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ENERGY: BIOFUELS No. 4
WORLD RESOURCES INSTITUTE

CORN STOVER FOR ETHANOL PRODUCTION: POTENTIAL AND PITFALLS

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KEY FINDINGS

1. Even moderate harvest of corn stover and other agricultural residues for use as an ethanol raw material, or "feedstock," threatens to significantly increase erosion and emissions of greenhouse gases (GHG) from the agricultural sector.
2. The estimates of stover availability appearing in the USDA/USDOE report "Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply" rely on harvest levels that would substantially increase erosion levels and GHG emissions from agriculture and are therefore unsustainable.
3. A large-scale switch to no-till agricultural production would mitigate the increased risk of erosion, but would be relatively ineffective at managing the risks of increased soil carbon loss and increased agricultural GHG emissions that arise with harvest of corn residues. Alternative best management practices (BMPs) for agriculture, including increased use of cover crops, green manures, and precision nitrogen management, may be effective at addressing negative impacts to air, water, and soil resources.
4. Effective integration of BMPs into crop rotations with corn stover harvest will require greatly increased federal investment in research on the long-term impacts and effectiveness of BMPs as well as on overcoming obstacles to farmer adoption.
5. The current system of incentives is not sufficient to induce farmers to voluntarily adopt BMPs such as no-till production in association with corn stover harvest to reduce damaging side effects. Farmers do not switch to no-till production unless the price received for stover is significantly higher than the price at which conventional stover enters the market. Additional incentives and safeguards must be established to ensure sustainable supply.

POLICY RECOMMENDATIONS

1. All biofuel incentive programs and policies, including the 2007 Renewable Fuel Standard and the Volumetric Ethanol Excise Tax Credit, should be revised to include a broad array of safeguards to protect air, soil, and water quality.
2. Existing federal biomass research programs, such as the jointly administered USDA/USDOE Biomass Research and Development Initiative, should be fully funded and should prioritize research on the short- and long-term environmental impacts of harvesting stover and other biomass crops in their funding allocations.
3. Environmental safeguards attached to feedstock production should be performance-based rather than technology- or feedstock-specific. Performance-based safeguards offer maximum flexibility in that they provide incentives for improving feedstock management practices without pre-judging what levels of sustainability are achievable by a given feedstock.
4. To complement feedstock-specific research, greater investment is required for the development of tools to measure the performance, or environmental impacts, of agricultural systems in an affordable and accurate way. Such tools are the foundation of cost-effective agricultural and biofuel sustainability policies.
5. Programs within both USDA and EPA should invest more heavily in research on the contribution of nitrogen (through nitrous oxide) and soil carbon to greenhouse-gas emissions from agriculture and in ways to manage those contributions through both on-farm and off-farm changes in production practices and land management.

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INTRODUCTION

Prompted by volatility in oil markets, growing concerns about global warming, and an interest in supporting farms and rural communities through stronger agricultural markets, several groups in the United States have turned their attention to the potential for ethanol to alleviate our dependence on oil. The domestic ethanol industry has expanded rapidly in recent years, but in the United States, as in other countries, that development has relied heavily on government support. Until 2005, direct support was primarily in the form of tax incentives; the Volumetric Ethanol Excise Tax Credit (VEETC) provides blenders with a tax refund for blending ethanol with gasoline that has ranged between $.54 per gallon and $.45 per gallon. To further catalyze expansion of the renewable fuels market, Congress passed in the 2005 and 2007 energy bills a federal Renewable Fuels Standard (RFS) that mandates increased blending of renewable fuels into our fuel supply.

The sugars found in corn kernels are currently the predominant feedstock for the burgeoning ethanol industry in the United States. However, as increasing world food prices heat up the food versus fuel debate, and scaling up corn production for ethanol use raises environmental concerns (Marshall and Greenhalgh, 2006; Marshall, 2007), increased attention has turned to the potential for second-generation ethanol technologies to free the domestic ethanol industry from its dependence on corn grain. Advanced technologies such as cellulosic conversion, which would allow the production of ethanol from the complex sugars in leaves and stalks, promise to radically broaden the range of possible ethanol feedstocks. Potential future feedstocks include woody biomass such as forest residues, post-consumer municipal solid waste, and agricultural residues such as wheat straw and corn stover—the leaves and stalks that remain behind when corn grain has been harvested.

It is widely believed that cellulosic technologies will allow us to produce ethanol with a smaller environmental footprint than corn-based ethanol. In the expanded RFS passed with the Energy Independence and Security Act of 2007, the amount of corn-grain ethanol that can qualify for the RFS was capped to provide an incentive for the development of second-generation technologies such as cellulosic ethanol. Furthermore, the 2008 Farm Bill includes a cellulosic biofuels production tax credit of up to $1.01/gallon, on top of the VEETC described above, and a "Biomass Crop Assistance Program" that supports farmers as they establish and grow cellulosic biomass crops.[1] As we advance policy to encourage cellulosic production, however, we cannot assume that "better than corn" means sustainable. Different feedstocks will have widely varying environmental footprints that must be understood and acknowledged within flexible biofuel policies that ensure sustainable outcomes. Designing such policies will require greatly increased investment in understanding the potential impacts of various proposed feedstocks, how producer decisions influence those impacts, and how producer decisions respond to policy and market incentives.

