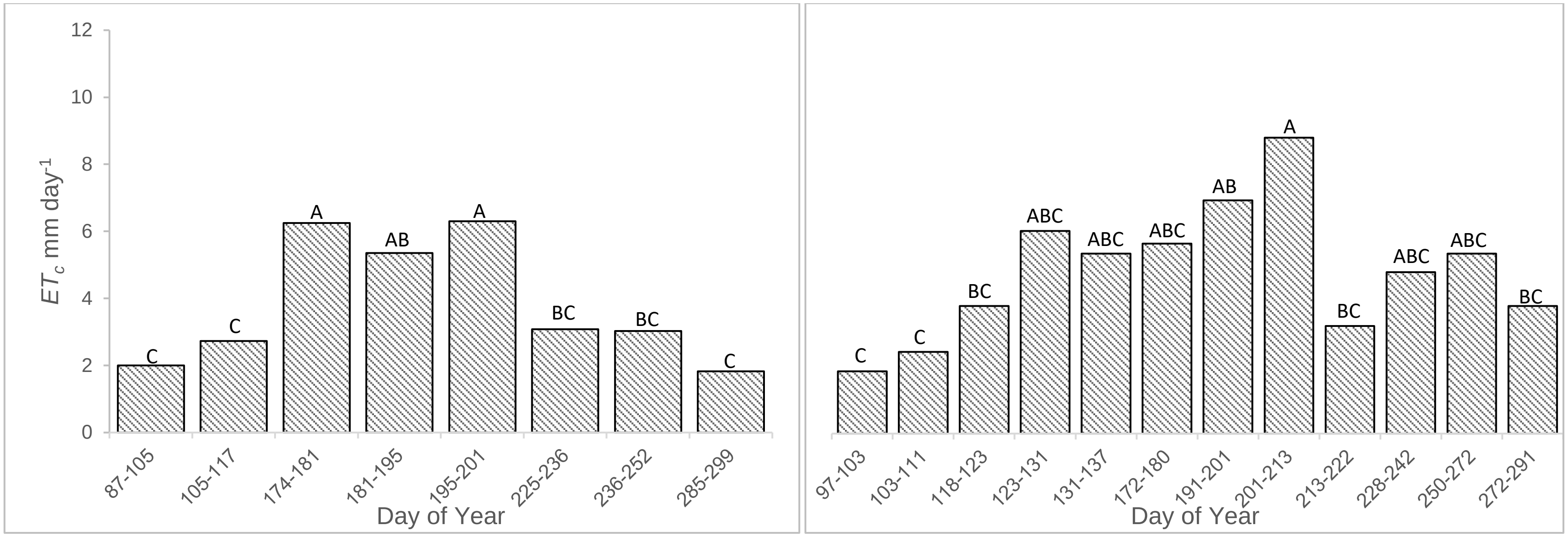

Figure 2.3 Observed miscanthus evapotranspiration (ET_c) rate for the 2016 (Left) and 2017 (Right) growing seasons for the experimental site in Salisbury NC. Letters indicate significant differences at the 0.05 probability level within year.

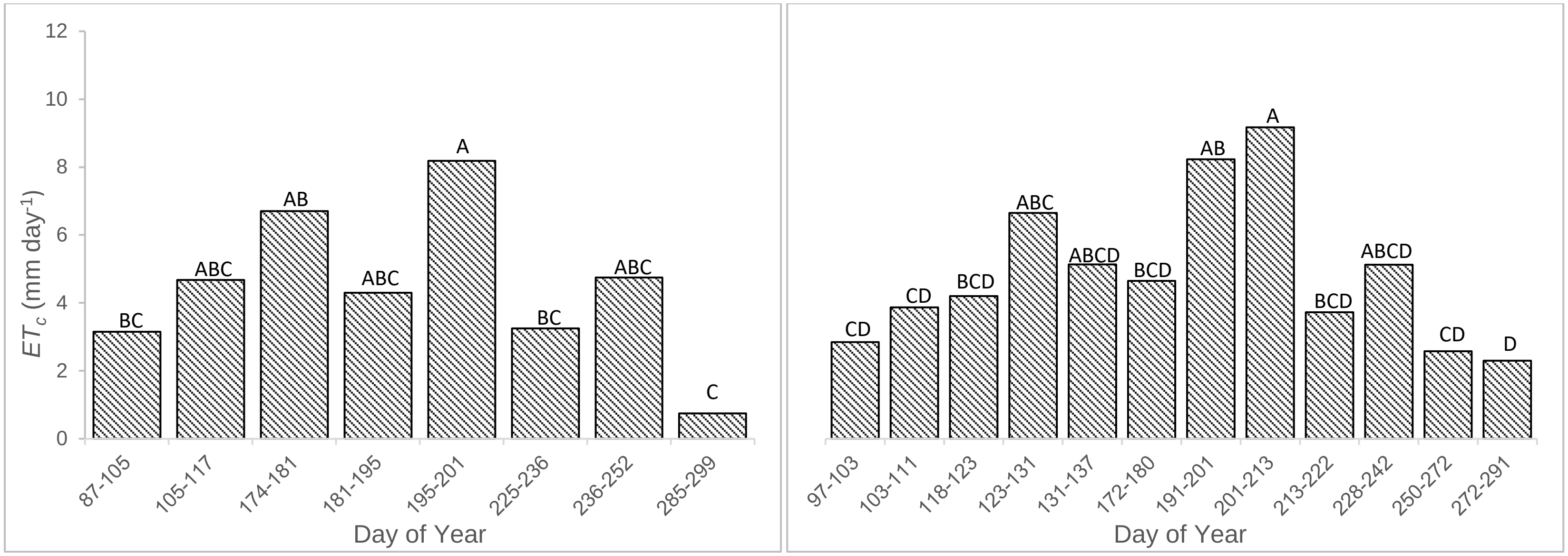

Figure 2.4 Observed switchgrass evapotranspiration (ET_c) rate for the 2016 (Left) and 2017 (Right) growing seasons for the experimental site in Salisbury NC. Letters indicate significant differences at the 0.05 probability level within year.

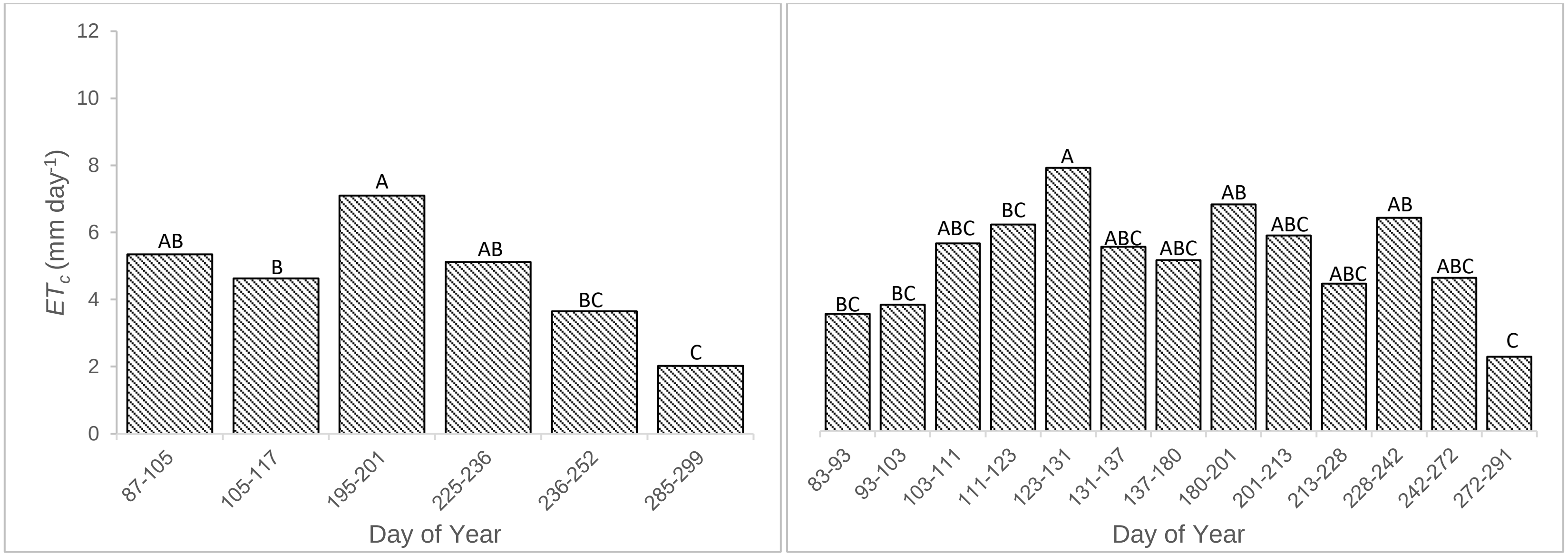

Figure 2.5 Observed fescue hay evapotranspiration (ET_c) rate for the 2016 (Left) and 2017 (Right) growing seasons for the experimental site in Salisbury NC. Letters indicate significant differences at the 0.05 probability level within year.

