

# Environmental and Economic Trade-Offs in a Watershed When Using Corn Stover for Bioenergy

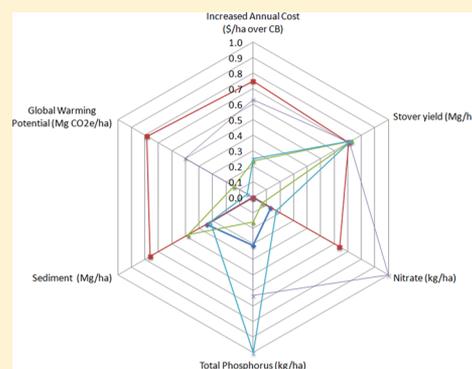
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**S** Supporting Information

**ABSTRACT:** There is an abundant supply of corn stover in the United States that remains after grain is harvested which could be used to produce cellulosic biofuels mandated by the current Renewable Fuel Standard (RFS). This research integrates the Soil Water Assessment Tool (SWAT) watershed model and the DayCent biogeochemical model to investigate water quality and soil greenhouse gas flux that results when corn stover is collected at two different rates from corn–soybean and continuous corn crop rotations with and without tillage. Multiobjective watershed-scale optimizations are performed for individual pollutant-cost minimization criteria based on the economic cost of each cropping practice and (individually) the effect on nitrate, total phosphorus, sediment, or global warming potential. We compare these results with a purely economic optimization that maximizes stover production at the lowest cost without taking environmental impacts into account. We illustrate trade-offs between cost and different environmental performance criteria, assuming that nutrients contained in any stover collected must be replaced. The key finding is that stover collection using the practices modeled results in increased contributions to atmospheric greenhouse gases while reducing nitrate and total phosphorus loading to the watershed relative to the status quo without stover collection. Stover collection increases sediment loading to waterways relative to when no stover is removed for each crop rotation–tillage practice combination considered; no-till in combination with stover collection reduced sediment loading below baseline conditions without stover collection. Our results suggest that additional information is needed about (i) the level of nutrient replacement required to maintain grain yields and (ii) cost-effective management practices capable of reducing soil erosion when crop residues are removed in order to avoid contributions to climate change and water quality impairments as a result of using corn stover to satisfy the RFS.



## INTRODUCTION

The United States has chosen to pursue an energy policy for liquid fuels based on a Renewable Fuels Standard (RFS) that mandates 36 billion gallons of renewable biofuels. The vast majority of total liquid fuel consumption accounted for by biofuels is currently derived from corn grain, referred to as first generation biofuels. The U.S. has a long history of government involvement in the production of ethanol, which has included subsidies for blending grain ethanol with unleaded gasoline and tax incentives for the construction of ethanol plants.<sup>1</sup> The most recent federal energy legislation requires 16 billion gallons of ethanol equivalent fuel per year to be produced from cellulosic feedstocks.<sup>2</sup> The feedstocks most frequently considered when evaluating how best to supply the quantity of biomass required to satisfy the RFS are corn stover (the crop residue—stalks, leaves, and cobs—that remains after corn grain is harvested), fast growing tree species such as willow or hybrid poplar, or perennial grasses.

Corn ethanol has advantages and disadvantages, but there are two predominant reasons why cellulose-derived biofuels and so-called “advanced” biofuels are part of the RFS. First, using corn grain for ethanol takes away from the supply of grain

available for human consumption and livestock feed, while stover collection is not expected to influence food prices or supply. Second, because stover is a byproduct of growing corn grain, there is a sustained supply of the feedstock available that does not require the production of new crops unfamiliar to farmers or bringing additional land into production (up to the limits of the total available supply of stover from cropland anyway). Taken together, these are the principal reasons corn stover has been looked upon favorably in the policy dialogue relative to dedicated bioenergy crops. Like other cellulosic feedstocks, stover will benefit from advances that drive down the cost of converting the energy content in plant cellulose into liquid fuels, and several feedstock logistics and processing hurdles remain before commercial-scale production will be a reality. Additionally, there may still be a large gap between farmers’ cost of supplying stover to a biorefinery and biorefineries’ willingness-to-pay for those feedstocks.<sup>3,4</sup>

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Table 1. Modeling Scenarios and Costs (Attributed to Corn) Per Hectare

scenario abbreviation <sup>a</sup>	crop rotation (year 1–year 2)	tillage <sup>b</sup>	harvest in each scenario	increased annual cost of corn production over baseline <sup>c</sup>	
				\$/ha	\$/Mg stover <sup>d</sup>
CB (baseline)	corn–soybean	yes	grain only (no stover removal)	\$0	no stover removal
CB38	corn–soybean	yes	grain + 38% stover removal	\$61.55	\$13.71
CB52	corn–soybean	yes	grain + 52% stover removal	\$92.76	\$15.06
CC38	continuous corn	yes	grain + 38% stover removal	\$194.70	\$44.63
CC52	continuous corn	yes	grain + 52% stover removal	\$259.47	\$43.24
CBNT38	corn–soybean	none	grain + 38% stover removal	\$64.79	\$14.51
CBNT52	corn–soybean	none	grain + 52% stover removal	\$95.42	\$15.55
CCNT38	continuous corn	none	grain + 38% stover removal	\$163.35	\$37.24
CCNT52	continuous corn	none	grain + 52% stover removal	\$228.13	\$37.78

<sup>a</sup>All scenarios with stover removal include nutrient replacement for nitrogen contained in biomass removed at the rate of 14.6 kg/Mg stover removed/hectare. <sup>b</sup>“Yes” indicates conventional tillage modeled as disking and chisel plow tillage before corn planting and no-till planting of soybeans into corn residue. “None” indicates a no-till system where all crops are continuously planted into residue from the previous crop without any field cultivation. <sup>c</sup>All cost estimates (details in Supporting Information Table S1) are based on the average yield across the entire watershed (see Table 2). There is spatially explicit variation in the cost per hectare and per Mg stover removed given the heterogeneity in yields for different locations. <sup>d</sup>Cost per Mg stover removed are calculated based on the simulated stover yields reported in Table 2 assuming no grain yield response to N replacement.