CORN STOVER AS A FEEDSTOCK

Corn stover is the most plentiful agricultural residue produced in the United States. In 2008, the United States planted corn on approximately 25 percent of its production acreage, or a total of 91 million acres. A 2005 study on biomass availability for bioenergy production jointly administered by the U.S. Department of Agriculture (USDA) and the U.S. Department of Energy (USDOE) estimated that 75 million dry tons (DT) of corn stover could be harvested sustainably from those acres. The study further estimated that with moderate-to-high yield increases that number could soar to between 170 and 256 million DT per year by 2030 (USDA/USDOE, 2005). At approximately 85 gallons of ethanol per DT biomass, those harvest estimates suggest that by 2030 a sustainable stover pool could support an ethanol production capacity of 14.5 to 21.8 billion gallons per year, which represents the energy equivalent of 9 to 14 percent of our current gasoline use.[2] Not surprisingly, therefore, corn stover is considered to have major potential as an ethanol feedstock once second-generation cellulosic conversion technologies are commercialized.

Despite the optimism of this seminal USDA/USDOE study, which has been dubbed the "Billion Ton" study, very few detailed analyses have been done on the expected impacts of a commercial corn stover market. Significant questions remain about how much corn stover would be supplied at various stover prices, and what the environmental impacts of that stover harvest would be. Total available biomass is not a perfect indicator of how much corn stover farmers would actually choose to supply to a market; confounding variables include costs and return from harvest, perceived impact on soil and productivity, terms of contract with ethanol refineries, etc. In recent studies, assumed market prices for biomass in studies of cellulosic ethanol have ranged widely, but early values appeared to be concentrated in the range of $50-$80/DT. These figures have been largely speculative, however, as no market yet exists against which to ground-truth them.

A great deal of uncertainty also surrounds the potential environmental impacts of stover removal to support such an industry. Corn stover and other agricultural residues currently perform important environmental services when left on the field by protecting productive topsoil from erosive wind and water and replenishing organic carbon and nitrogen in soil pools. Prior studies have highlighted the potential impacts of stover removal along several environmental dimensions (Wilhelm et al., 2004; Wilhelm et al., 2007); in this analysis we build on the tradition of Gallagher et al. (2003) and introduce cost and return estimates to more explicitly model the production decisions made by farmers under projected market agricultural conditions, as well as the implications of those decisions for national stover supply and aggregate environmental impacts of production.

WRI ANALYSIS

This study uses a national agro-environmental production model to evaluate the environmental and economic impacts of introducing a market for corn stover to support a stover-based ethanol industry. We explore the relationship between stover supply, aggregate environmental impacts, and different production practices or policies that can influence supply or mitigate environmental impact. In measuring the aggregate environmental impacts of stover harvest we look specifically at rates of soil erosion, which have been the focus of most existing and pilot agricultural conservation programs, and at agricultural GHG emissions, which are often under-represented in domestic and global dialogues about GHG emissions and mitigation potential. Although we limit the current analysis to impacts on soil erosion and GHG emissions, other potential impacts, such as to surface water and habitat quality, should also be included in a comprehensive assessment of the environmental impacts of stover harvest.

The analysis integrates the Regional Environmental and Agricultural Production model (REAP) —a national agricultural production model developed and maintained by USDA's Economic Research Service (ERS) —with the Environmental Policy Integrated Climate (EPIC) model, a plant growth and environmental impact model maintained by Texas A&M University. Combining these models allows us to project how the establishment of a market for corn stover will translate into regional changes in crops grown, tillage practices used, and crop rotations employed, and to then estimate the net environmental impacts of those changes when aggregated nationally.

Stover harvest decisions in this analysis are based on a comparison of producer costs and returns to stover harvest. Returns are based on price offered, which is varied to illustrate the sensitivity of the response to price, and on volume harvested, which depends on available stover volume (which varies by region and rotation) and on percentage of stover removed. Any corn production rotation with corn harvested at least every other year is considered eligible for stover harvest in the stover analysis. In accordance with the erosion-control assumptions of the Billion Ton study, systems operating under conventional or moldboard tillage are assumed to remove 33 percent of their residue, systems operating under reduced tillage are assumed to remove 54 percent of their residue, and systems operating using no-till methods are assumed to remove 68 percent of their residue.

