Effects of site-specific factors on corn stover removal thresholds and subsequent environmental impacts in the Upper Mississippi River Basin

M.N. Meki, J.P. Marcos, J.D. Atwood, L.M. Norfleet, E.M. Steglich, J.R. Williams, and T.J. Gerik

Abstract: Corn (Zea mays L.) stover removal thresholds are subject to many site-specific factors. Current data do not provide practical stover removal guidelines for given site-specific conditions. We used the Agricultural Policy Environmental Extender (APEX) model to assess the effects of site-specific factors and corn stover removal from 3,703 farm fields within the Upper Mississippi River Basin (UMRB). From among the many management and resource attribute factors across these farm fields, we chose the site-specific factors of two land types (highly erodible land [HEL] and non-HEL), three soil textures (clayey, loamy, and sandy), four hydrologic groups (A, B, C, and D), and two management scenarios (Baseline and Enhanced Conservation Treatment) to characterize the variability of stover production potential. The Baseline management reflects farmer management practices reported in the Conservation Effects Assessment Project National Cropland Assessment database, while the Enhanced Conservation Treatment reflects additional conservation practices and management scenarios needed to mitigate sediment, nutrient, and soil organic carbon (SOC) losses. For evaluation purposes, we used the Conservation Effects Assessment Project NationalCropland Assessment “acceptable planning criteria” but with more stringent SOC criteria, which does not allow stover removal on sites that lose SOC. Overall, grain and stover yields and N and P losses decreased, while sediment and SOC losses increased with increasing stover removal. On average, Baseline stover yields on HEL were slightly lower than on non-HEL, while yields were higher on loamy, followed by clayey, and then sandy soils. Hydrologic group D soils had the highest Baseline stover yields, followed by those in group B, then group C, and then group A with the lowest yields. The Enhanced Conservation Treatment management drastically mitigated sediment and nutrient losses by 69% and 57%, respectively. Differential impacts of stover removal were most pronounced among the soil textural classes, followed by soil hydrologic groups, and then land type. Overall, the findings of this research underscore the importance of site-specific factors in determining corn stover removal thresholds. For the Upper Mississippi River Basin and for sites meeting the “acceptable planning criteria,” sufficiently “safe” corn stover removals are possible such that only a portion of the available corn acreage would be required to produce enough ethanol to exceed the National 2012 Energy Independence and Security Act goal. However, we do not evaluate issues associated with ethanol plant economic feasibility, such as spatial concentration of stover production.

Key words: baseline—corn stover—hydrologic group—site-specific factors—soil texture

Because of the many positive attributes that crop residues provide, specific guidelines for stover harvest need to be developed to prevent soil degradation (Andrews 2006; Blanco-Canqui and Lal 2009a). Research literature strongly confirms that systematic stover removal decreases soil organic carbon (SOC); reduces soil microbial activity; increases soil susceptibility to compaction, runoff, and soil erosion; and reduces nutrient pools, water retention, soil fertility, and hence soil productivity and crop yield (Wilhelm et al. 2004; Andrews 2006; Blanco-Canqui and Lal 2009a). In some situations, removing the stover has the positive impact of reducing the pool of nutrients available for loss with water movement.

Recent estimates of sustainable corn stover removal thresholds—30% to 50% (Kim and Dale 2004; Graham et al. 2007), 40% (Petrolia 2006), ~25% (Blanco-Canqui and Lal 2007), and <40% (Lafond et al. 2009)—do not provide adequate guidelines to overcome the uncertainties for practical implementation. Nelson (2002) used the RUSLE2 (Revised Universal Soil Loss Equation, Version 2) model to estimate stover removal rates with acceptable soil loss in the eastern and midwestern United States. His estimates varied widely over time and location due to complex interactions between soil type, climate, and management. A similar study by Mann et al. (2002) failed to identify permissible stover removal rates but emphasized the need for long-term studies on the effects of stover harvest on soil and water quality, SOC dynamics, and interactions with cropping systems management and agro-

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climate. Graham et al. (2007) also used the RUSLE2 erosion prediction model to estimate permissible stover removal thresholds subject to soil conservation requirements but did not take into account variation due to impacts of site-specific factors. More recently, Newman et al. (2010) used the Water Erosion Prediction Project model to simulate potential impacts of various corn stover harvesting and management scenarios on water erosion in Iowa. The simulated results suggest that the amount of harvestable corn stover is not uniform in Iowa when management is solely guided by the need to control water erosion. Johnson et al. (2010) discuss and point out some general guidelines for determining if residues can be harvested while emphasizing conservation considerations for sustainable bioenergy feedstock production. For any given landscape, stover harvests will initially be limited by soil erosion risk, but as that risk decreases, maintenance of SOC and soil fertility become the main limiting factors. Noting the importance of crop residues in maintaining soil health and function, the USDA NRCS (2006) recommend that crop residue harvests need to consider soil type, climate, cropping system, and management in order to protect soil quality while allowing for residue harvest for biofuel production.

While some impact assessments of site-specific factors on corn grain yields are available, impacts on stover yields are not well documented. Data presented by Blanco-Canqui et al. (2006) suggest that corn stover removal impacts stover yields twice as much as grain yields, and a further study by the same authors (Blanco-Canqui and Lal 2007) showed that a stover removal rate of 50% reduced stover yield by 0.97 Mg ha⁻¹ (0.43 tn ac⁻¹). Larson (1979) conducted a study on crop residue removal in various parts of the United States and concluded that soil erosion limitations exist and that residue removal is highly susceptible to cropping practice and management. Nelson (2002) used land capability classes I-IV (Helms 1992) to estimate the amount of corn and wheat straw residue that can be harvested in 37 eastern and midwestern states and concluded that a significant quantity of corn stover can be harvested in Nebraska, Iowa, Illinois, Indiana, and Kansas, with sufficient stover quantities left to control wind and water erosion at the tolerable soil loss level.

Guidelines are urgently needed for site-specific corn stover removal thresholds if the fast-emerging lignocellulosic biofuel industry is to sustain productivity and protect the natural soil resource base. A major objective in the USDA Biofuels Strategic Production Report: A USDA Regional Roadmap to Meeting the Biofuels Goals of the Renewable Fuels Standard by 2022 is providing the practical knowledge from the field that enhances various models for biofuel production (USDA 2010). To this end, we performed a corn stover biofuel feedstock harvest simulation study with the APEX model (Agricultural Policy Environmental Extender) (Williams and Izaurralde 2005) to determine the effects of site-specific factors to ascertain corn stover removal thresholds and assess their impacts on corn grain and stover yields, SOC storage and rate of change, and sediment and nutrient losses from 3,703 farm fields within the Upper Mississippi River Basin (UMRB) (figure 1). While field studies are valuable and necessary, they are quite costly in time, personnel, and monetary resources. Cropping system simulation models, with their ability to integrate the results of research from many different disciplines and agroclimatic locations, allow researchers to test long-term effects of alternatives and provide insights into the sustainability and environmental impacts of proposed actions in an economical and time-efficient manner. Models like APEX and its predecessor EPIC (Erosion-Productivity Impact Calculator) have been successfully used in many studies over the last 30 years (Gassman et al. 2010). We used the APEX model because it can effectively account for complex cropping system interactions with site-specific factors of management, land condition, soil texture–hydrologic group interactions, slope, and agroclimate.