The literature on environmental and economic aspects of biofuels is quite extensive, especially for grain ethanol. There is a decidedly less encompassing literature that considers the economic and environmental implications of biofuels simultaneously; refs 5 and 6 are notable exceptions. Research that considers greenhouse gases, water quality, and farm-gate economics of cellulosic bioenergy crops together in a single integrated analysis is needed given societal concerns about the overall impact of using agricultural land to grow bioenergy crops.

Recent work focusing on greenhouse gas emissions in life-cycle analysis of corn stover for bioenergy has shed light on the land emissions implications of growing this feedstock<sup>7</sup> and has investigated the role of carbon debt in land use change driven by bioenergy crop production.<sup>8,9</sup> Other work has investigated water quality impacts of corn acreage expansion to meet biofuels mandates.<sup>10</sup> Federal regulations require cellulosic feedstocks to achieve a 60% reduction in greenhouse gas emissions compared to conventional gasoline in order to satisfy the RFS, but there is no parallel requirement to address other environmental effects despite documented potential for impacts to water resources.<sup>11,12</sup> There is a need for integrated analysis of economic and environmental quality considerations to evaluate the trade-offs involved in satisfying the RFS using crop residues even if stover is viewed as a near-term transitional feedstock until advanced biofuels are economically and technically viable.

Biomass production and amount of stover available depends on biophysical characteristics (e.g., slope, soil characteristics) for a given crop management practice. Similarly, amounts of pollutant losses are tightly linked with geophysical characteristics of a field.<sup>13–15</sup> It may be desirable to optimize the amount of stover that can be removed given different social objectives (e.g., maximize stover removal, minimize cost, and/or minimize pollutant losses) to guide watershed management planning. Previous optimization efforts have focused on improving water quality from selection and placement of various conservation practices<sup>16–20</sup> with little information currently available on how bioenergy crop production can be optimized under single and multiple objective functions to evaluate economic and environmental trade-offs.

The objective of this research is to analyze greenhouse gas emissions, water quality, and farm-scale economic costs of different cropping systems capable of supplying corn stover in an agriculture-dominated watershed typical of the Eastern U.S. Cornbelt. Biophysical models of the agro-ecosystem are used together with the cost of production to evaluate alternative scenarios that include corn–soybean and continuous corn crop rotations, two different residue removal rates, and both conventional tillage and no-till production practices. Multiple optimizations are performed using the watershed and soil emissions modeling results to illustrate the economic and environmental trade-offs from alternative ways of supplying crop residues to satisfy the RFS. The results from jointly minimizing individual water pollutants or carbon dioxide equivalent (CO<sub>2</sub>-e) emissions from cropland together with the economic cost of production are compared to jointly minimizing cost and maximizing stover production without taking environmental criteria into account. The paper proceeds by discussing the methods and models that are employed in this analysis, presenting the modeling and optimization results, and concludes with a discussion of the economic, environmental, and policy implications of the alternative corn stover harvesting scenarios studied.

## METHODS: WATERSHED AND GREENHOUSE GAS MODELING

No single model is capable of simulating the water quality and soil greenhouse gas emissions that result from agricultural production at the watershed scale. Two separate models are used together following the framework in ref 20 to integrate greenhouse gas emissions from the field-scale soil biogeochemical model DayCent<sup>21</sup> with crop yield and water quality from the Soil and Water Assessment Tool (SWAT)<sup>22</sup> watershed hydrological model. This framework is applied in the Wildcat Creek Watershed in Indiana to evaluate the economic and environmental sustainability of harvesting crop residue for use as a feedstock for cellulosic biofuels. SWAT has previously been used to model water quantity and quality effects of corn stover removal in the same watershed.<sup>13</sup> Additional details about the SWAT model of the watershed used in this study and hydrological and land-use details about the watershed itself

Table 2. Simulation Results: Average Annual Grain and Stover Yields, Water Pollutants, and Greenhouse Gas Emissions

scenario abbreviation <sup>a</sup>	average stover yield in years when collected, Mg/ha/yr <sup>b</sup>	total harvested biomass with N replacement, Mg/ha <sup>c</sup>	average annual pollutant contribution <sup>d</sup>			
			nitrate, kg/ha	total phosphorus, kg/ha	sediment, Mg/ha	greenhouse gas emissions from cropland, CO <sub>2</sub> -e <sup>e</sup> Mg/ha
CB (baseline)	no stover removal	10.07	8.49	1.83	2.23	5.98
CB38	4.490	14.56	8.38	1.74	2.29	6.25
CBS2	6.16	16.24	8.24	1.73	2.35	6.40
CC <sup>f</sup>	no stover removal	10.15	10.41	1.71	2.27	6.53
CC38	4.363	14.52	9.47	1.65	2.41	7.49
CC52	6.000	16.15	9.16	1.65	2.51	7.90
CBNT <sup>f</sup>	no stover removal	10.04	8.77	2.39	2.13	5.87
CBNT38	4.465	14.50	8.57	2.23	2.22	6.06
CBNT52	6.136	16.17	8.45	2.19	2.28	6.23
CCNT <sup>f</sup>	no stover removal	10.12	11.32	2.41	2.02	6.22
CCNT38	4.387	14.51	10.16	2.02	2.08	6.94
CCNT52	6.038	16.16	9.76	1.90	2.14	7.28

<sup>a</sup>See Table 1 for scenario details. <sup>b</sup>Assumes that N replacement maintains grain yields at level without stover collection for a given crop rotation and tillage. <sup>c</sup>Total harvested aboveground biomass reported equals grain yield plus stover removed for a given removal rate. <sup>d</sup>Average of 15 year simulations of each practice in SWAT based on uniform adoption in watershed. <sup>e</sup>CO<sub>2</sub>-equivalent emissions equal to the total global warming potential contribution from CO<sub>2</sub> and N<sub>2</sub>O simulated in DayCent. <sup>f</sup>Not included in optimization because no stover removal; presented here for informational purposes only.

can be found in ref 13. While the specific watershed and soils considered in this study are representative of the region, and thus the yields and pollutant effects of stover removal are deemed generalizable to similar watersheds, the optimization results reported are necessarily watershed-specific and do not necessarily carry over to similar watersheds.

