Environmental Science & Technology

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Cost of Abating Greenhouse Gas Emissions with Cellulosic Ethanol

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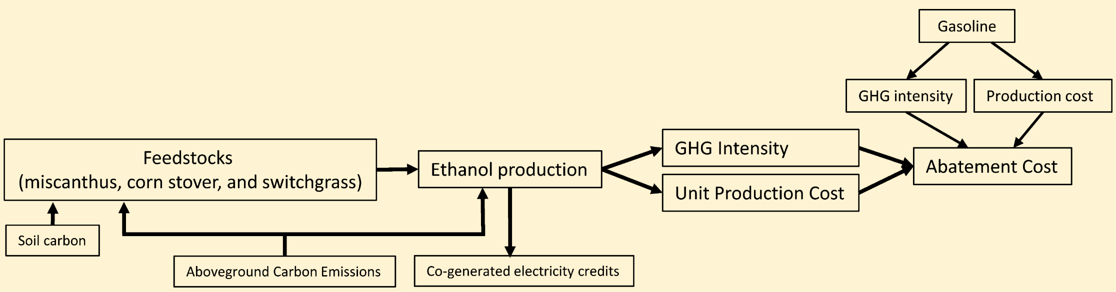
Supporting Information



ABSTRACT: We develop an integrated framework to determine and compare greenhouse gas (GHG) intensities and production costs of cellulosic ethanol derived from corn stover, switchgrass, and miscanthus grown on high and low quality soils for three representative counties in the Eastern United States. This information is critical for assessing the cost-effectiveness of utilizing cellulosic ethanol for mitigating GHG emissions and designing appropriate policy incentives to support cellulosic ethanol production nationwide. We find considerable variations in the GHG intensities and production costs of ethanol across feedstocks and locations mostly due to differences in yields and soil characteristics. As compared to gasoline, the GHG savings from miscanthus-based ethanol ranged between 130% and 156% whereas that from switchgrass ranged between 97% and 135%. The corresponding range for GHG savings with corn stover was 57% to 95% and marginally below the threshold of at least 60% for biofuels classified as cellulosic biofuels under the Renewable Fuels Standard. Estimates of the costs of producing ethanol relative to gasoline imply an abatement cost of at least \$48 Mg^{-1} of GHG emissions (carbon dioxide equivalent) abated and can be used to infer the minimum carbon tax rate needed to induce consumption of cellulosic ethanol.

INTRODUCTION

The Energy Independence and Security Act (EISA) of 2007 set a policy target of producing 60.5 billion liters of cellulosic biofuels by 2022. These biofuels are defined as those having a GHG intensity that is at least 60% lower than gasoline after including aboveground GHG emissions and GHG emissions related to direct and indirect land use changes (ILUCs). These biofuels can be produced from a variety of feedstocks (including crop residues and different types of energy crops) that are expected to differ in their production costs and GHG intensities. An assessment of the GHG intensity and production cost of cellulosic biofuels is critical for determining the cost of using cellulosic biofuels to abate GHG emissions from transportation fuels and the carbon tax needed to induce their production and consumption in the United States.

Among several possible feedstocks, corn stover and perennial grasses [switchgrass (*Pancium virgatum*) and miscanthus (*Miscanthus x giganteus*)] are particularly promising for producing cellulosic biofuels in the United States, as these can be grown in the rain-fed region of the Eastern United States. The yields of corn stover,[1,2] switchgrass,[3−9] and miscanthus[7,10−12] are dependent upon local soil, climatic conditions, and agronomic practices, and therefore, vary spatially. Studies conducting side-by-side field trials of switchgrass and miscanthus have typically found that miscanthus yield is higher than that of switchgrass, but this also depends on crop's age, cultivar, climate, and soil conditions.[7,13] However,

Received: June 6, 2014
Accepted: January 14, 2015
Published: January 14, 2015

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DOI: 10.1021/es5052588
Environ. Sci. Technol. 2015, 49, 2512−2522

Table 1. Scenarios Analyzed for Each County[a]

scenario names	crop system	life span	tillage choice	soil quality	removal rates (%)
original scenarios					
CoSo-CT	corn−soy (CoSo)	biennial	conventional (CT)	high	30
CoSo-NT	corn−soy (CoSo)	biennial	no (NT)	high	50
CoCo-CT	continuous corn (CoCo)	annual	conventional (CT)	high	30
CoCo-NT	continuous corn (CoCo)	annual	no (NT)	high	50
SG-HQ-OptN	switchgrass with optimized N fertilizer	10 years		high	100
SG-LQ-OptN	switchgrass with optimized N fertilizer	10 years		low	100
MIS-HQ-N0	miscanthus without N fertilizer	15 years		high	100
MIS-LQ-N0	miscanthus without N fertilizer	15 years		low	100
additional scenarios					
MIS-HQ-OptN	miscanthus with optimized N fertilizer	15 years		high	100
MIS-LQ-OptN	miscanthus with optimized N fertilizer	15 years		low	100

[a]Only the continuous corn cropping system is simulated for Talladega, AL, as the corn−soy cropping system is not practiced in this county. HQ refers to high quality soil; LQ refers to low quality soil.

evidence that perennial grasses like miscanthus and switchgrass can be grown productively on low quality soils is mostly anecdotal.

Some studies have analyzed the trajectory of soil carbon sequestration by corn stover, switchgrass, and switchgrass.[14−17] These studies typically do not consider the aboveground GHG emissions related with various agronomic practices and therefore, do not give an estimate of net carbon sequestered by these crops over time. Other studies, while estimating the GHG intensity of biofuels, do not consider carbon sequestered in soil or use time-averaged values[18−20] though carbon sequestered in soils could differ considerably across feedstocks and over time and can be a large positive in the case of perennial grasses or negative in the case of corn stover.[16,21,22] Liska et al.[23] estimated the soil carbon emissions due to corn stover and found that these were large enough to increase the GHG intensity of corn stover greater than that of gasoline. However, they only considered the near term effects of large rates of removal of stover under conventional tillage practices. A number of studies have estimated the cost of cellulosic biofuels from various feedstocks[13,24−28] but not the GHG intensity of ethanol derived from these feedstocks. Studies estimating the cost of GHG abatement with cellulosic biofuels include Pourhashem et al.[28] and Dwivedi and Khanna.[29,30] The former study focuses on crop residues as the only feedstock while the latter studies focus on woody feedstocks in the Southeastern United States. Recent studies also show that concerns about the invasiveness of miscanthus[31] are not supported,[32,33] and that the weed risk posed by miscanthus (currently propagated from rhizomes) and its threat of escape in the environment was lowest among several possible feedstocks, including switchgrass.[34]