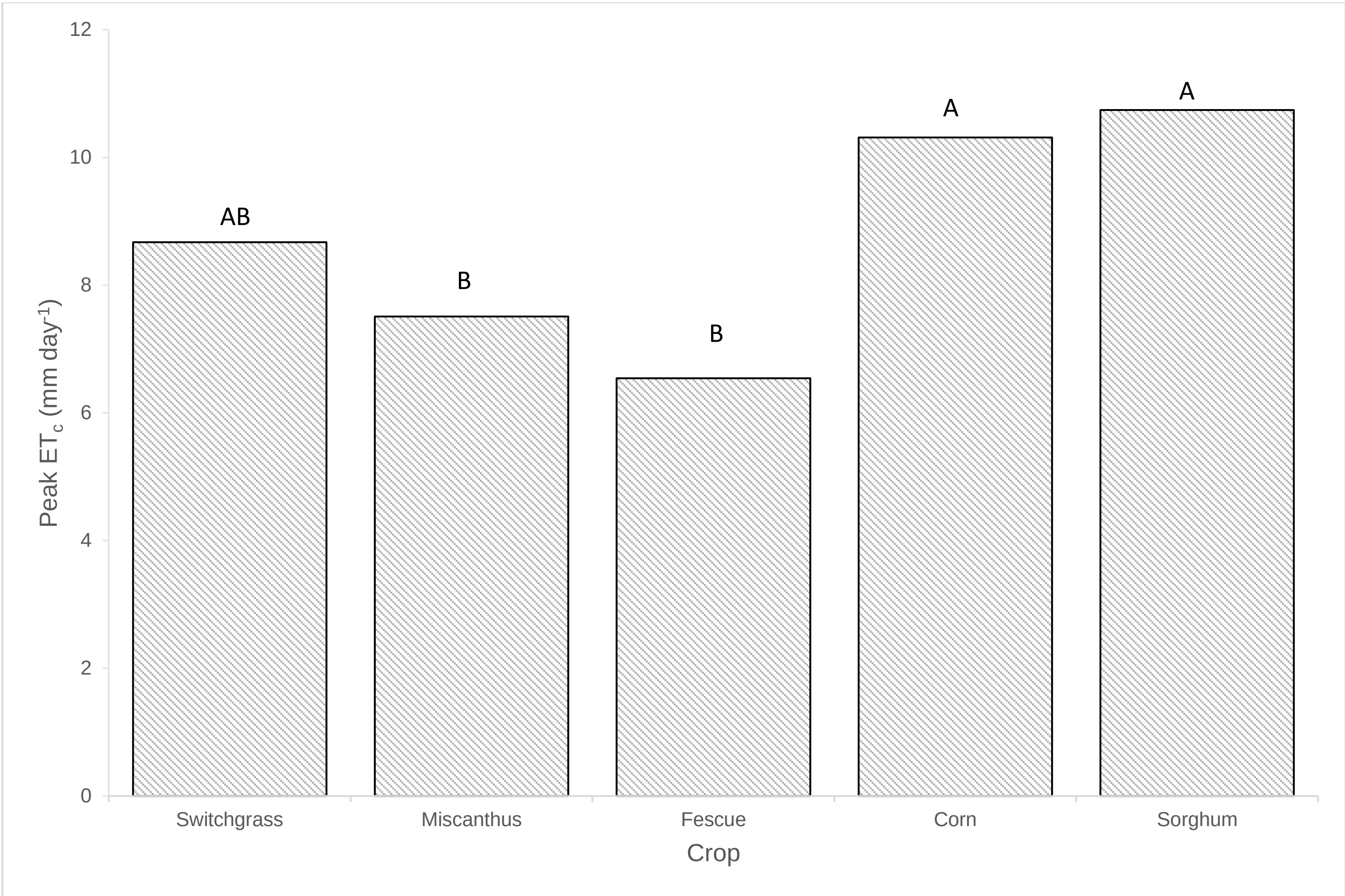

Figure 2.6 Peak observed evapotranspiration (ET_c) rate for the 2016-2017 growing seasons at the experimental site in Salisbury NC. Letters indicate significant differences at the 0.05 probability level between crops.

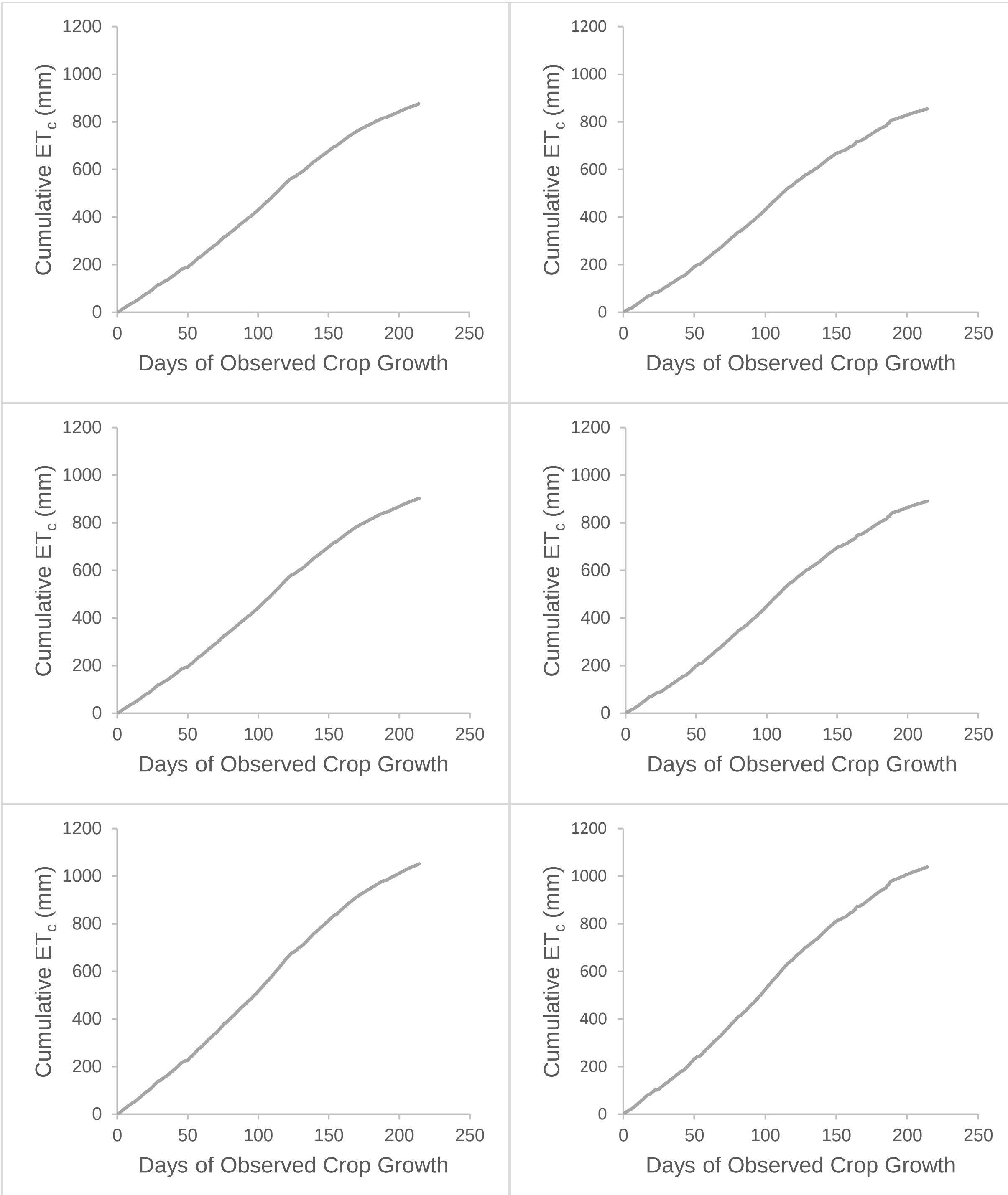

Figure 2.7 Cumulative $ET_{c,p}$ of the switchgrass (top), miscanthus (middle), and fescue hay (bottom) for the 2016 (left) and 2017 (right) growing seasons

