# WATER AND NITROGEN USE EFFICIENCY OF CORN AND SWITCHGRASS ON CLAYPAN SOIL LANDSCAPES

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## ABSTRACT

The Renewable Fuel Standard (RFS) mandated that 36 billion gallons of fuel must originate from renewable sources by 2022 with only 15 billion gallons originating from corn (*Zea mays* L.) grain. Therefore other sources must be investigated. This research was conducted at the University of Missouri, South Farm Research Center Soil Productivity Assessment for Renewable Energy and Conservation (SPARC) research site from 2009-2013. The soil depth to the claypan horizon treatment was classified into erosion classes as severely eroded (< 5 cm), moderately eroded (5-20 cm), slightly eroded (20-30 cm), or depositional (>30 cm). This investigation included corn and switchgrass (*Panicum virgatum* L.) with four replications per soil erosion class. Yearly simulations, using an original water-balance model, were run for the number of days of water stress, water used, runoff and Water Use Efficiency (WUE) based on recorded weather data from the research site and previously-derived relationships of water storage on variable claypan soil landscapes. Nitrogen content was measured for corn grain and switchgrass biomass to determine Agronomic Nitrogen Use Efficiency ($NUE_a$). The biomass and grain yield for each plot was used for WUE and $NUE_a$ calculations. Results of the simulated model indicate that switchgrass results in more days of water stress, but also less runoff and better WUE. In dry years, increased depth to claypan led to an increased WUE of 1.17-1.25 kg $m^{-3}$ for the severely eroded soils and 2.19-2.77 kg $m^{-3}$ for depositional soils for switchgrass compared to corn. Switchgrass $NUE_a$ was 14-18% more efficient than corn on severely eroded soils and 50-55% more efficient on depositional soils in dry years. This research indicates that when considering water and N use efficiency, switchgrass for biofuels is a viable option when grown on claypan soils, with better drought tolerance and low environmental impact when compared to corn.

**Keywords**: claypan, corn, switchgrass, agronomic nitrogen use efficiency, water use efficiency

# INTRODUCTION

In 2007, the United States government mandated that by 2022, 36 billion gallons of fuel (gasoline or diesel) must be generated annually from renewable sources. Of the 36 billion gallons, only 15 billion gallons can originate from corn grain; the remaining 21 billion gallons of renewable fuel must originate from other sources (EPA, 2014). Researchers are looking at other annual and perennial crops to meet this demand. One crop researchers have begun to investigate throughout the US for its potential as a biofuel crop is switchgrass (*Panicum virgatum* L.)(Parrish and Fike, 2005).

Missouri is a state that has begun to study switchgrass for biofuels, as it requires less fertilizer and can grow well on marginal soils. Missouri is made up of a diverse set of soils and landscapes. One unusual soil found in Missouri as well as Illinois is the claypan. Claypan soils account for approximately 4 million ha in Missouri and Illinois (MLRA 113)(USDA-NRCS, 2006). It is due to the physical and chemical properties of claypan soils that they are usually high in economic risk and low productivity (Massey, et al., 2008), and depending on the depth to claypan (DTC), that they can be considered marginal soils. These claypan soils have an argilic (45-65% clay (Bray, 1935)) horizon ranging from 0-40 cm below the soil surface (severely eroded to depositional). Because of the nature of the high concentration of clay found in the claypan layer, these soils behave uniquely, having slow water and nutrient permeability. This leads to the need for adjusted management practices (Jiang, et al., 2007, Myers, et al., 2007). The slow water permeability (Jiang, et al., 2007) of these soils can affect crop growth. At the concentration of clay found in these claypan soils, plant available water capacity (PAWC) can be as low as 0.12 $m^3$ $m^{-3}$ compared to the PAWC of the silt loam topsoils of 0.25 $m^3$ $m^{-3}$ (Jiang, et al., 2007). This can lead to high runoff with heavy precipitation as well as affect the state and availability of nutrients to the crop. Due to the differences in how crops take up and utilize nutrients, there can be a wide range in the amount and timing of nutrient uptake (Murrell, 2005).

