WRI POLICY NOTE

ENERGY: BIOFUELS No. 3

WORLD RESOURCES INSTITUTE

Finding Balance: Agricultural Residues, Ethanol, and the Environment

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Crop residues like wheat straw and corn stover—i.e. stalks and leaves— have been proposed as a sustainable feedstock for a "next-generation" cellulosic ethanol industry in the United States. However, use of agricultural residues should not be considered to have low environmental impacts simply because they are a by-product of an existing use of the land. Such residues currently replenish and protect soils on working agricultural lands, and their removal is unlikely to be sustainable unless accompanied by adoption of agricultural best management practices such as no-till production, cover crops, and precision fertilizer management.

Key Findings

1. Even moderate corn stover harvest increases erosion and depletes soil carbon on working lands.
2. The increased fertilizer application and increased erosion associated with harvest of corn stover leads to increased nutrient losses from the field, which will exacerbate critical surface and coastal water issues like the Gulf of Mexico's "dead zone."
3. A conversion to reduced tillage production can help protect against soil loss due to erosion, but it is relatively ineffective at protecting against the depletion of soil carbon.
4. Other best management practices such as winter cover crops are effective at capturing nutrients and replacing harvested residues as a source of soil enrichment, but are not widely used by farmers in practice.

Policy Recommendations:

1. All federal and state policies providing support for biofuel production (such as the Renewable Fuels Standard and the Volumetric Ethanol Excise Tax Credit) should include environmental performance requirements that ensure the adoption of best management practices to offset the environmental impacts of feedstock production.
2. Federal biomass research programs should be fully funded. Both USDA and USDOE should invest greater resources into research on the long-term sustainability of using biomass and agricultural residues for biofuel production.
3. All projects receiving federal funds to explore crop use for biofuel production should be required to explicitly address the soil, water, and greenhouse gas implications of the new crop varieties or production methods.
4. USDA should increase investment in research on obstacles and opportunities for adoption of agricultural best management practices, particularly cover crops and conservation tillage, and support programs and/or policies to overcome them.
5. In federal evaluations of biomass availability, the criteria for "sustainable" residue supply systems must be broadened beyond a consideration of erosion to include other ecosystem services provided by agricultural land such as soil carbon sequestration and water quality considerations.

Introduction

Renewable energy goals in the United States have proliferated since the turn of the millennium. Prompted by volatility in oil markets, a growing awareness of the irreversible contribution that fossil fuel combustion makes to global warming, and an interest in supporting farms and rural communities through stronger agricultural markets, Congress, federal agencies, and a diverse alliance of private interests have repeatedly re-affirmed their commitment to increasing the use of biomass as an alternative energy source in the United States. A 2005 study jointly administered by the U.S. Department of Agriculture (USDA) and U.S. Department of Energy (USDOE) concluded that the nation's agricultural and forest resources could sustainably produce sufficient biomass to displace 30% of the country's 2003 petroleum consumption (Perlack et al., 2005).[1]

In part due to recent studies highlighting the greenhouse gas impacts of land-use conversion for the production of dedicated energy crops (including both food and non-food feedstocks) (Searchinger et al., 2008; Fargione et al., 2008), much attention has been paid to the potential for agricultural "wastes" or residues to supply a significant portion of the necessary biomass for a next-generation ethanol industry without a substantial increase in cultivated acreage. In the USDA/USDOE study, dubbed the "Billion Ton" study, the majority of the available 1366 million dry tons of biomass is assumed to come from agriculture (nearly 1 billion tons), with 428 million tons of that coming from annual crop residues. Because nearly a quarter of the nation's cropland is planted in corn, corn stover (the stalks and leaves left on a field after corn harvest) is assumed to be the most abundant source of available agricultural residue. Soil scientists, however, are quick to point out that these residues currently serve a function on the farm; when left on fields, they help reduce erosion and its associated water-quality impacts, build up the soil's productivity through increased organic matter and nutrients, and sequester carbon that might otherwise be released into the atmosphere as a greenhouse gas (Wilhelm et al., 2004).

To address the issue of environmental impacts, a "sustainable" harvest rate is often calculated as one that controls erosion and maintains levels of soil loss below a specified "tolerable" limit (Graham et al., 2007; Perlack et al., 2005). Because vulnerability to erosion is often tied to the intensity with which the soil is tilled (i.e. how many passes tractors and tillage equipment make over the field and the depth of the soil that they disturb), many sustainable supply figures assume that no-till or low-till management systems, which minimize the disturbance of soil and the breakdown of remaining residues, are adopted before residue is harvested. The Billion Ton study's figure of 428 million tons of crop residue, for instance, assumes that all of that residue is produced on cropland that is managed using no-till practices, despite the fact that, according to the most recent USDA Agricultural Resource Management Survey (ARMS) data, less than 25% of corn acreage is currently managed using no-till practices.

