PREDICTING SWITCHGRASS BIOMASS AND ETHANOL POTENTIAL ON CLAYPAN SOIL LANDSCAPES

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By

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The undersigned, appointed by the dean of the Graduate School,

have examined the Thesis entitled

PREDICTING SWITCHGRASS BIOMASS AND ETHANOL POTENTIAL ON CLAYPAN SOIL LANDSCAPES

Presented by Arndt Gossel

A candidate for the degree of

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And hereby certify that, in their opinion, it is worthy of acceptance.

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Dr. Newell Kitchen

Dr. Kenneth Sudduth

Dr. Robert Mitchell

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List of Abbreviations

Actual total ethanol production from SSF (ETOHTLH)

Actual total ethanol yield from SSF (ETOHTL)

Agriculture Land Management Alternatives with Numerical Assessment Criteria (ALMANAC)

Apparent electrical conductivity (ECa)

Arabinose (ARA)

BioEnergy Feedstock Development Program (BFDP)

Cave-in-Rock (CR)

Depth to Claypan (DTC)

Environmental Policy Integrated Climate (EPIC)

Erosion Recovery and System Evaluation (ERASE)

Ethanol (ETOH)

Fructose (FRU)

Galactose (GAL)

Hectare (ha)

Herbaceous crops research (HECP)

Kanlow 2 cut, first cut (K2cut1)

Kanlow 2 cut, second cut (K2cut2)

Kanlow plus native legumes (K+NL)

Kanlow plus white clover (WC)

Kanlow with 0 kg ha^{-1} nitrogen (K0)

Kanlow with 101 kg ha^{-1} nitrogen (K101)

Kanlow with 67 kg ha^{-1} nitrogen (K67)

Kilogram (kg)

Leaf area index (LAI)

Liters (L)

Major Land Resource Area (MLRA)

Mannose (MAN)

Mega Joules (MJ)

Mega gram (Mg)

Missouri (MO)

Near-Infrared Spectroscopy (NIRS)

Oak Ridge National Laboratory (ORNL)

Radiation use efficiency (RUE)

Released pentose (PENT)

Renewable fuel standard (RFS).

Simultaneous saccharification and fermentation (SSF)

Soil Conservation Service (SCS)

Soil Productivity and Resource Conservation (SPARC)

Soil Survey Geographic Database (SSURGO)

Soluble Glucose (GLCS)

Starch (STA)

Sucrose (SUC)

Total theoretical ethanol production (ETOHTTLTH)

Total theoretical ethanol yield (ETOHTLT)

Water use efficiency (WUE)

Xylose (XYL)

Abstract

Switchgrass (*Panicum virgatum L.*) yield on claypan soils was evaluated with a crop growth model and for actual ethanol production potential. Specifically, Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) was evaluated for switchgrass production on claypan soils. Switchgrass was established on the Soil Productivity and Resource Conservation (SPARC) plots near Columbia, MO in 2009. ALMANAC soil inputs were modified with soil texture and bulk density from measured soil samples. ALMANAC results were compared to yearly SPARC measured switchgrass yields and consistently underestimated yields. Yield simulated by repeating a single weather year was cyclical for consecutive years based on three of the four weather year patterns. The model was run over a 30-year simulation period where mean simulated yields matched mean measured yields only when model N-rates were increased to levels greater than actual. Model yields did not increase with increased DTC as was observed with measured results for drier than average years of precipitation. ALMANAC simulated results were closer to measured results when harvest dates were artificially made earlier in the fall and N-rates were increased above actual application amounts.

From the SPARC switchgrass plots Biomass was analyzed with near-infrared spectroscopy (NIRS). NIRS was used to determine 20 compositional parameters and predict actual ethanol yield. The ethanol yield was then multiplied by the biomass yield to determine ethanol production. Switchgrass ethanol production increased with greater DTC and N-rates for years with drier than average years of precipitation. Ethanol yield decreased at greater DTC for the driest years.

Chapter 1: Literature Review

Switchgrass

Switchgrass (*Panicium virgatum* L.) a native perennial grass from North America, has been used for forage, conservation, and bioenergy. Switchgrass has been found naturally from Central America to southern Canada, and extending from the eastern United States to Nevada (Hitchcock & Chase, 1950). In 1992, research began to focus on switchgrass as part of the U.S. Department of Energy BioEnergy Feedstock Development Program (BFDP). The BFDP was first initiated at Oak Ridge National Laboratory (ORNL) in 1978 to evaluate multiple potential feedstocks for bioenergy. The objectives of this program were the selection of species for maximum potential yield, management requirements, environmental attributes, and economic return. In 1982, the Department of Energy included additional funding to ORNL to start a program primarily for herbaceous crops research (HECP) (Wright & Turhollow, 2010). The HECP main objective was to develop ways to produce herbaceous biomass and energy feedstocks to be commercially viable. Five institutions initiated research and selection of herbaceous crops. The study found yields from lignocellulosic crops were the greatest of sources studied. Switchgrass was the highest yielding candidate of the 30 herbaceous plant species included in the project. Switchgrass had deep roots, reduced risk for the grower, lower inputs, and environmental benefits such as minimizing soil erosion, increasing carbon sequestration, and providing wildlife habitat (Wright & Turhollow, 2010). As the program moved forward with switchgrass research, the goals were first to identify superior cultivars and their optimal production ranges, and second to initiate germplasm collection and breeding efforts to improve switchgrass.

There are two main switchgrass ecological types - lowland and upland. Lowland ecotypes naturally occur on lowland landscape positions in the southern regions of the United States. They are taller, have thicker stems and broader leaves and have greater yield potential than upland ecotypes. Upland ecotypes have a lower nitrogen (N) demand and occur on higher landscape positions that have less available water (Porter, 1966). Although the ecotypes are often characterized by northern and southern regions, they are not limited strictly to these regions. That said, for use in biomass production, it has been recommended switchgrass ecotypes should not be moved more than one hardiness zone from the population's origin (Casler, 2005), primarily due to the photoperiod sensitivity of switchgrass. The plant is well adapted to its specific area of origin for productivity, survival, and adaptability. Switchgrass lowland varieties showed improve survival when moved to southern regions; the equivalent is true for upland switchgrass when moved north (Casler et al., 2007). Switchgrass was responsive to latitude when comparing different species and ecotypes. The adaptations for five switchgrass varieties; Blackwell, Cave-in-Rock, Shawnee, Alamo, and Kanlow were compared below the Mason-Dixon Line. The upland varieties (Blackwell, Cave-in-Rock, and Shawnee) were shown to be limited to Texas in the south and Arkansas in the north. Alamo and Kanlow were not affected for the second year, but as the stand matured, the optimal region ranged from Missouri to Arkansas and Oklahoma. Kanlow and Alamo were the highest yielding when compared in Virginia, Tennessee, Iowa, West Virginia, Kentucky, North Carolina, Alabama, Georgia, and Texas (Kiniry et al., 2013).

Switchgrass grown on silty clay loam and sandy loam had significant differences in development for two varieties (Cave-in-Rock and Blackwell). Rooting development was better on sandy loam soils for the first year. As the switchgrass matured, biomass yield was greater on silty clay loam, because of increased water availability during a drier growing season (Nasso et al., 2015). Sand content had a poor correlation to switchgrass yield (Di Virgilio et al. 2007). Switchgrass yield had a positive correlation to soil N and phosphorous (P), moisture, and pH. Root distribution for switchgrass extended 330 cm below the soil surface. The majority of the roots were in the top 15 cm of the soil. The same study found that overall root weight density for Cave-in-Rock was 29.4 and 47.6% greater than Alamo and Kanlow, respectively (Ma et al., 2000).

Switchgrass responded to N application and moisture. Reported switchgrass yield during drought conditions was reduced by up to 80%. Yield increased with N application (Barney et al., 2009). Yield was influenced by ecotype and N application, with lowland ecotypes requiring less N than the upland variety (Porter 1966). When N was applied, regardless of geographic region, biomass yields increased. In a study considering overall dry matter (DM) yield for two N treatments and two water, levels, N was more important than moisture. Kanlow was less responsive to lower water stress than Alamo. Alamo was the highest yielding variety under all water conditions (Stroup et al., 2003). Switchgrass yield in Texas was not influenced by N and water during the first year, while in the second year, yield increased with N application but not increased water (Sanderson and Reed, 2000). Northern, upland varieties of switchgrass, had increased water use efficiency with added N (Stout, 1992). Many studies reported an optimal rate of N application. In Illinois, the reported optimal range of N was between 56 and 112 kg ha^{-1} (Anderson et al., 2013). In Iowa, N increased yield, but at higher N-rates the biomass yield response was lower (Lemus et al., 2008). In Texas, the optimal N-rate was 168 kg ha^{-1}. Lodging occurred at a rate of 224 kg ha^{-1} N. This study also found that P was not crucial to increasing biomass yield (Muir et al., 2001). The application of 224 kg ha^{-1} N increased yield over 30% for the three locations in Minnesota. The study also found P and potassium (K) application did not significantly increase yields. Therefore, the recommended N-rate was between 60 and 90 kg ha^{-1} annually (Jungers et al., 2014).

Harvest frequency is an important consideration for switchgrass management. Switchgrass harvested multiple times per year could be considered to meet multiple end-product uses. For example, the first harvest may taken early to provide quality forage for animals and the second harvest for bioenergy production. There is a downside to cutting multiple times, decreased overall yields (Gouzaye et al., 2014). A single cut system was optimal at maximizing overall yield for the south central United States (Sanderson et al., 1999). Another consideration is when to harvest. Delaying harvest beyond December resulted in a 5.4% decline in yield for switchgrass in Oklahoma (Gouzaye et al., 2014).

Claypan Region

Major Land Resource Area (MLRA) 113 is known as the Central Claypan Region. The 33,150 square kilometer (3.3 million ha) area is located in central Missouri and southern Illinois as shown in Fig. 1.1. Central Missouri comprises 31% of the total area or approximately 1 million ha. The region in central Missouri ranges across 17 counties (NRCS, 2006).

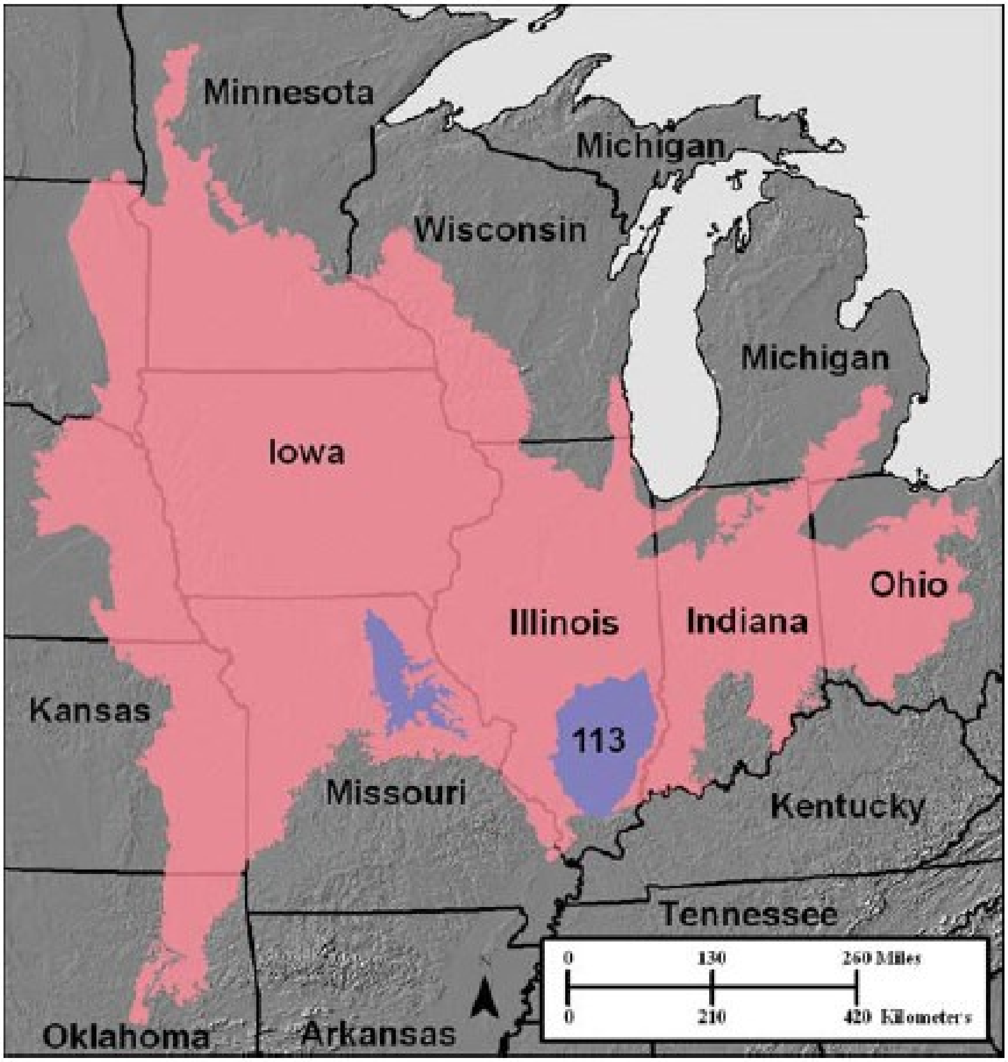

Figure 1.1: The claypan region MLRA 133 encompasses the purple highlighted area in Illinois and Missouri (NRCS, 2006).

The claypan region is characterized by extreme soil variability within the soil profile and across the landscape. Soils typically have an argillic (or claypan) horizon which contains <50% more clay than the above horizon (Kitchen et al., 1999). The claypan horizon often contains 45-65% clay. The depth of the restrictive clay layer was reported to be between 0.15 to 0.61 m below the soil surface (Jamison, 1968). A more recent study reported a range in depth to the claypan with summit landscape soils at around 35 cm, eroded backslopes to 10 cm or less, and depositional footslopes between 50 to 100 cm (Myers et al., 2007).

The claypan region has a diverse set of landuses; the most common is cropland comprising 67% of the total land. The remaining landuse includes grassland (11%), forest (13%), and urban (5%). The region's crops include corn, soybeans, feed grains, and hay for livestock (NRCS, 2006). This region is vulnerable to soil erosion, especially in areas where farming practices have not improved. Improved practices include reduced tillage, no-till, crop rotation with wheat or grasses, and cover crops (Lerch et al., 2008; Jamison, 1968).

MLRA 113 soils are characterized as Alfisols and the soils series include Armstrong, Hoyleton, Keswick, Hickory, Ava, Bluford, Mexico, Leonard, Putnam, Cisne, and Wynoose. The most common for the Missouri section of the claypan region are Armstrong, Adco, Leonard, Mexico, and Putnam (Myers et al., 2007; NRCS, 2006)

Claypan soils are dominated by smectitic clay minerals with high shrink-swell potential. During winter and spring, the soil is swollen with water. Water infiltration is lower in these soils because of lower saturated hydraulic conductivity (Blanco-Canqui et al. 2002). Claypan soils are known for perched water and lateral flow above the claypan (Blanco-Canqui et al., 2002). The hydraulic conductivity decreases because of soil density, texture, and structure as a function of depth. During summer months, the claypan soils develop cracks due to lack of water. The backslope landscape position has the largest cracks and water depletion (Baer and Anderson, 1997).

ALMANAC Model

Agriculture Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) is a process-oriented plant growth model initially developed to simulate crop-weed competition (Kiniry et al., 1992). The ALMANAC model was designed to be used for multiple crops with readily available weather and readily available SSURGO soil data for different geographic regions. The model uses Beer's Law to simulate the fraction of light interception by the plant's leaves. Each plant has a specific leaf area index (LAI) that determines the amount of light intercepted. Radiation use efficiency (RUE) which is influenced by vapor pressure deficit determines biomass growth directly (Kiniry et al., 1992). Nutrient balances are determined by meeting plant demands from soil nutrients available within the root zone. The model parameters for switchgrass were taken from parameters equal to pasture in the Environmental Policy Integrated Climate (EPIC) model (Kiniry et al., 1996). To determine stress, calculated in days, the model determines the available water and nutrients within the root zone and simulates plant uptake. Switchgrass rooting depth, used in the model, was obtained through lab measurements and set by default to 2.2 m (Kiniry et al., 1996).

The ALMANAC model has been used to simulate switchgrass yields on different sites in both the Northern and Southern United States. The Southern sites included the states of Texas, Louisiana, and Arkansas. The model successfully simulated mean yields for all locations, but year to year yield variability between simulated and measured yields was identified as a problem (Kiniry et al., 2005). Sensitivity analysis was completed for these southern sites for curve number and maximum stomatal conductance. Increasing curve number from 65 to 90 resulted in 0% to 16% change in yield at the different sites.

With greater maximum stomatal conductance, yields both increased and decreased (Kiniry et al., 2005).

The northern sites included the states of North Dakota, South Dakota, and Nebraska. The model simulated mean annual yield with differences between measured and simulated yields below 15% for seven of the ten sites. The sites with the greatest difference had the highest rainfall. Maximum and minimum simulated yields were within 15% of the mean measured yield. The northern sites were sensitive to season duration, soil water, and soil N when modeled (Kiniry et al., 2008). Curve number again was tested for sensitivity and yield did not change significantly. Increasing and decreasing curve number by ten units affected yield by less than 10%. Increasing temperature increased yield by 10%, but increasing in temperature by greater than 9^{o} C decreased yield by more than 32% (Kiniry et al., 1992).

ALMANAC was used to simulate water use efficiency (WUE) and radiation use efficiency (RUE) for switchgrass over diverse sites in the United States. The RUE was split into two groups. Alamo mean RUE was found to be 4.3 g Mj^{-1} over all sites. Cave-in-Rock was in the lower group with a mean RUE of 74% that of Alamo. Kanlow RUE was 86% of the mean of Alamo. WUE was within the range of measured values. Alamo WUE was the highest mean of 4.5 mg of plant dry weight per gram of water transpired (Kiniry et al., 2012).

Although the following studies do not address switchgrass, they do point out situations that highlight ALMANAC and its functions. Under water-stressed conditions, ALMANAC modeled yields for sunflowers were 13% different than measured yields (Kiniry et al., 1992). ALMANAC model results for these sites were similar to measured yields and demonstrated the potential that ALMANAC holds in simulating sunflower yields for different soils and different climate conditions. However, none of these soils included a claypan. A sensitivity analysis of solar radiation, rainfall, soil depth, plant available water, water in soil, and runoff curve number was done with corn and sorghum crops. A ten-year mean crop yield was evaluated for changes in these input parameters. Each parameter was independently evaluated. Increased solar radiation decreased yields for corn and sorghum simulations. Corn yield decreased under irrigated simulations for both an increase and decrease in solar radiation. Sorghum with irrigation showed increased yield with increased solar radiation. Corn was more sensitive to rainfall and soil depth changes. Decreased rainfall resulted in decreased yield for both corn and sorghum. The decreased soil depth also resulted in decreased yields. Plant available water was shown to only change yield by 10% for a 23% change in plant available water. Increased curve numbers were shown to decrease yields. Curve number and rainfall were shown to be sensitive in simulation including corn and sorghum yields (Xie et al., 2003). When ALMANAC was used to simulate switchgrass in Texas, the model accurately accounted for yield responses to drought and N limited sites. The model also showed a lack of sensitivity to crop parameters when environmental factors are significant. It was recommended that improved soil characteristics for plants with deep roots are needed (Kiniry et al., 1996)

Energy Composition with Near-Infrared Spectroscopy

Ethanol production from switchgrass has been determined using near-infrared spectroscopy (NIRS) (Roberts et al., 2004). This method is a non-destructive means to calculate both the actual and theoretical ethanol yield. Vogel et al. (2011) developed a calibration equation to determine 20 different compositional values. Studies report that the composition of biomass feedstocks can easily and cost-effectively be determined via NIRS. Sanderson et al. (1996) analyzed 121 samples consisting of woody and herbaceous feedstocks for ethanol extractives, ash, lignin, uronic acids, arabinose, xylose, mannose, galactose, glucose, C, H, N, and O using conventional laboratory analysis. These samples were then run through a NIR spectrometer. A modified partial least squares procedure was used to develop calibration equations (Sanderson et al. 1996). Only the equation for lignin, arabinose, and ethanol extractives were within the control limits. This indicates that additional samples were needed for the equations to become more robust (Sanderson et al., 1996).

Another study determined calibrated equations from switchgrass samples selected with a range of maturities, cultivars, ecotypes, fertility rates, and environments. Of the 482 samples, 112 samples were selected calibration. These equations were determined for 20 components including cell wall and soluble sugars. These parameters were then used to determine 13 complex feedstock traits. Feedstocks included theoretical and actual ethanol yields from hexose fermentation (Vogel et al., 2011). The study also determined statistical differences among the switchgrass cultivars, indicating that additional environmental factors may influence ethanol quality and quantity (Vogel et al., 2011).

Ethanol yield is determined from cellulose and hemicellulose sugars (Guimarães et al., 2014). Actual ethanol yields were determined from biomass ethanol parameter and released pentose yield from a laboratory simultaneous saccharification and fermentation (SSF). Theoretical ethanol conversion was assumed to be 100% but actual yields will be less for a biorefinery because of biochemical conversion efficiency and will be dependent on the pretreatment process, enzyme loading requirements, conversion rate, and ability to reduce inhibitors at all conversion stages (Schmer et al., 2012). Switchgrass strains were statistically different for theoretical and actual ethanol yield (Vogel et al., 2011).

Differences in theoretical ethanol yields based on location and time were evaluated using NIRS for sites in North Dakota, South Dakota, and Nebraska, using the cultivars Cave-in-Rock, Trailblazer, Shawnee, and Sunburst (Schmer et al., 2012).Theoretical ethanol yield varied within a single field. Also, precipitation varied quality and biomass yield over multiple years. Drought conditions increased hemicellulose concentration. In this study switchgrass biomass and quality varied temporally and spatially across the regions used in this study and within the field because of environmental factors (Schmer et al., 2012).

N, P, and K were evaluated for influence on switchgrass biomass yield and theoretical ethanol yield in locations in Minnesota. N improved biomass yield at these locations, but P and K had no effect on biomass yield. Ethanol production improved with increased N-rates because yield increased (Jungers et al., 2014).

Theoretical ethanol yield was evaluated based on an analysis of switchgrass response to biosolids application and harvest frequency. The study found that quality and production of Cave-in-Rock with applied biosolids equal to 0, 153, 306, and 549 kg ha^{-1} N showed an inconsistent response. Only during the second year was it observed that a two cut management system maximized yield. The ethanol yield was greatest for the single cutting treatment, and this study recommended that a single end of year cutting would be advantageous for feedstock quality (Liu et al., 2013)

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Chapter 2: Modeling Switchgrass Production on Claypan Soils using ALMANAC

Abstract

Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) was evaluated for modeling switchgrass (*Panicium virgatum* L.), a cellulosic biofuel, on claypan soils. Claypan soils are prone to grain yield fluctuation with varying amounts of precipitation. In this study, simulated yields from ALMANAC were compared with measured switchgrass yields from the Soil Productivity and Resource Conservation (SPARC) plots at the University of Missouri-Columbia. Switchgrass was evaluated with three nitrogen rates, 0, 67, 101 kg ha^{-1}. Switchgrass was established on the SPARC plots in 2009. The ALMANAC model primarily uses SSURGO soil files and for this study SSURGO files were modified with soil texture and bulk density from samples taken from SPARC. The ALMANAC model results underestimated yields when individual years were compared. Harvest dates in November and December did not capture maximum yield. Harvests in September and October improved model results. The model was also run with annually repeated weather data for the years of 2011, 2012, 2013, and 2014. Simulated yields were cyclical for consecutive years of the same weather based on three of the four weather year patterns. The cyclic pattern became less prevalent for higher N-rates. The model was also run over a 30-year simulation period where mean simulated yields were shown to match mean measured yields only when the N-rates were increased. ALMANAC yield prediction was not sensitive to differing depths to claypan, while measured yields increased with depth to claypan for drier than average

precipitation years. ALMANAC failed to accurately simulate switchgrass on the SPARC plots but through alterations to harvest date and N-rate, simulated yields improved.

Introduction

Grain crop productivity in the Central Claypan Region, Major Land Resource Area 113 (MLRA 113) in Central Missouri and similar claypan regions, is highly variable (Kitchen et al., 1999). The MLRA 113 region encompasses approximately 3.3 million ha in the central United States. The soil profile in this region is characterized by a layer of high clay content, approximately 20 to 40 cm below the soil surface, depending on landscape position. Producing grain crops on claypan soils has resulted in severe erosion and degradation of topsoil depth (Zhu et al., 1989). Erosion is problematic since reduced topsoil depth has been shown to decrease corn and soybean yields (Thompson et al., 1991). With focus shifting from traditional corn and soybean to bioenergy crops, switchgrass (*Panicum virgatum* L.) has the potential to be beneficial economically and environmentally in areas with marginal soils (Landers et al., 2012).

The Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model has been used to simulate switchgrass yields on various sites in both northern and southern regions of the United States. The ALMANAC model is a daily time step model that computes crop yields based on functions developed in the EPIC model (Kiniry et al., 1992b). For southern sites, including locations in the states of Texas, Louisiana, and Arkansas, the model could simulate mean switchgrass yields within 2% of the mean measured yields (Kiniry et al., 2005). They also showed that changes in SCS curve number and maximum stomatal conductance had variable impact on switchgrass yields. There was an indication that year-to-year variability was not accurately predicted by the model but it did accurately predict average yields (Kiniry et al., 2005). Mean simulated switchgrass yields of northern sites (ND, SD, and NE) were within 15% of the measured yields. Simulated yields for northern sites were sensitive to seasonal duration, soil water, and soil nitrogen (N) (Kiniry et al., 2008). The model simulations for mean switchgrass yields responded to changes in degree days to maturity and leaf area index during the growing season.

These results indicate the potential of ALMANAC in simulating switchgrass yields for different soils and different climate conditions. Model performance was dependent on soil depth, precipitation, solar radiation, and SCS curve number (Xie et al., 2003). However, none of the above studies included claypan soils of MLRA 113. Later, ALMANAC simulated yields were compared to measured yields over several areas, including central MO claypan soil. Measured yields for Kanlow switchgrass were greater than the simulated yields for the claypan site by 13.7%. The model over-estimated yields by an average of 33.4% for Blackwell and Cave-In-Rock switchgrass varieties for the same site. It was concluded that limited data on maximum rooting depths for different soil types restricts development of cultivar specific parameters (Behrman et al., 2014). In ALMANAC, maximum rooting depth for switchgrass is set to 2.2 m by default, independent of soil type (Kiniry et al., 1996).

