

Evaluating Local Crop Residue Biomass Supply: Economic and Environmental Impacts

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Abstract The increasing interest in energy production from biomass requires a better understanding of potential local production and environmental impacts. This information is needed by local producers, biomass industry, and other stakeholders, and for larger scale analyses. This study models biomass production decisions at the field level using a case example of a biomass gasification facility constructed at the University of Minnesota—Morris (UMM). This institutional-scale application has an anticipated feedstock demand of about 8,000 Mg year⁻¹. The model includes spatial impacts due to sub-field variation in soil characteristics and transportation costs. Results show that the amount of biomass producers could profitably supply within a 32.2-km radius of UMM increases as plant-gate biomass price increases from \$59 to \$84 Mg⁻¹, with 588,000 Mg annual biomass supply at \$84 Mg⁻¹. Results also show that the most profitable tillage and crop rotation practices shift in response to increasing biomass price with producers shifting from a corn-soybean rotation toward continuous corn. While biomass harvest is conducive to increased soil erosion rates and reduced soil organic carbon levels, changes in crop production practices are shown to at least partially offset these impacts. Transportation costs tend to concentrate and intensify biomass production near the biomass facility,

which also tends to concentrate environmental impacts near the facility.

Keywords Bioenergy · Gasification · Crop rotation · Tillage · Corn stover · Cellulosic biomass · Soil organic carbon · Soil erosion

Abbreviations

CP	Chisel plow
ST	Strip-tillage
C	Corn
SB	Soybean
SW	Spring wheat
CC	Continuous corn
UMM	University of Minnesota—Morris
SOC	Soil organic carbon
CDL	Cropland data layer
EPIC	Environmental Policy Integrated Climate
SSURGO	Soil Survey Geographic

Introduction

Demand for biomass as a renewable energy source in the USA is projected to increase in order to meet liquid fuel need under the Energy Independence and Security Act of 2007 [1] requirements and in response to state mandates for renewable energy. Use of corn grain (*Zea mays* L.) for biofuel has been shown to have negative impacts on the landscape and its provision of ecosystem services [2]. Use of biomass for bioenergy could reduce net greenhouse gas emissions, and use of crop residues may be particularly attractive since they are joint products with grain production and are less likely to lead to expansion of crop production in

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other regions, which could reduce net greenhouse gas benefits [3]. However, harvesting biomass for bioenergy will likely result in additional impacts on the landscape, which could further impede the provision of other ecosystem services. Many ecosystem services are sensitive to site-specific land use impacts and the distribution of practices across the landscape [4, 5]. This indicates a need for information on the potential impacts of bioenergy feedstock production on the spatial distribution of land uses across the landscape.

Typically, potential impacts of increased biofuel demand on agricultural production practices have been analyzed at a large scale [6–8]. These analyses provide useful information on potential changes in production practices. However, they include limited production alternatives and, due to computational and data acquisition limitations, are conducted at a relatively coarse spatial scale (e.g., county and larger). Thus, these analyses may miss effects of spatial variation in production practices within a region as influenced by soil characteristics and transportation costs. Course-scale analyses also may miss important localized economic and environmental impacts. High costs for transporting biomass have been shown to have substantial impacts on biomass supply and to be an important consideration for siting biomass facilities to minimize feedstock costs [9–12]. However, transportation costs could also affect the distribution of agricultural production practices within a region, particularly if optimum production practices are sensitive to changing biomass prices. Referring to potential ecological impacts of bioenergy production, Dale et al. [13] indicate the need for research at the regional scale, “which is less understood than either smaller or larger scales.” We contend that this need extends to first understanding potential production and land-use changes at this regional scale.

Biomass production could have positive and negative environmental impacts. Focusing on crop residue harvest, crop residues left in the field provide a variety of ecosystem services including nutrient cycling, erosion control, soil carbon sequestration, improvement of soil physical properties, and crop productivity [14]. Adverse outcomes from residue removal might include increased fertilizer application needs, increased soil erosion, and decreased soil organic carbon (if mineralization exceeds humification processes) [15, 16], while reduced N_2O emissions and reduced N losses due to leaching have been suggested as possible benefits [17]. Soil organic carbon is an important indicator of soil quality and is linked to many ecosystem functions [18]. While field and simulation studies have been used to identify potential impacts of bioenergy production alternatives on soil carbon levels for individual sites or groups of sites [19–24], few analyses have identified regional impacts of bioenergy demand on soil carbon. Sheehan et al. [9]

estimated soil carbon changes for the state of Iowa using county-level estimates of changes with different stover removal alternatives but did not account for potential differences among soil types within counties. Sheehan et al. also did not model effects of biomass price on optimum cropping practices but instead assumed all farmers switched from current cropping and tillage practices to CC under no-till. Kim et al. [25] show that understanding changes in cropping management is a key in estimating greenhouse gas emissions associated with bioenergy production. Gregg et al. [26] showed interactions of residue removal rates and conservation management practices for representative cropping systems across the USA. Results showed site-specific tradeoffs of harvest rate with soil erosion, soil organic carbon losses, and long-term productivity and nutrient losses, with conservation management generally allowing higher harvest rates [26]. However, the analysis did not evaluate whether conservation management was economically viable and resulting impacts on biomass supply [26]. Zhang et al. [24] developed a regional multiobjective framework to evaluate tradeoffs between biofuel production and multiple ecosystem service responses and provide spatially explicit estimates of environmental impacts [24]. However, while the system is designed to provide information for economic analysis, economic performance of alternative cropping practices and resulting environmental impacts were not included in the system [24].

Recognizing the importance of avoiding excessive erosion with biomass production, several studies have analyzed the costs of crop residues constraining harvest to lands that are not highly erodible or restricting harvest amounts to quantities that would not exceed specified erosion levels [9, 10, 27–29]. Constraining harvest rates based on limiting erosion is not necessarily sufficient to prevent a loss in SOC [30]. While many of these studies included potential impacts of changes in tillage system on biomass supply, none of them quantified the tillage and rotation shifts likely to occur as producers strive to maximize profitability in response to biomass demand. Petrolia [10] and Graham et al. [29] identified shifts in supply and biomass prices resulting from relaxing or further constraining harvest rates based on erosion levels. They also showed how adoption of conservation tillage practices could increase biomass supply while meeting erosion constraints. However, none of these cost analysis studies quantified the amount and spatial location of erosion changes that are likely to occur as related to biomass supply. However, this is critical information for determining potential impacts to water quality. Recent papers have modeled impacts of bioenergy demand on cropping practices at finer spatial resolution than previous studies and included impacts on soil erosion and SOC [31, 32]. However, these studies have not included impacts of transportation costs.