Much of the ensuing research on the impacts and implications of a large-scale diversion of residues from our nation's farms concludes that unless production practices and removal rates are carefully managed, large-scale stover removal could threaten the long-term health and productivity of the nation's agricultural soils. Blanco-Canqui et al. (2007) find that even under no-till field management systems, harvest of more than 25% of corn residue reduces soil productivity and organic carbon content on soils that are sloped or otherwise vulnerable to erosion. Wilhelm et al. (2007) compare the environmental impacts of stover harvest from continuous corn and corn-soybean rotations under both a conventional and a no-till management regime. They conclude that, although control of erosion is often used as the limiting factor in estimating sustainable removal rates, maintenance of soil organic content may be an even more limiting constraint. Additionally, Varvel and Wilhelm (2008) point out that there have been no long-term studies to definitively determine the sustainability of harvesting stover for biofuel production. Pressing ahead with large-scale production without first understanding the long-term impacts and how they might be mitigated may prove unwise if there are significant negative consequences for water quality, soil health, and agricultural productivity.

WRI Analysis

This analysis explores the implications of corn stover harvest for soil carbon loss, nutrient (nitrogen) pollution, and erosion, as well as the potential to mitigate those impacts using available agricultural best management practices (BMPs) such as reduced tillage intensity and integration of winter cover crops (WCC) into production rotations. We use a biophysical simulation model, Environmental Policy Integrated Climate (EPIC), that has been calibrated to simulate crop production, and the environmental impacts of production, in the Embarras Watershed in east-central Illinois.[2] As is characteristic of that area, the site that we simulate is relatively flat (2% slope) with a "non-highly-erodible" soil type.

To simulate corn production in both a continuous corn and corn/soybean rotation, planting, tillage, and fertilization schedules for a representative corn/soybean rotation in the Embarras watershed were modified to create baseline continuous corn and corn/soybean production systems. Both systems were then modified to include stover harvest scenarios in which 30% and 60% of stover residue, respectively, are removed from the fields.[3] These scenarios allowed us to compare the relative environmental impacts of introducing stover harvest into corn production and of moving between corn production rotation systems and between stover harvest amounts in stover supply. To explore the potential for adoption of best management practices (BMPs) as a tool for mitigating the negative environmental impacts of stover harvest under the various production scenarios, we created reduced tillage versions of each of the systems,[4] and we introduced into the production systems two winter cover crops available to the U.S. Corn Belt, winter wheat and hairy vetch.[5] Results from baseline systems where crop residues were totally retained were compared to systems with 30% and 60% stover removal, those with stover removal combined with introduced winter cover, and with low-till versions of all scenarios.

The results presented here are derived from simulation modeling, and as such are heavily dependent upon and sensitive to the assumptions and structure of the model used. EPIC, and the models that have evolved from it such as APEX, have been applied extensively to cropping systems worldwide on a variety of soils and cropping systems (see He et al.. (2006) for a review), and a number of validation studies have been performed to explore its handling of nutrient cycling and nutrient loss (Gassman et al.., 2005).

Results

Our analysis confirms a significant threat of increased environmental damage from even moderate (30%) corn stover harvest on working lands. Erosion and soil carbon loss increased sharply as a result of the removal of winter cover and of the failure to re-integrate organic matter into the soil. Nitrogen loss to waterways, a major contributor to nutrient pollution (eutrophication) and the expansion of the nation's "dead zones" (Selman et al., 2008), also increases significantly as production systems shift away from corn/soybean rotations to nitrogen-intensive continuous corn rotations that increase stover supply. The findings also demonstrate, however, the potential that exists to mitigate the environmental impacts of stover removal with increased adoption of best management practices such as reduced tillage intensity and/or winter cover crops.

Erosion

For decades, the sustainable agriculture community has urged farmers to adopt farm management practices that leave greater plant residue on the soil surface to protect soils from wind and water erosion. Wind and water erosion threaten both long-term soil productivity on the field, through loss of productive topsoil, and water quality off the field, as sediment and nutrients washed into surface waterways negatively impact aquatic plant and fish communities, accelerate eutrophication leading to algal blooms, increase costs of municipal and industrial water treatment, and lead to siltation of irrigation canals, transport channels and reservoirs.[6]

Despite the shallow slope and non-highly-erodible soil on the site, our results indicate that even moderate amounts of stover removal (30%) significantly increase erosion (Figure 1).