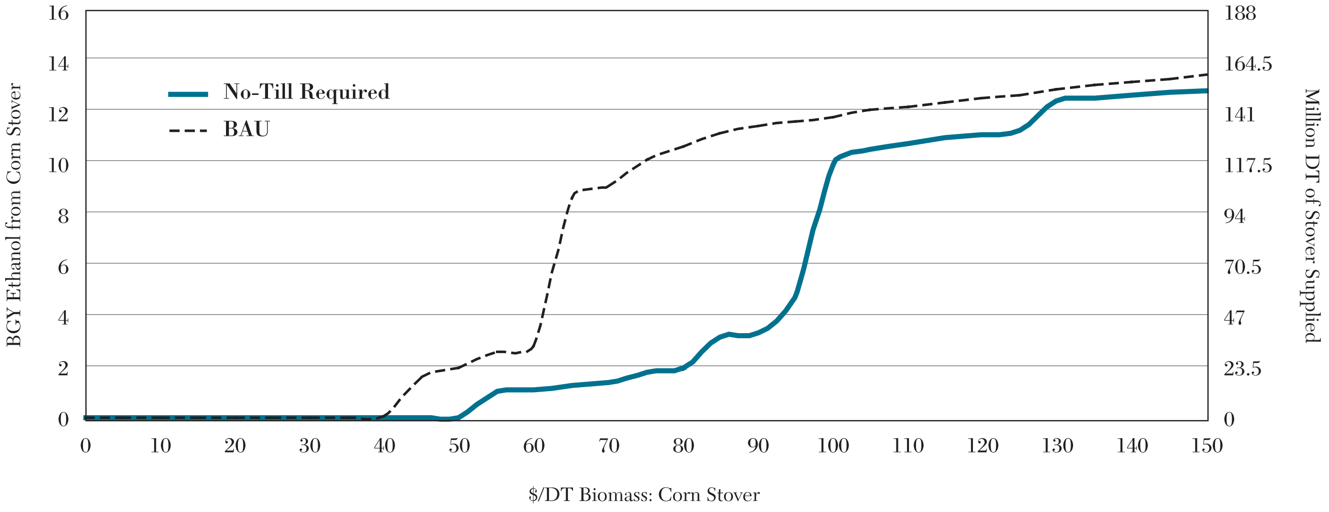
The increased costs associated with stover production largely arise through increased harvest costs and the cost of replacing nutrients that are removed from the field with the corn stover. Stover is assumed to be harvested using a multiple pass harvest system, where grain harvest is followed by mowing, raking, and baling of the stover. Several categories of cost increase as a result of the increased intensity of harvest and harvest machinery, including labor costs, energy costs, and repair and machine ownership costs. We further assume a baling cost of $12.00/DT stover and an arbitrary "minimum net return" to farmers of $8.00/DT.[3]

Additional adjustments to the production enterprises include replacement of the nutrients removed with stover removal. We assume stover nutrient concentrations of .008% nitrogen (N), .000982% phosphorus (P), and .010415% potassium (K) (Rankin; Hoskinson et al., 2007).[4] Farmers are assumed to replace 50% of the nutrients removed with stover through additional application of commercial fertilizer.

The baseline agricultural production scenario for our analysis uses the USDA's 2008 projected baseline for 2015 crop production patterns and a baseline grain-based ethanol production level of 13.3 billion gallons per year (BGY). We assume that a conversion efficiency of 85 gallons/DT biomass will be available for the cellulosic ethanol industry. Crop productivity (i.e. average yield per acre) is assumed to continue to increase until 2015 for corn and other crops according to the USDA's baseline projections for crop efficiency improvements.

We then introduce a corn stover market that pays up to $150/DT for stover and explore the stover supply and environmental impacts that result under two production scenarios: business as usual and no-till. The "business as usual" (BAU) scenario refers to an extension of current market conditions and poli-

FIGURE 1 Corn Stover Supply in Response to Market Price Under Different Production Policy Scenarios



cies, and essentially allows farmers to participate in a stover market under whatever production terms they choose. This does not imply a continuation of production practices, but of production incentives; as stover prices change, so too do the farmers' decisions about what practices will be used to supply stover, including changes in rotation and tillage type relative to the baseline.

In contrast, the "no-till" scenario represents an alternative policy scenario in which stover can only be harvested from rotations that use no-till production methods. Whereas the "business as usual" scenario reflects the results if farmers are given the choice to switch to no-till, the "no-till" scenario represents a case where farmers cannot participate in the market unless they can demonstrate that no-till production methods were used in the production of the stover. Under the "no-till" scenario, all farmers are assumed to harvest at the 68 percent stover removal rate.[5]