The affect variation in claypan soils over a landscape are presumed to have an impact on WUE and $NUE_a$. However, NUE and WUE can also differ by crop, with switchgrass being more efficient with both water and N than corn (Kiniry, et al., 2008). McLaughlin and Adams Kszos (2005) attributed this to the long-term effects of switchgrass on microbial communities and population, soil organic matter accumulation, and nutrient cycling. In a soil that can easily lose or immobilize N or water, having high crop $NUE_a$ and WUE is essential. It is also important as populations grow and more land is taken out of production, to have crops be as productive as possible. The objective of this research was to compare corn and switchgrass grown on variable claypan soil landscapes: 1) metrics of the soil-crop water balance, including simulated number of days of stress per soil layer, adjusted evapotranspiration (ETa) used, and runoff; and 2) the agronomic NUE and WUE.

# MATERIALS AND METHODS

## Fields and General Management

This experiment was conducted from 2009 to 2013 at the University of Missouri, South Farm Research Center, located near Columbia, Missouri. The soil at the research site is a Mexico silt loam (fine, smectitic, mesic, Vertic Epiaqualf). The research was conducted on the Soil Productivity Assessment for Renewable Energy and Conservation (SPARC) plots. This research site was created in 1982 to have varying topsoil depths over an argilic horizon, similar to what is found on a claypan soil toposequency. The plots were unused from 1993 through 2009. In 2009 the plots were re-assessed for topsoil thickness by soil $EC_a$, using a combination of the DUALEM-2S (Dualem Inc., Milton, ON, Canada) and the Veris 2000 (Veris Technologies, Salina, KS). The research site was then divided, based on topsoil thickness, into two experiments. This research was conducted on one of the two experimental sets. Each of the 16 blocks varying in topsoil thickness have both corn (in rotation with soybeans) and switchgrass and the blocks are in a completely randomized design with a split-plot for crop. Each crop has four replications of four soil classes (A. severely eroded (< 5 cm), B. moderately eroded (5-20 cm), C. slightly eroded (20-30 cm), or D. depositional (>30 cm)), for a total of 16 plots per crop. The corn was fertilized yearly with 168 kg $ha^{-1}$ of N fertilizer while the switchgrass was fertilized yearly with 67 kg $ha^{-1}$ of N. Corn was planted June 1, 2009, April 19, 2010, May 5, 2011, April 11, 2012, and June 5, 2013. It was harvested October 28, 2009, September 13, 2010, September 8, 2011, October 8, 2012, and October 22, 2013. Eight corn plants were harvested each year for N concentration analysis of grain while two rows were harvested with a research combine for yield. The switchgrass plots were prepared in 2009 with a rotary tiller and planted June 1, 2009 using a Brillion Drop Seeder at 8.97 kg PLS $ha^{-1}$. The summer of 2009 was considered the establishment year so the switchgrass was mowed during the summer for weed control. No yield was determined for 2009. Switchgrass was harvested on December 5, 2010, November 1, 2011, December 12, 2012, and November 18, 2013. The switchgrass had a swath harvested each year for yield. Subsamples of corn grain and switchgrass biomass were oven dried upon harvesting, ground to 1 mm fineness and processed using a LECO FP-428 N analyzer (LECO Corp., St. Joseph, MI) for N content.