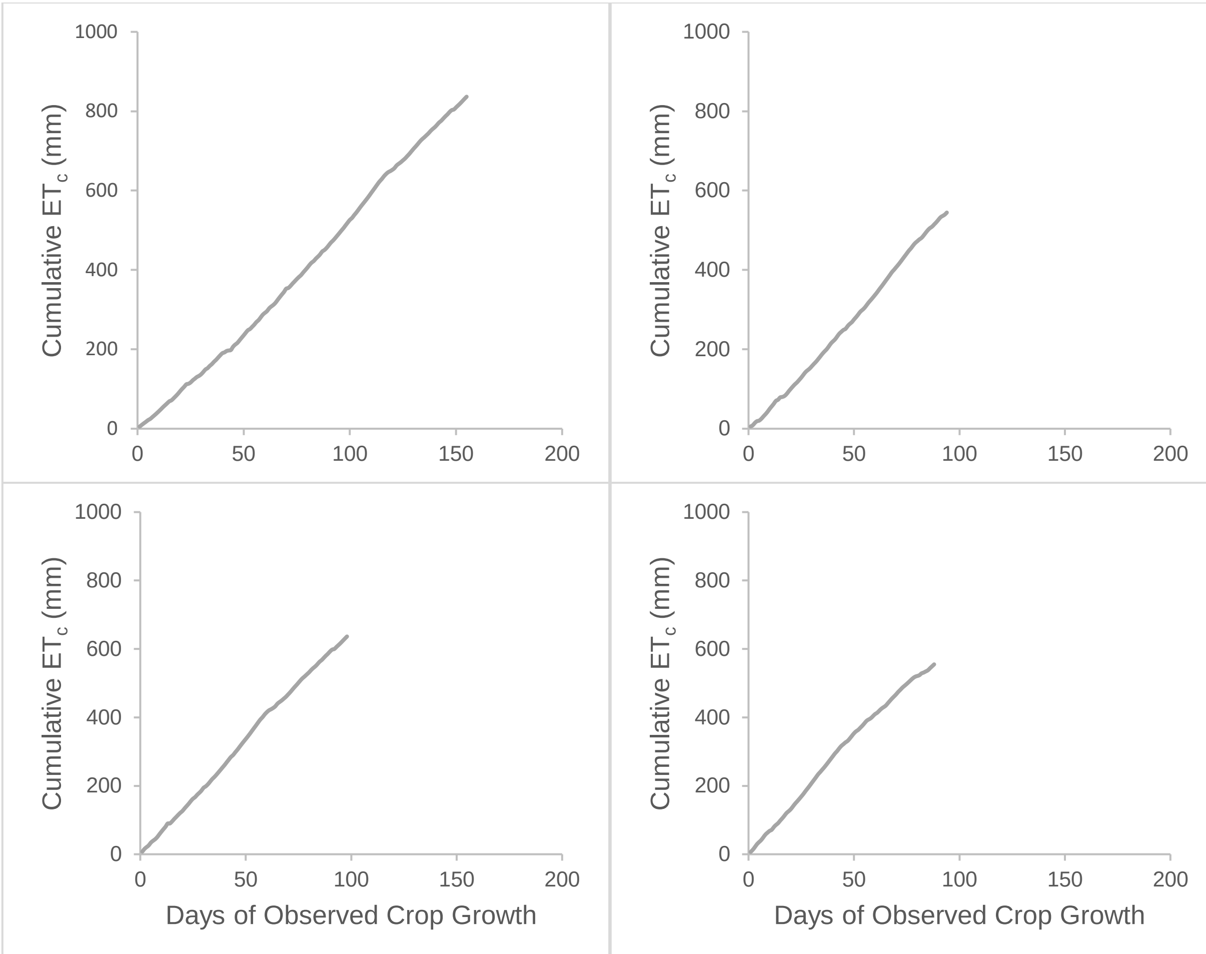

Figure 2.8 Cumulative $ET_{c,p}$ of corn (top) and sorghum (bottom) for the 2016 (left) and 2017 (right) growing seasons.

CHAPTER 3: Effect of Bioenergy Cropping Systems on Soil Physical Properties Following Land Conversion

3.1. Abstract

Bioenergy crops are a potential alternative to traditional row crops and pasture/hay systems in the North Carolina piedmont, but there is limited information available about the effects of these crops on soil physical properties following a land conversion. The objective of this study was to evaluate changes in soil physical properties 5-6 years after land conversion from fescue hay (*Lolium arundiainacea Schreb.*) to bioenergy cropping systems. Cropping systems studied at the site included three potential bioenergy crops; switchgrass (*Pancicum virgatum L.*), giant miscanthus (*Miscanthus x giganeus*), and biomass sorghum (*Sorghum bicolor spp.*), and a traditional crop for the region; corn silage (*Zea mays*) and fescue hay. Soil samples and cores were collected at the surface (0-7 cm) and subsurface (7-15 cm) from an existing field established in 2012 on a Mecklenburg clay loam. All systems were maintained using no-till practices except for switchgrass which was tilled during re-establishment the first year after the initial planting. Soil aggregate stability was evaluated following the 2016 and 2017 growing seasons using wet sieving and dispersion techniques. Soil bulk density, saturated hydraulic conductivity, and water retention were measured using intact soil cores collected after harvest in 2017. Several years after land conversion, switchgrass was the only cropping system with surface layer physical properties that differed from fescue hay, which was likely because of tillage in 2012. In the subsurface layer, miscanthus, sorghum, and switchgrass had fewer stable aggregates than fescue. Switchgrass and miscanthus also had lower saturated hydraulic conductivity in the subsurface layer in comparison to fescue. While some soil physical properties were slightly altered after land conversion, in general, soil physical property changes were

minimal after converting from fescue hay to potential bioenergy cropping systems using no-till practices.

3.2. Introduction

The North Carolina piedmont is a temperate and humid region of the southeastern US that supports diverse agricultural systems. Climatic conditions and landscape features within this region result in areas of moderately eroded and depleted soils referred to as marginal farmlands. Marginal farmlands are defined as land currently unsuitable for producing economically viable commodity crops and are commonly managed as hay/pasture systems (Blanco-Canqui, 2010). There is currently interest in converting marginal farmland from tall fescue hay (*Lolium arundiainacea Schreb.*) production to bioenergy cropping systems. Production of bioenergy crops on these marginal farmlands could lead to an economic gain for producers if the demand for bioenergy continues to increase.

Corn (*Zea mays*) is currently the most common source for bioenergy in the US. Because corn requires substantial nutrient inputs to maintain high yields, it is difficult to justify corn bioenergy production in the North Carolina piedmont where many of the soils are eroded and infertile. Other bioenergy crops, such as giant miscanthus (*Miscanthus x giganteus*) and switchgrass (*Panicum virgatum L.*), have shown potential to maintain high yields with low inputs, while also improving soil conditions in different regions of the US (Blanco-Canqui, 2010; Lee et al., 2014). Likewise, biomass sorghum (*Sorghum bicolor spp.*) is a prospective annual bioenergy crop that fits into common cropping rotations and has high yield potential (Zegada-Lizarazu and Monti, 2011). These crops may become economically viable sources of bioenergy if there is more investment in alternative energy sources. As demand for bioenergy increases, producers could consider replacing their hay/pasture systems with bioenergy crops to increase profitability and improve soil quality for their operation.

When converting to a new cropping system, how the crop affects soil properties is one factor in determining its environmental sustainability for a region. A common way to assess a cropping system's sustainability is by examining associated changes to soil structure (Lal, 1991). Soil structure refers to the size, shape, and arrangement of solids and voids, continuity of pores and voids, their capacity to retain and transmit fluids and chemical substances, and ability to support vigorous root growth and development (Lal, 1991). Soil structure is influenced by several soil physical properties which include, but are not limited to, soil aggregate stability, bulk density, pore size distribution and soil organic carbon. Changes to these soil parameters are used to quantify the effect of a cropping system on soil structure over time.

Measuring soil aggregate stability is a common way of assessing soil structure and stability. Soil aggregates are formed, facilitated, and reinforced by plant and microbial processes as well as residues that act as binding and flocculating agents for soil particles (Tisdall and Oades, 1982; Bronick and Lal, 2005; Blankinship et al., 2016; Jackson, 2017). The resistance of soil aggregates to the slaking and dispersive effects of water is referred to as soil aggregate stability (Haynes et al., 1991). For agricultural soils, regional climate, soil physical properties and the nature of the microbial population influence the stability of soil aggregates (Balesdent et al., 2000; Tolbert et al., 2002). Dispersion of aggregates by processes such as tillage and raindrop impact can decrease soil organic carbon (SOC), increase compaction, seal and crust soil surfaces, and make soils less suitable for production agriculture (Blanco-Canqui, 2010). The dispersion of soil particles by raindrop impact can increase the risk of erosion, especially during heavy rainfall events on sloped landscape such as those located in the marginal farmlands of the NC piedmont.

Removal of plant biomass from cropping systems, such as corn silage and bioenergy crop production, should be closely monitored and studied to better understand how soil stability is affected by this use of the landscape. Cropping systems with greater potential to increase aggregate stability may provide more sustainable uses of marginal lands.

Perennial warm season grasses (PWSGs) such as switchgrass and miscanthus have large quantities of above and below ground biomass which has been suggested to improve soil structural properties (Blanco-Canqui, 2010). Soil properties such as aggregate stability and bulk density are improved by the permanent surface cover and extensive rooting systems of these perennial grasses that provide resilience against both internal and external forces that compact soil (Clark et al., 1998; Lai et al., 2018). While assessing changes in soil quality in central Ohio, Das et al., (2016) reported that soils under switchgrass and miscanthus had lower soil bulk densities than soils under sweet sorghum. Switchgrass also had a statistically greater aggregate mean weight diameter than corn and sweet sorghum at a depth of 0-10 cm after two years of management. Similarly, Tiemann and Grandy (2015) compared aggregate stability under switchgrass, native grass, miscanthus, and continuous corn at two locations in the Great Plains region and found that aggregate stability was significantly influenced by cropping system, with switchgrass and native grass systems having greater aggregate stability than the corn system at both sites. Rachman et al. (2004) reported that soil bulk density was 10% lower in switchgrass buffers than in row crop systems, which resulted in twice as much macroporosity following 10 years of land management. Overall PWSGs have been observed to improve or maintain soil structural properties in various regions of the US.

A previous study in the piedmont region of North Carolina reported that perennial bioenergy crops switchgrass and miscanthus had altered soil properties three years after land conversion from fescue hay production (Wang et al., 2017). Bulk density, saturated hydraulic conductivity (K_{sat}) and macroporosity were measured at a depth of 0-15 cm. Switchgrass and miscanthus had a significantly lower K_{sat} and macroporosity than the fescue system. Differences in switchgrass properties were attributed to organic matter redistribution and disturbance of channel continuity caused by inversion tillage during reestablishment, while differences in miscanthus were not explained by management practices (Wang et al., 2017). It is possible that changes in soil properties under these bioenergy systems could have been altered by the cropping system during land conversions and improvement in regards to these soil physical properties could take more than three years to become measurable. Wang et al., (2017) concluded that since miscanthus and switchgrass stands have been reported to sustain harvest for more than 14 years, root activity and biomass would likely change as stand age increase, therefore more years would be needed to determine the long-term impacts of these cropping systems. Likewise, Blanco-Canqui, (2010) concluded that soil structural properties can be variable depending on soil type and management; therefore long-term monitoring of soil structure under field-scale plantation of PWSGs is needed to truly understand the magnitude of their impacts.

