2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

An ASABE Meeting Presentation

Paper Number: 12-1338038

Soil and Variety Effects on Energy Use and Carbon Emissions Associated with Switchgrass-Based Ethanol Production in Mississippi

Prem Woli

Mississippi State University, Agri. & Bio. Engineering Dept., 130 Creelman St., Starkville, MS 39762, prem.woli@msstate.edu.

Joel O Paz

Mississippi State University, Agri. & Bio. Engineering Dept., 130 Creelman St., Starkville, MS 39762, jpaz@abe.msstate.edu.

Brian S Baldwin

Mississippi State University, Plant and Soil Sciences Dept., 32 Creelman St., Starkville, MS 39762, bbaldwin@pss.msstate.edu.

David J Lang

Mississippi State University, Plant and Soil Sciences Dept., 32 Creelman St., Starkville, MS 39762, dlang@pss.msstate.edu.

James R Kiniry

Grassland Soil and Water Research Laboratory, 808 East Blackland Rd., Temple, TX 76502, jim.kiniry@ars.usda.gov.

Written for presentation at the
2012 ASABE Annual International Meeting
Sponsored by ASABE
Hilton Anatole
Dallas, Texas
July 29 – August 1, 2012

Abstract. *High biomass production potential, wide adaptability, low input requirement, and low environmental risk make switchgrass an economically and ecologically viable energy crop. The inherent variability in switchgrass productivity due to variations in soil and variety could affect the sustainability and eco-friendliness of switchgrass-based ethanol production. This study examined the soil and variety effects on these variables. Three locations in Mississippi were selected based on latitude and potential acreage. Using ALMANAC, switchgrass biomass yields were simulated for several scenarios of soils and varieties. The simulated yields were fed to IBSAL to compute energy* *use and CO_2 emissions in various operations in the biomass supply chain. From the energy and emissions values, the sustainability and eco-friendliness of ethanol production were determined using net energy value (NEV) and carbon credit balance (CCB) as indicators, respectively. Soil and variety effects on NEV and CCB were analyzed using the Kruskal-Wallis test. Results showed significant differences in NEV and CCB across soils and varieties. Both NEV and CCB increased in the direction of heavier to lighter soils and on the order of north-upland, south-upland, north-lowland, and south-lowland varieties. Only north-upland and south-lowland varieties were significantly different because they were different in both cytotype and ecotype. Gaps between lowland and upland varieties were smaller in a dry year than in a wet year. The NEV and CCB increased in the direction of dry to wet year. From south to north, they decreased for lowland cytotypes but increased for upland cytotypes. Thus, the differences among varieties decreased northwards.*

Keywords. ALMANAC, carbon emissions, cultivar, ethanol, IBSAL, net energy, soil, switchgrass.

Introduction

Bioethanol is a potential alternative energy source due to its economic, environmental, societal, and strategic benefits (USDE, 2006; NRC, 1999). It is a promising alternative to fossil resources for enhancing energy security and sustainability, promoting energy independence, and revitalizing rural economies (Kheshgi et al., 2000; McLaughlin et al., 2002; Tilman et al., 2009). It helps reduce greenhouse gas emissions and mitigate the potential impacts of climate change (Kheshgi et al., 2000; Smith et al., 2000; Cherubini and Jungmeier, 2010). Bioethanol can be produced basically from three kinds of plant materials: lignocellulose, starch, and sugar (Felix and Tilley, 2009). Sugar- and starch-based approaches have challenges related to food and feed security, grain price increase, and environmental degradation (Giampietro et al. 1997; Gnansounou and Dauriat 2010).

Lignocellulosic ethanol production does not have competition with food and feed and also has greenhouse gas advantages (Mu et al., 2010). Lignocellulosic ethanol can displace more non-renewable energy and reduce environmental risks more efficiently than can starch-based ethanol (Hammerschlag, 2006; Fischer et al., 2010). Lignocellulosic feedstocks are abundant and widely available (Perlack et al. 2005; Chandel and Singh 2011; Narayanaswamy et al. 2011). United States has an annual potential of producing about 189 million m^3 of biofuels from lignocellulosic feedstocks (Perlack et al. 2005). Lignocellulosic feedstock has a wider harvesting window and can be grown in marginal lands (Eksioglu et al., 2009). Its productivity per unit area is high (Kim and Dale, 2004; Perez-Verdin et al., 2009). Lignocellulosic ethanol is relatively inexpensive and reduces environmental risks of soil degradation and water and air pollution (Gnansounou and Dauriat, 2010; Mu et al., 2010). Lignocellulosic ethanol production technology is still evolving and is expected to become mature in 5-10 years and partly replace starch-based ethanol (Gnansounou and Dauriat, 2010). Lignocellulosic biomass has the potential to be the most promising future feedstock source (Dhugga, 2007; Huber and Dale, 2009). Lignocellulosic ethanol can be produced from crop residues, woody plant parts, and herbaceous crops such as switchgrass.

Switchgrass is an economically and ecologically viable dedicated energy crop candidate (Fike et al., 2006; Wright and Turhollow, 2010). It offers economic, energetic, environmental, and supply advantages over current biofuel sources (Hill et al., 2006). It combines the important attributes of high biomass productivity (McLaughlin et al., 1999; McLaughlin, 2006; Wullschleger, et al., 2010), high water and nutrient use efficiencies (Stout et al., 1988; Jessup, 2009; McIsaac et al., 2010), low production cost (Vadas et al., 2008), low energy and agrochemical consumption (Dunn et al. 1993; Farrell et al., 2006; McLaughlin, 2006), low management requirement (Hartman et al., 2011), high soil and water conservation ability, broad geographic adaptability (Sanderson et al., 1999; Brown et al., 2000; Fike et al., 2006), high marginal land suitability (McLaughlin et al., 1999; Hill et al., 2006; Jessup, 2009), excellent wildlife habitat (Murray et al., 2003; Sanderson et al., 2006; Williams et al., 2009), and high environmental benefit such as low soil erosion, low greenhouse gas emissions, low nitrogen leaching, high flood reduction, and high carbon sequestration (Wu et al., 2006; McIsaac et al., 2010; Hartman et al., 2011). It has excellent compatibility with existing farming operations (Vogel et al., 2002; Lewandowski et al., 2003; McLaughlin, 2006) and can be harvested and handled with conventional hay-making equipment (Cundiff and Marsh, 1996).

Switchgrass is an allogamous species, resulting in highly heterogeneous and variable populations (Casler, 2005). North American switchgrass populations fall in two different cytotypic groups: lowland and upland (Porter, 1966; Hultquist et al., 1996). Within a cytotype, the switchgrass populations have further been classified into two groups based on the latitude of origin: south and north (Casler et al., 2004). The cytotypic differentiation and latitudinal (ecotypic) adaptation in switchgrass thus lead to four varieties in this region: north-lowland, north-upland, south-lowland, and south-upland (Sanderson et al., 1996). Switchgrass biomass productivity strongly depends on the cytotype and ecotype of varieties (Jager et al., 2010; Wullschleger et al., 2010; Guretzky et al., 2011). The productivity of switchgrass varies substantially across locations, soils, and varieties (Hopkins et al., 1995; Casler et al., 2004; Parrish and Fike, 2005; Di Virgilio et al., 2007). The biomass yield of a variety varies across locations due to day-length sensitivity of switchgrass phenology (Benedict, 1940). The inherent variability in switchgrass productivity due to variations in soil and variety might affect the sustainability (in terms of non-renewable energy replacement) and the eco-friendliness (in terms of carbon emissions reduction) of switchgrass-based ethanol production. Previous studies that examined the sustainability and eco-friendliness of ethanol production systems did not explicitly address the effects of variability in soil and variety on energy crop yields and the associated ethanol production (Persson et al., 2009). Because switchgrass productivity is influenced by day-light and latitude, the effect of latitude on the sustainability and eco-friendliness of ethanol production also needs to be studied.

Due to long growing period and high rainfall, the southeastern United States is more suitable for biomass production than southwestern or northern region of the country (Persson et al., 2011). In Mississippi, a southeastern state, favorable weather and soil conditions make switchgrass a viable option for farmers. Most of the soils in this state have moderate to good aptness for switchgrass establishment and cropping (Arias et al., 2009). The response of switchgrass to the variability in climate, soil, and variety is largely unknown for the southeastern United States (Fike et al., 2006; Persson et al., 2011). Detailed knowledge about the impacts of this variability on switchgrass productivity and the sustainability and eco-friendliness of switchgrass-based ethanol production might be helpful in evaluating this grass as a potential future energy feedstock. Thus, more information is needed to characterize the productivity, sustainability, and eco-friendliness of switchgrass as a bioenergy crop in relation to soil and variety in this region.

The production and use of biofuels is associated with the issue of long-term energy security, that is, energy sustainability (Smith et al., 2000; McLaughlin and Kszos, 2005; Cherubini and Jungmeier, 2010). The energy sustainability issue is important because energy security is associated with importing fuel from other countries. The sustainability of biofuel production in terms of non-renewable energy replaced may be quantified using a measure, called the *net energy value* (NEV), which is defined as renewable energy produced minus non-renewable energy used to produce the renewable energy (Shapouri et al., 2002). A larger NEV value indicates that more non-renewable energy is replaced, and a positive value signifies that ethanol production is sustainable in terms of energy security, that is, non-renewable energy replacement.