## Simulated Water Stress, Water Used, and Runoff

Evapotranspiration and precipitation were determined using weather data collected from the South Farm Research Center weather station, approximately 2 miles from the research area. A modified Penman-Monteith equation was used to determine evapotranspiration. The PAWC was determined using a two layer approach as described by Jiang, et al. (2007), as that research was conducted on the same soil type at a separate research site within 40 km. Using this approach, the topsoil was treated as one layer and the argilic claypan and below was treated as the second layer, due to the impedance of the claypan to water infiltration and crop growth. A profile of 1.2 m was used for both crops. A simple water budget model was used to determine daily soil plant available water (PAW). The start date for each season was the day of planting for corn and when the running average air temperature was ≥ 13C for switchgrass (Grassini, et al., 2009). The final date of each model year was based on physiological maturity for corn (2600 growing degree days) and when the running average air temperature was ≤ 13C, for corn and switchgrass, respectively. Rooting depths were used to only allow as much of the PAWC to be available as the established plant root growth depth. With 2009 the establishment year for switchgrass, root growth depth was not considered optimal during that growing season. The model started root depth at 76 cm for 2010 (Brown, et al., 2010). The switchgrass then had a daily root growth added to determine PAWC. Daily PAW was calculated using the previous day's PAW – ETa + effective Precipitation. The ETa could not exceed what was available in the soil and precipitation could not exceed the PAWC for the profile. Precipitation was used on a daily basis, so intensity was not considered. Evapotranspiration was first taken from the topsoil layer and when it was depleted, the calculation then extracted ETa from the second layer. Precipitation first infiltrated the topsoil; if there was excess precipitation from the first layer, the second layer would then have an infiltration rate of 0.24 cm $d^{-1}$ for corn and 1.2 cm $d^{-1}$ for switchgrass (Jiang, et al., 2007). Days of plant stress were considered days that ETa demand could not be met by either of the two soil layers. All results for the water portion of this study were simulated through the described model and were not directly measured.

### Water and Agronomic Nitrogen Use Efficiency

Water use efficiency was calculated using values for water used (ETa) from each plot X year from the above model based on crop and topsoil thickness. Water use efficiency was calculated as Yield (kg $ha^{-1}$)/ETa (m). Agronomic N use efficiency was calculated as (Yield (kg $ha^{-1}$) * [N content])/N applied (kg $ha^{-1}$). Plots were grouped by their soil erosion classifications. Agronomic NUE for switchgrass used the yield of the above-ground biomass while the corn only used the grain. This was done to compare current practices, which mostly use corn grain, to a potential future practice.

### Data Analysis

The data for this analysis was analyzed using SAS9.2 (SAS, Cary, NC)(SAS, 2011). Simulated water stress per soil layer, water used, and runoff were analyzed for crop and erosion class using PROC GLM at $P \leq 0.05$.

Water Use Efficiency and $NUE_a$ were analyzed using PROC REG at $P \leq 0.05$ with stepwise regression. Only when regression slope and intersect parameters were significantly different were they shown to be different in the figures. The environmental parameters for each year used in this research varied considerably so each year was analyzed and interpreted separately.

## RESULTS AND DISCUSSION

### Simulated Water Stress, Water Used, and Runoff

Simulated water stress per soil layer was different by crop (Figure 1 and

Figure **2**); simulated water stress for both layers showed switchgrass to have more days of water stress than corn in all years. This was due to the higher rate of water use by an established perennial crop compared to an annual. Soil class was different for water stress of layer 1 all years with more stress simulated with the shallow topsoil depths (Table 1). This was due to the lower amount of PAW stored in the shallower topsoils found in the severely eroded soils. Water stress of layer 2 was only significant in 2010 and 2011 (Table 1). This was due to 2010 and 2011 being normal to high rainfall years that allowed for replenishment of PAW, while 2012 and 2013 were severe and moderate droughts, respectively, resulting in low PAW for both crops. Note, days of water stress only provide a metric of days that profile water was simulated to be depleted, and does not address the crop drought-stress physiological differences that undoubtedly exist between the perennial switchgrass and the annual corn. Measurements of photosynthetic rate and respiration under these stressed conditions would be needed.

Simulated water use was greater in switchgrass than in corn every year (Table 1 and Figure 3). Similar to days of water stress, this was expected as switchgrass has a longer growing season, is quicker to develop significant amounts of biomass each year, and depletes profile-water earlier in the season allowing for rainfall to be stored rather than shed as runoff. Simulated water use was greater with deeper topsoils each year regardless of rainfall. Again, this was the result of the amount of PAW stored in each of the soil classes, with the deeper topsoils able to store more PAW.