In part due to sheer volume, undisturbed corn residue is much more effective than soybean residue at protecting fields from erosion, which explains the drop in erosion observed when production moves from a corn/soybean rotation to a continuous corn rotation. When that residue is removed, however, erosion sharply increases on both rotations, and the erosion benefits of continuous corn versus corn/soybean are erased.

Our model results also illustrate, however, that agricultural best management practices such as reduced tillage intensity and/or winter cover crops can largely mitigate the additional erosion threat caused by stover removal (Figure 2). Lower tillage intensity reduced average annual combined wind and water erosion significantly, by between 52% and 79% across

FIGURE 1 Impact of Stover Harvest on Total Wind and Water Erosion

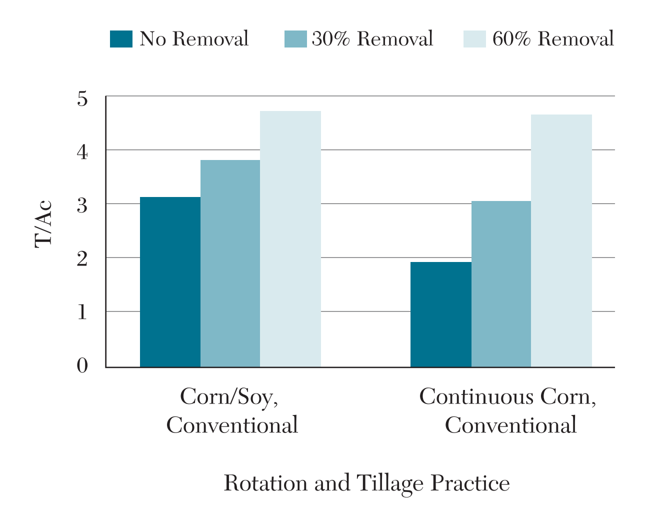
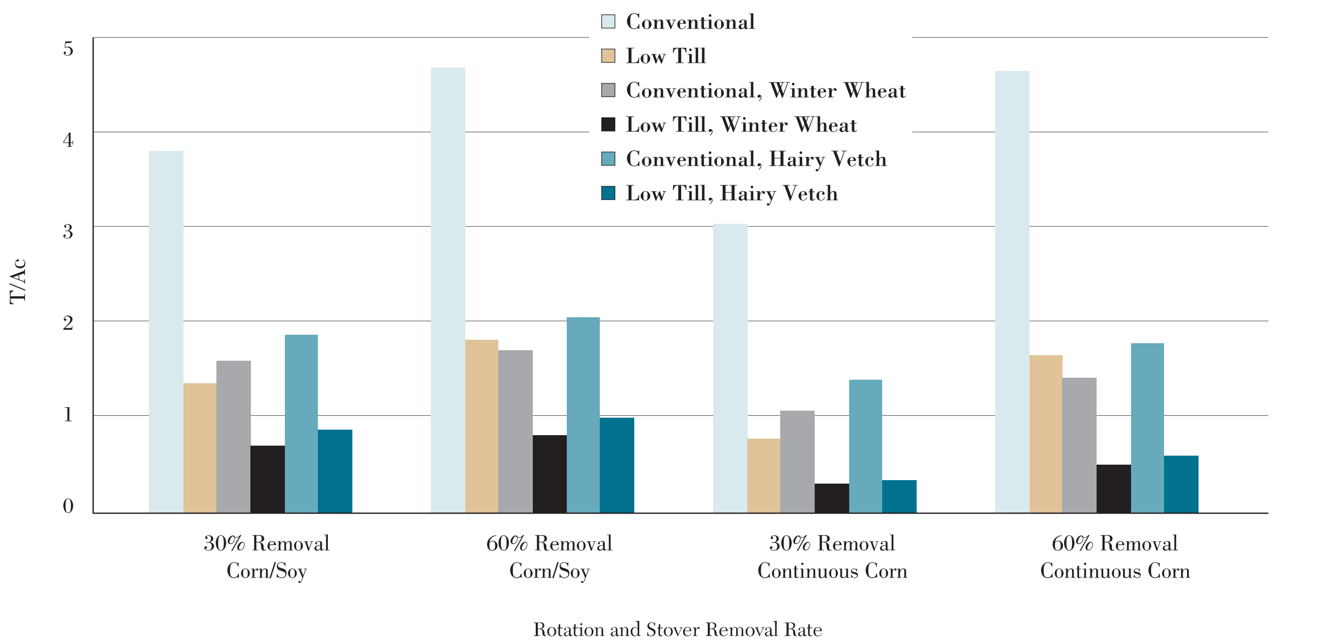


FIGURE 2 Impact of Best Management Practices Such as Low Till and Cover Crops on Total Erosion Levels with Stover Removal



all systems, with a proportionally greater impact on the systems without winter crops added. Incorporating a winter cover crop such as wheat or hairy vetch also strongly mitigates soil loss, even without a reduction in tillage intensity. Therefore, while stover harvest alone clearly poses a threat to surface water quality, and possibly to soil productivity, stover harvest in combination with adoption of sustainable agricultural practices can result in improved conditions relative to current practice.