This study builds on the previous studies by modeling biomass production decisions at the field level and including spatial impacts due to subfield variation in soil characteristics and transportation costs. The goal is to enhance the understanding of potential local production and environmental impacts, which are important to local producers, biomass industry, and other stakeholders, and which provide needed information for larger-scale analyses. While the methods presented could be used to evaluate impacts of multiple bioenergy facilities across a broader region, we demonstrate the methodology by evaluating biomass supply from crop residues for a single bioenergy facility and determine spatially explicit impacts on agricultural production practices, farm profitability, soil erosion, and SOC.

Methods

Description of Research Area

A biomass gasification facility at the University of Minnesota—Morris (UMM) (<http://renewables.morris.umn.edu/biomass/>) is used as a case study for this analysis. The plant was designed to generate sufficient steam to meet 80% of the campus' heating and cooling needs utilizing about 8,000 Mg of biomass year⁻¹. However, we also will show potential supplies and resulting environmental impacts for scaling up to meet additional energy demands including providing process heat for an existing corn grain ethanol plant (~100,000 Mg biomass year⁻¹) or the construction of a cellulosic ethanol plant (~200,000 Mg to 500,000 Mg biomass year⁻¹).

Potential biomass supply to the plant is analyzed by modeling field-level production alternatives for each crop field within a 32.2-km (20 miles) radius of the UMM plant. The 32.2-km radius was selected as a reasonable area to meet biomass supply needs while minimizing overlap with areas that would potentially supply biomass for process heat at existing neighboring corn grain ethanol plants located at Benson, MN, USA (40 km), Big Stone, SD, USA (58 km); Fergus Falls, MN, USA (82 km), and Rosholt, SD, USA (72 km). The predominant crops grown in this region are corn, soybean (*Glycine max* L. [Merr.]), and spring wheat (*Triticum aestivum* L.), with 52,550 ha corn, 44,900 ha soybean, and 6,150 ha spring wheat harvested in Stevens County in 2010 [33], which is located almost entirely within the 32.2-km radius and accounts for 65% of the cropland within the radius. Corn and soybean area has increased over time in this region, while spring wheat and other small grains have declined, with 36,000 ha corn, 36,050 ha soybean, and 28,900 ha spring wheat grown in Stevens County in 1990 [33].

Producers in this region typically use conventional tillage (moldboard or chisel plowing) to manage residue and avoid perceived negative impacts on crop yields due to cool, wet spring soil conditions. No-till adoption in the region is extremely limited, with 0.7% adoption reported for Stevens County in 2007 [34]. Fall strip tillage, which involves tilling a narrow strip in the fall and planting in the cleared strip in the spring, is a low-intensity tillage alternative that producers in the region may be more willing to adopt if additional crop residue is removed.

Soils in the area are generally glacial till, outwash sediment, or glacial lake sediment soils, predominantly Mollisols with a few Histosols. Within the 32.2-km radius of UMM, 6.6% of the soils are listed as highly erodible or potentially highly erodible [35, 36]. Average annual precipitation at Morris, MN, USA (1971–2000) is 645 mm, and mean monthly temperatures (1971–2000) range from -13.1°C in January to 21.7°C in July [37].

Economic Analysis and Simulation Modeling

The Environmental Policy Integrated Climate (EPIC) model [38] with the i_EPIC interface [39] is used to simulate crop and crop-residue biomass production alternatives, including effects on grain and biomass production, soil organic carbon, and wind and water erosion. Inputs to the EPIC simulation include Soil Survey Geographic (SSURGO) database soils information [35] and historical daily weather data from the West Central Research and Outreach Center located about 2 km from the UMM plant. Crop production alternatives include three rotations: corn–spring wheat–soybean (C-SW-SB), corn–soybean (C-SB), and continuous corn (CC); two tillage treatments: conventional chisel plow tillage (CP) and fall strip-tillage (ST); and four residue harvest alternatives: no residue harvest (none), corn stover harvested each year corn appears in the rotation (corn stover), wheat straw harvest each year wheat appears in the rotation (wheat straw), and harvesting both corn stover and wheat straw (stover and straw).

For this analysis, profit maximization was assumed, so producers would choose the most profitable practice at the field level based on rotation average net returns at a given biomass price. Potential impacts of other adoption assumptions will be discussed later. Supply curves are generated by calculating net returns for each field for all production alternatives and identifying the production alternative with the highest net returns for each increment in biomass price ranging from \$56 to 84 Mg⁻¹ in increments of \$1 Mg⁻¹. We utilize this point-wise procedure rather than the commonly used breakeven approach [40, 41] since we include multiple biomass production alternatives. While the breakeven approach could be used with multiple alternatives, this would require comparisons among each

of the alternatives, since there can be multiple break-even points where different practices may become optimal. Net returns for each cropping system within each field are calculated as:

$$\pi_{ij} = \pi_{0ij} + PB_{ij}(1 - L) - F_j - C_j B_{ij} - T_i B_{ij} - N_{ij} - A_{ij} \quad (1)$$

π_{ij}	net return for field i and cropping system j
π_{0ij}	net returns for grain production in field i and cropping system j
P	biomass price
B_{ij}	average annual biomass yield (quantity harvested ha^{-1}) in field i and cropping system j
L	portion of biomass loss during storage and transport
C_j	cost per unit of biomass for harvest
F_j	fixed cost for biomass harvest
T_i	biomass transportation cost from field i
N_{ij}	nutrient replacement costs
A_{ij}	tillage system adoption premium in field i and cropping system j

Note that biomass harvest costs include a variable portion that is proportional with the amount of residue harvested (C_j) and a fixed portion that is a constant per unit area harvested (F_j). Any effects of biomass harvest on grain yields are included in the grain net return factor. Production costs are based on enterprise budgets constructed for each of the cropping system alternatives using 2009 costs for machinery, labor, and inputs. Machinery, labor, and fuel costs are from the University of Minnesota Extension [42], and seed and fertilizer prices are from USDA-National Agricultural Statistics Service (NASS) [43]. Note that crop prices are fixed in this analysis, so potential effects of shifts in production practices on crop prices are not included. While this may be reasonable when analyzing a relatively small region, broader scale analyses would require inclusion of crop price effects. A tillage system adoption premium is included to account for the observation that conventional tillage continues to be used on nearly all cropland in the region, yet research shows alternative tillage systems may be more profitable [44]. This indicates that there may be costs (e.g., due to uncertainties) not captured by the enterprise budget analysis and that farmers may demand a premium in order to adopt conservation tillage practices [45]. The adoption premium is estimated for each field as the difference between the grain production net returns (no biomass harvest) for the most profitable CP crop rotation and the most profitable ST rotation. This is a conservative estimate of the adoption premium as it assumes that ST will be adopted on any field for any increase in ST profitability relative to the next best CP option.