The objective of this study was to evaluate the ALMANAC model for predicting switchgrass production on claypan soil landscapes. Specifically, the model simulated yields were compared to measured switchgrass yields using identical management scenarios as those used in the field as well as simulated earlier harvest dates. A secondary objective was to evaluate ALMANAC for a longer period using historical weather to predict long-term average switchgrass production on claypan soil landscapes.

Methods

Site Description

Switchgrass was established in 2009 on the Soil Productivity and Resource Conservation (SPARC) plots at the University of Missouri South Farm, near Columbia, MO. These plots were originated in 1982 as the ERASE plots by adding and removing topsoil depth to a Mexico Silt Loam (Gantzer and McCarty, 1987). Prior to SPARC, the plots were in corn and soybean production for 12 years (1982-1993) followed by fallow for 15 years with native vegetation (1994-2008).The SPARC plots consisted of 32 blocks divided equally into two different experiments in a completely randomized, split plot design. Topsoil depth was the main effect and grain and switchgrass management were the slit-plot treatments and randomized within blocks. Each block in Experiment 1 consisted of 4 plots, 6.1 by 10 m in dimension. Blocks in Experiment 2 consisted of 6 plots, 5.3 by 10 m in dimension. The plots were planted in June 2009 with Kanlow and Cave-In-Rock switchgrass varieties. The Cave-In-Rock was discontinued after 2011 to allow Miscanthus production to be evaluated on these same plots. Nitrogen fertilization treatments included N-rates of 0, 67, and 101 kg ha^{-1} applied in late spring to early summer. The first harvest was collected in December of 2010. Harvests for each year after were between November and December.

In 2010, switchgrass samples were harvested by cutting two 0.91 m by 7 m swaths from each switchgrass plot. In 2011, two 0.74 m by 7 m swaths were cut. From 2012 to 2014, switchgrass yield samples were harvested by cutting one 1.37 m by 7 m swath in the middle of each plot. Switchgrass was cut at approximately 10 to 17 cm above the soil surface (Allphin, 2011). Biomass was collected by hand and weight measurements were taken using a calibrated scale in the field. All biomass samples were dried in accordance with ASABE Standards S358.2. Moisture was calculated, and yields determined on a dry matter basis.

Annual values of total solar radiation and precipitation are shown in Fig. 2.1. For the 6-year period from 2009 through 2014, mean solar radiation was 5,190 MJ m^{-2} with little variation from year-to-year. However, the maximum precipitation difference for the same 6–year period was 726 mm. This large difference in precipitation was considered useful in evaluating how the model responded to available water.

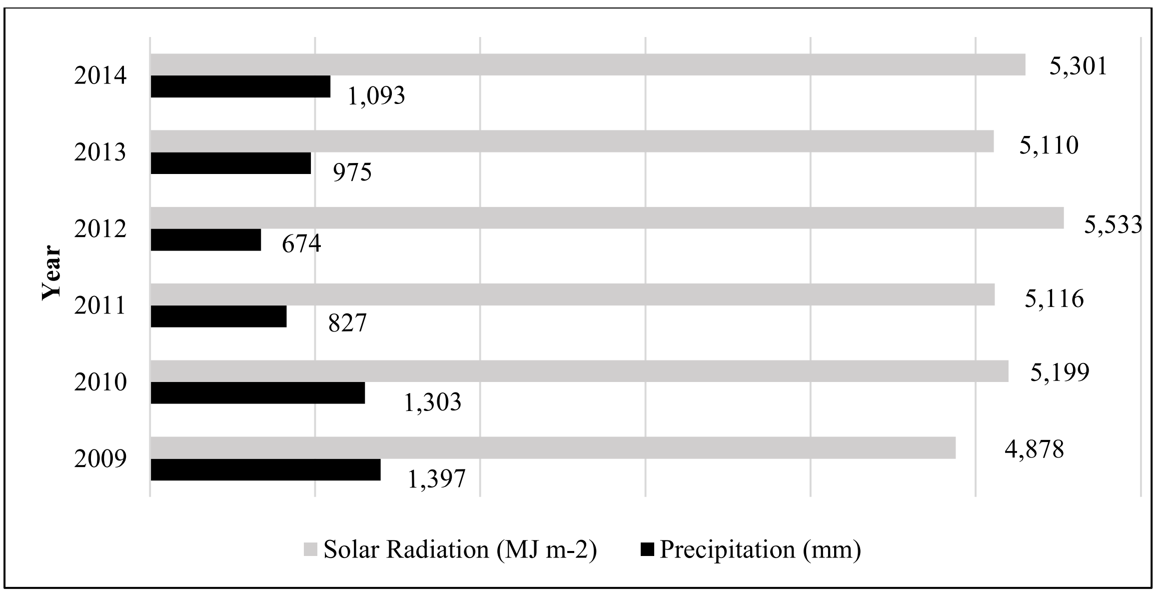

Figure 2.1: Total precipitation and total solar radiation for SPARC plots from South Farm, Columbia, MO weather station.

Soil Description

The Natural Resources Conservation Service SSURGO database was used as soil input in ALMANAC. Mexico Silt Loam, slopes 1 to 4% eroded, identified as the soil at SPARC, was used as the soil input for ALMANAC (Thompson et al., 1991). This soil has a high clay content of 56% starting at 0.3 m below the soil surface. For one modeling scenario (scenario 3), the SSURGO soil was then further modified with measured soil parameters including bulk density and sand, silt, and clay percentages. The measurements were from soil samples collected in 2009 at the beginning of the SPARC study. These samples were collected from each of the 32 blocks and analyzed by the University of Missouri Soil Characterization Lab. Each profile had the depth to the argillic horizon determined by a soil scientist. Apparent electrical conductivity (EC_a) was measured using DUALEM-2S (Dualem Inc., Milton, ON, Canada) for all 160 plots. A regression calibration with EC_a values and argillic horizon depths were converted into depth to claypan (DTC) following methods previously described (Kitchen et al., 1999; Sudduth et al., 2010). The plots were divided into four soil classifications based on average DTC. Soil classification "A" had a DTC less than 8 cm, classification "B" ranged from 8 to 15 cm, classification "C" ranged from 15 to 27 cm, and classification "D" was a DTC greater than 27 cm (Landers et al., 2012).

ALMANAC

The ALMANAC model supports a variety of simulations to evaluate effects of differences in soils and management on yields of diverse crops. For comparison to the measured yields, the simulation included three years of initialization to stabilize the model and soil conditions. These initial three years were run using generic management dates similar to the management that occurred on the plots during the actual years of harvest. The model weather inputs included solar radiation, maximum and minimum temperature, and precipitation measured at the weather station located at South Farm, Columbia, MO.

The model was run with fertilizer treatment rates of 0, 67, and 101 kg ha^{-1} N to simulate switchgrass yields for the measured plots. Simulated fertilizer application dates were the same as the actual dates used on SPARC. The simulations were run using actual SPARC harvest dates, plus October and September harvest dates as shown in Table 2.1. When SPARC harvest dates were not evaluated, November and December dates were used in addition to October and September.

Table 2.1: ALMANAC simulation harvest dates.

Simulation Year	Actual SPARC Dates	December Simulation	November Simulation	October Simulation	September Simulation
2010	December 5	December 5	November 5	October 5	September 5
2011	November 1	December 5	November 5	October 5	September 5
2012	December 12	December 5	November 5	October 5	September 5
2013	November 18	December 5	November 5	October 5	September 5
2014	December 1	December 5	November 5	October 5	September 5

Scenario 1: ALMANAC with SSURGO

To accomplish the first objective, ALMANAC was run using the SSURGO dataset soil Mexico Silt Loam, 1 to 4%, eroded for all three N-rates. The simulations were run first with actual SPARC harvest dates as shown in Table 2.1. Simulation harvest dates were then moved to earlier dates in October and September as in Table 2.1. To stabilize N and moisture in the soil, each simulation run included three initialization years. Therefore the model was run for a total of 9 years (2006 to 2014). Beginning with the 2010 year of the simulation, yields were compared to the coinciding SPARC yields with similar DTC based on the SSURGO Mexico silt loam, slopes 1 to 4% eroded and modified SSURGO Mexico silt loam, eroded.

Scenario 2: ALMANAC Weather Repetition

ALMANAC was additionally evaluated by repeating the same year's weather for every year of a 12-year simulation. Repeating the same weather conditions each year allowed the yields to be evaluated independent of variable weather conditions. Weather for the years of 2011, 2012, 2013, and 2014 were tested. Rates of N included were 0, 67, 101, 150, and 200 kg ha^{-1}. Planting occurred on June 1 in the first year of the simulations. Fertilizer was applied on June 17 every subsequent simulation year. Harvest was set for September 5th for all simulations after year 1.

Scenario 3: ALMANAC Modified SSURGO

ALMANAC was run using the modified SSURGO dataset soil Mexico Silt Loam, 1 to 4%, eroded for all three N-rates. The SSURGO dataset was altered to include soil texture and bulk density from SPARC measured soil samples. The soil horizon depths were altered to be consistent with depths corresponding to measured soil samples. The simulations were run first with actual SPARC harvest dates as shown in Table 2.1. Simulation harvest dates were then moved to earlier dates in October and September as in Table 2.1. To stabilize N and moisture in the soil, each simulation run included three initialization years. Therefore, the model was run for a total of 9 years (2006 to 2014). Beginning with the 2010 year of the simulation, yields were compared to the coinciding SPARC measured yield.

Scenario 4: Longer Simulation

The ALMANAC model 30-year mean simulated yield was compared to mean measured yields from SPARC. The comparison for long-term simulation of Kanlow switchgrass for 30 years used weather generated from means measured at Jefferson City airport, approximately 37 km from the research site. Rates of N simulated were 0, 67, 101, 150, and 200 kg ha^{-1}. Harvest dates included December, November, October, and September as shown in Table 2.1. Measured yields were calculated using SPARC data from 2011 to 2014 from for plots with claypan depths similar to that of the Mexico silt loam, 1 to 4% eroded. ALMANAC simulation was averaged over the 30-year simulation for the Mexico Silt Loam, 1 to 4% eroded as shown in Table 2.3.

Data Analysis

Measured results were averaged across claypan soil class, nitrogen treatment, and year. A 95% confidence interval was calculated for each mean yield.

Results and Discussion

Mean Measured SPARC Yield

Measured mean switchgrass yield for the three N-rates, 0, 67, and 101 kg N ha^{-1} were averaged, and a 95% confidence interval was determined as shown in Fig. 2.2. Mean switchgrass yield was compared for individual years, and yield appeared to increase between N-rates 0 and 67 kg ha^{-1}. That greater N-rate had greater yields can be expected, as multiple studies have reported this observation (Anderson et al., 2013; Lemus et al., 2008; Muir et al., 2001; Jungers et al., 2014). Mean switchgrass yield did not appear to increase from 67 to 101 kg N ha^{-1}. In 2012, mean switchgrass yield increased when comparing claypan soil classes “A” and “D”. Soil class “A” had the lowest topsoil depth and “D” the greatest. In years where precipitation was greater than 2012, only 2013 had a similar pattern, but only for the 67 and 101 kg ha^{-1} fertility rates.

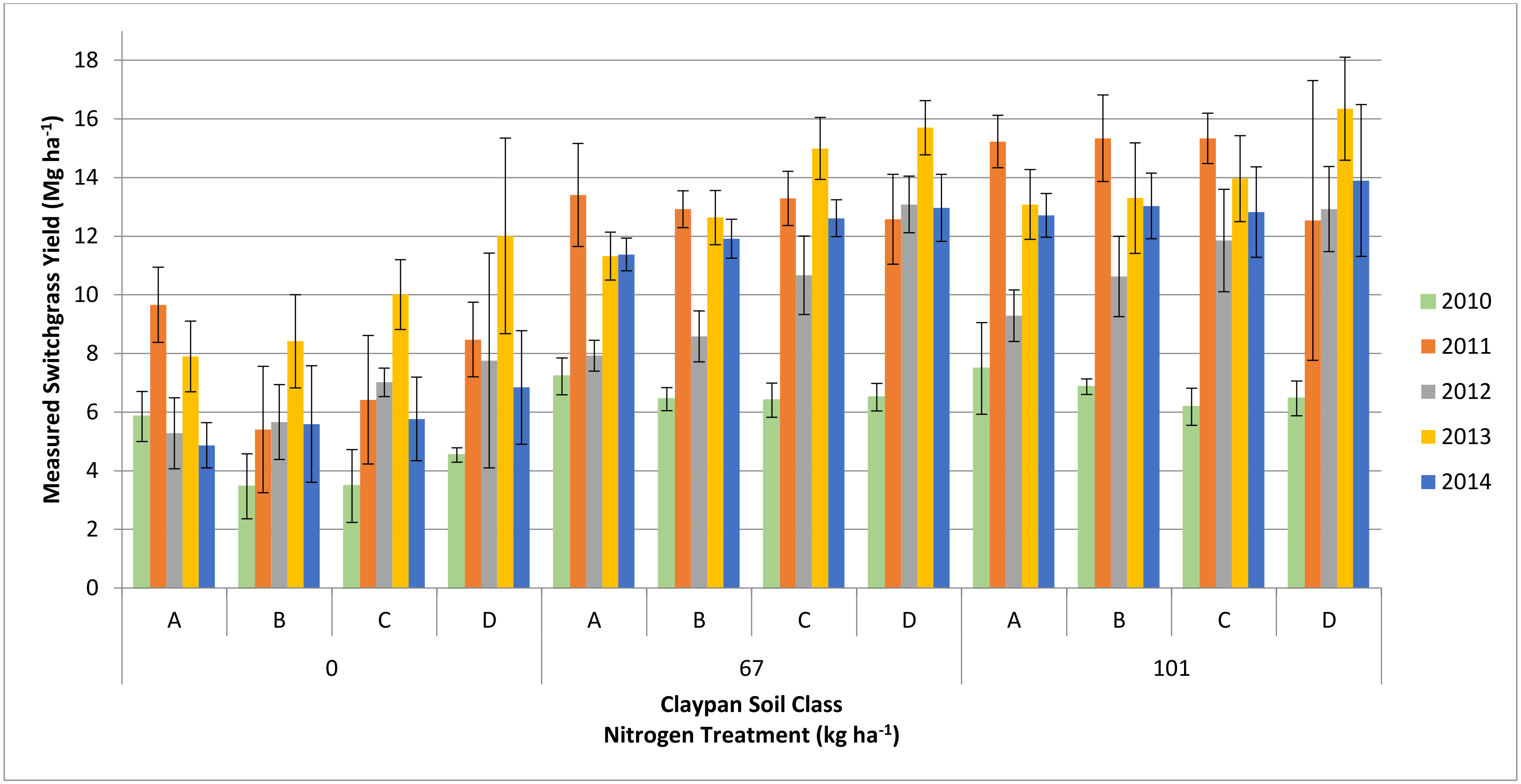

Figure 2.2: Measured switchgrass yields on SPARC plots located near Columbia, MO for three N-rates, from 2010 to 2014. Switchgrass yield was averaged over claypan soil class and N-rate. Confidence interval indicates a 95% probability that means lie within the interval.

Scenario 1: ALMANAC with SSURGO

The yields on the measured plots and simulated yields for the 9-year simulation with original SSURGO Mexico Silt Loam, slopes 1 to 4% eroded are shown in Fig. 2.2. The cumulative precipitation for 2010, 2011, 2012, 2013, and 2014 was 1,303 mm, 827 mm, 674 mm, 975 mm, and 1,093 mm, respectively. The measured yields averaged over the five years were 4.0, 5.1, and 4.9 Mg ha^{-1} greater than the simulated yields with original SPARC harvest dates for the 0, 67, and 101 kg ha^{-1} N treatments, respectively.

The simulation results showed that yield following a year with suppressed yields appeared to increase. The simulated yields were lower than measured yields for all years except the year of 2010 for all N treatments. That may be due in part to the assumption of resident N in the initial year when the switchgrass was still reaching maturity. N application improved simulated yields, and during the years of 2011 and 2013 showed that increased N yielded greater than the 0 kg ha^{-1} fertility treatment. Reduced yield for the simulation year 2014 was due in part to the selected harvest date.

The harvest date is important to the model as simulated biomass available for harvest decreases in October. SPARC harvest dates occurred in November and December and the model did not capture the maximum yield. In order to demonstrate the importance of harvest date in maximizing switchgrass yields, the simulated harvest dates were moved to early September and October. The simulated switchgrass yields for the earlier dates were greater than the simulated yield for the actual harvest dates, except in 2011 (Fig 2.3). In the simulations for 2013 and 2014 when the actual dates had lower yields, the yields for the earlier dates were noticeably greater. The simulated yields for 2013 were over 4 Mg ha^{-1} greater using the September and October harvest dates then the actual SPARC harvest dates. In actual field trials for Columbia, MO, harvest occurs following the first frost date. For Boone County MO, the average date of the first frost occurs on October 15th (Missouri Climate Center, 2000). Simulated switchgrass harvests for September and October occurred prior to this.

Scenario 2: ALMANAC Weather Repetition

To consider the impact of weather conditions on simulated yield, a longer simulation was developed by repeatedly using the same weather year. These simulations are shown in Figs. 2.4 to 2.7 for 2011 to 2014, respectively. The precipitation in 2012 was 293 mm lower than the average for 2011, 2013, and 2014 and that year did not have any observable yield cyclic pattern. A lack of water for switchgrass growth limited simulated yields in 2012. In the other three years, the model results indicated cyclical switchgrass yield fluctuation for lower N-rates and longer simulation periods as shown in Figs. 2.4, 2.6, and 2.7. The longer simulation exposed the cyclic trend over multiple years. This may indicate N storage from the previous year has a significant influence on the following year. The application of 101 kg ha^{-1} N increased yields compared to the 67 kg ha^{-1} N treatment, and eliminated the annual cyclical yield fluctuations for the years of 2011 and 2013, indicating the simulated cyclic response was likely related to N deficiency. The 2014 year demonstrated that with increased precipitation the model required greater N-rates to remove the cyclic pattern. With repeated singular weather years of 2011 and 2013 N applications of 150 kg ha^{-1} and 175 kg ha^{-1} were similar, demonstrating a maximum limit to yield considering the weather conditions for those years. Yield was maximized in 2012 using a 101 kg ha^{-1} N-rate. Any larger amounts of N, for that respective weather year, did not further increase yield. This implies that the

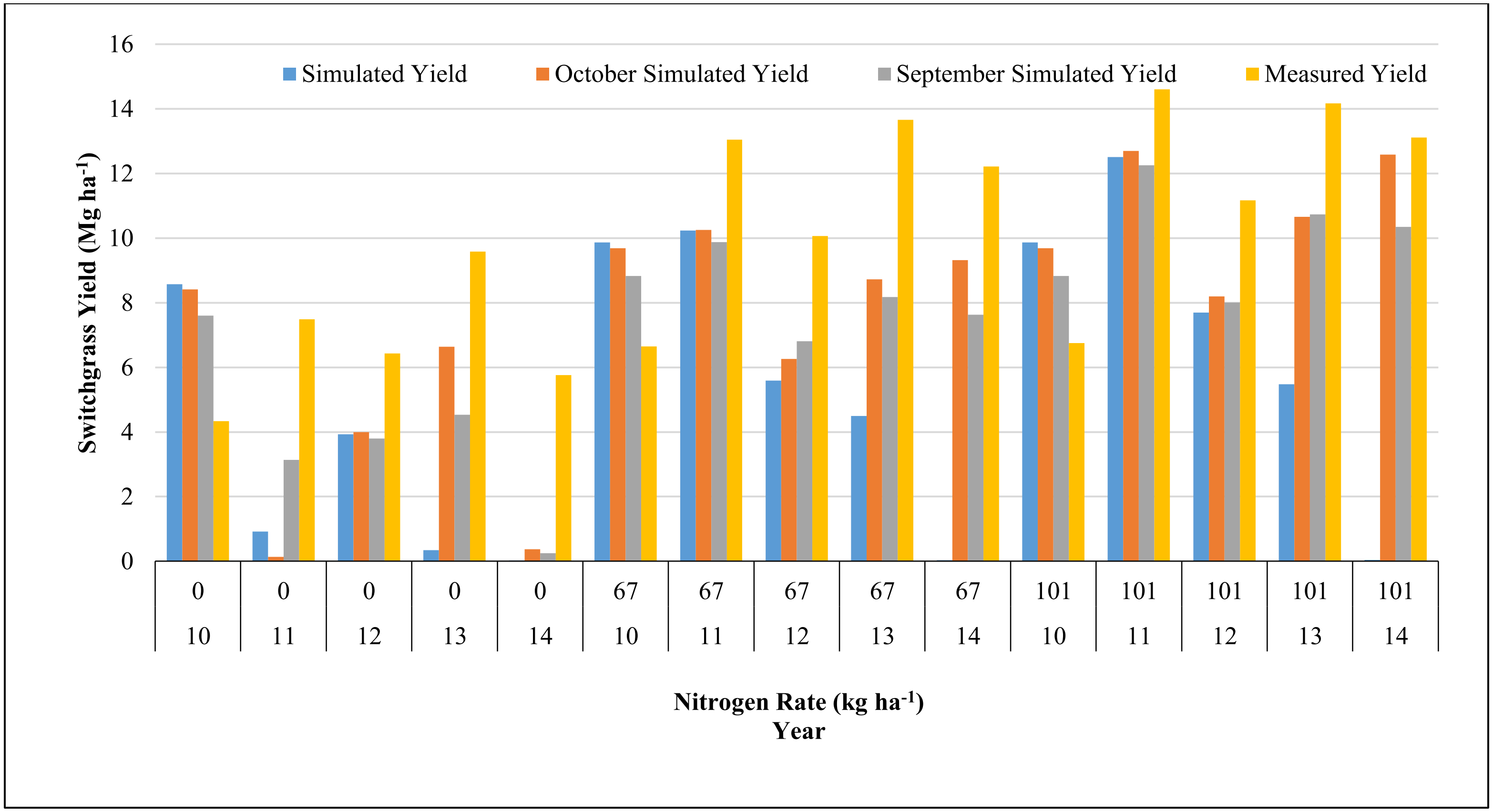

Figure 2.3: Simulated and measured switchgrass yields for SPARC and ALMANAC comparison using Mexico Silt Loam, slopes 1-4% SSURGO original. Yields were simulated with original, October, and September harvest dates for comparison.

plant was not N stressed although other conditions may be limiting perceived N uptake. The timing of harvest with these simulations was critical to matching measured yield. Simulations were run using a September 5th harvest date. When the harvest date was moved to December 5th, the yields for repeated weather years 2013 and 2014 were near 0 Mg ha^{-1} again indicating, degradation of maximum potential yield for the simulations with later harvest dates. Again, simulated biomass available for harvest declines after October. Perennial grasses are commonly harvested after the first killing frost. The model did not accurately simulate this.

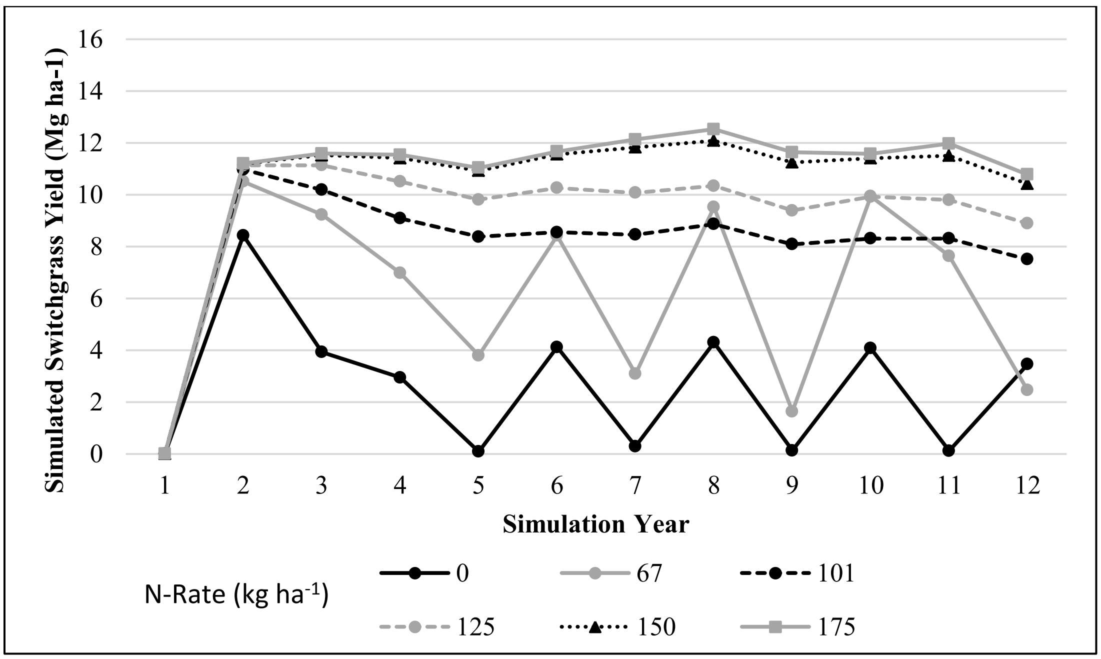

Figure 2.4: Simulated yield results for repeating 2011 Columbia, MO weather over 12 Years with ALMANAC with Mexico Silt Loam, 1-4%; N-rates 150 kg ha^{-1} and greater are similar.