Table 1. Significance values for simulated water stress for layers 1 and 2, water used, runoff, and runoff using the switchgrass growing season length.

| *Variable** | | *2010* | *2011* | *2012* | *2013* |
|---|---|---|---|---|---|
| Water Stress Layer 1 | Crop | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| | Soil Class | <0.0001 | 0.0002 | <0.0001 | 0.0003 |
| | Crop x Soil Class | 0.0116 | NS | 0.0050 | NS |
| Water Stress Layer 2 | Crop | 0.0139 | <0.0001 | <0.0001 | <0.0001 |
| | Soil Class | 0.0016 | 0.0231 | NS | NS |
| | Crop x Soil Class | NS | 0.0066 | 0.0155 | NS |
| Water Used | Crop | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| | Soil Class | 0.0145 | 0.0033 | 0.0084 | 0.0048 |
| | Crop x Soil Class | NS | NS | NS | NS |
| Runoff (Switchgrass growing season) | Crop | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| | Soil Class | <0.0001 | 0.0197 | 0.0005 | NS |
| | Crop x Soil Class | NS | NS | NS | NS |

*All variables are simulated, not measured values.

Simulated runoff was greater with corn each year and was greater in the shallow topsoil depths, with the exception of 2013 (Table 1 and Figure 4). After investigation into when the significant amount of runoff was occurring in switchgrass but not in corn, it was determined that the events took place before corn was planted. As runoff was still likely occurring in the corn plots, the corn season was extended to reflect the switchgrass growing season. The model was adjusted to have some vegetative weed grown on the corn plots before and after the corn season. When statistics were ran using the switchgrass growing season for both switchgrass and corn per year, simulated runoff increased for corn. The change in simulated runoff when compared to the runoff of each respective season was most readily displayed in 2013 when significant rainfall early in the season caused runoff in switchgrass, while the corn had not yet been planted. This caused the model to incorporate the simulated runoff into the switchgrass calculations but not the corn. Once the model was adjusted to reflect this alignment of simulation times, it resulted in the crop with more simulated runoff in 2013 to change from switchgrass to corn. This demonstrated that heavy rainfall in the spring before corn was planted can greatly affect runoff, due to the ground being mostly bare. Averaged over all years and erosion classes, simulated runoff was 49% less with switchgrass than corn.

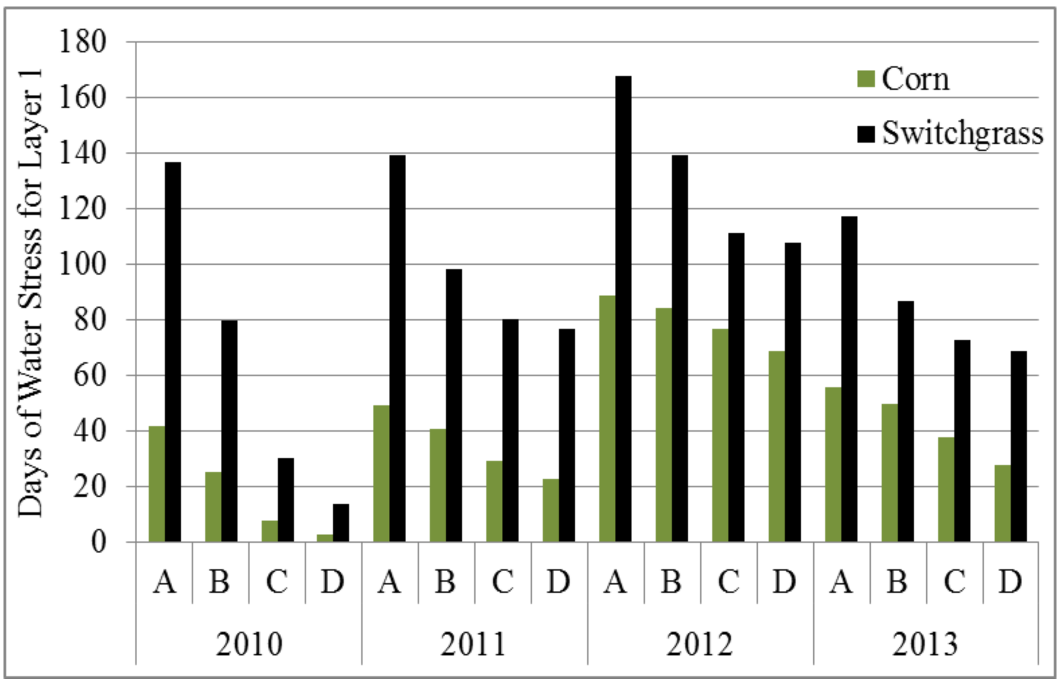

Figure 1. Simulated days of water stress for corn and switchgrass from layer 1.

