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Article

Performance-Based Payments for Soil Carbon Sequestration Can Enable a Low-Carbon Bioeconomy

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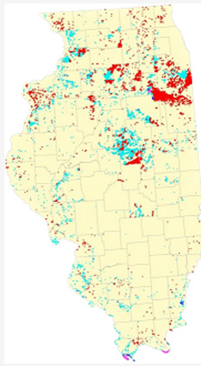
ABSTRACT: Incentivizing bioenergy crop production in locations with marginal soils, where low-input perennial crops can provide net carbon sequestration and economic benefits, will be crucial to building a successful bioeconomy. We developed an integrated assessment framework to compare switchgrass cultivation with corn-soybean rotations on the basis of production costs, revenues, and soil organic carbon (SOC) sequestration at a 100 m spatial resolution. We calculated profits (or losses) when marginal lands are converted from a corn-soy rotation to switchgrass across a range of farm gate biomass prices and payments for SOC sequestration in the State of Illinois, United States. The annual net SOC sequestration and switchgrass yields are estimated to range from 0.1 to 0.4 Mg ha^{-1} and 7.3 to 15.5 Mg dry matter ha^{-1}, respectively, across the state. Without payments for SOC sequestration, only a small fraction of marginal corn-soybean land would achieve a 20% profit margin if converted to switchgrass, but \$40−80 Mg^{-1} CO_2e compensation could increase the economically viable area by 140−414%. With the compensation, switchgrass cultivation for 10 years on 1.6 million ha of marginal land in Illinois will produce biomass worth \$1.6−2.9 billion (0.95−1.8 million Mg dry biomass) and mitigate 5−22 million Mg CO_2e.



■ INTRODUCTION

Meeting food, energy, water security, and environmental sustainability needs requires that all components of the agroecosystem be optimized for goods and services, but historically, these outputs have been narrowly defined to incorporate only salable food, feed, and other products. According to a 2019 emission report, U.S. agriculture contributed as much as 9.6% (620 million metric tons of carbon dioxide equivalent [CO_2e]) of total U.S. emissions.[1] Mitigating and reversing the environmental impacts of agricultural practices require a more holistic system for compensating farmers. High-yielding perennial crops have potential for supplying biomass feedstock for conversion to renewable liquid biofuels while simultaneously providing multiple ecosystem services (ESs). ESs are the goods and services provided by nature to human beings, such as the provisional services—food, water, and energy; the regulating services—soil carbon sequestration and climate regulation, nutrient cycling and biochemical regulation; and the cultural services such as recreational and nonmaterial benefits.[2] Planting perennial bioenergy crops can be particularly beneficial on marginal land that has been previously cultivated with row crops by supporting the bioeconomy, forestalling food-fuel conflicts, and producing ESs that contribute to climate change mitigation and environmental sustainability.[3−5] Wealth of geospatial environmental datasets and agroecosystem models makes it possible to identify, at a fine resolution, the specific combination of crops and cultivation practices to maximize the economic output of agricultural land in an environmentally sustainable way.[6]

Biomass production in 30−40 million ha of productive land or >50 million ha of marginal land can support the energy demand of the U.S.'s transportation sector.[7,8] The definition and acreage of "marginal lands" vary widely in the literature.[5,9,10] In the present study, we used the USDA-identified land capability classes 5−8 as marginal lands.[11] These marginal lands have considerable potential for producing cellulosic feedstock from perennial grasses.[4,5,12] In the U.S., depending upon the methods applied and the environmental factors considered, the estimated available marginal-land area ranges from 70 to 100 million ha.[5]

For farmers to consider growing bioenergy crops on either productive or marginal land, the net returns from new crops must exceed those from existing crops.[13,14] This study focuses on switchgrass as a representative perennial bioenergy crop. The economic profitability of switchgrass production relative to commercial crops on marginal lands is driven by multiple factors: (i) productivity of switchgrass compared to commercial crops in less fertile soils,[21] (ii) higher production costs for commercial crops per unit of output, and (iii) potential payments for ESs provided by switchgrass. Earlier work on the economic viability of switchgrass production relative to corn/soybean crops focused on some aspects of the problem. For

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example, Song et al.[14] focused on converting traditional productive croplands to dedicated energy crops. Other studies[15−18] either compared switchgrass with only the corn stover or conducted comparison of switchgrass and corn/soybean crops at relative coarse spatial resolution (regional, state, or county level). Swinton et al.[19] recommended identification of geographic clusters of marginal lands for integrating bioenergy crops at a greater spatial resolution using spatial analysis. Brandes et al.[20] conducted an analysis at a field scale, with focus on nitrate loss reduction from switchgrass rather than carbon sequestration. Previous studies have not integrated the impacts of spatial variability (at a high spatial resolution) of switchgrass yield and carbon sequestration potential on marginal lands with compensation for the ES.

Payment for ESs (PES) support farmers by complementing the revenue from sale of biomass to bioenergy facilities. Adoption of bioenergy crops changes the ecosystem structures and functions of the landscape, and these changes are translated to ESs when humans derive utility from them. Row-crop production supports food security, while it is also associated with degradation of the ecosystem (i.e., air, water, and soil degradation). Converting land to perennial bioenergy grasses increases feedstock supply for renewable biofuel production, sequesters carbon (by removing CO_2 from the atmosphere and fixing it in the soil[7]), retains nutrients and sediments, and provides a habitat to pollinators, birds, and animals. These benefits are translated to such ESs as climate change mitigation, water quality improvement, increased pollination and biodiversity, and enhanced recreation (hunting, birdwatching, etc.).[8,13,22,23] Cultivation of row crops on marginal lands has a negative return on investment and further deteriorates soil health by depleting the soil organic carbon (SOC) and releasing CO_2 to the atmosphere;[24] in contrast, growing perennial grasses can increase carbon sequestration and improve soil health.[25] Carbon sequestration potential primarily depends on existing soil carbon stocks, soil properties, climatic conditions, and land use and crop management history. Marginal lands under row crops are ideal locations for adopting bioenergy crops to generate biomass and support climate change mitigation.

The majority of prior bioenergy crop ES studies focused on water quality improvement and potential payment for this specific ES.[26−29] Some studies included quantification of additional ESs based on biodiversity, pollination, and pest control but not the ES valuation.[8,22,30] Although some previous studies quantified changes in soil carbon and nitrogen due to bioenergy crops,[12,13,23] none have estimated the spatially explicit values of the associated ES. Only a few studies focused on the costs, profits, and incentives for carbon sequestration due to bioenergy crops.[31,32] Furthermore, earlier studies on bioenergy ESs were either conducted at the field level,[33] watershed level,[34,35] or at coarse resolution for regional- or national-scale analysis.[6,36] A method for scaling the ES values from a pixel level to a county, watershed, or larger scale is a clear gap that needs to be addressed.