Materials and Methods

Site Description. The UMRB includes large parts of Illinois, Iowa, Minnesota, Missouri,
and Wisconsin, and small areas in Indiana, Michigan, and South Dakota (figure 1). The area includes 23.6 million ha (58.3 million ac) of cultivated cropland, of which nearly 75% are likely to have a crop rotation involving corn. On average, 11.3 million ha (27.9 million ac) (48%) are used for corn production each year (USDA NRCS 2010). The 3,703 farm fields are fields associated with the National Resource Inventory sample points selected for the CEAP Farmer Survey (USDA NRCS 2010). A statistical acreage weight is attached to each sample point so that the sum of the weights is equal to the cultivated cropland acreage in the area.

**Site-Specific Factors.** About 20% of the UMRB is classified as highly erodible land (HEL) (USDA NRCS 2010). Highly erodible land refers to land that is very susceptible to erosion, including fields that have at least 1/3 or 20.25 ha (50 ac) of soils with a natural erosion potential of at least eight times their soil loss tolerance level or T value. For a specific soil, the T value is the maximum amount of soil loss in tons per acre per year that can be tolerated and still permit a high level of crop productivity to be sustained economically and indefinitely. The T values range from 2.24 to 11.21 Mg ha–1 y–1 (1 to 5 tn ac–1 yr–1) (Womack 2005).

The cropland in the UMRB includes soils of 18 different soil textural classes. For the purposes of this study and analytical handling, we grouped the soil textures into three main textural classes: clayey, loamy, and sandy, as shown in table 1. Silty loams predominate, covering almost 50% of the basin.

Hydrologic soil groups define soil characteristics that affect their runoff potentials, with hydrologic group A (table 2), which is dominated by sandy soils, being characterized by the lowest runoff potential when thoroughly wet and the capability to allow water to move freely through the soil. Group B soils, composed mostly of loamy soils, have a moderately low runoff potential when thoroughly wet and allow water to transmit through unimpeded. Hydrologic group D soils have clayey textures and have properties opposite those of group A soils: a high runoff potential when thoroughly wet and restricted transmission of water through the soil. Hydrologic group C soil properties are intermediate between those of groups B and D and consist mostly of clayey loams.

Overall, impacts and crop responses to soil texture and hydrologic groups are intertwined, reflecting a given soil type’s inherent soil fertility and potential plant-available soil moisture. For the UMRB, loamy soils predominate, with 76% belonging to hydrologic group B, while 60% of clayey soils and 83% of sandy soils belong to hydrologic groups D and A, respectively. On average, clayey and loamy soils are inherently more fertile than sandy soils.

More detailed guidelines and interpretations of HEL and the T factor, soil textural classes and hydrologic groups are available in the USDA National Soil Survey Handbook (USDA NRCS 2011).

**Description of the Agricultural Policy Environmental Extender Model.** The APEX model is a field scale, daily time-step model designed to simulate the major physical and biological processes of agricultural systems, including weather, soil temperature, hydrology, farming operations, crop growth and yield, and the movement of water, soil carbon, nutrients, sediment, and pesticides across the field, off the field, and down through the soil profile. The APEX and EPIC models have a long history of use in simulation of agricultural and environmental processes and of the long-term effects of agricultural technology and government policy (Gassman et al. 2005). The APEX model was specifically developed to extend the EPIC model capabilities to whole farms and small watersheds. Farms may be subdivided into fields, soil types, landscape positions, or any other desirable configuration with the hydrologic links between the subareas simulated.

In addition to the EPIC functions, APEX has components for routing water, sediment, nutrients, and pesticides across complex landscapes and channel systems to the watershed outlet. The routing mechanisms provide for evaluation of impacts of management options on soil and water quality at each subarea and at the watershed outlet. A more detailed description of the model and how well APEX simulates measured data were recently published in Gassman et al. (2010). The APEX model is constantly being developed, and its output variables are continually parameterized on the basis of measured field data by various researchers across the country.

**The Agricultural Policy Environmental Extender Model Calibration and Testing.** Model simulations for this study were based on the CEAP Cropland Assessment project (USDA NRCS 2010) simulation protocols extended to examine the potential for corn stover harvest in the UMRB. The calibration and validation of the APEX model for the CEAP Cropland Assessment project is detailed and discussed in Williams et al. (2010). The testing of the model included comparisons of measured field data with model-simulated data for such parameters as crop yields, runoff, sediment and nutrient losses, and SOC storage. Overall, these

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**Table 1**

<table>
<thead>
<tr>
<th>Classification of the Upper Mississippi River Basin soil textures into three main textural classes of clayey, loamy, and sandy soils.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Clayey</strong></td>
</tr>
<tr>
<td>Clay</td>
</tr>
<tr>
<td>Silty clay</td>
</tr>
<tr>
<td>Fine sandy loam</td>
</tr>
<tr>
<td>Loam</td>
</tr>
<tr>
<td>Silt</td>
</tr>
<tr>
<td>Silty clay loam</td>
</tr>
<tr>
<td>Loamy sand</td>
</tr>
<tr>
<td>Sandy loam</td>
</tr>
</tbody>
</table>

**Table 2**

<table>
<thead>
<tr>
<th>Soil hydrologic group</th>
<th>Soil textures</th>
<th>Runoff potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Sand, loamy sand, or sandy loam</td>
<td>Low</td>
</tr>
<tr>
<td>B</td>
<td>Silt loam or loam</td>
<td>Moderate</td>
</tr>
<tr>
<td>C</td>
<td>Sandy clay loam</td>
<td>Moderate to High</td>
</tr>
<tr>
<td>D</td>
<td>Clay loam, silty clay loam, sandy clay, silty clay, or clay</td>
<td>High</td>
</tr>
</tbody>
</table>
studies showed good agreement between simulated results and field research data. In one such study (Wang et al. 2008), the APEX model was tested using 22 years of field data from two watersheds located in the North Appalachian Experimental Watershed (W109), Coshocton, Ohio (40°22’N, 81°48’W) planted to corn and soybeans. Corn and soybean yields were validated with $r^2$ values that ranged from 0.71 to 0.87. The percent simulation error for SOC in the top 30 cm (1.18 in) for the years 1985 and 1999 were 6.5% and 2.3%, respectively. The $r^2$ values for annual runoff and sediment yield were 0.87 and 0.73, respectively. More publications on the historical development and applications of the EPIC and APEX models, model calibration and validation, sensitivity and uncertainty analyses of crop yields, runoff, sediment and nutrient losses, and SOC storage are documented in Gassman et al. (2010).