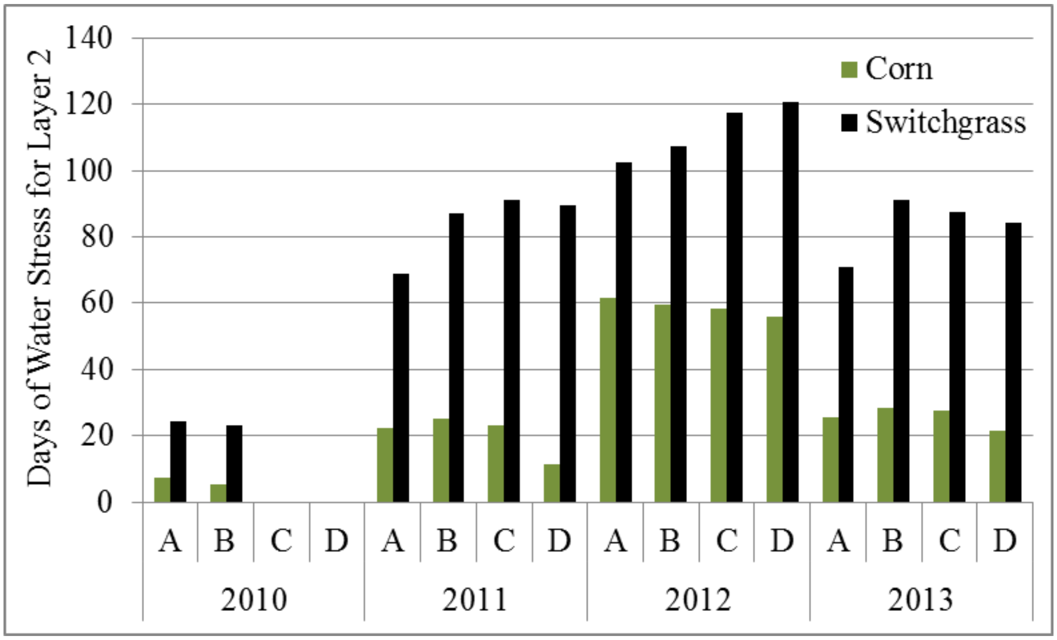


Figure 2. Simulated days of water stress for corn and switchgrass from layer 2.