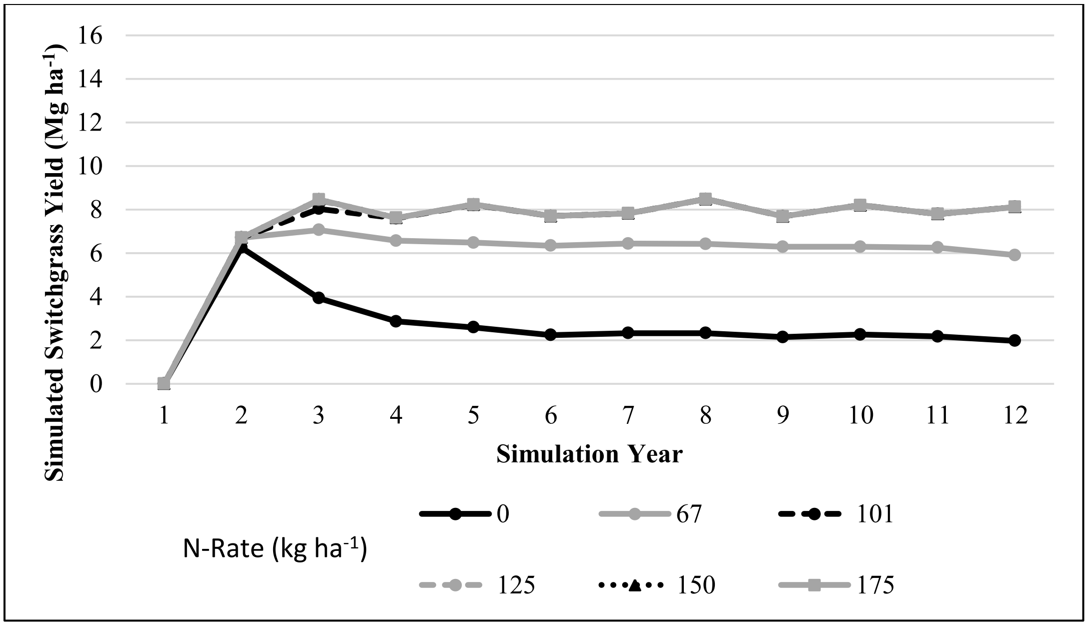

Figure 2.5: Simulated yield results for repeating 2012 Columbia, MO weather over 12 Years with ALMANAC with Mexico Silt Loam, 1-4%; N-rates 67 kg ha^{-1} and greater are similar.

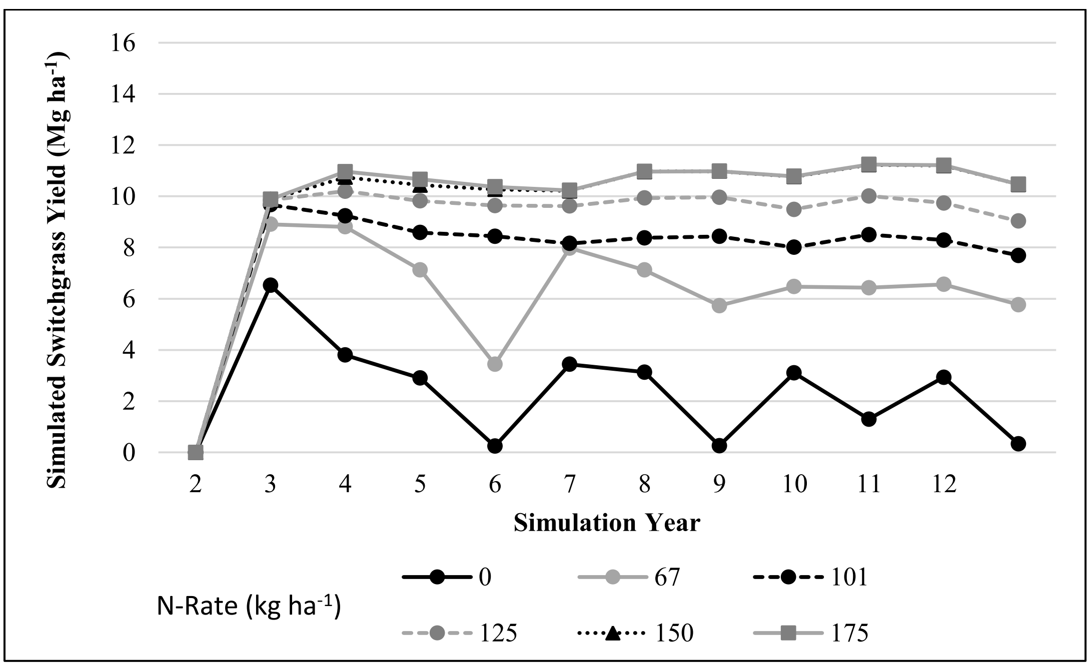

Figure 2.6: Simulated yield results for repeating 2013 Columbia, MO weather over 12 Years with ALMANAC with Mexico Silt Loam, 1-4%; N-rates 150 kg ha^{-1} and greater are similar.

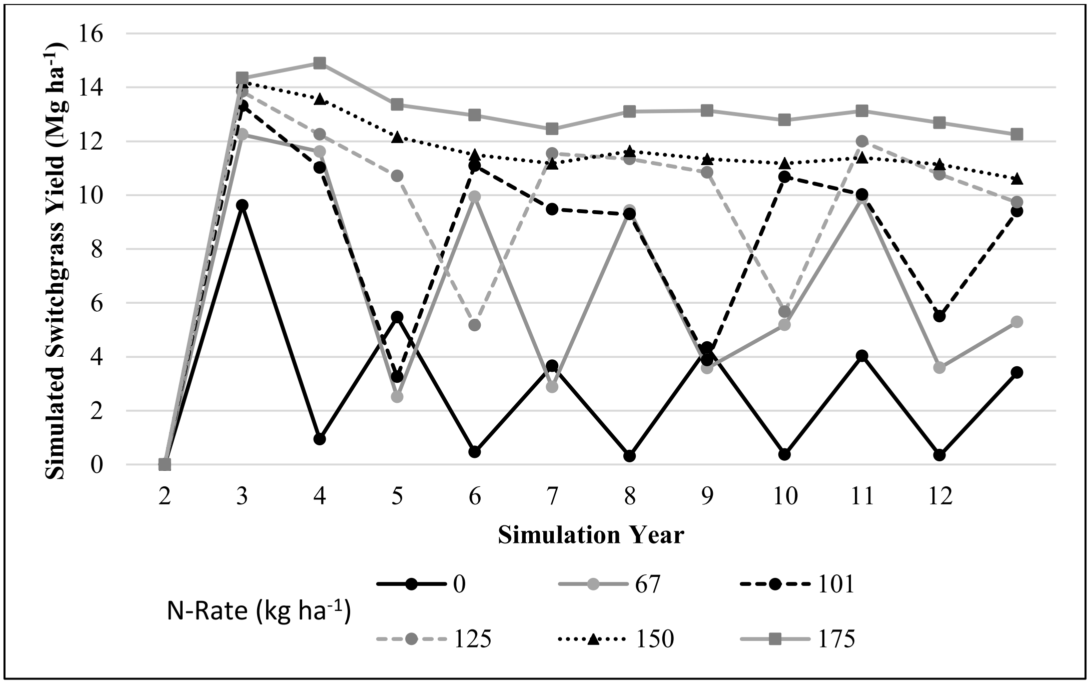

Figure 2.7: Simulated yield results for repeating 2014 Columbia, MO weather over 12 Years with ALMANAC with Mexico Silt Loam, 1-4%.

Scenario 3: ALMANAC Modified SSURGO

To study ALMANAC simulations and the response of switchgrass yield to depth to claypan (DTC), SPARC soil samples were used to modify the SSURGO database with measured bulk density and texture. The model was run for three different N-rates for each soil sample. Switchgrass harvests were also altered to September and October dates as seen in Table 2.1. Simulated switchgrass yields showed (Fig 2.8) that regardless of the year and N treatment, the DTC had little influence on yield. This is contrary to what was observed in the measured switchgrass yields for SPARC during the years of 2012 and 2013. Measured yields increased with DTC during drier years as seen in Fig. 2.2. Unlike simulations run without modified SSURGO soil, simulated yields were similar to measured yields only for the 0 kg ha^{-1} N treatment. Yields increased in 2011 and 2013 and decreased in 2012 and 2013. For the two higher N treatments, the yields were maximum during 2011 and decreased each subsequent year. When looking specifically at 2012, the simulated yield without N inputs was less than 2013 yield. When N was applied, 2012 yield was greater than the 2013 yield demonstrating that the N application improved yield for that specific year compared to the treatment without N. The yields were largely under-simulated for all runs. Yield maximums occurred in the years 2011 and 2013 for the simulated and measured plots, respectively. The simulated yields in 2014 were below 0.5 Mg ha $^{-1}$. This may again be due in part to later harvest date and the cyclic fashion of simulated N and water storage and use. Although modification of soil texture and bulk density altered trends for yield simulations, the model may require modification of additional soil parameters to correctly simulate any difference in claypan soils.

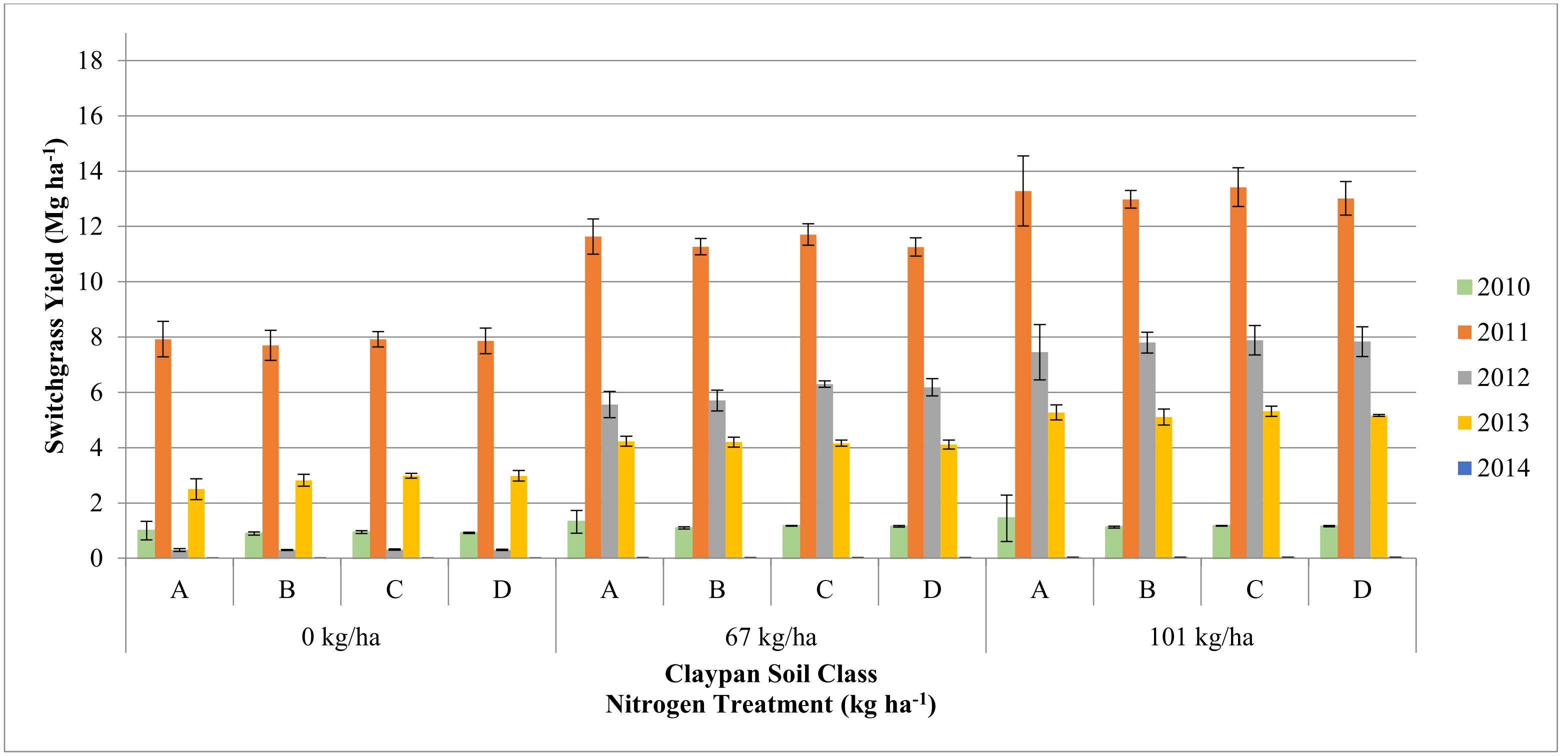

Figure 2.8: Average simulated switchgrass yield with ALMANAC with modified soil SSURGO with different N-rates using SPARC harvest dates for 2010 to 2014. Switchgrass results were averaged based on claypan soil class. Results for 2014 are not observable on the graph due to very low simulated yields. Confidence interval indicates a 95% probability that means lie within the interval.

When comparing measured versus simulated switchgrass yields for individual plots, the measured yields were higher than the simulated yields and usually were higher than simulated yields for all fertility rates as shown in Table 2.2. The measured yields were greater than the simulated yields in 89, 97, and 99% of the plots for 0, 67, 101 kg ha^{-1} N treatments, respectively. Mean simulated yields were lower than the measured yield for all simulations in 2010, 2012, 2013, and 2014 as shown in Table 2.2. Within a given year, simulated yields differed little, even though DTC were different, and the measured yields had a broad range of values as shown in Figs. 2.9, 2.10, and 2.11. The average difference between the measured and simulated yields was lowest for the 0 kg ha^{-1} N treatment with the earlier harvest dates. The lowest difference between simulated and measured yields with the actual harvest dates was at the highest fertility rate. For the 0 kg ha^{-1} N treatment, average simulated yield for a September harvest was 3.55 Mg ha^{-1} lower than the measured yield as shown in Table 2.2. The 2011 simulated yield showed the lowest difference of the five years. The other N treatments shown in Figs. 2.12 through 2.17 demonstrated that earlier harvest dates were necessary to improve the relationship between measured and simulated switchgrass yields. Although the differences between measured and simulated yields decreased, selection of an earlier harvest date may only be one consideration in improving simulated yields. Increased application of N also improved model performance.

Table 2.2: Average difference of ALMANAC simulated yield and SPARC measured yields for different N-rates, simulated harvest dates, and year.

N treatment	101 kg ha^{-1}			67 kg ha^{-1}			0 kg ha^{-1}		
Dates	SPARC	Oct.	Sept.	SPARC	Oct.	Sept.	SPARC	Oct.	Sept.
2010	3.40	3.41	3.45	5.46	5.48	5.30	5.52	5.01	4.64
2011	-0.36	-0.59	0.14	1.58	0.78	1.36	1.43	1.01	1.47
2012	6.12	6.11	4.99	4.13	3.65	3.63	3.43	3.19	2.63
2013	6.76	3.86	5.02	9.49	5.50	5.65	8.77	3.48	3.55
2014	5.76	5.45	4.83	12.19	2.87	4.54	13.08	0.75	2.80
Overall	4.33	3.65	3.69	6.57	3.66	4.10	6.48	2.72	3.05

Note: Simulated yield subtracted from measured

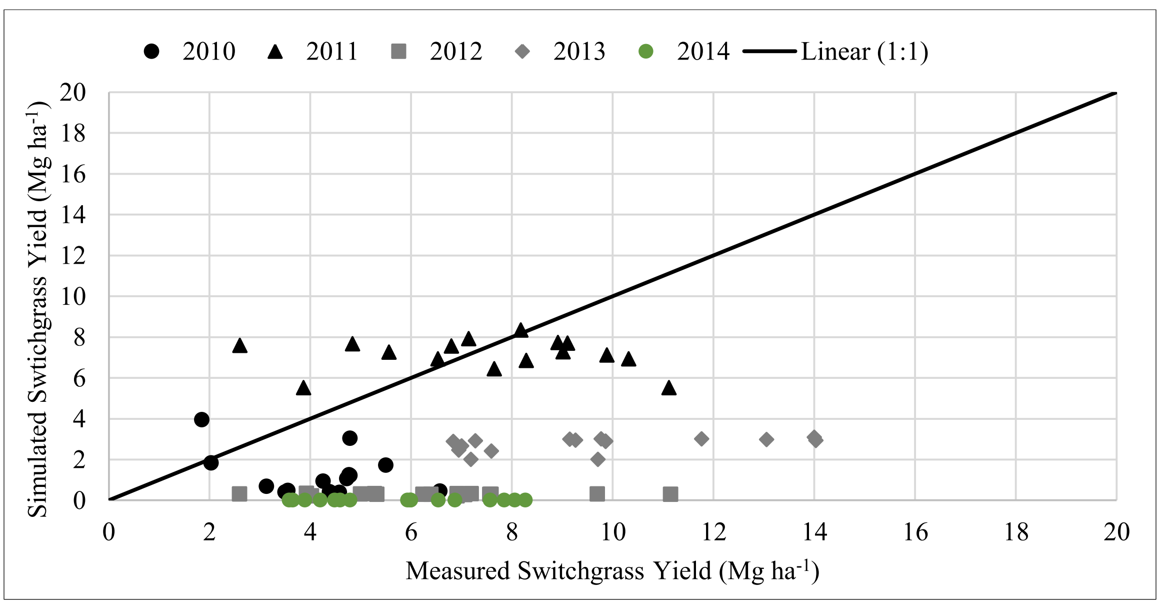

Figure 2.9: ALMANAC simulated vs. measured SPARC switchgrass yields for 0 kg ha^{-1} N-rate using modified SSURGO soil and actual SPARC harvest dates.

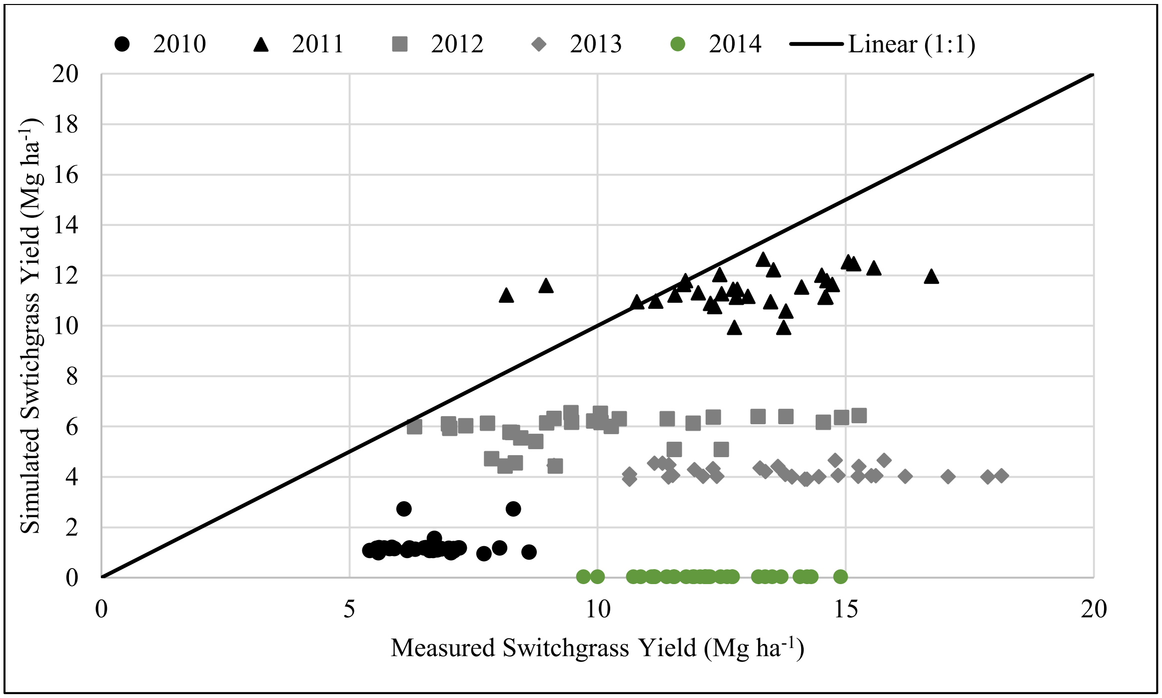

Figure 2.10: ALMANAC simulated vs. measured SPARC switchgrass yields for 67 kg ha^{-1} N-rate using modified SSURGO soil and actual SPARC harvest dates.

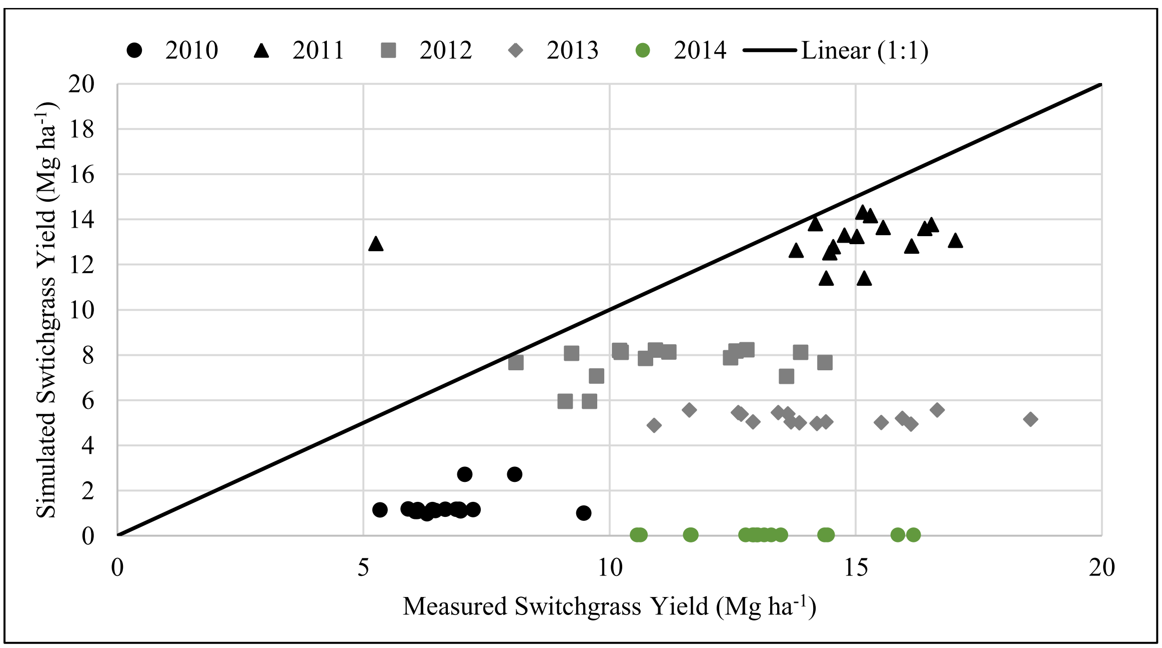

Figure 2.11: ALMANAC simulated vs. measured SPARC switchgrass yields for 101 kg ha^{-1} N-rate using modified SSURGO soil and actual SPARC harvest dates.

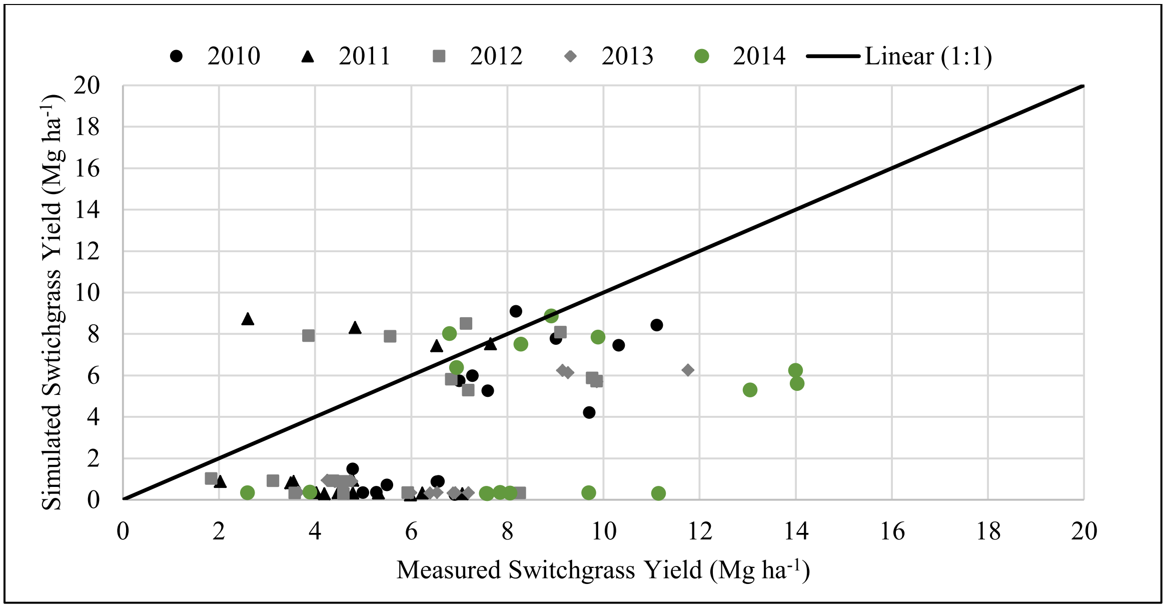

Figure 2.12: ALMANAC simulated vs. measured SPARC switchgrass yields for 0 kg ha^{-1} N-rate using modified SSURGO soil and October harvest dates.

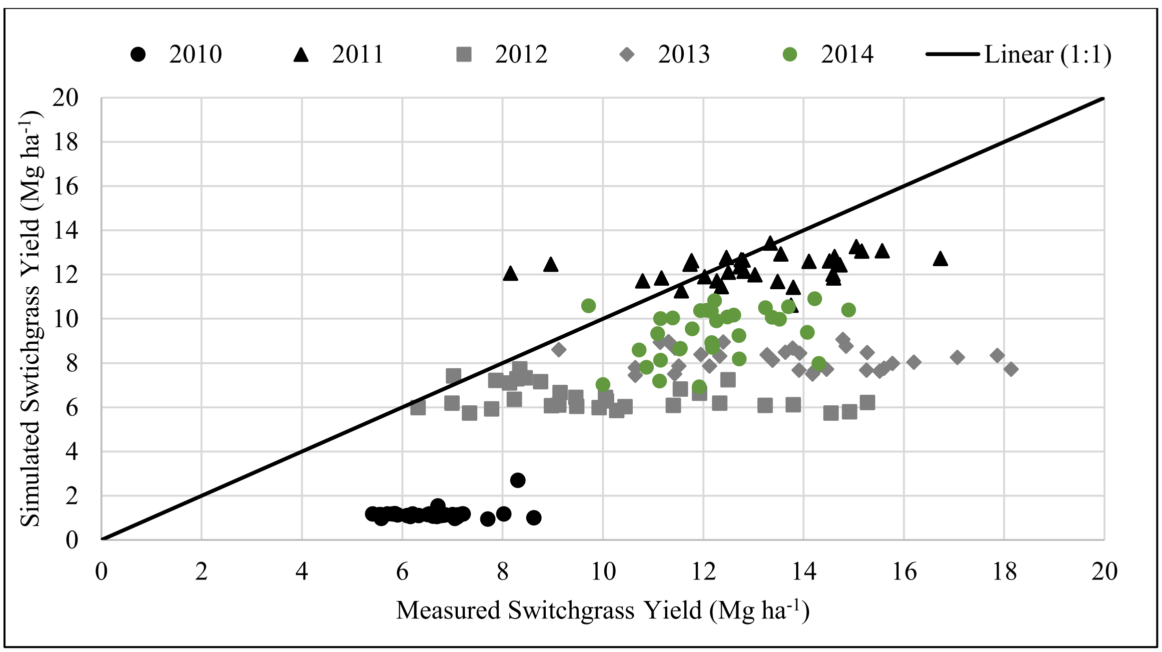

Figure 2.13: ALMANAC simulated vs. measured SPARC switchgrass yields for 67 kg ha^{-1} N-rate using modified SSURGO soil and October harvest dates.