The emission of CO_2, a greenhouse gas, during the delivery of feedstock and ethanol processing is another important issue (Sokhansanj et al. 2006; Perez-Verdin et al., 2009; Morey et al., 2010). Increasing CO_2 emissions have been identified as a cause of global climate change (Kheshgi et al., 2000; Smith et al., 2000), which in turn is a driver of environmental problems. As concern about global climate change grows, studying CO_2 emissions becomes increasingly important. Many studies have used CO_2 emissions as a basis for determining the effect of ethanol production on the environment (Marland and Turhollow, 1991; De Oliveira et al., 2005; Larson et al., 2010a). With an increase in stover yield, the amount of carbon emitted during delivery and processing also increases due to the increased use of fossil fuel. Although yield increase is generally beneficial, the associated increase in emitted carbon is not. The current approach, which evaluates the harmful effects of an ethanol production system in terms of the amount of CO_2 emitted to the atmosphere, gives an impression that increasing yield is not environmentally beneficial, which is not always true. To reflect the positive aspect of increased yield as well as the negative aspect of the associated increased emissions, a new approach is followed in this study – using *carbon credits balance* (CCB). One carbon credit denotes a reward for extracting one ton of CO_2 gas from the atmosphere. The CCB is defined as carbon credits earned (CCE) minus carbon credits used (CCU), where CCE is the amount of CO_2 (ton) taken by the switchgrass plant from the atmosphere through fixation and stored in the harvested biomass, and CCU is the amount of CO_2 (ton) emitted to the atmosphere while producing and supplying a given quantity of switchgrass biomass to a biorefinery, processing the ethanol at the refinery, and transporting, distributing, and combusting the ethanol after its production. A positive (negative) CCB value indicates that the ethanol production system is (not) environmentally friendly in terms of carbon emissions reduction, and a larger (smaller) CCB value indicates that the system is more (less) environmentally friendly.

This study examined how variations in soil and variety would affect the sustainability (in terms of non-renewable energy replacement) and eco-friendliness (in terms of carbon emissions reduction) of switchgrass-based ethanol production in Mississippi. Specifically, the study explored the soil and variety effects on the NEV and CCB of ethanol derived from switchgrass.

Materials and Methods

This is a simulation study. Switchgrass biomass yields were simulated using the Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) (Kiniry et al., 1992), a widely used crop model that realistically simulates switchgrass biomass yields for a wide range of environments, including those in the southeastern United States (Kiniry et al., 1996, 2005, 2007, 2008b; Persson et al., 2011). The ALMANAC-simulated biomass yield was used as an input to the Integrated Biomass Supply and Logistics (IBSAL) to estimate the energy use and CO_2 emissions associated with supplying the feedstock from the production field to a biorefinery facility. The IBSAL model was developed to simulate the dynamic flow of biomass from its production field to a biorefinery and estimate the associated delivered cost, biomass loss, energy consumption, and CO_2 emissions (Sokhansanj et al., 2006). It is one of the most applicable biomass logistics system simulation frameworks (Ebadian et al., 2011) and provides fundamental insights into the operation of bioenergy supply chains (Dunnett et al., 2007). The model effectively simulates real-world logistics conditions (Stephen, 2008) and gives accurate values (Kumar et al., 2006). The energy use and carbon emissions from IBSAL simulations were later used to compute NEV and CCB.

Sites and Data

Three locations in Mississippi were selected based on weather data availability, potential switchgrass growing area, and latitude: Meridian (32.33°N, 88.75°W), Grenada (33.77°N, 89.82°W), and Tunica (34.68°N, 90.42°W), which lie in the Central Prairies, North Central Hills, and Delta regions of Mississippi state, respectively. The Central Prairies, one of the most fertile farming regions of the state, comprises wide rolling grasslands that are easily converted to farmland. The North Central Hills consists of ridges and valleys with mostly alfisol soils. The Delta region, an alluvial plain in the northwest section of the state, is remarkably flat and contains highly fertile soils. This region is a major agricultural area in the state, and agriculture is the mainstay of the economy in this region.

For each location, daily historical weather data of the climatic normal period of 1971-2000 were obtained from the Delta Agricultural Weather Centre (DAWC, 2012) and the National Climate Data Center (NCDC, 2012). These data comprised maximum and minimum air temperatures and precipitation only. The daily values of solar radiation for these locations and years were estimated using the WP method described by Woli and Paz (2012).

Factors and Treatments

The effects of two factors, namely soil and variety, on NEV, and CCB were examined. Based on the suitability to growing switchgrass and the proportion of availability, five most dominant soils were considered for Tunica (silt loam, sandy loam, silty clay loam, silty clay, and clay) and Grenada (silt loam, silt, sand, silty clay loam, and clay) and four most dominant soils for Meridian (loam, loamy sand, sand, and sandy loam) (Natural Resource Conservation Service (NRCS), 2012a, b). Necessary profile data about these soils were obtained from the Soil Data Mart (NRCS, 2012a). The varieties considered were north-lowland (NL), north-upland (NU), south-lowland (SL), and south-upland (SU). Rainfed farming was assumed because farmers do not generally irrigate switchgrass in this region. Planting date effect was not explored as switchgrass is a perennial crop. The effects of soil and variety on NEV and CCB were assessed for three weather conditions: dry, wet, and average. For the dry (wet) condition analysis, the driest (wettest) year was chosen for each location from the climatic normal period of 1971-2000. For the average condition analysis, all the thirty years were considered.

Yield Simulations

For analyses, the ALMANAC-simulated switchgrass biomass yields were used. Because the model has been applied successfully in several locations, most of the parameters of the model were not changed. The default parameter values used in several studies have given fairly reasonable results (McLaughlin et al., 2006; Kiniry et al., 2008b). In this study, therefore, only radiation use efficiency (RUE), maximum leaf area index (DMLA), light extinction coefficient (EXTINC), and potential heat unit (PHU) parameters were adjusted based on literature and expert knowledge. Values used for RUE were 4.7 g MJ^{-1} for SL (Kiniry et al., 1996, 1999, 2007; McLaughlin et al., 2006; Persson et al., 2011), 78% of SL for NU and SU, and 94% of SL for NL. The EXTINC was set at 0.33 (Kiniry et al., 1999, 2007, 2008a, 2008b; McLaughlin et al., 2006). For DMLA, the following values were used: 6 for SL and NL (Kiniry et al., 1996, 2007, 2008a; McLaughlin et al., 2006; Thomson et al., 2009), 5 for SU, and 4 for NU. The PHU values used for simulations were 2300 for SL, 2200 for NL, 2150 for SU, and 2050 for NU. The values of DMLA, PHU, and RUE used for NU, SL, and SU were based on expert knowledge (Jim Kiniry, personal communication, 7 Nov 2011). For the other parameters, default values were used.

Before the application of ALMANAC for yield simulations, it was evaluated for Mississippi condition. For the evaluation, 21 switchgrass biomass yields belonging to Alamo (SL), Kanlow (NL), and Cave-in-rock (NU) observed in Starkville, Mississippi during 2001-2007 were used. After the model was evaluated, switch grass biomass yields were simulated for 48 scenarios for Meridian (4 soils x 4 varieties x 3 weather conditions) and 60 scenarios for Grenada and Tunica each (5 soils x 4 varieties x 3 weather conditions). For simulations, planting date was assumed to be May 1, considering mid-April to mid-June as the planting window for Mississippi (Lemus, 2008). Fertilizer was applied as follows: 67 kg ha^{-1} N, 45 kg ha^{-1} P_2O_5, and 90 kg ha^{-1} K_2O (Garland, 2011). Due to less energy and fertilizer requirement, higher feedstock quality, more nutrient translocation and carbon sequestration, and less greenhouse gas emissions, once-a-year harvesting approach was used (McLaughlin and Kszos, 2005; Guretzky et al., 2011).

Biomass Logistics

Using the ALMANAC-simulated biomass yield as an input to IBSAL, the energy use and CO_2 emissions associated with supplying the feedstock from the production field to a biorefinery facility were estimated for each of the 48 or 60 scenarios belonging to each location. The harvesting window for IBSAL use was assumed to start in the beginning of October (Barnhart et al., 2003; Adler et al., 2006;) and continue until the end of December (Hwang et al., 2009) as harvesting until this time and over this period can reduce the amount of nutrient uptake and also result in maximum biomass yield (Hwang et al., 2009). During the harvesting window, the area of switchgrass harvested was assumed to be uniformly distributed. The moisture content of standing switchgrass at harvest was assumed to be 25% in the beginning of October (Kumar and Sokhansanj, 2007), decrease linearly to 15% at the end of November (Hwang et al., 2009), and remain 15% thereafter (Hwang et al., 2009). The demand for switchgrass feedstock was assumed to be 2000 Mg d^{-1} (Kumar and Sokhansanj, 2007; Hess et al., 2009; Hwang et al. 2009; Sokhansanj et al., 2009). Large rectangular bales (3 x 4 x 8 feet) were considered as they have harvest, handling, transport, and storage economies of size advantages over round and square bales (Cundiff and Marsh, 1996; Thorsell et al., 2004; Larson et al., 2010b).

