Economic Potential of Biomass Based Fuels for Greenhouse Gas Emission Mitigation

Uwe A. Schneider*
Research Associate
Center for Agricultural and Rural Development
Iowa State University
578 Heady Hall
Ames, Iowa, 50011-1070
Phone: 515-294-6173
Fax: 515-294-6336
Email: uwe@iastate.edu

Bruce A. McCarl
Professor
Department of Agricultural Economics
Texas A&M University
College Station, TX, 77843-2124
Phone: 979 845 1706
Fax: 979 845 7504
Email: mccarl@tamu.edu

This paper has not been submitted elsewhere in identical or similar form, nor will it be during the first three months after its submission to the publisher. Seniority of authorship is shared. The contained work was partially funded by EPA, the Texas and Iowa Agricultural Experiment Stations and USAID through the SANREM CRSP.

* Corresponding author

Abstract (188 Words):

Use of biofuels diminishes fossil fuel combustion thereby also reducing net greenhouse gas emissions. However, subsidies are needed to make agricultural biofuel production economically feasible. To explore the economic potential of biofuels in a greenhouse gas mitigation market, we incorporate data on production and biofuel processing for the designated energy crops switchgrass, hybrid poplar, and willow in an U.S. Agricultural Sector Model along with data on traditional crop-livestock production and processing, and afforestation of cropland. Net emission coefficients on all included agricultural practices are estimated through crop growth simulation models or taken from the literature. Potential emission mitigation policies or markets are simulated via hypothetical carbon prices. At each carbon price level, the Agricultural Sector Model computes the new market equilibrium, revealing agricultural commodity prices, regionally specific production, input use, and welfare levels, environmental impacts, and adoption of alternative management practices such as biofuel production. Results indicate no role for biofuels below carbon prices of $40 per ton of carbon equivalent. At these incentive levels, emission reductions via reduced soil tillage and afforestation are more cost efficient. For carbon prices above $70, biofuels dominate all other agricultural mitigation strategies.

Keywords:

Agricultural Sector Model, Alternative Energy, Biofuel Economics, Biomass Power Plants, Greenhouse Gas Emission Mitigation, Short Rotation Woody Crops, Switchgrass

Abbreviations:

ASM	=	Agricultural Sector Model
ASMGHG	=	Agricultural Sector Model for Greenhouse Gas Assessment
CE	=	Carbon Equivalent
EPA	=	Environmental Protection Agency
EPIC	=	Erosion Productivity Integrated Climate (Original Name: Environmental Policy Impact Calculator, name change in 1995 after increasing the models complexity to account for more environmental impacts than erosion)
FASOM	=	Forest and Agricultural Sector Optimization Model
GHG	=	Greenhouse Gas
GWP	=	Global Warming Potential
IPCC	=	International Panel on Climate Change
MMTCE	=	Million Metric Tons of Carbon Equivalent
SOM	=	Soil Organic Matter
TCE	=	Tons of Carbon Equivalent

Today society faces important decisions regarding climate change mitigation. Increasingly, concerns are being expressed about the potential implications of the build-up in atmospheric concentrations of greenhouse gases (GHG). A scientific consensus is emerging that this buildup will affect the global climate, most likely stimulating warming. Also, there are arguments that the disturbances caused by increased GHG concentrations will take a long time to reverse. The International Panel on Climate Change (IPCC) argues that it will take: a) centuries for the sea level to stop rising from a warming increase; b) decades for atmospheric GHG concentrations to stabilize once emissions have stabilized; and c) decades to fully retrofit and/or replace the stock of equipment, vehicles and technology which is associated with current anthropogenic emissions.

Society must decide whether to let emission increases continue or reduce emissions in an effort to stabilize atmospheric concentrations. Moves in either direction face the uncertain future effects of GHG induced climate change, which have varying implications for many sectors of the economy (Mendelsohn and Newman, U.S. Global Change Research Program National Climate Change Assessment). The decision involves whether to insure against possible future deleterious effects by either directly reducing emissions or indirectly through the enhancement of sinks.

Agriculture can potentially play a role in an effort to reduce net emissions of greenhouse gases. While agriculture is a small emitter of the most prevalent greenhouse gas (carbon dioxide - CO_2), it is important in the total picture. According to the latest United States EPA inventory, anthropogenic GHG emissions from agriculture contribute 7 percent of total carbon equivalent (CE) emissions releasing about 28 percent of methane and almost 70 percent of nitrous oxide. Furthermore, agriculture has substantial potential for absorbing emissions, particularly CO_2, through changes in tillage or land use including conversion of cropland to grassland or forest. Agriculture can also offset GHG emissions by increasing production of biomass commodities, which can serve either as feedstock for electricity generating power plants or as a substitute for fossil fuel based gasoline. Biofuels mitigate GHG emissions because their usage reduces total use of fossil fuels (see Cushman, Marland, and Schlamadinger for more discussion of offset possibilities). The net carbon emissions from a poplar fed power plant for example amount to approximately 5 percent of the emissions from extraction and combustion of an energy equivalent amount of coal after netting out the CO_2 absorbed during tree growth (Kline, Hargrove and Vanderlan).

The production of biofuel feedstocks from agricultural and forestry sources has been considered for many years, particularly after the 1970's "energy crisis". However, in the U.S. biofuel production has not proven to be broadly economically feasible without subsidies (the late 1990's U.S. ethanol subsidies amounted to over 50 percent of product sale price) nor is it likely to be in the near future. There are four possible political justifications for subsidization of biofuels. First, biofuel subsidies serve to support agricultural prices by adding to demand for feedstock commodities and, in turn, supporting agricultural incomes. Second, the biofuel product ethanol has desirable environmental/health attributes relative to petroleum-based fuels, which play a role in meeting clean air standards. Third, increased biofuel use reduces dependence on petroleum extending the life of existing stocks and possibly reducing reliance on nondomestic supplies. Fourth, as mentioned above, biofuel combustion substantially offsets net GHG emissions relative to fossil fuel combustion.

In this paper, we examine the first and fourth motivations for biofuel feedstock production in a U.S. setting. We analyze the role biofuels might play in total greenhouse gas mitigation policy and the implications for the agricultural sector. Biofuels are measured in terms of their net contribution to GHG emissions in terms of net emissions of CO_2, nitrous oxide and methane. We also consider biofuels not independently but rather in comparison with a total suite of agricultural mitigation options. Such a comparison allows us to examine the relative desirability of biofuels Vis a Vis other GHG emission mitigation strategies such as tillage alteration, tree planting, fertilization alteration, livestock dietary alteration and manure management.

Background: Agriculture's Role in Total Greenhouse Gas Mitigation Strategy

Agriculture can participate in GHG emission mitigation efforts as an emission reducer, sink, or offsetter. Here we consider these roles simultaneously. To provide context we first summarize the potential ways agriculture can participate in net GHG emission reductions (for more comprehensive treatment see McCarl and Schneider (1999,2000)).

In terms of direct emissions agriculture is responsible for a) methane emissions as influenced by the size of the livestock population, the use of livestock rearing practices which influence enteric fermentation (diet and growth rate stimulation), and the management of manure; b) nitrous oxide emissions as influenced by fertilization quantity and practices (through increased soil testing, use of denitrification inhibitors, or increased manure substitution); c) methane emissions from rice fields as influenced by total rice acreage and water management; and d) CO_2 emissions from fossil fuels used in production, transport, processing, and input manufacture (EPA,1999a,b).

In terms of emission absorption, agricultural GHG sinks can be expanded by increasing: a) the proportion of cropped acres tilled by less intensive methods relative to that tilled by conventional deep plowing (Rosenberg, Izaurralde, and Malone; Marland, McCarl, and Schneider; and Cole et al.), b) the acreage transformed from cropping usage to grasslands or forests (Sedjo, McCarl), or c) the carbon holding capacity of degraded crop, pasture or abandoned lands by altering vegetative cover use or by improving management (Lal et al., Cole et al.).

Finally, in the context of agriculture as an offsetter one can a) use biofuel based strategies as discussed above or b) otherwise produce agricultural commodities which through their consumption substantially offset emission intensive non-agricultural commodities (Marland and Schlamadinger). For example, wood from forests may be substituted for steel or concrete in building construction.