Although the APEX model has been widely tested to simulate corn grain yields, published data on stover yields for comparison to simulation results is not readily available. Nonetheless, in the APEX model, as in the EPIC model, corn stover is directly related to grain yield through the harvest index (HI). The APEX model computes potential crop growth based on leaf area index, radiation interception, and radiation-use efficiency. For grain crops, potential grain yield is computed as a percentage, commonly referred to as the HI, of the total aboveground dry matter at physiological maturity. For corn, the APEX model uses an HI value of 0.53. The remaining 0.47 (47%) of the total aboveground dry matter represents the corn stover. The HI statistic has been widely tested through comparisons of measured and simulated grain yields (Gassman et al. 2010; Williams et al. 2010).

**Model Simulations.** To assess the effects of site-specific factors on corn stover removal thresholds and their impacts on corn grain and stover yields and the environment, we conducted APEX model simulations comparing four levels of corn stover removal (0%, 40%, 60%, and 80%), and two management practices (Baseline and Enhanced Conservation Treatment [ECT]) across two land types (highly erodible [HEL] and non-HEL), three broad soil textural classes (clayey, loamy, and sandy), and the four soil hydrologic groups (A, B, C, and D) for 3,703 farm fields within the UMRB. Simulations were run over a 47-year time series, using actual daily weather data from the period of 1960 to 2006.

**Baseline and Enhanced Conservation Treatment Management Scenarios.** The CEAP cropland assessment (USDA NRCS 2010) includes a database of three years of farm management practices for periods within the 2001 to 2006 survey period. Approximately one-fourth of the sample was collected in each of the 2003 to 2006 annual surveys, for a total of 3,703 farm fields in the UMRB. For the Baseline management, the APEX model simulations were developed based on farmer management practices collected in the 2003 to 2006 survey. The use of the Baseline management scenarios improves on previous model simulation work on corn stover removal by allowing for a more realistic spatial resolution of actual farmer’s conditions and management practices.

Analysis of the 2003 to 2006 CEAP cropland assessment survey data determined that the suite of practices in use was often inadequate to address excessive losses of sediment and nutrients (USDA NRCS 2010). Hence, the Baseline management practices were modified to make the Enhanced Conservation Treatment (ECT) management, representing alternative conservation practice scenarios that mitigated sediment, nutrient, and SOC losses.

The ECT involved two types of conservation practice treatment: treatment with additional erosion control practices and treatment with nutrient management in addition to erosion control practices.

Treatment with additional erosion control practices consisted of adding in-field practices to control overland flow (terraces, contouring, or strip-cropping) for field acres without overland flow control practices having a slope of more than 2%, and adding edge-of-field buffering or filtering practices to all field acres without edge-of-field practices. Treatment with nutrient management in addition to erosion control practices was simulated by adjusting the commercial fertilizer and manure applications to reflect the appropriate rate, time, and method of application (USDA NRCS 2010).

**Simulation of Stover Removal Rates in the Agricultural Policy Environmental Extender.** We simulated harvestable stover removal using a one-pass harvester that recovers the grain and stover at the same time. For purposes of this study, we assigned the three rates of stover removal of 40%, 60%, and 80%, to represent the stover that is recovered at harvest, as a proportion of the stover yield with no stover removal at all (0% stover removal rate). Collection and removal of more than 80% of the corn stover is nearly impossible without some specialized equipment, and harvesting less than 40% of the residue is not likely to be economical, given the cost of the equipment operation (these limits are implied by Perlack et al. [2005] and other similar analyses).

**Results and Discussion**

**Corn Stover Yields.** For the Baseline, stover removal rates of 40%, 60%, and 80% yielded 3.27, 4.86 and 6.43 Mg ha$^{-1}$ (1.46, 2.17, and 2.87 tn ac$^{-1}$ yr$^{-1}$) of stover (table 3). Averaged across stover removal rates, HEL and non-HEL yields were 4.82 and 4.86 Mg ha$^{-1}$ yr$^{-1}$ (2.15 and 2.17 tn ac$^{-1}$ yr$^{-1}$), while clayey, loamy, and sandy soils yielded 4.61, 4.87, and 4.44 Mg ha$^{-1}$ yr$^{-1}$ (2.05, 2.17, and 1.98 tn ac$^{-1}$ yr$^{-1}$). Hydrologic group D soils had the highest Baseline stover yields (5.05 Mg ha$^{-1}$ yr$^{-1}$ [2.25 tn ac$^{-1}$ yr$^{-1}$]), followed by those in group B (4.82 Mg ha$^{-1}$ yr$^{-1}$ [2.15 tn ac$^{-1}$ yr$^{-1}$]), group C (4.78 Mg ha$^{-1}$ yr$^{-1}$ [2.13 tn ac$^{-1}$ yr$^{-1}$]), and then group A (4.46 Mg ha$^{-1}$ yr$^{-1}$ [1.99 tn ac$^{-1}$ yr$^{-1}$]).

Our Baseline stover yields are comparable to yields recently reported by Karlen et al. (2011) at the stover removal rates of 50% (3.40 Mg ha$^{-1}$ yr$^{-1}$ [1.52 tn ac$^{-1}$ yr$^{-1}$]) and 90% (6.40 Mg ha$^{-1}$ yr$^{-1}$ [2.85 tn ac$^{-1}$ yr$^{-1}$]), averaged across the years 2008 and 2009. There was a slight decline in stover yields under ECT management compared to the Baseline, with the 40%, 60%, and 80% stover removal rates yielding 3.23, 4.81, and 6.36 Mg ha$^{-1}$ yr$^{-1}$ (1.44, 2.15, and 2.84 tn ac$^{-1}$ yr$^{-1}$). Stover yields under HEL and non-HEL were the same (4.75 Mg ha$^{-1}$ yr$^{-1}$ [2.12 tn ac$^{-1}$ yr$^{-1}$]). The reduced stover yields under ECT were due to lower commercial fertilizer and manure applications for many of the samples. As pointed out earlier, these scenarios were simulated to reflect the use of appropriate rate, time, and method of commercial fertilizer and manure application, compared to the Baseline.

**Corn Grain Yields.** A comparison of the APEX–simulated corn grain yields at the Baseline with no stover removal (i.e., 0% removal rate) against the National Agricultural Statistics Service (NASS) corn grain yield estimations for the five main UMRB states (Illinois, Iowa, Minnesota, Missouri, and Wisconsin) during the period...
to 0.87 (Wang et al. 2008). Similar studies demonstrating the APEX’s ability to accurately simulate crop yields have been reviewed by Gassman et al. (2010).