The details of both simulation models used are kept to a minimum because they are well-documented elsewhere in the peer-reviewed scientific literature.<sup>13,20</sup> Emphasis is placed on stover removal, the simulated water quality and soil greenhouse gas emissions associated with different cropping practices, and the economic and environmental outcomes from harvesting corn stover as a feedstock for cellulosic biofuels.

The modeling baseline for comparison with stover collection scenarios is the predominant corn–soybean rotation in the watershed today, where soybeans are no-tilled into corn residue and conventional tillage is used following soybeans prior to planting corn in alternating years. Alternative rotations include conventionally tilled and no-till continuous corn systems. Two different stover removal rates (38% and 52%) are modeled in DayCent and SWAT for each crop rotation and tillage practice listed in Table 1. These rates are based on the least-cost technically feasible means of stover collection using conventional corn and forage harvesting equipment in ref 23. One fundamental distinction between all scenarios that involve a corn–soybean rotation and those that consider continuous corn is that for any two years there are two stover harvests from the same field under continuous corn but only one stover crop under a corn–soybean rotation. This means that the annual average stover yield over all years will necessarily be less for all land where a corn–soybean rotation is in place compared to continuous corn, because every other year stover yield is zero in a two crop rotation.

SWAT model output for each individual land unit ( $n = 922$ ) in the watershed consists of corn stover yield, nitrate (NO<sub>3</sub>) yield, total phosphorus (TP) yield, and the contribution of total suspended solids (“sediment”) from each cropping system scenario, where the units of each nonpoint source pollutant reflect the annual average total contribution to the watershed

from each land unit. DayCent model output is the change in soil organic carbon (SOC), which reflects additional carbon sequestration or loss of soil organic carbon, plus nitrogen loss as N<sub>2</sub>O, both quantified in units of total CO<sub>2</sub>-e emissions for each scenario. The economic cost in Table 1 is assumed to be constant per unit of land area in the watershed and is calculated for each cropping scenario as the increased annual cost attributed to corn production relative to the baseline cropping system. Cost calculations are based on the individual practice budgets contained in Table S1 of the Supporting Information (SI).

## MODELING RESULTS

The simulation results from both models are summarized in Table 2 in terms of total harvested aboveground biomass (grain + stover), stover yield, and water and greenhouse gas pollutant contributions, reported as the annual average from a 15-year simulation for the years 1995–2009. The reported stover yields assume that the N replacement rate maintains grain yield in stover removal scenarios equivalent to the no stover removal scenario (CB, CC, CBNT, CCNT) level for each rotation–tillage combination, as this was the basis for including N replacement in the study. The simulated biomass yields from SWAT reveal higher stover yields when corn is grown in rotation with soybeans (CB) than when grown continuously (CC).

Stover harvest increases the cost of any crop rotation relative to when no stover collection occurs because of the additional cost of nutrient replacement and stover collection, storage, and average transportation (Table S1 in SI). Stover collection from the CB rotation has a lower cost relative to the CC rotation because all costs are reported as the increased annual cost relative to a baseline of corn–soybean grown without stover harvest. Optimization results reported below reflect this, with stover collection from a CB rotation always maximizing stover while minimizing cost in individual years when stover is harvested. Close inspection of Table 2 reveals that the reported stover yields (column 2) represent a greater percentage of the aboveground harvested biomass (column 3) for the “no stover

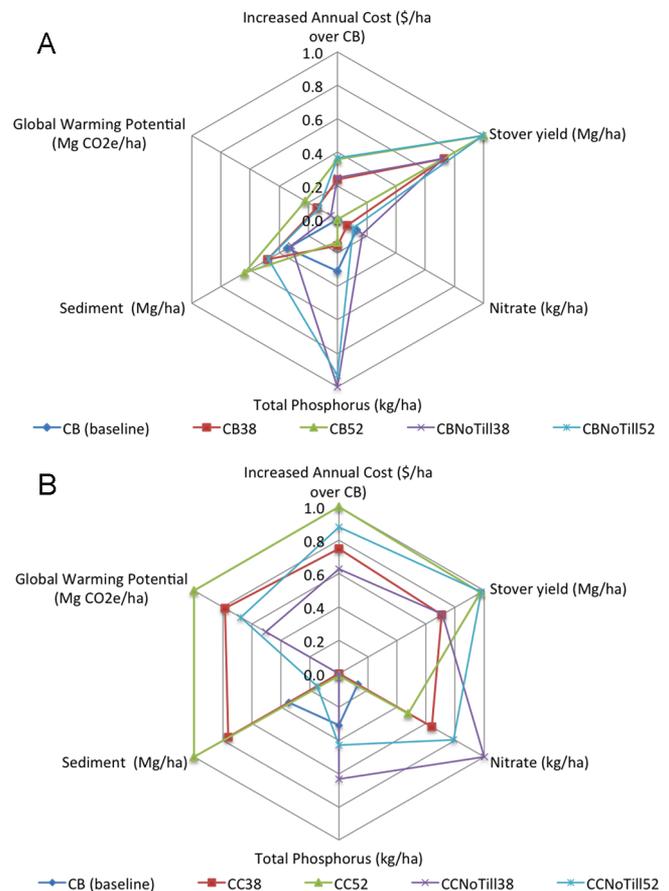
removal” scenario for each rotation–tillage combination than the simulated 38% and 52% removal rates. This suggests that there is in fact grain yield response, and thus stover yield response. This is likely a result of nutrient replacement in our simulations, amounts for which are based on ref 23. These results strongly suggest that the modeled level of nutrient replacement is higher than is required to maintain grain yields. This result is consistent with recent findings from the agronomy literature that stover collection without any nutrient replacement has a positive effect on yield in the short term.<sup>24,25</sup> The net effect of lower or no N replacement would be lower total cost per hectare for all scenarios (Table S1); greenhouse gas emissions are also expected to be lower because of lower N fertilizer applied.