In this study, we developed an integrated approach to assess the GHG intensity and production cost of cellulosic ethanol using the same system boundary for three feedstocks (corn stover, switchgrass, and miscanthus) produced in three major agro-ecological zones of the rain-fed region of the Eastern United States[35] over a 30 year time horizon. We use this approach to compare the cost of GHG abatement for ethanol derived from each of the selected feedstocks. This study makes several contributions to the existing literature. We performed a side-by-side comparison of yields of energy crops (miscanthus and switchgrass) on high and low quality soils which has implications for the extent to which production of cellulosic biofuels can be expanded in the United States without any adverse implications for food and feed production.[36] We obtain estimates of GHG abatement cost that are internally consistent and comparable across feedstocks, locations, and soil quality by using the same system boundaries to estimate the GHG intensity and costs of production of each of the three feedstocks. Our estimates of the soil carbon effects of energy crops are determined jointly with the yield of these crops under 30 years of weather conditions and based on a newly calibrated and validated version of DayCent by utilizing recent measurements obtained from several experimental field sites. These estimates can be used to infer the carbon tax that will be needed to induce the production of cellulosic biofuels from these feedstocks. Unlike previous studies that provide a single estimate of GHG intensity of cellulosic biofuel from a particular feedstock, our analysis shows the heterogeneity in the GHG intensity of cellulosic biofuels depending on feedstock, location of feedstock production, and soil quality as well as the trade-offs involved between costs of biofuels and their potential to reduce GHG emissions relative to gasoline. Trancik and Cross-Call[37] use a similar framework to examine the trade-offs between the cost and GHG intensity of existing and new electricity generating technologies.

DATA AND METHODS

Study Region. In each of three major agro-ecological zones in the rain-fed region of the continental United States,[35] we selected the county with the median five year average corn yield (2006−2010)[38] among the counties that devoted at least 20% of their crop acreage[38] in 2006 to corn. These counties are representative of locations that have the temperature, precipitation, and growing season required to grow energy crops (and provide corn stover) on land currently under agricultural/pasture production.

The three selected counties were Marion in Illinois (IL), Adams in Indiana (IN), and Talladega in Alabama (AL). Soil attributes and climate conditions in these three counties together with the assumptions about fertilizer application rates were used to simulate yields for the feedstocks examined in this study. For each location, we considered eight scenarios of feedstock production (Table 1).

DayCent Model. Model simulations of crop yield and soil carbon content were performed using the biogeochemical process-based model DayCent v. 4.5;[39] the most recent daily time step version of CENTURY. DayCent simulates the effects of climate and land use change on carbon and nutrient cycling

DOI: 10.1021/es5052588
Environ. Sci. Technol. 2015, 49, 2512−2522

in terrestrial ecosystems and has been validated for use in crop, grassland, and forest ecosystems globally.[40−42] The DayCent model has been extensively used to simulate site level and regional predictions of miscanthus and switchgrass yields along with changes in soil nitrous oxide fluxes and soil carbon and nitrogen levels resulting from growth of miscanthus and switchgrass in agricultural ecosystems.[17,43] The model mechanistically represents ecosystem processes using mathematical equations and uses these equations to predict response variables under new combinations of driving variables. DayCent calculates potential plant growth as a function of water, light, and soil temperature and limits actual plant growth based on soil nutrient availability. Soil organic carbon is estimated from the turnover of soil organic matter pools which changes with the decomposition rate of dead plant material. For this study, DayCent was parametrized to model soil organic carbon dynamics to a depth of 30 cm.

Calibration and Evaluation. We compiled measured yield data on miscanthus (*Miscanthus x giganteus*, a perennial sterile C4 grass and a hybrid of *Miscanthus sinensis* and *Miscanthus sacchariflorus*)[44] and several switchgrass (*Panicium virgatum*) cultivars from the BETYdb database[45] and the EBI (Energy Biosciences Institute) Energy Farm[46] to calibrate the crop productivity parameters that relate soil attributes with yields in DayCent.[39] For switchgrass, we categorized the observed data into three yield classes to represent the observed range of cultivar yields as different crop definitions in DayCent. We assumed a high-yielding cultivar would be planted in each county and selected the switchgrass calibration that would simulate the highest observed yields of switchgrass in proximity to each county. An extensive evaluation of the new DayCent calibration using data from the EBI Energy Farm (located at the University of Illinois at Urbana−Champaign) was completed by Hudiburg et al.[43] Model predictions for corn yields were in close agreement with historical estimates of mean annual county corn productivity data[38] in all three counties from 1925−2011 (R^2 = 0.83, 0.72, and 0.77; Figure S1, Supporting Information). For switchgrass and miscanthus, we used data from research sites across the Eastern United States[47] to regress model predictions of yield on observed data (R^2 = 0.62 and 0.86 for switchgrass and miscanthus, respectively; Figure S2a, Supporting Information). We also compared the modeled soil organic carbon with the State Soil Geographic (SSURGO) database for each soil type at each research site for site initial conditions (R^2 = 0.95; Figure S2b, Supporting Information).

Simulations of Feedstock Yield and Soil Carbon. We simulated yield and soil carbon for each of the selected scenarios over a 30 year period using daily weather data for the years 1980−2011. These data were obtained for each county from the DAYMET database[48] and soils data were acquired from the SSURGO database.[49] For miscanthus and switchgrass, we used two soil types for each county, identified as agricultural soil of high and low quality using the land capability class in the SSURGO database[49] (Table S1, Supporting Information). High quality soils had land capability classifications of 1 or 2 and were among the highest yielding soils in the county, as determined by the reported corn yields. Low quality soils were defined as those land types whose land capability classification was greater than 5; a classification of greater than 5 is considered not suitable for cultivation. Nitrogen (N) application rates were determined based on the N removed in crop residues for corn stover and optimized to maximize yield on high and on low quality soils for switchgrass. Long-term trials of miscanthus have typically shown no or very little effect of N fertilization,[12,50−52] but recent field trials[53] across sites in IL over 8−10 years showed a small but statistically significant yield increase in response to a rate of 202 kg of N ha^{-1} yr^{-1} at some locations. Therefore, we used both a zero and optimal N application rate for miscanthus. Finally, miscanthus and switchgrass were simulated using a 15 and 10 year rotation, respectively. We did not account for release of higher yielding cultivars over the 30 year period as the potential for that is currently unknown.