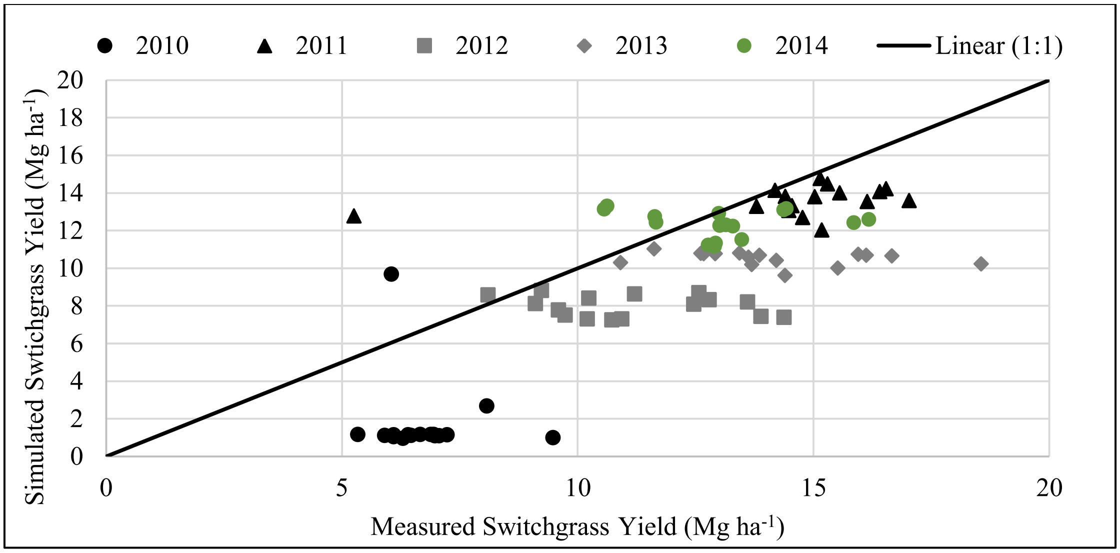

Figure 2.14: ALMANAC simulated vs. measured SPARC switchgrass yields for 101 kg ha^{-1} N-rate using modified SSURGO soil and October harvest dates.

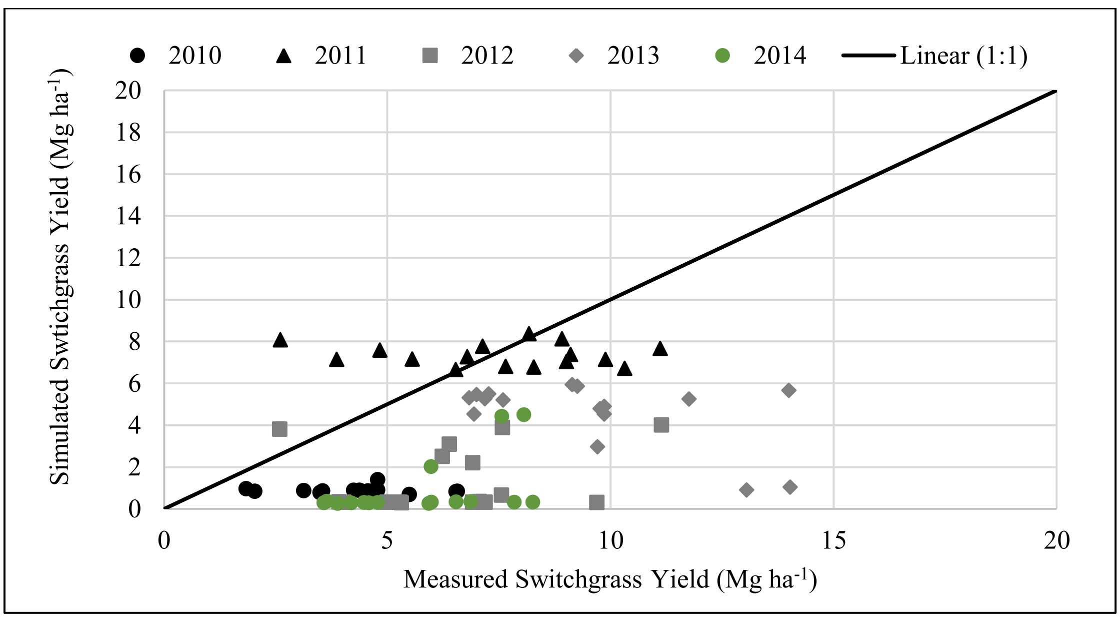

Figure 2.15: ALMANAC simulated vs. measured SPARC switchgrass yields for 0 kg ha^{-1} N-rate using modified SSURGO soil and September harvest dates.

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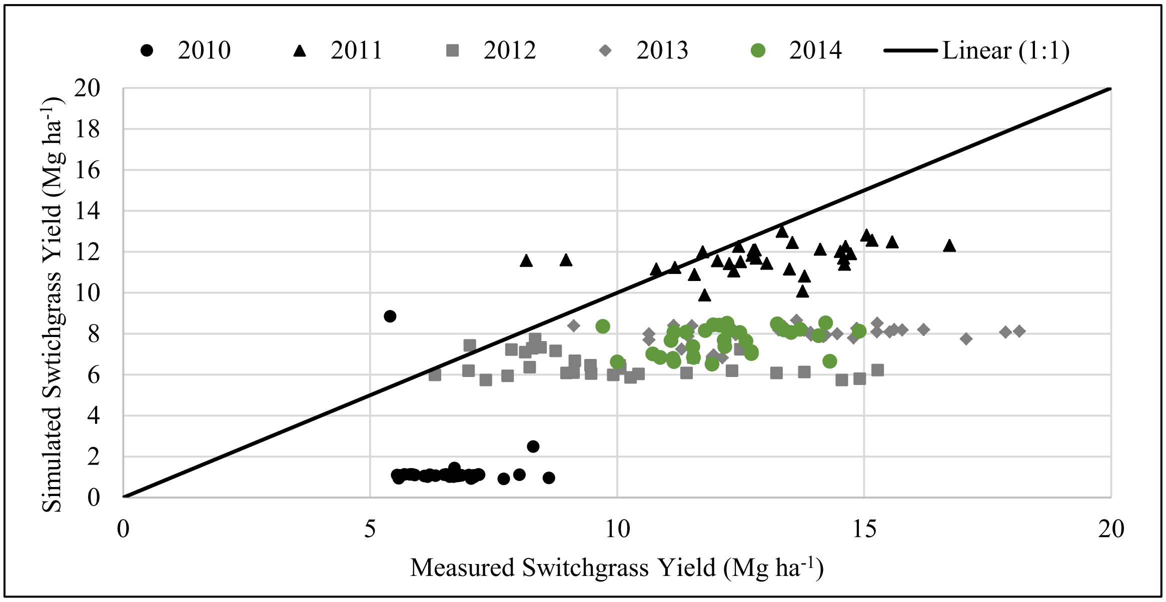

Figure 2.16: ALMANAC simulated vs. measured SPARC switchgrass yields for 67 kg ha^{-1} N-rate using modified SSURGO soil and September harvest dates.

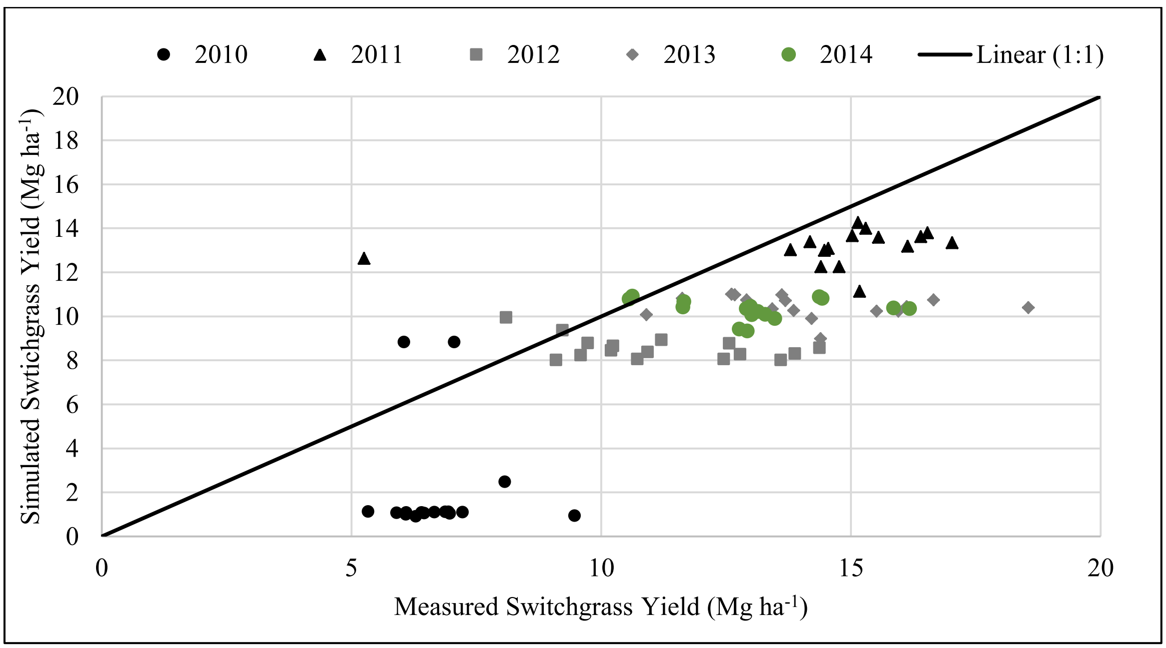

Figure 2.17: ALMANAC simulated vs. measured SPARC switchgrass yields for 101 kg ha^{-1} N-rate using modified SSURGO soil and September harvest dates.

Simulated yields using the modified SSURGO database were further evaluated based on altering harvest date to test how maximum simulated yield potential varied with earlier harvest dates. Under these simulations, the harvest dates were altered in accordance with Table 2.1. The mean simulated yield for SPARC harvest dates was lower because the biomass declined in the months of October and November. With earlier harvest dates, the yields were greater than simulations using actual SPARC dates for the year of 2014 under all circumstances except with 101 kg ha^{-1} N-rate, as seen in Fig. 2.18, 2.19, and 2.20. The simulated yields for 2014 with 67 and 101 kg ha^{-1} N treatments were greater for October dates than the September and SPARC harvest date, except for the 0 kg ha^{-1} N-rate. This indicates that N fertilizer influenced a delay in maximizing yield. For the switchgrass yields with 0 kg ha^{-1} N, it appeared that earlier harvest dates did not influence yield except in 2013. Harvest date may vary optimally based on N-rate and year for each given ALMANAC simulation. In 2011 and 2012 the simulated switchgrass yield was not sensitive to harvest date. The altering of harvest date to maximize the simulated switchgrass yield may require substantial input from the user to define a specific harvest date. The differences in switchgrass yield when using earlier harvest dates and those of the SPARC plots demonstrate that a decline in biomass is difficult to predict in the model. To simulate switchgrass in central Missouri, a harvest date in early October would allow the model to capture biomass that declines in latter parts of the month. Again switchgrass harvests often occur following the first frost. The recommendation to have an early simulated harvest date would not be typical of actual harvests.

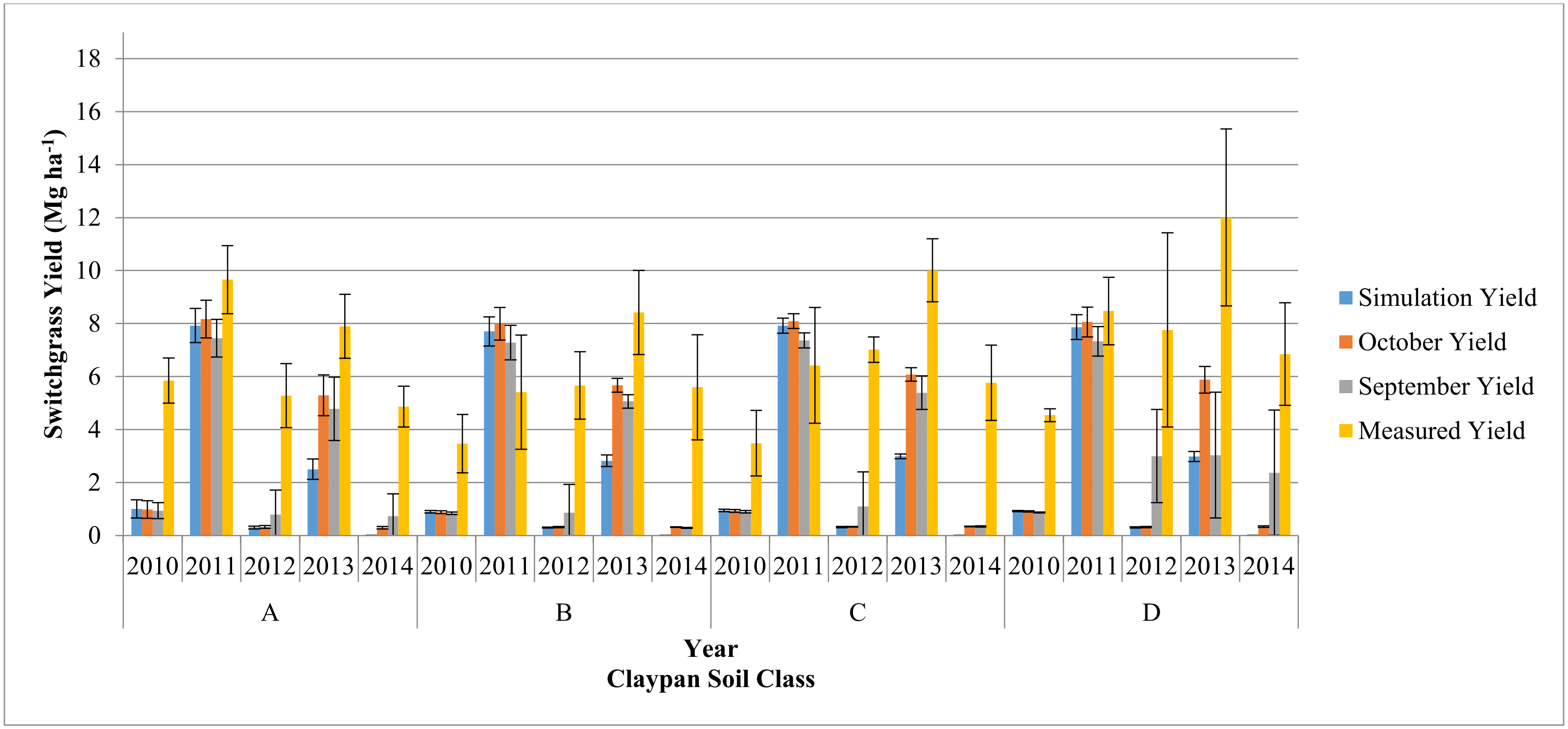

Figure 2.18: Simulate and simulated switchgrass yields for 0 kg ha^{-1} N simulations using SSURGO modified soil profile and multiple harvest dates compared to SPARC measured switchgrass yields. Confidence interval indicates a 95% probability that means lie within the interval.

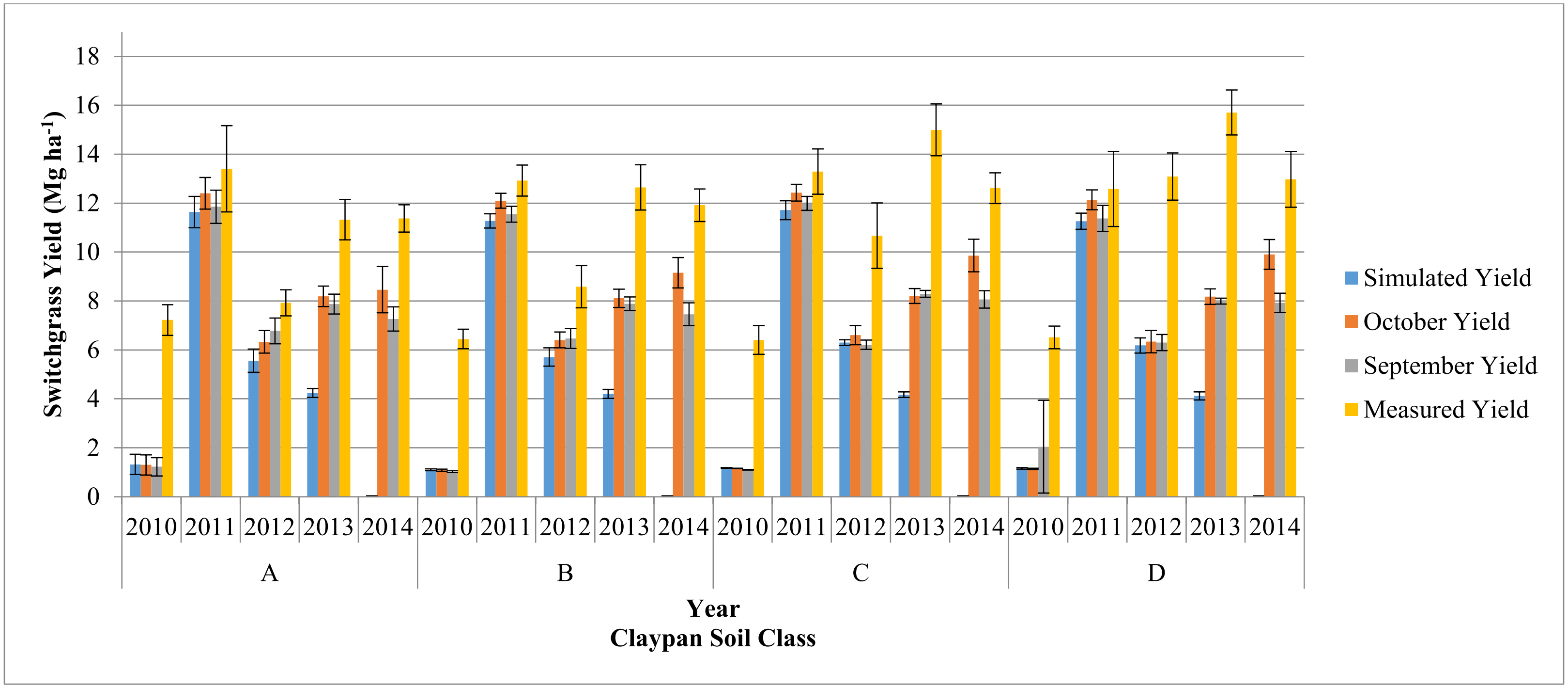

Figure 2.19: Simulated and measured switchgrass yields for 67 kg ha^{-1} N simulations using SSURGO modified soil profile and multiple harvest dates compared to SPARC measured switchgrass yields. Confidence interval indicates a 95% probability that means lie within the interval.

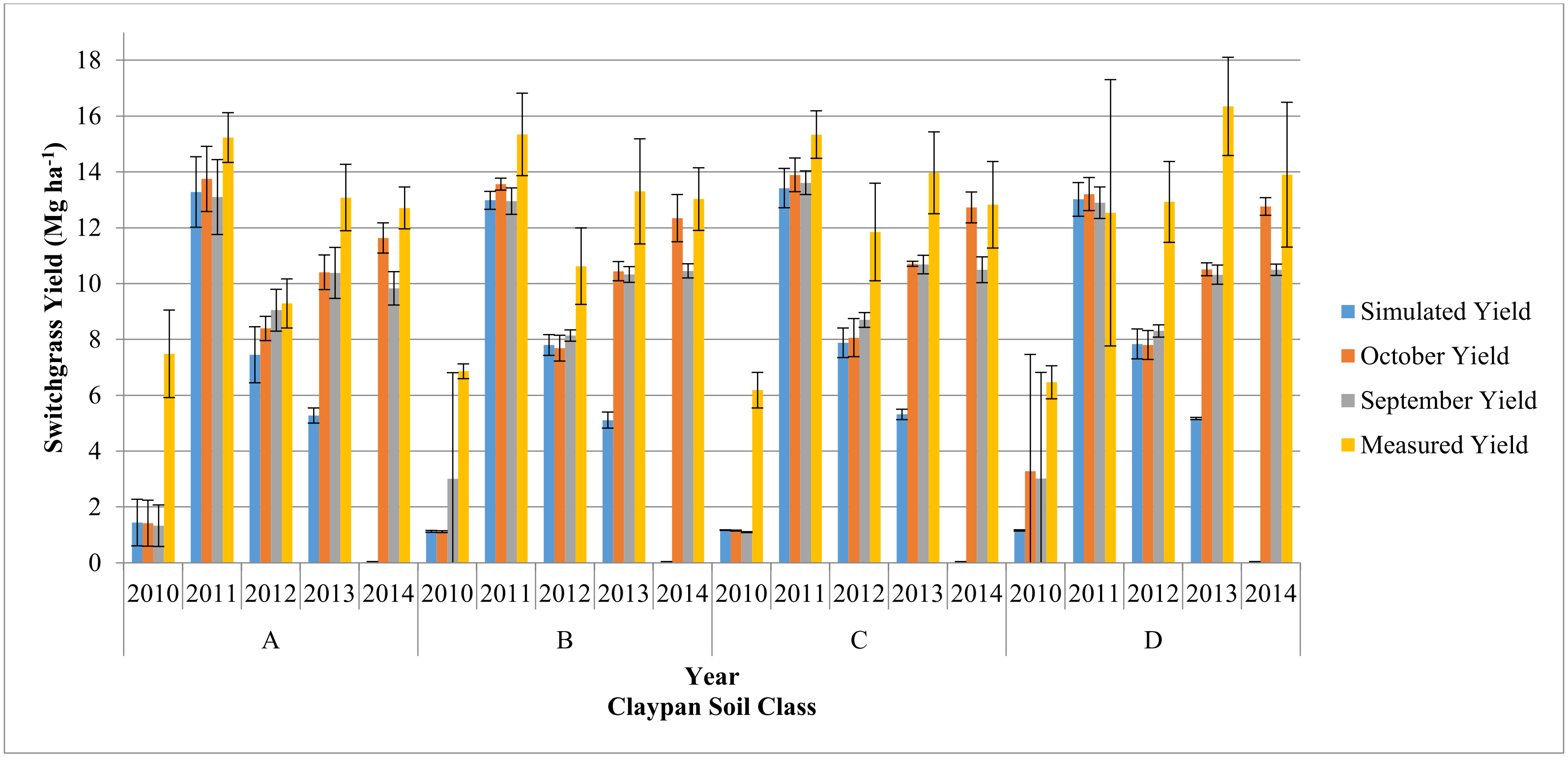

Figure 2.20: Simulated and measured switchgrass yields for 101 kg ha^{-1} N simulations using SSURGO modified soil profile and multiple harvest dates compared to SPARC measured switchgrass. Confidence interval indicates a 95% probability that means lie within the interval.

Scenario 4: Longer Simulations

When the ALMANAC model was evaluated by comparing specific years, it under-predicted measured yields. The ALMANAC model may be more appropriate for longer simulations periods for average yields over time. Therefore, the final objective was to simulate a longer 30-year period with generated weather data.

When averaged, simulated yields were lower than the measured yields. Percent differences decreased on average from 61% to 36% when N-rate increased to 101 kg ha^{-1}. The differences for 67 and 101 kg N ha^{-1} were smaller than the 0 kg ha^{-1} N treatment for this study. Percent differences between the measured and simulated yields were larger than the 13.7%, previously reported for Kanlow switchgrass and 0 kg ha^{-1} nitrogen application (Behrman et al., 2014).

Using earlier harvest dates also improved simulated yields when compared to actual SPARC harvest dates. October harvest dates showed the lowest percent difference between measured and simulated yields. When the N was increased to 101, 150, and 200 kg ha^{-1} in the simulations and compared to the 0, 67, 101 kg ha^{-1} N treatment measured yields, respectively, the percent differences were less than 10%. This indicated that the model may artificially require more N to produce results similar to actual measurements.

Table 2.3: Thirty year switchgrass yield overview for simulated weather for claypan soil with ALMANAC on Mexico Silt Loam, 1-4% eroded comparison to average measured switchgrass plots yield.

Harvest Date	**N-Rate (kg ha^{-1})**	**ALMANAC 30-Year Average (Mg ha^{-1})**	**Average Measured Yields (Mg ha^{-1})**	**% Difference**
December	0	3.3	8.5	-61
	67	6.4	12.5	-49
	101	8.2	13.5	-39
	150	11.3		
	200	13.8		
November	0	3.1	8.5	-63
	67	7.0	12.5	-44
	101	8.8	13.5	-35
	150	11.9		
	200	14.8		
October	0	3.6	8.5	-57
	67	7.0	12.5	-44
	101	8.9	13.5	-34
	150	11.9		
	200	14.8		
September	0	3.1	8.5	-64
	67	6.8	12.5	-46
	101	8.9	13.5	-34
	150	11.8		
	200	14.6		

The model was used to simulate the yield for 30 years on various soils in Boone County, MO. These soils were selected to represent claypan soils in Central Missouri.

The SSURGO data, shown in Fig. 2.21, indicates the difference between the maximum and minimum DTC for these soils is 0.28 m. Note that DTC had little effect on long-term averages of simulated SPARC switchgrass yield using ALMANAC.

The 2012 year had low precipitation, and yield was greater as DTC increased. Simulated switchgrass yields showed a small difference between the 67 and 101 kg ha^{-1} N treatments. This is also true for the measured yields as shown in Fig. 2.2. The average simulated yield, shown in Fig. 2.22, showed little difference with varying DTC. Simulated long-term yields showed that the average percent difference from the maximum and minimum switchgrass yield were 156% and 83%, respectively. Therefore, a consistent yield is not maintained throughout, reinforcing the results previously stated when comparing individual years. Long-term yield averages do not represent measured results well, as there are observable fluctuations.