The purpose of the present study is to develop and use an integrated assessment approach (IAA) that couples a biophysical-agroecosystem model with spatially explicit economic analysis to (i) locate plots where growing bioenergy crops is economically viable at varying farm gate prices and (ii) identify locations where compensation for soil carbon sequestration causes switchgrass cultivation to be preferred over row crops on marginal-land plots. While the IAA is applicable to a number of bioenergy crops and ESs, in this study, we focused on demonstrating this approach using switchgrass crop and soil carbon sequestration. We chose switchgrass as the bioenergy crop in this study because it is a native grass of North America, well adapted to marginal lands, has high soil carbon sequestration potential, and has been widely studied as a promising bioenergy crop in Illinois and the Midwest region.[37−40] The spatial economic analysis in the IAA allows us to couple environmental attributes with crop yields, prices, and production costs at <1 ha pixel levels, to locate economically viable lands for growing bioenergy crops, and to quantify associated profits with and without compensation for soil carbon sequestration. Our approach quantifies and valuates ESs to generate spatially explicit information on profitability of marginal-land plots, which can support decisions.

Specific objectives of this study include (i) identifying the distribution of marginal lands in the State of Illinois currently under corn/soy rotation, (ii) estimating the amount of potential switchgrass biomass production on marginal lands, (iii) quantifying the soil carbon sequestration rate, and (iv) evaluating the total profits at various spatial scales with and without incorporating climate change mitigation benefits of soil carbon sequestration. We generate high-resolution maps for the state of Illinois that could inform relevant local stakeholders in the bioeconomy value chain, stewards of soil health, and pro-low-carbon companies. Being able to understand the spatial distribution of economically viable as well as environmentally sustainable land is the first critical step of the biofuel value chain. Information that we have generated is critical in developing a secure and sustainable biofuel value chain, mitigating climate change, and improving soil health.

MATERIALS AND METHODS

The IAA approach presented in this paper integrates agronomy, agroecosystem modeling, and geospatial and economic analysis (Figure 1). The first component of the IAA is biophysical modeling to simulate the biomass productivity and soil carbon sequestration potential across the croplands of Illinois using the Daily Century (DAYCENT) model. The second component is spatial analysis to identify the distribution of marginal lands where corn and soybeans (row crops) are grown. The third component is economic analysis to (i) identify economically viable locations and estimate the associated total economic profitability, (ii) examine the impacts of compensation for soil carbon sequestration on profitability, and (iii) determine economically viable locations for growing switchgrass across Illinois at a high spatial resolution.

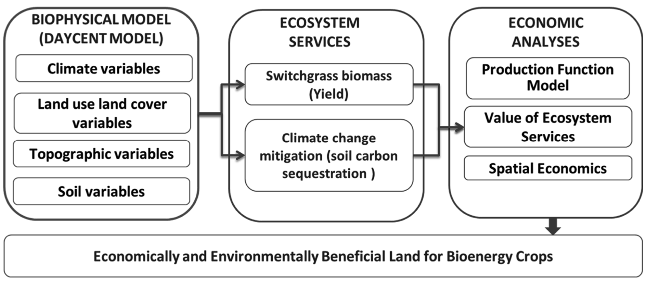

Figure 1. Integrated assessment framework for the systematic analysis of land use change.

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Agroecosystem Model Simulation. We used the DAYCENT model to simulate switchgrass productivity and soil carbon sequestration at a 4 km grid scale over the State of Illinois. DAYCENT is a daily time-step process-based agroecosystem model designed to simulate the impact of land management and climate on biogeochemical cycles.[41,42] DAYCENT simulates exchanges of soil nutrients (carbon, nitrogen, and sulfur) between the atmosphere and terrestrial ecosystems, as well as other soil water and temperature processes. DAYCENT has been widely used to predict soil carbon changes, GHG emissions, and plant productivity. Major model inputs include climatic inputs such as daily temperature and precipitation datasets; soil factors such as texture, soil hydraulic properties, and agricultural management; and historical details on land use, fertilization, tillage, and other management activities. DAYCENT simulates major soil processes such as decomposition and nutrient mineralization of plant litter and soil organic matter. The crop growth model in DAYCENT simulates plant growth and phenology, net primary productivity and its allocation to different compartments (grain, roots, and shoots), and the C/N ratio of these plant compartments. Plant growth and different field management operations were scheduled in accordance with the temperature-based growing degree day submodel.

We used the U.S. Department of Agriculture (USDA), National Agricultural Statistics Service (NASS) Cropland Data Layer map to analyze locations of targeted land use.[43] The 30-year daily precipitation and minimum and maximum air temperature data extracted from the Global Historical Climatology Network datasets of the National Centers for Environment Information were used to define model inputs for weather.[44] The study used weather stations that had data ranging from 1989 to 2018 (30 years of datasets). Ninety weather stations in the State of Illinois had the required 30-year datasets. From 1989 to 2018, the average annual rainfall and daily temperature were 980 mm and 10 °C, respectively. We used weather-generator-simulated weather data that were based on 30 years of historical data as input for the long-term historical simulation of the native vegetation in the study area.

To assign the weather station for simulation points, we selected the nearest weather station, based on the haversine distance between the centroid of the grid and the weather station. The major soil parameters for the DAYCENT model include the multilayer soil texture, bulk density, soil water characteristic curve data, hydraulic conductivity, soil organic matter, and soil pH. The Soil Survey Geographic Database was used to build the model input database, and soil water characteristic curve data (wilting point and field capacity) were calculated using pedo-transfer functions.[11,45] Table S1 (see the Supporting Information) presents a summary of the datasets used in this analysis and their sources.

To initialize the model prior to simulating the corn-soybean and switchgrass crops, we estimated the steady-state soil organic matter levels and the plant productivity under native vegetation over a 4000-year spin-up period. We used region-specific grass types based on earlier studies to simulate the equilibrium soil organic matter pools by using different grasses appropriate to each region.[46] We also ran two scenarios: one with a continuous corn-soybean rotation and a switchgrass-based land use change scenario. More details on implementation of the DAYCENT model for large-scale simulation of bioenergy crops can be found in Gautam et al.[47]

Marginal-Land Identification. In the present study, we used the USDA's Soil Survey Geographic Database and identified land capability classes 5−8 as marginal lands. This approach uses soil properties and biophysical environmental properties to classify U.S. lands into eight distinct categories. As the number increases from 1 to 8, the land's suitability for vegetation growth decreases.[9] We combined the marginal-land data layer and the cropland data layer[43] to identify the marginal-land plots under row crops (corn and soybean crops) in Illinois that could potentially be converted to switchgrass.