FIGURE 3 Impact of Management Practices on Organic Carbon Flux in Conventional Systems

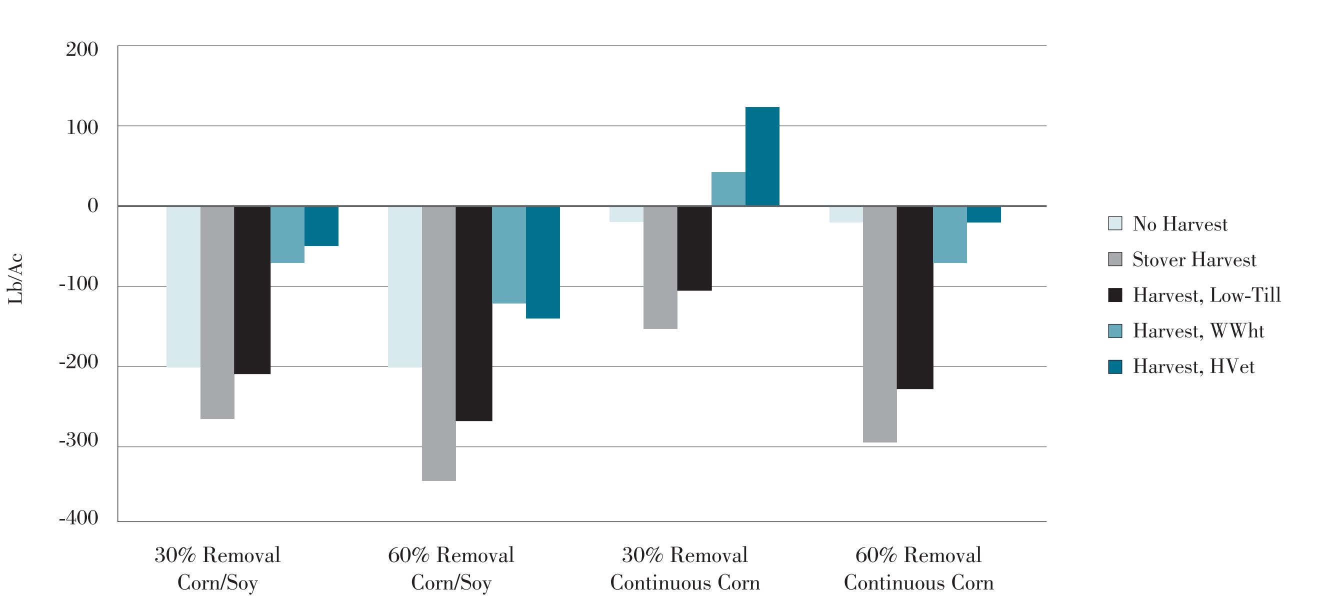


TABLE 1. Average change in soil organic carbon (lb/ac)

	Conventional	Low Till
Corn/Soy (CS)	-202.1	-147.8
Continuous Corn (CC)	-20.5	-0.7
CS, 30% Stover Harv.	-267.2	-209.7
CC, 30% Stover Harv.	-153.8	-104.5
CS, 60% Stover Harv.	-342.5	-269.3
CC, 60% Stover Harv.	-295.8	-229.3
CS, 30% Stover Harv., WWht	-70.1	-55.8
CC, 30% Stover Harv., WWht	41.7	50.7
CS, 60% Stover Harv., WWht	-121.0	-101.1
CC, 60% Stover Harv., WWht	-70.0	-49.4
CS, 30% Stover Harv., HVet	-48.1	-31.8
CC, 30% Stover Harv., HVet	122.1	121.1
CS, 60% Stover Harv., HVet	-140.8	-98.9
CC, 60% Stover Harv., HVet	-19.9	-3.9

Soil Organic Carbon

Maintenance and enhancement of soil organic carbon on agricultural soils has been suggested as a way to sequester carbon and decrease aggregate greenhouse gas emissions from agriculture. Agricultural residues, however, play a key role in that scenario, because they, together with the carbon returned to the soil through root growth, represent the primary physical pathway along which carbon is moved into the soil for storage. Although analyses have traditionally focused on erosion as the limiting factor in determining sustainable stover removal, recent research has indicated that impacts on soil organic carbon may be a more limiting factor (Wilhelm et al., 2007; Blanco-Canqui and Lal, 2007). Our analysis confirms that even moderate stover harvest substantially decreases soil organic carbon, but that integration of a winter cover crop can replace the carbon lost and enhance soil carbon storage (Figure 3).