Since the long-term simulated switchgrass yields with a total N application between 101 and 150 kg ha^{-1} N were comparable to measured yields for 67 and 101 kg ha^{-1} N, using mean simulated yields from ALMANAC to estimate potential biomass production is feasible. However, there is a need to further investigate the variation of switchgrass yield with depth to claypan and the cyclical variability observed in individual years when using ALMANAC.

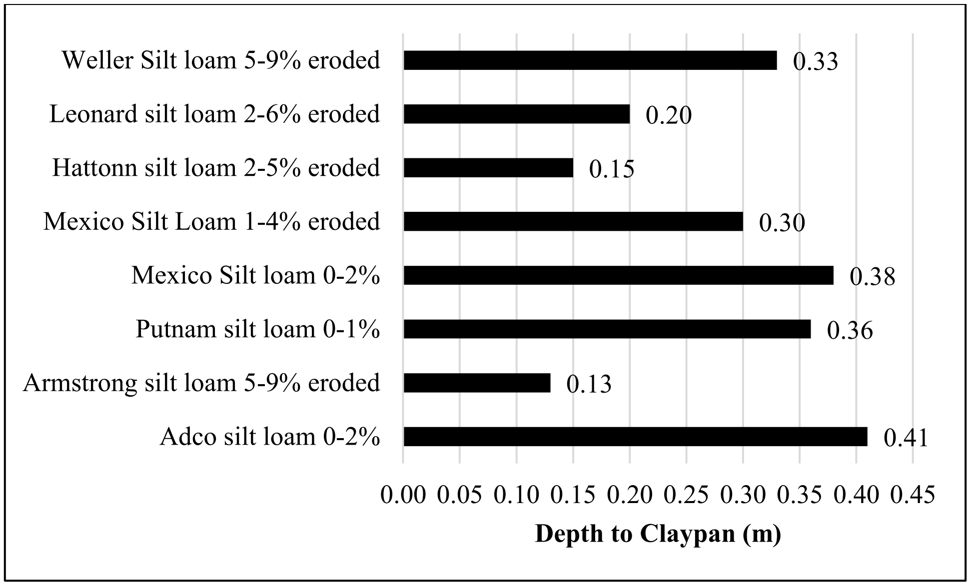

Figure 2.21: Depth to claypan for various NRCS SSURGO soils in Boone Count

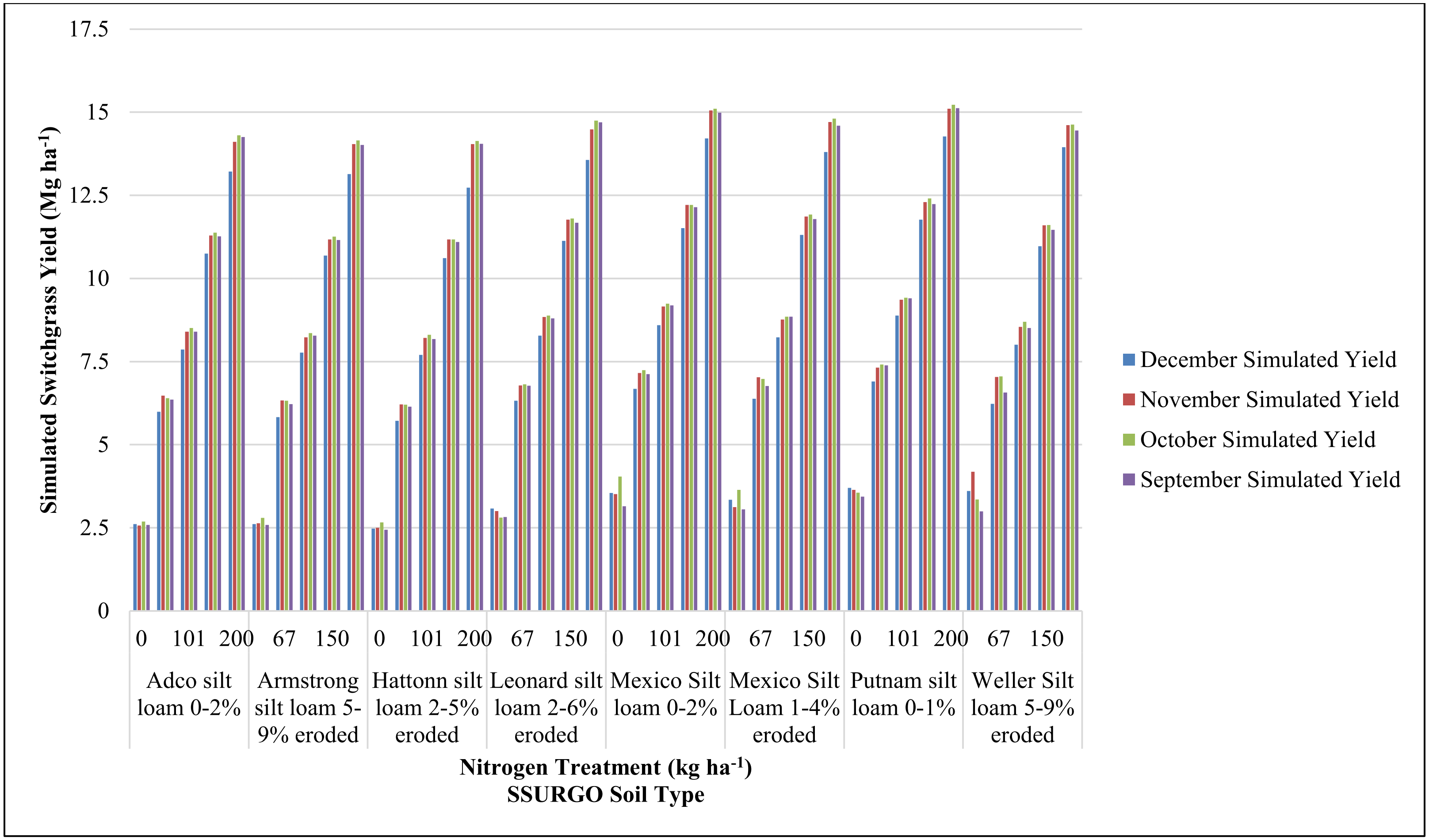

Figure 2.22: Thirty year average ALMANAC simulated switchgrass yield for simulated weather for various SSURGO claypan soils and with a range of N-rates.

Conclusion

The ALMANAC crop model has previously simulated switchgrass yield successfully at various locations within the United States. In this study, ALMANAC was evaluated against measured switchgrass production on claypan soil and it was found that the model under-predicted the field yields for all three N-rates over a 5-year period. When the model was run for modified SSURGO soil profiles, the switchgrass yields did not increase with greater topsoil depths. The model did not partition plant N well, and greater yields negatively impacted the next years switchgrass growth. When repeatedly using the same weather conditions for a given year over a longer simulated period, the model indicated cyclic switchgrass yield variation from year to year influenced by different amounts of precipitation and N-rates. This cyclic yield pattern decreased with a greater N application. ALMANAC did not simulate the increase in yield as switchgrass matures, appearing to model a mature stand of switchgrass for each year of simulation. With constant weather, simulated yields plateaued at a certain N-rate. The model also indicated a decline in biomass during later months of harvest. Simulated yields averaged over a 30-year period compared well to the average for the 5 years of measured switchgrass average yields from the SPARC plots for the Mexico Silt Loam, 1 to 4% eroded when simulated N was increased to a level higher than the actual N on the measured plots. The model greatly underestimated yields for all N-rates compared to measured yields on the SPARC plots, which may be due in part to the assumption of existing N in the initial year. When the model was used to simulate switchgrass yields on different claypan soils with a range of depths to claypan, the model showed similar yields for all soils regardless of depth to claypan. There is a need for specific cultivar parameters within ALMANAC for differing soil types, and for further study on the model with respect to soil moisture, N storage, and harvestable yield for claypan soils across years.

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Chapter 3: Influence of Depth to Claypan and Management Practices on Switchgrass Biomass Yield and Ethanol Potential

Abstract

Switchgrass (*Panicum virgatum L.)* ethanol production was evaluated for significance of treatment and depth to claypan (DTC). The claypan region is characterized by varying depths of topsoil over the argillic horizon. The response of switchgrass, an alternative cellulosic biofuel feedstock, biomass and ethanol production to management and DTC, is unknown. Switchgrass was established in 2009 near Columbia, MO. The switchgrass plots were initially developed with two cultivars of switchgrass, Cave-in-Rock (CR) and Kanlow. Kanlow switchgrass included treatments of nitrogen fertilizer rate (0, 67, and 101 kg ha^{-1}) and plots with native legumes, white clover inter-seeded, and two cuttings. Near-Infrared Spectroscopy (NIRS) was used to determine 20 compositional parameters and estimate actual ethanol yield. The actual ethanol yield was then multiplied by the biomass yield to determine ethanol production. Total ethanol production regression curve increased for N-rates 67 and 101 kg ha^{-1} and deeper DTC for the driest years of the study (2012 and 2013). Switchgrass ethanol production without N fertilizer had a greater response to deeper DTC. Switchgrass ethanol yield was greatest for the driest year (2012). Ethanol yield was negatively affected for deeper DTC during the driest years (2012 and 2013). Ethanol yield increased for the second cutting in 2012 but decreased for treatments where N was applied. Switchgrass biomass yield and ethanol production increased for greater DTC and N-rate, and declined for lower precipitation depths. Switchgrass grown for ethanol production

should consider regional soil characteristics and management treatments to maximize biomass yields and not ethanol quality.

Introduction

Switchgrass, (*Panicum virgatum L.)* a North American perennial prairie grass, is an option to help meet the national renewable fuel standard (RFS). The RFS was first enacted in 2005 as a mandate to produce 7.5 billion gallons of ethanol fuel by 2012. The goal was revised in 2007 to increase the overall goal to 36 billion gallons of ethanol by 2022. Corn ethanol can only comprise 15 billion gallons of the total. The remaining amount of ethanol must be met from alternatives such as cellulosic sources including switchgrass (EPA, 2014).

Switchgrass has been shown to be a viable crop on a broad range of soil types and climates in the Central United States (McLaughlin and Kszos, 2005; Schmer et al., 2012; Thomason et al., 2004). With switchgrass, management decisions play an important role with respect to maximizing biomass yield. To maximize switchgrass yield across the United States optimal N-rates are needed. Thomason et al. (2004) found a 30 to 46% increase in biomass yield with 224 kg ha^{-1} N application compared to a treatment without N for locations in Oklahoma. The overall maximum yield came from three cuttings and 448 kg ha^{-1} N. In another study in which animal biosolids were land applied, biomass yield increased by at least 25% with biosolids equivalent to 100 kg ha^{-1} N applied versus treatments without biosolids applied for Virginia (Liu et al., 2013). In Minnesota, optimal N-rates were between 60 to 90 kg ha^{-1} (Jungers et al., 2014). As these studies demonstrate, optimal N-rates vary for different locations.

Grain crop productivity in the Central Claypan Region, Major Land Resource Area 113 (MLRA 113) in Central Missouri and similar claypan regions, is highly variable (Kitchen et al., 1999). The MLRA 113 region encompasses approximately 3.3 million ha in the central United States. The soil profile is characterized by a layer of high clay content, depending on landscape position, approximately 20 to 40 cm below the soil surface. Producing grain crops on claypan soils has resulted in severe erosion and degradation of topsoil depth (Zhu et al., 1989). Erosion is problematic since reduced topsoil depth has been shown to decrease corn and soybean yields (Thompson et al., 1991). With the focus shifting from traditional corn and soybean to bioenergy crops, switchgrass (*Panicum virgatum L.*) has the potential to be economically feasible for areas with marginal soils. For example, switchgrass on claypan soils had a breakeven price between \$60 to \$80 Mg^{-1} compared to conventional grain production (Landers et al., 2012).

Near-infrared spectroscopy (NIRS) has been used for nondestructive estimates of plant composition for switchgrass and other crops because of its reliability, speed, and cost. NIRS uses spectral analysis to determine analytes based on a prediction equation from calibration samples (Vogel et al., 2011). Near-infrared spectroscopy can be used for switchgrass testing to determine 20 compositional values. Vogel et al. (2011) determined both actual ethanol (ETOHTL) and theoretical ethanol yield (ETOHTLT) prediction equations based on NIRS values. ETOHTL constitutes both biomass ethanol from dry forage and released pentose sugars (Vogel et al., 2011). ETOHTLT is described as all biomass sugars and assumes a 100% conversion to ethanol. Lorenz et al. (2009)

described ETOHTLT as the maximum ethanol yield from structural carbohydrates. Theoretical ethanol results are found in Appendix A

Near-infrared spectroscopy has been used in other studies to efficiently predict ethanol production with biosolids application. ETOHTLT was significant both spatially and temporally, with changes in field location and year influencing both biomass yield and quality (Liu et al., 2013). In another study, environmental factors related to precipitation were significant for ethanol quality and biomass (Schmer et al., 2012). Theoretical ethanol production from switchgrass increased at greater N-rates, but ethanol yield was found to decrease (Jungers et al., 2014).

The objective of this study was to determine if management practices and depth to claypan (DTC) influence biomass yield, actual ethanol yield (ETOHTL), and actual ethanol production (ETHOTHLH) from switchgrass on the Soil Productivity and Resource Conservation (SPARC) plots. For this study, theoretical ethanol results are found in Appendix A

Methods

Site Description

Switchgrass was established in 2009 on the SPARC plots at the University of Missouri South Farm, near Columbia, MO. These plots were established in 1982 as the ERASE plots by adding and removing topsoil depth to a Mexico Silt Loam (Gantzer and McCarty, 1987). Prior to switchgrass, the plots were in corn and soybean production for 12 years (1982-1993) followed by fallow for 15 years with native vegetation (1994-2008). The SPARC plots were arranged in a completely randomized, split plot design.

Topsoil depth was the main effect and grain and switchgrass management were the split-plot treatments and randomized within blocks. There were 32 blocks divided into two experiments. Each block in Experiment 1 consisted of 4 plots, 6.1 by 10 m in dimension. Blocks in Experiment 2 consisted of 6 plots, 5.3 by 10 m in dimension.

SPARC Management

The switchgrass plots were planted from seed in June 2009, with Kanlow and Cave-In-Rock (CR) switchgrass varieties. The Cave-In-Rock was fertilized with 67 kg ha^{-1} N and discontinued in 2011 for miscanthus because the yields for Cave-In-Rock were consistently lower than Kanlow. Treatments for Kanlow included N-rates of 0 (K0), 67 (K67), and 101 (K101) kg ha^{-1} applied in late spring to early summer. In 2010, the N application was split to reduce weed growth. Three additional treatments with Kanlow were: native legumes (KNL), white clover (KWC), and a two-cut system. In 2010, the legume system was sprayed with herbicide to reduce weed competition. To simulate legume nitrogen fixation, 34 kg ha^{-1} N was applied on these plots. The two-cut system consisted of harvesting switchgrass during the summer (K2cut1) and a second harvest in the fall (K2cut2) at the same time as the other treatments. The first switchgrass harvest was not conducted in 2010 due to limited plant growth. Additionally, the K2cut1 was not harvested during 2012 as there was a significant drought during the summer. The first switchgrass harvest was late fall of the second year (2010) after plants were dormant. Harvests were in November or December for all subsequent years. In 2010, switchgrass samples were harvested by cutting two .091 m by 7 m swaths from each switchgrass plot. In 2011, two 0.74 m by 7 m swaths were cut in each plot. From 2012 to 2014, switchgrass yield samples were harvested by cutting a 1.37 m by 7 m swath in the middle of each plot. Switchgrass was cut at approximately 10 to 17 cm above the soil surface

(Allphin, 2011). Biomass was collected by hand and weight measurements were taken in the field using a calibrated scale. All biomass samples were dried in accordance with ASABE Standard S358.2. Moisture was calculated and yields determined on a dry matter basis. Samples were sent to the USDA Agricultural Research Service Forage Quality Laboratory at Lincoln, Nebraska for analysis using NIRS. Procedures for NIRS analysis are described by Vogel et al. (2011).

SPARC Soil

A soil sample from each of the 32 blocks was collected in 2009 at the beginning of the SPARC study. These samples were collected and analyzed by the University of Missouri Soil Characterization Lab. The depth to the argillic horizon was determined by a soil scientist for each sample. The apparent electrical conductivity (EC_a) was measured using the DUALEM-2S (Dualem Inc., Milton, ON, Canada) for all 160 plots. A regression calibration with EC_a values and argillic horizon depths was used to map DTC following methods described previously (Kitchen et al., 1999; Sudduth et al., 2010). The plots were divided into four soil classifications based on DTC. Soil classification "A" had a DTC less than 8 cm, classification "B" ranged from 8 to 15 cm, classification "C" ranged from 15 to 27 cm, and classification "D" was a DTC greater than 27 cm (Landers et al., 2012).

NIRS

Switchgrass samples were first ground with a 1 mm cyclone type mill. Samples were scanned using a near-infrared spectrometer Foss NIRSystems, Type XM-1000, XDS Rapid Content Analyzer. Samples were scanned and parameters determined based on previously calibrated prediction equations. These prediction equations were calculated via wet laboratory analysis for chemical composition, ethanol, and pentose sugar yields following pretreatment, simultaneous saccharification and fermentation (SSF) using commercial cellulases and *Saccharomyces cerevisiae*, and forage quality traits. The calibrated prediction equation determines a Global H statistic. Global H represents the multivariate distance of the specimen sample from the center of the equation population.

Actual Ethanol

Switchgrass samples were analyzed using NIRS, and parameters were calculated from the calibrated equations. Using these parameters, actual ethanol was determined. Actual ethanol is different than theoretical, as actual includes only sugars fermentable by SSF. Actual total ethanol yield or quality from SSF (ETOHTL) was calculated from ethanol (ETOH) and released pentose (PENT) as shown in Eqn. 1. To calculate overall actual ethanol production from SSF (ETOHTLH), biomass yield was multiplied by ETOHTL using Eqn. 2 (Vogel et al., 2011). Parameter definitions and units are listed in Table 3.1.

$$\boldsymbol{ETOHTL}\ (\boldsymbol{L\ Mg^{-1}}) = ((\boldsymbol{ETOH} * \mathbf{1.267}) + (\boldsymbol{PENT} * \mathbf{0.51} * \mathbf{1.267} * \mathbf{0.8})) \tag{1}$$

$$\boldsymbol{ETOHTLH}\ (\boldsymbol{L\ ha^{-1}}) = \boldsymbol{biomass\ yield} * \boldsymbol{ETOHTL} \tag{2}$$

Table 3.1: NIRS actual switchgrass ethanol parameter variables and units.

Variable Abbreviation	Variable	Units
ETOHTL	Total ethanol yield from SSF	L Mg^{-1}
ETOHTLH	Total ethanol production per ha from SSF	L ha^{-1}
ETOH	Ethanol/g dry forage	mg g^{-1}
PENT	Pentose sugars released/g dry forage	mg g^{-1}

Statistics

Following the calculation of ethanol yield and production, PROC GLM within the SAS statistical software was used to conduct a regression analysis of five parameters: Biomass yield, ETOHTL, and ETOHTLH (SAS Institute Inc., 2012). First a Type III sum of squares test was run to test the significance of the interaction of DTC and treatment. Then parameters were evaluated as a function of treatment and DTC. The base reference treatment was the K67, which was regarded as the standard N treatment. The reference treatment K67 was evaluated for significance against zero for intercept and slope. The remaining treatments were evaluated against the reference treatment intercept and slope. Treatment intercept and slope were shown to be significant at a p-level less than 0.05. For this study, samples with DTC greater than 100 cm were not included because it was assumed they did not have a DTC. Only 10 of the 478 samples were excluded in the four years of this study.

Site Weather

Annual precipitation was measured at the University of Missouri South Farm weather station located near Columbia, MO (Fig. 3.1). Columbia Regional Airport, located approximately 11 km south of the research farm reported average annual precipitation of 1039 mm over the years of 1970 to 2013 (University of Nebraska-Lincoln, 2015). The precipitation for years 2011 to 2013 was 827, 674, and 975mm, respectively, which was below the 43-year annual average for Columbia, MO. Precipitation for the years 2009 and 2010 were above the annual average. Cumulative precipitation for 2010 to 2013 began at the beginning of the year (Fig.3.2). For 2012, precipitation did not occur regularly between May and September. Cumulative precipitation for 2010 was lower than 2013 from June until July in which there was a significant rainfall event over a short period of time that increased cumulative amounts for 2010. In 2011 cumulative precipitation was below 2012 for much of the early growing season after April 1, but became greater after the middle of June. Cumulative amounts were similar until the middle of April in which difference became more prevalent.

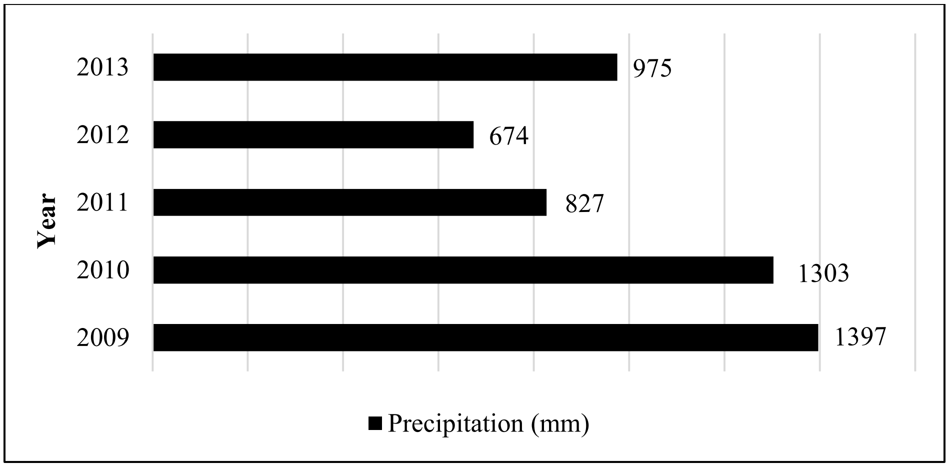

Figure 3.1: Annual precipitation for SPARC plots from South Farm, Columbia, Missouri, weather station.

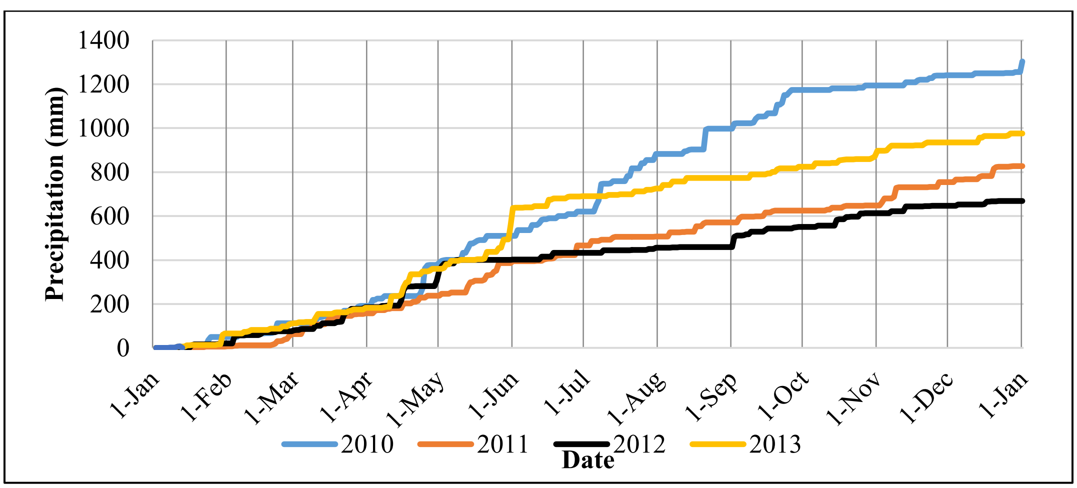

Figure 3.2: Cumulative precipitation for 2010 to 2013 from South Farm, Columbia, Missouri weather station.

Results and Discussion

Global H

The calibrated prediction equation determines a Global H statistic. This value determines the multivariate distance of a specimen sample from the center of the equation population (Vogel et al., 2011). The mean Global H value for switchgrass samples analyzed in this study are found in Table 3.2. The greater the value the further the sample is from the center of the equation population. Samples in 2010 and 2011 were the lowest of the four-year study. Samples for 2012 and 2013 were above 3.0 on average. These values in 2012 and 2013 are furthest from the center of the prediction equation. Samples further from the center are considered less reliable.

Table 3.2: Mean Global H values calculated from calibrated prediction equation for all switchgrass samples with NIRS.

Year	Mean Global H	Maximum	Minimum	Standard Deviation
2010	1.97	7.36	1.15	0.92
2011	2.93	4.34	1.80	0.45
2012	3.31	5.41	1.94	0.67
2013	4.23	6.12	2.98	0.65

Average Yield and Production

The actual ethanol yield and production values were averaged over all DTC and categorized by year and treatment as shown in Table 3.3. Biomass yield decreased in 2012 (the driest year) from 2011 and then increased in 2013. From 2011 to 2012, K0 yield decreased by 15%. From 2012 to 2013, K0 yield increased by 40%. This fluctuation in yield is due in part to precipitation. For K101, a treatment with 101 kg ha^{-1} more N than K0, biomass yield declined in yield by 31% from 2011 to 2012. From 2012 to 2013, biomass yield increased by 24%. Switchgrass yield fluctuations were attributed to changes in precipitation. From 2011 to 2013, the K2cut mean yield was lowest of all the treatments.

In 2012, actual ethanol yield was greater than other years, indicating that sugar concentration increased relative to a lower biomass yield. Mean ethanol yields were greater for switchgrass without fertilizer applied. The K67 and K101 treatments yields were lower than CR, K0, and K+NL. Production of ethanol appears to follow a similar pattern to that of biomass yield. In 2012, the production of ethanol decreased relative to 2011. This occurs with biomass yield and not ethanol yield.

Table 3.3: Switchgrass quality and quantity averages for the years of 2010 to 2013 with different management treatments for SPARC plots near Columbia, MO.