RESULTS

National Stover Supply

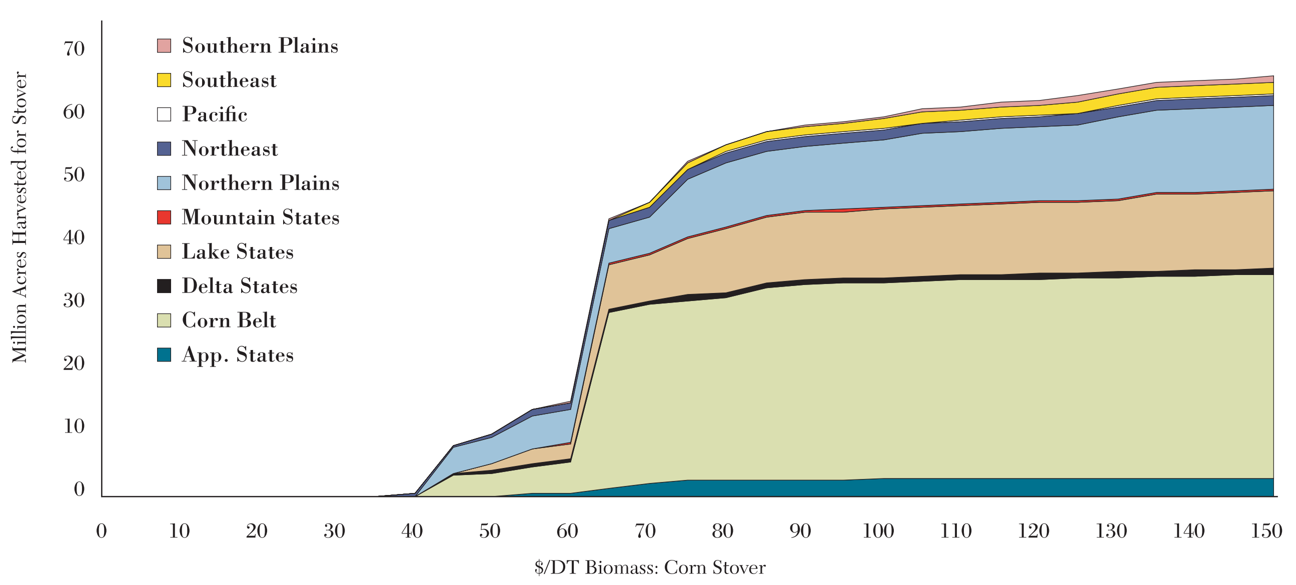
Our supply analysis suggests that, under the business as usual scenario (i.e. when tied to no production criteria other than the harvest limitations), stover supply does not increase substantially until stover price exceeds ~$63/DT. This number is considerably higher than that found in a study by Gallagher et al. (2003), which projected that corn stover supply in the Midwest would jump when prices moved from $15/ton to $21/ton.[6] According to our analysis, feedstock prices in the range of $50 to $80 per dry ton, which are often cited in literature analyzing potential feedstock markets, would support a stover-based ethanol industry of up to 9 BGY under the business as usual case (Figure 1). The majority of this stover is supplied by harvest from the Corn Belt region, but the Northern Plains and the Lakes States are significant contributors as well (Figure 2).

Under the no-till scenario, the upper end of the common biomass price range ($80/DT) would only result in a stover supply of 16.4 million DT and support an industry of roughly 1.4 BGY. Supply under the no-till scenario does not significantly increase until the feedstock price reaches $95/DT. As in the BAU production case, subsequent price increases lead to a supply plateau, so that even at $150/DT the amount of biomass supplied is inadequate to supply an industry of greater than 14 BGY (Figure 1). It is unlikely that sufficient refining capacity for 14 BGY of ethanol production from corn stover would exist in 2015, as the conversion technology is not yet mature and the infrastructure will take time to develop, but this curve is illustrative of the underlying dynamics of farmer response and supply. When evaluating future potential, it is important to note that a supply curve generated for later years would reflect an upward shift in supply as crop and/or residue production increase with improved breeding over time.

Environmental Costs of Stover Harvest

The full costs associated with stover harvest exceed those that the farmer bears in terms of increased harvest cost and nutri-