The change in soil organic carbon resulting from agricultural production is highly dependent on the management practices used. Our results suggest that current conventional production practices result in a loss, rather than an increase, of soil carbon. Total organic carbon losses for basic continuous corn are an average of 20 lb/ac/yr and for corn-soybeans are 202 lb/ac/yr. As mentioned earlier, corn has a much greater volume of plant residue than soybeans and is therefore more effective at returning carbon to the soil through residues; during the last 15 years of the simulation, the continuous corn system is close to a carbon equilibrium, with just as much carbon returned to the soil through residues as is lost through decomposition, tillage, organic carbon in runoff, etc. The corn/soybean rotation, on the other hand, does not produce enough residue, even without stover harvest, to offset the losses from conventional agricultural practice and is a net releaser of carbon.

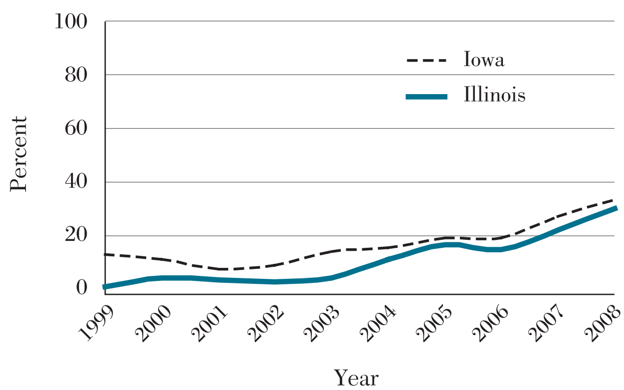
In the absence of cover crop establishment, stover removal significantly increases soil carbon loss, particularly from continuous corn rotations, where stover is removed annually. Removal of 30% of stover residue increases soil carbon loss by 65 lbs/ac/year in the corn-soybean rotation and by 133 lbs/ac/year in the continuous corn rotation, while removal of 60% of corn stover residue increases soil carbon loss by 140 lbs/ac/yr in the corn-soybean rotation and by 275 lbs/ac/yr in the continuous corn rotations. Switching to a low-tillage production practice does not fully compensate for the carbon lost through stover removal, and in the case of continuous corn only prevents a fraction of the loss (Table 1). Cover crops, on the other hand, are highly effective at slowing, and even reversing, the carbon loss associated with stover removal. In the case of continuous corn with a 30% stover harvest, cover crops planted annually were able to convert the system into a net carbon sequesterer rather than an emitter.

Nitrogen Loss

The problem of nutrient pollution has occupied a pivotal position in the agricultural sustainability debate since the early 1980s,[7] when nitrogen-rich agricultural runoff from Midwest corn fields was implicated as the primary cause of the Gulf of Mexico's "dead zone"—a seasonal phenomenon in which a huge swath of the Gulf is rendered lifeless for lack of oxygen. The nation's largest commodity crop—corn—demands large nitrogen applications to thrive, but the nitrogen (and phosphorus) not captured by the plant can get washed out of soil and into surface waterways for transport to the Gulf.

For decades, a concerted effort has been made to reduce nitrogen demand (and loss from fields) through improved nitrogen use efficiency of corn varieties, diversified rotations that include nitrogen-fixing crops, which capture nitrogen from the air and release it into the soil as the residues decompose, and, more recently, precision application to encourage more efficient nitrogen uptake by plants. Farmers have steadily been moving from continuous corn to corn/soybean rotations to take advantage of the "nitrogen credit" provided by nitrogen-fixing soybeans as well as to avoid the pest and disease issues associated with monoculture production. In recent years, however, the nation has observed a trend back toward continuous corn production to reap the benefits of high corn grain prices (Fig-

FIGURE 4 Percentage of Corn Planted on New Cropland or Following Corn*



* This figure assumes that all cropland in these states is planted in soy or corn, so that any corn not following soy is assumed to follow corn or be planted on new cropland. Data from USDA Crop Production Reports.

ure 4). Fertilizer demand and prices surged as well; after a wet spring, nitrogen loading into the Gulf in 2008 was estimated to be 37% larger than the 2007 loading levels, and the 2008 dead zone covered a near-record 8,000 square miles, almost double its 10-year average size (Garber, 2008; Achenbach, 2008).

The rising prices of fertilizer and of soybeans, which compete with corn for land resources, slow the conversion of land to continuous corn or rotation variations that include multiple years of corn to one year of soybeans. However, combining increased returns generated by a market for corn stover with existing incentives for corn production will have the opposite effect, providing a countervailing incentive for the inclusion of more corn in production rotations. This trend poses a continuing threat to surface waterways, and our results suggest that the best management practices explored here would be relatively ineffective at mitigating that threat (Figure 5).