Unit Production Cost. We considered the following costs related to the production of cellulosic ethanol at the biorefinery gate over the simulation period: (a) feedstock production cost at the farm gate including establishment and maintenance, harvesting, storing, and transportation costs during harvest years; (b) opportunity cost of land use; (c) feedstock processing cost at the biorefinery net of income due to supply of cogenerated electricity to the grid. The opportunity cost of land use arises because land has to be converted from an existing use to energy crop production. In the case of high quality soils, we assume that the existing land use is corn and soybean with various rotation and tillage choices in IL and IN and continuous corn in AL. The foregone profits from these existing land uses represent the opportunity cost for producing an energy crop over the 30 year time horizon considered here. These profits vary over time due to annual variability in the yields of corn and soybean. Low quality soils are assumed to earn a return that is a proxy of the rental payment for enrollment in the Conservation Reserve Program. These payments were assumed constant over 30 years. For corn stover, there is no opportunity cost of land use change for each of the four scenarios as we have assumed that the corn is the most profitable crop in these counties and there was no land use change from one tillage/rotation practice to another.

We assumed that biomass was converted to cellulosic ethanol using enzymatic hydrolysis. Feedstock conversion efficiency and conversion cost were based on a 231 million L yr^{-1} biorefinery utilizing enzymatic hydrolysis.[54] We used a recent estimate of the conversion cost and efficiency for a mature technology as reported by Humbird et al.[54] Existing studies have not analyzed the effect of feedstock type on the feedstock conversion costs or ethanol yields.[54] Therefore, we assumed that they remain same across all feedstocks.[28,55−57] Transportation cost of feedstock was determined based on the distance from which the feedstock would need to be collected to meet the demand of a biorefinery and varied inversely with the crop yield. We estimated the transportation distance for each feedstock as the minimum radius of the biomass catchment area needed to source annual quantities of biomass for the biorefinery located at the center of the biomass catchment area (Table S2, Supporting Information). Because the costs of producing perennials differ over their lifecycle, we estimated the discounted net present value of the feedstock costs over 30 years and then annualized it using a discount rate of 2%.[24] All assumptions for estimating unit cost of cellulosic ethanol are in Table S3 (Supporting Information) and expressed in 2010 dollars.

GHG Intensity. We included GHG emissions related to feedstock production (including carbon sequestered in soils), feedstock processing, feedstock transportation, conversion of feedstock to ethanol, and those related to ILUC for estimating the GHG intensity of ethanol produced over 30 years and for each year within the simulation period in selected counties.

DOI: 10.1021/es5052588
Environ. Sci. Technol. 2015, 49, 2512−2522

Table 2. Average Yields of Feedstocks (with Standard Deviation, Minimum Yield, and Maximum Yield) in Selected Scenarios and Counties[a]

scenarios name	Talladega, AL (Mg ha^{-1})	Marion, IL (Mg ha^{-1})	Adams, IN (Mg ha^{-1})
original scenarios			
CoSo-CT		2.5 (0.7,1.4,3.7)	2.9 (0.7,1.1,3.6)
CoSo-NT		4.3 (1.0,2.7,6.4)	4.4 (0.9,1.9,5.4)
CoCo-CT	1.7 (0.5,0.6,2.5)	2.3 (0.7,1.4,3.5)	1.9 (0.6,0.6,2.8)
CoCo-NT	2.6 (0.6,0.8,3.7)	3.9 (1.1,2.3,6.0)	3.1 (1.0,1.1,4.4)
SG-HQ-OptN	18.2 (7.6,10.4,27.7)	17.1 (6.2,13.2,22.1)	15.7 (5.5,13.4,19.3)
SG-LQ-OptN	15.2 (6.3,9.3,23.4)	15.9 (5.9,13.5,22.0)	15.2 (5.4,13.5,19.2)
MIS-HQ-N0	24.6 (9.8,12.8,38.1)	27.2 (9.0,14.6,36.0)	28.3 (8.7,15.4,35.0)
MIS-LQ-N0	19.5 (8.4, 6.6,32.0)	25.0 (8.7,9.7,33.9)	23.9 (7.8,11.1,30.6)
additional scenarios			
MIS-HQ-OptN	28.4 (10.6, 15.8, 42.6)	31.4 (10.0, 18.9, 40.2)	31.1 (9.3, 18.8, 38.2)
MIS-LQ-OptN	25.3 (10.0, 12.4, 39.4)	31.3 (9.9, 19.3, 40.0)	30.6 (9.4, 18.6, 39.0)

[a]For corn stover under the corn–soy cropping system, average yields are based on estimates for every alternate year. All yields are reported with 15% moisture.

Using the same input application rates and stages as used for estimating the GHG intensity, we estimated the annual and annualized production cost of ethanol for each feedstock in each county. Tables S4, S5, and S6 (Supporting Information) summarize material inputs for corn stover, switchgrass, and miscanthus, respectively. Table S7 (Supporting Information) presents the key GHG intensity parameters obtained from the GREET model.[57] These input application rates were used to change the default values in the GREET model and calculate aboveground GHG intensity of cellulosic ethanol.

Abatement Cost. We estimated the annual cost of GHG abatement in each of the harvest years under each scenario. We used the following formula to ascertain the GHG abatement cost for each scenario.

$$\text{GHG abatement cost} = \frac{\text{production cost of ethanol per MJ} - \text{wholesale price of gasoline per MJ in 2010}}{\text{carbon intensity of gasoline per MJ} - \text{carbon intensity of ethanol per MJ}}$$

The wholesale price of gasoline[58] in 2010 was US \$0.60 L^{-1}. Carbon intensity of gasoline[57] was assumed to be 94 g CO_2e MJ^{-1}.