Overall, grain yields were impacted more by soil texture and hydrologic group than by rate of stover removal (table 3). For the Baseline management, loamy soils had the highest average grain yield of 8.56 Mg ha\(^{-1}\) (134 bu ac\(^{-1}\) yr\(^{-1}\)) followed by clayey soils (8.08 Mg ha\(^{-1}\) y\(^{-1}\) [126 bu ac\(^{-1}\) yr\(^{-1}\)]), and sandy soils (7.69 Mg ha\(^{-1}\) y\(^{-1}\) [120 bu ac\(^{-1}\) yr\(^{-1}\)]). Increasing stover removal rates slightly decreased grain yields across the three soil textures but with a comparatively higher decrease on sandy soils. Baseline soil hydrologic group grain yields followed a somewhat similar trend to stover yields, with higher average yields in groups D (8.86 Mg ha\(^{-1}\) y\(^{-1}\) [138 bu ac\(^{-1}\) yr\(^{-1}\)]), followed by group B (8.49 Mg ha\(^{-1}\) y\(^{-1}\) [132 bu ac\(^{-1}\) yr\(^{-1}\)]), group C (8.4 Mg ha\(^{-1}\) y\(^{-1}\) [131 bu ac\(^{-1}\) yr\(^{-1}\)]), and then group A (7.68 Mg ha\(^{-1}\) y\(^{-1}\) [120 bu ac\(^{-1}\) yr\(^{-1}\)]). Averaged across land type, HEL class, soil texture, and hydrologic group, the ECT

2000 to 2006 is presented in table 4. The period includes the 2003 to 2006 CEAP national cropland assessment survey period, over which the Baseline model simulations were developed based on surveyed farmer management practices, plus an additional three years prior to the survey (2000 to 2002). Overall, APEX was able to predict yields with acceptable accuracy with an average simulation error of −6%. Moreover, our simulated yield levels are within the range of some long-term measured and APEX–simulated corn yields (22 years) at the North Appalachian Experimental watershed (W109), Coshocton, Ohio (40°22'N, 81°48'W). Measured and simulated corn grain yields had \(r^2\) values ranging from 0.71 to 0.87 (Wang et al. 2008). Similar studies demonstrating the APEX’s ability to accurately simulate crop yields have been reviewed by Gassman et al. (2010).

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<table>
<thead>
<tr>
<th>Year</th>
<th>Simulated (Mg ha(^{-1}))</th>
<th>Measured* (Mg ha(^{-1}))</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>9.3</td>
<td>9.0</td>
<td>4.1</td>
</tr>
<tr>
<td>2001</td>
<td>8.2</td>
<td>8.6</td>
<td>-5.4</td>
</tr>
<tr>
<td>2002</td>
<td>8.2</td>
<td>8.7</td>
<td>-6.0</td>
</tr>
<tr>
<td>2003</td>
<td>8.0</td>
<td>8.8</td>
<td>-9.1</td>
</tr>
<tr>
<td>2004</td>
<td>9.7</td>
<td>10.3</td>
<td>-5.4</td>
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<td>2005</td>
<td>8.3</td>
<td>9.4</td>
<td>-11.2</td>
</tr>
<tr>
<td>2006</td>
<td>8.8</td>
<td>9.7</td>
<td>-8.9</td>
</tr>
<tr>
<td>Mean</td>
<td>8.7</td>
<td>9.2</td>
<td>-6.0</td>
</tr>
</tbody>
</table>

practice gave a slightly lower grain yield to the Baseline (8.46 and 8.52 Mg ha⁻¹ yr⁻¹ [132 and 133 bu ac⁻¹ yr⁻¹] respectively). Besides the low available plant soil moisture, the lower grain and stover yields under sandy and hydrologic group A soils, as will be shown later, could be tied to the relatively higher nitrogen (N) leaching losses.

Studies on corn stover removal impacts on corn grain yields showed varied results, with risks or benefits varying depending on seasonal climatic conditions, soil type, and management. Corn grain yield reduction trends, similar to our study, have been reported elsewhere: corn grain yields were reduced by 0.13 Mg ha⁻¹ (2 bu ac⁻¹) for each Mg ha⁻¹ of the previous corn crop stover removed (Wilhelm et al. 1986), stover removal from a loamy sand reduced corn yield by about 23% in Nebraska (Powers et al. 1998) and by 1 Mg ha⁻¹ (15 bu ac⁻¹) in Minnesota (Linden et al. 2000), and a corn stover removal rate of 50% reduced grain yield by 1.94 Mg ha⁻¹ (30 bu ac⁻¹) (Blanco-Canqui and Lal 2007). However, corn stover removal or retention had no impact on corn yields on a loamy soil in Indiana (Barber 1979) and in the US southern coastal plain (Karlen et al. 1984). Similarly, Dam et al. (2004) found no differences in grain or dry matter yields on a sandy loam. Corn stover removal negatively impacts soil fertility, and hence productivity, through direct removal of nutrients and reduced crop–water availability due to loss of soil cover. Conversely, high stover retention has also been shown to negatively affect corn growth and yield (Benoit and Lindstrom 1987; Swan et al. 1996) because of excessively wet and cold soils, poor seed placement and emergence, retarded plant growth, and poor weed control.

**Soil Organic Carbon Storage.** Soil organic carbon storage was hugely impacted by site-specific factors (table 5). For Baseline management, the total SOC storage (whole soil profile) with no stover removal was 81.0 Mg ha⁻¹ (36.1 tn ac⁻¹). The stover removal rates of 40%, 60%, and 80% decreased total SOC storage by 7%, 9%, and 12%, respectively. Averaged across stover removal rates, the Baseline HEL had a 5% lower SOC storage than non-HEL. Baseline clayey soils had the highest average SOC storage of 86.7 Mg ha⁻¹ (38.7 tn ac⁻¹), followed by sandy soils (76.9 Mg ha⁻¹ [34.3 tn ac⁻¹]), and sandy soils with 54.1 Mg ha⁻¹ (24.1 tn ac⁻¹). Soil hydrologic group D had the highest average SOC storage (90.5 Mg ha⁻¹ [40.4 tn ac⁻¹]), followed by groups C (77.5 Mg ha⁻¹ [34.6 tn ac⁻¹]), B (72.6 Mg ha⁻¹ [32.4 tn ac⁻¹]), and A (51.5 Mg ha⁻¹ [23.0 tn ac⁻¹]). Overall, ECT practices enhanced SOC storage by 4%, with site-specific SOC storage increases of HEL (6%), non-HEL (4%), clayey soils (4%), loamy soils (5%), sandy soils (2%), and hydrologic groups A (2%), B (5%), C (5%), and D (4%).