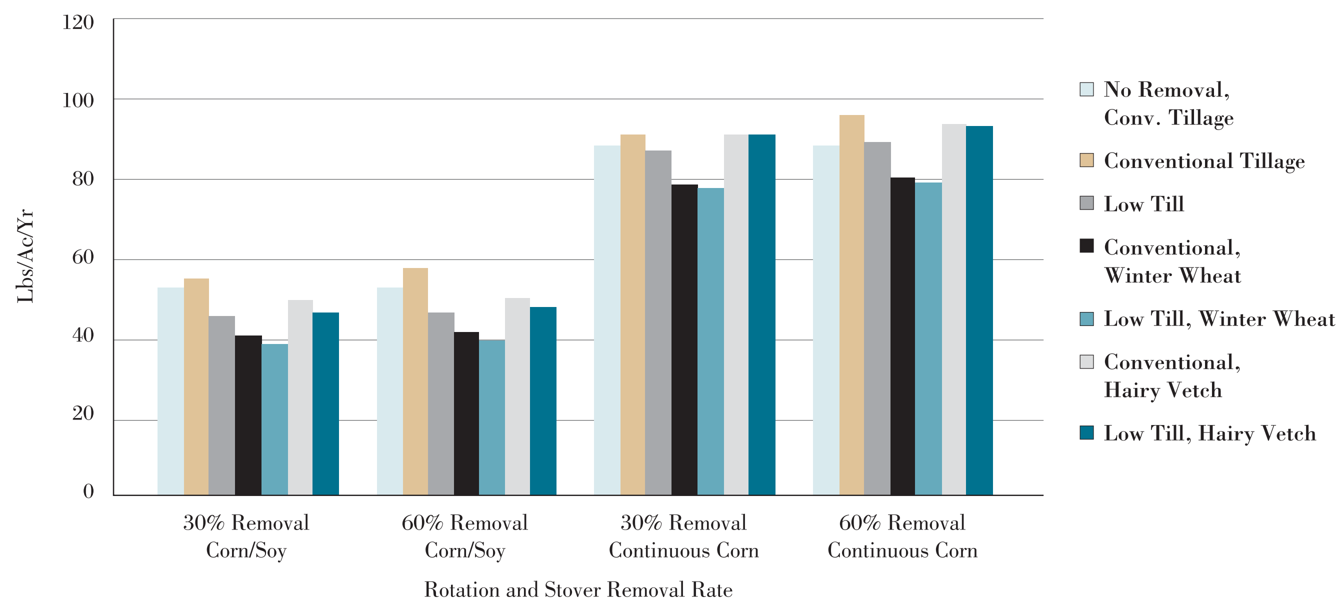
Although there is a slight increase in nitrogen loss with stover harvest, clearly, the nitrogen problem from this acreage is related less to the stover harvest and more to the baseline nitrogen needs of corn production. The most effective management option for reducing nitrogen loss from the fields appears to be introduction of a non-leguminous winter cover crop such as winter wheat, which reduces nitrogen loss by 14-28%. Wheat, also a nitrogen-intensive crop, pulls available nitrogen out of the soil rather than allowing it to be flushed from the soil during winter and spring rains. Hairy vetch is less effective when introduced into systems with a fixed nitrogen fertilizer application rate, as simulated here, because it is a nitrogen-fixer itself and therefore actually introduces additional nitrogen into the soil in the form of organic matter. Over time, however, that nitrogen-rich organic matter enhances the soil's capacity to provide for the crop's nitrogen needs, and should therefore result in a decreased need for synthetic fertilizer application, which would improve the system's long-term performance with respect to nitrogen loss. Research into the optimal timing and levels of fertilizer application after leguminous winter cover crops, and how that dynamic changes during the years in which soil composition is changing and building, is needed to clarify the true potential of such crops as nitrogen management tools in these systems.

Estimating Industry-scale Impacts

It is impossible to use a field-scale analysis to precisely estimate the aggregate impacts of harvesting corn stover to support a cellulosic industry of a given size, but a sense of the magnitude of the potential problem can be achieved by considering the acreage required to support an ethanol industry using stover as a feedstock. The Renewable Fuel Standard (RFS) passed in December 2007 as part of the Energy Independence and Security Act requires that by 2022, 36 billion gallons/year of renewable fuels be blended into the nation's transport fuel supply. Because the RFS caps qualifying corn-based ethanol at 15 billion gallons/year and calls for 5 billion gallons/year of "advanced" biofuels such as high-efficiency sugarcane-based ethanol, and because the U.S. transport system is primarily gasoline-dependent rather than diesel-dependent, the bulk of the remaining 16 billion gallons will likely come from cellulosic ethanol or other next-generation gasoline substitutes currently under development (i.e., biobutanol, etc.).