Sensitivity Analysis. We analyze the robustness of our estimates of GHG intensity for ethanol derived from selected feedstocks to several factors. These include uncertainty about the magnitude of GHG emissions related to the ILUC effect for switchgrass and miscanthus. We analyze the effects of low and high values of the ILUC effect (Table S8, Supporting Information) on the annualized GHG intensity of produced ethanol. We also analyzed the impact of yearly variation in the yields on the GHG intensity over 30 years of weather conditions. Similarly, we analyze the sensitivity of our estimates of annualized production costs by varying average cost of baling and storing feedstock and rate of feedstock loss during storage and transportation reported in Table S3 (Supporting Information) by ±20%. We varied the conversion cost as there exists a considerable uncertainty about the cost of conversion of feedstock to fuel in the absence of a commercial technology.[59] We assume that the cost of conversion of a mature technology is \$0.42 L^{-1} based on Humbird et al.[54] and then analyze sensitivity to a cost estimate of \$ 0.66 L^{-1}. Given the uncertainty about the impact of N application on miscanthus and switchgrass yields, we analyzed cases with zero and optimal rate of N application to maximize yield on high and on low quality soils. Additionally, we considered a range of gasoline prices (±20% of the average gasoline price of US \$0.60 L^{-1}). We used various combinations of these uncertain parameters (for yields, weather, cost of feedstock-baling and storage, rate of feedstock loss during storage and transportation, conversion cost, and gasoline prices) to determine the distribution and range of abatement costs.

RESULTS

Projected Yields. Simulated annual harvestable yields differed considerably across feedstocks and locations (referred to as AL, IL, and IN hereafter) over time (Figure S3, Supporting Information). Harvestable yields of corn stover were more sensitive to changes in local weather conditions than the yields of switchgrass and miscanthus. Miscanthus yield was on average at least 28% higher than that of switchgrass and at least 5 times higher than the corn stover yield (Table 2). Yield of perennial grasses was slightly lower on low than high quality soils, with the difference ranging from 8% to 20% for miscanthus and 3% to 16% for switchgrass. This difference was not statistically significant at any of the three locations. Differences in crop yields led to differences in the average volume of ethanol across feedstocks (Table S9, Supporting Information).

GHG Intensity. We compared the additional carbon sequestered by each feedstock in soils relative to the baseline level that would have occurred in the absence of the production of that feedstock. For perennial grasses grown on low quality soils, the baseline level used was the soil carbon present at the beginning of the simulation period, assuming that the initial level would have remained unchanged over time if the land was maintained in its existing use. For perennial grasses grown on high quality soils, the baseline was soil carbon sequestered under a corn–soy cropping system with conventional tillage and zero corn stover removal for IL and IN. The corresponding baseline used for AL was continuous corn cropping system with conventional tillage and zero corn stover removal because the corn–soy cropping system is not practiced in AL. The soil carbon impact of corn stover removal was estimated relative to

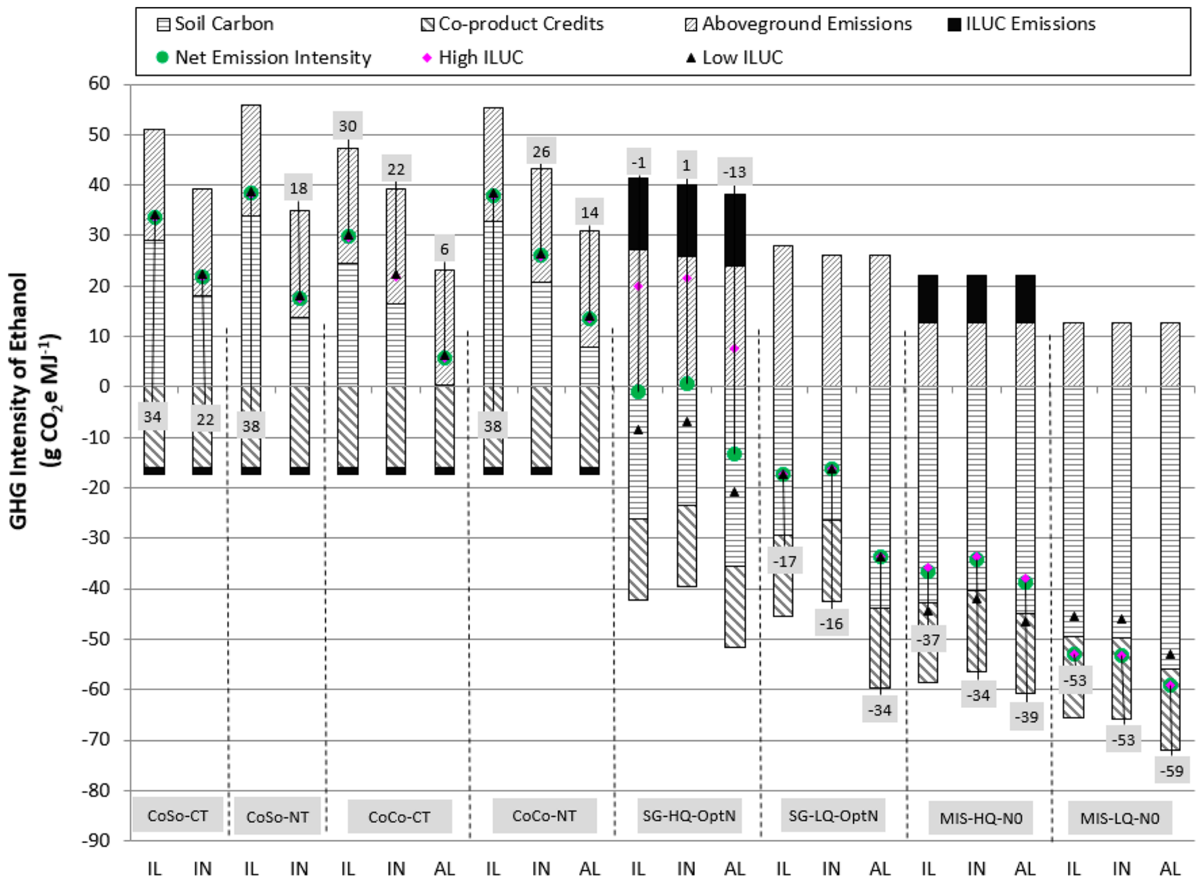

Figure 1. Components of average GHG intensity of ethanol over simulation period. Positive values represent GHG emissions to the atmosphere whereas negative values show sequestration. Aboveground emissions include GHG emissions related to feedstock production, feedstock transportation, and conversion of feedstock to ethanol. Net emission intensity (circle) is the summation of additional carbon sequestered in soil, avoided GHG emissions due to supply of cogenerated electricity to the grid, aboveground GHG emissions, and GHG emissions due to average ILUC. Diamonds and triangles represent net GHG emissions intensity with high and low ILUC effect, respectively. Estimates underlying this graph are provided in Table S10 (Supporting Information). Range of GHG emissions related to ILUC is reported in Table S8 (Supporting Information).

the soil carbon level with zero corn stover removal under the same cropping system and tillage choice.