A switch to continuous no-till (NT) results in slightly lower biomass yield relative to the same stover removal rate in a CB rotation under conventional tillage. In contrast to refs 24 and 25, there is a slight increase in stover yield in no-till CC scenarios compared to the same removal rate under conventional tillage. For a given crop rotation and removal rate, NT results in lower GHG emissions from agricultural land, such that CB[CC] scenarios have higher GHG emissions than CBNT[CCNT] scenarios. Comparing the results for the no stover removal scenarios (CB, CC, CBNT, CCNT) also suggests that if continuous corn replaces corn–soybean rotation, the result is expected to be higher nitrate loading to waterways and increased contribution to global warming potential from agricultural soils. Thus, even in the absence of corn stover collection for cellulosic biofuels, increased demand for grain for food, feed, or grain-derived ethanol that triggers supply response, would result in an increase in these pollutants from agricultural lands.

For a given rotation–tillage combination, the contribution to total global warming potential (GWP) is strictly increasing in the stover removal rate. This is a result of reduced soil carbon when residue is no longer incorporated into the soil and higher N fertilizer application rates compared to when stover is not collected. There is reduced  $N_2O$  flux from decomposition of residue in farm fields when stover is collected relative to a no collection baseline. This reduction in trace gas flux from residue decomposition is more than offset by the increased  $N_2O$  emissions from additional N fertilizer required by CC cropping systems relative to the CB baseline without stover removal.

The relationship between stover removal and losses of nonpoint source pollutants to receiving waters is mixed across the three pollutants considered. As discussed in detail in refs 13 and 14, nitrate is decreasing (except following fertilizer application, see 13 for details), total P is decreasing and sediment is increasing in the removal rate for a given crop rotation–tillage practice combination.

The costs of each stover harvest cropping system and the GHG and water quality modeling results from Tables 1 and 2 are presented graphically in Figure 1. The radar plots facilitate direct comparison of individual scenarios: each line connecting the axes is a single scenario, with each axis (measuring cost, yield, or a pollutant) showing the relative magnitude of a given environmental or economic metric for all scenarios. The values in each panel are the indexed (0 = lowest, 1 = highest) watershed average per hectare for each metric, including the baseline with no stover collection for reference, and are divided into two panels for the two crop rotations. As can be seen in Figure 1b, the levels of nitrate,  $CO_2$ -e, and additional cost above the baseline are uniformly higher for continuous corn



**Figure 1.** Comparison of environmental and economic performance metrics from watershed and greenhouse modeling: (a) corn–soybean rotation stover removal relative to the no removal baseline, (b) continuous corn stover removal relative to the no removal baseline. All metrics are reported as an index value between 0 (lowest) and 1 (highest) over all nine unique cropping systems in both panels. Underlying values are reported in Tables 1 and 2.

than for corn–soybean rotations. Differences in the indexed level of sediment and total P seem to be driven by tillage more so than crop rotation, with the relative levels overlapping across the two panels.

## ■ OPTIMIZATION FRAMEWORK

The raw simulation results compared in Figure 1 are the average per hectare stover and pollutant yields calculated from simulating a given cropping system on all the cropland in the watershed. Different combinations of cropping systems implemented in different locations throughout the watershed will necessarily lead to different aggregate stover yields, pollutant flows from agricultural land, and cost of producing stover. DayCent and SWAT simulation results must be taken into account together to determine different spatial allocations of cropping practices that satisfy social objectives of either minimizing the cost of supplying biomass or minimizing the level of a given pollutant at the lowest possible cost. A mathematical structure for evaluating stover production, pollutants, and costs is needed to enable optimization to achieve different social objectives. The multiobjective optimization tool (MOBOT)<sup>15</sup> is adapted to evaluate GHGs, water pollutants, stover yield, and economic cost across the Wildcat Creek Watershed. The MOBOT applies a multiobjective

genetic algorithm (NSGA-II) to search through the combined simulation results, evaluating combinations of individual management practices across the entire watershed in a spatially explicit manner that takes into account the cost of implementation along with either pollutant load or stover yield based on the specified objective function. The result of an individual multiobjective optimization is a frontier of points that demonstrate the trade-off between cost per hectare and pollution or stover yield per hectare that is achievable for different allocations of practices across the watershed; each point on the frontier that results represents a unique allocation of practices over the 922 land units in the watershed. There is not a single “best” solution because our problem is unconstrained and attempts to jointly optimize two objectives.

A multiobjective approach is necessary in order to evaluate economic costs together with either pollutant loading or stover yields. Maximizing harvest of cellulosic biomass, minimizing cost alone, or minimizing a pollutant of concern without taking other societal objectives into account will lead to decisions based on incomplete information. The current study demonstrates an integrated approach that can be used to evaluate different, oftentimes competing, societal objectives that frequently arise in considering environmental and energy policies such as the RFS. An important consideration for policymakers that is outside the scope of the current study is taking into account what stover harvest and environmental outcomes will result from decentralized private decisions made on individual farms and how policy mechanisms might be used to align private incentives with public policy objectives to increase social welfare.