NEV Computation

The NEV of switchgrass-based ethanol production was computed as renewable energy obtained from the switchgrass-derived ethanol minus non-renewable energy used for obtaining the renewable energy as

$$NEV = \gamma Y(E_e - E_f - E_l - E_p - E_t) \quad (1)$$

where NEV is net energy value (MJ ha^{-1}); γ is switchgrass biomass to ethanol conversion ratio; Y is switchgrass biomass yield (Mg ha^{-1}); E_e is the energy obtained from ethanol (MJ L^{-1}); and E_f, E_l, E_p, and E_t are the energy used for biomass production, biomass logistics (harvesting, collection, storage, and transportation), ethanol processing (conversion), and ethanol transport and distribution, respectively, all in MJ L^{-1} of ethanol produced. For γ, 334 L Mg^{-1} was assumed (Mitchell et al., 2012; Qualls et al., 2012). The value of Y for each scenario was simulated using the ALMANAC model. For E_e, 21.2 MJ L^{-1} was assumed (Hammerschlag, 2006; Luo et al., 2009, 2010; Schmer et al., 2008; Hattori and Morita, 2010). The E_f was estimated as a function of Y using the relationship given by Sokhansanj et al. (2009): $E_f = (0.1036Y^2 - 9.9909Y + 812.73)/\gamma$. The values of E_f thus estimated ranged from 1.9-2.2 MJ L^{-1}, depending on the switchgrass biomass yield as influenced by soil, cultivar, weather, and location. These values were about the same as those (1.5-2.3 MJ L^{-1}) observed by Schmer et al. (2008), Hattori and Morita, (2010), Qin et al. (2006), and Vadas et al. (2008). The E_l values were estimated dividing the IBSAL-computed energy use (MJ Mg^{-1}) by the γ. For E_p, 1.1 MJ L^{-1} was used (Wu et al., 2006; Lemus and Parrish, 2009; Hattori and Morita, 2010; Luo et al., 2010). For E_t, 0.6 MJ L^{-1} was estimated using GREET1_2011, the Greenhouse gases Regulated Emissions and Energy use in Transportation model (Wang et al., 2007; ANL, 2012).

Switchgrass harvested in winter, especially after the first killing frost, which generally occurs in October in Mississippi (Kelly, 2010), removes less nutrients from the soil due to their retranslocation from foliage to crowns and roots (McLaughlin et al., 1999; McLaughlin and Kszos, 2005; Ogden et al., 2010). Switchgrass has an extensive and deep root system providing increased soil carbon storage (Stout et al., 1988; Wright and Turhollow, 2010). Therefore, no significant depletion of nutrients or soil organic matter was assumed with switchgrass harvest, and accordingly, no carbon or nutrient replacement cost was considered.

CCB Computation

The CCB associated with each switchgrass-based ethanol production scenario was computed as the amount of CO_2 (ton) fixed from the atmosphere by the harvested biomass minus the amount (ton) released back into the atmosphere as:

$$CCB = Y[\alpha\beta - \gamma(C_f + C_l + C_p + C_t + C_c)/1000] \quad (2)$$

where CCB is the carbon credit balance (credits ha^{-1}); α is the carbon content of biomass (Mg Mg^{-1}); β is the CO_2 to C ratio (44/12 Mg Mg^{-1}); and C_f, C_l, C_p, C_t, and C_c are the amounts of CO_2 emitted through energy consumption for biomass production, biomass logistics, ethanol processing, ethanol transport and distribution, and ethanol combustion, respectively, all in kg CO_2 L^{-1} of ethanol produced. For α, 0.4204 was used (Qin et al., 2006). The C_f was estimated using the relation $C_f = 0.069E_f$ derived by regressing the energy use and CO_2 emissions values computed by the IBSAL model. The estimated C_f value ranged from 0.13 to 0.15 kg CO_2 L^{-1}, depending on biomass yield. These values were close to those of Spatari et al. (2005) (0.12 kg CO_2 L^{-1}) and Qin et al. (2006) (0.19 kg CO_2 L^{-1}). The values of C_l were estimated dividing the IBSAL-computed emissions values (kg CO_2 Mg^{-1}) by γ. For C_p, 0.13 kg CO_2 L^{-1} was used (Schmer et al., 2008). For C_t, 0.05 kg CO_2 L^{-1} was estimated using the GREET1_2011 software. For C_c, a value of 1.5 kg CO_2 L^{-1} was used (Spatari et al., 2005; Wang et al., 2011).

Statistical Analyses

The effects of soil and variety on the NEV and CCB of switchgrass-based ethanol production were determined using the Kruskal-Wallis procedure, a nonparametric alternative to the classical one-way analysis of variance (ANOVA) test and an extension of the Wilcoxon rank sum test to more than two groups (MathWorks, 2012a). The Kruskal-Wallis test was used in place of the ANOVA because the assumption of normality was not met for each soil and variety. Tests were performed to find out if values of NEV and CCB were significantly different across soils and cultivars. Such tests were carried out for each location and each of the three weather conditions: dry, wet, and average.

Using medians, the Kruskal-Wallis procedure compares samples from two or more groups. The null hypothesis of the test is that all samples are drawn from the same population or from different populations with the same distribution. Its ANOVA table is calculated using the ranks of the data instead of their numeric values. The ranks are obtained by sorting the data from the smallest to the largest observation across all groups and taking the numeric index of this ordering. The test uses a chi-square statistic instead of the F statistic of the classical one-way ANOVA, whose significance is measured by the p value. The p value close to zero suggests that at least one sample median is significantly different from the others. For further information about which pairs of mean ranks were significantly different, the multiple comparison procedure (MathWorks, 2012b) was used with the Tukey-Kramer LSD test.

Results and Discussion

ALMANAC Evaluation

Values of the goodness-of-fit measures used to evaluate the ALMANAC model – the root mean square error (RMSE), the Willmott index of agreement (Willmott, 1981), the modeling efficiency (Nash and Sutcliffe, 1970), and the coefficient of determination (R^2) – showed that the model worked reasonably well in simulating the switchgrass biomass yields for Mississippi (fig. 1). Although the yields of Cave-in-rock, an upland cytotype, were slightly overestimated by the model relative to Alamo and Kanlow, lowland cytotypes, the overall agreement of the observed and model-estimated yields was good.

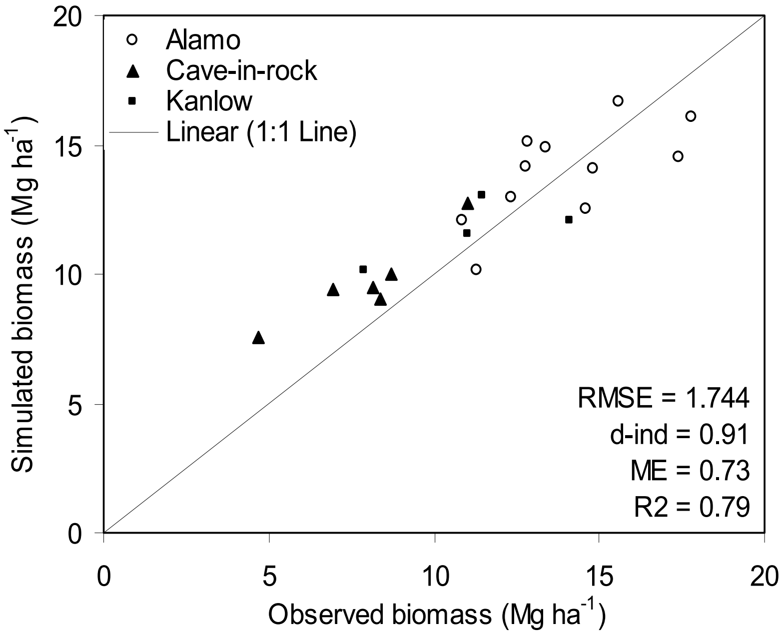

Figure 1. The simulated vs. observed biomass yields of switchgrass (Mg ha^{-1}) belonging to three cultivars (Alamo, Cave-in-rock, and Kanlow) for Starkville, Mississippi during 2001-2007. Note: RMSE = root mean square error (Mg ha^{-1}), d-ind = the Willmott index, ME = modeling efficiency (the Nash-Sutcliffe index), and R^2 = coefficient of determination.

Soil Effect

The results showed significant difference in the NEV and CCB of switchgrass-based ethanol production among soils for all locations (Table 1). In general, values of both NEV and CCB increased in the direction of heavier to lighter soils for all locations: clay to silt loam for Tunica and Grenada and loam to sandy loam for Meridian (fig. 2). For Tunica, the values of NEV and CCB each for loam soils were significantly higher than those for clay. Silty loam, sandy loam, and silty clay loam were not different, and neither were silty clay and clay. Silty clay was different from silty loam and sandy loam only. For Grenada, silty loam and silt had significantly higher values of NEV and CCB than silty clay loam and clay. Sand was different from only clay among the five soils. Silty clay loam was different from silty loam and silt but the same as sand and clay. For Meridian, only sandy loam values were significantly higher than those of loam. Sandy loam, sand, and loamy sand were about the same, and so were sand, loamy sand, and loam. The differences among the soils were likely because of the variation in soil physical and chemical characteristics (Stout, 1992). Soil texture defines its water-holding capacity, an important factor in the establishment, growth, productivity, and survival of switchgrass (Parrish and Fike, 2005). Finer-textured soils with higher water-holding capacities yielded more biomass by promoting the establishment and growth of switchgrass.