Given the wide range of possible agricultural contributions to GHG mitigation efforts, the question becomes: Which strategies are feasible from a combined political, technical and economic viewpoint? From here on we will investigate this question from an economic viewpoint.

Issues in Appraising Economics of Agricultural Emission Reductions

Emission reductions via agriculture raise several important issues concerning the economic analysis framework. These include: a) need of sectoral level analysis, b) incorporation of mitigation alternatives, and c) depiction of multiple gas tradeoffs.

Need for Sector Analysis

To assess how U.S. agriculture might respond to incentives for GHG emission mitigation, a sector-level approach is needed. This notion will be justified by placing agricultural emissions in perspective with the Kyoto Protocol.

U.S. cropland amounts to approximately 325 million acres. The literature suggests an annual maximum potential for agricultural carbon sinks around one ton of carbon per acre of cropland (for example see Stavins). Using this maximum, total agricultural contribution to carbon storage may be bounded at about 300 million tons of carbon, annually. The Kyoto Protocol, however, contains a 1990 less seven percent U.S. limit on net emissions for six greenhouse gas categories (United Nations, Framework Convention on Climate Change). Using EPA emissions inventory data, such an agreement would imply annual carbon emission reductions of about 300 million tons plus emissions growth by 2010 (which by linear extrapolation would add 400 million more tons) for a total in the neighborhood of 700 million tons. Clearly, such large emission offsets could not be supplied through cropping agriculture even if all available cropland were retired.

The above argument suggests that agriculture may face high demand for emission offsets, if it can verifiably mitigate GHG emissions at relatively low costs. However, large-scale mitigation efforts, which would involve a large amount of the available cropland base, would greatly impact the agricultural sector with accompanying adjustments in production, prices, and welfare. To capture such effects, a sector wide analysis is appropriate. In pursuing such an analysis we will employ a price endogenous sector model utilizing a soil type and tillage system dependent version of the Agricultural Sector Model (ASM) maintained by McCarl et al.

Incorporation of Mitigation Alternatives

Adoption of certain agricultural mitigation strategies impacts possible adoption of other agricultural strategies. This impact can be either competitive or complementary. For example, the more cropland farmers allocate to biofuels, the less cropland will be available for establishing permanent forests or adopting emission absorbing tillage practices. On the other hand, farmers may supply corn for ethanol processing and at the same time sequester soil carbon through minimum tillage.

Several previous studies have independently estimated the economic mitigation potential of specific agricultural strategies. For example, afforestation has been examined by Stavins, and Moulton and Richards; biofuels have been assessed by Wang, Saricks, and Santini, Mann and Spath, McCarl, Adams, and Alig; and Lal et al. and soil carbon sequestration on U.S. croplands has been analyzed by Babcock and Pautsch. These individual strategy examinations may be biased however because alternative mitigation options are left out. In general, omission of competitive strategies will overstate the economic potential of a certain strategy but omission of complementary strategies will understate it. To determine the true economic potential of all agricultural strategies, it is important to examine them simultaneously.

We tried to accomplish this by including as many strategies as we had consistent data for. A summary list of the GHG emission mitigation options considered herein is provided in Table 1.

Multiple Gas Tradeoffs

Agricultural enterprises contribute to emissions of multiple GHGs. For example, a crop-livestock farm releases CO_2 when combusting the fuel necessary to operate field machinery, emits nitrous oxide through fertilizer applications, releases methane through enteric fermentation from ruminant animals or as a manure byproduct, but possibly augments the soil carbon stock by using a reduced tillage system. Tradeoffs between these emissions may occur if, for example, more fertilizer is needed under reduced tillage or if usage of growth hormones for animals alters the required acreage to produce feed.

In this study, the IPCC's global warming potential (GWP) concept was used to construct an aggregate measure of agricultural emissions. The GWP compares the radiative forcing of the various GHGs relative to CO_2 over a given time period (Cole et al.). The 100-year GWP for CO_2 equals 1. Higher values for methane (21) and nitrous oxide (310) reflect a greater heat trapping ability. We formed an aggregate ton of "carbon equivalent" measure also factoring in an adjustment for the molecular weight of carbon in CO_2.

Agricultural Sector Model

This study is based on the ASM model of McCarl and associates (Chang et al., McCarl et al.). The ASM model was first developed in the mid-1970s and has been used in many economic appraisals regarding environmental policies. Previous applications addressed tropospheric and stratospheric ozone, acid rain, coastal zone management, soil conservation policy, farm program policy, global warming, pesticide policy, GHG mitigation, and a variety of other agricultural/environmental programs (see the review in Chang et al. for references). In these appraisals ASM has been used to study the effects of long-term changes on agricultural income, production, consumption, trade, and environmental attributes. For this study, Schneider modified and expanded ASM to include GHG emission accounting and mitigation possibilities. Hereafter, the new model will be called ASMGHG.

Scope of ASMGHG

ASMGHG is an U.S. wide agricultural sector model, which also incorporates production and trade activity in the rest of the world. It depicts production in 63 U.S. agricultural sub-regions endogenizing crop choice, irrigation choice, livestock numbers, and livestock management. Commodity coverage is broad with more than 30 commodities considered including the major U.S. feed and food grains, oilseeds, fiber, hay, silage, sweetener, cattle, sheep, poultry, dairy and hog commodities. There is also a depiction of production of eight major internationally traded commodities in 27 rest-of-the-world regions and detailed international trade depiction for those commodities. Trade and consumption of more than 50 other commodities are modeled at a more aggregate level. Production is gathered together into ten U.S. marketing regions and in turn shipped on to processing, consumption, or international markets.

ASMGHG solutions provide projections of land use and commodity production within the 63 U.S. areas, commodity production in the rest of the world, international trade, crop and livestock commodity prices, processed commodity prices, consumption of agricultural goods, producer income effects, consumer welfare effects, and various environmental impacts.

Greenhouse Gas Features

ASMGHG contains GHG emission and sink accounts adding up net agricultural emissions of carbon dioxide, methane, and nitrous oxide as well as total carbon equivalents based on GWP. ASMGHG is used to examine the impact of mitigation incentives on the agricultural sector. At each incentive level, it identifies the optimal choice of mitigation strategy.

Below we will highlight some important characteristics and assumptions of ASMGHG. A more detailed and technical description is available in Schneider or by contacting the authors.

Biofuel Feedstock Modeling

The biofuel feedstock components used were adapted from earlier ASM studies (see McCarl, Adams and Alig). Therein production possibilities include growing biomass crops of willow, switchgrass, or poplar as feedstock for electrical power plants as well as the diversion of a conventional crop (corn) for ethanol production. The willow, switchgrass, or poplar production technologies are specified using data from the Oakridge National Laboratory (Walsh et al., see Table 3 for yield assumptions). The ethanol from cornstarch technology is based on data from Coble et al. and Shapouri.

Net emission savings from biofuel production represent savings over net emissions from conventional fuels. Complete lifecycle assessments of conventional and biofuel based energy sources (Spath and Mann; Mann and Spath; Wang; and Wang, Saricks, and Santini) provided necessary emission coefficients for this calculation (Table 2 and Table 4). No lifecycle assessments were available for switchgrass based power plants. We therefore assumed a conservative carbon closure[1] of 90 percent for switchgrass based power plants. The literature suggests both higher (Samson and Duxbury) and lower values of carbon closure for switchgrass based energy (Mann and Spath) depending on the assumed change in soil organic matter.

Almost all biofuels produced in the U.S. today are still subsidized. Ethanol suppliers receive, on average, a $0.54 per gallon subsidy (Yacobucci and Womach). In ASMGHG, the producer price of ethanol equals the producer price of conventional

---

[1] Carbon closure represents the recycled fraction of the entire carbon emitted in the process of electricity generation.

gasoline plus the $0.54 subsidy. Governmental incentives to promote biomass power include project co-funding; various tax credits, deductions and exemptions, as well as direct subsidy payments (Badin and Kirschner). Because these instruments are highly project specific, we did not include subsidies for biomass power plants.