Initial carbon stock in the soil differed considerably across the three locations and across high and low quality soils at each location (Figure S4, Supporting Information). Soil carbon sequestered by perennial grasses increased by at least 50% over 30 years. The increase in carbon sequestered in soils relative to the baseline was about two times larger for miscanthus than switchgrass on high and low quality soils (Figure S5, Supporting Information). For corn stover grown with no-till and 50% removal rate, soil carbon sequestered decreased relative to the corresponding baseline with zero removal under both types of cropping systems. Corn stover grown using conventional tillage with 30% removal rate also led to a decline in soil carbon for both cropping systems.

Change in carbon sequestered in soil and above-ground emissions during the process of producing the feedstocks and the ethanol were key determinants of the overall GHG intensity of ethanol (Figure 1, Table S10, Supporting Information). The GHG intensity of ethanol derived from miscanthus was negative and lower than that from switchgrass at all locations. The GHG intensity of ethanol derived from corn stover with both types of tillage and rotation was positive and greater than that of ethanol derived from miscanthus and switchgrass. The GHG intensities of ethanol derived from switchgrass and miscanthus in this study (−1 to −34 g CO_2e MJ^{-1} for switchgrass and −34 to −59 g CO_2e MJ^{-1} for miscanthus) were lower than the GHG intensities reported by Wang et al.[19] (+12 and −7 g CO_2e MJ^{-1} for ethanol derived from switchgrass and miscanthus, respectively) due to the higher values of net carbon sequestered in soils over time under switchgrass and miscanthus. The GHG intensity of ethanol varied annually with the variations being the largest for corn stover (Figure S6, Supporting Information). Even with a high estimate of the GHG emissions related to ILUC, the overall GHG intensity of ethanol produced from miscanthus on high quality soils was still negative and lower than that of ethanol produced from switchgrass on either quality of soils. However, the GHG intensity of switchgrass grown on high quality soils became positive with a high ILUC effect.

The application of N lead to a statistically significant increase in miscanthus yields compared to yields with zero application at all locations for only low quality soils (Table 2). The yield increases were 27% and 13% on average for low and high quality soils, respectively. Increased fertilizer rates increased the GHG intensity of ethanol derived from miscanthus on low quality soils while the effect on high quality soils was negligible (Figure S7, Supporting Information). We also examined the responsiveness of switchgrass to N application by examining the impact of a zero application rate. In contrast to miscanthus, application of an optimal level of N to switchgrass increases yield by 161% and 219% on an average on high and low quality

DOI: 10.1021/es5052588
Environ. Sci. Technol. 2015, 49, 2512−2522

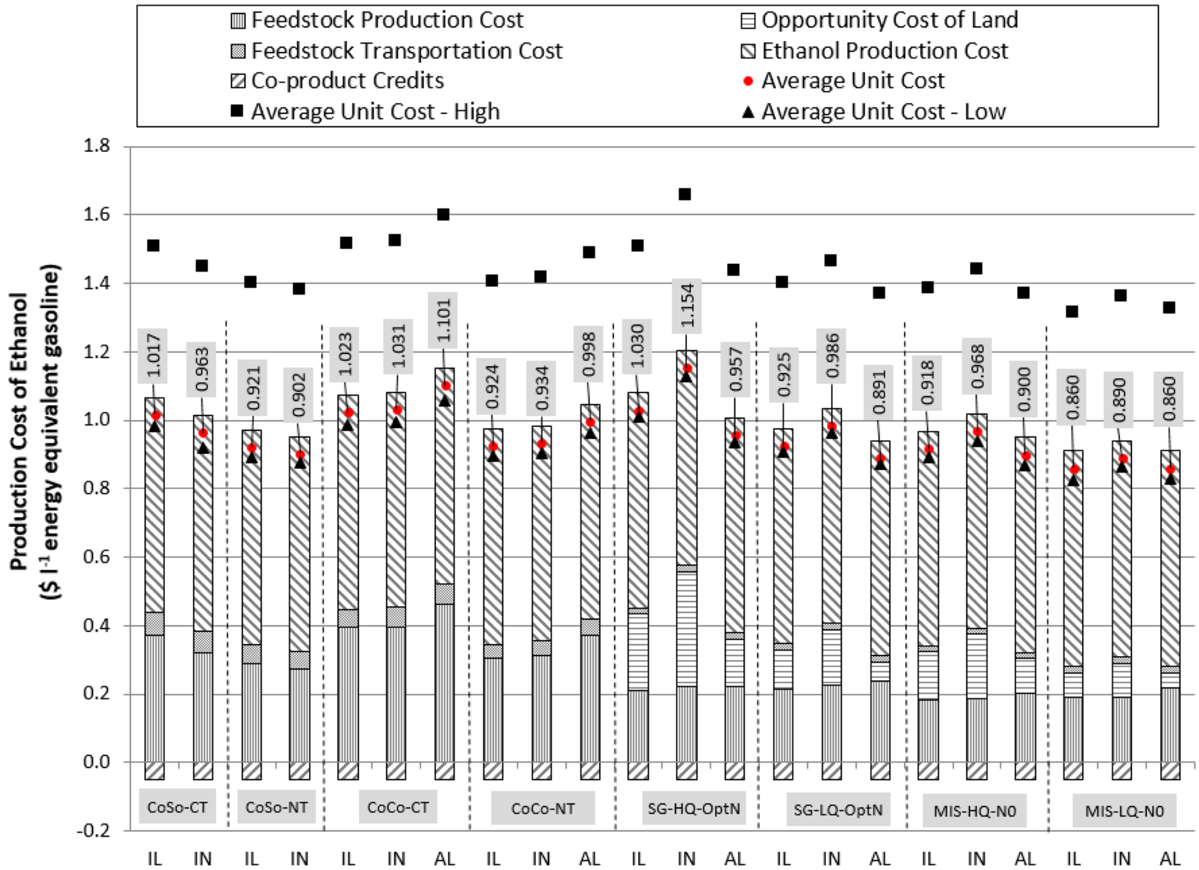

Figure 2. Components of average production cost of ethanol over simulation period. Underlying estimates are reported in Table S12 (Supporting Information). "Average unit cost - High" represents the case where cost of baling and storing the feedstock and rate of biomass loss during storage and transportation are 20% higher than the benchmark values reported in Table S3 (Supporting Information). "Average Unit Cost - Low" represents the case where these costs are 20% lower than the benchmark values. The biomass to ethanol conversion cost is \$ 0.66 L^{-1} of ethanol produced in the high cost case and \$ 0.42 L^{-1} in the low cost and baseline cases. This range of conversion cost is based on Humbird et al.[54]

soils, respectively. It also raises the GHG intensity of ethanol significantly by 87% and 15% on an average for high and low quality soils, respectively.