The effect of soil on CCB was the same as on NEV (Table 2) because the former had linear relationships with the latter: CCB = 0.1548NEV for Tunica, CCB = 0.1550NEV for Grenada, and CCB = 0.1556NEV for Meridian.

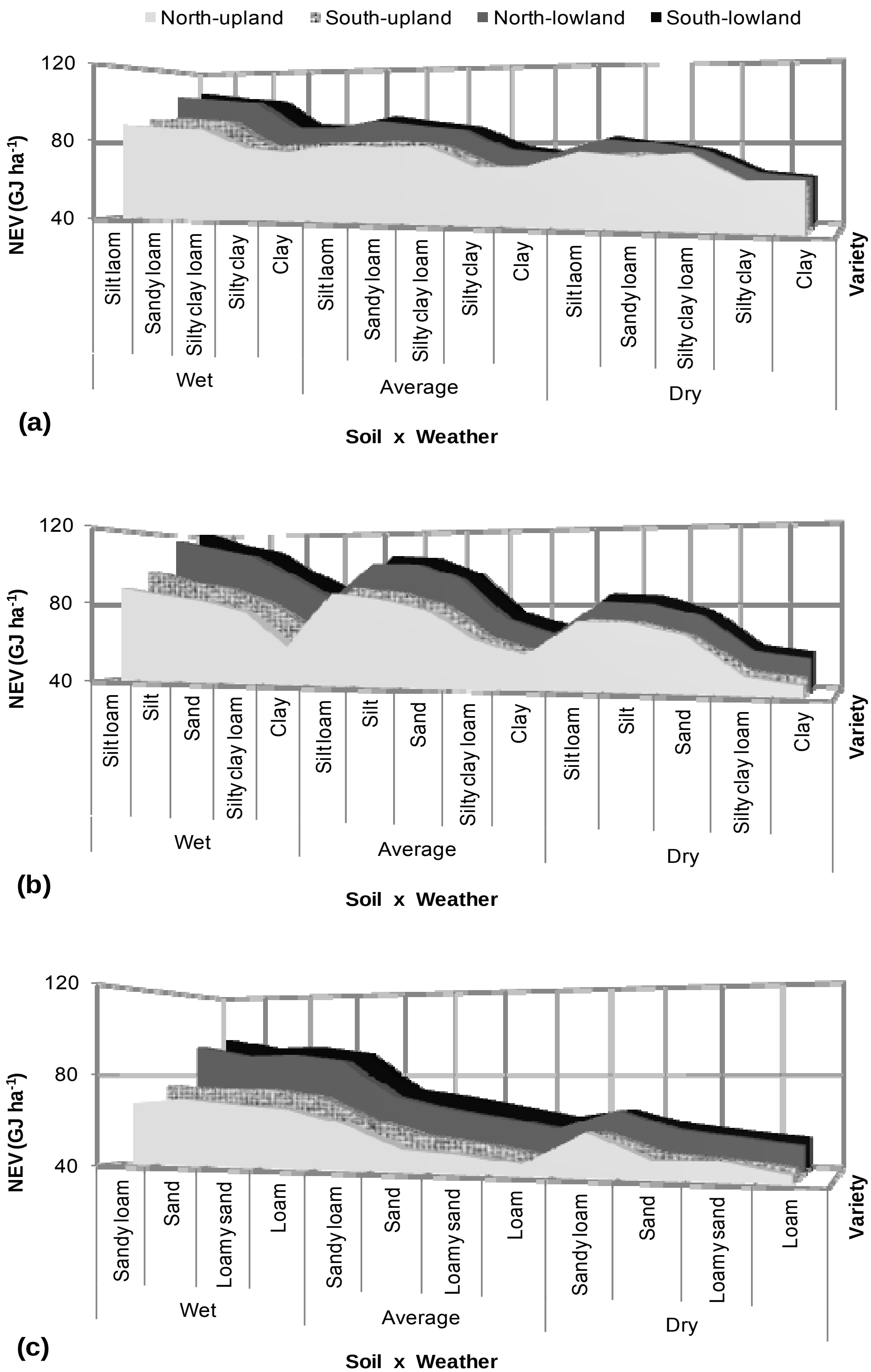

Figure 2. Net energy values (NEV) associated with various soils, weather conditions, and varieties for: (a) Tunica, (b) Grenada, and (c) Meridian in Mississippi.

Table 1. The medians of net energy value (NEV: GJ ha^{-1}) associated with various soils, varieties, weather, and locations in Mississippi, USA.

Variable	Meridian Treatment	NEV	Grenada Treatment	NEV	Tunica Treatment	NEV
Soil	Sandy loam	67.4[a*]	Silty loam	87.8[a]	Silty loam	88.9[a]
	Sand	64.5[ab]	Silt	85.5[a]	Sandy loam	86.8[a]
	Loamy sand	60.9[ab]	Sand	81.3[ab]	Silty clay loam	85.6[ab]
	Loam	55.5[b]	Silty clay loam	71.6[bc]	Silty clay	75.3[bc]
			Clay	64.7[c]	Clay	74.0[c]
Variety	South-lowland	69.5[a]	South-lowland	85.0[a]	South-lowland	82.6[a]
	North-lowland	64.8[ab]	North-lowland	82.2[ab]	North-lowland	81.0[ab]
	South-upland	56.7[ab]	South-upland	72.4[ab]	South-upland	77.0[ab]
	North-upland	55.6[b]	North-upland	71.6[b]	North-upland	74.8[b]
Weather	Dry year	53.2[b]	Dry year	65.8[c]	Dry year	73.3[c]
	Average year	59.2[b]	Average year	79.3[b]	Average year	77.2[b]
	Wet year	74.6[a]	Wet year	89.8[a]	Wet year	88.2[a]
Location		65.1[b**]		77.0[a]		77.8[a]

[*] Values followed by the same letter across treatments within a location and variable (or across locations) are not significantly different at $P < 0.05$ by the Tukey-Kramer LSD test.

Table 2. The medians of carbon credit balance (CCB: credits ha^{-1}) associated with various soils, varieties, weather, and locations in Mississippi, USA.

Variable	Meridian Treatment	CCB	Grenada Treatment	CCB	Tunica Treatment	CCB
Soil	Sandy loam	10.5[a*]	Silty loam	13.6[a]	Silty loam	13.8[a]
	Sand	10.1[ab]	Silt	13.2[a]	Sandy loam	13.4[a]
	Loamy sand	9.5[ab]	Sand	12.6[ab]	Silty clay loam	13.2[ab]
	Loam	8.8[b]	Silty clay loam	11.4[bc]	Silty clay	11.7[bc]
			Clay	10.3[c]	Clay	11.5[c]
Variety	South-lowland	10.8[a]	South-lowland	13.2[a]	South-lowland	12.8[a]
	North-lowland	10.1[ab]	North-lowland	12.7[ab]	North-lowland	12.5[ab]
	South-upland	8.9[ab]	South-upland	11.2[ab]	South-upland	11.9[ab]
	North-upland	8.1[b]	North-upland	11.1[b]	North-upland	11.8[b]
Weather	Dry year	8.3[b]	Dry year	10.2[c]	Dry year	11.4[c]
	Average year	9.2[b]	Average year	12.7[b]	Average year	12.0[b]
	Wet year	11.6[a]	Wet year	13.6[a]	Wet year	13.6[a]
Location		10.2[b*]		11.9[a]		12.1[a]

[*] Values followed by the same letter across treatments within a location and variable (or across locations) are not significantly different at $P < 0.05$ by the Tukey-Kramer LSD test.

Variety Effect

In general, the values of both NEV and CCB increased on the order of north-upland, south-upland, north-lowland, and south-lowland for all locations (fig. 2). These results agree with those of Casler et al. (2004), who observed that the similar trend of biomass yields occurs for the locations with latitudes up to about 40°N, above which north-lowland produces larger than does the south-lowland. The proportion of increase from south-upland to north-lowland, however, was larger than those from north-upland to south-upland and from north-lowland to south-lowland, indicating that the inter-cytotype (lowland vs. upland) difference is larger than the inter-ecotype difference within the cytotype (north vs. south) in the southern part of the country. The difference among the varieties is because upland cytotypes have preferential adaptation to northern latitudes, and lowland cytotypes have preferential adaptation to southern latitudes (Casler et al., 2004). The yield advantage of lowland cytotypes in southern Iowa is not as great as in Texas (Lemus et al., 2002).