Afforestation

We used solution information from the forest and agricultural sector optimization model (FASOM-Adams et al., 1996, Alig et al., 1998) to obtain estimates of tree carbon sequestration for carbon prices ranging from zero to $400 per ton of carbon equivalent. For each simulated carbon price we recorded the FASOM generated a) land transfer from agriculture to forestry, d) carbon sequestration, and c) land values. To export dynamic FASOM results into the static equilibrium ASMGHG, we computed average annual carbon sequestered and the amount of land transferred between 2000 and 2030. We computed the economic cost of land transfers utilizing the marginal values (shadow prices) of both cropland and forestland. The shadow price on cropland represents the forgone per acre value of giving up crop production while the shadow price on forestland represents the per acre value of growing forests. Thus, by subtracting cropland values from forestland values we approximated the per acre costs of afforestation.

Finally, we had to make assumptions about the fate of the sequestered carbon. While many scenarios are possible, we decided to use just one likely setup as documented in Table 5. McCarl and Murray provide a detailed description of the dynamics of saturating sinks along with examination of many alternative setups. Our setup leads to a 25 percent value reduction of saturating forest carbon relative to nonsaturating carbon emission reductions. Thus, if we introduce a carbon price of $20 per ton in ASMGHG, carbon sequestered from trees receives only 75 percent of this price or in this case $15 per ton.

Traditional Crop Production

Opportunities for emission mitigation in the traditional crop sector are numerous and geographically diverse. For example, the potential of a particular region to enhance soil carbon storage depends on soil types, current tillage systems, crop rotations, and management practices. Numerical specification of a full set of management alternatives requires a detailed and comprehensive data set giving the implications of all of the practices for each location. Such a data set was not available but could be developed using a crop and carbon simulation model.

For this analysis, we used the Erosion Productivity Impact Calculator[2] (EPIC) because we had a large set of EPIC input files (Benson) available that was geographically and management wise consistent with ASM dimensions. Through EPIC (Version EPIC8120, Williams et al.) we simulated management impacts across five representative soil classes in 63 U.S. regions for numerous crops under a range of fertilization, tillage, and irrigation practices. The EPIC simulation output contained estimates of soil carbon

---

[2] EPIC was originally developed to estimate erosion impacts based on crop and management choice. Recent efforts however have focused on a variety of other environmental impacts such as nutrient and pesticide movements as well as greenhouse gas emission and sequestration.

sequestration, nitrous oxide release, and several other environmental effects (erosion, nutrient pollution).

Caution needed to be taken in interpreting the EPIC simulation results. We decided not to rely blindly on EPIC's absolute soil organic matter (SOM) estimates but to consider only relative changes. (In recent communication with the EPIC authors we found out that they felt the version we used underestimated soil carbon.) To compute and calibrate absolute SOM change numbers we made a few aggregate assumptions based on other studies from the existing literature. Lal et al. reports a total soil carbon sequestration potential of U.S. cropland in the range of 75 to 208 million metric tons of carbon equivalents (MMTCE) annually with tillage change potential falling at the lower end. Based on these estimates we calibrated the model to develop 75 MMTCE of soil carbon if all tillage changes to zero tillage were made. Technical details of this calibration are available in Schneider.

Soil sequestration like tree biomass is subject to saturation. After comparing several studies on SOM accumulation from reduced tillage, West, Post, Amthor and Marland found that most changes occurred up to 25 years from the tillage switch. McCarl and Murray applied a net present value analysis to various possible scenarios and found a 38 to 55 percent value reduction for sequestered soil carbon relative to offsets from biomass for power plants. In this study we used one likely scenario setup (Table 5) leading to a 50 percent value discount for soil carbon sequestration.

Results

To analyze agricultural mitigation efforts, we simulated sectoral response to a range of hypothetical carbon prices. These prices may arise through an emissions tax, sequestration subsidy, or a cap and trade system where limited emissions stimulate emergence of an emissions market. The price range in our analysis was chosen to span the projections of potential carbon prices we found in the literature. For example, the U.S. President's Council of Economic Advisers has taken a position that the carbon price will be somewhere in vicinity of $20 per ton while estimates by modeling groups such as MacCracken et al. show carbon prices between $18 and $260 per ton. Based on these and other estimates we chose to vary the carbon price in $10 increments between $0 and $500 per ton with the high-end chosen in an effort to find total mitigation potential (technical potential) regardless of cost.

Emission Reduction Potential

Figure 1 shows total emission reductions from all incorporated agricultural mitigation options. The results indicate steady increases in net emission reductions up to almost 400 MMTCE at the highest simulated price level. However, for prices in the range of $50 to $100, overall reductions remain between 126 and 264 MMTCE. In Figure 1, total agricultural net emission reductions are decomposed into contributions from individual GHGs. Carbon dioxide abatement strategies constitute the largest supply component. Methane and nitrous oxide abatement strategies add considerably less not exceeding a combined total of 50 MMTCE even under high reduction incentives.

Figure 2 provides details on individual carbon dioxide mitigation options including the production of biofuels. The simultaneous inclusion of major agricultural mitigation strategies allows us to identify preferred strategies at each incentive level. At low prices the model concentrates on the usage of soil based carbon sequestration for traditional crops. As the price level increases above $30 per ton, switchgrass based biomass comes into production and starting between $40-$70 per ton we also encounter willow and poplar based biomass. Furthermore, for prices above $70 per ton, the combined bioelectricity offsets from switchgrass, hybrid poplar, and willow dominate the contribution of all other agricultural GHG mitigation strategies. These observations confirm that switchgrass and woody biomass are not competitive at the current zero price for carbon but could become so if the price is increased. Using a crude estimate of the carbon content of biofuel feedstocks as approximately 50 percent, a $50 subsidy per ton of carbon implies an additional benefit of about $25 per ton of the biomass commodity. This compares to current feedstock prices in the $40-50 per ton range and shows that a carbon program would offset the current cost of the biofuel feedstock making them competitive.

Cornstarch-based ethanol does not increase beyond current levels of production even if stimulated by high mitigation incentives. We also studied emission offsets from cellulose-based ethanol. Since we did not have accurate cost data for this process, we conducted a sensitivity analysis over a wide range of cost assumptions. For processing cost above $0.50 per gallon of ethanol, no cellulose-based ethanol was generated under all carbon price scenarios. Processing cost between zero and $0.50 yielded emission offsets up to 3.6 MMTCE for carbon prices between zero and $100 per ton. Under higher carbon prices, switchgrass, poplar, and willow were used to generate electricity in favor of ethanol. In summary, current ethanol technologies based on either cornstarch or cellulose offer limited potential to successfully compete within the total spectrum of agricultural mitigation strategies.

As indicated before, some of the biofuel parameters were not known with certainty. To assess the impact of alternative specifications, we conducted a sensitivity analysis on three biofuel characteristics (Table 6). First, we decreased the carbon cycle efficiency of switchgrass from 90 to 80 percent. Second, we assumed the same positive soil sequestration effect for perennial biofuel crops as applied for cropland retirement into grassland. Third, we tested the effect of equal carbon credit values for sinks and biofuel offsets. While the addition of soil sequestration effects to biofuels has the highest impact on supply of total agricultural emission reductions, omission of carbon sink credit adjustments leads to the biggest change in strategy contributions.

Mitigation Induced Welfare Effects

ASMGHG computes welfare effects on producers, consumers, and foreign trading partners in the agricultural sector context. As mitigation incentives increase, total welfare decreases monotonically (Figure 3). This decrease can be identified as dead weight loss and provides a measure of the minimum benefits society must gain from reduced levels of GHG emissions plus any co-benefits attained through cleaner water or reduced erosion to meet the Kaldor Hicks potential compensation test. In addition the transaction costs of policy implementation would need to be considered.

Decreasing total agricultural sector economic surplus shows that current welfare levels are in part dependent upon emission intensive agricultural technologies. Adoption of biofuel production or other mitigation alternatives to reduce emissions competes with traditional production and uses resources with opportunity costs. The welfare gains and losses from adopting emission-abating practices are not equally distributed among agricultural market segments. In particular, higher operational costs to producers are more than offset by higher revenues due to increased prices. As shown in Figure 3, the net effect on producers' welfare is positive. Domestic consumers' and foreign welfare, on the other hand, decreases.