To further assess the impacts of bioenergy crops in the piedmont region of North Carolina, a follow up study to Wang et al., (2017) was conducted to examine soil property changes following years 5 and 6 of consistent land management. The specific objective of this study was to evaluate changes in soil physical properties following land conversion from fescue hay to corn silage (traditional crop); and potential bioenergy crops biomass sorghum, switchgrass, and miscanthus to determine their effect on soil structure.

3.3. Materials and Methods

3.3.1. Site Description, Crop Management, and Crop Measurements

Soil samples were collected from an existing bioenergy field experiment, previously described in Wang et al. (2017), located at the Piedmont Research Station in Salisbury, NC (35°41'N, 80°37'W). The soil type is a Mecklenburg clay loam (fine, kaolinitic, thermic, Ultic Hapludalf). The site was previously used for tall fescue (*Festuca arundinacea schreb*) hay production with consistent management for more than five years prior to establishment of the experiment in 2012. Five cropping systems were included: three perennials; giant miscanthus ‘Freedom’, switchgrass ‘Colony’, tall fescue hay (traditional system), and two annual; corn silage ‘Pioneer 31G71’ and fiber sorghum ‘Blade ES5200’. The crops were arranged in a randomized complete block design with four replications. Each plot was 9 m x 12 m in area.

Perennial bioenergy grass systems (switchgrass and miscanthus) were established in 2012 using no-till practices whereas fescue hay was maintained from previous land management before 2012. Switchgrass cultivar seeds were planted using a no-till drill at a population of 11.2 kg seed ha^{-1}. Giant miscanthus plugs were established using a no-till transplanter with in-row spacing of 80 cm and between-row spacing of 100 cm. Due to intense weed pressure following initial establishment, switchgrass treatments were tilled to a depth of 30 cm and then replanted by hand with plugs using an in-row spacing of 46 cm and between row spacing of 60 cm. The fescue hay treatment consisted of experimental units which were predominantly tall fescue with some mixed grasses that was established more than 5 years prior to 2012. This treatment was sprayed with glyphosate following the first harvest in May 2017 due to intense weed pressure and was not reseeded. The plots naturally reestablished with mixed grasses for the remainder of the growing season.

Annual cropping systems corn silage and biomass sorghum were established each spring using no till practices. Prior to the 2016 growing season the continuous corn silage treatment was a corn/wheat/soybean rotation. The corn/wheat/soybean rotation was replaced with a continuous corn silage treatment to allow for comparison of corn biomass to biomass harvest collected from other cropping systems. Corn was planted in April or May each year with a no-till planter at a rate of 74,195 seed ha^{-1} and a row spacing of 80 cm. Biomass sorghum was planted in June each year using the same no-till planter and row spacing with a population of 247,100 seed ha^{-1}.

Harvest of switchgrass and miscanthus occurred after winter senescence in December each year where the center swath of the experimental units were harvested using a mechanical forage plot harvester (Wintersteiger Inc., Salt Lake City, UT, USA). Sorghum and corn were harvested by hand by cutting two 1.52-m lengths of row from two random locations within the center four rows of each plot. Biomass remaining on the plots was removed with a silage cutter and disposed of offsite. Fescue hay was harvested twice in 2016 and three times in 2017 by removing and weighing all biomass from the plots by hand.

3.3.2 Residue Cover

Residue cover was quantified using the line-transect method (Morrison et al., 1993). Residue was measured in all experimental units during March 2017 and January 2018 while crops were not actively growing. A string 127 cm in length with 80 knots tied at equal intervals was stretched diagonally across each plot with caution to avoid edges of plots and areas of other field sampling procedures. Residue cover was reported as a percentage of knots where crop and other plant residues (i.e. weeds and grass) covered the soil surface out of the total knots on the string and then values were averaged within each cropping system.

3.3.3. Aggregate Stability

Aggregate samples were collected in December 2016 and January 2018 following all harvest operations. Surface (0-7 cm) and subsurface (7-15 cm) soil samples were collected in-between plants or rows at random locations within the each plot with a shovel. Two surface and subsurface soil samples were collected from each plot in 2016. In 2018, soil was collected from three locations in a plot and combined into separate composite samples of surface and subsurface soil. Surface and subsurface aggregates were sampled in adjacent holes to minimize shovel impact on subsurface aggregates. Aggregates were air dried until the mass became stable under laboratory conditions.

Macroaggregates were tested for aggregate stability using an adjusted single sieve method (Kemper and Rosenau, 1986). Air-dried aggregates were broken apart at natural planes of weakness and sieved so that only 1-2 mm aggregates were used for this measurement. Eight grams of 1-2 mm aggregates were placed on a 7-cm diameter, 0.25-mm mesh sieve and then wetted with deionized water for 10 min under a vacuum. The samples were then raised and lowered 3.5 cm in a column of water at 34 oscillations min^{-1} for 3 min. To correct for the mass of sand with diameter >0.25 mm in the sample, a replicate sample of 1-2 mm aggregates was placed on a separate 0.25-mm sieve and was treated as described above except for deionized water was substituted with a dispersing agent, 2% sodium hydroxide, to disperse all aggregates since the soil pH was < 7 (Kemper and Rosenau, 1986). Samples were then dried at 105 ^{o}C for 24 h and weighed. Variations in moisture contents of the initial samples were adjusted by oven drying a subsample and correcting the initial mass in post processing. Macroaggregate stability was calculated according to Amezketa et al. (1996),

$$AS = \left(\frac{Stable\ Aggregates - Sand}{Original\ Soil - Sand}\right) \times 100 \tag{1}$$

where *AS* is percent of water stable aggregates ≥ 0.25 mm; *Stable Aggregates* is the mass of stable aggregate (g) collected on the 0.25-mm mesh sieve; *Original Soil* is the initial mass of the soil (g) used for analysis; and *Sand* is the mass of sand (g) ≥ 0.25-mm in the samples.

Microaggregate stability quantifies the stable silt- and clay-size aggregates of the soil. Microaggregate stability was measured using the Soil Conservations Service double hydrometer test to determine a dispersion ratio (DR) (Maharaj and Paige-Green, 2013). The dispersion ratio evaluates microaggregate stability based on the proportion of stable silt- and clay-size aggregates of a soil sample in solution compared to a soil sample that has been dispersed with a dispersing agent. Air dried samples were passed through a 2-mm sieve using a hammer-mill style soil grinder. The assessment of microaggregate stability consisted of two measurements: a particle size analysis with a dispersion agent referred to as dispersed samples and a particle size analysis without a dispersion agent referred to as undispersed samples. Dispersed samples were measured following the hydrometer procedure of Gee and Bauder (1986). Organic matter was removed from a ~50 g sample with 10 ml of 30% hydrogen peroxide and water was added to submerse the sample ((Kunze and Dixon, 1986). After organic matter was burned off the soil was dried for 3 d at 65 ^{o}C. Following drying, the samples were passed through a 2-mm sieve and a subsample was dried to determine the moisture content. A subsample with 40 g of air-dried soil was mixed with 50 ml of 10% sodium metaphosphate and deionized water and allowed to soak for 24 h. Samples were then mixed using a mechanical mixer for five min before being transferred into settling cylinders. Deionized water was added to the samples to bring the suspension volume to 1000 ml. The samples were measured using the hydrometer method at time intervals of 0.5, 1.5, 360, 960 min.

Undispersed samples were measured using the same procedure as described above except sodium metaphosphate was not added and the samples were not mechanically mixed to maintain the integrity of the microaggregates. Because aggregates sized 20-250 μm largely consist of particles 2-20 μm in diameter bonded by various cementing agents including persistent organic materials Tisdall and Oades, (1982), organic matter was not removed from these samples. Forty grams of soil was mixed with water and allowed to soak for 24 h before being transferred into settling cylinders and hydrometer measurement were collected for the same time intervals listed above. Data from the particle size measurements are used to calculate the DR as:

$$DR = \left(\frac{Mass\ of\ particles < 50\ \mu m\ in\ undispersed\ suspension}{Mass\ of\ particles < 50\ \mu m\ in\ dispersed\ suspension}\right) \times 100 \qquad (2)$$

3.3.4. Additional Soil Sampling and Measurements

A sub-sample of the aggregate material was analyzed for carbon with a Perkin-Elmer 2400 Series II CHNS/O Elemental Analyzer (Perkin-Elmer, Waltham, MA, USA) for total carbon analysis using gas chromatography. One surface and one subsurface sample from each plot were used for this analysis. Approximate sample size used by the lab was 1 to 2 g.