FIGURE 2 Breakdown of Supply Regions for Corn Stover Market Under BAU Scenario

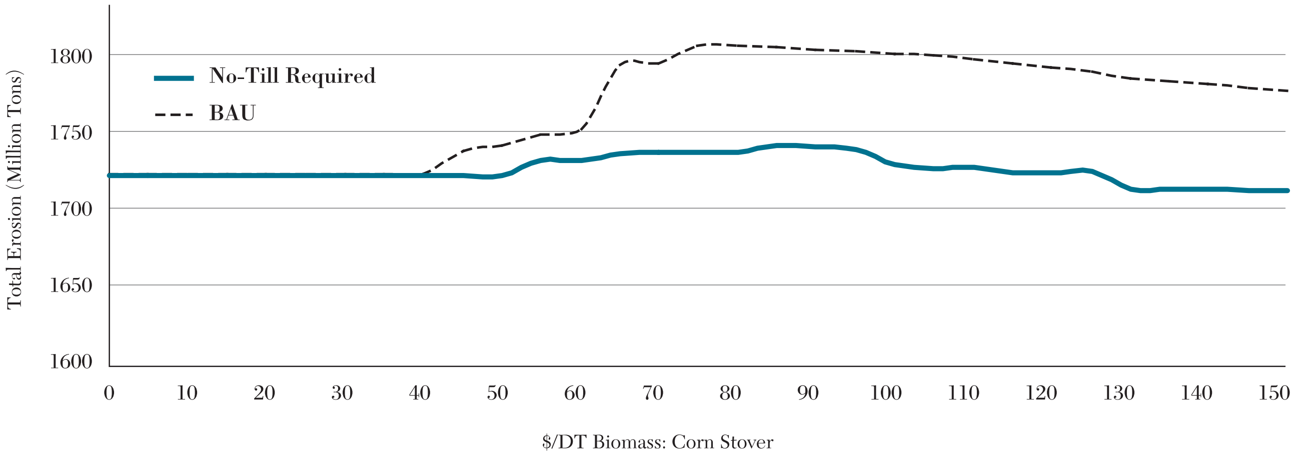


ent application requirements. Because leaving corn stover on fields currently serves a number of environmental purposes, its removal can have negative environmental impacts if not accompanied by changes in production practices to mitigate those impacts. The adoption of residue management practices has been successful in the U.S. over the last few decades at reducing soil erosion from working cropland, but the potential removal of residues from 25 percent of the nation's crop acreage (or more, when other residue sources such as wheat straw are considered) threatens to reverse that trend. Our results suggest harvest of corn stover carries with it a substantial threat of increased erosion from prime agricultural lands (Figure 3). We also find that no-till production methods are an effective way to manage the threat of increased soil erosion from stover removal, but that they will not automatically be adopted by farmers participating in stover markets.

Under the business as usual scenario in Figure 3, stover harvest induces a sharp initial increase in total soil erosion (from both wind and water), which begins to decline only when feedstock prices reach a level sufficient to induce farmers to voluntarily transfer corn production acreage over to no-till production methods. Under the no-till scenario, on the other hand, the required no-till production methods are relatively successful at forestalling the increased erosion, even when high levels of stover (68%) are removed from no-till corn acreage.[7] No-till's success at managing erosion levels varies regionally, and different prices induce different regions to enter the stover market. The slight increase in erosion shown when prices under the no-till scenario reach $50/DT, for instance, reflects the impacts of increased corn stover harvest in the Northern Plains region. In that region, the reduction in tillage intensity is able to keep soil erosion from water (sheet & rill erosion) constant even with stover harvest, but it cannot as effectively mitigate wind erosion, which increases slightly as winter residue is removed from fields. The subsequent decline in erosion as stover price increases illustrates that this effect is later offset by erosion reductions on additional acres converted to no-till production in other regions.

The potential increase in yearly erosion under the business as usual scenario reaches a maximum at a corn stover price of approximately $80/DT. At that level, aggregate erosion from farmland increases by 84.4 million tons per year, or roughly 5 percent, relative to a scenario with no corn stover harvest. To put that figure in context, consider that in 2008 the Farm Services Administration released a report concluding that the 36.8 million acres enrolled in the Conservation Reserve Program (CRP), a voluntary set-aside program in which farmers retire cropland in exchange for a yearly rental payment from the government, resulted in an estimated erosion decrease of 470 million tons per year, at a cost in 2007 of $1.82 billion in CRP payments (USDA/FSA, 2008). Assuming for the moment that CRP payments are based largely on soil erosion benefits, those numbers yield a rough value estimate for avoided erosion of $3.87/ton.[8] By that same estimate, allowing aggregate

FIGURE 3 Impacts of Stover Market on Total Soil Erosion (Wind and Water) from Agricultural Lands Under Different Production Scenarios



erosion to increase by 84.4 million tons per year in response to stover harvest would cost $327 million in lost value in terms of the environmental benefits that society enjoys from avoiding soil erosion. On the other hand, at $80/DT, imposition of a no-till requirement is estimated to lower total erosion loss by 70 million tons relative to the business as usual case; using the same estimate for the value of avoided erosion, that no-till requirement would have a social value, in terms of avoided erosion, of approximately $270 million/year.