Effects on Traditional Agricultural Product Markets

Large-scale production of emissions offsets diverts land away from traditional agricultural production to biofuels and forests (Figure 4). The increased land resource competition affects agricultural commodity markets (Figure 5). Agricultural commodity prices rise because of higher land rental costs and increased costs of emission-intensive key inputs like fertilizer and fossil fuel. Changes in production and prices accelerate for carbon prices above $30 per ton of carbon when biofuel-based mitigation begins to dominate. Because biofuel mitigation efforts strictly reduce traditional agricultural commodities, prices rise faster. Low cost strategies such as reduced tillage do not markedly reduce traditional agricultural commodity supply. In case reduced tillage increases traditional long-term crop yields because of the beneficial effects of increased soil organic matter on nutrient availability, water holding capacity, and physical soil structure.

Effects on Other Environmental Matters

Emissions of GHGs constitute just one out of many environmental externalities linked to agricultural production. For this study, we examined the effects of mitigation incentives on two measures of nitrogen pollution, one aggregated measure of phosphorous pollution, and erosion (Figure 6). Because we did not have adequate EPIC input data for perennial biofuel crops or trees, our analysis of environmental side effects is limited to pollution from traditional crop production. Figure 6 shows strongly decreasing levels of non-GHG pollution on traditional cropland as carbon prices take on low levels between zero and $50 per ton. Thus, most of the gains occur during the carbon prices where mitigation efforts involve no or only little biofuel production. As the biofuels begin to dominate (carbon price > $70 per ton), some of externality accounts begin to increase. This behavior illustrates that biofuel options, which reduce traditional cropland, increase pressure to intensify traditional crop production on the remaining land.

Conclusions

This study examined the relative role of agriculture based biofuels in a policy arena where broad efforts were made to slow down the increase in atmospheric GHG concentrations by creating a market that values emission reductions. Given current technologies, biofuels could play an important part in such a market provided the carbon equivalent price was above $30 per metric ton. For lower prices, the opportunity costs of resources required for biofuel production exceed the value the feedstock plus the carbon offset generated. Only the ability to collect considerable additional benefits from carbon savings makes the biofuels competitive. The increased competitiveness at higher prices arises because biofuels continually offset fossil fuel based emissions and fare well in comparison to carbon sink. The reduced tillage strategy, for example, initially leads to increases in soil carbon but then later saturates since the soil reaches the new equilibrium. Biofuels may also yield other ancillary benefits in terms of air quality, but that is not explored in this study.

In presenting our research we must note several limitations. First, our results are driven by the quality of the underlying data. Many data were derived from simulation models, i.e. EPIC, and thus echo the quality and accuracy of these models. Second, the findings reflect currently available technologies and associated data. However, technology may evolve rapidly, because of increased research efforts many of which are government funded. The complexity of the ASMGHG makes it inappropriate to conduct a sensitivity analysis on all possible parameters, which may change due to technological improvements.

Some simplifying assumptions in ASMGHG may lead to either over or understatements of the true economic biofuel impact. In particular, the location of the biofuel offset supply curve may be overstated because: a) there are no market penetration limits imposed on biomass based electrical power plants, b) there are no policy transaction cost in our model, c) the price for electricity is assumed to be perfectly elastic to biomass producers, and d) alternative agricultural land uses may be more competitive in the future thus raising the opportunity costs of biofuel production. At the same time, the biofuel offset supply curve may be understated because of: a) future technological improvements of biofuels b) additional biofuel uses currently left out, i.e., district heating, c) future increases of fossil fuel cost not due to emission policies, d) potential governmental subsidies for biomass electricity as implemented in Denmark, and e) the Western states of the U.S. were not considered.

Despite the above noted empirical limitations, our study suggests that biofuels may face a brighter future than portended by previous economic analyses. However, the big question is: Will society choose to reward their carbon recycling characteristics? This will entail society making a decision to attach a substantial price to the right to emit GHGs into the atmosphere.

Bibliography

Adams, D.M., R.J. Alig, J.M. Callaway, and B.A. McCarl., *The Forest and Agricultural Sector Optimization Model (FASOM): Model Structure and Policy Applications*, USDA Forest Service Report PNW-RP-495, 1996

Alig, R.J., D.M.Adams and B.A.McCarl. "Impacts of Incorporating Land Exchanges Between Forestry and Agriculture in Sector Models*", Journal of Agricultural and Applied Economics*, 30(2), 389-401, 1998.

Babcock, B.A., and G.R. Pautsch. "Relative Efficiency of Sequestering Carbon in Agricultural Soils Through Second Best Instruments." Paper presented at the Third Toulouse Conference on Environment and Resource Economics - Environment, Energy Uses and Climate Change, Toulouse, France, 14-16 June 1999.

Badin, J. and J. Kirschner. "Biomass Greens U.S. Power Production." *Renewable Energy World* 1,3(November 1998):40-45.

Benson, V. National Resource Conservation Service, U.S. Department of Agriculture Crop Enterprise Budgets, Personal Communication, February 1999.

Chang, C.C., B.A. McCarl, J.W. Mjelde, and J.W. Richardson. "Sectoral Implications of Farm Program Modifications." *American Journal of Agricultural Economics*. 74(1992):38-49.

Coble, K.H., C.C. Chang, B.A. McCarl, B.R. Eddleman. "Assessing Economic Implications of New Technology: The Case of Cornstarch-Based Biodegradable Plastics." *Review of Agricultural Economics* 14(1992): 33-43.

Cole, C.V., C. Cerri, K. Minami, A. Mosier, N. Rosenberg, D. Sauerbeck, J. Dumanski, J. Duxbury, J. Freney, R. Gupta, O. Heinemeyer, T. Kolchugina, J. Lee, K. Paustian, D. Powlson, N. Sampson, H. Tiessen, M. van Noordwijk, and Q. Zhao. "Agricultural options for the mitigation of greenhouse gas emissions" Chapter 23 in *Climate Change 1995: Impacts, Adaptation, and Mitigation of Climate Change: Scientific-Technical Analyses*, prepared by IPCC Working Group II, 726-771. Cambridge, England: Cambridge University Press, 1996.

Council of Economic Advisors (CEA). "The Kyoto Protocol and the President's Policies to Address Climate Change: Administration Economic Analysis" [Online]. Available HTTP: www.whitehouse.gov/WH/New/html/augnew98.html#Kyoto. July 1998.

Cushman, J., G. Marland, and B. Schlamadinger. "Biomass Fuels, Energy, Carbon, and Global Climate Change." In: *Energy and Global Climate Change*, Oak Ridge National Laboratory Review, 28 (2 & 3): special issue (1995) pp 14-21. [Online]. Available HTTP: www.ornl.gov/ORNLReview/rev28-2/text/contents.htm.

Gallagher, P. and D. Johnson. "Some New Ethanol Technology: Cost Competition and Adoption Effects in the Petroleum Market," *The Energy Journal* 20,2(1999):89-120.

IPCC. *Land Use, Land-use Change, and Forestry*. Special Report of the Intergovernmental Panel on Climate Change, Geneva Switzerland, Robert T. Watson, Ian R. Noble, Bert Bolin, N. H. Ravindranath, David J. Verardo and David J. Dokken (Eds.) Cambridge University Press, UK. pp 375, 2000.

Kline D., T. Hargrove and C. Vanderlan. *The Treatment of Biomass Fuels in Carbon Emissions Trading Systems*. Prepared for the Center for Clean Air Policy's Greenhouse Gas Emissions Trading Braintrust, [Online]. Available HTTP: www.ccap.org/m-pub-d.htm#AIRLIEPUB. Washington, March 1998.

Lal, R., J. M. Kimble, R. F. Follett, and C. V. Cole. *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect*, 128 pp., Sleeping Bear Press Inc., Chelsea MI,1998.

Mann, M.K. and P.L. Spath. *Life Cycle Assessment of a Biomass Gasification Combined-Cycle Power System*. National Renewable Energy Laboratory, Golden, CO, TP-430-23076. (1997).