Ethanol Production Cost. The cost of producing the feedstock (including land rent) was lowest (\$49 Mg^{-1}) for miscanthus on low quality soils in IL and highest (\$105 Mg^{-1}) for switchgrass on high quality soils in IN (Table S11, Supporting Information). The cost of converting feedstock to ethanol was the largest component of the overall cost of ethanol followed by feedstock production cost and opportunity cost of land (Figure 2, Table S12, Supporting Information). Because conversion cost and income from cogenerated electricity were the same across feedstocks and over time, the differences in the production cost of ethanol across feedstocks was largely due to differences in yield related production costs, opportunity cost of land, and transportation cost of feedstock. The cost of ethanol was lowest for miscanthus and higher for switchgrass produced on low quality soils because of the relative lower feedstock cost and transportation costs. Ethanol from corn stover grown with no-tillage had a lower cost than that with conventional tillage. In general, corn stover ethanol was relatively cheaper in IN and IL than in AL while switchgrass and miscanthus ethanol was cheaper in AL on both soil types than in IN and IL. The lowest cost ethanol was derived from miscanthus grown on low quality soils in IL (\$0.86 L^{-1}) and the highest cost ethanol (\$1.15 L^{-1}) was from switchgrass on high quality soils in IN.

Our results clearly indicate that production cost of ethanol due to uncertainties in key parameters could range from a lower estimate of \$0.88 to a higher estimate of \$1.66 L^{-1}. We also found that ethanol conversion cost was a key determinant of any change in the overall production cost of ethanol derived from selected feedstocks. The annual production costs of ethanol varied considerably mostly because of variations in feedstock yields and changes in input parameters for high, average, and low cost estimates. This variations was highest in the case of corn stover followed by miscanthus (Figure S8, Supporting Information). The average cost of producing ethanol derived from miscanthus with or without N fertilization was very similar across all scenarios. The increase in yields due to the addition of N fertilizer was offset by the increase in the cost of fertilizer application (Figure S9, Supporting Information). In the case of switchgrass, however, the application of N significantly lowered overall costs because of the substantially higher yields. These results indicate that producers are likely to have an economic incentive to apply N to switchgrass but not to miscanthus.

Cost of GHG Abatement. The annual cost of GHG abatement differed across feedstocks and was determined, to a large extent, by yields, opportunity cost of land, net carbon sequestered in soils, and input cost assumptions (Figure 3). This cost was lowest for miscanthus without any N application followed by switchgrass grown on low quality soils. The annual GHG abatement cost showed considerable variability for a

DOI: 10.1021/es5052588
Environ. Sci. Technol. 2015, 49, 2512−2522

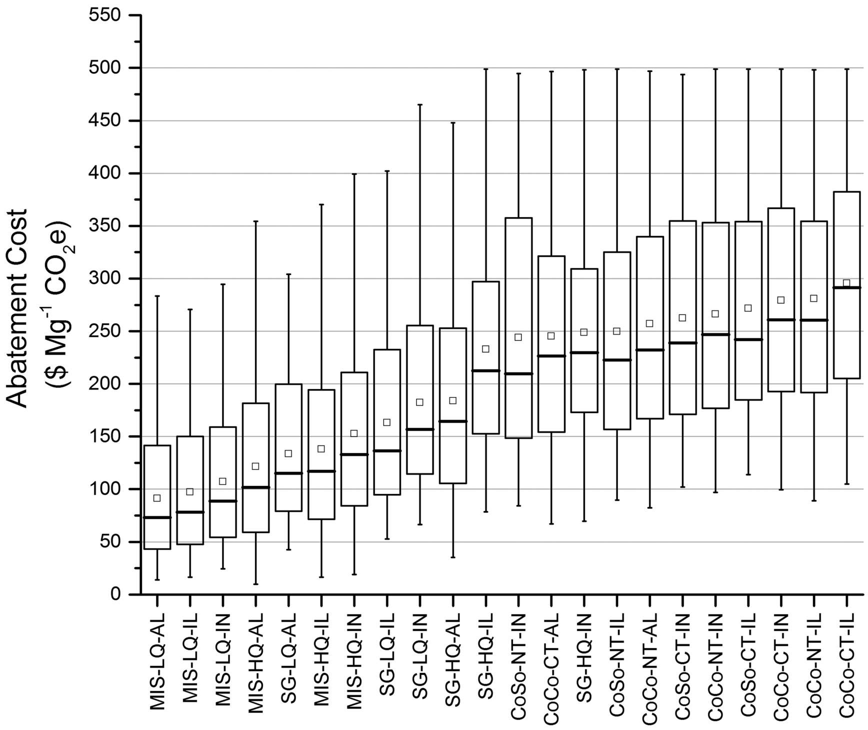

Figure 3. Range of GHG abatement cost for selected scenarios. These values are based on GHG intensities and cost of ethanol produced each year during the simulation period. Only harvest years are used for estimating annual GHG intensities and production costs. GHG intensity includes carbon sequestered in soil, avoided GHG emissions due to supply of cogenerated electricity to the grid, aboveground GHG emissions, and GHG emissions with average ILUC effect. This also includes high, average, and low estimates of ethanol production costs coupled with high and low prices of gasoline (±20%). Distribution of higher interquartile range (+50%), 75% percentile, mean (square in shape), median, 25% percentile, and lower interquartile range (−50%) is shown for each scenario.