Denote each cropping practice (8 scenarios with 38% and 52% stover removal) in Table 1 by  $\gamma_k$  where  $\Gamma = \{\gamma_1, \gamma_2, \dots, \gamma_8\}$  and the area of each land unit  $i$  in the watershed by  $x_i$  where  $\mathbf{X} = \{x_1, x_2, \dots, x_{922}\}$  is a vector containing the size data for all of the individual land units in the watershed. The watershed-average per hectare pollutant load or feedstock yield for each of the four pollutants and the feedstock can then be written as

$$f^j(\Gamma, \mathbf{X}) = \frac{\sum_i P_j(\gamma_{ki})x_i}{\sum_i x_i} \text{ for any } j \in \{\text{NO}_3, \text{TP, TSS, GWP, } (-\text{Stover})\} \quad (1)$$

where  $P_j(\gamma_{ki})$  represents the load of a pollutant or supply of feedstock  $j$  per hectare produced from practice  $\gamma_k$  implemented on land unit  $i$  and is a function of the underlying hydrological and soil characteristics. The values for stover yield and each nonpoint source water pollutant come from the SWAT simulations and the values for GWP come from the DayCent simulation results. Because the optimization that follows is formulated as a minimization problem and we are interested in either jointly minimizing cost and pollution yield or minimizing cost while simultaneously maximizing the amount of stover collected, stover enters eq 1 as a negative value. The baseline pollutant loading rate for optimization on all land units is  $P_j(\gamma_0) \forall j$ , where  $\gamma_0$  denotes the corn–soybean rotation with no stover collection.

The per-hectare costs of  $\Gamma$  are in Table 1, and all land units have different areas in hectares. Hence the cost of implementing each practice on each field is a function of the area of that field. The net additional cost per hectare of implementing  $\gamma_k$  on land unit  $i$  relative to the baseline corn–soybean rotation with no stover collection is denoted  $C(\gamma_{ki}) \forall k$

$\neq 0$  and the watershed average cost per hectare of crop production is

$$g(\Gamma, \mathbf{X}) = \frac{\sum_i C(\gamma_{ki})x_i}{\sum_i x_i} \quad (2)$$

All optimizations presented in this analysis seek to jointly minimize eqs 1 and 2, either by minimizing cost together with an individual pollutant,  $j \in \{\text{NO}_3, \text{TP, TSS, GWP}\}$  in eq 1, or by maximizing the stover yield,  $j = \{-\text{Stover}\}$  in eq 1, at the lowest possible cost. All optimizations are conducted based on the average per hectare cost and pollutant load or crop yield of a given arrangement of cropping practices across the entire watershed according to the general objective function

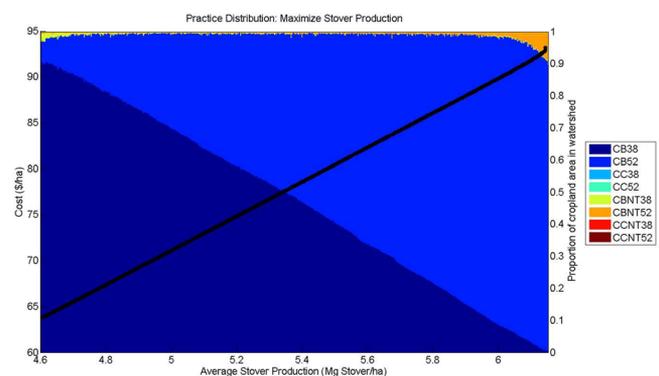
$$\min_{\gamma_{ki}} \{f^j(\Gamma, \mathbf{X}) \wedge g(\Gamma, \mathbf{X})\} \text{ given } j \in \{\text{NO}_3, \text{TP, TSS, GWP, } (-\text{Stover})\} \quad (3)$$

This structure for the objective function is adapted from ref 16 to allow greenhouse gas emissions and stover production to be considered together with water quality and the additional production costs relative to a baseline without stover collection.

### ■ OPTIMIZATION RESULTS

Five individual optimizations are run based on joint minimization of cost per hectare and pollutant yield per hectare for each of the four pollutants, and a joint minimization of cost and maximization of stover collected per hectare. In all optimizations, the choices are constrained to choose one of the eight stover removal practices instead of the baseline rotation without stover collection. The focus of the discussion of results is largely around the relationship between stover collection and cost and environmental metrics because the applied focus of this research is around cellulosic biofuels development. There are of course other insights possible from this modeling and optimization framework when considering reactive N flows in the environment or ecosystem service flows from agricultural watersheds under biofuels development.

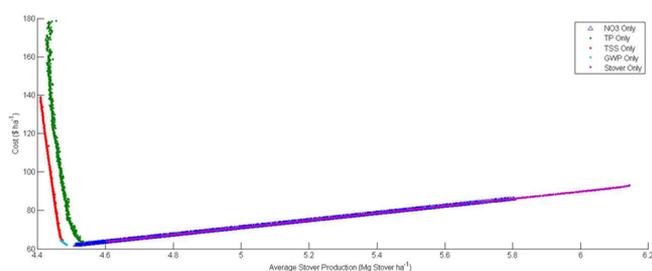
When stover collection is maximized at the lowest possible cost, the trade-off frontier that results from the optimization is depicted in Figure 2. The four practices with the lowest cost per hectare and highest stover yield per hectare are visible in Figure 2, but only two of these practices are selected for more than 10% of the watershed over the entire length of the trade-off frontier. The low and high levels of stover removal from a



**Figure 2.** Stover–Cost trade-off frontier and watershed distribution of cropping practices from joint maximization of stover and minimization of cost.

conventionally tilled corn–soybean rotation are the two predominant practices, with small shares of the watershed devoted to no-till management of the same rotations and removal rates at the lowest and highest cost ends of the frontier, respectively. It is important to keep in mind that the values reported in Tables 1 and 2 and Figure 1 are watershed wide averages for individual cropping practices and that the trade-off frontier in Figure 2 reflects spatially explicit deployment of different combinations of practices across the watershed. The right vertical axis denotes the proportion of the cropland in the watershed allocated to each practice at a given point on the trade-off frontier. For stover maximization at minimum cost, the frontier reflects a larger share of the total cropland available being managed as a conventional till corn–soybean rotation at the higher removal rate to achieve higher average stover yield per hectare. At the highest average cost and stover yield per hectare points on the frontier, no-till corn–soybean at the high removal rate displaces lower cost per hectare (and per Mg stover) practices to optimize stover yield and cost. For comparison of our multiobjective optimization with more standard approaches, each point on the cost–stover trade-off frontier (Figure 2) would correspond to the solution of a standard single objective cost minimization problem subject to a constraint equal to the stover yield (either yield/ha in Figure 2 or the associated total yield for the watershed) at that point on the frontier derived.