Marland, G., B.A. McCarl, and U.A. Schneider. "Soil Carbon: Policy and Economics." *Carbon Sequestration in Soils: Science, Monitoring, and Beyond.* Proceedings of the St. Michaelis Workshop. N.J. Rosenberg, R.C. Izaurralde, and E.L. Malone, ed., pp. 151-178 , St. Michaels, MD, December 3-5,1998.

Marland, G. and B. Schlamadinger. "Forests for Carbon Sequestration or Fossil Fuel Substitution A Sensitivity Analysis." *Biomass and Bioenergy* 13(1997):389-397.

McCarl, B.A., C.C. Chang, J.D. Atwood, and W.I. Nayda, 'Documentation of ASM: The U.S. Agricultural Sector Model.' Unpublished Report, Texas A&M University, 2001, [Online]. Available HTTP: ageco.tamu.edu/faculty/mccarl/asm.htm.

McCarl, B.A. "Carbon Sequestration via Tree Planting on Agricultural Lands: An Economic Study of Costs and Policy Design Alternatives." Paper presented at the Energy Modeling Forum, Snowmass CO, 3-11 August 1998, [Online]. Available HTTP: ageco.tamu.edu/faculty/mccarl/papers/676.pdf.

McCarl, B.A., D.M. Adams, and R.J. Alig. "Analysis of Biomass Fueled Electrical Powerplants: Implications in the Agricultural & Forestry Sectors." *Annals of Operations Research* 94(2000):37-55.

McCarl, B.A. and B.C. Murray. "Harvesting the Greenhouse: Comparing Biological Sequestration with Emissions Offsets", Department of Agricultural Economics, Texas A&M University, College Station, TX, 2001, [Online]. Available HTTP: ageco.tamu.edu/faculty/mccarl/papers/885.pdf.

McCarl, B.A. and U.A. Schneider. "Curbing Greenhouse Gases: Agriculture's Role." *Choices*, First Quarter 1999:9-12.

McCarl, B.A. and U.A. Schneider. "U.S. Agriculture's Role in a Greenhouse Gas Mitigation World: An Economic Perspective." *Review of Agricultural Economics* 22, No.1(2000):134-159.

McCarl, B.A. and U.A. Schneider. “The Cost of Greenhouse Gas Mitigation in U.S. Agriculture and Forestry” *Science*. Forthcoming 2001

MacCracken, C.N., J.A. Edmonds, S.H. Kim and R.D. Sands , The Economics of the Kyoto Protocol, in *The Costs of the Kyoto Protocol: A Multi-Model Evaluation.* Special Issue of *The Energy Journal* (May 1999):25-72.

Mendelsohn, R, and J.E. Neumann. *The Impact Of Climate Change On The United States Economy*, 344 pp., Cambridge University Press, 1999.

Moulton, R.J., and K.B. Richards. "Costs of Sequestering Carbon Through Tree Planting and Forest Management in the U.S. " USDA Forest Service, General Technical Report WO-58, Washington DC, 1990.

Rosenberg, N.J., R.C. Izaurralde, and E.L. Malone, eds *Carbon Sequestration in Soils: Science, Monitoring, and Beyond.* Proceedings of the St. Michaelis Workshop, Batelle Pacific Northwest Laboratory, 1999.

Samson, R. and P. Duxbury. "Assessment of Pelletized Biofuels.", Resource Efficient Agricultural Production – Canada, Quebec, [Online]. Available HTTP: www.reap.ca/Reports/pelletaug2000.html, April 2000.

Schneider, U.A. *Agricultural Sector Analysis on Greenhouse Gas Emission Mitigation in the U.S.*, PhD Dissertation, Department of Agricultural Economics, Texas A&M University, December 2000.

Sedjo, R.A. "Forests, a Tool to Moderate Global Warming?" *Environment* 13(1989):1,14.

Shapouri, H. Personal Communication USDA Office of Energy, Washington D.C. Feb 2000.

Spath, P.L and M.K. Mann. *Life Cycle Assessment of Coal-fired Power Production*. National Renewable Energy Laboratory, Golden, CO, TP-570-25119(1999).

Stavins, R.N. "The Costs of Carbon Sequestration: A Revealed-Preference Approach." *American Economics Review* 89, no. 4, (September 1999):994-1009.

United Nations, Framework Convention on Climate Change. *Kyoto Protocol*. Climate Change Secretariat (UNFCCC). [Online]. Available HTTP: www.unfccc.de/resource/convkp.html (March 1998).

U.S. Environmental Protection Agency. *Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-1997*. EPA-236-R-99-003, Washington DC, May 1999a.

U.S. Environmental Protection Agency. *U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions*. EPA 430-R-99-013, Washington DC, September 1999b.

U.S. Global Change Research Program. *U.S. National Assessment, The Potential Consequences of Climate Variability and Change*. [Online]. Available HTTP: www.nacc.usgcrp.gov, 2000

Walsh, M.E., D. de la Torre Ugarte, S. Slinsky, R.L. Graham, H. Shapouri, and D. Ray. "Economic Analysis of Energy Crop Production in the U.S. - Location, Quantities, Price and Impacts on the Traditional Agricultural Crops." *Bioenergy 98: Expanding Bioenergy Partnerships*, Madison Wisconsin, October 4-8, vol. 2 (1998):1302-1310.

Wang, M.Q. *GREET 1.5 – Transportation Fuel Cycle Model*. Argonne National Laboratory Report ANL/ESD-39, August 1999.

Wang, W., C. Saricks, and D. Santini. *Effects of Fuel Ethanol Use on Fuel-Cycle Energy and Greenhouse Gas Emissions*. Center for Transportation Research, Argonne National Laboratory, ANL/ESD-38, January(1999).

West, T., M. Post, J. Amthor and G. Marland, "Review of Task 2.1" National Carbon Sequestration Assessment" Presentation at DOE Center for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystems (CSITE) Program Review, Oakridge National Laboratories, TN, Nov 2000.

Williams, J. R., C. A. Jones, J. R. Kiniry, and D. A. Spaniel.:1989, "The EPIC Crop Growth Model." *Transactions of The American Society of Agricultural Engineers*. 32 :497-511.

Yacobucci, B.D. and J. Womach. "RL30369: Fuel Ethanol: Background and Public Policy Issues", The National Council for Science and the Environment, Washington, D.C., [Online]. Available at: http://www.cnie.org/nle/eng-59.html, March 2000.