Two intact soil cores were obtained in-between plants from each plot using 5.1 cm diameter steel rings for analysis of soil physical properties in January 2018. One core was from 1.3-6.4 cm depth and the other was from 8.9-14 cm, representing soil depths of approximately 0-7 and 7-15 cm, respectively, for comparison to aggregate samples. These intact soil cores were used to measure K_{sat} using the constant head method (Klute and Dirksen, 1986). Soil water retention was determined at pressures of 10, 20, 30, 40, 60, 80, and 100 cm H_2O using the suction table method from the same cores immediately after K_{sat} measurements (Klute, 1986). Soil cores were then dried to determine bulk density (Blake and Hartge, 1986). Soil pore size distribution was obtained from water retention data. Equivalent soil pore size diameter was estimated using the capillary rise equation:

$$h = \frac{2\gamma \cos \alpha}{\rho wrg} \tag{3}$$

where h is the soil water pressure head (cm), γ is the surface tension of water (72 dyne cm^{-1}), α is the contact angle of water (assumed to be 0 for wettable soil), ρw is the density of water (1.0 g cm^{-3}), r is the equivalent pore size radius (cm), and g is the gravitational constant (981 cm s^{-2}). Pores with a nominal diameter >50μm were classified as effective porosity (P_e), while pores with a nominal diameter <50 μm were classified as residual porosity (P_r) (Deeks et al., 2004; Zhang et al., 2017). The P_e provides drainage channels for potentially rapid flow (Ahuja et al., 1984), whereas P_r offers longer term storage space for water following gravitational drainage (Zhang et al., 2017).

3.3.5. Statistical Analysis

Since data from both growing seasons were collected from the same experimental unit, year was treated as a repeated measure. Crop species and year were considered to be fixed effects while replications were considered random effects. Residue cover, total carbon, and soil macro- and micro-aggregate stability were analyzed using the Glimmix procedure in SAS ver. 9.3 (SAS institute Cary, NC) to determine main effects and interactions between crop and years. Means for these parameters were compared by Fisher's least significant difference (LSD). Significance was determined at the 5% probability level. For total carbon and macro and microaggregate stability the crop × year interaction was not significant ($p < 0.05$) (Table 3.1) so those values were averaged for the two growing seasons. There was a significant year interaction for microaggregate stability but this interaction had no effect on the general conclusions of this study (Table 3.1). Simple linear regressions between soil properties were analyzed using the Proc Reg procedure in SAS ver. 9.3 at the 5% probability level. Bulk density, K_{sat} and porosity data were analyzed using the GLM procedure in SAS ver. 9.3. Means were separated using LSD at the 5% probability level. A log transform was used during the analysis of K_{sat} because the data were not normally distributed.

3.4. Results and Discussion

It is important to acknowledge potential relationships between soil physical properties evaluated at this site as changes in one property may affect other soil properties which ultimately could impact soil structure. Surface residues protect soil aggregates from raindrop impact and rapid wetting and drying cycles which could lead to aggregate breakdown and decreases in soil carbon (Blanco-Canqui and Lal, 2009). Soil aggregates can also be influenced by the carbon content of the soil, especially soil organic carbon. For most soils, macroaggregates are stabilized by transient and relatively undecomposed organic binding agents (Tisdall and Oades, 1982; Mulumba and Lal, 2008), in which increases in soil carbon have been correlated to increases in soil aggregate stability (Bronick and Lal, 2005; Wright and Hons, 2005; Blanco-Canqui and Lal, 2009). Soil structure depends on the presence of stable aggregates which affect movement and storage of water, compaction, and the growth of crops in soils (Amézketa, 1999). Aggregate stability may alter soil structure through its effect on other soil physical properties such as bulk density which can influence crop root growth, fluid transport, and water holding capacity of the soil by changing the total porosity and the pore size distribution (Horn, 1990). Small variations in pore size can ultimately affect water retention and K_{sat} of the soil by affecting the amount of water that can be stored at a given dryness state or conducted at a given hydraulic gradient (Bouma et al., 1977). Since most of these properties are connected and can be manipulated by crop management decisions, cropping system effects on soil properties were evaluated at this site. In order to evaluate the cropping system effect, soil physical properties under the bioenergy cropping systems were compared to fescue hay, the previous land management.

3.4.1. Residue Cover

The post-harvest residue cover for the 2016 and 2017 growing seasons is presented in Table 3.2 Fescue hay and miscanthus had significantly greater residue cover than sorghum and switchgrass. The fescue hay system had substantial residue cover because it was a well-established cool season grass with a thick plant density resulting in nearly complete ground cover year-round. Miscanthus had a thick mulch layer as a result of leaf loss during crop senescence, which resulted in similar residue cover to that of fescue. Miscanthus has been noted to have a high annual leaf input and slow decomposition rate; abscised leaves lost approximately 54% of their initial mass due to decomposition for a silt loam in France while the remaining mass accumulated as a mulch layer at the soil surface (Amougou et al., 2012). Unlike miscanthus, switchgrass did not have a thick mulch layer even with the same harvest date. This is likely a result of the bunch type grass characteristics where the inter rows of the cropping system were still noticeable following harvest. For the annual systems, corn had significantly higher residue cover than sorghum for both years of observations. Corn had an earlier planting date in which the crop reached senescence earlier in the year than sorghum could have resulted in greater reestablishment of weedy ground cover. Surface residue covers have been noted to enhance infiltration, dissipate raindrop energy, minimize aggregate breakdown and surface sealing and retard surface water flow, which will all increase aggregate stability (Cassel et al., 1995). Surface residues did not appear to have this affect at this site where residue cover and macroaggregate stability were weakly correlated ($R^2 = 0.08$) (data not shown). This was likely due to relatively large amounts of residue cover in all cropping systems as a result of the no-till management where there was only one case of < 70% residue cover on the soil surface (Table 3.2).

3.4.2. Total Carbon

Total carbon was measured following the 2016 and 2017 growing seasons for the surface (0 to 7 cm) and subsurface (7 to 15 cm) layers (Table 3.3). Total carbon content of the surface layer for all treatments was significantly higher than the carbon content of the subsurface layer (Table 3.1), which can be attributed to plant residues deposited at the soil surface. Because the crop × year interaction was not significant (Table 3.1) total carbon contents for both seasons were averaged separately for both depths. The total carbon content of switchgrass was lower in the surface and subsurface layers in comparison to fescue hay whereas all other cropping systems were similar to fescue. This was likely due to the redistribution of organic matter by inversion tillage at reestablishment of the switchgrass. Tilling the soil breaks down aggregates, which facilitates the loss of soil organic matter by microbial degradation (Roberson et al., 1991; Amézketa, 1999). The true effect of converting from a fescue hay to a switchgrass system on total carbon is slightly masked by the tillage event after the switchgrass was established, but the evaluation of this cropping system provided information on the long-term physical property effects from a differing establishment technique and the rate at which the soil was able to recover. Similarities in total carbon between the other cropping systems are likely a result of the no-till crop management. Although warm season perennial C_4 grasses have been noted to increase soil carbon (Blanco-Canqui, 2010), total carbon contents at this site did not significantly increase following land conversion to perennial bioenergy cropping systems for either soil depth. This is likely because land management practices prior to land conversion and after conversion were similar in below-ground carbon contributions. This result is similar to Garten and

Wullschleger (1999) where they found no strong evidence for greater soil organic carbon beneath switchgrass than tall fescue in the Southeastern USA. Overall land conversion from tall fescue hay to these potential cropping systems did not significantly alter total soil carbon content.

3.4.3. Macroaggregate Stability

Macroaggregate stability was measured for the five cropping systems following the 2016 and 2017 growing season. Since there was no significant crop × year interaction (Table 3.1) macroaggregate stabilities for both years were averaged for each depth (Table 3.3). Surface layer macroaggregates of switchgrass were less stable than fescue hay and the other cropping systems. In the subsurface layer, sorghum, miscanthus, and switchgrass all had less stable macroaggregates than fescue. Corn had similar macroaggregate stability to fescue hay and was more stable than switchgrass. The macroaggregate stability of the switchgrass was lower than fescue hay likely due to the lower amount of total soil carbon. Total carbon at this site exhibited a significant positive relationship to macroaggregate stability ($P < 0.05$) with an r^2 value of 0.64 for the surface and subsurface layers (Fig. 3.1). Macroaggregate stability is often influenced by changes in soil carbon content, particularly soil organic carbon which is plant and animal residues that decompose and act as binding and cementing agents for soil aggregates (Haynes et al., 1991; Bronick and Lal, 2005). Similarities in corn and fescue hay macroaggregate stability were likely a result of previous crop management which included a cropping rotation and cover crop for the corn treatment. While aggregate dynamics vary among different crops, crop rotations and cover crops, cover crop residues may enhance soil microbial biomass and respiration which could lead to increased aggregation (Schutter and Dick, 2002; Jarecki and Lal, 2003; Bronick and Lal, 2005). Other studies have shown that perennial warm season grasses increase soil macroaggregate stability in comparison to row crop production on a wide range of soil types (Blanco-Canqui, 2010; Tiemann and Grandy, 2015; Das et al., 2016). In the case of this study we believe that the magnitude of difference in soil aggregation under the different cropping systems in this study was reduced because of no-till management of the crops.

3.4.4. Microaggregate Stability

Microaggregate stability was measured following the 2016 and 2017 growing seasons for the surface (0-7 cm) and subsurface (7-15 cm) layers. Microaggregate stability for all cropping systems was significantly higher in 2016 than 2017 (Table 3.1) likely because of differences in sampling conditions between the years. While there was a year effect for microaggregate stability there was not a significant crop × year interaction (Table 3.1) therefore, microaggregate stabilities were averaged for both years at each depth.

Microaggregates in the surface layer were less stable for switchgrass and miscanthus than for fescue, while for the subsurface layer sorghum, switchgrass, and miscanthus were all less stable than fescue hay (Table 3.3). Differences in subsurface microaggregates for sorghum, miscanthus, and switchgrass followed the same pattern to that observed in macroaggregate stability where these systems also had significantly lower subsurface values than fescue. Microaggregate stability of the surface and subsurface at this site exhibited significant positive relationship to macroaggregate stability $r^2 = 0.29$ ($p < 0.05$) (Fig. 3.2) suggesting that they may both be controlled by similar factors.