continuous corn cropping system for both tillage choices. It was generally higher for corn stover produced with continuous corn than with a corn−soy cropping system and higher with conventional tillage than with no-tillage choice. Generally, the GHG abatement cost of ethanol from corn stover produced under a corn−soy cropping system with no-tillage was comparable to that with ethanol from switchgrass grown on high quality soils. Average cost of abatement with miscanthus grown with N application was higher than without N application at all locations and soil types (Figure S10, Supporting Information). Our estimates of GHG abatement cost with corn stover ethanol are higher than those of Pourhashem et al.[28] due to differences in the ethanol production process, feedstock cost, and baselines for assessing changes in soil carbon sequestration. We found that the minimum cost of abating GHG emissions with cellulosic biofuels was \$48 Mg^{-1} of GHG emissions and could be as high as \$375 Mg^{-1} of GHG emissions. These costs will be higher if the credits for soil carbon sequestration and cogenerated electricity are not realized.[30] This suggests that at a minimum a carbon tax of \$48 Mg^{-1} of GHG emissions (CO_2 equivalent) would be needed to equalize the energy equivalent cost of consuming cellulosic ethanol and gasoline in 2010 prices.

■ DISCUSSION

Our findings indicate that there is likely to be considerable variation in GHG intensities and production costs of cellulosic ethanol across feedstocks, regions, and time periods due to location and weather driven differences in yields. Simulated miscanthus yields were higher than switchgrass yields, although this may not be the case for all locations across the United States.[6,9,13] We also find that perennial grasses can be grown productively on low quality soils; although there is some yield penalty, it is not substantial, and its effects on the breakeven cost of ethanol are more than offset by the lower costs of that land relative to land with high quality soils. As a result, the cost of ethanol derived from miscanthus and switchgrass on low quality soils is about 6% and 9% lower than for ethanol derived from the same feedstocks grown on high quality soils, respectively. Application of N on miscanthus did lead to a statistically significant increase in yields at most locations but this was more than offset by the increase in cost of production making it unlikely preferable to growing miscanthus with no N application. The economic incentive for applying N on miscanthus is likely to be further diminished in the presence of a price on GHG emissions because it worsened the GHG intensity of ethanol relative to that with no N application.

We also find that soil quality does not negatively affect soil carbon sequestration with perennial grasses. In fact, carbon sequestered in soils was greater on low than high quality soils (Table S13, Supporting Information). Our findings are supported by other combined measurement and modeling experiments. Soil carbon is expected to increase at a rate of 2−3 Mg C ha^{-1} yr^{-1} under miscanthus on arable land in Ireland,[60] at a rate of 1.1 Mg C ha^{-1} yr^{-1} under miscanthus on arable land in West Germany,[61] and at a rate of about 1 Mg C ha^{-1} yr^{-1} under switchgrass in Nebraska.[62] Biometric estimates of carbon balance[14] as well as eddy-covariance data indicates that the Energy Farm perennial grass plots are storing 0.4, 1.0, and 2.0 Mg C ha^{-1} yr^{-1} for native prairie, switchgrass, and miscanthus, respectively, after accounting for harvest removals.[63] On the other hand, we find that even low collection rates of corn stover

DOI: 10.1021/es5052588
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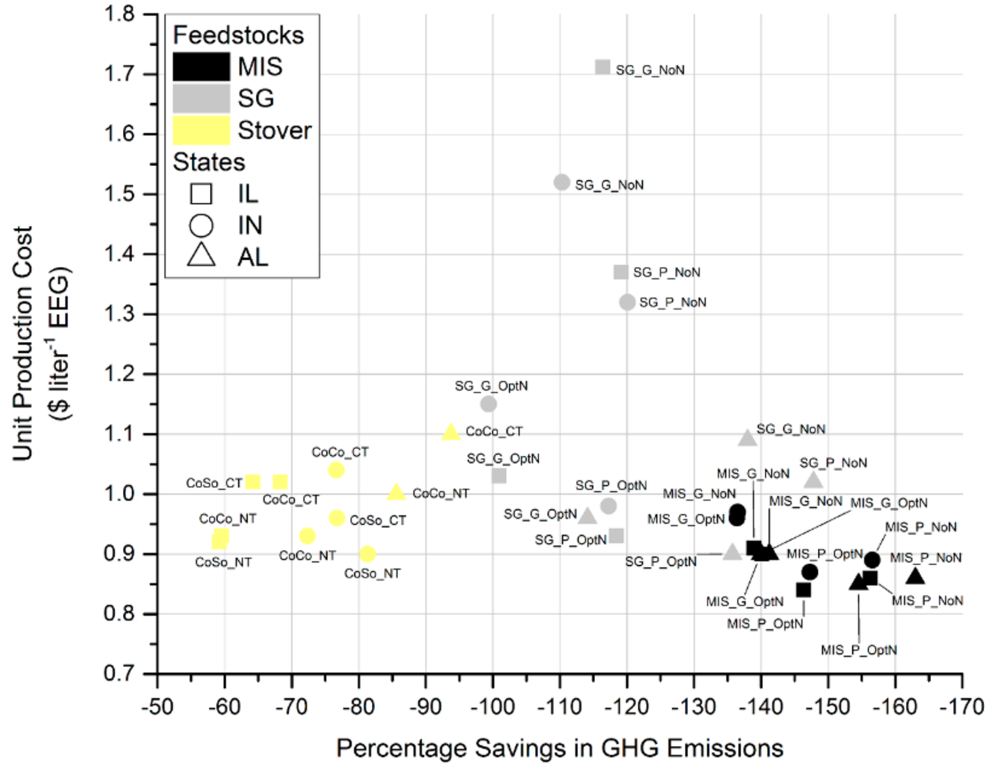

Figure 4. Scatter plot of production cost of cellulosic ethanol and percentage GHG savings relative to energy equivalent gasoline over simulation period. GHG savings are based on GHG intensities calculated by considering net carbon sequestered in soils, avoided GHG emissions due to supply of cogenerated electricity to the grid, aboveground GHG emissions, and GHG emissions with average ILUC effect. Production cost of ethanol is annualized over the simulation period. Average parameter values are used for determining production costs.

(30–38% with conventional tillage and 50–52% with no-till), assumed in other studies[64] could lead to a decrease in carbon sequestered in soil relative to zero removal under the same cropping system and tillage choices.