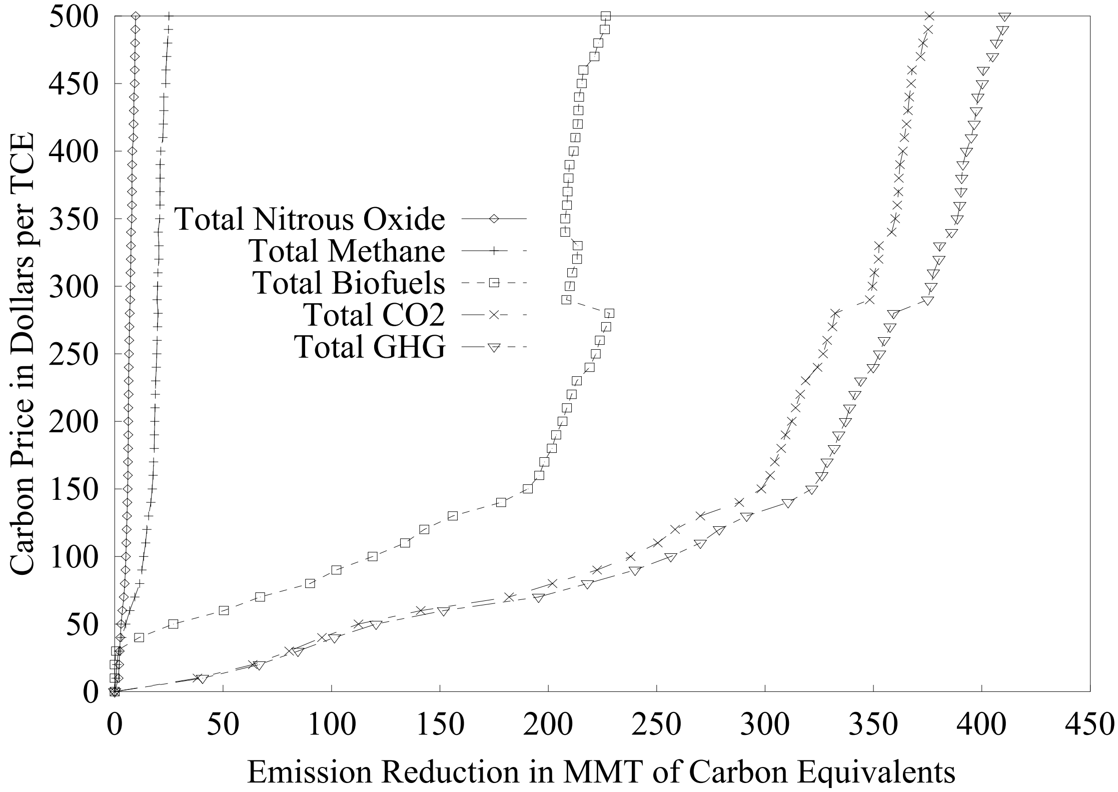

Figure 1 **Contribution of biofuels to GHG abatement supply from agricultural sources. Carbon price is externally established and jointly applied to all CO2, methane, and nitrous oxide strategies. "Total GHG" equals the GWP weighted sum of "Total Nitrous Oxide", "Total Methane", and "Total CO2".**

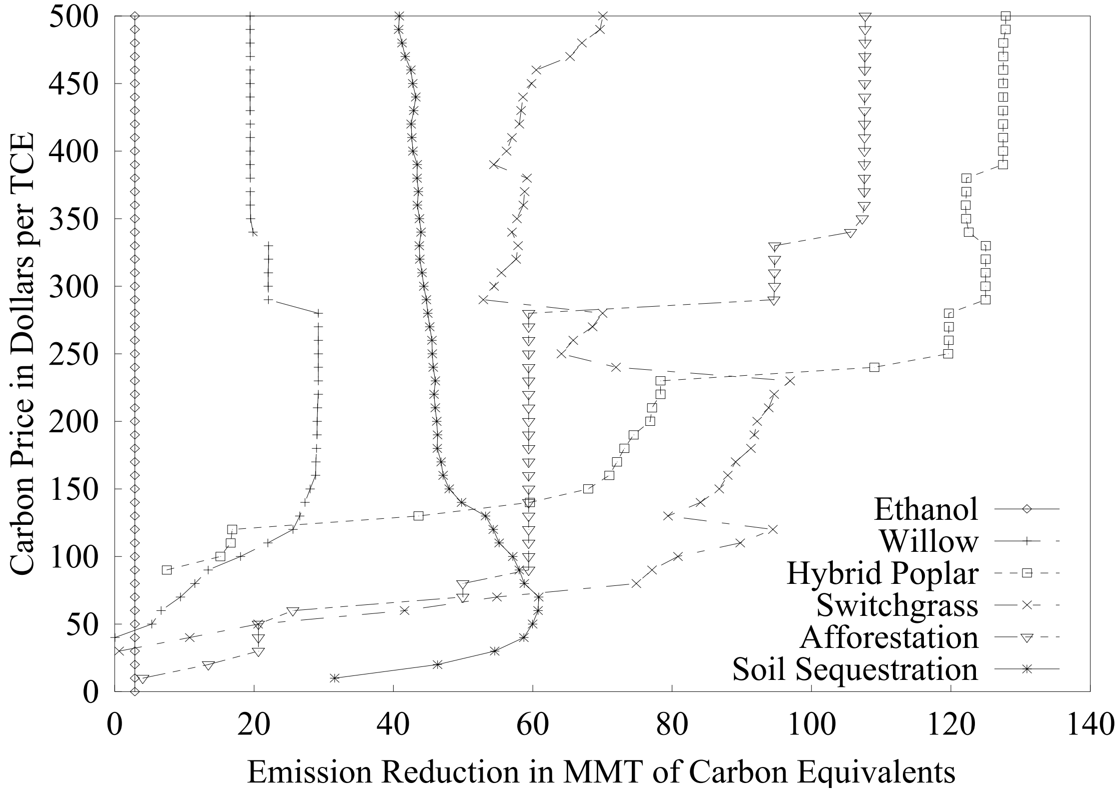

Figure 2 **Total amount of carbon emissions abated by major carbon strategy. Willow, hybrid poplar, and switchgrass are used for electricity generation. The value of carbon credits is discounted by 50 percent for soil sequestration and by 25 percent for carbon savings from afforestation. Soil organic matter of perennial biofuel plantations is assumed to remain constant**

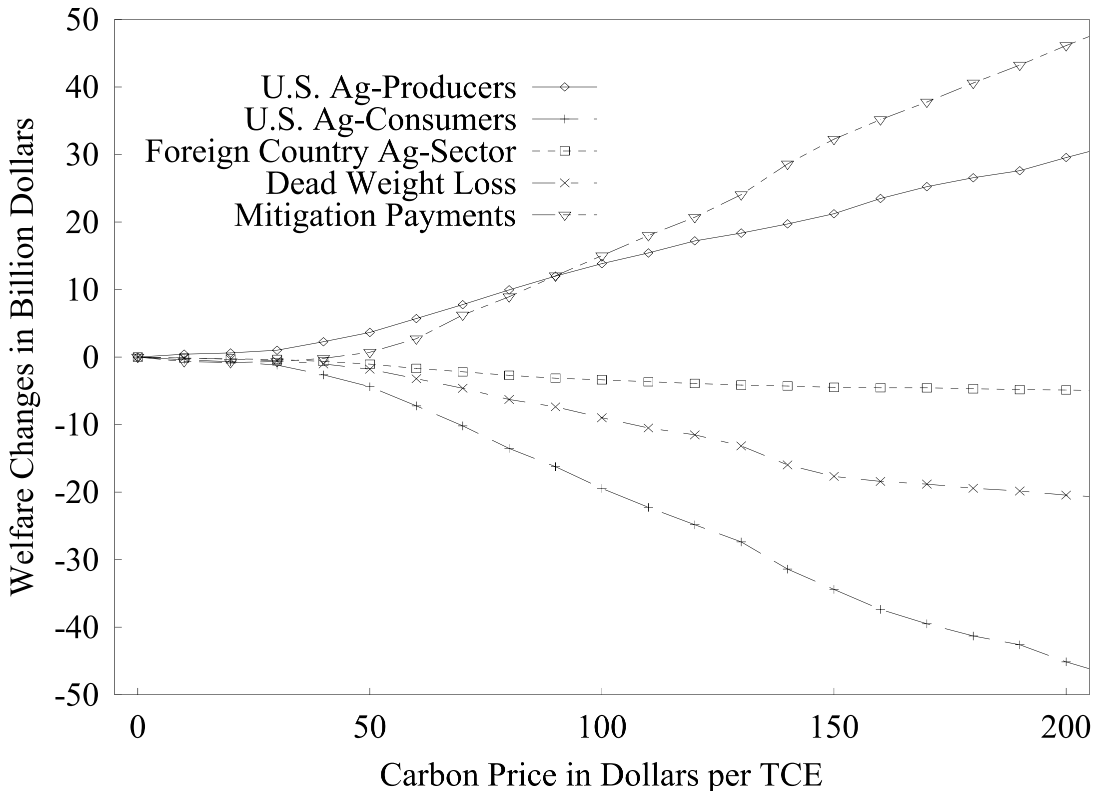

Figure 3 **Welfare effects of agricultural sector in response to carbon prices. Mitigation payments are calculated as product of net emitted carbon equivalents times carbon price. Dead weight loss represents the total welfare loss to all agricultural market segments plus the institution, which collects tax on emissions and pays for emission offsets. Not included are social benefits from lower atmospheric GHG concentrations due to agricultural mitigation efforts.**