3.4.5. Bulk Density

Bulk density was measured from soil cores collected following the 2017 growing season for the surface (0-7 cm) and subsurface (7-15 cm) layers (Table 3.4). Surface soil bulk density was significantly lower in miscanthus than switchgrass ($p < 0.05$) while all cropping systems were similar to the bulk density observed for fescue hay (Table 3.4). There were no significant differences in bulk density for the subsurface layer between the cropping systems ($p < 0.05$). This result indicates that there was no major change in the bulk density following land conversion from tall fescue. The results from the surface layer bulk density during this study were mostly consistent with the trend reported by Wang et al. (2017) where switchgrass had the highest bulk density for the 0-15 cm soil layer at this site during the first three years of establishment. There were no differences between the cropping systems for the subsurface layer likely because changes in bulk density often occur nearest the soil surface where there is the most root activity and greatest impact of traffic (Schmer et al., 2011; Wang et al., 2017). Studies have shown that perennial cropping systems tend to have lower bulk density in comparison to row crops (Rachman et al., 2004; Blanco-Canqui, 2010; Das et al., 2016). This result was not observed at this site likely because of the land management which included no-till establishment for both annual and perennial crops.

3.4.6. Pore Size Distribution

The pore size distribution often affects the hydraulic properties of the soil and was calculated using water retention measurements for the surface (0-7 cm) and subsurface (7-15 cm) layers (Figs. 3.3 – 3.4) from soil cores collected following the 2017 growing season. According to the soil water retention data for these cropping systems, the majority of water release occurred between 0 and about 60 cm of pressure which corresponds to an effective pore diameter of about 50 µm, therefore all pores larger than 50µm were considered to contribute to P_e. This threshold was similar to those used in previous studies cited above.

The P_e for the surface layer was similar to fescue hay in all cropping systems except for switchgrass, which had a lower P_e likely because of previous management practices (Table 3.4).

The lower P_e of switchgrass was also noted in Wang et al. (2017), where macroporosity was less for switchgrass than fescue, corn, and sorghum for the surface layer (0-15 cm) following three years of consistent management at this site. All cropping systems had similar P_e in the subsurface layers. P_r is an indicator of soil pores which retain water and do not contribute to rapid water movement (i.e. drainage). Miscanthus had a greater P_r than fescue, corn, and sorghum for the surface layer while having a greater P_r than corn in the subsurface layer (Table 3.4). This result indicates that soils under miscanthus management could possibly retain more water for the surface layer than fescue, corn, and sorghum. A similar result was observed in Wang et al., (2017) where miscanthus had a greater volume of micropores than all other cropping systems in the surface layer (0 – 15 cm).

3.4.7. Saturated Hydraulic Conductivity

The K_{sat} was measured for the surface (0-7 cm) and subsurface layers (7-15 cm). A log transform was used to analyze these data due to their high variability within each cropping system and since results were not normally distributed (Table 3.4). The untransformed K_{sat} data are shown for the surface layer in Fig. 3.5. This variability could be attributed to root channels or worm holes within the cores used for measurements. Measurements of K_{sat} using the core method have been shown to be highly variable due to localized macropores within the soil cores that could be created by plant root channels or animal activity (Bouma, 1982).

There were no significant differences in surface layer K_{sat} ($p < 0.05$) among the cropping systems (Table 3.4). While cropping systems exhibited trends of increasing or decreasing K_{sat} in comparison to fescue, it was hard to differentiate the treatments due to variability (Fig. 3.5) among replicates. K_{sat} measurements were also variable for the subsurface layer but there were statistical differences (Table 3.4). Miscanthus and switchgrass had significantly lower K_{sat} than other cropping systems ($p < 0.05$). Previous work at this site also noted a lower K_{sat} for miscanthus and switchgrass in comparison to the fescue hay for the surface layer (0 - 15 cm) (Wang et al., 2017). When these prior results are taken together with K_{sat} results of our study, it does suggests that land conversion from fescue hay to perennial bioenergy cropping systems appeared to decrease K_{sat} at our site but the reasons for this are not completely clear or evident from other physical property measurements.

3.5. Conclusions

The fescue hay cropping system represents the land use that many producers prefer for marginal cropland in the region. Typical bioenergy crops introduced to the site in 2012 represent alternative options for marginal cropland use in the piedmont region of North Carolina. Soil physical properties were evaluated at the surface and subsurface layers of each cropping system in order to compare how converting marginal cropland from fescue hay production to bioenergy production could affect soil structure.

Surface layer physical properties were not substantially altered by the cropping systems at this site in comparison to fescue. Subsurface layer physical properties, however, were in some cases influenced by the cropping systems. Miscanthus, sorghum, and switchgrass all had significantly less stable macro and microaggregates than fescue hay for the subsurface layer. The decrease in aggregate stability of sorghum did not appear to influence other soil properties (i.e. bulk density, K_{sat} and effective porosity). The K_{sat} was significantly lower in miscanthus and switchgrass than fescue hay for the subsurface layer, but were not explained by results of other soil physical property measurements. Impacts of switchgrass production on physical properties were likely influenced by tillage disturbance during establishment. Results for this system may have been different had establishment of switchgrass been consistent with the other cropping systems. Overall, land conversion from fescue hay production to these annual and perennial bioenergy cropping systems appeared to maintain similar soil structure at the soil surface (0-15 cm) when using no-till establishment practices. Long-term land conversion to these cropping systems in the North Carolina piedmont seems feasible based on the findings at this site however before wide spread adoption of these cropping systems other environmental and economic variables should be considered.

3.6. References

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Table 3.1. Analysis of variance p values for the residue cover, total carbon, macroaggregate stability and microaggregate stability for crop, year, depth, and crop × year interaction following the 2016 and 2017 growing seasons for the bioenergy cropping systems in Salisbury, NC.

Soil Physical Property	Cropping System	Year	Depth	Crop × Year Interaction
Residue Cover	0.001*	0.001*	-	0.001*
Total Carbon	0.001*	0.062	0.001*	0.293
Macroaggregate Stability	0.001*	0.124	0.001*	0.596
Microaggregate Stability	0.001*	0.001*	0.001*	0.123

* Represent statistical significance ($p < 0.05$)

Table 3.2. Surface residue cover following harvest of the cropping systems for the 2016 and 2017 growing seasons at experimental site in Salisbury, NC.

Crop	Year			
	2016		2017	
	%			
Switchgrass	71	B	80	BC
Miscanthus	93	A	97	A
Fescue Hay	90	A	97	A
Corn	90	A	89	AB
Sorghum	47	C	78	C

Letters represent statistical significance between cropping systems ($p < 0.05$)

Table 3.3. Total carbon, macroaggregate and microaggregate stability for the surface (0-7 cm) and subsurface layer (7-15 cm) for the experimental site in Salisbury, NC. Values presented represent averages over the two observational years and two sampling events. Microaggregate stability was computed as 100 – dispersion ratio, DR (as defined in text).

Crop	Total Carbon				Macroaggregate Stability				Microaggregate Stability			
	Surface		Subsurface		Surface		Subsurface		Surface		Subsurface	
	%				%				%			
Switchgrass	1.94	B	1.15	B	49.8	B	38.5	C	50.4	C	40.5	B
Miscanthus	2.56	A	1.23	AB	64.6	A	41.3	BC	51.2	BC	38.6	B
Fescue Hay	2.83	A	1.41	A	68.4	A	53.1	A	57.0	A	49.1	A
Corn	2.48	A	1.30	AB	65.1	A	48.6	AB	59.3	A	43.8	AB
Sorghum	2.45	A	1.31	AB	60.7	A	42.7	BC	55.7	AB	39.8	B

Letters represent statistical significance between cropping systems ($p < 0.05$)

Table 3.4. Soil bulk density, pore space distribution, and saturated hydraulic conductivity following 2017 growing season for the surface (0 -7 cm) and subsurface (7 -15 cm) at the bioenergy crop at the experimental site in Salisbury, NC.