The impacts of corn stover removal on SOC storage under Baseline management for the three soil textural classes at the end of the 47-year simulation period are shown in figure 2. Soil organic carbon storage gains were obtained at the 0% stover removal rate in clayey and loamy soils (5.0 and 4.4 Mg ha⁻¹ [2.2 and 2.0 tn ac⁻¹], respectively) over the 47-year simulation period, while sandy soils maintained SOC levels with no gain or loss in SOC (0.1 Mg ha⁻¹ [0.05 tn ac⁻¹]). Overall, stover removal reduced SOC storage by reducing the rate of SOC gain. For clayey soils, harvesting stover at the 40% and 60% removal rates still maintained SOC storage gains over the 47-year simulation period, increasing SOC storage from the beginning to the end of the simulation by 1.3 and 0.5 Mg ha⁻¹ (0.6 and 0.2 tn ac⁻¹), respectively. However, SOC storage declined by 0.7 Mg ha⁻¹ (0.3 tn ac⁻¹) at the 80% removal rate. A similar trend was observed on loamy soils. For sandy soils, there was a decline in SOC storage at all the three stover removal rates: 40% (1.5 Mg ha⁻¹ [0.7 tn ac⁻¹]), 60% (2.0 Mg ha⁻¹ [0.9 tn ac⁻¹]), and 80% (2.4 Mg ha⁻¹ [1.1 tn ac⁻¹]). Identifying stover removal rates that maintain a positive SOC storage balance over time is crucial as the rates could signify permissible stover removal rates that allow for both erosion control and SOC balance. Permissible stover removal thresholds should be based on reducing soil erosion risks, maintaining SOC, offsetting carbon dioxide emissions, maintaining nutrient cycling and soil fertility, and sustaining crop yields (Lal 2005). According to Karlen et al. (2011), total soil organic carbon is a soil quality indicator that needs to be closely monitored to quantify crop residue removal effects.

Several researchers have reported similar impacts of corn stover removal on SOC storage to those observed in our study. Allmaras et al. (2004) reported a 35% reduction in SOC in a 13-year study due to complete stover removal from no-till systems on a silt loam. In a related study, but on a silty clay loam, Wilts et al. (2004) recorded a 30% to 39% reduction in SOC after 29 years of complete stover removal. Blanco-Canqui and Lal (2007) reported more drastic depletion of SOC after stover removal in two silt loam soils compared to clayey soils over a short period of time and a half years. On average, their data show a reduction in the total SOC storage, with stover removal rates as low as 25%. According to Needelman et al. (1999) and Six et al. (2002), soil organic carbon depletion is higher in sandy soils, and some loamy soils, because of enhanced decomposition of organic matter due to higher rates of water and air fluxes. In clayey soils, high water retention and inadequate air supply inhibits organic matter decomposition and hence SOC depletion.

**Rate of Soil Organic Carbon Change.** Figure 3 shows the cumulative percent hectare distributions for average rates of SOC change for the Baseline simulations under 0%, 40%, 60%, and 80% stover removal rates for the 3,703 farm fields in the UMRB over the simulated 47-year timescale. Even with no stover harvest, 9% of the corn hectares in the UMRB lose SOC, while the stover removal rates of 40%, 60%, and 80% increased the corn hectares losing SOC by 11%, 15%, and 21%, respectively, trends most likely to be impermissible.

For the Baseline management, increasing stover removal drastically reduced rates of SOC sequestration (table 5). The 80% removal rate resulted in average SOC losses of 17.6 kg ha⁻¹ yr⁻¹ (15.7 lb ac⁻¹ yr⁻¹). Soil organic carbon gains were obtained with no stover removal across all site-specific conditions, except on sandy soils, which lost SOC across all stover removal rates. For HEL, SOC losses were observed at the stover removal rates of 60% and 80%, while SOC losses for non-HEL were observed at the 80% rate of stover removal. Clayey and loamy soils had losses at the 80% removal rate. Only soils in hydrologic group B gained SOC across all four stover removal rates. Hydrologic groups A, C, and D, respectively, had on average, SOC losses of 18.8, 15.9, and 47.1 kg ha⁻¹ yr⁻¹ (16.8, 14.2, and 42.1 lb ac⁻¹ yr⁻¹). Published data on corn stover removal effects on the rate of SOC change are scarce. Our estimations of the rate of SOC change at the 0% stover removal rate are within the range of estimates by Paustian et al. (2002) and Causarano et al. (2008): 0 to 910 kg C ha⁻¹ yr⁻¹ (813 lb C ac⁻¹ yr⁻¹). Rates for the US Corn Belt are highly variable and have been
estimated at 540 ± 360 kg C ha⁻¹ yr⁻¹ (482 ± 321 lb C ac⁻¹ yr⁻¹) (Johnson et al. 2007).
The ECT practices effectively enhanced SOC sequestration across most site-specific constraining conditions and corn stover removal rates (table 5). According to Wilhelm et al. (2007), crop management practices greatly impact the rate of organic matter decomposition and hence harvestable stover. A study by Hooker et al. (2005) at a site in Connecticut with similar climatic conditions to the Corn Belt suggests that corn stover

Table 5
Effects of site-specific factors and corn stover removal on total soil organic carbon (SOC) storage and annual rate of SOC change in the Upper Mississippi River Basin.

<table>
<thead>
<tr>
<th>Site-specific factors</th>
<th>Land type</th>
<th>Soil textural class</th>
<th>Soil hydrologic group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stover removal</td>
<td>HEL</td>
<td>non-HEL</td>
<td>Clayey</td>
</tr>
<tr>
<td>Baseline management</td>
<td>0%</td>
<td>81.9 ± 0.1</td>
<td>91.8 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>40%</td>
<td>77.6 ± 0.1</td>
<td>87.3 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>60%</td>
<td>72.0 ± 0.1</td>
<td>76.0 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>80%</td>
<td>67.6 ± 0.1</td>
<td>67.6 ± 0.6</td>
</tr>
<tr>
<td>Enhanced conservation</td>
<td>0%</td>
<td>84.4 ± 0.1</td>
<td>94.8 ± 0.5</td>
</tr>
<tr>
<td>treatment</td>
<td>40%</td>
<td>80.4 ± 0.1</td>
<td>80.4 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>60%</td>
<td>78.0 ± 0.1</td>
<td>78.0 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>80%</td>
<td>76.8 ± 0.1</td>
<td>76.8 ± 0.1</td>
</tr>
</tbody>
</table>

Rate of SOC change (kg ha⁻¹ yr⁻¹)

<table>
<thead>
<tr>
<th>Soil textural class</th>
<th>Clayey</th>
<th>Loamy</th>
<th>Sandy</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEL</td>
<td>104.4 ± 0.4</td>
<td>117.6 ± 12.1</td>
<td>117.6 ± 12.1</td>
</tr>
<tr>
<td>non-HEL</td>
<td>109.0 ± 23.0</td>
<td>170.7 ± 11.7</td>
<td>170.7 ± 11.7</td>
</tr>
</tbody>
</table>

Notes: Mean confidence limits at p ≤ 0.05. HEL = highly erodible land.