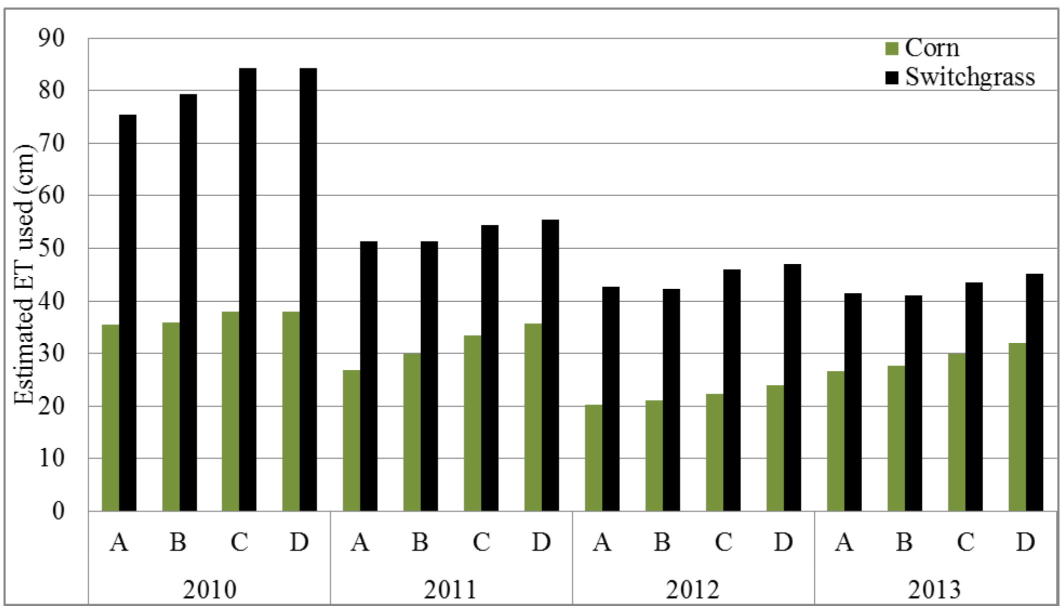


Figure 3. Estimated water used (cm) due to evapotranspiration for corn and switchgrass.

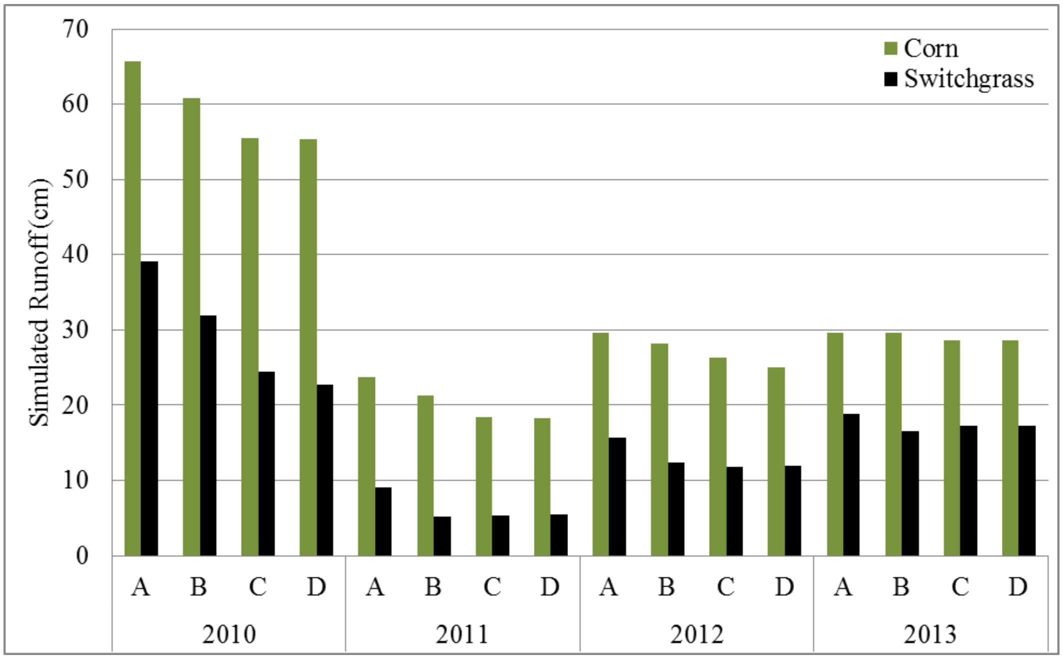

Figure 4. Simulated runoff (cm) using the switchgrass growing season for the calculations of both corn and switchgrass.

## Water Use Efficiency

In 2010, WUE was greater in corn than switchgrass with no effect of depth to claypan (Figure 5). This was thought to be due to the switchgrass not being mature and at maximum rooting depth at the beginning of the second year. Brown, et al. (2010) showed that switchgrass roots were ~76 cm at the end of the first season and beginning of the second season. This would lead to a large amount of plant energy expended in 2010 to establish mature-plant rooting that would not be necessary in following years. By 2011, when switchgrass roots were presumed to be fully established, switchgrass WUE was greater than corn. The 2010 growing season had adequate precipitation, 2011 had a late summer drought and 2012 and 2013 were considered drought years, with 2012 considered a severe drought. The drought conditions had an effect on switchgrass in both 2012 and 2013 resulting in greater WUE with increased DTC. However corn had no effect of DTC either year and had much lower WUE than switchgrass. In dry years, increased DTC led to an increased WUE of 1.17-1.25 kg $m^{-3}$ for the severely eroded soils and 2.19-2.77 kg $m^{-3}$ for the depositional soils for switchgrass compared to corn. The increased WUE with increased DTC in the drought years was due to the higher PAWC for the topsoil layer (0.25 $m^3$ $m^{-3}$) compared to the claypan layer (0.12 $m^3$ $m^{-3}$). These values were measured for the topsoil and claypan layers of the Mexico silt loam soils found in this region (Jiang, et al., 2007). This results in greater plant available water in soils with deeper DTC. Water use efficiency was more sensitive to drought for corn than switchgrass due to the nature of corn being an annual crop, having to establish its root system each year; while switchgrass, beyond the first two years, has an established rooting system that enables it to better take up water throughout the growing season.