Crop	Bulk Density		Effective Pororsity (> 50 μm)		Residual Porosity (< 50 μm)		Saturated Hydraulic Conductivity	
	Surface	Subsurface	Surface	Subsurface	Surface	Subsurface	Surface	Subsurface
	$g\ cm^{-3}$		$m^3\ m^{-3}$				$\log_{10}$ $cm\ hr^{-1}$	
Switchgrass	1.25 A	1.40 ns†	0.09 B	0.07 ns	0.44 AB	0.40 AB	0.37 ns	-0.73 B
Miscanthus	1.01 B	1.31 ns	0.14 AB	0.06 ns	0.47 A	0.44 A	0.94 ns	-0.31 B
Fescue Hay	1.15 AB	1.32 ns	0.17 A	0.10 ns	0.40 B	0.40 AB	1.22 ns	0.65 A
Corn	1.14 AB	1.36 ns	0.17 A	0.10 ns	0.41 B	0.38 B	1.36 ns	0.86 A
Sorghum	1.15 AB	1.29 ns	0.17 A	0.10 ns	0.39 B	0.41 AB	1.37 ns	0.97 A

Letters represent statistical significance between cropping systems ($p < 0.05$)

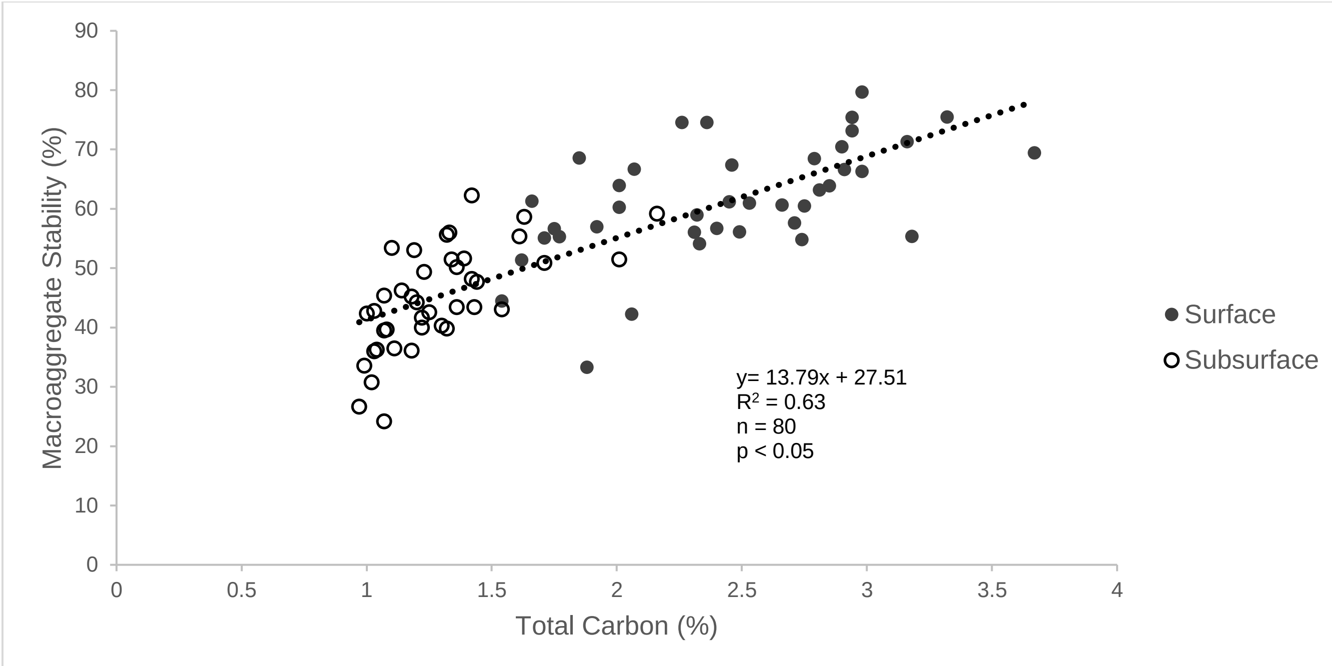

Figure 3.1 Linear regression of total carbon and macroaggregate stability for surface (0 -7 cm) and subsurface (7 - 15cm) layers at the experimental site in Salisbury, NC.

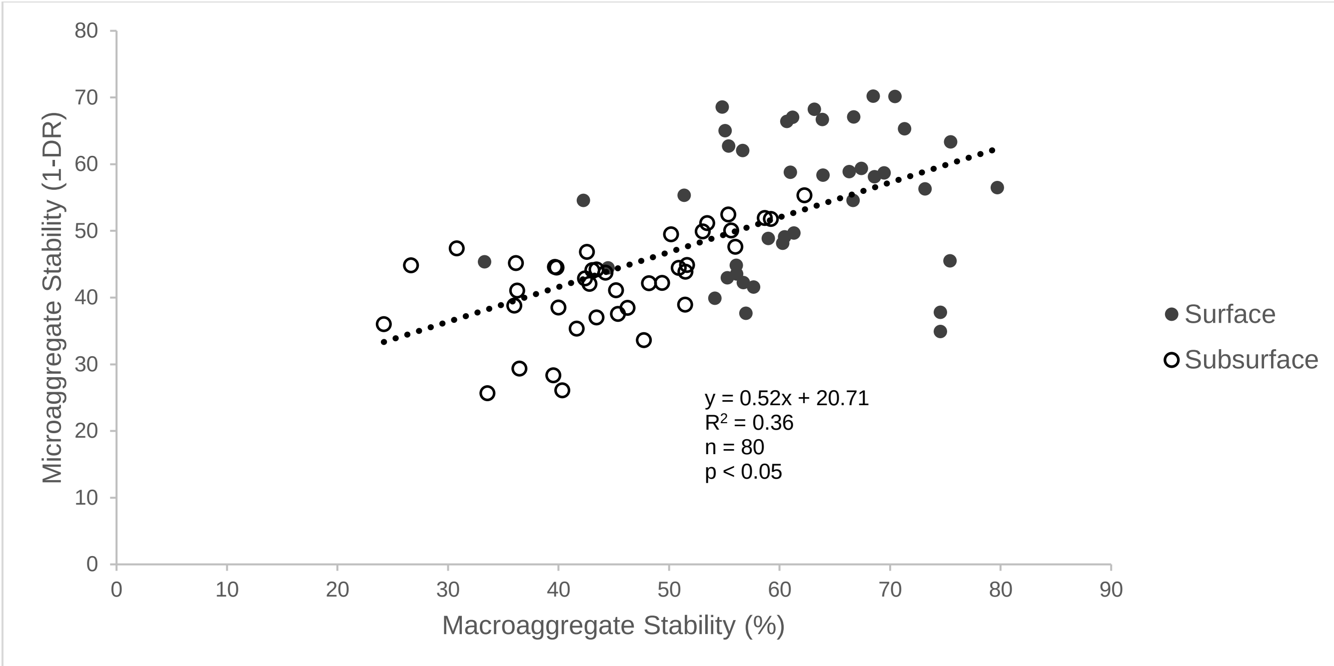

Figure 3.2 Linear regression of macroaggregate stability and microaggregate stability for surface and subsurface layers at the experimental site in Salisbury, NC. Microaggregate stability was computed as 100 – dispersion ratio, DR (as defined in text).

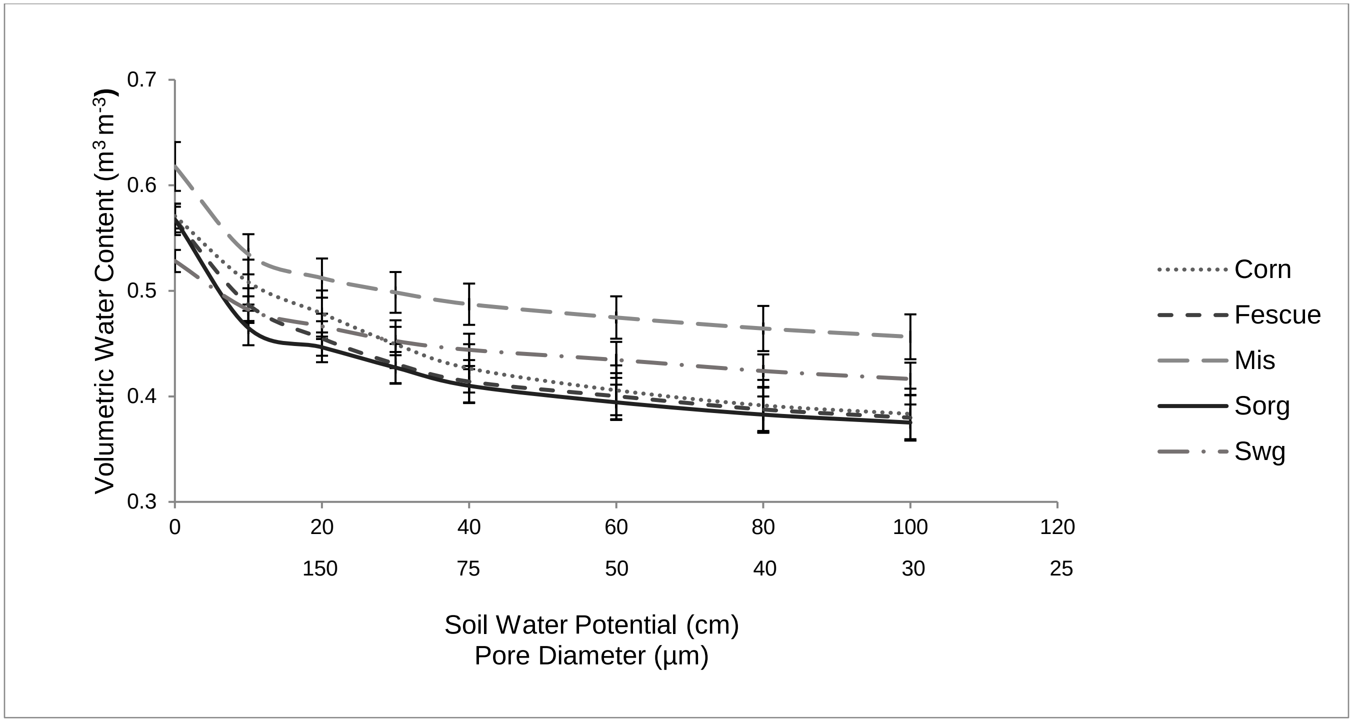

Figure 3.3 Soil water retention following the 2017 growing season for the surface layer (0-7 cm) at the experimental site in Salisbury, NC. Error bars are shown as standard errors. The second row of numbers on the x-axis correspond to equivalent pore diameters at each soil water potential.