Figure 2
Simulated long-term (47 years, 1960 to 2007) impacts of corn stover removal on soil organic carbon (SOC) storage under (a) clayey, (b) loamy, and (c) sandy soils under the Baseline management in the Upper Mississippi River Basin.
Figure 3
Cumulative percent hectare distributions for Baseline simulations of average rates of soil organic carbon (SOC) change in the Upper Mississippi River Basin. Each curve shows how rates of SOC change varied across simulated farm fields under the four rates of stover removal, starting with simulations with SOC losses (−) and increasing to simulations with SOC gains (+).

Legend
Stover removal
- - - - 0%
- - - 40%
- - - 60%
- - - 80%

Sediment Losses. Total sediment losses are composed of losses by wind and water erosion. For the UMRB, wind erosion is a relatively minor constraint (figure 4), with model-simulated average annual rates of wind erosion being only 0.68 Mg ha\(^{-1}\) yr\(^{-1}\) (0.30 tn ac\(^{-1}\) yr\(^{-1}\)), compared to an average of 3.36 Mg ha\(^{-1}\) yr\(^{-1}\) (1.50 tn ac\(^{-1}\) yr\(^{-1}\)) for water erosion. For the Baseline management, the stover removal rates of 40%, 60%, and 80% on average increased sediment losses across all corn hectares by 16%, 28%, and 42%, respectively (table 6 and figure 5). Averaged across the four stover removal rates, Baseline HEL sediment losses are 36% higher than non-HEL losses. Sandy soils had the least sediment losses of 2.65 Mg ha\(^{-1}\) yr\(^{-1}\) (1.18 tn ac\(^{-1}\) yr\(^{-1}\)), followed by clayey soils (3.04 Mg ha\(^{-1}\) yr\(^{-1}\) [1.36 tn ac\(^{-1}\) yr\(^{-1}\)]), and then loamy soils (4.11 Mg ha\(^{-1}\) yr\(^{-1}\) [1.83 tn ac\(^{-1}\) yr\(^{-1}\)]). Sediment losses were highest for hydrologic group C soils (5.02 Mg ha\(^{-1}\) yr\(^{-1}\) [2.23 tn ac\(^{-1}\) yr\(^{-1}\)]), followed by groups D and B (3.93 Mg ha\(^{-1}\) yr\(^{-1}\) [1.75 tn ac\(^{-1}\) yr\(^{-1}\)]) and group A (2.35 Mg ha\(^{-1}\) yr\(^{-1}\) [1.05 tn ac\(^{-1}\) yr\(^{-1}\)]. Soil hydrologic groups D and C had a high runoff potential when thoroughly wet, which made them prone to higher sediment losses. Group B soils had a moderate runoff potential, and group A soils have the least runoff potential. Overall, the ECT practices effectively mitigated sediment losses by 69%.

The APEX model’s ability to accurately simulate sediment losses was tested by Wang et al. (2008) at a field-scale watershed (W3) at Treynor, Iowa (41°9’N, 95°38’W). The APEX’s simulated sediment losses of 1.67 Mg ha\(^{-1}\) yr\(^{-1}\) (0.74 tn ac\(^{-1}\) yr\(^{-1}\)) agreed well with the measured value of 1.71 Mg ha\(^{-1}\) yr\(^{-1}\) (0.76 tn ac\(^{-1}\) yr\(^{-1}\)). Field studies on the impacts of stover removal on sediment loss are limited. Lindstrom (1986) demonstrated that leaving low levels of stover on the surface increased runoff and sediment loss. However, data from the same study suggests that removing 30% or less stover has little impact on soil erosion. Dabney et al. (2004) reported soil loss increases of 26% to 47% on tilled soils following complete removal of surface crop residues. Recently, Newman et al. (2010) used the Water Erosion Prediction Project simulation model to construct soil erosion risk maps based on T values to assess safe areas for stover removal in Iowa. These maps indicate corn stover removal risk at the following levels: extreme, high, medium, or low. The Newman et al. (2010) simulated results suggest that the amount of harvestable corn stover is not uniform in Iowa when water erosion control guides are followed. Although not fully discussed here, it is important to note that high stover removal–induced sediment losses can also result in considerable SOC and nutrient losses in sediment.

Nitrogen and Phosphorus Losses. The results of corn stover removal on total N and phosphorus (P) losses are shown in table 7. For Baseline management, the stover removal rates of 40%, 60%, and 80% decreased N losses by 6%, 9%, and 12%, respectively, across the two land types, three soil textural classes, and four hydrologic groups. Nitrogen losses were higher from HEL and sandy and hydrologic group A soils. For Baseline management, losses are dominated by leaching (35%), N attached to wind and water eroded sediments (33%), and volatilization (22%). Losses through runoff, denitrification, and subsurface flow are comparably minor, all accounting to 10% of total losses (data not shown). Soil textural differences were highly noticeable, with sandy soils having the highest total N losses, which were dominated by leaching losses, followed by loamy and...
there were no noticeable differences in N with runoff increased with increased rate of sediments, and volatilization contributed the ing, N attached to wind and water eroded were equally important. Nitrogen leaching, N attached to wind and water eroded sediments, denitrification, and volatilization were equally important. Nitrogen leaching, N attached to wind and water eroded sediments, and volatilization contributed the most N losses in loamy soils. Nitrogen losses with runoff increased with increased rate of stover removal in clayey and loamy soils, but there were no noticeable differences in N losses in sandy soils due to the low runoff potential. A beneficial tradeoff occurs from corn stover harvest. On average, removal of corn stover reduces the pool of nutrients available for loss, resulting in decreased losses. This can be seen by construction of a nutrient balance account for each farm field, based on model input and results. Despite the limited field data on the effects of corn stover removal on N losses, the APEX model was successfully calibrated and tested for simulating organic and mineral N losses across nine forested watersheds in Alto, Texas (31°39'0" N, 95°4'26" W) (Wang et al. 2007) with average simulation errors of 16% and 6%, respectively. Although the total N storage between clayey and loamy soils was not statistically different, both Baseline clayey and loamy soils had significantly higher total N storage (7.7 Mg ha\(^{-1}\) [3.4 tn ac\(^{-1}\)]) and 6.7 Mg ha\(^{-1}\) [3.0 tn ac\(^{-1}\)], respectively) than sandy soils (4.8 Mg ha\(^{-1}\) [2.1 tn ac\(^{-1}\)]) (figure 6). Overall, increased rates of stover removal, coupled with N losses, decreased total soil N storage. The Baseline residue removal rates of 40%, 60%, and 80% decreased total soil N storage by 4%, 5%, and 7%, respectively. Total soil N storage for non-HEL with Baseline management was, on average, 6% higher than HEL (data not shown). Averaged across land types, total soil N storage declined linearly from 6.9 Mg ha\(^{-1}\) (3.1 tn ac\(^{-1}\)) at the 0% residue removal rate to 6.5 Mg ha\(^{-1}\) (2.9 tn ac\(^{-1}\)) at the 80% removal rate. Total P losses were small, and corn stover removal effects generally followed a similar trend to that of N losses (table 7). On average, ECT practices effectively mitigated N and P losses across HEL and non-HEL, the three soil textural classes, and the four hydrologic groups by 57%.