Optimizations were also conducted to jointly minimize cost per hectare and each individual pollutant in order to determine whether different optimization criteria lead to similar or divergent cost and environmental outcomes compared to stover maximization. Figure 3 plots the points along the cost



**Figure 3.** Relationship between stover production and practice cost per hectare for all multiobjective optimizations. Individual pollutant trade-off frontiers in SI Figures S1–S4 and relationship between cost and individual pollutants in Figure 4.

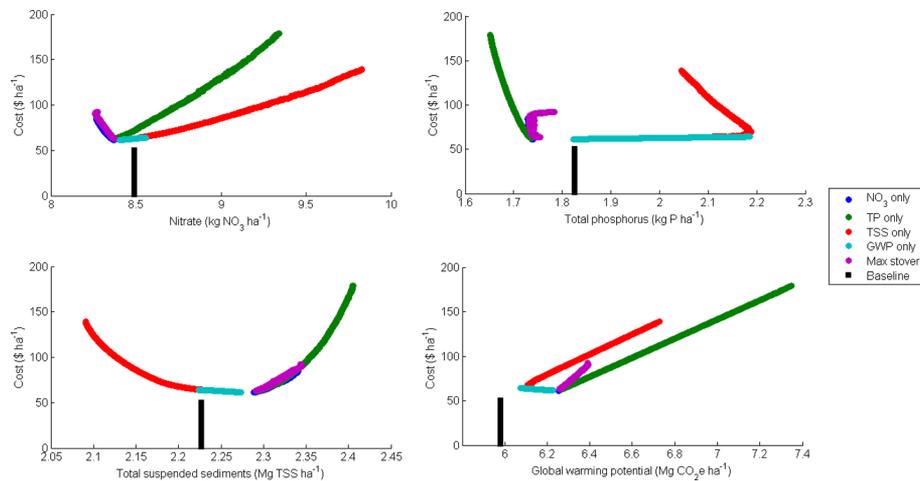
trade-off frontier that result from each of these individual optimizations (SI Figures S1–S4) together with the stover trade-off frontier from Figure 2 to illustrate the relationship between average stover production in the watershed and cost per hectare of the practices selected based on environmental and cost criteria without taking stover production into account. Figure 3 reveals that the nitrate minimization frontier overlaps heavily with the stover maximization frontier, reflecting the relationship between nitrate and stover removal for a given rotation–tillage combination in Table 2. This is in stark contrast to the relationship between stover production and the other pollutant curves in Figure 3. The range of levels of stover production spanned by the curves that plot the cost minimizing levels of TP, sediment and GWP is very small, though TP and sediment minimizing practices cover a very wide range of costs, from \$63 to \$178 per hectare to control these pollutants at

different levels, as depicted in Figure 4 and the SI. Because each point on a trade-off frontier is a distribution of practices on all cropland across the entire watershed, these values are an area-weighted average cost per hectare of the combination of practices chosen by the genetic algorithm for a given optimization.

Optimization of stover yield and cost does not take into account the pollution that results from supplying stover in the watershed. The relationship between cost per hectare and the pollution metrics considered can be seen in Figure 4, which combines the results of all of the individual optimizations depicted in Figures 2 and S1–S4 into a single figure for intercomparison. Each panel of Figure 4 displays the information in the same format as Figure 3, but plots cost per hectare against each pollutant modeled. By examining the stover maximization frontier in each panel of Figure 4 it can be seen that, as cost per hectare increases, maximizing stover collected at minimum cost results in increasing levels of soil erosion and GWP, decreasing levels of nitrate and lower than baseline levels of TP per hectare. This can also be seen in the individual panels of Figure S5. Increased soil GHG flux over the baseline level occurs when any stover is collected because additional fertilizer is applied to replace nutrients removed with stover and the resulting contribution to GWP is greater per hectare than the baseline. Switching to no-till can reduce annual contribution to GWP from stover collection cropping systems, achieving lower GHG emissions per hectare at 52% removal than 38% removal under conventional tillage despite higher fertilizer usage (see Table 2). A more general finding is that no matter which optimization criterion is applied, the result will be an increase in the average GHG flux per hectare from agricultural soils when stover is collected using the practices modeled (Figure 4d). Nitrate and TP contribution to the watershed, however, are lower than in the baseline over the entire stover maximization frontier.

Notice that the southwesterly most frontier in each individual panel of Figure 4 is the frontier that results from joint minimization of cost and the pollutant measured by the horizontal axis in each panel. Intuitively this should make sense because, of the five frontiers depicted in each panel of Figure 4, only one frontier is the result of minimizing the pollutant that is the focus of each panel. The other 4 frontiers in each panel depict the coincidental levels of the pollutant that result from minimizing another pollutant (or maximizing stover collection) together with cost. Thus, the stover maximization frontier is not the southwesterly most frontier in any panel of Figure 4. The individual trade-off frontiers (similar to Figure 2) that result from each individual optimization of cost and a pollutant are depicted in Figures S1–S4.