Although the NEV and CCB values followed the above pattern, only north-upland and south-lowland varieties were significantly different from each other for all locations (Tables 1 and 2). This was likely because these two cultivars are different not only in terms of cytotype (upland vs. lowland) but also in terms of ecotype (north vs. south). The other pairs did not vary from one another because they belonged to either the same ecotype or the same cytotype. The varieties south-upland and north-lowland were also about the same because they belonged to the same origin (central Oklahoma), whereas south-lowland and north-upland were originated in the central/south Texas and central Great Plains, respectively (Sanderson et al., 1996). Several researchers such as Sanderson et al. (1999), Stroup et al. (2003), Casler (2004), Parrish and Fike (2005), and Lemus et al. (2002) found similar results, that is, upland ecotypes yielded substantially less than lowland ecotypes at all sites of their experiments. Significant differences occurred among upland and lowland varieties for total dry matter yield. Lowland types yielded higher because they are better adapted to warmer and moister habitats of its southern range (McLaughlin et al., 1999). The reason for the poor performance of the upland ecotypes relative to lowland ecotypes in southern locations may be related to their response to daylength and their early maturity (Sanderson et al., 1999). The upland varieties usually mature earlier than their lowland counterparts. Lowland cultivars have larger yields because of late maturity (Stroup et al., 2003; Van Esbroeck et al., 1997). Larger yields are likely due to warmer temperature and or longer growing season of the more southern locations. Switchgrass is highly photoperiod-sensitive; moving upland types south reduces the daylength they are exposed to, prompting them to flower early and thus to reduce yields. On the other hand, moving lowland types north delays their reproductive maturity, extends their growing season and increases yields (Casler et al., 2004).

The results also gave an impression that differences among upland and lowland ecotypes are environmentally dependent. Gaps between lowland and upland varieties were smaller in a dry year than in a wet year for all locations (fig. 2). These results agree with those of Wullschleger et al. (1996), who found that differences between upland and lowland ecotypes were seasonally and environmentally dependent. In their study, upland ecotypes had shown less reduction in photosynthetic rates than their lowland counterparts in a dry year. Upland types had exhibited less decrease in yields than had lowland types under water stress conditions (Stroup et al., 2003). Lowland cytotypes are associated with more hydric areas, whereas upland cytotypes are associated with more mesic regions (Moser et al., 2004). Upland types are generally considered more moisture stress tolerant than lowland types (Porter, 1966; Stroup et al., 2003).

Weather Effect

In general, the values of both NEV and CCB increased on the order of dry year, average year, and wet year for all locations (fig. 2). These results were likely because wet years produced more biomass yield and thus larger values of these variables. Accordingly, the NEV and CCB values in a wet year were significantly larger than those in a dry year for all locations (Tables 1 and 2). The difference between an average year and a dry or wet year, however, depended on location. For Grenada and Tunica, the average year was significantly different from both wet and dry years, whereas it was about the same as dry year for Meridian. These differences were due to variations in precipitation. The amount of precipitation in Meridian in an average year was not very different from that in a dry year. That is, the precipitation in this location had a skewed distribution. Switchgrass plants have a reduction in photosynthesis rates and leaf water potential under water stress conditions (Stroup et al., 2003).

The differences between upland and lowland varieties were larger for wet conditions than for dry conditions (fig. 2). These results indicated that the predominant factor affecting switchgrass productivity in southern locations is precipitation. Sanderson et al. (1999) found similar results and drew similar conclusion. In their studies, upland varieties from the Midwest matured early and did not produce as much biomass as lowland varieties from the southern U.S. Among climate variables, temperature is the most important for upland cytotypes, whereas the precipitation is the most important for lowland cytotype (Tulbure et al., 2012).

Location / Latitude Effect

Generally, values of both response variables increased in the direction of south to north (fig. 2). The proportion of difference in this direction, however, was not the same for all locations. While the values of both NEV and CCB for Meridian were significantly different from those for Grenada and Tunica each, values for Grenada and Tunica were about the same. This variation was because Grenada and Tunica had similar soils (each with silt loam, silty clay loam, and clay) and similar precipitation distributions (normal), whereas the soils (loamy sand and sandy loam) and the precipitation distribution (skewed) in Grenada were different from those in the other two locations.

The above differences among the locations were mainly due to variations in soil texture and precipitation. The absolute values of NEV and CCB, therefore, would not reflect the effect of latitude, if any, on these variables. Thus, normalized values of these variables were used instead of absolute values to eliminate location effects (soil and weather), if any. The normalized value of a response variable R for location L, denoted as N_R^L, was computed as: $N_R^L = V_R^L / L_R$, where R is NEV or CCB, V_R^L is the value of R for location L and variety V, and L_R is the value of R for location L. The N_R^L values for lowland types decreased, whereas those for upland types increased northwards (fig. 3). Thus, the differences among the varieties increased southwards although only north-upland and south-lowland varieties were significantly different. The results were in agreement with those of Casler et al.(2004), who observed that upland cytotypes had preferential adaptation to northern latitudes, and lowland ones had preferential adaptation to southern latitudes (Casler et al., 2004). They found that north-upland types had steeper positive slopes than south-upland types, and south-lowland types had steeper negative slopes than northern-lowland types. When grown in southern regions, south-lowland types tend to have a higher dry mass yield potential than north-upland types, whereas the north-upland types outperform in northern regions (Sanderson et al., 1999; Lemus et al., 2002; Casler et al., 2004; Cassida et al., 2005). Upland types usually are better adapted to well-drained soils in mid to northern latitudes, whereas lowland ones are typically adapted to lower latitudes and moist locations (Porter, 1966). Moving upland varieties southward causes rapid maturity (Sanderson and Wolf, 1995; Van Esbroeck et al., 1997), whereas moving lowland varieties northward delays reproductive maturity, prolongs growing season, and usually results in increased yields (Vogel et al., 1984).

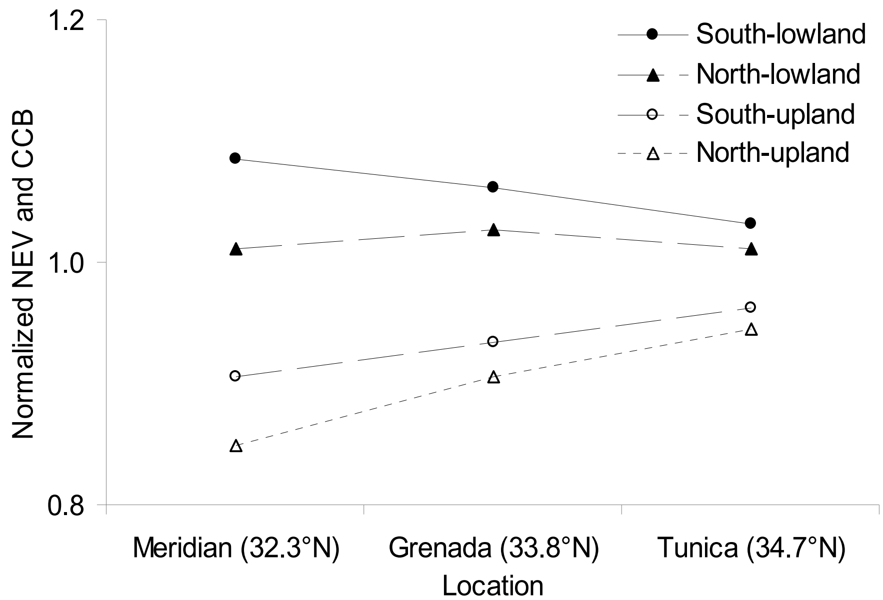

Figure 3. The normalized values of net energy value (NEV) and carbon credit balance (CCB) belonging to four cytotypes for three locations in Mississippi.

Conclusion

This study demonstrated that different soils in combination with different varieties change the NEV and CCB of switchgrass-based ethanol production. This study is different from the previous ones that examined biofuel production systems in that not only did it analyze switchgrass-based ethanol production from NEV and CCB perspectives, but also explicitly accounted for the effects of variability in soil and variety using a modeling approach. This study showed that variety can significantly affect the NEV and CCB of switchgrass-based ethanol production in Mississippi. Generally, the values of both NEV and CCB increased on the order of north-upland, south-upland, north-lowland, and south-lowland. The results also gave an indication that differences among upland and lowland ecotypes are environmentally dependent. The study further showed that variation in soil can significantly change the values of NEV and CCB. For a change from one soil type to another, values of these variables changed by 15-36%, depending on soil and location. Lighter soils with moderate water holding capacity and good aeration produced larger values of NEV and CCB than did heavier soils with poor aeration or coarse soils with low water holding capacity. The normalized values of NEV and CCB for lowland types decreased, whereas those for upland types increased northwards. Thus, the differences among the varieties increased southwards. The positive values of NEV and CCB for all scenarios indicated that switchgrass-based ethanol production in Mississippi is both sustainable in terms of non-renewable energy replacement and environmentally friendly in terms of carbon emissions reduction.

The study showed that the sustainability and eco-friendliness of switchgrass-based ethanol production in Mississippi, expressed in terms of NEV and CCB, respectively, could be increased with alternative soil and variety options. The location-specific information on the responses of

NEV and CCB to these options might be helpful to switchgrass producers and biorefineries in this region in promoting the sustainability (in terms of non-renewable energy replacement) and eco-friendliness (in terms of carbon emissions reduction) of ethanol production. Farming practices increasing NEV and CCB might be promoted through various measures, policies, and programs.