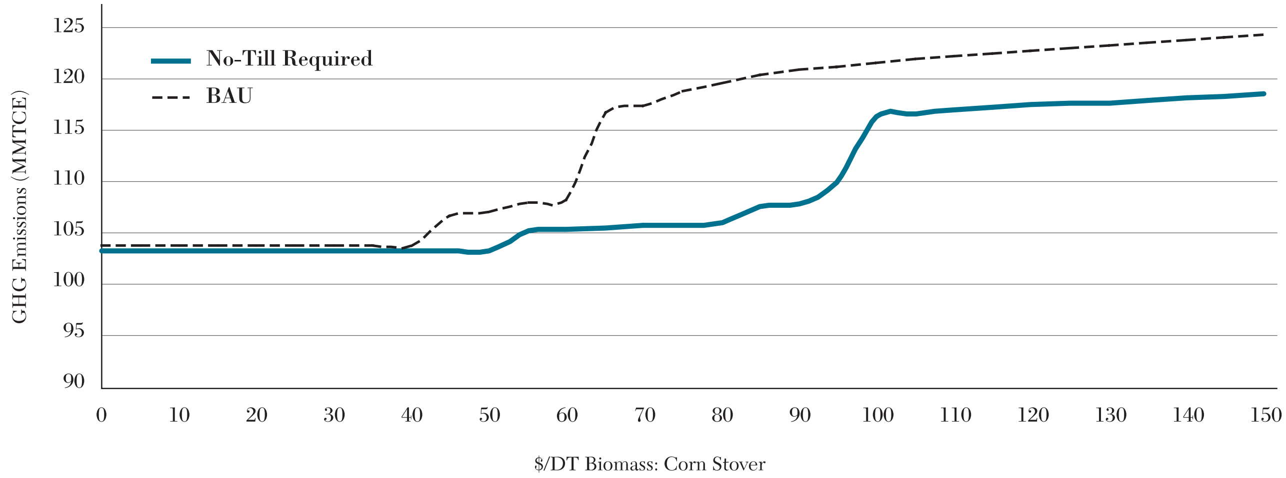
Unfortunately, no-till production methods alone are not successful at managing the threat of increased greenhouse gas emissions from agriculture arising from stover removal (Figure 4). These increased emissions arise through two primary pathways: increased nitrous oxide emissions from additional nitrogen fertilizer application, and loss of the soil carbon sequestration that arises from re-incorporation of residues into the soil. The no-till practices simulated in this study are relatively ineffective at addressing either of these emissions pathways; no-till is able to reduce the rate at which carbon residues break down in the soil, but that effect is not sufficient to compensate for the carbon volume that fails to be returned to the soil as residue. Furthermore, because no-till production practices are not necessarily accompanied by significant reductions in nitrogen application when applied to corn,[9] they do not offset the increased nitrogen fertilizer application associated with stover removal.

Although conventional wisdom associates no-till production with soil enrichment, which could over time result in reduced demand for applied nitrogen, the removal of stover residues complicates that assessment by significantly reducing the volume of organic material available for soil enrichment. Designing an appropriate nitrogen management strategy for production enterprises with stover removal will require increased investment in research programs on soil carbon and nitrogen dynamics under stover harvest schedules. Additional resources should also be directed at ongoing efforts to develop precision nitrogen application and slow-release fertilizer technologies, as well as to development of nitrogen-efficient crop varieties and an improved understanding of the tradeoffs among yield, nitrogen use and the use of other inputs (particularly water and land) in the production of ethanol feedstocks.

Alternative or additional methods of managing soil carbon sequestration with stover removal could take many forms. For on-farm mitigation and management, cover crops and green manures are a promising technology for return of carbon to soil (Marshall and Sugg, 2008). Despite multiple environmental benefits, however, cover crops have traditionally been underutilized in the U.S., and insufficient research expenditures have been dedicated to determining and designing cost-effective crop rotations and production plans that integrate cover crops, and to identifying and overcoming obstacles to their adoption.

Another approach to aggregate agricultural soil carbon management would be to offset on-farm losses with off-farm gains through agricultural and forest land management elsewhere. In addition to the erosion benefits mentioned above, the Conser-

FIGURE 4 Impact of Corn Stover Market on GHG Emissions from Agriculture Under Different Production Scenarios



vation Reserve Program (CRP) has been cited as a successful program for encouraging additional carbon sequestration on retired lands (USDA/FSA, 2008). There are many reasons why farmers choose to enroll their land in the CRP, but as production returns increase with increasing commodity prices, the economic incentive to participate in the retirement program declines. In the fall of 2007, for instance, the CRP suffered a loss of 2.6 million acres from its total enrollment of 36.8 million acres as farmers chose to withdraw their land from the program in response to strong agricultural market conditions. The 2008 Farm Bill then lowered the authorized program size from 39.2 to 32 million acres, so further acreage losses are expected. Nevertheless, if the program is to remain competitive and to maintain authorized acreage levels, CRP payments and appropriations may have to increase. For the program to expand in order to offset the increased GHG emissions associated with stover harvest nationwide, payment levels will have to increase significantly and the acreage cap established by the 2008 Farm Bill will have to be raised.

Our analysis suggests, for instance, that under the BAU scenario, a 10 BGY industry will be associated with a biomass price of about $75/DT (Figure 1) and, at that stover price, with an increase in agricultural GHG emissions of nearly 15 million metric tons of carbon equivalent (MMTCE) (Figure 4). In-house WRI analyses estimate that if the CRP were expanded from the assumed 2015 baseline CRP acreage of 32 million acres to 47.9 million acres, the additional acreage would be sufficient to offset the additional 15 MMTCE of agricultural emissions associated with the ethanol feedstock production. However, CRP payments would have to be nearly tripled to provide sufficient incentive for a voluntary expansion of the CRP program size of that magnitude. The combined increase in per acre payments and program acreage results in an estimated increase in total CRP expenditures of $5.044 billion per year—from the baseline estimate of $1.874 billion to $6.918 billion per year.