That scale of fuel production from biomass will require an enormous amount of acreage. Our simulated field, for instance, yielded an estimated 1.07 T/acre of stover when harvested at 30% and 2.10 T/acre when harvested at 60%. Supporting a stover-based ethanol production level of 10 billion gallons/year, using a conversion rate of 85 gallons ethanol/DT, would require 118 million tons of stover each year. At an average yield of 1.07 T/acre, that level of production would require 120 million acres of harvested stover, which is almost 20% larger than the total acres planted to corn in 2007. If you assume instead that the necessary stover is harvested using a 60% harvest rate, only 59 million acres are required, but the environmental impacts of such intensive harvest are also proportionally greater. WRI is currently engaged in a study using a national agricultural production model with differentiated regions and production

FIGURE 5 Impact of Stover Removal and Management Practice on Nitrogen Loss from Fields



enterprises based on field-scale analyses such as this one to estimate the aggregate environmental impacts of harvesting corn stover at such scales (Marshall et al., 2008).

Adoption of Agricultural Best Management Practices

There is a wealth of knowledge about the benefits of agricultural best management practices such as reduced tillage and cover cropping. Unfortunately, such practices have been slow to catch on in the United States. A survey of 3500 active farmers in Iowa, Minnesota, Illinois, and Indiana found that despite generally being aware of the major benefits of cover crops, only 11% had planted them at some point in the previous five years and that even fewer (8%) planted them in the fall of the growing year the survey was conducted (Singer et al., 2007). Furthermore, these plantings only comprised about 6% of the total land of the average farm. Lower impact tillage practices have seen more widespread adoption, but are still not overwhelmingly used, as reduced tillage is practiced on only 26% of planted corn acres and no-till on just 24% (USDA/ERS).

In this analysis, we explored the impact potential of two agricultural BMPs, but there are many others that could lessen the environmental impacts of stover removal, including subsurface fertilizer application, conservation buffers such as filter strips and grassed waterways, drainage and irrigation water management, and practices to reduce erosion such as contour farming and terracing. Additionally, precision farming techniques incorporating technologies such as GPS and remote sensing can result in more efficient nutrient application. However, these practices also face hurdles to more widespread implementation.The reasons cited for the reluctance to adopt such practices have ranged from cost and technical feasibility to availability of technical expertise and resources.

The survey mentioned above found that more than half of respondents would use cover crops if cost-sharing was available, and also identified a need for increased targeted education of producers on key factors such as cost, crop selection, and management. Dobermann and others (2004) note that precision farming requires substantial up-front investment in technology and a potentially sizable learning curve that can be prohibitive for many farmers, in addition to other disincentives. Further, a recent survey of Great Plains producers found that although farmers may understand the benefits of BMPs, they may not use conservation practices because they do not perceive water quality as a severe problem (Smith et al., 2007). Additional reasons for non-adoption may include a desire for greater flexibility in land-use decisions than programs permit, and the inherent time requirements of enrollment paperwork and navigating the complexities of the programs. The researchers suggest that although increased cost-sharing assistance would likely increase enrollment to some degree, more funding alone would not be as effective as an approach addressing these other obstacles as well. To further advance adoption of agricultural best management practices, increased resources should be dedicated to the study of the extent and relative importance of these barriers and the design of programs to overcome actual or perceived obstacles.

In addition to currently available best management practices, new practices and technologies are being explored that hold promise for facilitating nutrient recycling and carbon sequestration when used in conjunction with energy crop production. In a departure from more common visions of cellulosic ethanol fermentation biorefineries, one such technology involves the use of small scale pyrolyzers to convert biomass into syngas, bio-oil, and charcoal at processing areas close to the point of feedstock production. According to one scenario, the syn-gas produced can be used to power the pyrolysis process, the bio-oil can be transported as a higher density feedstock to a central refinery for processing to fuel, and the charcoal can be returned to the soil to replenish soil carbon and nutrients (Laird, 2008). Although research suggests that charcoal has positive impacts on soil such as providing slow-release nutrients and improving water retention, aeration, and root penetration (Glaser et al., 2002), few long-term studies have been conducted on the accumulated impacts of charcoal re-introduction over time or on the cost-effectiveness of these biomass processing systems. Clearly this is another area where accelerated research and development could help in the design of sustainable biomass to bioenergy systems.