On average, savings in GHG emissions for ethanol derived from miscanthus relative to gasoline varied between 135% and 165% depending on soil quality and location. This range was 100% to 150% for ethanol derived from switchgrass. These estimates are higher than the ranges reported for ethanol derived from switchgrass (57%–97%)[18,19,65] and miscanthus (80%–115%)[19,55] by other studies, mostly due to higher estimates of the amount of carbon sequestered in soils over the simulation period. The corresponding range for GHG savings with corn stover was 59% to 95% with the GHG savings in IL being marginally below the policy threshold of at least 60% for cellulosic biofuels. These estimates differ from those of Liska et al.[23] because we are estimating soil carbon effects of 30% of crop residue removal and a 30 year time period instead of the effects of 100% removal during the first 9 years. Unlike their study, our aboveground GHG emissions intensity in the baseline case accounts for coproduct credit due to electricity generation during the process of producing ethanol. Our estimates of relative savings in GHG emissions are close to the range (60%–113%) reported by other studies[18,19,28,66,67] for ethanol derived from corn stover in the United States.

We find that the cost of producing energy crops (including the opportunity cost of land) ranged between \$49–\$61 Mg^{-1} for miscanthus and \$55–\$105 Mg^{-1} for switchgrass. These costs were lower on low quality soils and in locations where yields were higher (Table S11, Supporting Information). These estimates are comparable to those of other studies that find that the production cost of miscanthus ranged between \$45–\$53 Mg^{-1}[24,25,27] but could be as high as \$153–\$200 Mg^{-1} in northern states if costs of establishment were excessively high or yields were low due to cooler climates. Similar to our results, other studies also find that the cost of producing miscanthus is about two-thirds that of switchgrass (due to its relatively higher yield per hectare); cost of switchgrass in these studies ranged from \$88 to \$144 Mg^{-1} and were high on high quality land and in northern regions of the U.S. with low yields.[24] Our estimates of corn stover costs range from \$50 to \$87 Mg^{-1} with the upper end of the range being applicable for southern regions where corn yields are low. Our estimates for these costs in the Midwest Region are similar to the estimate of \$57 for corn stover from continuous corn production and \$75 Mg^{-1} from corn–soybean production in other studies.[68]

In general, we find that ethanol derived from miscanthus (with or without N application) has the lowest costs of production and highest GHG savings relative to other feedstocks (Figure 4). Ethanol from corn stover produced with no-tillage in IL and IN and switchgrass on low quality soils in AL has relatively low costs as well although these were higher than those of miscanthus based ethanol in most cases. These findings suggest that the production of perennial grasses on low quality soils is likely to be more economically viable and lead to larger accumulation of soil carbon than on high quality soils. Ethanol derived from miscanthus grown on low quality soils in AL and IL has the lowest cost and leads to the largest savings in GHG emissions. However, other feedstocks pose a trade-off between low production costs and GHG intensities. For example, ethanol derived from corn stover under no-tillage choice is cheaper in IL and IN than miscanthus grown on high

DOI: 10.1021/es5052588
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quality soils but had 59−93% lower GHG intensity than gasoline relative to miscanthus which could lead to a saving of at least 136% relative to gasoline even after including ILUC emissions. Similarly, ethanol derived from switchgrass has lower GHG intensity but higher cost than corn stover ethanol even when the former is grown on low quality soils in some locations.

The potential heterogeneity in costs and GHG intensities across cellulosic biofuels from alternative feedstocks suggests a critical role for policy incentives that reward low GHG intensity feedstocks and do not treat all feedstocks in the same manner. The Renewable Fuel Standard provides uniform incentives for all cellulosic biofuels provided they meet a 60% threshold level of GHG savings relative to gasoline. Such policies, by themselves, are unlikely to create the incentives to use cellulosic feedstocks that could lead to less GHG intensive biofuels but may be more expensive to produce. Although a carbon tax would provide the differential incentives needed, it would need to be at least \$48 Mg^{-1} of GHG emissions (CO_2 equivalent) to equalize the post-tax cost of cellulosic biofuel and energy equivalent gasoline. In addition to varying with feedstock, yield, location, and climate variables, this estimate depends on the cost of conversion of cellulosic feedstocks to biofuel, the components of life-cycle GHG emissions included, and the price of gasoline.

Although we analyze the yields, costs of production, and GHG intensity of producing perennial grasses on high and low quality soils at locations representative of three agro-ecological zones, we leave the assessment of the land availability of different qualities in these three zones to support a biorefinery to the future research. Our analysis also relies on other studies for the estimate of the ILUC effect of converting land to perennial energy crop production. This estimate can be expected to vary across locations and across low and high quality soils. Lastly, our analysis relies on simulated yields of miscanthus and switchgrass that were calibrated using data from experimental plots. These may be overestimated compared to simulated corn stover yields that were calibrated using observed data on corn yields. We leave it to future research to assess the ILUC effects of producing energy crops and the yields of these crops in commercial settings more precisely.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Model evaluation with National Agricultural Statistics (NASS) corn yield data for selected counties, model evaluation of miscanthus and switchgrass harvested yields and soil organic carbon to a depth of 30 cm with NRCS Soil Survey Statistics, temporal variability in yields of selected feedstocks, carbon accumulated in soil over simulation period, change in carbon sequestered in soil relative to selected baselines over simulation period, range of GHG intensity for selected scenarios, effect of nitrogen fertilizer application rate on the GHG intensity of ethanol derived from miscanthus, range of ethanol production cost for selected scenarios, effect of nitrogen application rates on the average unit production cost of ethanol derived from miscanthus, effect of nitrogen application on the average GHG abatement costs for ethanol derived from miscanthus, site soil characteristics used for DayCent simulations, average radius of biomass catchment area to source annual quantities of biomass required for ethanol production, parametric assumptions for economic analysis, material usage for corn stover production, material usage for switchgrass production, material usage for miscanthus production, parameters used for estimating above-ground GHG emissions, indirect land use change related GHG intensity, average ethanol production in selected scenarios, GHG intensity of ethanol produced per unit energy, components of feedstock production cost at the biorefinery gate, cost of ethanol produced, and average rate of carbon sequestered in soils annually. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This research was supported by funding from the North Central Regional Sun Grant Center at South Dakota State University through a grant provided by the U.S. Department of Energy Office of Biomass Programs (award # DE-FG36-08GO88073) and from the Energy Biosciences Institute, University of California, Berkeley.

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