We identified 1.57 million ha of Illinois's agricultural lands as marginal lands. Figure S1 shows the distribution of marginal lands in Illinois based on the marginality classification metrics, as explained by Soil Survey Staff.[11] The area of marginal-land plots for the year 2019 under corn/soybean rotation in Illinois was estimated to be 154,979 ha. The largest number of these plots of sizes larger than 1000 ha is situated at the intersection of Kankakee, Grundy, and Livingston counties (Figure S2). More than 10,000 ha of marginal-land plots where row crops are grown are located in each of the following Illinois counties: Kankakee, McLean, De Witt, Bureau, and Will counties. We designed the analysis to capture plots of 10 ha and larger, which also includes irregularly shaped plots of 6 ha or larger, which are approximated as 10 ha rectangular plots.

Economic Model. Farmers' crop cultivation decisions are driven by economic profitability. Farmers make decisions about crop choice, farm management operations, and cultivation practices to maximize their net returns from the farm; farm management includes deciding the quantities and timing of farm inputs (seeds, fertilizers, and pesticides), whereas cultivation practices cover farm preparation, harvesting, storage, and selling of the produce. Their objective of maximizing their profits can be expressed as

$$\underset{x}{\mathrm{Max}} f = \sum_{i=1}^{N} [(Y \times P - C) \times x]_i \tag{1}$$

where Y is the yield of crop i, P is the price, C is the cost of production, x is the area under crop i, and N is the total number of crops grown by the farmer.

To inform economic welfare and environmental sustainability decisions in the county, watershed, sub-basin, or any other landscape level, the objective function is modified as follows

$$\underset{x}{\mathrm{Max}} f = \sum_{s=1}^{S} \sum_{i=1}^{N} \pi_{si} x_{si} \tag{2}$$

where π is the profit from land use i in county s and x is the area under land use i in county s.

In this study, the land of interest for potential switchgrass cultivation includes marginal-land plots that are currently being used for row crops. The economic efficiency of converting a marginal plot from a row-crop to switchgrass-incorporated landscape depends upon the yield of the row crops and switchgrass, the costs of production of both crops, the prices of all row crops, and the farm gate price of the switchgrass biomass. The profit from converting a marginal-land plot under row crops to switchgrass is estimated using eq 3

$$\pi_{sg} = (Y_{sg} \times P_{sg} - C_{sg}) \times x_{msg} - [(Y_{co} \times P_{co} - C_{co}) \times x_{mco} + (Y_{so} \times P_{so} - C_{so}) \times x_{mso}] \tag{3}$$

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where Y is the yield, P is the price, C is the cost of production, and x_{msg} is the area of marginal-land plot converted to switchgrass. Subscripts "sg", "co", and "so" denote switchgrass, corn, and soybean, respectively. The cost of production of corn includes the cost of grain production. Similarly, the price of corn includes the grain price. The marginal-land plot at each location x_{msg} is the sum of the area under corn and soybeans in marginal land (x_{mco} + x_{mso}). We also conducted analyses adding the cost of stover removal (windrowing, baling, and stacking) and the stover price in eq 3. We added the profit from selling the stover to the profit from corn and soy grains to calculate the total foregone profit from converting row crops into switchgrass.

Often, farmers are discouraged from adopting an alternative crop by the potential loss of revenue from row crops, as well as the market uncertainty for switchgrass biomass. An assured increase in profit margin meets a necessary condition for switching from row crops to new crops. Marginal land that meets the condition of a 20 or 30% increase in profit margin, as shown in eq 4, was identified as economically viable land for conversion to switchgrass.

$$\frac{\pi_{sg} - (\pi_{co} + \pi_{so})}{(\pi_{co} + \pi_{so})} \geq 20\% \tag{4}$$

where π_{co} is the profit from corn and π_{so} is the profit from soybeans.

Incentives such as PESs of switchgrass could be one way to alleviate the revenue gap and meet 20 or 30% profit margin. To analyze the impact of incorporating the PESs (i.e., carbon sequestration) on the profitability of land producing a switchgrass crop, we introduced PES_{cc} (where $_{CC}$ denotes carbon credits) into eq 3

$$\pi_{sg} = (Y_{sg} \times P_{sg} - C_{sg}) \times x_{sg} + PES_{cc} \tag{5}$$

While replacing the row-crop land with switchgrass generates ecosystem services, corn stover removal is associated with increased soil erosion, loss of sequestered carbon, and nutrient replacement (additional fertilizer application) for the next cropping season.[48] Valuation of all negative externalities of corn stover removal is beyond the scope of this work; as such, we conducted analyses including the costs of corn stover windrowing, baling, and stacking.

Integration of Economic and Process-Based Model Outputs to Identify Economically Viable Land Areas for Switchgrass. The spatial variabilities in crop yield, production cost, and marginal-land acreage are the determining factors for identifying marginal-land plots that could be economically viable if converted to switchgrass cultivation. To examine the areas that could potentially be used for growing bioenergy crops, we collected data and information from various sources in both spatial and nonspatial formats. DAYCENT model outputs on switchgrass biomass yield at 4 km resolution were used. Yield data for corn and soybeans were collected from the USDA for all counties in Illinois. The yield data for corn and soybeans for marginal land is not available; therefore, we used five-year minimum yield as a proxy for the yield at marginal land. Annual price data for the corn and soybean crops at the state level were collected for five years (2013–2017), and the average annual price was used for further analysis. We obtained the cost-of-production data for corn and soybeans from University of Illinois Extension reports from 2000 through 2018 (Tables S2 and S3). The University of Illinois Extension collects data in coordination with the Illinois Farm Business and Farm Management Association. We used the variable cost of production per ha in our analysis. We used information on potential prices (\$40, \$60, and \$80 Mg^{-1} dry biomass) collected from the literature, as there is no market for switchgrass biomass.[7] To conduct an economic analysis for each marginal-land plot across Illinois, we used spatial analysis tools to transform spatial and nonspatial data collected and generated by the biophysical models at various resolutions to spatial data for each marginal plot. We conducted the analysis at the level of marginal-land plots and aggregated the results at the county level. Datasets used in the economic analysis of this study and their sources are presented in Table S1.