## Agronomic Nitrogen Use Efficiency

Similar to WUE, 2010 switchgrass $NUE_a$ was less than corn due to the energy required to fully establish the switchgrass rooting system during its second season (Figure 5). In 2011, the estimated water used for both corn and switchgrass increased with increased DTC. As plants require sufficient water to take up N, this had an effect on $NUE_a$ leading to increased $NUE_a$ with increased DTC for both crops. This was the only year that DTC had an effect on $NUE_a$. This was thought to be due to a combination of different fertilizer being used in 2010/2011 (ammonium nitrate) versus 2012/2013 (SuperU) and increased effect of water used in 2011 for corn compared to other years. The 2012 growing season had a severe drought, resulting in lowered $NUE_a$ for both corn and switchgrass but switchgrass did have an increased $NUE_a$ with increased DTC. This was due to increased amount of PAW found in the deeper DTC soils. The $NUE_a$ for 2013 was very similar to 2012 with both the corn and switchgrass shifting to a greater $NUE_a$ but with a similar trend. The same trends were found of corn $NUE_a$ having no effect from DTC while switchgrass $NUE_a$ increased with DTC. In dry years, switchgrass was 14-18% more efficient than corn on severely eroded soils while it was 50-55% more efficient on depositional soils.

Table 2. Fit of model using stepwise regression for WUE and $NUE_a$.

| Response | Year | Crop | Equation | $R^2$ |
|---|---|---|---|---|
| WUE | 2010 | Corn | Y=2.20 | 0.88 |
| | | Switchgrass | Y=0.84 | 0.88 |
| | 2011 | Corn | Y=1.34 | 0.70 |
| | | Switchgrass | Y=2.48 | 0.70 |
| | 2012 | Corn | Y=0.47 | 0.90 |
| | | Switchgrass | Y=1.72+0.03*DTC | 0.90 |
| | 2013 | Corn | Y=1.64 | 0.87 |
| | | Switchgrass | Y=2.80+0.023*DTC | 0.87 |
| $NUE_a$ | 2010 | Corn | Y=58.67 | 0.42 |
| | | Switchgrass | Y=43.73 | 0.42 |
| | 2011 | Corn | Y=21.79+0.57*DTC | 0.24 |
| | | Switchgrass | Y=21.79+0.57*DTC | 0.24 |
| | 2012 | Corn | Y=8.77 | 0.87 |
| | | Switchgrass | Y=23.13+0.90*DTC | 0.87 |
| | 2013 | Corn | Y=30.19 | 0.68 |
| | | Switchgrass | Y=48.40+0.72*DTC | 0.678 |