A chop, rake, and bale harvest system is assumed for the corn stover harvest using a residue harvest rate of 50% of above ground non-grain biomass based on Shinnars et al. [46]. Costs for this system are based on the round bale scenario analyzed by Petrolia [47]. Wheat straw is assumed to be harvested by directly baling windrows left by the combine and using a 40% harvest rate based on literature reported values [48, 49]. Bales are assumed to be wrapped with plastic net wrap to reduce losses during storage and transportation. Baling and bale wrap costs are included as a constant per unit of biomass harvested, and shredding and raking costs are included as a constant per area harvested (Table 1). Fertilizer applications in the simulation occurred at planting for all crops with a side-dress application applied 45 days after planting for corn. Annual N applications were automatically adjusted in the model with pre-plant and side-dress applications adjusted based on crop needs. Fertilizer P and K costs were calculated based on nutrient removal rates in grain and biomass of 0.0012 Mg P and 0.00674 Mg K Mg^{-1} corn stover, 0.00064 Mg P 0.01174 Mg K Mg^{-1} wheat straw, 0.0091 Mg P and 0.021 Mg K Mg^{-1} soybean grain, 0.002 Mg P and 0.004 Mg K Mg^{-1} corn grain, and 0.003 Mg P and 0.005 Mg K Mg^{-1} wheat grain [50–55]. Production and biomass harvest costs for each cropping system are shown in Table 2. Note that corn stover harvest costs are higher for CP than for ST since shredding is typically already used in the CP systems, so it is already included in the production costs. In order to include the effects of conservation compliance requirements for farmers to maintain farm program eligibility, crop residue harvest on highly erodible land was limited in the analysis to occur only if ST was adopted.

Following Petrolia [47], it is assumed that bales are collected in the field using an automated bale picker with a capacity of 14 round bales and unloaded at the edge of the field. The bales are later loaded onto a truck using a telehandler and transported to outdoor storage at the biomass facility. The $\$70.99 \text{ h}^{-1}$ cost of the bale picker is allocated between collection and within-field transportation assuming 18 min per 14 bale load (1.29 min per bale) for collection

Table 1 Costs for biomass harvest, collection, transportation, and storage operations

Operation	Cost	
Shredding	28.69	$\$ \text{ha}^{-1}$
Raking	13.28	$\$ \text{ha}^{-1}$
Baling	8.35	$\$ \text{Mg}^{-1}$
Bale Wrap	5.07	$\$ \text{Mg}^{-1}$
Bale Picker	70.99	$\$ \text{h}^{-1}$
Trucking	0.243	$\$ \text{Mg}^{-1} \text{ km}^{-1}$
Loading/unloading	3.42	$\$ \text{Mg}^{-1}$
Storage	$\$7.90$	$\$ \text{Mg}^{-1}$

Table 2 Crop production costs including operating and ownership costs, the fixed portion of biomass harvest costs, and the variable portion of biomass harvest costs for each crop, within a crop rotation and tillage system

Crop	Rotation	Tillage	Non-fertilizer operating costs \$ ha ⁻¹	Ownership costs	Fixed biomass harvest cost	Variable biomass harvest cost \$ Mg ⁻¹
Corn	C-SB	CP	370.61	107.46	13.28	13.42
		ST	368.25	106.82	41.97	13.42
	CC	CP	384.23	123.32	13.28	13.42
		ST	368.25	106.82	41.97	13.42
	C-SW-SB	CP	370.61	107.46	13.28	13.42
		ST	368.25	106.82	41.97	13.42
Soybean	C-SB	CP	259.47	88.42		
		ST	243.51	71.91		
	C-SW-SB	CP	245.85	72.56		
		ST	243.51	71.91		
Spring wheat	C-SW-SB	CP	199.52	84.38	0.00	13.42
		ST	171.74	51.76	0.00	13.42

C-SB corn-soybean, CC continuous corn, C-SW-SB corn–spring wheat–soybean rotations, CP chisel plow, ST strip tillage.

and unloading at the field edge which is \$21.30 load⁻¹ or \$4.54 Mg⁻¹ dry biomass. The assumed loading and unloading time is longer than the times used by Morey et al. [56] and Perlack and Turhollow [57] of 0.86 and 1.0 min per bale, respectively. Within field transportation assumes a speed of 16 km h⁻¹, which is \$1.88 Mg⁻¹ km⁻¹ loaded distance. Therefore, round-trip transit time from the center of a square 65 ha field to the field edge would be 3 min per load, giving a total loading, unloading, and round-trip transit time to the field edge of 21 min per load (1.5 min per bale). This is consistent with the rates used by Petrolia [47] of 20 min per 14 bale load (1.43 min per bale) and Perlack and Turhollow [57] of 25 min per 17 bale load (1.47 min per bale) for collection, unloading, and round-trip transit time to the field edge. In contrast, Sokhansanj and Turhollow [58] reported a time of 60 min for 14 bales. However, this included transit time to storage at a distance of 8.05 km each way.

On-road biomass transportation costs are calculated using Minnesota Department of Transportation road network maps [59]. Total biomass transportation costs are calculated on a 30-m grid using the cost of \$1.88 Mg⁻¹ km⁻¹ within fields and \$0.243 Mg⁻¹ km⁻¹ along roads. Following Petrolia [47], the on-road transportation rate is based on the second quarter 2010 grain truck mileage rates of \$2.62 km⁻¹ for loaded trips <40 km reported by the USDA Agricultural Marketing Service [60] and assuming 10.8 Mg biomass per load. Biomass loading costs are \$3.42 Mg⁻¹ dry biomass. Storage cost are \$7.90 Mg⁻¹ based on Petrolia [47], and storage losses were 7.8% based on monthly losses reported by Shinnars et al. [46] and assuming 6 months storage.

EPIC was calibrated using crop yield data from three studies conducted at the Swan Lake Research Farm located

near Morris, MN (45°41' N, 95°48'W, elevation 370 m). These studies include a range of tillage and crop rotation treatments [44, 61] and an ongoing field study that includes corn stover harvest and tillage treatment combinations. Additional field data from a multilocation field study [50] were used to verify that model-predicted nutrient removal was consistent with field observations. Ideally, field data would also be used in calibrating EPIC soil carbon to field observations. Unfortunately, this was not done because insufficient data were available from the field studies. However, the model has been extensively validated and is widely used in simulating SOC and erosion impacts without additional calibration [26, 62–65], and this is consistent with the use of these types of models for assessment of alternative land management scenarios and for spatial estimation of environmental impacts where experimental data are scarce [24].

Crop land within the 32.2-km radius is identified using the 2009 USDA-NASS Cropland Data Layer [66] in ArcGIS 9.2. Any land shown as an annual crop in the CDL was classified as cropland potentially available for biomass production in this analysis. The CDL is also used to define individual fields assuming that contiguous land mapped as a single crop is a single field. The spatial SSURGO soil map units are overlaid on the field boundaries to determine the area of each soil map unit within each field. The EPIC simulations are conducted for each SSURGO soil component series within a soil map unit (there can be multiple soil component series within a map unit), and net return calculations, soil organic carbon, and soil erosion results for each soil component series are aggregated to the soil map unit level based on the SSURGO reported relative areal

distribution of component series within the map unit. Results are further aggregated to the field level based on the area of each soil map unit within each field. Net return calculations and aggregation calculations to the field level are all conducted in a Microsoft Access database.