Another factor that we aim to examine in this study is the impact of additional payment for soil carbon sequestration climate change mitigation services generated by switchgrass on the profitability of plots. To assess this impact, first, we estimated the number of carbon credits generated, using the DAYCENT model results on the quantity of soil carbon sequestered; we then monetized the value of the carbon credits generated in each marginal plot and finally added the value per plot to the profit equations for each marginal-land plot. The change in quantity of SOC sequestered by changing to switchgrass from row crops was converted to carbon credits (CC [Mg CO_2e]) by using the atomic weight of carbon and the molecular weight of CO_2

$$CC(Mg/ha) = \frac{44}{12 \times 10} \sum_{T=1}^{10} \{(SOC(Mg/ha)_{sw}) - SOC(Mg/ha)_{rowcrops}\}_t \tag{6}$$

Earlier work on the economics of soil carbon sequestration estimated that the marginal cost of carbon ranges from \$12 to \$500/Mg depending upon the quantity of carbon sequestered, the type of contract or payment mechanism used, and the site-specific characteristics of the areas.[26] Stiglitz et al. concluded that the price level would be at least \$40–80 Mg^{-1} CO_2e by 2020 and \$50–100 Mg^{-1} CO_2e by 2030.[49] Voluntary carbon credit markets in the U.S., including the California cap-and-trade program, NORI carbon market, and Ecosystem Services market consortium, price carbon credits at \$15 Mg^{-1} CO_2e. The actual global climate change mitigation benefits of bioenergy crops are reflected when the carbon price estimated by Stiglitz et al.[49] is used. However, it is not feasible for farmers to receive the carbon credit at such a high rate when the current carbon market transaction rate is \$15 Mg^{-1} CO_2e, which is less than half the \$40 Mg^{-1} CO_2e lower-bound price of Stiglitz et al.[49] Therefore, we used the voluntary market price of \$15 Mg^{-1} CO_2e as well as \$40–80 Mg^{-1} CO_2e to identify the profitability of each marginal plot. We determined economically viable plots for switchgrass for two scenarios: plots with either an increase in 20 or 30% profit margin relative to corn/soybean rotation at various farm gate prices of switchgrass with including the compensation for the carbon credit and without including the compensation. In addition to presenting plot-level high-resolution results, the framework allows us to also aggregate results at the county, sub-basin, state, or higher levels, which is important for decision makers at private companies or government agencies. This framework is applicable to identify economically viable land to switch from current land use to crops other than switchgrass such as

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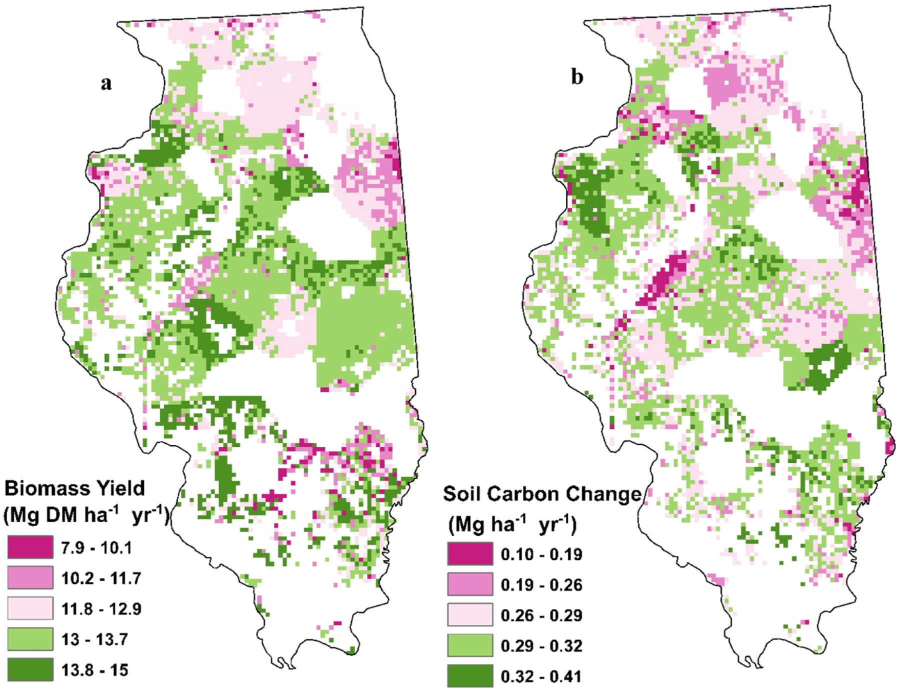

Figure 2. Switchgrass biomass yield under rain-fed conditions simulated by DAYCENT for the State of Illinois (a). Projected change in annual soil organic carbon due to decade-long bioenergy-based land use conversion (corn-soybeans to switchgrass) on marginal lands (b).

sorghum, energy cane, etc. and potential payment for ESs other than climate change mitigation such as improved or increased water quality or quantity, increased biodiversity, improved pollination services, etc. Furthermore, this approach can be used nationally or in an international context.

RESULTS AND DISCUSSION

Switchgrass Biomass Yield and Soil Carbon Sequestration. We estimated that switchgrass biomass yields for agricultural land in Illinois had a range of 7.3−15.5 Mg DM ha^{-1} $year^{-1}$. The spatially averaged annual switchgrass biomass yield in the marginal land of Illinois was simulated to be 12.6 Mg DM ha^{-1} $year^{-1}$, with lower and upper quartiles of 12.2 and 13.0 Mg DM ha^{-1} $year^{-1}$, respectively (Figure 2a). Similar yield ranges were reported for switchgrass field trials in Illinois; a biomass yield range of 3.7−18.8 Mg DM ha^{-1} $year^{-1}$ was reported across three different locations in 2004 and 2005.[50] No specific spatial pattern of switchgrass yield was observed; high-yield pockets were distributed throughout the state of Illinois (Figure 2a). The yield response was correlated with the temperature and precipitation distribution in the state; the southern part of the state, which has a higher average annual daily temperature and higher average annual precipitation, showed a higher biomass yield.

The predicted SOC change ranged from 0.1 to 0.4 Mg C ha^{-1} $year^{-1}$ (Figure 2b) in 0−20 cm soil depth. The higher root biomass and deep rooting system of switchgrass and the absence of tillage led to more SOC sequestration in lands under switchgrass compared to row crops.[50] In an experimental study, Follett et al. reported an accrual of 1 Mg C ha^{-1} $year^{-1}$ at 0−30 cm depth due to switchgrass cultivation.[51] In another study, Anderson-Teixeira et al. observed an accrual of 2 Mg C ha^{-1} $year^{-1}$ in the whole-soil profile (0−150 cm depth) and reported that half of the SOC accrual was within the depth of 0−30 cm.[52] Likewise, Jaggard reported an annual accrual of 0.4−0.9 Mg C ha^{-1} due to switchgrass cultivation.[53] Our conservative estimates of the SOC sequestration rate for 0 to 20 cm depths are within the range reported in the literature. Because of the deep root system of switchgrass, total carbon sequestration over the entire soil profile due to switchgrass cultivation could be higher.

Estimation of Potential Profits and Suitable Land for Switchgrass. *Profits with and without Compensation for Carbon Sequestration.* We estimated the total amount of profit and biomass produced from the marginal lands of Illinois under a number of scenarios that included a combination of yield variability, price ranges of switchgrass, and a number of potential compensation for carbon sequestration. The heat map (Table 1) shows the profits (losses) from switching all marginal lands currently under corn and soybeans in Illinois to switchgrass. Biomass prices are provided in \$ Mg^{-1} of dry biomass.