			---Treatment---							
Parameter	**Units**	**Year**	**K0**	**K67**	**K101**	**K+NL**	**K2cut1**	**K2cut2**	**K+WC**	**CR**
Switchgrass Biomass	Mg ha^{-1}	2010	4.34	6.64	6.77	5.98	-	6.66	6.31	5.19
		2011	7.49	13.05	15.23	8.60	8.33	3.15	8.41	8.58
		2012	6.43	10.06	11.19	3.25	-	0.52	-	-
		2013	9.58	13.66	14.17	8.65	8.14	2.33	-	-
ETOHTL	L Mg^{-1}	2010	216.98	208.59	203.99	212.77	-	209.17	213.02	201.14
		2011	207.41	201.47	194.58	207.22	208.13	209.63	203.38	213.69
		2012	234.71	232.33	230.00	239.78	-	253.11	-	-
		2013	216.24	208.65	205.48	214.93	205.89	206.88	-	-
ETOHTLH	L ha^{-1}	2010	1895.23	2878.44	2917.16	2628.48	-	2913.11	2770.50	2203.79
		2011	3300.43	5750.49	6691.48	3801.96	3232.67	1361.13	3683.08	3691.92
		2012	2926.67	4579.56	5105.34	1455.45	-	222.02	-	-
		2013	4477.16	6330.09	6470.66	4040.69	3353.16	1013.49	-	-

Biomass Yield

The reference treatment regression line intercept for biomass yield was statistically different from zero (Table 3.4). Generalized linear regression curves in the graphs below are present only if the intercept and/or slope were significantly different than the reference. Otherwise, they are represented by the reference curve in black (K67). In 2010, all treatment intercepts except CR and K0 were not statistically different from the reference treatment (Fig 3.3). This is because switchgrass in 2010 was in the second year of growth. K0 and CR were 66 and 76% lower than the reference treatment intercept, respectively. For 2011 and 2013, all treatments except K101 for 2012 and 2013 were statistically different from the reference intercept (Figs 3.4 to 3.6). The K101 treatment in 2011 was greater than the reference treatment. Precipitation for this year was below the long-term mean and followed a year with above average precipitation. Switchgrass with N-rates greater than the reference increased the intercept. In 2012 and 2013, K101 was not statistically different from the reference intercept. Rates of N above the reference treatment did not significantly increase the intercept the regression curve. The K0, K2cut1, K2cut2, K+WC, K+NL, and CR intercepts were all lower than the reference in years 2011 to 2013.

In 2010 and 2011, the slope was not statistically different from zero for any treatments as seen in Figs 3.3 and 3.4. Switchgrass yield did not respond to greater DTC for those years. The combined precipitation for those two years was greater than the combined for the last two years. In 2012, the slope was significant, and the slope was equivalent for K0 and K101. The K+NL and K2cut2 treatment slopes were statistically different from the reference slope. Slopes for those treatments were smaller than the reference slope and indicated yields do not respond similarly to greater DTC. In 2013, only K2cut1 was significantly different from the reference slope. This treatment was close to zero indicating that early in the season switchgrass does not respond as well to greater DTC. Biomass yields increased as a function of DTC for years with below average rainfall that also were after a year with below average rainfall.

Table 3.4: Statistical results for generalized linear model for switchgrass biomass yield from 2010 to 2013 for SPARC plots near Columbia, MO.

		Biomass (Mg ha^{-1})	Statistical Effect**		
Year*	Treatment	Regression Equation	Intercept	Linear	r^2
			---------probability--------		
2010	K67 (ref)	Y = 6.89	<0.0001	NS	0.075
	CR	Y = 5.24	0.0006	NS	0.003
	K+NL	Y = 6.89	NS	NS	0.008
	K0	Y = 4.52	<0.0001	NS	0.010
	K2cut2	Y = 6.89	NS	NS	0.001
	K+WC	Y = 6.89	NS	NS	0.024
	K101	Y = 6.89	NS	NS	0.091
2011	K67 (ref)	Y = 13.59	<.0001	NS	0.074
	CR	Y = 7.84	<.0001	NS	0.192
	K+NL	Y = 8.45	<.0001	NS	0.003
	K0	Y = 6.89	<.0001	NS	0.031
	K2cut1	Y = 7.79	<.0001	NS	0.079
	K2cut2	Y = 2.46	<.0001	NS	0.455
	K+WC	Y = 7.73	<.0001	NS	0.153
	K101	Y = 15.43	0.0288	NS	0.026
2012	K67 (ref)	Y = 8.09 + 0.089X	<.0001	<.0001	0.537
	K+NL	Y = 2.58 + 0.033X	<.0001	0.0217	0.267
	K0	Y = 4.44 + 0.089X	<.0001	NS	0.598
	K2cut2	Y = 0.30 + 0.008X	<.0001	<.0001	0.376
	K101	Y = 8.09 + 0.089X	NS	NS	0.485
2013	K67 (ref)	Y = 11.98 + 0.076X	<.0001	<.0001	0.477
	K+NL	Y = 7.66 + 0.076X	<.0001	NS	0.260
	K0	Y = 7.06 + 0.076X	<.0001	NS	0.710
	K2cut1	Y = 7.06 + 0.007X	<.0001	0.0012	0.015
	K2cut2	Y = 1.36 + 0.076X	<.0001	NS	0.541
	K101	Y = 11.98 + 0.076X	NS	NS	0.412

*Each year was tested independently.

** Treatment and Treatment*DTC were tested first with Type III sum of squares where H_0: $\beta_i = 0$. β_i represents both intercept and the interaction term. Then treatments were tested where H_0: $\beta_{i(treatment)}=\beta_{i(reference)}$.

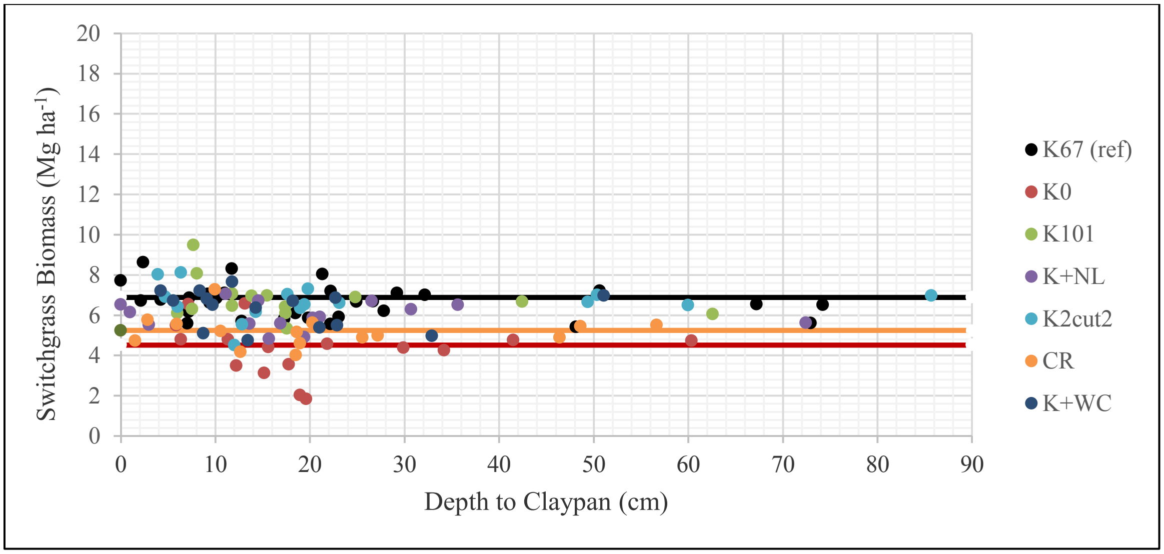

Figure 3.3: Switchgrass biomass yield for 2010 from SPARC plots near Columbia, MO. Switchgrass biomass yield was analyzed with a general linear model and regression curves calculated in comparison to the reference treatment (K67). The reference treatment was tested for significance against zero for both intercept and slope.

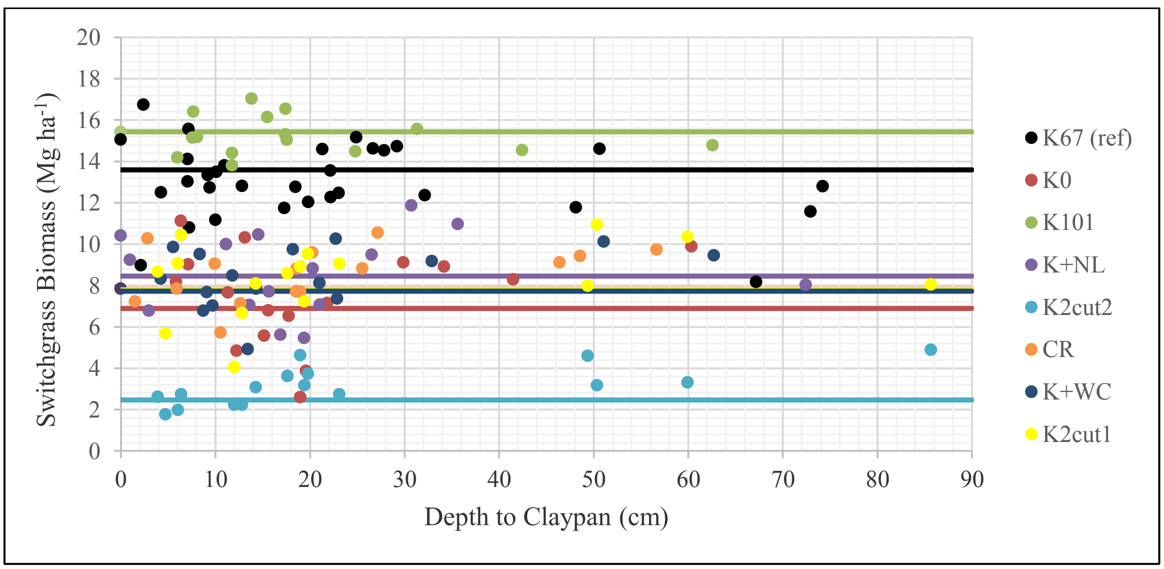

Figure 3.4: Switchgrass biomass yield for 2011 from SPARC plots near Columbia, MO. Switchgrass biomass yield was analyzed with a general linear model and regression curves calculated in comparison to the reference treatment (K67). The reference treatment was tested for significance against zero for both intercept and slope.

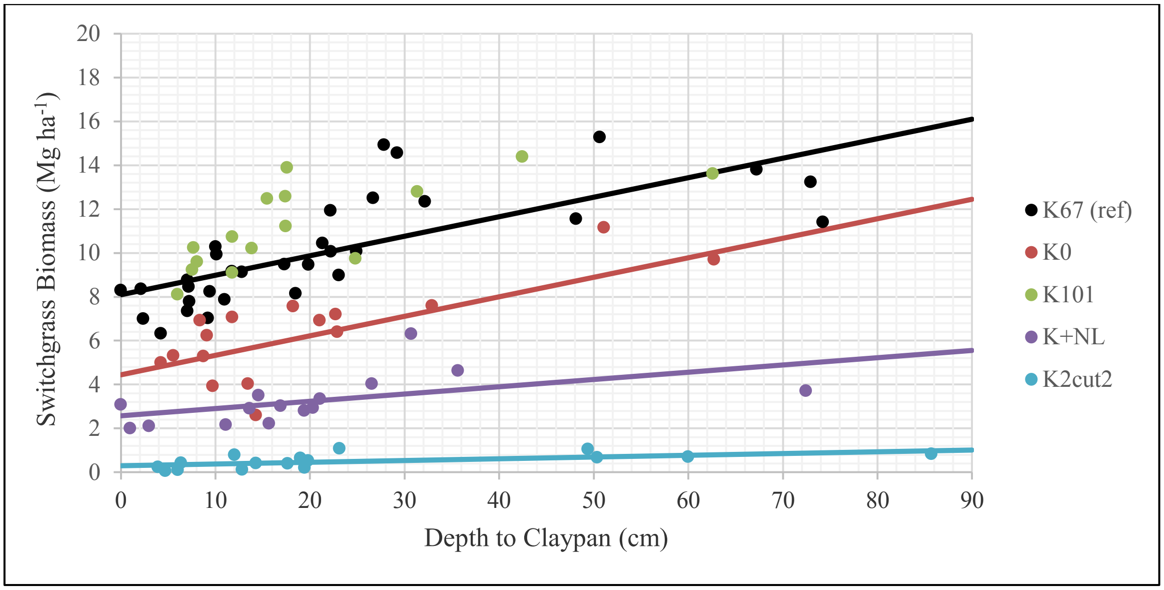

Figure 3.5: Switchgrass biomass yield for 2012 from SPARC plots near Columbia, MO. Switchgrass biomass yield was analyzed with a general linear model and regression curves calculated in comparison to the reference treatment (K67). The reference treatment was tested for significance against zero for both intercept and slope.

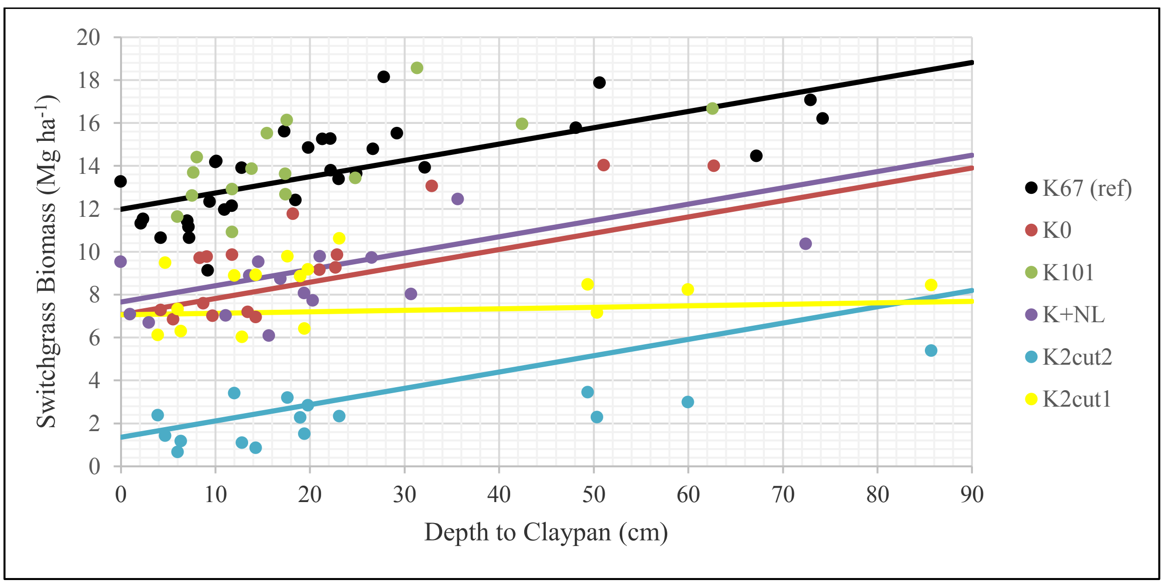

Figure 3.6: Switchgrass biomass yield for 2013 from SPARC plots near Columbia, MO. Switchgrass biomass yield was analyzed with general linear model and regression curves calculated in comparison to the reference treatment (K67). The reference treatment was tested for significance against zero for both intercept and slope.

ETOHTL-Total ethanol from SSF

The reference treatment regression line intercept for ethanol quality from SSF was statistically different from zero (Table 3.5). In 2010, treatment intercepts were not statistically different from the reference intercept of 211.36 L Mg^{-1} (Fig 3.7). Treatments in the first year of harvest indicate no difference with management treatment with respect to actual ethanol yield. In 2011, treatment intercepts for CR, K+NL, and K0 were statistically greater than the reference by 6, 4, and 4%, respectively (Fig. 3.8). The K101 treatment intercept was statistically lower than the reference for the same year (2011). The application of higher N-rates appears to decrease the quality of ethanol in switchgrass. In 2012, the intercept for K2cut2 was greater than the reference treatment. Results indicated switchgrass quality improved with a higher intercept during the driest year (2012) when compared to other years. Ethanol quality for the first and last year were 211.36 and 212.45 L Mg^{-1}, respectively. Quality for a new crop (2010) was greater than other years (2011) with lower precipitation. Ethanol quality as a function of DTC was not significantly different from zero for 2010 and 2012. In 2012 and 2013, quality decreased as DTC increased. It is not apparent why quality decreased at greater DTC but it does occur during the drier years (2012 and 2013).

Table 3.5: Statistical results for generalized linear model for ethanol yield from SSF (ETOHTL) from 2010 to 2013 from SPARC switchgrass plots near Columbia, MO

		ETOHTL (L Mg^{-1})	Statistical Effect		
Year*	Treatment	Regression Equation	Intercept	Linear	r^2
			---------probability--------		
2010	K67 (ref)	Y = 211.36	<.0001	NS	0.083
	CR	Y = 211.36	NS	NS	0.256
	K+NL	Y = 211.36	NS	NS	0.051
	K0	Y = 211.36	NS	NS	0.069
	K2cut2	Y = 211.36	NS	NS	0.467
	K+WC	Y = 211.36	NS	NS	0.050
	K101	Y = 211.36	NS	NS	0.008
2011	K67 (ref)	Y = 202.42	<.0001	NS	0.008
	CR	Y = 213.57	0.0041	NS	0.000
	K+NL	Y = 210.02	0.038	NS	0.211
	K0	Y = 211.21	0.0266	NS	0.184
	K2cut1	Y = 202.42	NS	NS	0.059
	K2cut2	Y = 202.42	NS	NS	0.010
	K+WC	Y = 202.42	NS	NS	0.068
	K101	Y = 192.89	0.0138	NS	0.061
2012	K67 (ref)	Y = 236.46-0.186X	<.0001	0.0045	0.197
	K+NL	Y = 236.46-0.186X	NS	NS	0.027
	K0	Y = 236.46-0.186X	NS	NS	0.151
	K2cut2	Y = 253.35-0.186X	<.0001	NS	0.003
	K101	Y = 236.46-0.186X	NS	NS	0.014
2013	K67 (ref)	Y = 212.45-0.171X	<.0001	0.0218	0.111
	K+NL	Y = 212.45-0.171X	NS	NS	0.214
	K0	Y = 212.45-0.171X	NS	NS	0.002
	K2cut1	Y = 212.45-0.171X	NS	NS	0.212
	K2cut2	Y = 212.45-0.171X	NS	NS	0.172
	K101	Y = 212.45-0.171X	NS	NS	0.172

**Each year was tested independently.

**Treatment and interaction term were analyzed with Type III sum of squares where H_0: $\beta_i = 0$. β_i represents both intercept and the interaction term. Then treatments were analyzed with a two-tailed T test where H_0: $\beta_{i(treatment)}=\beta_{i(reference)}$.

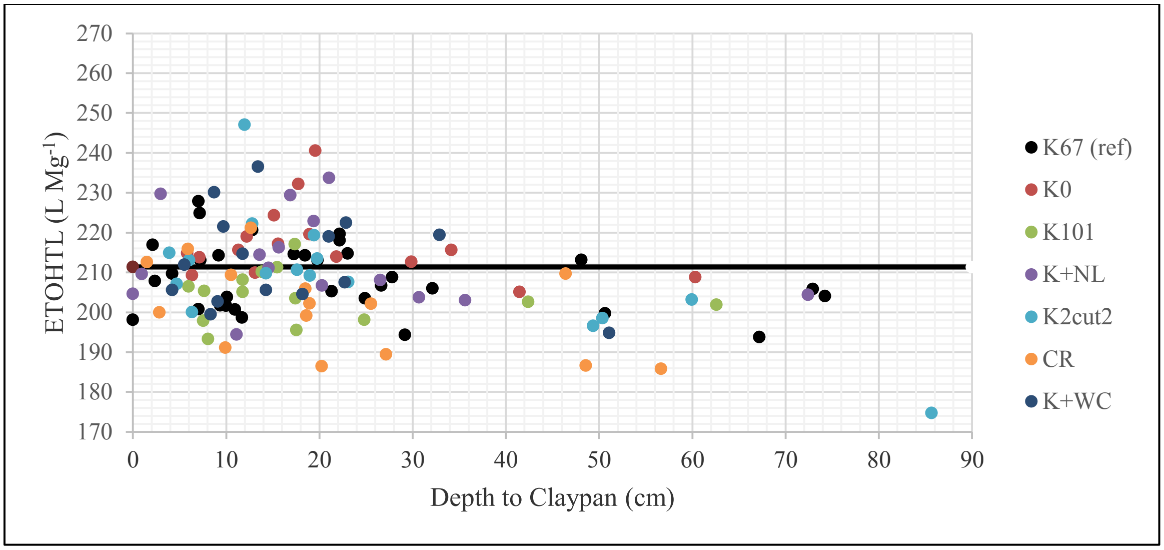

Figure 3.7: Switchgrass ethanol yield from SSF (ETOHTL) for 2010 from SPARC plots near Columbia, MO. Switchgrass actual ethanol yield was analyzed with a general linear model and regression curves calculated in comparison to the reference treatment (K67). The reference treatment was tested for significance against zero for both intercept and slope.

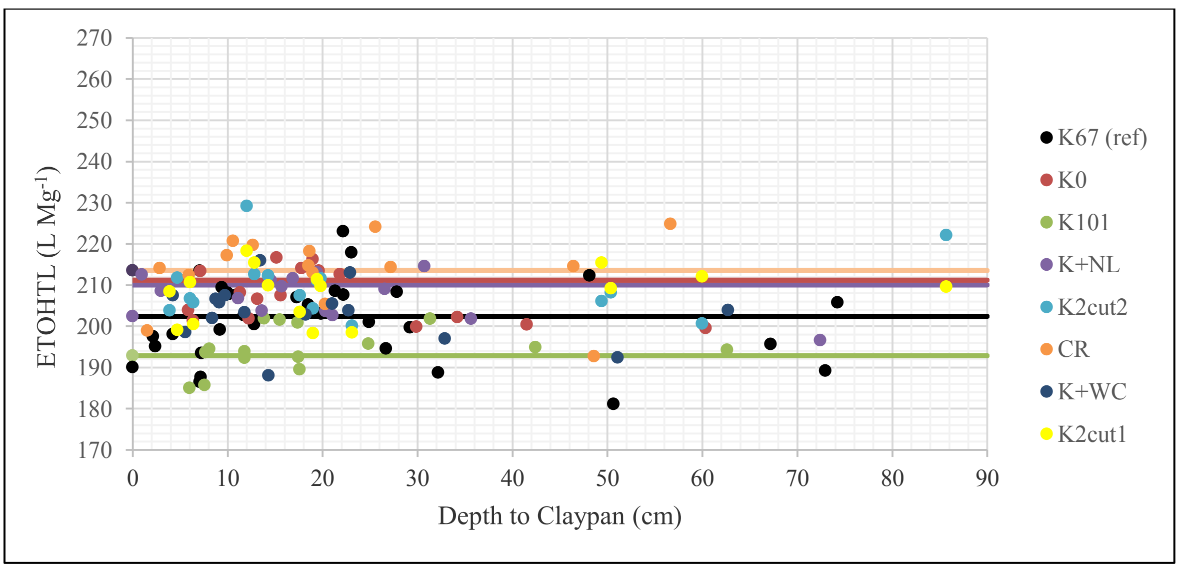

Figure 3.8: Switchgrass ethanol yield from SSF (ETOHTL) for 2011 from SPARC plots near Columbia, MO. Switchgrass actual ethanol yield was analyzed with a general linear model and regression curves calculated in comparison to the reference treatment (K67). The reference treatment was tested for significance against zero for both intercept and slope.

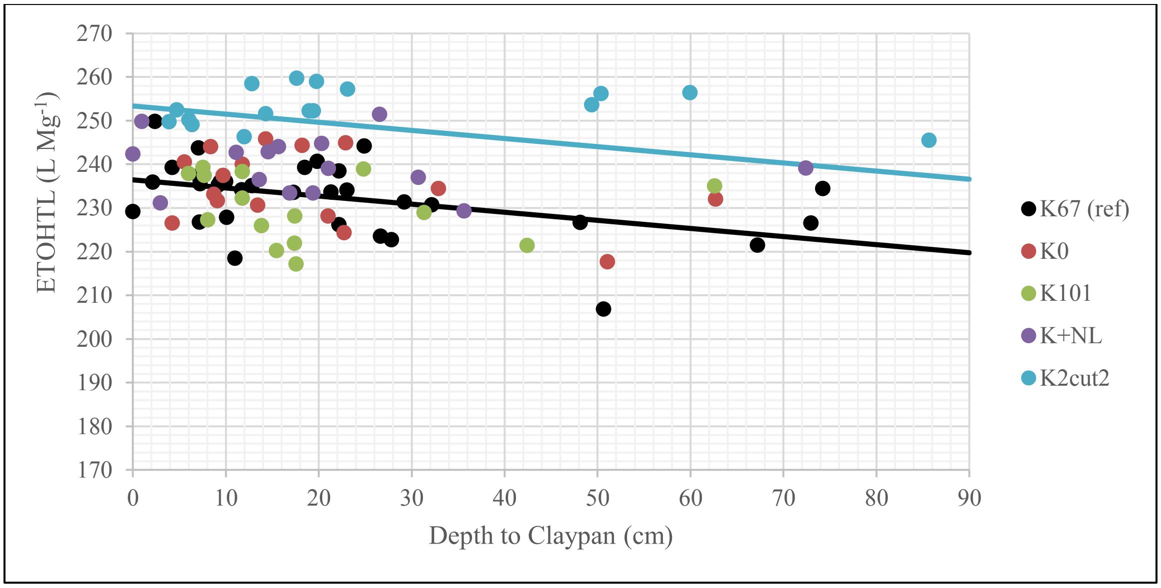

Figure 3.9: Switchgrass ethanol yield from SSF (ETOHTL) for 2012 from SPARC plots near Columbia, MO. Switchgrass actual ethanol yield was analyzed with a general linear model and regression curves calculated in comparison to the reference treatment (K67). The reference treatment was tested for significance against zero for both intercept and slope.