This work may be regarded as an example of studying the effects of soil and variety on the NEV and CCB of ethanol from crop residues and other lignocellulosic resources. The effects of these variables on other feedstocks may be studied by applying the methodology used in this study. To provide a broader perspective of soil, variety, and management effects on greenhouse gas emissions, additional gases such as methane and nitrous oxide may be considered.

Acknowledgements

This material is based upon work performed through the Sustainable Energy Research Centre at Mississippi State University and is supported by the Department of Energy under Award DE-FG3606GO86025.

References

Adler, P. I. R., M. A. Sanderson, A. A. Boateng, P.J. Weimer, and H. J. G. Jung. 2006. Biomass yield and biofuel quality of switchgrass harvested in fall or spring. *Agron. J.* 98: 1518-1525.

ANL. 2012. The GREET model. Argonne, Ill.: Argonne National Laboratory. Available at: http://greet.es.anl.gov/. Accessed 6 June 2012.

Barnhart, S., A. Teel, and G. Miller. 2003. Management guide for the production of switchgrass for biomass fuel in southern Iowa. Ames, Iowa: Iowa State University Extension. Available at: www.extension.iastate.edu/publications/PM1710.pdf. Accessed 9 May 2012.

Benedict, H. M. 1940. Effect of day length and temperature on the flowering and growth of four species of grasses. *J. Agric. Res*. 61: 661-672.

Brown, R. A., N. J. Roserberg, C. J. Hays, W. E. Easterling, and L. O. Mearns. 2000. Potential production and environmental effects of switchgrass and traditional crops under current and greenhouse-altered climate in the central United States: a simulation study. *Agric. Ecosys. Environ*. 78: 31-47.

Casler, M. D., K. P. Vogel, C. M. Taliaferro, and R. L. Wynia. 2004. Latitudinal adaptation of switchgrass populations. *Crop Sci*. 44: 293-303.

Casler, M. D. 2005. Ecotypic variation among switchgrass populations from the northern USA. *Crop Sci*. 45: 388-398.

Cassida, K. A., J. P. Muir, J. C. Hussey, B. C. Venuto, and W. R. Ocumpaugh. 2005. Biomass yield and stand characteristics of switchgrass in south central U.S. environments. *Crop Sci*. 45: 673-681.

Chandel, A. K., and O. V. Singh. 2011. Weedy lignocellulosic feedstock and microbial metabolic engineering: advancing the generation of ‘Biofuel’. *Appl. Microbiol. Biotech*. 89: 1289-1303.

Cherubini, F. and G. Jungmeier. 2010. LCA of biorefinery concept producting bioethanol, bioenergy, and chemicals from switchgrass. *Intl. J. Life Cycle Assess*. 15: 53-66.

Cundiff, J. S., and L. S. Marsh. 1996. Harvest and storage costs for bales of switchgrass in the southeastern United States. *Biores. Tech*. 56: 95-101.

DAWC. 2012. Delta Agricultural Weather Center. Starkville, Miss.: Mississippi State University Extension. Available at: www.deltaweather.msstate.edu/. Accessed 9 June 2012.

Dhugga, K. S. 2007. Maize biomass yield and composition for biofuels. *Crop Sci*. 47: 2211-2227.

De Oliveira, M. E. D., B. Vaughan, and E. J. Rykiel Jr. 2005. Ethanol as fuel: Energy, carbon dioxide balances, and ecological footprint. *BioScience* 55(7): 593-602.

Di Virgilio, N., A. Monti, and G. Venturi. 2007. Spatial variability of switchgrass (Panicum virgatum L.) yield as related to soil parameters in a small field. *Field Crops Res*. 101: 232-239.

Dunn, C. P., F. Stearns, G. R. Guntenspergen, and D. M. Sharpe. 1993. Ecological benefits of the conservation reserve program. *Conserv. Biol*. 7(1): 132-139.

Dunnett, A., C. Adjiman, and N. Shah. 2007. Biomass to heat supply chains - Applications of process optimization. *Trans IChemE* 85: 419-429.

Arias, E. F., W. Cooke, Z. Fan, and W. Kingery. 2009. Classification of soil aptness to establish of Panicum virgatum in Mississippi using sensitivity analysis and GIS. *World Academy Sci. Eng. Tech*. 54: 777-783.

Ebadian, M., T. Sowlati, S. Sokhansanj, M. Stumborg, and L. Townley-Smith. 2011. A new simulation model for multi-agricultural biomass logistics system in bioenergy production. *Biosyst. Eng*. 110: 280-290.

Eksioglu, S. D., A. Acharya, L. E. Leightley, and S. Arora. 2009. Analyzing the design and management of biomass-to-biorefinery supply chain. *Comput. Ind. Eng*. 57: 1342-1352.

Farrell, A. E., R. J. Plevin, B. T. Turner, A. D. Jones, M. O'Hare, D. M. Kammen. 2006. Ethanol can contribute to energy and environmental goals. *Science* 311: 506–508.

Felix, E., and D. R. Tilley. 2009. Integrated energy, environmental and financial analysis of ethanol production from cellulosic switchgrass. *Energy* 34: 410-436.

Fike, J. H., D. J. Parrish, D. D. Wolf, J. A. Balasko, J. T. Green Jr., M. Rasnake, J. H. Reynolds. 2006. Switchgrass production for the upper southeastern USA: Influence of cultivar and cutting frequency on biomass yields. *Biomass Bioenergy* 30: 207-213.

Fischer, G., S. Prieler, H. Van Velthuizen, S. M. Lensink, M. Londo, and M. De Wit. 2010. Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures. Part I: Land productivity potentials. *Biomass Bioenergy* 34: 159-172.

Garland, C. D. 2011. Growing and harvesting switchgrass for ethanol production in Tennessee. Knoxville, Tenn.: University of Tennessee Agricultural Extension Service. Available at: http://trace.tennessee.edu/cgi/viewcontent.cgi?article=1005&context=utk_agexbiof. Accessed 9 June 2012.

Giampietro, M., S. Ulgiati, and L, D. Pimente. 1997. Feasibility of large-scale biofuel production. *Bioscience* 47: 587-600.

Gnansounou, E., and A. Dauriat. 2010. Techno-economic analysis of lignocellulosic ethanol: A review. *Biores. Tech*. 101: 4980-4991.

Guretzky, J. A., J. T. Biermacher, B. J. Cook, M. K. Kering, and J. Mosali. 2011. Switchgrass for forage and bioenergy: harvest and nitrogen rate effects on biomass yields and nutrient composition. *Plant Soil* 339: 69-81.

Hattori, T., and S. Morita. 2010. Energy crops for sustainable bioethanol production: Which, where, and how? *Plant Prod. Sci*. 13(3): 221-234.

Hammerschlag, R. 2006. Ethanol's energy return on investment: a survey of the literature 1990-present. *Environ. Sci. Tech*. 40: 1744-1750.

Hartman, J. C., J. B. Nippert, R. A. Orozco, and C. J. Springer. 2011. Potential ecological impacts of switchgrass (Panicum virgatum L.) biofuel cultivation in the central Great Plains, USA. *Biomass Bioenergy* 35: 3415-3421.

Hess, J., K. L. Kenney, L. P. Ovard, E. M. Searcy, and C. T. Wright. 2009. Volume A: Uniform-format bioenergy feedstock supply system design report series. In *Uniform-format Vision and Conventional-Bale Supply System*. Washington, D.C.: US Department of Energy / Idaho National Lab.

Hill, J., E. Nelson, D. Tilman, S. Polasky, and D. Tiffany. 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proc. Natl. Acad. Sci. USA* 103: 11206-11210.

Hopkins, A. A., K. P. Vogel, K. J. Moore, K. D. Johnson, and I. T. Carlson. 1995. Genotypic effects and genotype x environment interactions for traits of elite switchgrass populations. *Crop Sci*. 35: 125-31.

Huber, G. W, and B. E. Dale. 2009. Grassoline at the pump. *Sci. Am. Ind*. 4: 40-45.

Hultquist S. J., K. P. Vogel, D. J. Lee, K. Arumuganathan, and S. Kaeppler. 1996. Chloroplast DNA and nuclear DNA content variations among cultivars of switchgrass, Panicum virgatum L. *Crop Sci*. 36: 1049-1052.

Hwang, S., F. M. Epplin, B. Lee, and R. Huhnke. 2009. A probabilistic estimate of the frequency of mowing and baling days available in Oklahoma USA for the harvest of switchgrass for use in biorefineries. *Biomass Bioenergy* 33: 1037-1045.

Jager, H. I., L. M. Baskaran, C. C. Brandt, E. B. Davis, C. A. Gunderson, and S. D. Wullschleger. 2010. Empirical geographic modeling of switchgrass yields in the United States. *GCB Bioenergy* 2: 248-257.

Jessup, J. W. 2009. Development and status of dedicated energy crops in the United States. *In Vitro Cell. Dev. Biol. Plant* 45: 282-290

Kelly, L. S. 2010. North Mississippi gardening tips. Starkville, Miss.: Mississippi State University Extension Service. Available at: http://msucares.com/lawn/garden/northmissgarden/10/10.html. Accessed 19 June 2012.