Table 1. Profit (or Loss in Million \$) from Conversion to Switchgrass across All Marginal Lands in Illinois

Carbon Credit	Switchgrass Yield	Profit at Price		
		\$40 Mg^{-1}	\$60 Mg^{-1}	\$80 Mg^{-1}
\$80 Mg^{-1}	Q3	-68	19	33
	Mean	-75	-28	19
	Q1	-81	-36	8
\$40 Mg^{-1}	Q3	-76	-26	25
	Mean	-83	-36	11
	Q1	-88	-44	0.4
\$15 Mg^{-1}	Q3	-81	-30	20
	Mean	-88	-41	6
	Q1	-93	-49	-5
\$0 Mg^{-1}	Q3	-84	-33	17
	Mean	-91	-44	4
	Q1	-96	-52	-7

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The marginal-land plots, where converting corn-soybean cropland to switchgrass would lead to an increase in profit margin by 20% (or 30%), were defined as economically viable plots for growing switchgrass. At a farm gate price of switchgrass biomass at \$40 Mg^{-1}, none of the plots were found to be economically viable for growing switchgrass, with or without compensation for SOC sequestered. At a price of \$60 Mg^{-1}, only a carbon compensation of \$80 Mg^{-1} CO_2e in combination with high switchgrass yield would deem 54,000 ha of marginal land economically viable. That scale of row-crop land conversion generates total profit, biomass, and carbon credits of \$54 million, 0.8 million Mg, and 58,900, respectively. At a price of switchgrass biomass of \$80 Mg^{-1}, the marginal land was found to be economically viable across the switchgrass yield range and at 20% profit margin with or without compensation for carbon. Only a few of the marginal-land plots met a requirement of 30% increase in profit margin when converted from row crops to switchgrass. Figure S3 shows the total profit and biomass production under the two profit margins and carbon compensation scenarios. Figure 3 illustrates the locations of the economically viable plots under various scenarios.

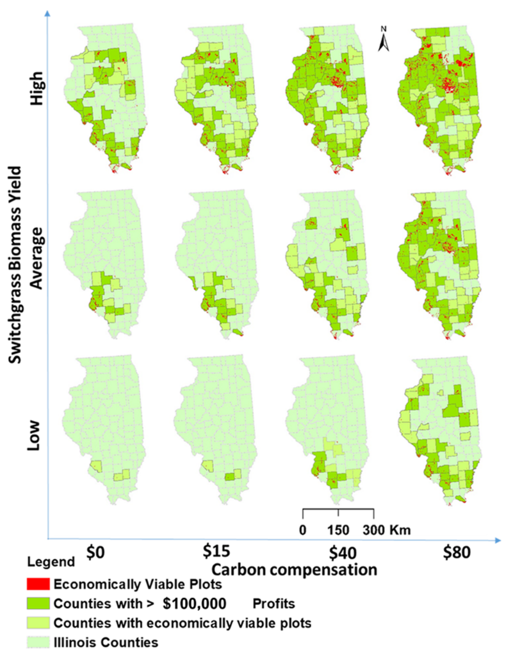

Figure 3. Distribution of economically viable plots (20% increase in profit margin) under various scenarios for converting marginal land from corn and soybean rotation to switchgrass. Switchgrass biomass yield scenarios for each marginal-land plot include 1st quartile (low) yield, mean (Average) yield, and 3rd quartile (High) yield. Potential compensation scenarios include no payment, current market price of carbon credit at \$15 Mg^{-1} CO_2e, and the social cost of carbon at \$40 and \$80 Mg^{-1} CO_2e.

We identified that 3000−28,000 ha out of 0.15 million ha of marginal lands under corn-soybean would be economically viable to convert to switchgrass without a compensation for SOC sequestration. With a compensation at \$15 Mg^{-1} CO_2e, a total of 6000−39,000 ha of marginal land would become economically viable. An increase in compensation to \$40−\$80 Mg^{-1} CO_2e would increase the economically feasible area, profits, and biomass, which would respectively increase up to 13−128 thousand ha, \$13−135 million, and 0.2−1.8 million Mg of switchgrass. In Illinois, corn and soybeans are grown on 8.5 million ha of land.[43] The total amount of profit realized by converting 0.5% of the total corn-soybean land of Illinois (42,000 out of 8.5 million ha) to switchgrass is estimated at \$6−40 million from switchgrass biomass. Switchgrass cultivation on 0.15 million ha of land in Illinois for 10 years will generate 1.6 million (0.5−2.1 million Mg CO_2e) in carbon credits, which is equivalent to \$64−171 million in global benefit from climate change mitigation only. The distribution of economically viable areas for switchgrass crops under various yields and carbon compensation scenarios is shown in Figure 3 and Figure S2.

The economically viable marginal-land plots are densely distributed over a number of counties. Our analysis showed that a net profit of more than \$100,000 was predicted from land use change from corn/soybeans to switchgrass in 26 counties, considering an increase in profit margin of 20% for farmers. With a potential compensation for soil carbon sequestration at \$15, \$40, and \$80 Mg^{-1} CO_2e, the number of counties increases to 33, 49, and 60 counties, respectively (Figure 3). We found that profit of more than \$1 million in each county could be generated by changing land use to switchgrass in Bureau, Champaign, Gallatin, Grundy, Jackson, Livingston, Massac, Monroe, St. Clair, and Union counties. With compensation for soil carbon sequestration at \$15, \$40, and \$80 Mg^{-1} CO_2e, the economically viable area could increase by 43, 140, and 414%, respectively, and the number of counties with more than \$1 million profit per county would increase from 10 counties to 13, 18, and 27 counties, respectively.

We also estimated the potential area that could be profitably converted to switchgrass, the resultant quantity of carbon sequestration, and the associated total profits considering returns from the corn stover. We found decreases in the profitable area for converting row-crop land areas to switchgrass, which could be because of the increased profit from row-crop land while the profit from switchgrass stays the same. However, this is not the complete picture. In order to provide a complete picture, the damage costs associated with corn stover removal through the loss of sequestered carbon, soil erosion, and nutrient replacement need to be added to the equation. The potential climate change mitigation (carbon credit generation), biomass production, and associated profits under various scenarios of switchgrass prices, switchgrass yields, and carbon credit compensation were computed, and the resultant maps of profitable areas in the state of Illinois under various yield and carbon compensation scenarios are shown in Figure S4.