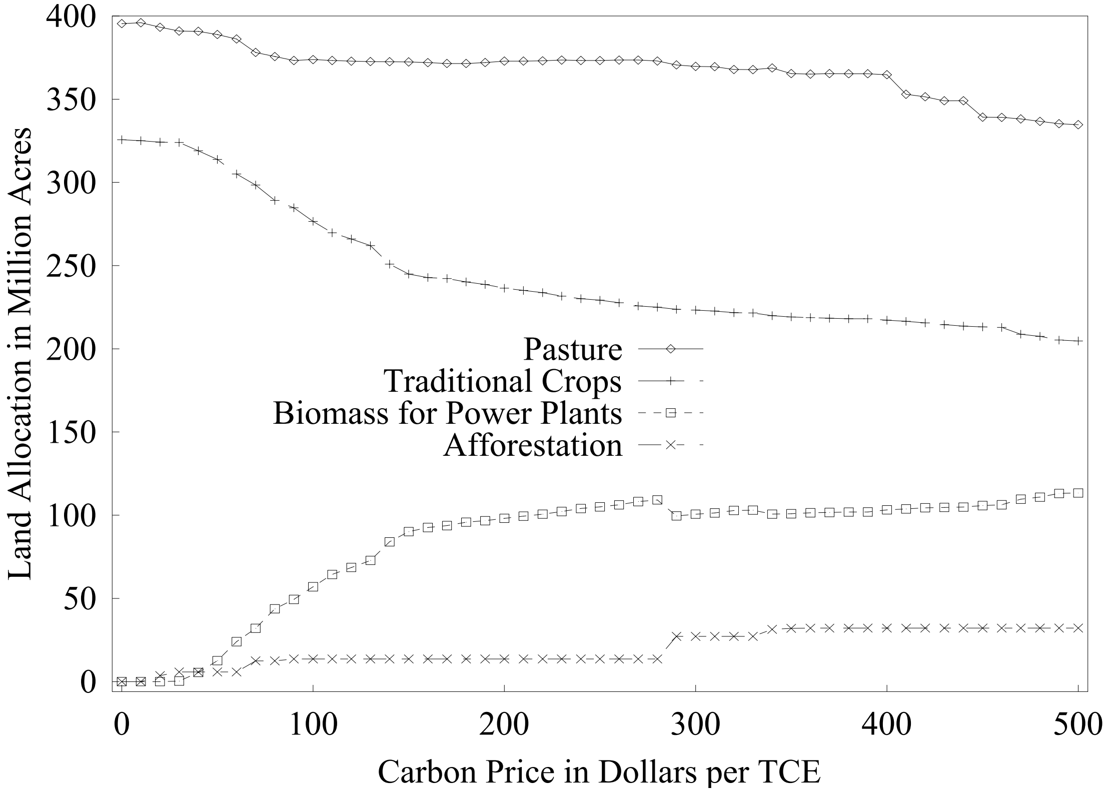

Figure 4 **Effects of agricultural GHG emission mitigation incentives on land use. Carbon sink credits and soil sequestration of perennial biomass cropland are treated as noted in Figure 2.**

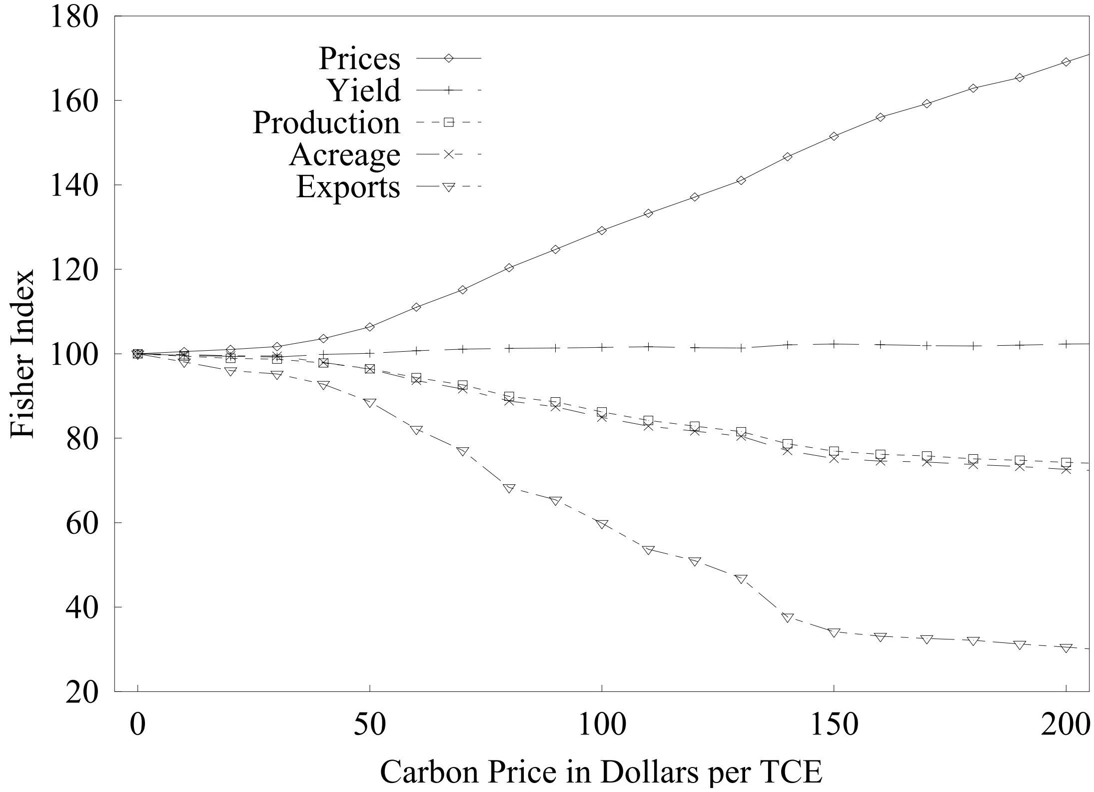

Figure 5 **Effects of agricultural GHG mitigation efforts on traditional crop production. Price, production, and export impacts were aggregated using Fisher's ideal index. Acreage represents total cropland excluding afforested land, land used for perennial biomass crops, and pasture land. The average impact on yields equals the production index divided by the acreage index.**

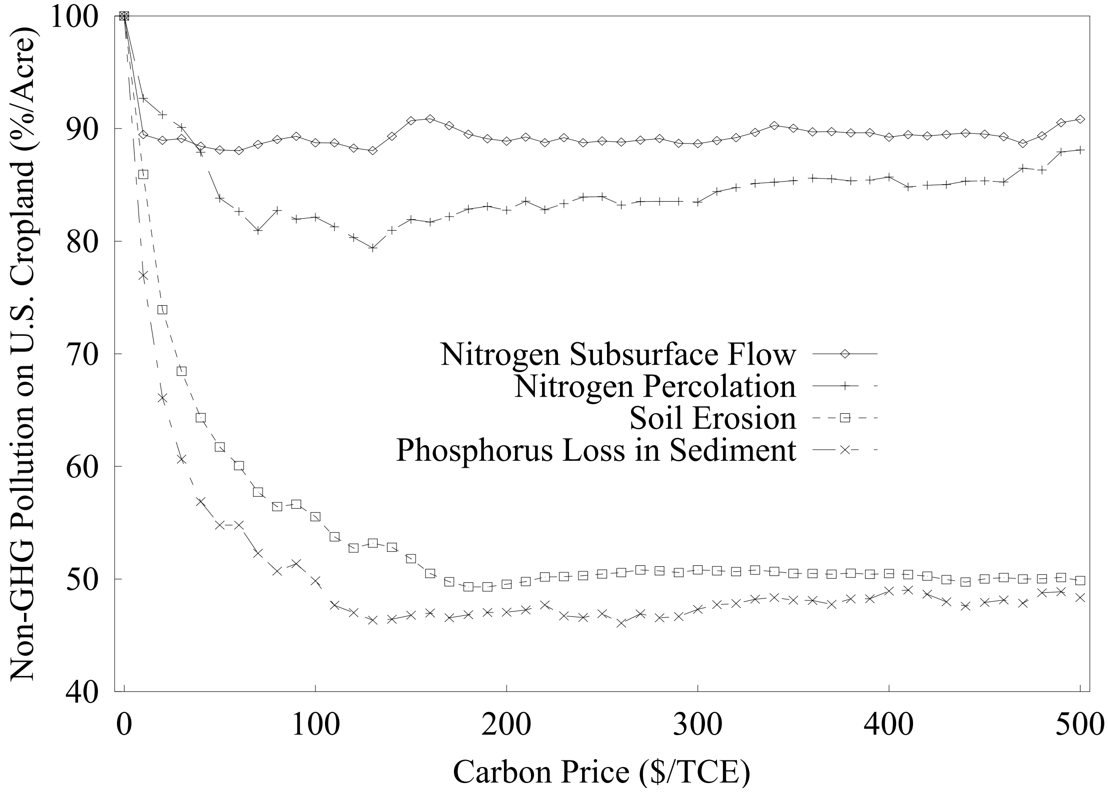

Figure 6 **Effects of agricultural GHG mitigation efforts on unregulated non-GHG environmental accounts. All changes were calculated by summing the product of ASMGHG solutions on alternative crop management acreage times the EPIC simulated coefficients for each alternative crop management.**