Kheshgi, H. S, R. C. Princes, and G. Marland. 2000. The potential of biomass fuels in the context of global climate change: focus on transportation fuels. *Ann. Rev. Energy Environ*. 25: 199-244.

Kim, S., and E. B. Dale. 2004. Global potential bioethanol production from wasted crops and crop residues. *Biomass Bioenergy* 26: 361-375.

Kiniry, J. R., J. R. Williams, P. W. Gassman, and P. Debaeke. 1992. A general, process-oriented model for two competing plant species. *Trans. ASAE* 35(3): 801-810.

Kiniry, J. R., M. A. Sanderson, J. R. Williams, C. R. Tischler. M. A. Hussey, W. R. Ocumpaugh, J. C. Read, G. van Esbroeck, and R. L. Reed. 1996. Simulating Alamo switchgrass with the ALMANAC model. *Agron. J*. 88: 602-606.

Kiniry, J. R., C. R. Tischler, and G. A. van Esbroeck. 1999. Radiation use efficiency and leaf CO2 exchange for diverse C4 grasses. *Biomass Bioenergy* 17: 95-112.

Kiniry, J. R., K. A. Cassida, M. A. Hussey, J. P. Muir, W. R. Ocumpaugh, J. C. Read, R. L. Reed, M. A. Sanderson, B. C. Venuto, and J. R. Williams. 2005. Switchgrass simulation by the ALMANAC model at diverse sites in the southern US. *Biomass Bioenergy* 29: 419-425.

Kiniry, J. R., B. L. Burson, G. W. Evers, J. R. Williams, H. Sanchez, C. Wade, J. W. Featherston, and J. Greenwade. 2007. Coastal Bermudagrass, Bahiagrass, and native range simulation at diverse sites in Texas. *Agron. J*. 99: 450-461.

Kiniry, J. R., L. Lynd, N. Greene, M. V. V. Johnson, M. Casler, and M. S. Laser. 2008a. Biofuels and water use: comparison of maize and switchgrass and general perspectives. *New Res. Biofuels* ISBN 978-1-60456-828-8.

Kiniry, J. R., M. R. Schmer, K. P. Vogel, and R. B. Mitchell. 2008b. Switchgrass biomass simulation at diverse sites in the Northern Great Plains of the U.S. *Bioenergy Res*. 1: 259-264.

Kumar, A., S. Sokhansanj, and P. C. Flynn. 2006. Development of a multicriteria assessment model for ranking biomass feedstock collection and transportation systems. *Appl. Biochem. Biotech*. 129-132: 71-87.

Kumar, A., and S. Sokhansanj. 2007. Switchgrass (Panicum vigratum, L.) delivery to a biorefinery using integrated biomass supply analysis and logistics (IBSAL) model. *Biores. Tech*. 98: 1033-1044.

Larson, J. A., B. C. English, D. G. De La Torre Ugarte, R. J. Menard, C. M. Hellwinckel, and T. O. West. 2010a. Economic and environmental impacts of the corn grain ethanol industry on the United States agricultural sector. *J. Soil Water Conserv*. 65(5): 267-279.

Larson, J. A., T. Yu, B. C. English, D. F. Mooney, and C. Wang. 2010b. Cost Evaluation of alternative switchgrass producing, harvesting, storing, and transporting systems and their logistics in the Southeastern USA. *Agric. Finance Rev*. 70: 184-200.

Lemus, R., E. C. Brummer, K.J. Moore, N. E. Molstad, C. L. Burras, and M. R. Barker. 2002. Biomass yield and quality of 20 switchgrass populations in southern Iowa, USA. *Biomass Bioenergy* 23: 433-442.

Lemus, R. 2008. Establishing and managing switchgrass as a forage. Starkville, Miss.: Mississippi State University Cooperative Extension Service. Available at: http://msucares.com/crops/forages/newsletters/08/8.pdf. Accessed 9 June 2012.

Lemus, R., and D. J. Parrish. 2009. Herbaceous crops with potential for biofuel production in the USA. *CAB Rev.: Perspectives Agric. Vet. Sci. Nutrition Natural Res*. 4(57): 1-23.

Lewandowski, I., J. M. O. Scurlock, E. Lindvall, M. Christou. 2003. The development and current status of potential rhizomatous grasses as energy crops in the US and Europe. *Biomass Bioenergy* 25(4): 335-361.

Luo, L., E. van der Voet, and G. Huppes. 2009. An energy analysis of ethanol from cellulosic feedstock - maize stover. *Renewable Sustainable Energy Rev*. 13: 2003-2011.

Luo, L., E. van der Voet, and G. Huppes. 2010. Energy and environmental performance of bioethanol from different lignocelluloses. *Intl. J. Chem. Eng*. 1-12. doi:10.1155/2010/740962.

Marland, G., and A. F. Turhollow. 1991. CO_2 emissions from the production and combustion of fuel ethanol from corn. *Energy* 16(11-12): 1307-1316.

MathWorks. 2012a. Kruskal-Wallis test. Natick, Mass.: The MathWorks, Inc. Available at: www.mathworks.com/help/toolbox/stats/kruskalwallis.html. Accessed 8 June 2012.

MathWorks. 2012b. Multiple comparison test. Natick, Mass.: The MathWorks, Inc. Available at: www.mathworks.com/help/toolbox/stats/multcompare.html. Accessed 8 June 2012.

McIsaac, G. F., M. B. David, and C. A. Mitchell. 2010. Miscanthus and switchgrass production in central Illinois: Impacts on hydrology and inorganic nitrogen leaching. *J. Environ. Qual*. 39: 1790-1799.

McLaughlin, S. B., J. Bouton, D. Bransby, B. V. Conger, W. R. Ocumpaugh, D. J. Parrish, C. Taliaferro, K. P. Vogel, and S. D. Wullschleger. 1999. Developing switchgrass as a bioenergy crop. In *Perspectives on New Crops and New Uses*, 282-299. J. Janick, ed. Alexandria, Va.: ASHS Press.

McLaughlin, S. B., D. G. de La Torre Ugarte, C. T. Garten Jr., L. R. Lynd, M. A. Sanderson, V. R. Tolbert, and D. D. Wolf. 2002. High value renewable energy from prairie grasses. *Environ. Sci. Tech*. 36: 2122-2129.

McLaughlin, S. B., and L. A. Kszos. 2005. Development of switchgrass (Panicum virgatum) as a bioenergy feedstock in the United States. *Biomass Bioenergy* 28: 515-535.

McLaughlin, S. B., J. R. Kiniry, C. M. Taliaferro, and D. De La Torre Ugarte. 2006. Projecting yield and utilization potential of switchgrass as an energy crop. *Adv. Agron*. 90: 267-296.

Mitchell, R., K. P. Vogel, and D. R. Uden, 2012. The feasibility of switchgrass for biofuel production. *Biofuels* 3(1): 47-59.

Morey, R. V., N. Kaliyan, D. G. Tiffany, and D. R. Schmidt. 2010. A corn stover supply logistics system. *Applied Engineering in Agriculture* 26: 455-461.

Moser, L. E., B. L. Burson, and L. E. Sollenberger. 2004. Warm-season (C4) grasses: Switchgrass. *Agronomy monograph* no. 45.

Mu, D., T. Seager, and P. S. Rao. 2010. Comparative lifecycle assessment of lignocellulosic ethanol production: Biochemical versus thermochemical conversion. *Environ. Mgmt*. 46: 565-578.

Murray, L. D., L. B. Best, T. J. Jacobsen, and M. L. Braster. 2003. Potential effects on grassland birds of converting marginal cropland to switchgrass biomass production. *Biomass Bioenergy* 25(2): 167-175.

Narayanaswamy, N., A. Faik, D. J. Goetz, and T. Gu. 2011. Supercritical carbon dioxide pretreatment of corn stover and switchgrass for lignocellulosic ethanol production. Biores. Tech. 102: 6995-7000.

Nash, J. E., and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models part I: A discussion of principles. *J. Hydrol*. 10: 282-290.

NCDC. 2012. Locate weather observation station record. Washington DC: US Department of Commerce. Available at: www.ncdc.noaa.gov/oa/climate/stationlocator.html; Accessed 9 June 2012.

NRC. 1999. *Review of the research strategy for biomass-derived transportation fuels*. Washington, D.C.: National Research Council (NRC), National Academy Press.

NRCS. 2012a. Soil Data Mart. Washington, D.C.: USDA Natural Resources Conservation Service. Available at: soildatamart.nrcs.usda.gov. Accessed 17 March 2012.

NRCS. 2012b. Web Soil Survey: Published Soil Surveys for Mississippi. Washington, D.C.: USDA Natural Resources Conservation Service. Available at: soils.usda.gov/survey/printed_surveys/state.asp?state=Mississippi&abbr=MS. Accessed 17 March 2012.

Ogden, C. A., K. E. Ileleji, K. D. Johnson, and Q. Wang. 2010. In-field direct combustion fuel property changes of switchgrass harvested from summer to fall. *Fuel Process. Tech*. 91: 266-271.

Parrish, D. J., and J. H. Fike. 2005. The biology and agronomy of switchgrass for biofuels. *Crit. Rev. Plant Sci*. 24(5-6): 423-459.