In conducting the simulation analysis, the model is first initialized by running a 100-year simulation on each soil map unit for a C-SB rotation with CP tillage and no residue harvest. Soil output at the end of the initialization is used as input for all subsequent simulation runs. After initialization, each treatment is simulated on each soil component series over a 20-year horizon using historical weather data from 1988–2007. For soil map units with multiple components, results are weighted to the map unit level based on the component extents reported in the SSURGO database. Average annual changes in SOC are calculated by linear regression of annual SOC content on year for each treatment and soil map unit. Linear regression was chosen over the commonly used alternative calculating the total SOC change as the difference between the beginning and ending SOC levels, since this method relies on only two points and can be sensitive to changes due to annual variation [67]. While SOC change may be nonlinear in the long term [67, 68], a linear approximation provided a reasonable fit over the relatively short 20-year horizon used for this analysis.

Results

The EPIC model calibration resulted in simulated yields within 0.6%, 0.3%, and 2.8% of mean observed yields for soybean, corn, and spring wheat, respectively. While average yields were well-calibrated, the model tended to underestimate yields for CP tillage and overestimate yields for ST tillage systems, with average simulated CP yields 1.8%, 4.1%, and 0.7% below observed and average simulated ST yields 3.6%, 6.4%, and 6.7% above observed for soybean, corn, and spring wheat, respectively. Modeled wheat yields were intentionally calibrated to closely match observed CP wheat yields and overestimate ST wheat yields due to the presence of volunteer alfalfa in the field study that likely would have been controlled with better herbicide management. Correlations between annual simulated and observed yields were generally high ranging from 0.57 for CP corn to 0.72 for CP soybean. However, an exception was for CP spring wheat, where correlation between annual simulated and observed yields was only 0.19, largely as a result of a single year. Omitting this observation resulted in correlation increasing to 0.62. This is a limitation in the use of the EPIC simulation model in that it does not consider some severe episodic events (e.g., hail, high winds, pest outbreaks), and thus simulated yield may occasionally deviate widely from observed yields [24].

Average N fertilizer applications varied by rotation and across soils with an average of 166.9 kg N ha⁻¹ applied for CC and a standard deviation across soils of 23.2 kg ha⁻¹ (Table 3). Average additional N applied with corn stover harvest is related to the amount of stover harvested, and ranged from 4.9 to 6.5 kg N Mg⁻¹ stover for C-SW-SB and CC, respectively. This is comparable to the average N content reported by Johnson et al. [50] of 7.45, 6.41, and 5.46 kg Mg⁻¹ for the above ear, below ear, and cob portions, respectively. Average additional N applied with wheat straw harvest was 2.1 kg N Mg⁻¹ straw, which is less than the average N content reported by Jacobsen et al. [53] of 7 kg N Mg⁻¹ wheat straw.

Transportation and loading costs range from \$8.46 to \$19.96 Mg⁻¹ for fields within 32.2 km (20 miles) of the UMM gasification plant (Fig. 1). Differences in transportation costs due to field location provide an incentive for fields closer to the gasification plant to be harvested at a lower plant gate biomass than fields further from the plant.

Optimum production practices are defined as those that maximize profits at the field level. Results for a single field illustrate how the optimum production practices change as biomass price changes (Fig. 2). For the sample field, the profit maximizing system without biomass harvest is a C-SB rotation with CP tillage. This provides highest net returns for biomass prices less than \$64 Mg⁻¹, at which point it becomes profitable to harvest corn stover. Harvesting corn stover from a C-SB rotation with CP tillage is optimized for biomass prices ranging from \$64 to \$76 Mg⁻¹. For prices above \$76 Mg⁻¹, the optimum cropping system is CC with CP tillage and harvesting corn stover every year. The CC rotation becomes relatively more profitable at higher stover prices due to higher annual stover production (rotation average) than for the C-SB rotation. It is important to note that, although the breakeven point for harvesting corn stover from a CC rotation relative to the baseline practice of C-SB with no residue harvest is \$70 Mg⁻¹, the CC system does not become optimum until

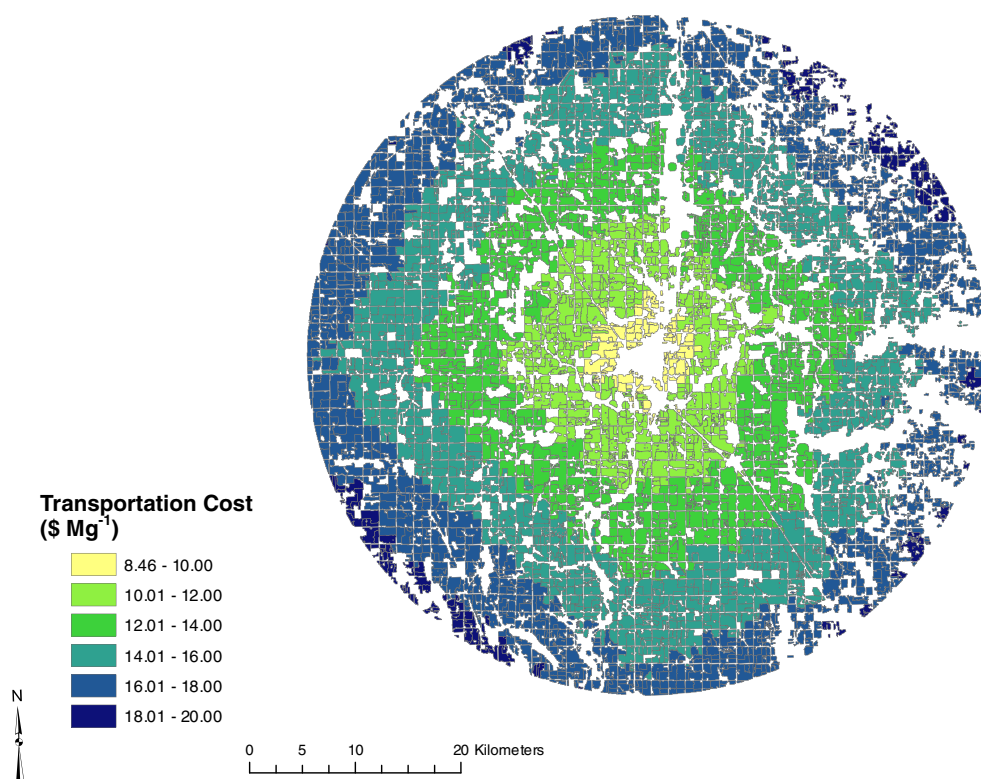
Table 3 Average annual nitrogen fertilizer applications for each rotation, and average additional N fertilizer applied per unit biomass harvested for corn stover and wheat straw harvest