Table 1 Mitigation Strategies Included in the Analysis

Strategy	Basic Nature	Greenhouse Gas Affected		
		CO2	CH4	N2O
Biomass Electricity Production	Offset	X	X	X
Ethanol Production	Offset	X	X	X
Afforestation / Timberland Management	Sequestration	X		
Crop Mix Alteration	Emission, Sequestration	X	X	X
Crop Fertilization Alteration	Emission, Sequestration	X		X
Crop Input Alteration	Emission	X		X
Crop Tillage Alteration	Emission	X		X
Grassland Conversion	Sequestration	X		
Irrigated /Dry land Conversion	Emission	X		X
Livestock Management	Emission		X	
Livestock Herd Size Alteration	Emission		X	X
Livestock Production System Substitution	Emission		X	X
Manure Management	Emission		X	

Table 2 Key Parameters for Computation of GHG Emission Offsets from Cornstarch Based Ethanol

Parameter	Value
GWP weighted total GHG emissions from production, processing, and combustion of fossil fuel based gasoline (computed based on GREET model, Wang)	3.13 kg CE / Gallon
GWP weighted total GHG emissions from processing corn into gasoline substitutes (wet milling, market-value-based co-credit method, 10 percent ethanol blend, computed based on GREET model, Wang)	0.39 kg CE / Gallon
GWP weighted total GHG emissions from corn production	Vary according to corn management and region
Corn yields	Vary according to corn management and region
Wet milling yields (per bushel of corn)	31.5 lbs of cornstarch 15.4 lbs corn gluten feed 1.5 lbs corn oil
Ethanol yield (per 1000 lbs of cornstarch)	79 Gallons
Ethanol price	$1.20 per Gallon

Table 3 **Average Annual Yields for Herbaceous and Woody Crops Used as Power Plant Feedstock based on Walsh et al.**

Region	Switchgrass Dry Tons/acre	Hybrid Poplar Dry Tons/acre	Willow Dry Tons/acre
Alabama	5.14	4.45	
Arkansas	4.98	4.38	
Connecticut	4.04		5.41
Delaware	3.59		
Florida	3.59	4.50	
Georgia	4.96	4.29	
Illinois	6.39	4.93	
Indiana	6.34	4.81	
Iowa	6.07	4.65	
Louisiana	5.07	4.80	
Maine			3.87
Maryland	4.16		4.50
Massachusetts	4.16		5.07
Michigan	4.22	4.25	
Minnesota	4.32	4.36	
Mississippi	5.12	4.76	
Missouri	4.78	4.43	
New Hampshire	4.04		4.87
New Jersey	4.44		4.98
New York	4.37		5.13
Ohio	5.77	4.31	
Pennsylvania	4.93		5.01
Rhode Island	3.59		5.40
South Carolina	4.67	4.22	
Vermont	4.04		4.37
Wisconsin	4.38	4.62	

Table 4 **Key Parameters for Computation of GHG Emission Offsets From Biomass Power Plants**

Region	Processing Costs (in $1,000 per 7 Trillion BTU)[3]		
	Switchgrass	Hybrid Poplar	Willow
Northeast	1476		1455
Lake States	1435	1552	
Cornbelt	1435	1552	
Southeast	1333	1540	
Delta States	1380	1621	
	Power Plant Requirements (in 1,000 Dry Tons per 7 Trillion BTU)		
	Switchgrass	Hybrid Poplar	Willow
All Regions	482.76	424.24	424.24
	GHG Emission Offsets (in kg CE per dry ton)		
	Switchgrass	Hybrid Poplar	Willow
All Regions	369.61	420.59	420.59
	Producer Price (in $ per MBTU)		
	Switchgrass	Hybrid Poplar	Willow
All Regions	0.83	0.83	0.83

[3] 7 Trillion BTU is the average annual energy generation of the examined biomass power plants.

Table 5 Key Parameters and Assumptions for Saturating Sinks

Parameter / Assumptions	Soil Tillage Reduction	Afforestation
Sequestration Potential	20 years	40 years
Subsequent Action	Revert back to conventional tillage	Harvest trees
Carbon Fate	All sequestered carbon is released during three years following the tillage reversion in equal increments of 33%	Sequestered carbon is lost at harvest, some goes to product pool and decays, some goes to biofuels and offsets fossil fuel use
Carbon Discount Rate	4%	4%
Carbon Price Change Over Time	No change	No change
Resulting Carbon Value Adjustment	-50%	-25%

Table 6 Sensitivity of GHG Emission Reductions from Various Agricultural Accounts to Alternative Biofuel Parameter Specifications (MMTCE)

Sink Carbon Credit Adjustment (Ag-Soils/ Forests)	Assumed Soil Carbon Sequestration for Perennial Biofuel Crops	Assumed Carbon Closure for Switchgrass Based Electricity	GHG Emission Mitigation Account	Carbon Price in $/TCE					
				10	20	50	100	200	500
	ASMGHG Base Scenario								
-50%/-25%	None	90 %	Biofuels	0	0	31,199	122,643	196,815	169,581
-50%/-25%	None	90 %	Ag-Soils	31,045	45,821	58,843	55,493	47,024	49,789
-50%/-25%	None	90 %	Afforestation	4,028	13,445	20,619	59,407	59,407	117,703
-50%/-25%	None	90 %	Total Carbon	38,395	63,892	117,116	244,772	311,898	349,808
-50%/-25%	None	90 %	Total GHG	41,183	67,328	126,053	263,950	336,666	385,517
	Reduced Carbon Closure for Switchgrass								
-50%/-25%	None	80 %	Biofuels	0	0	18,666	101,664	193,720	166,238
-50%/-25%	None	80 %	Ag-Soils	31,045	45,821	60,403	57,422	46,998	49,784
-50%/-25%	None	80 %	Afforestation	4,028	13,445	20,619	59,407	59,407	123,106
-50%/-25%	None	80 %	Total Carbon	38,395	63,892	106,096	225,395	308,615	351,877
-50%/-25%	None	80 %	Total GHG	41,183	67,328	113,840	243,779	333,410	387,372
	Soil Organic Matter Changes as in Grassland								
-50%/-25%	Grassland	90 %	Biofuels	0	0	42,390	138,196	198,272	188,955
-50%/-25%	Grassland	90 %	Ag-Soils	31,045	45,821	65,995	80,876	89,744	90,271
-50%/-25%	Grassland	90 %	Afforestation	4,028	13,445	20,619	59,407	59,407	89,698
-50%/-25%	Grassland	90 %	Total Carbon	38,395	63,892	135,338	285,261	355,891	381,180
-50%/-25%	Grassland	90 %	Total GHG	41,239	67,328	145,137	305,687	380,723	417,636
	No Carbon Credit Discounting for Carbon Sinks								
None	None	90 %	Biofuels	0	0	24,997	116,910	148,432	128,993
None	None	90 %	Ag-Soils	44,135	56,646	69,272	61,770	53,079	57,809
None	None	90 %	Afforestation	4,028	13,445	49,957	59,407	133,380	183,054
None	None	90 %	Total Carbon	52,051	75,252	150,562	245,560	343,680	380,867
None	None	90 %	Total GHG	54,560	78,116	159,089	263,549	366,836	411,442