Fixen (2007) observed similar reductions in N, P, and potassium (K) storage in the US Corn Belt due to corn stover removal. Removing 40% of corn stover decreased soil N content by 20%, P by 14%, and K by 100%. Blanco-Canqui and Lal (2009b) reported a 40% reduction in available soil P

### Table 6

<table>
<thead>
<tr>
<th>Site-specific factors</th>
<th>Annual sediment losses (Mg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stover removal</td>
<td>HEL</td>
</tr>
<tr>
<td>0%</td>
<td>4.62 ± 0.10</td>
</tr>
<tr>
<td>40%</td>
<td>5.30 ± 0.10</td>
</tr>
<tr>
<td>60%</td>
<td>5.81 ± 0.11</td>
</tr>
<tr>
<td>80%</td>
<td>6.46 ± 0.11</td>
</tr>
</tbody>
</table>

Notes: Mean confidence limits at \(p \leq 0.05\). HEL = highly erodible land.

### Figure 4

Estimates of average annual water and wind sediment losses for cultivated croplands in the Upper Mississippi River Basin.
due to complete stover removal. In contrast, Karlen et al. (1984) observed no significant differences in total N concentration under different corn stover removal rates in a sandy loam. However, a further study showed significant decreases in total N concentration in a silt loam (Karlen et al. 1994). Blanco-Canqui and Lal (2009) also observed similar changes in total soil N content in silt loam soils but no difference in clay loams. Stover removal–induced depletion of nutrient pools implies that increased fertilization rates will be required to sustain productivity.

**Assessment of Potential Sustainable Corn Stover Removal Thresholds.** To assess potential site-specific corn stover removal thresholds, it was assumed that stover should only be harvested on sites and under management practices that protect the land from excessive soil erosion and SOC and plant nutrient losses. Hence, for these simulation studies, we evaluated each modeled farm field relative to a set of acceptable planning criteria used in the CEAP analysis to judge whether or not a farm field needed additional conservation treatment (USDA NRCS 2010). Acceptable criteria included (a) N in surface runoff of <16.8 kg ha⁻¹ yr⁻¹ (<15.0 lb ac⁻¹ yr⁻¹), (b) N in subsurface runoff of <28.0 kg ha⁻¹ yr⁻¹ (<25.0 lb ac⁻¹ yr⁻¹), (c) total P losses of <4.5 kg ha⁻¹ yr⁻¹ (<4.0 lb ac⁻¹ yr⁻¹), (d) sediment loss of <4.5 Mg ha⁻¹ yr⁻¹ (<2.0 tn ac⁻¹ yr⁻¹) (USDA NRCS 2010), and (e) SOC with a more stringent restriction that the annual rate of change must be positive (i.e., an annual rate of SOC change ≥ 0). Given the critical functions of SOC in maintaining soil quality and productivity, stover removal can only be justified if it does not deplete the SOC pool. These acceptable levels represent field-level losses that are feasible to attain using traditional conservation treatment (nutrient management and soil erosion control) and are agronomically feasible within the UMRB. Scientific literature on field research and edge-of-field monitoring in the US Midwest, coupled with model simulation of conservation practice effects, provided guidance for identifying these thresholds (USDA NRCS 2010).

As previously shown in figure 3, 9% of the UMRB corn acreage under the Baseline management fails to meet the SOC change acceptable planning criteria, even without any stover removal. Increasing stover removal increased the area that fails to meet the planning criteria. Approximately 36% of Baseline non-HEL and 33% of HEL meet all planning criteria (table 8) across the three stover removal rates of 40%, 60%, and 80%. Similarly, 35% of the predominant loamy soils meet all the planning criteria. Although occurring in smaller proportions relative to the loamy soils, 38% of clayey and 42% of sandy soils meet the planning criteria. For soil hydrologic groups, 42% of sites on group A soils, 38% on group B soils, 32% on group C soils, and 31% on group D soils meet the planning criteria.
meeting all of the above criteria (table 8), the planning criteria.

* For the Baseline management, approximately 4 million ha meet the planning criteria.

** Table 7**
Effects of site-specific factors and corn stover removal on annual nitrogen and phosphorus losses in the Upper Mississippi River Basin.

<table>
<thead>
<tr>
<th>Site-specific factors</th>
<th>Land type</th>
<th>Soil textural class</th>
<th>Soil hydrologic group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HEL</td>
<td>non-HEL</td>
<td>A</td>
</tr>
<tr>
<td>Nitrogen losses (kg ha(^{-1}) y(^{-1}))</td>
<td>0%</td>
<td>0.0 ± 0.0</td>
<td>2.5 ± 0.0</td>
</tr>
<tr>
<td></td>
<td>20%</td>
<td>2.0 ± 0.0</td>
<td>4.0 ± 0.0</td>
</tr>
<tr>
<td></td>
<td>60%</td>
<td>6.0 ± 0.0</td>
<td>12.0 ± 0.0</td>
</tr>
<tr>
<td></td>
<td>80%</td>
<td>8.0 ± 0.0</td>
<td>16.0 ± 0.0</td>
</tr>
</tbody>
</table>

** Phosphorus losses (kg ha\(^{-1}\) y\(^{-1}\))**

| Baseline management  | HEL       | 0.0 ± 0.0           | 1.0 ± 0.0            | 2.0 ± 0.0       | 4.0 ± 0.0       | 8.0 ± 0.0       | 4.00 ± 0.0 |
|                       | 20%       | 1.0 ± 0.0           | 2.0 ± 0.0            | 4.0 ± 0.0       | 8.0 ± 0.0       | 16.0 ± 0.0      | 8.00 ± 0.0 |
|                       | 60%       | 4.0 ± 0.0           | 8.0 ± 0.0            | 16.0 ± 0.0      | 32.0 ± 0.0      | 64.0 ± 0.0      | 32.00 ± 0.0 |
|                       | 80%       | 6.0 ± 0.0           | 12.0 ± 0.0           | 24.0 ± 0.0      | 48.0 ± 0.0      | 96.0 ± 0.0      | 48.00 ± 0.0 |

Enhanced conservation treatment

| HEL       | 0.0 ± 0.0           | 1.0 ± 0.0            | 2.0 ± 0.0            | 4.0 ± 0.0       | 8.0 ± 0.0       | 16.0 ± 0.0      | 8.00 ± 0.0 |
| 20%       | 1.0 ± 0.0           | 2.0 ± 0.0            | 4.0 ± 0.0            | 8.0 ± 0.0       | 16.0 ± 0.0      | 32.0 ± 0.0      | 16.00 ± 0.0 |
| 60%       | 4.0 ± 0.0           | 8.0 ± 0.0            | 16.0 ± 0.0           | 32.0 ± 0.0      | 64.0 ± 0.0      | 128.0 ± 0.0     | 64.00 ± 0.0 |
| 80%       | 6.0 ± 0.0           | 12.0 ± 0.0           | 24.0 ± 0.0           | 48.0 ± 0.0      | 96.0 ± 0.0      | 192.0 ± 0.0     | 96.00 ± 0.0 |

Notes: Mean confidence limits at p ≤ 0.05. HEL = highly erodible land.