Rotation	N applied with no residue harvest kg ha ⁻¹	Additional N applied with corn stover harvest kg Mg ⁻¹	Additional N applied with wheat straw harvest
CC	166.9 (23.2) ^a	6.5 (1.3)	
C-SB	72.2 (11.9)	5.6 (1.7)	
C-SW-SB	82.3	4.9 (1.3)	2.1 (1.7)

CC continuous corn, C-SB corn–soybean, C-SW-SB corn–spring wheat–soybean rotations

^a Standard deviations across soil map units shown in parentheses

Fig. 1 Biomass bale collection, loading, and transportation costs for fields within a 32.2-km radius of the UMM gasification plant



the biomass price reaches $\$76 \text{ Mg}^{-1}$. The availability of a lower cost biomass production alternative (C-SB harvesting corn stover) raises the price at which the CC corn stover harvest becomes optimum. This is similar to observations by others that the breakeven biomass price for perennial biomass production alternatives is often higher when corn stover is included as a production alternative [41, 69] and highlights the need to calculate a “comparative breakeven,” which includes the opportunity cost of the next most profitable option. Our point-wise maximization procedure, comparing the profitability of all alternatives for $\$1 \text{ Mg}^{-1}$ increments in biomass price, provides a direct calculation

of the most profitable option for each biomass price evaluated, avoiding the need to identify opportunity costs, but also only provides a discrete approximation to the breakeven prices (in $\$1 \text{ Mg}^{-1}$ increments).

Optimum cropping practices and relationship to biomass price varies across fields within the vicinity of the UMM gasification plant. The relationships between biomass price and optimum tillage, rotation, and biomass harvest practices within a 32.2-km radius of the UMM gasification plant are shown in Fig. 3a–c. For biomass prices below $\$57 \text{ Mg}^{-1}$ maximum net returns occur with 100% of cropped land in a CP tillage system (Fig. 3a). This is the result of including the tillage adoption premium in the baseline to match modeled tillage adoption with the high level of observed conventional tillage in the study area. The optimum crop rotation is CC on 55% of the cropped area, C-SB on 45%, and C-SW-SB on 0.03%, and no biomass is harvested (Fig. 3b). The modeled proportion of CC in the baseline is higher than observed and the proportion in C-SW-SB is lower than observed in the study area. As biomass price increases, the proportion of land in ST increases to 5.5% at $\$76 \text{ Mg}^{-1}$ (Fig. 3a). In addition, as biomass price increases, the profit maximizing rotation continues to shift from C-CB to CC, with 99.7% of the cropped area in CC at a biomass price of $\$84 \text{ Mg}^{-1}$ (Fig. 3b). This indicates that the presence of a biomass market could accelerate the observed shift toward corn production in the region. The C-SW-SB rotation was selected as a profit-maximizing rotation on $<0.05\%$ of the cropped acres at any biomass price. This is consistent with

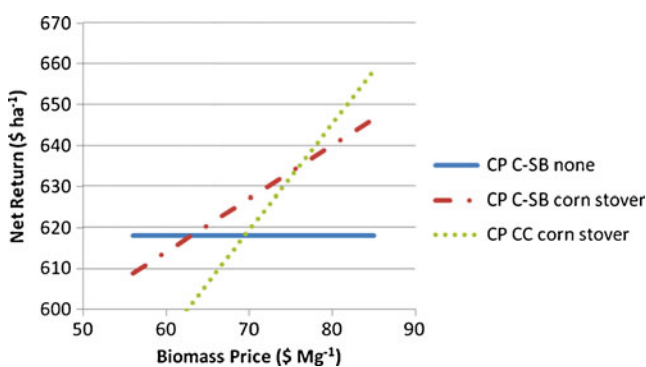


Fig. 2 Net returns for profit maximizing production practices on a selected field for biomass prices ranging from $\$56 \text{ Mg}^{-1}$ to $\$102 \text{ Mg}^{-1}$. CP chisel plow tillage, C-SB corn-soybean rotation, CC continuous corn rotation, none no biomass harvest, corn stover corn stover biomass harvest

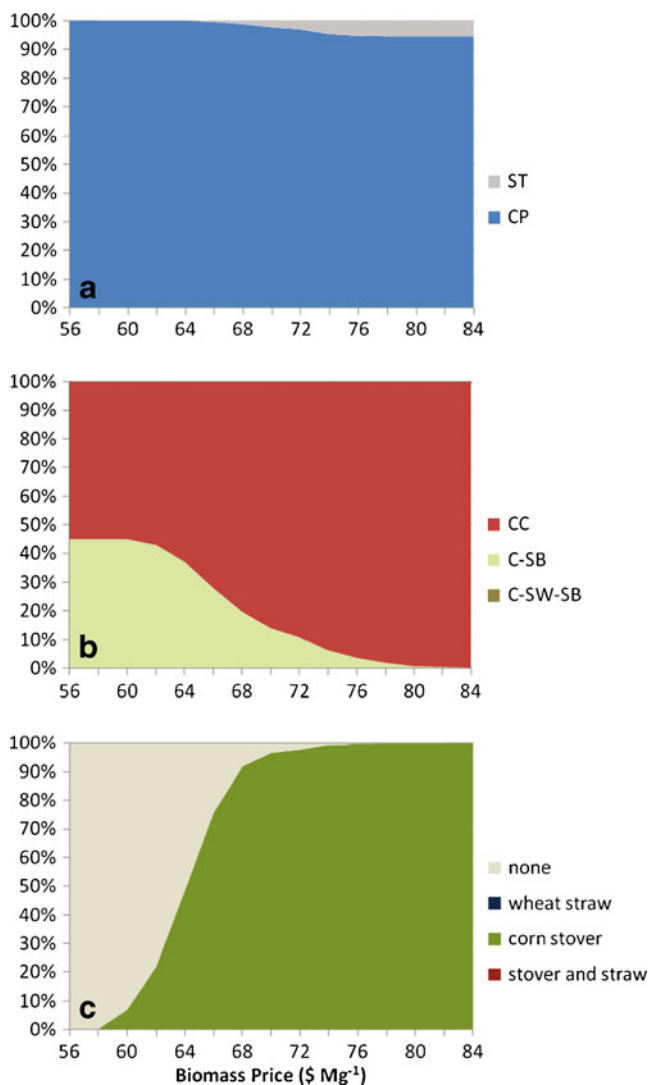


Fig. 3 a–c Effect of biomass price on profit maximizing a tillage system, b crop rotation, and c residue harvest as a portion of total cropped area within 32.2-km radius of the UMM gasification plant. CP chisel plow tillage, ST strip tillage, C-SB corn–soybean rotation, CC continuous corn rotation, none no biomass harvest, corn stover corn stover biomass harvest

observed declines in spring wheat acreage in the region. Note that the optimum area of SW production and wheat straw harvest are so small that the C-SW-SB rotation (Fig. 3b), and wheat straw harvest and stover and straw harvest (Fig. 3c) values are not visible on the figures.