Bioenergy Production Potential. Although switchgrass has potential uses as a forage crop, our analysis is motivated by its suitability as a bioenergy feedstock.[54] A commercial-scale cellulosic biofuel facility must source approximately 2000 bone dry Mg of biomass per day to take advantage of economies of scale.[55] With an uptime of 96%, this translates to 700,000 Mg switchgrass biomass annual intake. In the highest yield, the \$80 Mg^{-1} CO_2e compensation scenario (1.8 million Mg switchgrass production), Illinois could likely support two commercial-scale biorefineries located in the northern half of the state, with biomass produced in southern Illinois either used for other purposes or pelletized prior to transport to reduce long-distance trucking costs. We calculated the density of cultivation and biomass yield per unit area for each county, and much of the production is likely to be concentrated in just a few

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counties: Massac (25−56% land cultivated for switchgrass), Union (∼16% cultivated across all scenarios), and De Witt (∼4−10%), whereas most of the other counties are cultivated at <1% of the total land area. If biorefineries can only draw from areas with switchgrass cultivation on >10% of the total land area, then the total utilizable biomass in the highest-yield \$80 Mg^{-1} CO_2e compensation scenario is reduced to 989,000 Mg per year (likely supporting two smaller biorefineries). If the biomass is baled and delivered directly to the facility, then trucking can cost \$20−30 Mg^{-1} or more on a dry-matter basis, depending on local labor costs and farm-to-biorefinery distances, while pelletizing for long-distance transport may add an additional \$10−20 Mg^{-1}.[56] Converting all 1.8 million Mg of switchgrass to ethanol at an approximate yield of 269 liters of ethanol per dry Mg would result in 486 million liters of ethanol (for comparison, the Renewable Fuel Standard calls for 136 billion liters of renewable fuel production by 2022).[57]

One caveat is that we do not attempt to capture the effects of long-term contractual agreements between farmers and biorefineries on the profitability of growing switchgrass, nor do we explore the indirect impacts of replacing corn/soy rotations with bioenergy crops. Additionally, the proposed land use change to switchgrass generates a number of other ESs in addition to the soil carbon sequestration that we focused on in this study. Thus, our estimates do not include the impact of other ESs on bioenergy feedstock production. These topics could be considered for further studies. If additional ESs were quantified, valuated, and incorporated into the economic analysis, then the number and area of the economically efficient plots of marginal land could be further refined. Understanding the spatial distribution of economically viable land parcels for producing energy crops (switchgrass) is the first critical step in supporting the bioeconomy and decarbonization.

Study Implications and Future Work. The United Nations Food and Agriculture Organization[58] emphasizes the need to address agriculture, people's livelihoods, and management of natural resources as a single issue rather than separate isolated concerns. Multifunctional landscapes provide critical benefits, and the benefits are studied using ESs as a linkage.[23,59] PESs can add to the profit from biomass to improve the value proposition of bioenergy crops and increase their adoption. Strategic placement of cellulosic bioenergy crops in marginal land, matching perennial grasses to the site characteristics, has been shown to provide climate change mitigation benefits through soil carbon sequestration.[6,60,61] At the rate of \$40−80 Mg^{-1} CO_2e by 2020 and \$50−100 Mg^{-1} CO_2e by 2030, switchgrass cultivation for 10 years on 1.57 million ha of land in Illinois will generate 17 million (5−22 million) carbon credits, which is equivalent to \$206−870 million and \$0.4−1.7 billion of global benefit just from climate change mitigation, at lower- and upper-bound carbon prices, respectively. Techniques such as switchgrass cultivation are thus significant tools for climate change mitigation, providing a wider framework for society to decarbonize.[62] The other values of switchgrass-led soil carbon sequestration such as improved soil health and increase in productivty are not included in our work. Furthermore, including a number of other ecosystem services generated by converting land in row crops to switchgrass such as downstream water quality improvement and biodiversity (insects, birds, and animals) could improve the value proposition of the switchgrass crop for Illinois. The economics of bioenergy crops for other states and counties with larger number of hectares with marginality conditions may be different from that for Illinois. Unlike carbon credits, the value of ecosystem services for water quality and biodiversity is location-dependent. It leads to an important question on how the values of those location-dependent ecosystem services would interact with the site-specific biophysical and economic factors that were examined in our work to change the value proposition of bioenergy crops at various locations in the U.S.

The method developed and used for this study demonstrates a way to bridge the gap between field-scale and large-scale studies by coupling agroecosystem models, economic analysis, and spatial analysis in an IAA. Information generated may be useful for a range of stakeholders interested in implementing and facilitating bioeconomy as well as decarbonization. The maps for locating the economically viable counties and plots for converting to switchgrass and plot-level information on biomass, carbon credits, and total profits could inform decisions by farmers, buyers of carbon credits, and regulators who design incentives to promote bioeconomy, climate change mitigation, and natural-resource conservation. Farmers facing financial losses due to changes in weather and policies could benefit from this information in making decisions on diversifying their farm portfolio by growing switchgrass biomass, as well as generating an additional source of income from carbon sequestration. This framework can be used to assess economically viable land in and beyond the United States to support the development of a secure and sustainable biofuel/bioproduct value chain system through the utilization of marginal lands—which otherwise act as environmental and economical drains—for biomass production, soil health improvement, and climate change mitigation.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c06452.

Spatial distribution of marginal land in Illinois, map of economically viable plots for converting corn/soy land to switchgrass production under carbon compensation scenarios including a corn stover and without a stover, total potential profits and biomass production in Illinois, and data sources supplied as Supporting Information (PDF)

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Author Contributions

S.K.M. conceptualized and designed the study and conducted the economic analysis. U.M. and S.G. worked on soil carbon sequestration modeling. C.D.S. conducted additional analysis on the bioenergy production potential section. S.K.M., S.G., U.M., and C.D.S. prepared the manuscript.

Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) United States Department of Environmental Protection. *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. 2019 https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks (12/1/2019).

(2) Millenium Ecosystem Assessment. *Ecosystems and human well-being: a framework for assessment*; World Resources Institute, 2005.

(3) Gelfand, I.; Zenone, T.; Jasrotia, P.; Chen, J.; Hamilton, S. K.; Robertson, G. P. Carbon debt of Conservation Reserve Program (CRP) grasslands converted to bioenergy production. *Proc. Natl. Acad. Sci. U. S. A.* **2011**, *108*, 13864−13869.

(4) Campbell, J. E.; Lobell, D. B.; Genova, R. C.; Field, C. B. The global potential of bioenergy on abandoned agriculture lands. *Environ. Sci. Technol.* **2008**, *42*, 5791−5794.

(5) Campbell, J. E.; Lobell, D. B.; Genova, R. C.; Zumkehr, A.; Field, C. B. Seasonal energy storage using bioenergy production from abandoned croplands. *Environ. Res. Lett.* **2013**, *8*, 035012.

(6) Mishra, U.; Torn, M. S.; Fingerman, K. Miscanthus biomass productivity within US croplands and its potential impact on soil organic carbon. *GCB Bioenergy* **2013**, *5*, 391−399.

(7) Langholtz, M. H.; Stokes, B. J.; Eaton, L., 2016 Billion-ton report: Advancing domestic resources for a thriving bioeconomy, Volume 1: Economic availability of feedstock. In *Oak Ridge National Laboratory, Oak Ridge, Tennessee, managed by UT-Battelle, LLC for the US Department of Energy*; USDA, 2016, 1−411.