** Table 8**
Average annual grain and stover yields, sediment losses, rate of soil organic carbon change (SOC), nitrogen (N) losses in runoff and subsurface flow, total phosphorus (P) losses, and percent of Upper Mississippi River Basin* croplands with sites meeting all of the CEAP National Cropland Assessment acceptable planning criteria.

<table>
<thead>
<tr>
<th>Grain yield (Mg ha(^{-1}))</th>
<th>Stover yield (Mg ha(^{-1}))</th>
<th>Sediment loss (Mg ha(^{-1}))</th>
<th>SOC change (kg ha(^{-1}) y(^{-1}))</th>
<th>Runoff N loss (kg ha(^{-1}) y(^{-1}))</th>
<th>Subsurface flow N loss (kg ha(^{-1}) y(^{-1}))</th>
<th>Total P loss (kg ha(^{-1}) y(^{-1}))</th>
<th>Croplands meeting criteria (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline management practice</td>
<td>8.65 ± 0.02</td>
<td>4.89 ± 0.03</td>
<td>1.34 ± 0.01</td>
<td>1.03 ± 0.01</td>
<td>0.05</td>
<td>0.00</td>
<td>1.2</td>
</tr>
</tbody>
</table>

** Land type**

- Highly erodible: 8.64 ± 0.02
- Nonhighly erodible: 8.67 ± 0.01

** Soil textural class**

- Clayey: 8.28 ± 0.07
- Loamy: 8.69 ± 0.01
- Sandy: 8.04 ± 0.06

** Soil hydrologic group**

- A: 8.10 ± 0.06
- B: 8.64 ± 0.01
- C: 8.58 ± 0.03
- D: 8.91 ± 0.02

Notes: Mean confidence limits at p ≤ 0.05.
* For the Baseline management, approximately 4 million ha meet the planning criteria.

For the Baseline management and for sites meeting all of the above criteria (table 8), the average corn grain and stover yields were 8.65 and 4.89 Mg ha\(^{-1}\) (135 bu ac\(^{-1}\) and 2.18 tn ac\(^{-1}\)) from approximately 4.0 million ha (9.9 million ac), giving a total grain and stover production of 34.8 and 19.2 million Mg (1.4 billion bu and 21.2 million tn), respectively. The stover production of 19.2 million...
Mg is equivalent to 6.5 billion L (1.7 billion gal) of ethanol, which exceeds the National Energy Independence and Security Act goal for 2012 of 3.8 billion L (1 billion gal). However, this study does not address industry concerns of location and capacity of ethanol production plants. A key concern is the concentration of corn acreage at an economic distance from the plants. These concerns are beyond the scope of this study.

These results show that the UMRB has tremendous potential for lignocellulosic ethanol production and that corn stover removal thresholds meeting the acceptable planning criteria are permissible, while utilizing less corn acreage. The planning criteria are crucial in securing sustainable corn stover feedstock production guidelines with acceptable environmental tradeoffs. Differential impacts of stover removal were most pronounced among the soil textural classes, followed by soil hydrologic groups, and then land types. Overall, sandy soils seem to be the most vulnerable to the impacts of stover removal on grain and stover yields and the environment. Stover harvest rate should be decreased when soil texture becomes coarser (Andrews 2006). Johnson et al. (2010) recommend exclusion of stover harvest from HEL and other marginal lands and emphasized management strategies to protect against erosion. For agricultural lands with moderate to low erosion risk, stover removal should take into account the need to maintain SOC.

Finally, in figure 7, we illustrated the spatial variation of simulated corn stover yields, annual change in soil organic carbon, sediment loss, and annual N nutrient loss at the 60% stover removal rate across the Upper Mississippi River Basin as impacted by site-specific factors of land type, soil texture, hydrologic group, and agroclimate.

**Summary and Conclusions**

Although the results of this study are based on a simulation approach, they underscore the importance of site-specific factors and their effects on corn grain and stover yield, and the impact of corn stover removal on the environment. It is apparent that sustainable stover removal thresholds cannot be based on a one-size-fits-all approach but will most likely be met through a range of corn stover removal rates that will depend on management practice, land type, and landscape site-specific factors or conditions such as, topography, soil texture-hydrologic group interactions, agroclimate, and socioeconomic. By making use of the acceptable planning criteria, it is possible to identify and quantify resilient production sites (i.e., those meeting the planning criteria) against vulnerable sites based on site-specific conditions. We also showed that applying the ECT management practices considerably mitigates some of the sediment, nutrient, and SOC losses on the vulnerable sites. Still, even when fully treated, some of the vulnerable sites will still have unacceptable losses negatively impacting the soil resource base, environmental quality and hence potential productivity. For these areas, intermittent stover harvests should be considered (e.g., removing corn stover only every other year or even less frequently) coupled with other alternative biofuel feedstocks production systems, such as the growing of herbaceous species and short-rotation woody crops like switchgrass and hybrid poplar. There is no doubt information derived from this study can also be used to develop better guidelines for producers to apply precision conservation techniques across varying farm landscapes, land types, and soil texture-hydrologic groups.

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**References**


Figure 7
Spatial variation of simulated (a) corn stover yields, (b) annual change in soil organic carbon (SOC), (c) sediment loss, and (d) annual nitrogen nutrient loss at the 60% stover removal rate across the upper Mississippi River Basin.

(a) Corn stover (mg ha$^{-1}$)
- 0.0 to 2.5
- 2.6 to 5.0
- >5.0

(b) SOC (kg ha$^{-1}$ y$^{-1}$)
- -700 to -100 losing
- -99 to 100 maintaining
- 101 to 905 gaining

(c) Sediment loss (mg ha$^{-1}$)
- 0.0 to 5.0
- 5.1 to 20.0
- >20.0

(d) Nitrogen (kg ha$^{-1}$ y$^{-1}$)
- 0 to 25
- 26 to 50
- 51 to 150
- >150

Legend for all maps:
- Lake Superior
- Lake Michigan
- Mississippi River

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