Biomass supply is shown in Fig. 4. The annual biomass needs of the UMM gasification plant could be easily met by harvesting crop residues, with over 8,000 Mg available at a farm-gate price of \$59 Mg⁻¹. The amount of biomass producers could profitably supply rapidly increases as plant-gate biomass price increases from \$57 to \$72 Mg⁻¹, with 120,000 Mg supplied at \$62 Mg⁻¹, and over 500,000 Mg supplied at \$68 Mg⁻¹. Note that this likely underestimates the supply at higher prices (>\$64 Mg⁻¹) as producers

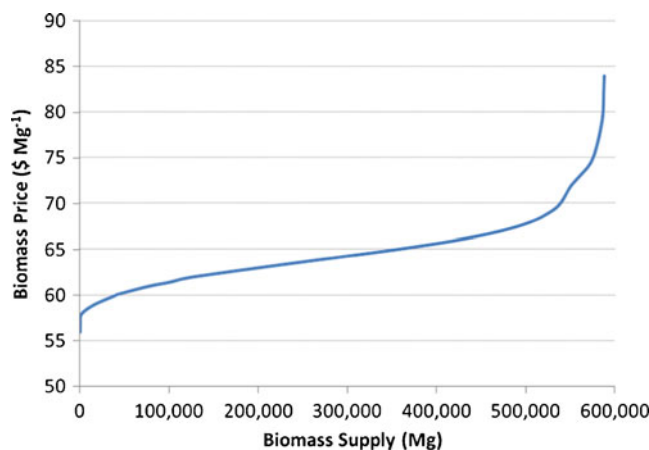


Fig. 4 Relationship between the plant-gate biomass price and biomass supply from crop residue within a 32.2-km radius of the UMM gasification plant

outside the 32.2 km radius around the plant would eventually find it profitable to harvest biomass. However, the key point illustrated in the analysis is that increasing biomass prices can lead to cropping shifts that increase biomass harvest intensity.

As biomass price increases, producer profitability also increases (Fig. 5). Even though we assumed producers would harvest crop residue as soon as net returns were more profitable than any alternatives, producers with a low breakeven price for harvesting crop residue, either due to low transportation costs or biomass production advantages, could see increases in profitability. At a price of \$64 Mg⁻¹, net return increases would range from \$0 to \$22 ha⁻¹ depending on location and biomass production costs (Fig. 6). Within the 32.2-km radius annual farm income would increase by

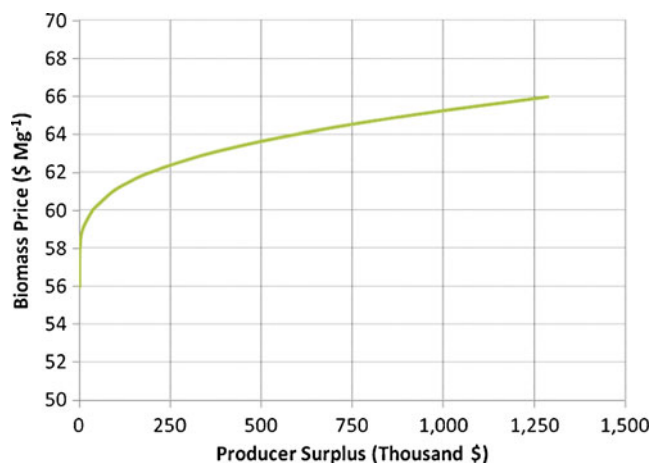
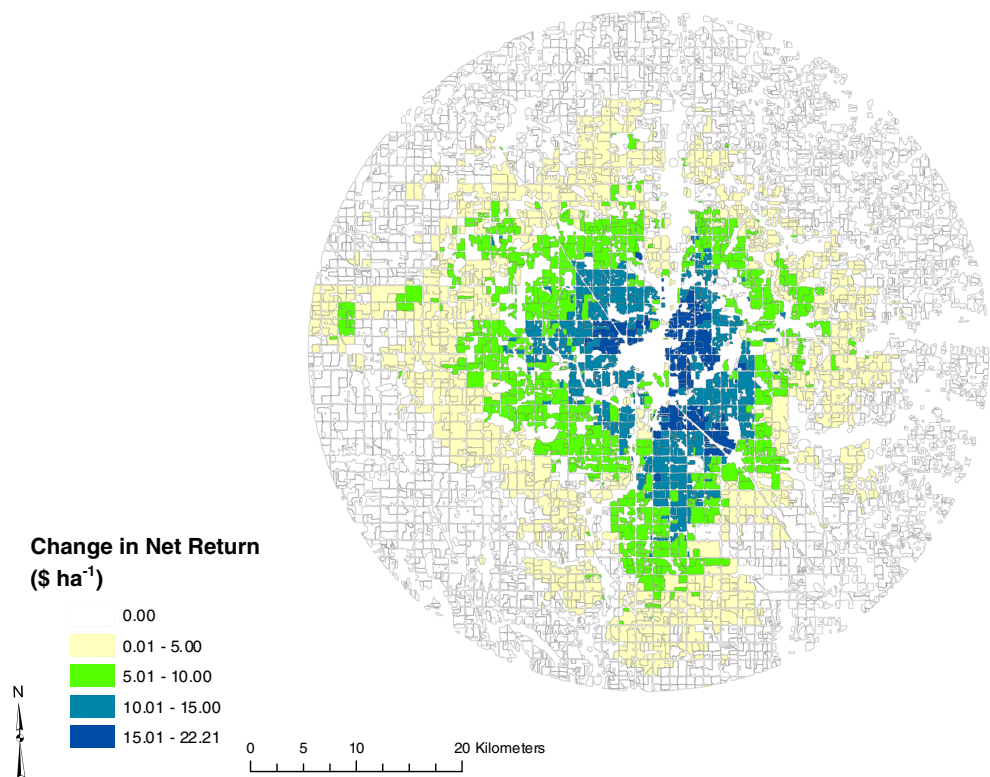


Fig. 5 Relationship between the plant-gate biomass price and the cumulative change in farm net returns (producer surplus) for profit maximizing production practices including opportunities for biomass harvest and sale relative to profit maximizing production practices with no biomass harvest within a 32.2-km radius of the UMM gasification plant

Fig. 6 Map of field-level changes in profitability for profit maximizing production practices with the opportunity to sell crop residue at a plant-gate price of $\$85 \text{ Mg}^{-1}$ relative to profit maximizing production practices with no biomass harvest



$\$587,000$ (Fig. 6) with 273,000 Mg of biomass supplied, or an average of $\$2$ increase in annual farm income per megagram biomass harvested. Note that with the exception of a small area at the western edge, biomass supplied at a price of $\$64 \text{ Mg}^{-1}$ generally comes from fields well within the 32.2-km radius, so little would be expected to be supplied from outside of the radius at this price level (Fig. 6).