Perez-Verdin, G., D. L. Grebner, C. Sun, I. A. Munn, E. B. Schultz, and T. G. Matney. 2009. Woody biomass availability for bioethanol conversion in Mississippi. *Biomass Bioenergy* 33: 492-503.

Perlack, R. D., L. L. Wright, A. F. Turhollow, R. L. Graham, B. J. Stokes, and D. C. Erbach. 2005. Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. Washington, D.C.: US Department of Energy / US Department of Agriculture. Available at:

www1.eere.energy.gov/biomass/pdfs/final_billionton_vision_report2.pdf. Accessed 20 July 2011.

Persson, T., A. Garcia Y Garcia, J. O. Paz, J. W. Jones, and G. Hoogenboom. 2009. Maize ethanol feedstock production and net energy value as affected by climate variability and crop management practices. *Agric. Syst*. 100: 11-21.

Persson, T., B. V. Ortiz, D. I. Bransby, W. Wu, and G. Hoogenboom. 2011. Determining the impact of climate and soil variability on switchgrass (Panicum virgatum L.) production in the south-eastern USA; a simulation study. *Biofuels Bioprod. Bioref*. wileyonlinelibrary.com. DOI: 10.1002/bbb.288

Porter, C. L. 1966. An analysis of variation between upland and lowland switchgrass, Panicum virgatum L., in central Oklahoma. *Ecology* 47: 980-992.

Qualls, D. J., K. L. Jensen, C. D. Clark, B. C. English, J. A. Larson, and S. T. Yen. 2012. Analysis of factors affecting willingness to produce switchgrass in the southeastern United States. *Biomass Bioenergy* 39: 159-167.

Qin, X., T. Mohan, M. El-Halwagi, G. Cornforth, and B. A. McCarl. 20006. Switchgrass as an alternate feedstock for power generation: an integrated environmental, energy and economic life-cycle assessment. *Clean Tech. Environ. Policy* 8: 233-249.

Sanderson, M. A., and D. D. Wolf. 1995. Morphological development of switchgrass in diverse environments. *Agron. J*. 87: 908-915.

Sanderson, M. A., R. L. Reed, S. McLaughlin, S. D. Wullschleger, B. V. Conger, D. J. Parrish, D. D. Wolf, C. Taliaferro, A. A. Hopkins, W. R. Ocumpaugh, M. A. Hussey, J. C. Read, and C. R. Tischler. 1996. Switchgrass as a sustainable bioenergy crop. *Biores. Tech*. 56(1): 83-93.

Sanderson, M. A., J. C. Read, and R. R. Reed. 1999. Harvest management of switchgrass for biomass feedstock and forage production. *Agron. J*. 91: 5-10.

Sanderson, M. A., P. R. Adler, A. A. Boateng, M. D. Casler, and G. Sarath. 2006. Switchgrass as a biofuels feedstock in the USA. *Can. J. Plant. Sci*. 86: 1315-1325.

Schmer, M. R., K. P. Vogel, R. B. Mitchell, and R. K. Perrin, 2008. Net energy of cellulosic ethanol from switchgrass. *PNAS* 105(2): 464-469.

Shapouri, H., J. A. Duffield, and M. Wang. 2002. The energy balance of corn ethanol: An update. Agricultural Economic Report 814. Washington, D.C.: U. S. Department of Agriculture.

Smith, P., D. S. Powlson, J. U. Smith, P. Falloon, and K. Coleman. 2000. Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture. *Global Change Biol*. 6: 525-539.

Sokhansanj, S., A. Kumar, and A. F. Turhollow. 2006. Development and implementation of integrated biomass supply analysis and logistics model (IBSAL). *Biomass Bioenergy* 30: 838-847.

Sokhansanj, S., S. Mani, A. Turhollow, A. Kumar, D. Bransby, L. Lynd, and M. Laser. 2009. Large-scale production, harvest and logistics of switchgrass (Panicum virgatum L.) – current technology and envisioning a mature technology. *Biofuels Bioprod. Bioref*. 3: 124-141.

Spatari, S., Y. Zhang, and H. L. Maclean. 2005. Life cycle assessment of switchgrass- and corn stover-derived ethanol-fueled automobiles. *Environ. Sci. Tech*. 39: 9750-9758.

Stephen, J. D. 2008. Biorefinery feedstock availability and price variability: Case study of the Peace River region, Alberta. M.S. Thesis. Vancouver, Canada: Chemical and Biological Engineering Department of the University of British Columbia.

Stout, W. L., G. A. Jung, and J. A. Shaffer. 1988. Effects of soil and nitrogen on water-use efficiency of tall fescue and switchgrass under humid conditions. *Soil Sci. Soc. Am. J*. 52(2): 429-434.

Stout, W. L. 1992. Water-use efficiency of grasses as affected by soil, nitrogen, and temperature*. Soil Sci. Am. J*. 56: 897-902.

Stroup, J. A., M. A. Sanderson, J. P. Muir, M. J. McFarland, and R. L. Reed. 2003. Comparison of growth and performance in upland and lowland switchgrass types to water and nitrogen stress. *Biores. Tech*. 86, 65-72.

Thomson, A. M., R. C. Izarrualde, T. O. West, D. J. Parrish, D. D. Tyler, and J. R. Williams. 2009. *Simulating potential switchgrass production in the United States*. Richland, Wash.: Pacific Northwest National Laboratory.

Thorsell, S., F. M. Epplin, R. L. Huhnke, and C. M. Taliaferro. 2004. Economics of a coordinated biorefinery feedstock harvest system: Lignocellulosic biomass harvest cost. *Biomass Bioenergy* 27: 327-337.

Tilman, D., R. Socolow, J. A. Foley, J. Hill, E. Larson, L. Lynd, S. Pacala, J. Reilly, T. Seachinger, C. Somerville, and R. Williams. 2009. Beneficial biofuels: The food, energy, and environment trilemma. *Science* 325: 270-271.

Tulbure, M. G., M. C. Wimberly, A. Boe, and V. N. Owens. 2012. Climatic and genetic controls of yields of switchgrass, a model bioenergy species. *Agric. Ecosyst. Environ*. 146: 121-129.

USDE. 2006. Office of the biomass program: Multiyear analysis plan FY04-FY08. Washington, D.C.: US Department of Energy. Available at: www.nrel.gov/docs/fy05osti/36999.pdf. Accessed 9 June 2012.

Vadas, P. A., K. H. Barnett, and D. J. Undersander. 2008. Economics and energy of ethanol production from alfalfa, corn, and switchgrass in the upper Midwest, USA. *Bioenergy Res*. 1: 44-55.

Van Esbroeck, G. A., M. A. Hussey, and M. A. Sanderson. 1997. Leaf appearance rate and final leaf number of switchgrass cultivars. *Crop Sci*. 37: 864-870.

Vogel, K. P., C. L. Dewald, H. J. Gorz, and F. A. Haskins. 1984. Improvement of switchgrass, Indiangrass, and eastern Gamagrass: current status and future. In *Symp. Range Plant Improvement in Western North America*, 51-62. Denver, Colo.: Soc. Range Mgmt.

Vogel, K. P., J. J. Brejda, D. T. Walters, and D. R. Buxton. 2002. Switchgrass biomass production in the Midwest USA: Harvest and nitrogen management. *Agron. J*. 94(3), 413-420.

Wang, M., Y. Wu, and A. Elgowainy. 2007. Operating manual for GREET: Version 1.7. Argonne, Ill.: Argonne National Laboratory. Available at: www.transportation.anl.gov/pdfs/TA/353.pdf. Accessed on 6 June 2012.

Wang, M. Q., J. Han, Z. Haq, W. E. Tyner, M. Wu, and A. Elgowainy. 2011. Energy and greenhouse gas emission effects of corn and cellulosic ethanol with technology improvements and land use changes. *Biomass Bioenergy* 35: 1885-1896.

Williams, P. R. D., D. Inman, A. Aden, and G. A. Heath. 2009. Environmental and sustainability factors associated with next-generation biofuels in the U.S.: What do we really know? *Environ. Sci. Tech*. 43: 4763-4775.

Willmott, C.J., 1981. On the validation of models. *Phys. Geogr*. 2: 184-194.

Woli, P., and J. O. Paz. 2012. Evaluation of various methods for estimating global solar radiation in the southeastern USA. *J. Appl. Meteorol. Climatol*. 51(5): 972-985.

Wright, L., and A. Turhollow. 2010. Switchgrass selection as a “model” bioenergy crop: A history of the process. *Biomass Bioenergy* 34: 851-868.

Wu, M., Y. Wu, and M. Wang. 2006. Energy and emission benefits of alternative transportation liquid fuels derived from switchgrass: A fuel life cycle assessment. *Biotech. Prog*. 22(4): 1012-1024.

Wullschleger, S. D., M. A. Sanderson, S. B. McLaughlin, D. P. Biradar, and A. L. Rayburn. 1996. Photosynthetic rates and ploidy levels among populations of switchgrass. *Crop Sci*. 36: 306-312.

Wullschleger, S. D., E. B. Davis, M. E. Borsuk, C. A. Gunderson, and L. R. Lynd. 2010. Biomass production in switchgrass across the United States: Database description and determinants of yield. *Agron. J*. 102: 1158-1168.