An analysis of the cost-effectiveness of this strategy for stover-related GHG management may find that expansion of the CRP in a strong agricultural market environment is not a cost-effective tool when evaluated solely as an "off-farm" GHG emissions management strategy. There are also likely to be market and price implications of retiring significant additional acreage from production. However, a complete accounting of the benefits of the increased CRP expenditures would require that we assign values to the erosion and other benefits associated with CRP set-asides as well. While beyond the scope of this report, such analyses will be critical to identifying cost-effective ways to mitigate the impact of increased residue harvest on our nation's working lands. The social cost associated with losing corn stover's carbon sequestration and nutrient replenishment services is substantial, and the necessary costs of abatement and mitigation must be considered in policy decisions comparing the costs and benefits of scaling up removal of corn residues for ethanol production.

CONCLUSIONS AND POLICY IMPLICATIONS

Our results suggest that the Billion Ton study's 2005 estimates of available sustainable stover volumes of 75 million DT are optimistic and rely upon unrealistic assumptions about farmer adoption of no-till production methods to mitigate the impacts of stover harvest. According to this analysis, in the absence of other incentives for adoption, adoption of no-till practices will not be common in the low range of stover biomass prices. Harvest of 75 million DT of stover is therefore accompanied by roughly 30 million additional tons of erosion and an additional 9.6 million MTCE in GHG emissions from agriculture. If no-till practices are required for participation in the stover market, it could effectively mitigate the erosion increases, but it would be ineffective at managing the threat of increased GHG emissions from agriculture as a result of stover harvest. Furthermore, the price offered to attract 75 million DT of stover supply would have to increase from approximately $63/DT to around $97/DT if no-till production practices are required for participation in corn stover markets.

Removal of stover residues can therefore not be assumed to be either economically or environmentally feasible at large scales despite the fact that corn stover is a residue of an existing production activity. In fact, stover harvest could potentially come at great environmental cost. Building a sustainable cellulosic ethanol industry that relies on corn stover as a feedstock will require increased investment in research on the impacts of, and obstacles to adoption of, best management practices such as no-till production, precision fertilizer management, and cover crop use in rotations that include stover harvest. If safeguards are not put in place to protect against the potential impacts outlined here, scaling up corn stover harvest may result in unacceptable losses of productive topsoil to erosion, declines in surface water quality due to increased sedimentation and eutrophication, and loss of agricultural carbon sequestration capacity and associated increases in GHG emissions from agricultural activities. Such safeguards attached to the production of feedstocks, including agricultural residues, should be required for participation in any government programs that provide incentives for the ethanol industry.

As evidence mounts that there could be significant land-use impacts associated with scaling up feedstock production to support expanded ethanol production, it is becoming increasingly difficult to justify support of the biofuels industry in the absence of assurance that the biofuels produced achieve policy objectives without unacceptable soil, water, and air quality impacts. Accordingly, existing policies and programs to provide incentives for biofuels development should be modified to include stringent safeguards for feedstock production, including the Volumetric Ethanol Excise Tax Credit (VEETC) and the revised Renewable Fuel Standard (RFS). The revised 2007 RFS has established an important precedent for such protective measures by including a partial list of requirements for feedstock production that must be met for fuels to qualify for RFS credit; these requirements include basic safeguards related to greenhouse gas "content," or life-cycle emissions assessments, of biofuels and restrictions on the type or location of land that can be converted to feedstock production. The potential for negative impacts on land and water resources, however, extends far beyond the impacts accounted for by those safeguards; the RFS safeguards should be expanded to ensure that all significant threats, including those to soil, water, and climate stability, are addressed. Unfortunately, such safeguards are entirely missing from the VEETC. If we hope to build a sustainable biofuels industry, such regulatory oversights must be corrected in both existing and future biofuels-related policy.

Furthermore, to maximize the flexibility of these protective measures as the biofuels industry matures and explores new technologies and feedstocks, safeguards should be, to the extent possible, performance-based rather than technology- or feedstock-specific. Performance-based safeguards would stipulate the level of environmental performance that must be maintained in conjunction with feedstock production, rather than telling farmers, for instance, what production practices must be used or what feedstocks can and cannot be produced. In this study, for instance, we explored the impacts of no-till production methods on erosion and soil carbon loss, but other best management practices exist that can address one or both of these environmental performance objectives. In prior studies, we have found cover crops and green manures to be effective at managing both, for instance, and applying manure rather than synthetic nitrogen fertilizer has been found to improve soil carbon gains in corn production (Marshall & Sugg, 2008; Pendell et al., 2006). It should be left to the farmer to decide what combination of practices best suits the conditions on their farm to achieve the necessary environmental performance required in association with feedstock production. Performance-based measures also do not pre-judge the achievable sustainability of any given feedstock; advances in breeding and production methods may reduce the environmental footprint of feedstocks in ways we cannot foresee, and protective policies should encourage, not stifle, such innovations.