Examining all the frontiers across the panels in Figure 4 reveals some trends in the different optimization results. Two trends that stand out in Figure 4 are that the nitrate and stover curves in each panel are always together and that the GWP and nitrate curves go in opposite directions (as cost increases) in all panels. Minimization of nitrate or maximization of stover both result in lower than baseline levels of nitrate and TP runoff in the watershed, and greater than baseline levels of sediment and GWP. This suggests that even if stover production were the sole criterion (together with cost) used to optimize placement of the cropping systems considered there is likely to be an improvement in nitrate and TP in surface water relative to the status quo. If erosion (TSS) is the focus of optimization, our results suggest that implementation of any allocation of



**Figure 4.** Combined trade-off frontiers for all multiobjective optimizations and pollutants. Vertical baseline indicates the level of the pollutant in the baseline scenario without stover removal.

practices along the cost–TSS trade-off frontier will result in higher than baseline contributions of  $\text{NO}_3$ , TP, and GWP from cropland to the environment.

Optimization solely on the basis of climate change mitigation is expected to result in increased levels of sediment, TP, and GWP relative to a no stover collection baseline, but there is a range of points along the GWP minimization frontier (Figure 4a) that result in lower than baseline levels of nitrate. It is important to note that about half of the length of the GWP curve in panel (a) results in increased average nitrate runoff, so care must be taken in balancing nitrate and GWP pollution concerns when stover is collected as a bioenergy feedstock. Furthermore, the points along the GWP curve in panel (a) that are below the baseline nitrate level correspond to the highest average contribution to climate change along the GWP curve in panel (d); this can be seen by noting where the cost per hectare along the GWP curve is equal in both panels.

## DISCUSSION

Corn stover is an attractive feedstock to help the United States achieve the current RFS in the near-term because of the already abundant supply of crop residue available. However, little research has considered the joint environmental and economic implications of stover collection in helping to meet this goal. This work employs an integrated optimization framework to examine the environmental and economic trade-offs that result from stover collection in an agricultural watershed typical of the Eastern U.S. Cornbelt. The framework combines outputs from a SWAT hydrological model and the DayCent greenhouse gas emissions model with farm-scale economic production costs. A genetic algorithm is used to optimize the spatial allocation of different stover collection practices throughout the watershed either by jointly minimizing production cost and pollutant loads, or by minimizing cost and maximizing stover production without consideration for any environmental criteria.

Results from the joint optimization of stover collection and cost demonstrate a fundamental trade-off between stover collection and environmental quality. By maximizing stover production, it was shown that, while loss of nitrate (Figure 4a) and phosphorus (Figure 4b) to surface waters is reduced to below-baseline levels, sediment loss (Figure 4c) and greenhouse gas emissions (Figure 4d) increase with stover collection. Indeed, increases in greenhouse gas emissions from agricultural

land occur regardless of the amount of stover collected for the eight cropping systems investigated. These results do not mean that these are the necessary outcomes of stover collection; emissions to the atmosphere and water pollutant loading that result from stover collection might be mitigated if lower N fertilizer replacement rates or management practices like leguminous cover crops can be integrated with stover collection. While other environmental outcomes are possible, we find that the practices most frequently proposed for stover removal in bioenergy cropping systems will increase GHG emissions from agricultural fields and soil erosion.

The water pollution–GHG relationships identified in this research have significant implications for the sustainability of using corn stover to help meet the RFS. While the reduction of greenhouse gas emissions is the only stated environmental requirement of the RFS, the use of corn stover as a short-term transition technology has the effect of helping to improve water quality by reducing nutrient losses to surface waters. Whether corn stover is capable of satisfying the greenhouse gas reduction requirement will require analysis of the entire life cycle of emissions from producing a gallon of cellulosic biofuels using corn stover.<sup>26,27</sup> A full life-cycle analysis is outside the scope of this research.

This analysis serves as a first attempt at investigating the joint environmental and economic consequences of stover collection in agricultural watersheds. We investigated different spatial deployments of corn stover removal practices at the watershed scale based on economic and environmental optimization criteria. Adopting a purely economic strategy that maximizes stover collection at the lowest possible cost is found to increase greenhouse gas emissions from cropland and sediment loading rates in streams while lowering nutrient loading rates from nitrate and phosphorus. Minimizing cost together with the loading or emissions rate of a particular pollutant generates a frontier revealing the trade-off between cost and the rate of emissions or water pollution loading per hectare of farmland that results from stover collection. This analysis informs research priorities (i.e., the optimal level of N replacement), and environmental and energy policy discussions going forward. Additional research is necessary to understand alternative ways that stover collection cropping systems can be managed to mitigate GHG flux from agricultural soils and soil erosion while realizing the benefits from nutrient loading

reductions that coincide with cost-minimizing stover collection found in this study.

## ■ ASSOCIATED CONTENT

### 📄 Supporting Information

Partial budgets used for the cost of each cropping system, farm management details of each scenario modeled, and additional supporting figures referenced in the text. This information is available free of charge via the Internet at <http://pubs.acs.org>.