However, increasing biomass supply also tends to increase annual wind and water erosion and decrease SOC (Fig. 7), at least until shifts in tillage occur. Annual water erosion increases and SOC decreases at a declining rate until

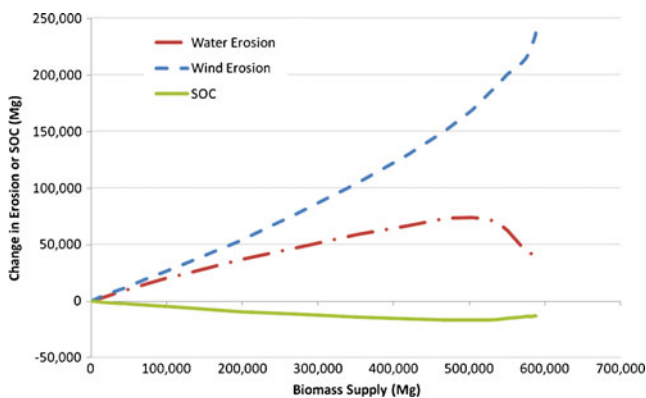


Fig. 7 Cumulative change in annual water erosion, wind erosion, and SOC for profit maximizing production practices including opportunities for biomass harvest and sale relative to profit maximizing production practices with no biomass harvest within a 32.2-km radius of the UMM gasification plant as a function of biomass supply

ST begins to substantially increase at supply of about 525,000 Mg, which corresponds to a price of about $\$69 \text{ Mg}^{-1}$ (Fig. 5). The decreasing rate may be in part due to the shift toward CC beginning at a supply of 273,000 Mg and a price of $\$64 \text{ Mg}^{-1}$. Wind erosion increases at an accelerating rate with biomass supply with little effect of a shift to ST. Even though ST leaves more crop residue above ground than CT, it is less effective at reducing wind erosion than water erosion, since the residue gets flattened during biomass harvest.

The location of erosion increases may be important in determining impacts to local water bodies. Because transportation costs tend to increase biomass harvest near the biomass facility, this also tends to concentrate erosion increases near the plant as well (Fig. 8). The importance of including biomass transportation costs in the analysis is illustrated in Fig. 9, which shows the location of erosion increases providing a supply of 100,000 Mg of biomass to the gasification plant, where the location of biomass harvest is determined by the most profitable practices *excluding* transportation costs. Comparing this to Fig. 8, which shows the location of erosion increases providing the same supply of 100,000 Mg biomass with transportation costs included, shows distinct differences in where erosion increases occur. While much of the erosion increases occur within a single watershed when transportation costs are included (Fig. 8), erosion increases are scattered among multiple watersheds when these costs are excluded (Fig. 9).

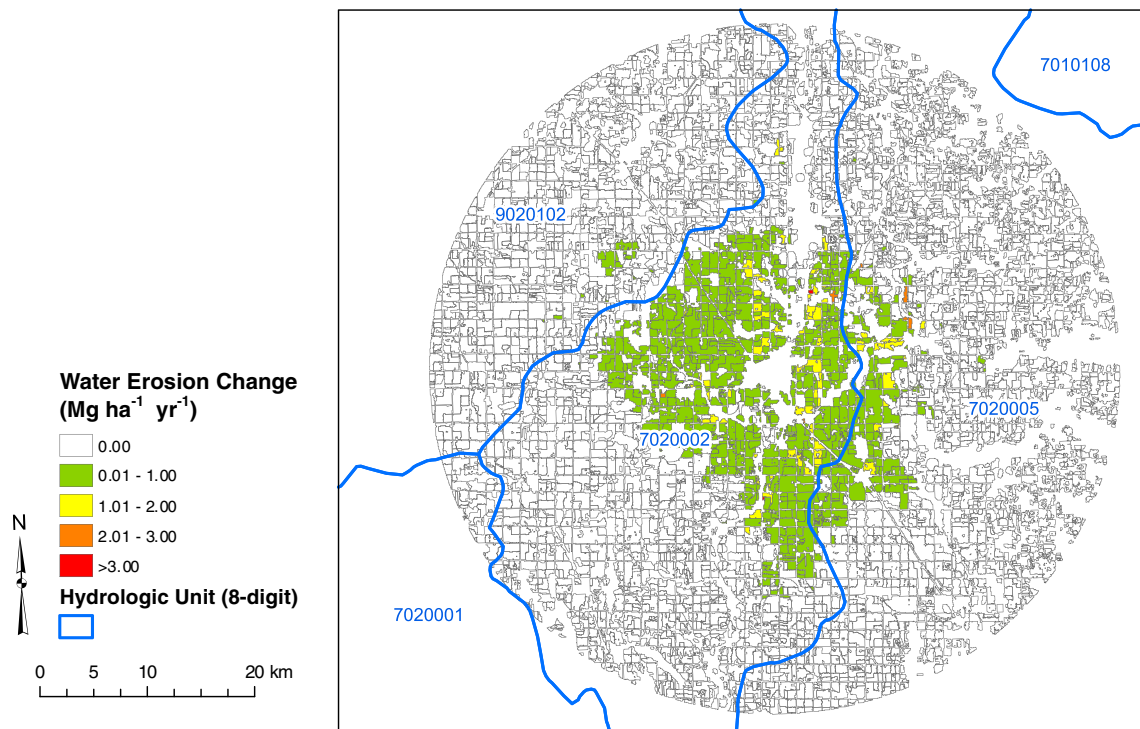


Fig. 8 Map of water erosion change for profit maximizing production practices including opportunities for biomass harvest and sale relative to profit maximizing production practices with no biomass harvest

supplying 100,000 Mg biomass (plant-gate biomass price $\$61.47 \text{ Mg}^{-1}$) by maximizing net returns at the field level and including transportation costs