(8) Robertson, G. P.; Hamilton, S. K.; Del Grosso, S. J.; Parton, W. J. The biogeochemistry of bioenergy landscapes: carbon, nitrogen, and water considerations. *Ecol. Appl.* **2011**, *21*, 1055−1067.

(9) Milbrandt, A. R.; Heimiller, D. M.; Perry, A. D.; Field, C. B. Renewable energy potential on marginal lands in the United States. *Renewable Sustainable Energy Rev.* **2014**, *29*, 473−481.

(10) Emery, I.; Mueller, S.; Qin, Z.; Dunn, J. B. Evaluating the potential of marginal land for cellulosic feedstock production and carbon sequestration in the United States. *Environ. Sci. Technol.* **2017**, *51*, 733−741.

(11) NRCS. Soil Survey Staff. Natural Resources Conservation Service. United States Department of Agriculture. *Soil Survey Geographic (SSURGO) Database*; NRCS, 2015.

(12) Gelfand, I.; Sahajpal, R.; Zhang, X.; Izaurralde, R. C.; Gross, K. L.; Robertson, G. P. Sustainable bioenergy production from marginal lands in the US Midwest. *Nature* **2013**, *493*, 514−517.

(13) Robertson, G. P.; Hamilton, S. K.; Barham, B. L.; Dale, B. E.; Izaurralde, R. C.; Jackson, R. D.; Landis, D. A.; Swinton, S. M.; Thelen, K. D.; Tiedje, J. M. Cellulosic biofuel contributions to a sustainable energy future: Choices and outcomes. *Science* **2017**, *356*, eaal2324.

(14) Song, F.; Zhao, J.; Swinton, S. M. Switching to perennial energy crops under uncertainty and costly reversibility. *Am. J. Agric. Econ.* **2011**, *93*, 768−783.

(15) National Resource Council. *Liquid transportation fuels from coal and biomass: technological status, costs, and environmental impacts*; National Academies Press, 2009.

(16) Khanna, M.; Dhungana, B.; Clifton-Brown, J. Costs of producing miscanthus and switchgrass for bioenergy in Illinois. *Biomass Bioenergy* **2008**, *32*, 482−493.

(17) Perrin, R.; Sesmero, J.; Wamisho, K.; Bacha, D. Biomass supply schedules for Great Plains delivery points. *Biomass Bioenergy* **2012**, *37*, 213−220.

(18) Turhollow, A.; Epplin, F., Estimating region specific costs to produce and deliver switchgrass. In *Switchgrass*, Springer: 2012; pp. 187−203, DOI: 10.1007/978-1-4471-2903-5_8.

(19) Swinton, S. M.; Tanner, S.; Barham, B. L.; Mooney, D. F.; Skevas, T. How willing are landowners to supply land for bioenergy crops in the Northern Great Lakes Region? *GCB Bioenergy* **2017**, *9*, 414−428.

(20) Brandes, E.; McNunn, G. S.; Schulte, L. A.; Muth, D. J.; VanLoocke, A.; Heaton, E. A. Targeted subfield switchgrass integration could improve the farm economy, water quality, and bioenergy feedstock production. *GCB Bioenergy* **2018**, *10*, 199−212.

(21) Tilman, D.; Hill, J.; Lehman, C. Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science* **2006**, *314*, 1598−1600.

(22) Werling, B. P.; Dickson, T. L.; Isaacs, R.; Gaines, H.; Gratton, C.; Gross, K. L.; Liere, H.; Malmstrom, C. M.; Meehan, T. D.; Ruan, L.; Robertson, B. A.; Robertson, G. P.; Schmidt, T. M.; Schrotenboer, A. C.; Teal, T. K.; Wilson, J. K.; Landis, D. A. Perennial grasslands enhance biodiversity and multiple ecosystem services in bioenergy landscapes. *Proc. Natl. Acad. Sci. U. S. A.* **2014**, *111*, 1652−1657.

(23) Mishra, S. K.; Negri, M. C.; Kozak, J.; Cacho, J. F.; Quinn, J.; Secchi, S.; Ssegane, H. Valuation of ecosystem services in alternative bioenergy landscape scenarios. *GCB Bioenergy* **2019**, *11*, 748−762.

(24) Lal, R. Soil carbon sequestration impacts on global climate change and food security. *Science* **2004**, *304*, 1623−1627.

(25) Chambers, A.; Lal, R.; Paustian, K. Soil carbon sequestration potential of US croplands and grasslands: Implementing the 4 per Thousand Initiative. *J. Soil Water Conserv.* **2016**, *71*, 68A−74A.

(26) Woodbury, P. B.; Kemanian, A. R.; Jacobson, M.; Langholtz, M. Improving water quality in the Chesapeake Bay using payments for ecosystem services for perennial biomass for bioenergy and biofuel production. *Biomass Bioenergy* **2018**, *114*, 132−142.

(27) Jager, H. I.; Efroymson, R. A. Can upstream biofuel production increase the flow of downstream ecosystem goods and services? *Biomass Bioenergy* **2018**, *114*, 125−131.

(28) Xu, H.; Wu, M.; Ha, M. Recognizing economic value in multifunctional buffers in the lower Mississippi river basin. *Biofuels, Bioprod. Biorefin.* **2019**, *13*, 55−73.

(29) Li, X.; Zipp, K. Y. Dynamics and Uncertainty in Land Use Conversion for Perennial Energy Crop Production: Exploring Effects of Payments for Ecosystem Services Policies. *Agric. Resour. Econ. Rev.* **2019**, *48*, 328−358.

(30) Landis, D. A.; Gratton, C.; Jackson, R. D.; Gross, K. L.; Duncan, D. S.; Liang, C.; Meehan, T. D.; Robertson, B. A.; Schmidt, T. M.; Stahlheber, K. A.; Tiedje, J. M.; Werling, B. P. Biomass and

biofuel crop effects on biodiversity and ecosystem services in the North Central US. *Biomass Bioenergy* **2018**, *114*, 18−29.

(31) Antle, J. M.; Capalbo, S. M.; Paustian, K.; Ali, M. K. Estimating the economic potential for agricultural soil carbon sequestration in the Central United States using an aggregate econometric-process simulation model. *Climatic Change* **2007**, *80*, 145−171.

(32) Antle, J. M.; Capalbo, S. M.; Mooney, S.; Elliott, E. T.; Paustian, K. H. Economic analysis of agricultural soil carbon sequestration: an integrated assessment approach. *J. Agric. Resour. Econ.* **2001**, *26*, 344−367.

(33) Ssegane, H.; Negri, M. C. An integrated landscape designed for commodity and bioenergy crops for a tile-drained agricultural watershed. *J. Environ. Qual.* **2016**, *45*, 1588−1596.