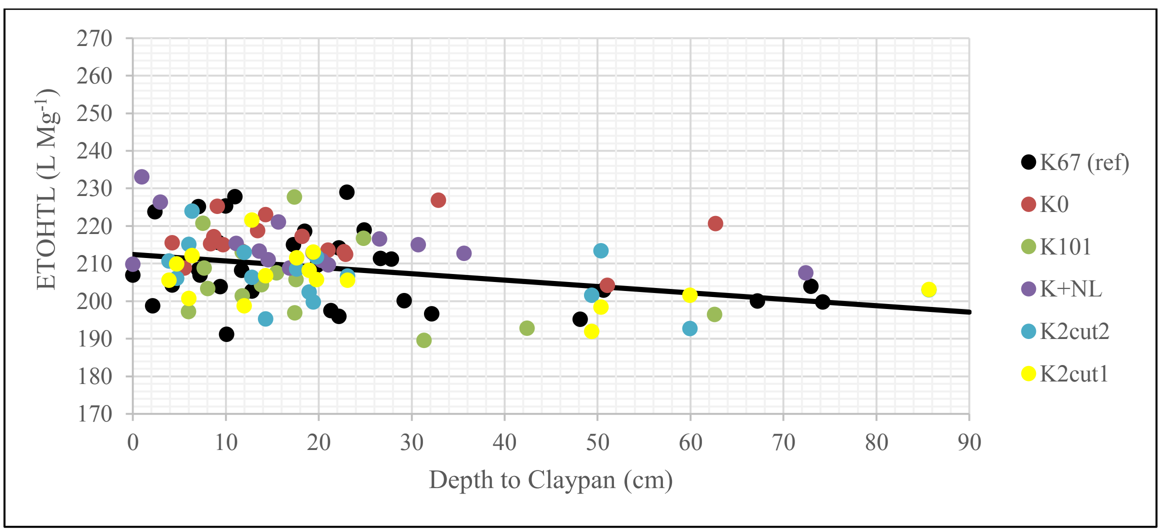

Figure 3.10: Switchgrass ethanol yield from SSF (ETOHTL) for 2013 from SPARC plots near Columbia, MO. Switchgrass actual ethanol yield was analyzed with a general linear model and regression curves calculated in comparison to the reference treatment (K67). The reference treatment was tested for significance against zero for both intercept and slope.

ETOHTLH-Total ethanol production from SSF

Actual ethanol production is the product of actual ethanol yield and biomass yield. The reference treatment regression line intercept for ETOHTLH was significantly different from zero for all years (Table 3.6). The treatment intercepts in 2010 for CR and K0 were statistically different from the reference intercept (Fig 3.11). The K0 and CR treatment intercepts were 68 and 75% of the reference treatment, respectively. Biomass yield showed similar relationships, with the intercept 66 and 76% of the reference treatment, respectively. This indicates that biomass yield is critical for ethanol production. The differences in biomass yield regression curves will influence ethanol production. All treatment intercepts except K101 were statistically lower than the reference treatment for the years 2011 to 2013. K2cut2 had the lowest intercept of all the treatments in 2011 to 2013, equivalent to findings for biomass yield. The second cutting is designated for bioenergy and was the lowest of all treatments. Switchgrass with native legumes and without N applied had lower intercepts for 2011 to 2013. In this study the application of 67 kg N ha^{-1} produced the highest intercepts for actual ethanol production.

The slope for actual ethanol production was not significant in 2010 and 2011, as with biomass and ethanol yield. Actual ethanol production did not see the benefit to greater topsoil depths for the first two years of harvest. Slopes during 2012 and 2013 were significant Figs. 3.13, and 3.14. The K2cut1 slope in 2013 was smaller than the other treatments indicating that a two cut system did not have a similar response to DTC as the reference treatment. The slope for K0 had a greater slope than the reference treatment and indicated that switchgrass without N applied as fertilizer responded more strongly to greater DTC.

Switchgrass ethanol production appears to be influenced by biomass changes more than quality. This indicates that improving biomass growth does improve production. Improving quality did not appear to affect production. Greater DTC improved biomass yield and production during drier years.

Table 3.6: Statistical results from the generalized linear model for ethanol production from SSF (ETOHTLH) from 2010 to 2013 from SPARC switchgrass plots near Columbia, MO.

		ETOHTLH (L ha^{-1})	Statistical Effect**		
Year*	Treatment	Regression Equation	Intercept	Linear	r^2
			---------probability--------		
2010	K67 (ref)	Y = 1450.36	<.0001	NS	0.164
	CR	Y = 1087.53	<.0001	NS	0.081
	K+NL	Y = 1450.36	NS	NS	0.054
	K0	Y = 985.99	<.0001	NS	0.020
	K2cut2	Y = 1450.36	NS	NS	0.155
	K+WC	Y = 1450.36	NS	NS	0.097
	K101	Y = 1450.36	NS	NS	0.097
2011	K67 (ref)	Y = 2744.21	<.0001	NS	0.086
	CR	Y = 1673.26	<.0001	NS	0.184
	K+NL	Y = 1772.45	<.0001	NS	0.000
	K0	Y = 1454.51	<.0001	NS	0.018
	K2cut1	Y = 1601.39	<.0001	NS	0.108
	K2cut2	Y = 509.69	<.0001	NS	0.484
	K+WC	Y = 1585.14	<.0001	NS	0.136
	K101	Y = 2744.21	NS	NS	0.002
2012	K67 (ref)	Y = 1917.38 + 18.399X	<.0001	<.0001	0.532
	K+NL	Y = 621.77 + 7.760X	<.0001	0.0368	0.262
	K0	Y = 1074.19 + 18.399X	<.0001	NS	0.563
	K2cut2	Y = 76.62 + 2.132X	<.0001	0.0001	0.369
	K101	Y = 1917.38 + 18.399X	NS	NS	0.605
2013	K67 (ref)	Y = 2549.70 + 13.288X	<.0001	<.0001	0.367
	K+NL	Y = 1671.52 + 13.288X	<.0001	NS	0.226
	K0	Y = 1533.73 + 27.217X	<.0001	0.0145	0.681
	K2cut1	Y = 1661.75 + 0.432X	<.0001	0.0042	0.001
	K2cut2	Y = 290.57 + 13.288X	<.0001	NS	0.500
	K101	Y = 2549.70 + 13.288X	NS	NS	0.280

*Each year was tested independently.

** Treatment and Treatment*DTC were tested first with Type III sum of squares where H_0: $\beta_i = 0$. β_i represents both intercept and the interaction term. Then treatments were tested where H_0: $\beta_{i(treatment)}=\beta_{i(reference)}$.

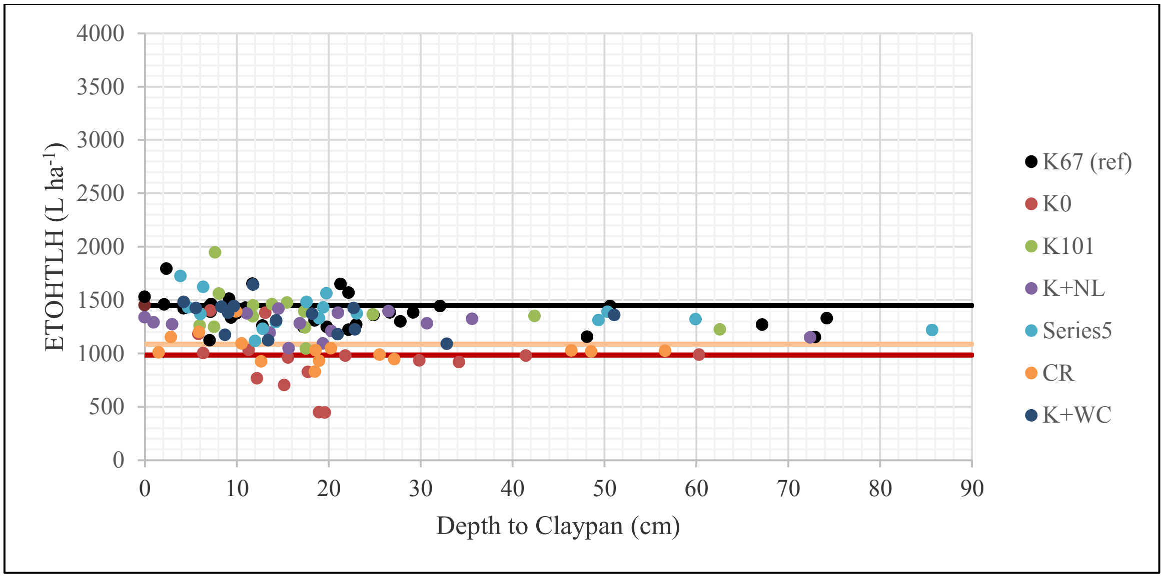

Figure 3.11: Switchgrass ethanol production from SSF (ETHOTLH) for 2010 from SPARC plots near Columbia, MO. Switchgrass actual ethanol production was analyzed with a general linear model and regression curves calculated in comparison to the reference treatment (K67). The reference treatment was tested for significance against zero for both intercept and slope.

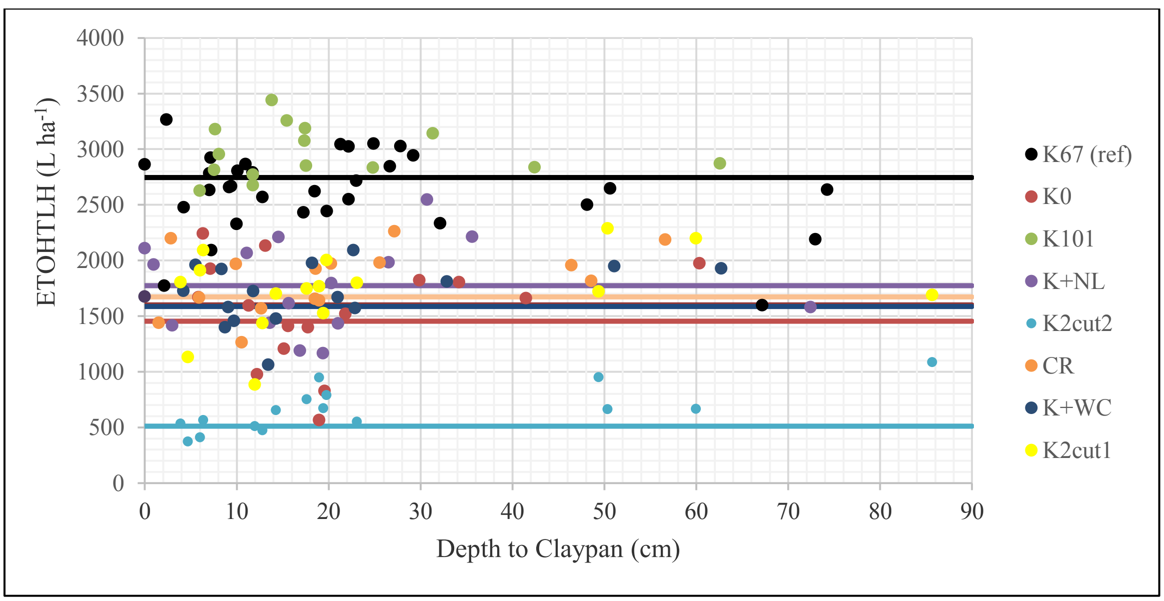

Figure 3.12: Switchgrass ethanol production from SSF (ETOHTLH) for 2011 from SPARC plots near Columbia, MO. Switchgrass actual ethanol production was analyzed with a general linear model and regression curves calculated in comparison to the reference treatment (K67). The reference treatment was tested for significance against zero for both intercept and slope.

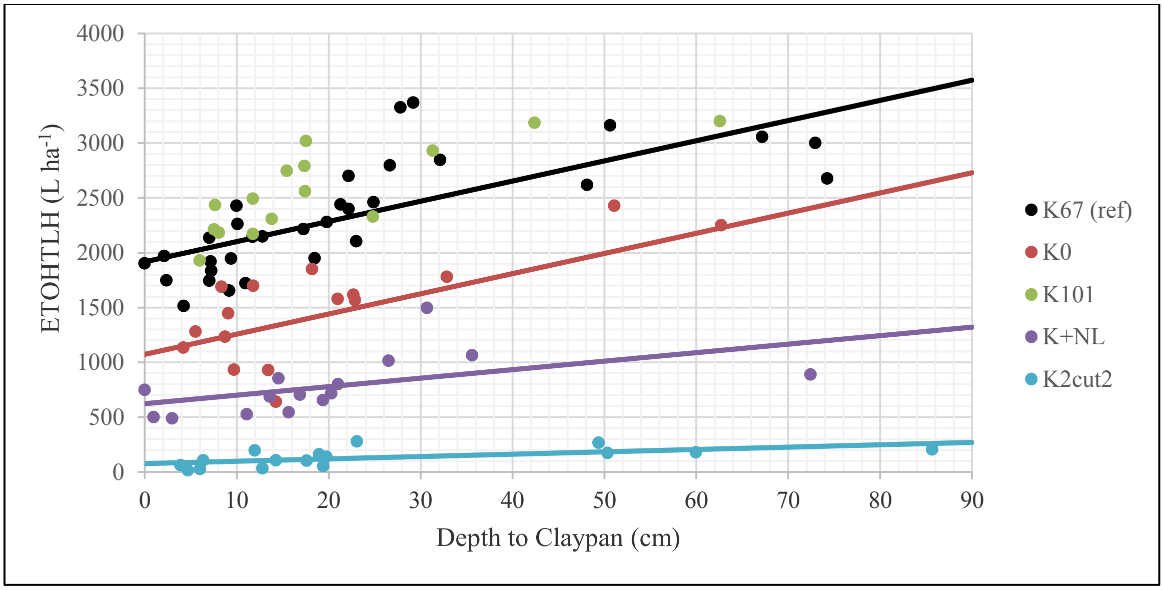

Figure 3.13: Switchgrass ethanol production from SSF (ETOHTLH) for 2012 from SPARC plots near Columbia, MO. Switchgrass actual ethanol production was analyzed with a general linear model and regression curves calculated in comparison to the reference treatment (K67). The reference treatment was tested for significance against zero for both intercept and slope.

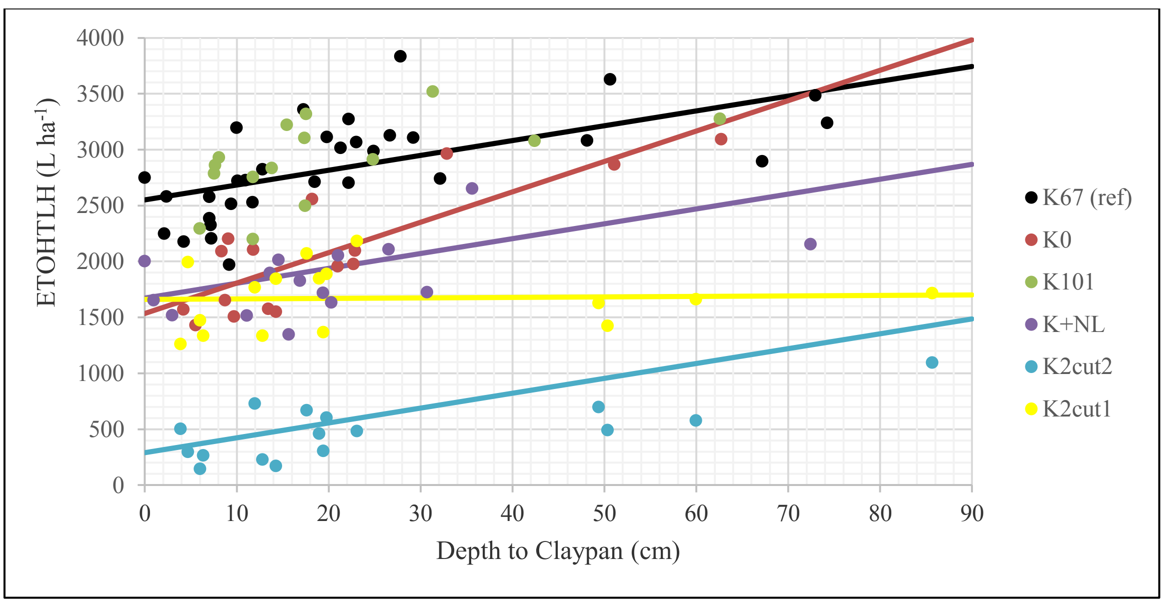

Figure 3.14: Switchgrass ethanol production from SSF (ETHOTLH) for 2013 from SPARC plots near Columbia, MO. Switchgrass actual ethanol production was analyzed with general linear model and regression curves calculated in comparison to the reference treatment (K67). The reference treatment was tested for significance against zero for both intercept and slope.

Conclusion

Switchgrass grown for cellulosic ethanol production should consider regional soil characteristics and management treatments that maximize both overall biomass yield and overall production of ethanol. For the claypan region of Central MO, DTC is a significant factor influencing ethanol production during dry years. Results from this study found that during drier years (2012 and 2013), total switchgrass ethanol production increased with greater N-rates and greater DTC. Ethanol yields responded negatively to greater DTC.

In the first year of harvest (2010), many of the management treatments and DTC did not significantly influence overall ethanol production from SSF relative to the reference (K67). The first year (2010) of harvest had lower biomass yields compared to the three other years due to the immature switchgrass stand that year. Switchgrass early in its maturity can be attributed to this finding. In 2011, ethanol quality was greater for treatments with N-rates lower than K67. For the final two years of this study, ethanol quality was only different for the K2cut2 treatment in 2012. Actual ethanol quality was greatest for the driest year in this study. For 2012 and 2012, switchgrass quality at greater DTC decreased. It is not apparent why quality decreased at greater DTC.

The 101 kg N ha^{-1} treatment was statistically no different than the baseline rate of 67 kg N ha^{-1} for ethanol production, but economic analysis is needed to understand at what point this increase in N-rate is no longer beneficial. Biomass yield and ethanol production were similar in that if biomass treatments were significantly different from the reference, the same would hold for ethanol production. The equivalent is true, with respect to the slope of the regression curves, except for K0 in 2013. The K0 had a greater response at deeper DTC.

Future research should focus on developing increased yield through genetics and improving management to increase biomass yields. Results here indicate that switchgrass treatments were significant during both dry and wet years for biomass yield and ethanol from SSF. The DTC influenced biomass yield of switchgrass only during drier years. Switchgrass ethanol quality should consider the individual sugars in the quality equation.

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Chapter 4: Conclusion

Conclusions based on this study for switchgrass biomass yields as simulated from Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) are as follows:

- The mean simulated and measured yields were compared and ALMANAC simulated yields were 4.0, 5.1, and 4.9 Mg ha^{-1} less than the measured yields for the 0, 67, and 101 kg ha^{-1} N treatments, respectively. ALMANAC under-predicted yearly yields.
- Harvests dates play an important role in simulating maximum switchgrass yields with ALMANAC. Specifically, harvest dates in November and December under-estimated switchgrass yields compared to those in September and October. When harvest dates occurred after October, the model under-predicted yields when compared to measured yields that were harvested during those later months.
- ALMANAC simulated yields were cyclical when the same weather year was repeated for 12 consecutive years. During years in which the precipitation was lowest (2012), the cyclic pattern did not occur, but during years in which precipitation was greater (2011, 2013, and 2014) there was a cyclical pattern. N-rates above 101 kg ha^{-1} removed the cyclic pattern during 2011 and 2013.
- ALMANAC simulated yields using modified SSURGO soils and run with SPARC management dates indicated no influence of depth to claypan (DTC) even though measured yields increased with DTC in drier years.

- When ALMANAC was used to simulate switchgrass over 30 years for different SSURGO soils common within Central Missouri, simulated yields were between 34 and 61% lower than measured yields.

Conclusions based on this study for the influence of depth to claypan and management practices on switchgrass biomass yield and ethanol potential was determined are as follows:

- Switchgrass biomass was evaluated for different management treatments and DTC. Biomass was greatest for both the 67 and 101 kg ha^{-1} N treatments for 2011 to 2013. The other treatments yielded statistically lower biomass. Greater DTC was found to improve biomass for all treatments for drier years (2012 and 2013).
- Actual ethanol yield was greater for treatments with lower N-rates. Ethanol quality decreased with greater DTC for the drier years (2012 and 2013).
- Actual ethanol production increased with DTC for drier years (2012 and 2013). Management treatments with 67 and 101 kg ha^{-1} N had higher production than other treatments.

Suggestions for Future Study

Based on the results obtained from this study, the recommendations for future work are:

- Evaluate potential biomass yields for the claypan region, based on empirical results from measured switchgrass yields developed from a correlation between SSURGO soils and DTC. As shown above, the mechanistic approach with ALMANAC under-predicted yields and demonstrated no impact of soil texture and bulk density alteration to the model yields.

- Improve ALMANAC for optimal harvest dates that maximize simulated yields over a multiple year simulation similar to the SPARC plots. The ALMANAC model simulated yields were shown to improve with earlier harvest dates.
- Improve N cycling within ALMANAC for soils within the claypan region as increased N improved yearly yields over multiple year simulations. The simulations from this study indicated that N was lacking year to year. A possible scaling factor would be necessary to improve yields on claypan soils.
- Determine differences in ethanol sugars to ascertain which influence ethanol production.

Appendix 1: Theoretical Ethanol

Methods

Theoretical ethanol is not currently feasible using current large-scale production methods. Theoretical ethanol is determined using all biomass sugars. Total theoretical ethanol yield or quality (ETOHTLT) was calculated via Mannose (MAN), Galactose (GAL), Starch (STA), soluble Glucose (GLCS), Fructose (FRU), Sucrose (SUC), Arabinose (ARA), and Xylose (XYL) using Eqn. 1 (Vogel et al., 2011). Theoretical ethanol production (ETOHTLTH), is calculated by multiplying biomass yield by ETOHTLT as in Eqn. 2 (Vogel et al., 2011). Parameter definitions and units are listed in Table A.1.

$$\mathbf{ETOHTLT\ (L\ Mg^{-1})} = \Big(\mathbf{(((MAN + GAL + STA) * 0.57) + ((GLCS + FRU) * 0.51) + (SUC * 0.537)) * 1.267) + \big((ARA + XYL) * 0.579 * 1.267\big)}\Big) \qquad \textbf{(1)}$$

$$\boldsymbol{ETOHTLTH\ (L\ ha^{-1}) = biomass\ yield} * \mathbf{ETOHTLT} \qquad \textbf{(2)}$$

Table A.1: NIRS theoretical ethanol parameter variables and units

Variable Abbreviation	Variable	Units
ETOHTLT	Total theoretical ethanol yield from all biomass sugars	L Mg^{-1}
ETOHTLTH	Total Theoretical ethanol production from all biomass sugars	L ha^{-1}
MAN	Mannose	mg g^{-1}
GAL	Galactose	mg g^{-1}
STA	Starch	mg g^{-1}
GLCS	Soluble glucose	mg g^{-1}
FRU	Fructose	mg g^{-1}
SUC	Sucrose	mg g^{-1}
ARA	Arabinose	mg g^{-1}
XYL	Xylose	mg g^{-1}

Following the calculation of ethanol yield and production, PROC GLM within the SAS statistical software was used to conduct a regression analysis of five parameters: ETOHTLT and ETOHTLTH (SAS Institute Inc., 2012). First a Type III sum of squares test was run to test the significance of the interaction of DTC and treatment. Then parameters were evaluated as a function of treatment and DTC. The base reference treatment was the K67, which was regarded as the standard N treatment. The reference treatment K67 was evaluated for significance against zero for intercept and slope. The remaining treatments were evaluated against the reference treatment intercept and slope. Treatment intercept and slope were shown to be significant at a p-level less than 0.05. For this study, samples with DTC greater than 100 cm were not included.

Average Yield and Production

Theoretical ethanol yield and production were averaged over the four years for the SPARC plots. The average ethanol yield (ETOHTLT) average increased over the four years for K0, K67, K101, K+NL, and CR as shown in Table A.2. This indicates that ethanol yield did not improve for years with lower precipitation. Switchgrass theoretical ethanol quality improved as the stands matured. Mean theoretical ethanol production (ETOHTLTH) followed similar trends to biomass production, as was shown previously in Chapter 3 with actual ethanol production.

Table A.2: Switchgrass quality and quantity averages for the years of 2010 to 2013 with different management treatments for SPARC plots near Columbia, MO.

			---Treatment---							
Parameter	Units	Year	K0	K67	K101	K+NL	K2cut1	K2cut2	K+WC	CR
ETOHTLTH	L ha^{-1}	2010	1895.23	2878.44	2917.16	2628.48	-	2913.11	2770.50	2203.79
		2011	3300.43	5750.49	6691.48	3801.96	3232.67	1361.13	3683.08	3691.92
		2012	2926.67	4579.56	5105.34	1455.45	-	222.02	-	-
		2013	4477.16	6330.09	6470.66	4040.69	3353.16	1013.49	-	-
ETOHTLT	L Mg^{-1}	2010	437.37	433.50	430.37	440.07	-	437.65	439.54	425.38
		2011	441.06	440.45	439.21	442.52	387.61	431.70	437.82	430.29
		2012	454.64	455.44	457.14	447.16	-	428.44	-	-
		2013	467.46	463.60	457.31	467.11	412.50	435.31	-	-

ETOHTLT-Theoretical ethanol yield from all biomass sugars

The reference treatment (K67) regression curve intercept was statistically different than zero (Table A.3). In 2010, theoretical ethanol yield (quality) resulted in greater intercepts for the K+WC, K2cut2, and K+NL in 2010 (Fig. A.1). In 2011, the treatments CR, K2cut2, and K2cut1 had lower intercepts (Fig. A.2). In the final two years, the two cut system had a lower intercept than the reference. In 2012, the driest year, the K+NL was also lower than the reference. These results indicate that as switchgrass matures the quality decreased for treatments without native legumes, white clover, and without two cuttings. For theoretical ethanol yield, greater DTC did not increase yield, except in 2012 for K+NL as shown in Fig. A.3. This was statistically different from the reference treatment (K67). Precipitation appears to not influence theoretical ethanol yield.