Conclusions

In light of the projected expansion of the ethanol industry, with estimated domestic industry growth toward 20 to 60 billion gallons of cellulosic ethanol per year over the next several decades, further research on the long-term impacts of providing the feedstocks necessary for that industry is critical. Our research indicates that removing agricultural residues, which are widely believed to be relatively benign from an environmental perspective because they have a lower land-use footprint than other feedstocks, can have a significant environmental impact in terms of increasing erosion and decreasing carbon sequestration services on existing agricultural land. With proposed residue removal scaled up to levels such as the USDA estimate of 428 million dry tons per year, even with increased crop productivity the potential for long-term decreases in soil productivity, increases in greenhouse gas emissions from the agricultural sector, and worsened surface water quality cannot be ignored.

There is also great potential to mitigate some of those impacts through the adoption of agricultural best management practices. Our research suggests that, although reduced tillage is effective at controlling erosion, it is not nearly as effective at dealing with the reduced carbon sequestration capacity of agricultural fields after stover removal. Cover crops, on the other hand, are effective at dealing with both issues, but a host of obstacles to their adoption must be addressed before they are likely to be widely adopted in conjunction with stover harvest.

Agriculture is at a crossroads worldwide. Proposals to displace a portion of our petroleum fuel use with renewable fuels produced from biomass promise to open up new market opportunities for farmers and strengthen the ability of agricultural systems to support themselves without government support. The potential environmental costs associated with these new markets are significant however. Under current agricultural policies, there is no guarantee that best management practices will be adopted to address those impacts. In the United States, where requirements for BMP adoption have traditionally only existed when tied to government support payments, incentives for adoption may actually decline in future years as higher prices result in a decline of government support.

There is, however, also tremendous opportunity at this juncture to link new types of BMP compliance requirements to the emergence of new opportunities such as biomass markets to keep those impacts to a minimum. Because new market opportunities for farmers and new sources of energy to promote energy independence must not come at an unacceptable cost to the nation's soil, water, and air resources, it is critical that we understand those costs and take the policy steps required to ensure that biomass supply systems evolve within acceptable impact limits. The relevant policy arena is broad—encompassing agricultural, energy, transport and trade policy—as are the available policy tools, which include certification systems, trade restrictions, direct regulations on agricultural practices or impacts associated with biomass harvest, etc. Unfortunately, we have little experience or understanding of how such policies (domestic and international) could accommodate sustainability requirements, how multiple policies would interact, and how they will impact suppliers and supply systems. Stakeholders must invest the resources necessary to move that discussion forward. It is not enough to understand what *could* make biomass supply sustainable; we must create and support the institutions that *will* make biomass supply sustainable.

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Acknowledgments

The authors would like to thank Tom Damassa and Christian Layke from WRI, John Sadler from USDA, and Jill Euken from Iowa State University for their constructive feedback and suggestions. WRI would also like to thank the U.S. Department of Energy, U.S. Department of Agriculture, National Science Foundation, Doris Duke Charitable Foundation, Robertson Foundation, and BP Foundation for support of its climate and biofuels programs.

Notes

1. Although biomass can be used for energy in several ways— burned directly to generate heat and power, dried and densified into solid fuels such as wood or corn pellets, or converted into liquid or gaseous fuels such as ethanol for use in stationary or mobile source combustion—that feasibility study focused on its potential for conversion of liquid transport fuels to displace petroleum consumption.
2. For a more representative simulation, crop growth and nitrogen cycle parameters are adjusted so that results closely mimic observed yield, runoff and nitrate loss numbers for a 15-year period from 1992–2006. Data were provided by Mark David at University of Illinois. Data for the calibration were provided by Mark David at the University of Illinois.
3. In the stover harvesting scenarios, nutrient application was adjusted to compensate for the nutrients removed from the field with the stover. Adjustments to applied fertilizer N and P were based on modeled average stover yields for each system under baseline nutrient application, assuming a loss of 0.0035 g N/g stover collected and .0018 g P/g stover collected (Powers, 2005).
4. Each reduced tillage enterprise included light field and row cultivation, but removed the tandem disc and point chisel plow operations found in the conventional production systems. No-till planters were also used in place of row planters.
5. Winter cover crops were drill planted in the fall immediately after harvest and killed in the spring but left on the fields; the winter wheat did not mature to harvest stage and therefore both crops served as winter cover, then green manure in the spring.
6. Several research efforts have focused on determining how much residue must be left on the field to keep soil loss from erosion within acceptable, or “tolerable,” levels for maintenance of soil productivity, as indicated by a soil’s “T”-value. Most of the T-values for soils in Illinois range from 3-5 T/ac (Univ Illinois Extension, 2004). T-values do not include a consideration of water quality impacts, however.
7. Nutrient pollution refers to the concentrated nitrogen and phosphorus loads delivered to surface waterways in agricultural and urban runoff.

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ISBN 978-1-56973-705-7