It is worth noting from Figure 1 that the largest price differential between what would attract conventional stover into the market and what would be necessary to attract no-till stover into the market is ~$40/DT. At the assumed yield of 85 gallons/ton, that additional feedstock price costs an additional $.47 per gallon, or two cents per gallon more than the VEETC level of $.45/gallon established under the 2008 Farm Bill. These estimates therefore suggest that establishing sustainability criteria for the VEETC requiring that stover be produced using no-till methods would result in increased costs to blenders (if the price of the increased feedstock is fully passed along to blenders) that are comparable to the magnitude of the VEETC itself. The results presented here, however, suggest that no-till production is not sufficient to fully manage all of the potential negative impacts of stover harvest, so additional incentives may be required for farmers to adopt alternative or additional management approaches that address a more comprehensive set of dimensions (Marshall and Sugg, 2008). The cellulosic ethanol production tax credit established under the 2008 Farm Bill could be a powerful vehicle for encouraging adoption of such alternative management practices if that credit is tied to requirements related to bioenergy production system practices and/or performance. Additional research into best management practices and how they fit into bioenergy systems will also be critical to bringing down costs and overcoming other obstacles to adoption.

Designing a renewable fuel production system that is truly sustainable will require a comprehensive but flexible framework of environmental safeguards and a concerted effort to collect improved information about the environmental performance of biomass-derived fuels and how production impacts respond to management tools. Such impacts include the short-term impacts illustrated here, as well as a suite of other short- and long-term issues including impacts on soil productivity, fertilizer demand and nutrient pollution, as well as on biodiversity and habitat quality. Our results suggest that corn stover, though promising as a feedstock because of the existing corn production infrastructure, has drawbacks from an environmental perspective because it is already performing a valuable soil and water quality service in replenishing soil carbon and controlling erosion. The feasibility and costs of replacing those services must be carefully weighed in an analysis of the desirability of diverting corn stover, or any other agricultural residues serving the same environmental functions, for ethanol production.

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NOTES

1. The Biomass Crop Assistance Program provides cost-sharing for the site preparation and establishment of perennial crops, annual payments to cover lost revenue while the crops are establishing themselves, and a per ton subsidy to help cover harvest, storage, and transport costs as the logistics of that infrastructure are worked out.
2. Assuming 924.4 million barrels per day, or 3372.6 million barrels per year, of gasoline use (EIA, 2008) and a heat content equivalence of 1.5 gallons of ethanol per gallon of gasoline.
3. Net returns to farmers may exceed the $8.00/ DT, depending on cost and return conditions, but we assume that farmers will not choose to harvest stover for less than a net $8.00/DT. This figure is slightly more conservative than that used by Sheehan et al. (2005) of $10/DT, which was also described as "arbitrary". Because it is a fixed figure per ton, when adjusted the minimum net return figure merely shifts the supply curve by a fixed amount. It is therefore simple to extrapolate to different "net return" assumptions.
4. These figures are given in elemental concentrations; the corresponding fertilizer weight equivalents are 16 lbs N, 4.5 lbs P_2O_5, and 25 lbs K_20 per ton of corn stover.
5. Crop productivity in the stover scenarios remains at the levels calibrated to in the 2015 baseline runs, no matter how large the stover industry gets in response to the prices that we introduce. It is unlikely, for instance, that a stover-based ethanol industry could scale up as high as 12 BGY by 2015, but we do not attempt to capture that effect in a dynamic analysis of price change, industry growth, and crop productivity improvements over time. The curves we present, therefore, are illustrative snapshots of the relative scale of potential supply impact for different prices and industry sizes, at a fixed crop productivity level. It is relevant to note that impacts may decline over time as crop productivity increases with research and breeding, but that impact will be highly sensitive to the production methods, and inputs, required to produce the new crop strains.

6. A more recent government report entitled "Increasing Feedstock Production for Biofuels" suggests that in 2015, a biomass price of $45/DT would be sufficient to attract ~35-50 million DT of agricultural residues into the market, depending on the assumptions made about availability of other biomass feedstocks for ethanol production (BRDI, 2008). Because that residue supply figure includes wheat straw as well as corn stover, however, it is not possible to directly compare that result to our estimated supply of 19 million DT of corn stover at a biomass price of $45/DT.
7. The ability of no-till production to mitigate erosion impacts in our scenarios is enhanced by the assumption that entire rotations are transferred into no-till production, not individual crops. As a result, any mixed crop rotation that harvests stover must ensure that all other crops in the rotation (most predominantly soybeans) are produced using no-till methods as well.
8. In fact, land offered for enrollment in CRP is evaluated based on an "Environmental Benefits Index", which encompasses a suite of factors including habitat quality and water quality benefits resulting from reduced nutrient loading, as well as the air and water quality benefits of reduced soil erosion. A more sophisticated analysis of the relative weight placed on each of these benefits would be required to disaggregate payments by benefit type. This number is a rough upper bound estimate assuming that payments and land selection are driven largely by erosion benefits.
9. USDA's Agricultural Resource Management Survey (ARMS) provides data on fertilizer application by tillage type that can be broken out regionally. This data was used to update fertilizer applications in REAP in the fall of 2008.

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