(34) Motew, M.; Chen, X.; Booth, E. G.; Carpenter, S. R.; Pinkas, P.; Zipper, S. C.; Loheide, S. P., II; Donner, S. D.; Tsuruta, K.; Vadas, P. A.; Kucharik, C. J. The influence of legacy P on lake water quality in a Midwestern agricultural watershed. *Ecosystems* **2017**, *20*, 1468−1482.

(35) Mortensen, J. G.; González-Pinzón, R.; Dahm, C. N.; Wang, J.; Zeglin, L. H.; Van Horn, D. J. Advancing the food-energy−water nexus: closing nutrient loops in arid river corridors. *Environ. Sci. Technol.* **2016**, *50*, 8485−8496.

(36) Iyer, G.; Calvin, K.; Clarke, L.; Edmonds, J.; Hultman, N.; Hartin, C.; McJeon, H.; Aldy, J.; Pizer, W. Implications of sustainable development considerations for comparability across nationally determined contributions. *Nat. Clim. Change* **2018**, *8*, 124−129.

(37) Cope, M. A.; McLafferty, S.; Rhoads, B. L. Farmer attitudes toward production of perennial energy grasses in east central Illinois: implications for community-based decision making. *Ann. Assoc. Am. Geogr.* **2011**, *101*, 852−862.

(38) Liebig, M. A.; Schmer, M. R.; Vogel, K. P.; Mitchell, R. B. Soil carbon storage by switchgrass grown for bioenergy. *Bioenergy Res.* **2008**, *1*, 215−222.

(39) Wright, L., Historical perspective on how and why switchgrass was selected as a "model" high-potential energy crop. *ORNL/TM-2007/109 Oak Ridge, TN: Bioenergy Resources and Engineering Systems*; Oak Ridge National Laboratory, 2007, 1.

(40) Mitchell, R.; Vogel, K. P.; Sarath, G. Managing and enhancing switchgrass as a bioenergy feedstock. *Biofuels, Bioprod. Biorefin.* **2008**, *2*, 530−539.

(41) Parton, W. J.; Hartman, M.; Ojima, D.; Schimel, D. DAYCENT and its land surface submodel: description and testing. *Global Planet. Change* **1998**, *19*, 35−48.

(42) Del Grosso, S. J.; Parton, W. J.; Mosier, A. R.; Walsh, M. K.; Ojima, D. S.; Thornton, P. E. DAYCENT national-scale simulations of nitrous oxide emissions from cropped soils in the United States. *J. Environ. Qual.* **2006**, *35*, 1451−1460.

(43) NASS-CDL, *Cropland Data Layer Releases*; NASS-CDL, 2019.

(44) Menne, M. J.; Durre, I.; Vose, R. S.; Gleason, B. E.; Houston, T. G. An overview of the global historical climatology network-daily database. *J. Atmos. Oceanic Technol.* **2012**, *29*, 897−910.

(45) Saxton, K. E.; Rawls, W. J. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. *Soil Sci. Soc. Am. J.* **2006**, *70*, 1569−1578.

(46) USEPA. *Inventory of U.S. greenhouse gas emissions and sinks: 1990−2003*; USEPA: Washington, DC, 2005.

(47) Gautam, S.; Mishra, U.; Scown, C. D.; Zhang, Y. Sorghum biomass production in the continental United States and its potential impacts on soil organic carbon and nitrous oxide emissions. *GCB Bioenergy* **2020**, *12*, 878−890.

(48) Tilman, D.; Cassman, K. G.; Matson, P. A.; Naylor, R.; Polasky, S. Agricultural sustainability and intensive production practices. *Nature* **2002**, *418*, 671−677.

(49) Stiglitz, J. E.; Stern, N.; Duan, M.; Edenhofer, O.; Giraud, G.; Heal, G. M.; Rovere, E. L.; Morris, A.; Moyer, E.; Pangestu, M. *Report of the high-level commission on carbon prices*; Columbia University Libraries, 2017.

(50) Heaton, E.; Voigt, T.; Long, S., Miscanthus x giganteus: the results of trials alongside switchgrass (*Panicum virgatum*) in Illinois. *Department of Plant Biology, University of Illinois at Urbana-Champaign*; *Unpublished Manuscript* 2006, 1−37.

(51) Follett, R. F.; Vogel, K. P.; Varvel, G. E.; Mitchell, R. B.; Kimble, J. Soil carbon sequestration by switchgrass and no-till maize grown for bioenergy. *BioEnergy Res.* **2012**, *5*, 866−875.

(52) ANDERSON-TEIXEIRA, K. J.; Davis, S. C.; Masters, M. D.; Delucia, E. H. Changes in soil organic carbon under biofuel crops. *Gcb Bioenergy* **2009**, *1*, 75−96.

(53) Jaggard, E. L. *Soil carbon dynamics following switchgrass establishment for bioenergy production in Southeastern Ontario*; Queen's University:Canada, 2012.

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

(55) Baral, N. R.; Kavvada, O.; Mendez Perez, D.; Mukhopadhyay, A.; Lee, T. S.; Simmons, B. A.; Scown, C. D. Greenhouse Gas Footprint, Water-Intensity, and Production Cost of Bio-Based Isopentenol as a Renewable Transportation Fuel. *ACS Sustainable Chem. Eng.* **2019**, *7*, 15434−15444.

(56) Baral, N. R.; Quiroz-Arita, C.; Bradley, T. H. Uncertainties in corn stover feedstock supply logistics cost and life-cycle greenhouse gas emissions for butanol production. *Applied Energy* **2017**, *208*, 1343−1356.

(57) Bracmort, K.; Cowan, T. *The Renewable Fuel Standard (RFS): Waiver Authority and Modification of Volumes*; Congressional Research Service, 2017.

(58) Food and Agriculture Organization of the United Nations. *Transforming food and agriculture to achieve the SDGs*; Food and Agriculture Organization of the United Nations, 2018.

(59) Fagerholm, N.; Martín-López, B.; Torralba, M.; Oteros-Rozas, E.; Lechner, A. M.; Bieling, C.; Stahl Olafsson, A.; Albert, C.; Raymond, C. M.; Garcia-Martin, M.; Gulsrud, N.; Plieninger, T. Perceived contributions of multifunctional landscapes to human well-being: Evidence from 13 European sites. *People and Nature* **2020**, *2*, 217−234.

(60) Lal, R. Carbon management in agricultural soils. *Mitigation Adapt. Strategies Global Change* **2007**, *12*, 303−322.

(61) Guzman, J. G.; Lal, R.; Byrd, S.; Apfelbaum, S. I.; Thompson, R. L. Carbon life cycle assessment for prairie as a crop in reclaimed mine land. *Land Degrad. Dev.* **2016**, *27*, 1196−1204.

(62) Amundson, R.; Biardeau, L. Opinion: Soil carbon sequestration is an elusive climate mitigation tool. *Proc. Natl. Acad. Sci. U. S. A.* **2018**, *115*, 11652−11656.