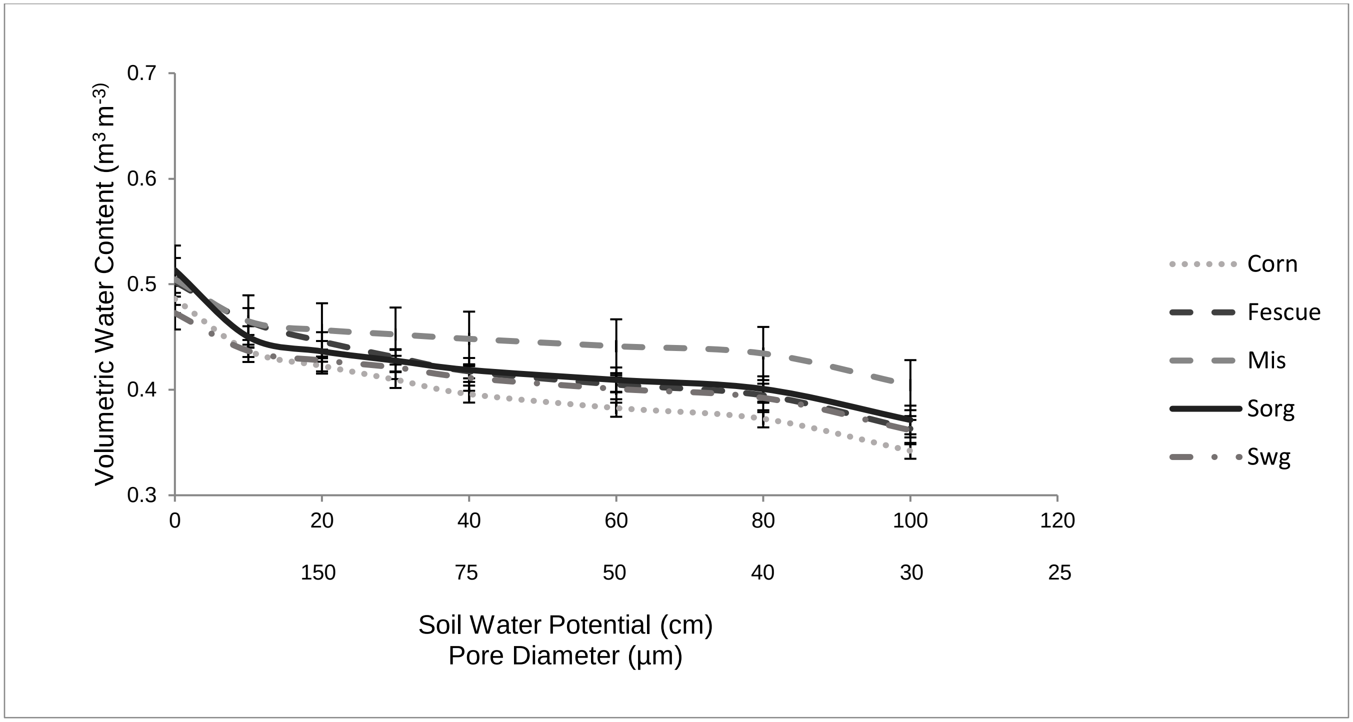

Figure 3.4 Soil water retention following the 2017 growing season for the subsurface layer (7-15 cm) at the experimental site in Salisbury, NC. Error bars are shown as standard errors. The second row of numbers on the x-axis correspond to equivalent pore diameters at each soil water potential.

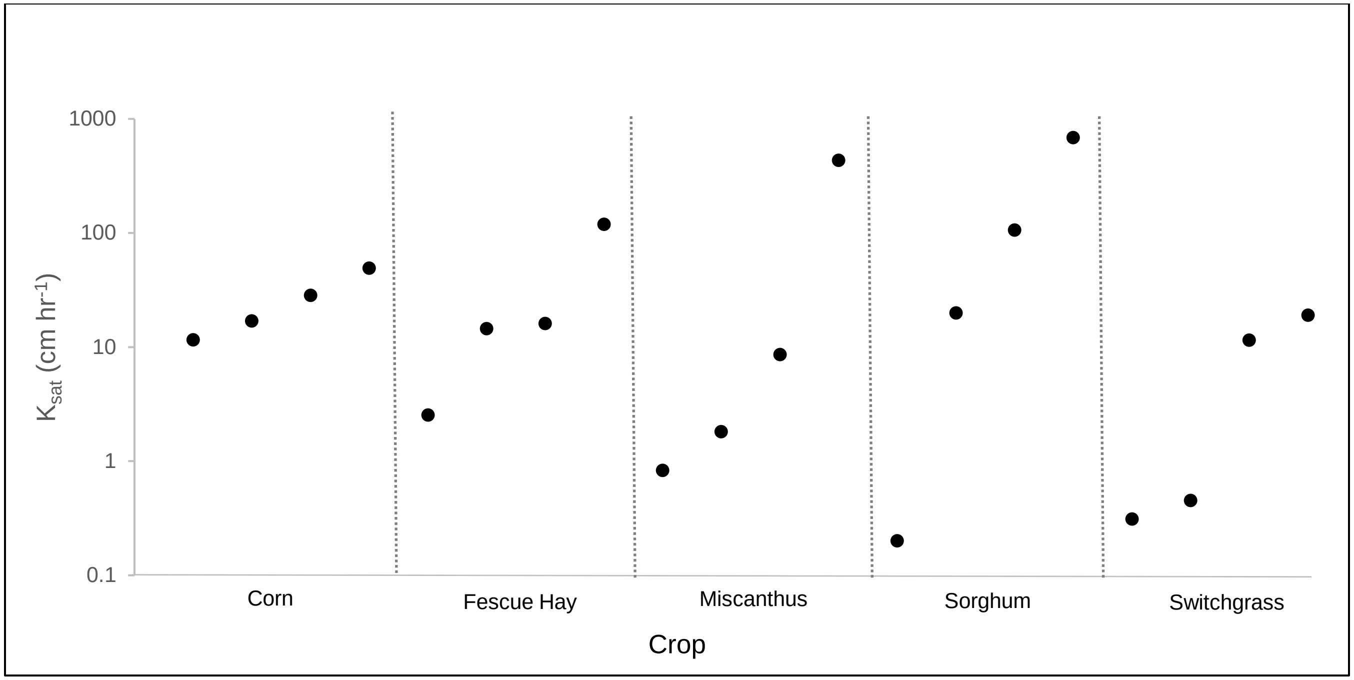

Figure 3.5 Values of measured saturated hydraulic conductivity (K_{sat}) of surface (0- 7 cm) layer soil cores collected from cropping systems following the 2017 growing season at the experimental site in Salisbury, NC.

Chapter 4: Conclusions and Future Work

4.1. Conclusion

Production of bioenergy crops in the NC piedmont appears promising based on results of these studies. Predicted water use from weather and field data indicated that all potential bioenergy crops consumed less water while producing similar to higher amounts of biomass than fescue hay. Soil physical properties measured at the site also indicate that long term management of these cropping systems without detrimental effects on soil physical properties appears feasible. Crops did not significantly alter surface physical properties at this site when compared to the previous land management, fescue hay, when using no-till establishment practices. Some subsurface physical properties were slightly altered by management of miscanthus and sorghum, but effects of these properties did not appear to decrease productivity of the cropping systems.

Based on the findings in these studies all cropping systems evaluated appear to be suitable bioenergy crops for this region. Giant miscanthus seems to be the most promising of the perennial systems based on its water use efficiency where it produces the most biomass of all cropping systems with similar water use to the other perennial grass systems. Sorghum could be implemented as an alternative rotational crop given its similar water requirements and yields to that of corn silage. This could allow growers to add a bioenergy crop into their rotation without making a long-term commitment into the industry. However before wide-spread adoption of these cropping systems other environmental and economic factors should be considered.

4.2. Future Work

Future work in this area could involve a more in-depth study into the water use of these cropping systems with the use of a lysimeter to determine daily water use over multiple seasons. During this study water use was quantified using a water balance where many time intervals had to be eliminated due to uncertainties of runoff. The use of a lysimeter would allow for crop evapotranspiration to be evaluated on a daily basis with less uncertainty. This consistency in data collection would allow for enough data to develop crop coefficients by growth stages. This method would allow for a more precise understanding of the cumulative water use of these systems rather than predicting seasonal water use using a single season-long crop coefficient. This could be valuable to growers who would like to understand the changes is crop water uptake over a growing season instead of total season consumption.

Evaluation of the water use efficiency of these cropping systems during years of limiting rainfall would allow for a better understanding of the range of water use. It has been well documented that the timing and amount of rainfall impacts yields of corn and sorghum. During the two years that crop water use was studied at this site there was sufficient rainfall to produce similar yields during both years. Prior to this study sorghum yields decreased during a year of limiting rainfall conditions while the perennial systems maintained a constant yield. Understanding the efficiencies of these crops during years of limiting rainfall could help growers make decisions about what crop is most suitable for their management practices.

Finally, economic factors of these cropping systems should be evaluated. It has been documented that this region can sustain growth of miscanthus, switchgrass, and biomass sorghum based on scientific metrics, but it is still unknown if production of these crops are economically feasible for growers. It is critical that the economic feasibly of producing bioenergy cropping systems is evaluated for this region in order to convince growers to pursue these crops. Until the growers are convinced to implement these bioenergy cropping systems into their operations, it will be hard to create a bioenergy industry in the North Carolina Piedmont.