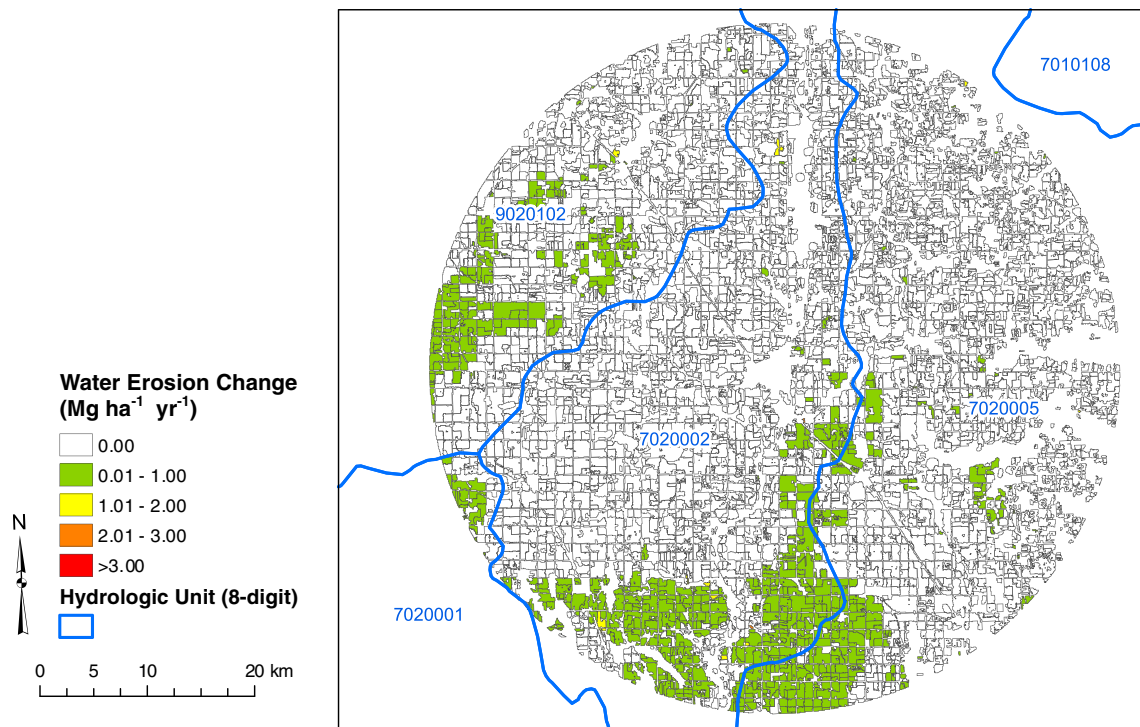


Fig. 9 Map of water erosion change for profit maximizing production practices including opportunities for biomass harvest and sale relative to profit maximizing production practices with no biomass harvest

supplying 100,000 Mg biomass by maximizing profits at the field level excluding transportation costs (in-field biomass price $\$40.14 \text{ Mg}^{-1}$)

Discussion

As a small bioenergy facility, the biomass needs for the UMM gasification plant could be easily met by harvesting crop residues within a 32.2-km radius. Scaling up, for example to meet process heat needs for a 150 million liters per year grain ethanol facility (~100,000 Mg biomass), would increase biomass costs and negative impacts on soil erosion and SOC. Within this range, only a small shift toward CC would be anticipated. Further scale-up, for example as feedstock for a 150 million liters per year cellulosic ethanol facility (~500,000 Mg biomass), would lead to substantially higher biomass costs and increased erosion potential but also could lead to shifts in tillage that decrease impacts on water erosion and SOC. However, at this large scale, significant biomass supplies could come from outside of the 32.2-km radius, which would reduce the price needed to attract sufficient biomass for the facility, reducing the potential for tillage shifts. The spatial location of biomass harvest and resulting environmental impacts are strongly influenced not only by transportation costs but also by spatial variability in production costs as influenced by soil type. Potentially, environmental impacts could be offset by compensatory conservation practices [70]; however, these practices may alter production costs. Quantifying the tradeoffs between costs of these compensatory practices and environmental impacts is an area for future research.

Simulation results indicated productivity impacts of biomass harvest on grain yields were small and short term, provided additional nutrients were applied to account for those removed by biomass harvest. Thus, profitability calculations did not include any cost for long-term productivity losses. The lack of long-term productivity impacts was surprising since the simulations showed a general decline of SOC with biomass removal, and SOC decline has been linked with productivity loss [26, 71], although mixed response to residue removal were reported in a review by Karlen [72]. This identifies a need for research to quantify potential long-term productivity effects of biomass harvest in this region.

For this analysis, cropping practices and biomass harvest were assumed to be driven by profit-maximizing behavior. Inherent in this assumption is that biomass prices had to just exceed breakeven levels for producers to be willing to harvest biomass. There is some evidence that profitability would need to exceed a higher threshold before producers would be willing to harvest biomass and that this threshold may vary across producers [73]. Including a constant profitability threshold would not change our results other than shifting the price relationships upward by the threshold amount. However, including variable profit thresholds across producers would tend to disperse production across the region for a given biomass price, depending on the

preferences of individual producers and their locations. This would tend to counteract the effect of transportation costs in concentrating production near the biomass facility. Other analyses [74] have included a participation rate assumption that is independent of profitability. Assuming participation is uniformly distributed across the region in our example would reduce the amount of biomass supplied at a given price, resulting in a higher cost to obtain a needed supply. Spatially, this would reduce the concentration of biomass production across the region, with fields that would not be used for biomass harvest at any price scattered randomly across the region. A more realistic assumption is likely that participation is a function of profitability as indicated by Altman et al. [73]. There is a need for research to better understand factors influencing adoption of biomass harvest practices so that these factors can be linked to spatially explicit models as presented here.

Biomass supplies, and resulting environmental impacts, were based entirely on crop residues in this analysis. Other biomass sources including woody biomass and perennial grasses such as switchgrass (*Panicum virgatum* L.) could also potentially be produced in the area. Preliminary analysis on one cropland soil showed that the breakeven price for switchgrass was far above the breakeven price for corn stover or wheat straw, similar to what has been observed by others [41]. Thus, a decision was made not to include switchgrass in the analysis, as it was not expected to enter the profit maximizing solution at any of the price levels analyzed. There is, however, the potential that these crops could be profitably produced on areas that are currently not cropped, which would reduce the supplies needed from crop residues.

The analysis also did not include potential impacts of time or labor constraints, which could be particularly important for corn stover harvest in the northern Corn Belt where the harvest window may be limited by cold wet fall conditions. As a result, our model may overestimate available biomass supply, and may underestimate the incentives for wheat straw to be harvested in order to extend the biomass harvest window. It was also assumed for this analysis that producers would bear the costs of biomass harvest, storage, and transport to the biomass facility or that these costs would be reflected in the price offered to individual producers at the farm level. Biomass harvest decisions in the analysis were also based on average production levels and did not include risk and uncertainty. Larson et al. [75] showed that risk and alternative contracting options can have important impacts on the price at which producers would be willing to supply biomass and the types of biomass supplied. However, they did not include spatial aspects of biomass production and resulting environmental effects. Inclusion of time constraints, risk, and contracting options are areas for future research.

This analysis is unique in including effects of biomass price on production practices, biomass production profitability, and the spatial location of these practices at the field level. This ensures that spatial factors such as transportation costs and soil productivity attributes are reflected in biomass supply costs and provides site-specific measures of environmental and economic impacts. Many environmental impacts are sensitive to location (e.g., soil erosion, SOC, wildlife habitat, nutrient and pesticide runoff and leaching), so providing spatial information on potential effects is critical to accurately assessing these impacts. For this analysis, only wind and water erosion, and SOC impacts were included; however, the methodology presented could be used to assess other environmental impacts.

A critical link to assessing environmental impacts is identifying effects of bioenergy demand on agricultural production practices. This analysis demonstrates that agricultural production practices, including tillage and crop rotation, may shift in response to biomass prices, and that regional variation in soil characteristics and transportation costs affect the distribution of production practices across the region.

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