Table A.3: Statistical results for switchgrass theoretical ethanol yield (ETHOTLT) from 2010 to 2013 for SPARC plots near Columbia, MO

		ETOHTLT (L Mg^{-1})	Statistical Effect**		
Year*	Treatment	Regression Equation	Intercept	Linear	r^2
			---------probability--------		
2010	K67 (ref)	Y = 434.62	<.0001	NS	0.011
	CR	Y = 434.62	NS	NS	0.275
	K+NL	Y = 443.26	0.0352	NS	0.076
	K0	Y = 434.62	NS	NS	0.103
	K2cut2	Y = 443.00	0.0334	NS	0.351
	K+WC	Y = 445.81	0.0129	NS	0.246
	K101	Y = 434.62	NS	NS	0.095
2011	K67 (ref)	Y = 442.35	<.0001	NS	0.071
	CR	Y = 434.11	0.0194	NS	0.109
	K+NL	Y = 442.35	NS	NS	0.046
	K0	Y = 442.35	NS	NS	0.202
	K2cut1	Y = 393.13	<.0001	NS	0.178
	K2cut2	Y = 432.22	0.0017	NS	0.006
	K+WC	Y = 442.35	NS	NS	0.032
	K101	Y = 442.35	NS	NS	0.015
2012	K67 (ref)	Y = 457.03	<.0001	NS	0.053
	K+NL	Y = 441.48 + 0.282X	<.0001	0.0056	0.254
	K0	Y = 457.03	NS	NS	0.002
	K2cut2	Y = 428.29	<.0001	NS	0.000
	K101	Y = 457.03	NS	NS	0.226
2013	K67 (ref)	Y = 466.36	<.0001	NS	0.120
	K+NL	Y = 466.36	NS	NS	0.000
	K0	Y = 466.36	NS	NS	0.001
	K2cut1	Y = 413.78	<.0001	NS	0.030
	K2cut2	Y = 438.54	<.0001	NS	0.151
	K101	Y = 466.36	NS	NS	0.177

**Each year was tested independently.
**Treatment and interaction term were with Type III test sum of squares where H_0: $\beta_i = 0$. β_i represents both intercept and the interaction term. Then treatments were analyzed with a two-tailed T where H_0: $\beta_{i(treatment)}=\beta_{i(reference)}$.

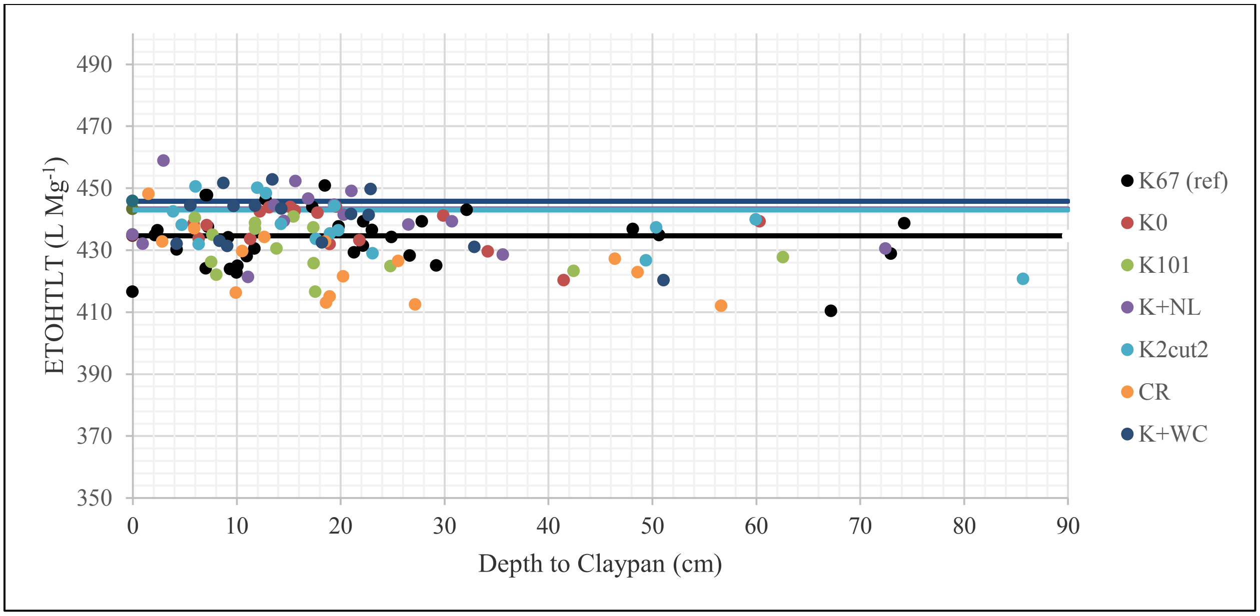

Figure A.1: Switchgrass theoretical ethanol yield (ETOHTLT) for 2010 from SPARC plots near Columbia, MO. Switchgrass theoretical ethanol yield was analyzed with general linear model and regression curves calculated in comparison to the reference treatment (K67). The reference treatment was tested for significance against zero for both intercept and slope.

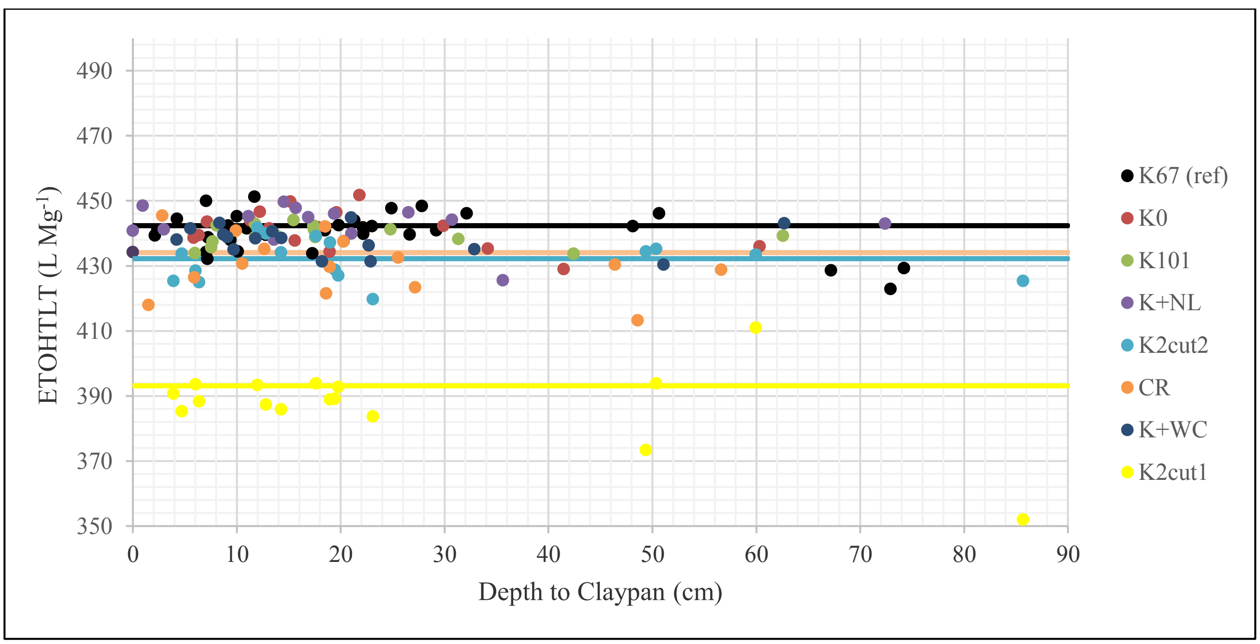

Figure A.2: Switchgrass theoretical ethanol yield (ETOHTLT) for 2011 from SPARC plots near Columbia, MO. Switchgrass theoretical ethanol yield was analyzed with a general linear model and regression curves calculated in comparison to the reference treatment (K67). The reference treatment was tested for significance against zero for both intercept and slope.

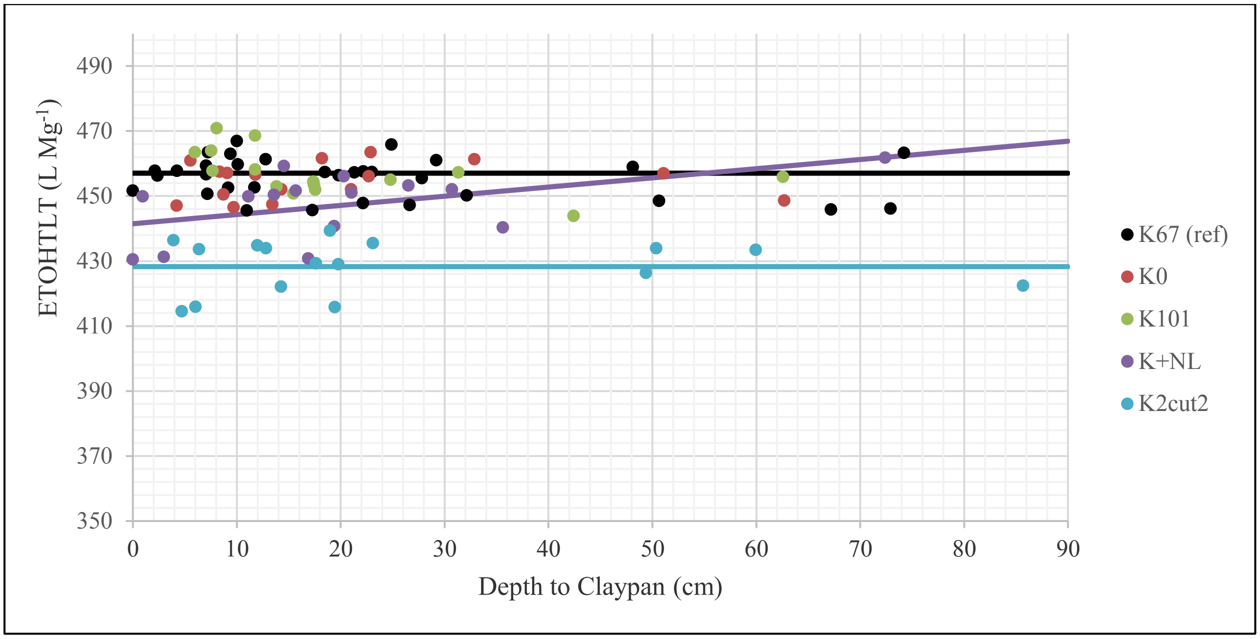

Figure A.3: Switchgrass theoretical ethanol yield (ETOHTLT) for 2012 from SPARC plots near Columbia, MO. Switchgrass theoretical ethanol yield was analyzed with a general linear model and regression curves calculated in comparison to the reference treatment (K67). The reference treatment was tested for significance against zero for both intercept and slope.

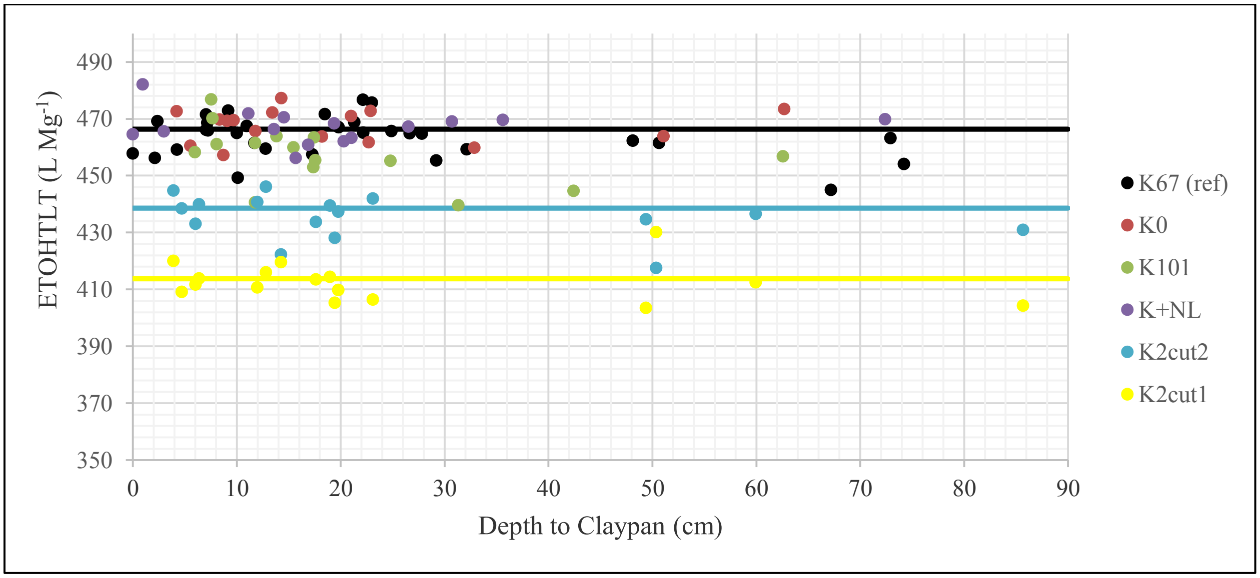

Figure A.4: Switchgrass theoretical ethanol yield (ETOHTLT) for 2013 from SPARC plots near Columbia, MO. Switchgrass theoretical ethanol yield was analyzed with a general linear model and regression curves calculated in comparison to the reference treatment (K67). The reference treatment was tested for significance against zero for both intercept and slope.

ETOHTLTH-Total theoretical ethanol production from all biomass sugars

The reference treatment (K67) regression curve intercept was statistically different than zero (Table A.4). Total theoretical ethanol production (ETOHTLTH) results indicate that CR and K0 had statistically lower intercepts than the reference treatment (K67) in 2010 (Fig. A.5). In 2011, all treatments were all statistically different than the reference intercept (Fig. A.6). K101 and K67 produced the most ethanol of the treatment group. In 2012 and 2013, the same is true (Figs. A.7 and A.8). This indicates that N-rate improves the amount of ethanol produced. DTC was not significant in 2010 and 2011. In 2012 and 2013, DTC did improve production of ethanol. Theoretical ethanol production increases as biomass yield increases and increases at greater DTC for drier years.

Table A.4: Statistical results for switchgrass theoretical ethanol production (ETOHTLTH) from 2010 to 2013 for SPARC plots near Columbia, MO

		ETOHTLTH (L ha^{-1})	Statistical Effect**		
Year*	Treatment	Regression Equation	Intercept	Linear	r^2
			---------probability--------		
2010	K67 (ref)	Y = 2988.01	<.0001	NS	0.089
	CR	Y = 2262.98	0.0004	NS	0.022
	K+NL	Y = 2988.01	NS	NS	0.024
	K0	Y = 1990.17	<.0001	NS	0.013
	K2cut2	Y = 2988.01	NS	NS	0.004
	K+WC	Y = 2988.01	NS	NS	0.056
	K101	Y = 2988.01	NS	NS	0.107
2011	K67 (ref)	Y = 6006.38	<.0001	NS	0.082
	CR	Y = 3412.26	<.0001	NS	0.142
	K+NL	Y = 3753.91	<.0001	NS	0.001
	K0	Y = 3069.69	<.0001	NS	0.025
	K2cut1	Y = 3061.25	<.0001	NS	0.048
	K2cut2	Y = 1067.02	<.0001	NS	0.444
	K+WC	Y = 3391.43	<.0001	NS	0.146
	K101	Y = 6783.81	0.0354	NS	0.028
2012	K67 (ref)	Y = 3702.14 + 39.558X	<.0001	<.0001	0.528
	K+NL	Y = 1136.68 + 15.839X	<.0001	0.0295	0.292
	K0	Y = 2026.04 + 39.558X	<.0001	NS	0.584
	K2cut2	Y = 130.85 + 3.606X	<.0001	<.0001	0.362
	K101	Y = 4355.67 + 39.558X	0.0365	NS	0.490
2013	K67 (ref)	Y = 5589.33 + 33.397X	<.0001	<.0001	0.447
	K+NL	Y = 3575.57 + 33.397X	<.0001	NS	0.260
	K0	Y = 3295.78 + 59.671X	<.0001	0.0288	0.725
	K2cut1	Y = 3288.31 + 2.565X	<.0001	0.0013	0.011
	K2cut2	Y = 601.84 + 33.397X	<.0001	NS	0.521
	K101	Y = 5589.33 + 33.397X	NS	NS	0.383

**Each year was tested independently.
**Treatment and interaction term were with Type III test sum of squares where H_0: $\beta_i = 0$. β_i represents both intercept and the interaction term. Then treatments were analyzed with a two-tailed T where H_0: $\beta_{i(treatment)}=\beta_{i(reference)}$.

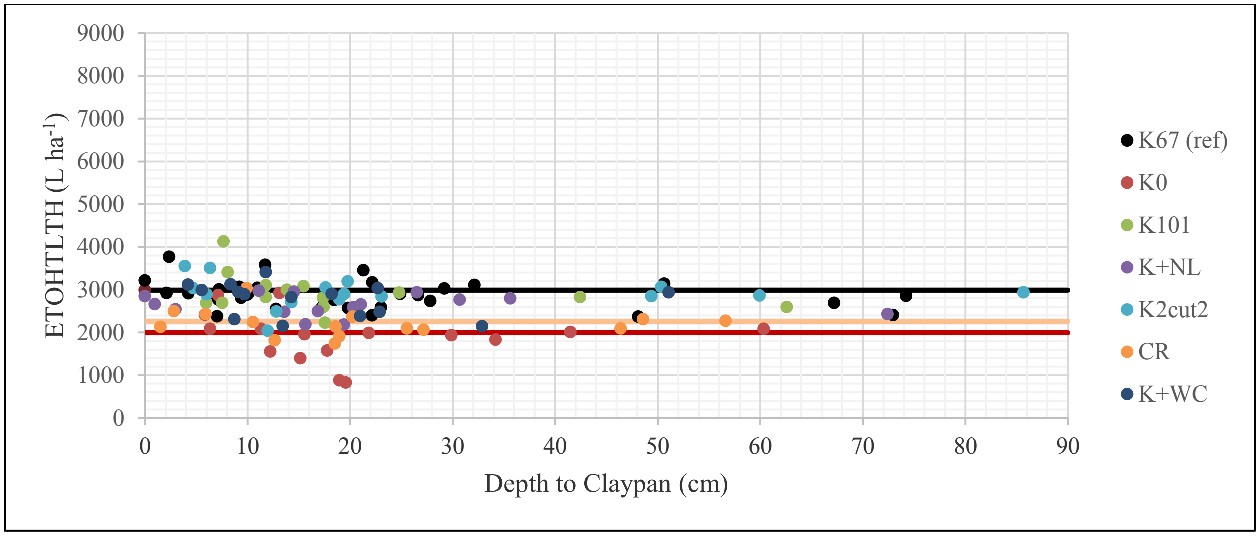

Figure A.5: Switchgrass theoretical ethanol production (ETOHTLTH) for 2010 from SPARC plots near Columbia, MO. Switchgrass theoretical ethanol production was analyzed with a general linear model and regression curves calculated in comparison to the reference treatment (K67). The reference treatment was tested for significance against zero for both intercept and slope.

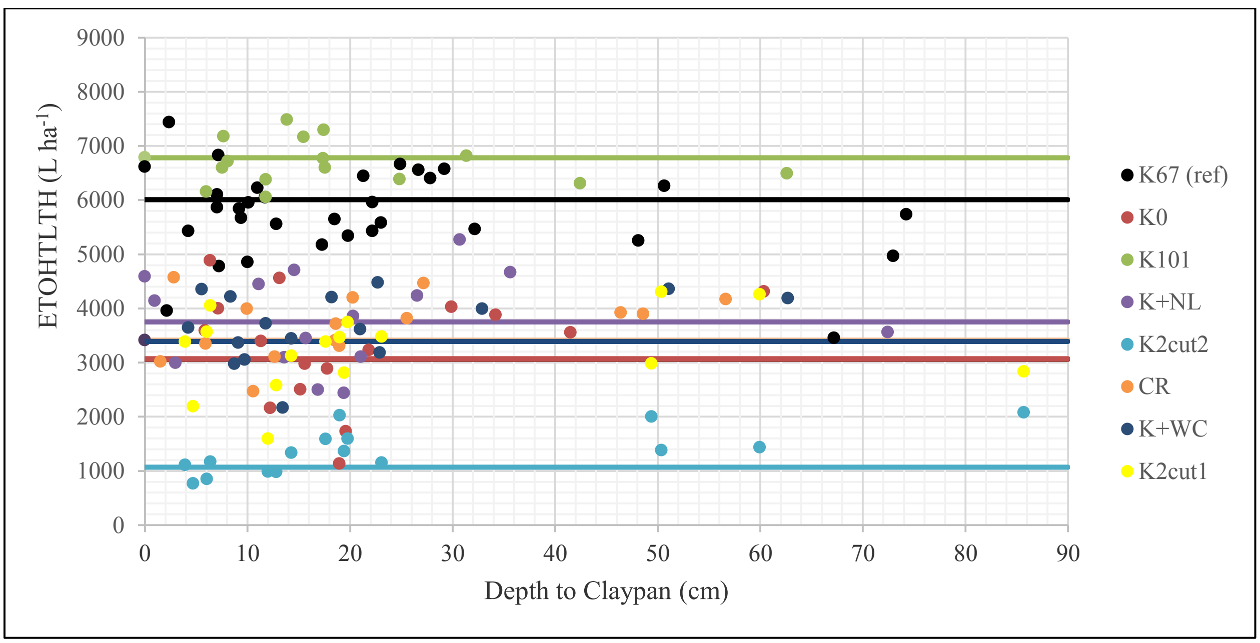

Figure A.6: Switchgrass theoretical ethanol production (ETOHTLTH) for 2011 from SPARC plots near Columbia, MO. Switchgrass theoretical ethanol production was analyzed with a general linear model and regression curves calculated in comparison to the reference treatment (K67). The reference treatment was tested for significance against zero for both intercept and slope.

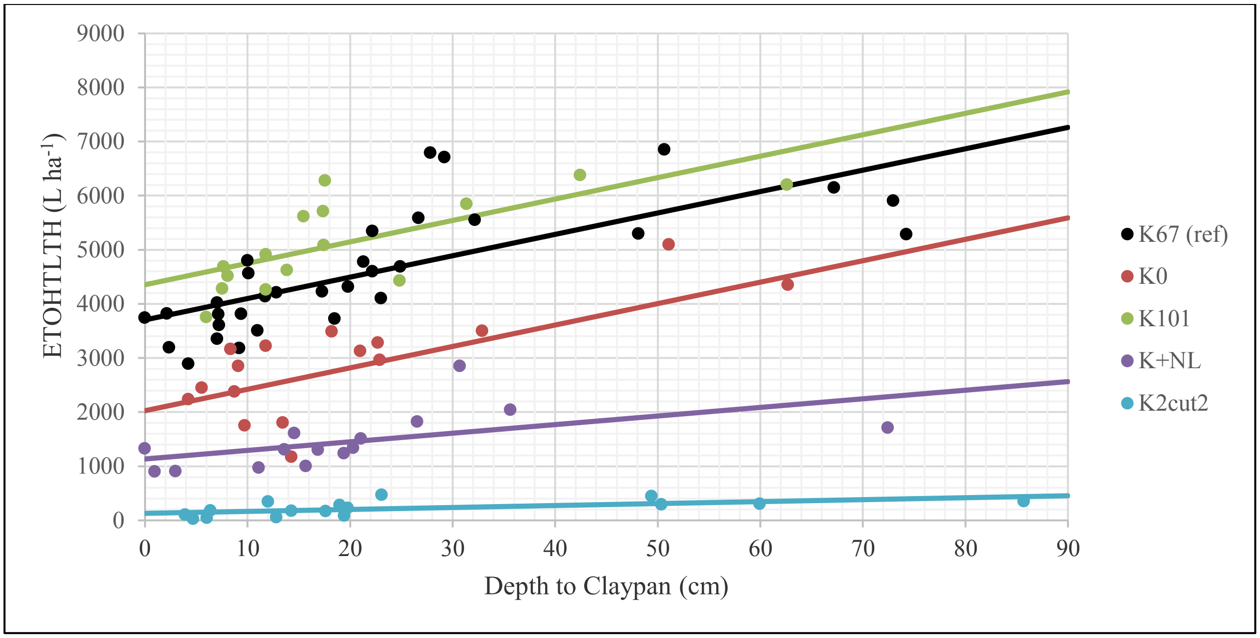

Figure A.7: Switchgrass theoretical ethanol production (ETOHTLTH) for 2012 from SPARC plots near Columbia, MO. Switchgrass theoretical ethanol production was analyzed with a general linear model and regression curves calculated in comparison to the reference treatment (K67). The reference treatment was tested for significance against zero for both intercept and slope.

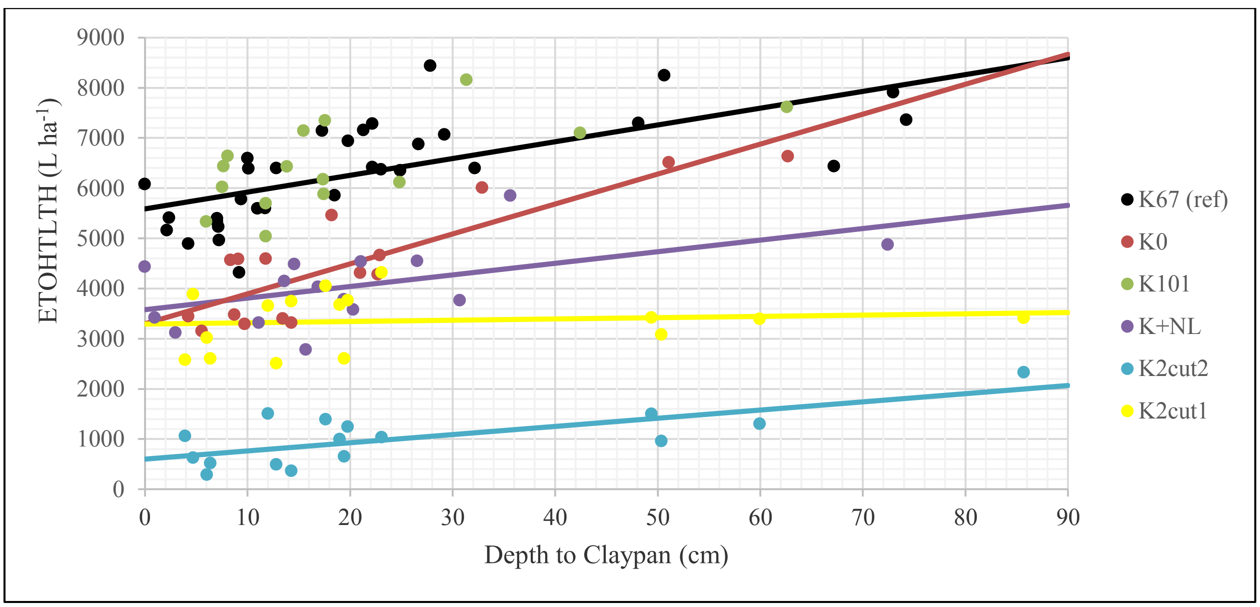

Figure A.8: Switchgrass theoretical ethanol production (ETOHTLTH) for 2013 from SPARC plots near Columbia, MO. Switchgrass theoretical ethanol production was analyzed with a general linear model and regression curves calculated in comparison to the reference treatment (K67). The reference treatment was tested for significance against zero for both intercept and slope.

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