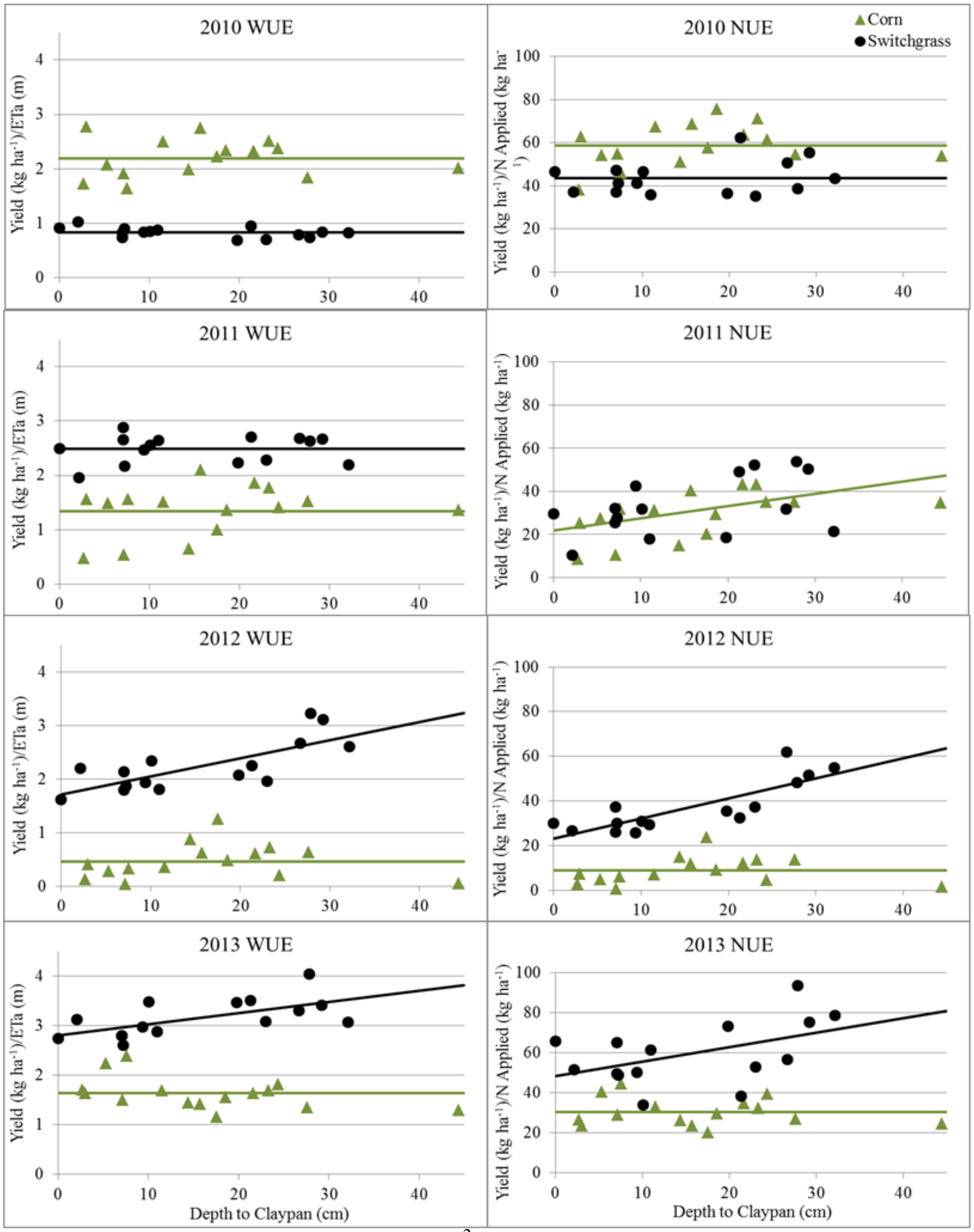


Figure 5. Water Use Efficiency (kg $m^{-3}$) and Agronomic Nitrogen Use Efficiency ((Yield (kg $ha^{-1}$) * [N])/N applied (kg $ha^{-1}$)) for corn and switchgrass by depth to claypan.

## CONCLUSIONS

The Renewable Fuel Standard mandates the incorporation of 36 billion gallons of renewable fuel into gasoline or diesel fuel by 2022, with only 15 billion gallons originating from corn grain. This has led to the investigation of other crops for the use of biofuels. This study shows that the marginal claypan soils found in Missouri and Illinois have greater WUE and $NUE_a$ for switchgrass compared to corn, with switchgrass having even greater WUE and $NUE_a$ with increased DTC, especially in drought years. This study also showed through simulation, that switchgrass results in less runoff, once fully established, due to the perennial nature of the crop. These marginal soils may be better utilized by growing switchgrass than corn as an alternative source for renewable fuels.

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Mention of trade name or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

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