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### Notes

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## ■ REFERENCES

- (1) Tyner, W. E. The US Ethanol and Biofuels Boom: Its Origins, Current Status, and Future Prospects. *BioScience* **2008**, *58* (7), 646–653.
- (2) *Energy Independence and Security Act of 2007*. Public Law 110-140, H.R. 6, 2007.
- (3) Rosburg, A.; Miranowski, J. An Economic Evaluation of US Biofuel Expansion Using the Breakeven Program with GHG Accounting. *AgBioForum* **2011**, *14* (3), 111–119.
- (4) National Research Council, Committee on Economic and Environmental Impacts of Increasing Biofuels Production. *Renewable Fuel Standard: Potential Economic and Environmental Effects of U.S. Biofuel Policy*; The National Academies Press, 2011.
- (5) Hill, J.; Polasky, S.; Nelson, E.; Tilman, D.; Huo, H.; Ludwig, L.; Neumann, J.; Zheng, H.; Bonta, D. Climate change and health costs of air emissions from biofuels and gasoline. *Proc. Natl. Acad. Sci.* **2009**, *106* (6), 2077.
- (6) Searchinger, T.; Heimlich, R.; Houghton, R.; Dong, F.; Elobeid, A.; Fabiosa, J.; Tokgoz, S.; Hayes, D.; Yu, T. Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* **2008**, *319* (5867), 1238–1240.
- (7) Kim, S.; Dale, B. E. Effects of nitrogen fertilizer application on greenhouse gas emissions and economics of corn production. *Environ. Sci. Technol.* **2008**, *42* (16), 6028–6033.
- (8) Kim, H.; Kim, S.; Dale, B. E. Biofuels Land Use Change, and Greenhouse Gas Emissions: Some Unexplored Variables. *Environ. Sci. Technol.* **2009**, *43* (3), 961–967.
- (9) Fargione, J.; Hill, J.; Tilman, D.; Polasky, S.; Hawthorne, P. Land Clearing and the Biofuel Carbon Debt. *Science* **2008**, *319* (5867), 1235–1238.
- (10) Secchi, S.; Gassman, P. W.; Jha, M.; Kurkalova, L.; Kling, C. L. Potential water quality changes due to corn expansion in the Upper Mississippi River Basin. *Ecol. Appl.* **2010**, *21* (4), 1068–1084.
- (11) Tilman, D.; Socolow, R.; Foley, J.; Hill, J.; Larson, E.; Lynd, L.; Pacala, S.; Reilly, J.; Searchinger, T.; Somerville, C.; Williams, R. Beneficial Biofuels-The Food, Energy, and Environment Trilemma. *Science* **2009**, *325* (5938), 270–271.
- (12) Simpson, T. W.; Sharpley, A. N.; Howarth, R. W.; Paerl, H. W.; Mankin, K. R. The New Gold Rush: Fueling Ethanol Production while Protecting Water Quality. *J. Environ. Qual.* **2008**, *37* (2), 318–324.
- (13) Cibir, R.; Chaubey, I.; Engel, B. Watershed scale impacts of corn stover removal for biofuel on hydrology and water quality. *Hydrol. Proc.* **2011**, *26* (11), 1629–1641.
- (14) Thomas, M. A.; Engel, B. E.; Chaubey, I. Water quality impacts of corn production to meet biofuel demands. *J. Environ. Eng.* **2009**, *135* (11), 1123–1135.
- (15) Maringanti, C.; Chaubey, I.; Popp, J. Development of a multiobjective optimization tool for the selection and placement of best management practices for nonpoint source pollution control. *Water Resour. Res.* **2009**, *45*.
- (16) Maringanti, C.; Chaubey, I.; Arabi, M.; Engel, B. Application of a multi-objective optimization method to provide least cost alternatives for NPS pollution control. *Environ. Manage.* **2011**, *48* (3), 448–461.
- (17) Rodriguez, H. G.; Popp, J.; Maringanti, C.; Chaubey, I. Selection and placement of best management practices used to reduce water quality degradation in Lincoln Lake Watershed. *Water Resour. Res.* **2011**, *47*.
- (18) Veith, T. L.; Wolfe, M. L.; Heatwole, C. D. Optimization Procedure for Cost Effective BMP Placement at a Watershed Scale. *J. Am. Water Resour. Assoc.* **2003**, *39* (6), 1331–1343.
- (19) Rabotyagov, S.; Campbell, T.; Jha, M.; Gassman, P. W.; Arnold, J.; Kurkalova, L.; Secchi, S.; Feng, H.; Kling, C. L. Least-cost control of agricultural nutrient contributions to the Gulf of Mexico hypoxic zone. *Ecol. Appl.* **2009**, *20* (6), 1542–1555.
- (20) Reeling, C. J.; Gramig, B. M. A novel framework for analysis of cross-media environmental effects from agricultural conservation practices. *Agric. Ecosyst. Environ.* **2012**, *146* (1), 44–51.
- (21) Natural Resource Ecology Laboratory (NREL). *DAYCENT, 4.5*; Colorado State University: Fort Collins, CO.
- (22) Arnold, J. G.; Srinivasan, R.; Muttiah, R. S.; Williams, J. R. Large area hydrologic modeling assessment: part I. Model development. *J. Am. Water Resour. Assoc.* **1998**, *34* (1), 73–89.
- (23) Brechbill, S. C.; Tyner, W. E.; Ileeji, K. E. The Economics of Biomass Collection and Transportation and Its Supply to Indiana Cellulosic and Electric Utility Facilities. *Bioenergy Res.* **2011**, *4* (2), 141–152.
- (24) Coulter, J. A. Continuous Corn Response to Residue Management and Nitrogen Fertilization. *Agron. J.* **2008**, *100* (6), 1774–1780.
- (25) Coulter, J. A.; Lamb, J.; Sindelar, A.; Vetsch, J.; Quiring, S. *Tillage, Residue, and Nitrogen Management in High-Yield Continuous Corn for Grain, Ethanol, and Soil Carbon*. [http://sroc.cfans.umn.edu/prod/groups/cfans/@pub/@cfans/@sroc/@research/documents/article/cfans\\_article\\_315245.pdf](http://sroc.cfans.umn.edu/prod/groups/cfans/@pub/@cfans/@sroc/@research/documents/article/cfans_article_315245.pdf) (April 1, 2012).
- (26) Kim, S.; Dale, B. E.; Jenkins, R. Life cycle assessment of corn grain and corn stover in the United States. *Int. J. Life Cycle Assess.* **2009**, *14* (2), 160–174.
- (27) Sheehan, J.; Aden, A.; Paustian, K.; Killian, K.; Brenner, J.; Walsh, M.; Nelson, R. Energy and environmental aspects of using corn stover for fuel ethanol. *J. Ind. Ecol.* **2003**, *7* (3), 117–146.