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Economic Potential of Biomass-Based Fuels for Greenhouse Gas Emission Mitigation

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Keywords

Agricultural Sector Model, alternative energy, biofuel economics, biomass power plants, greenhouse gas emission mitigation, short rotation woody crops, switchgrass

Disciplines

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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 a 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 are taken from the literature. We simulate potential emission mitigation policies or markets using hypothetical carbon prices ranging between $0 and $500 per ton of carbon equivalent. At each carbon price level, the Agricultural Sector Model computes the new market equilibrium, revealing agricultural commodity prices, regionally specific production, input use, welfare levels, environmental impacts, and adoption of alternative management practices such as biofuel production. Results indicate there is no role for biofuels below carbon prices of $50 per ton of carbon equivalent. At these incentive levels, emission reductions through reduced soil tillage and afforestation are more cost efficient. At carbon prices above $50, however, biofuels become increasingly important, and at prices above $180 they dominate all other agricultural strategies.

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ECONOMIC POTENTIAL OF BIOMASS-BASED FUELS FOR GREENHOUSE GAS EMISSION MITIGATION

Introduction

Today, society faces important decisions regarding climate change mitigation. Many express concerns about the potential implications of the buildup 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, some scientists argue that the disturbances caused by increased GHG concentrations will take a long time to reverse. The International Panel on Climate Change (IPCC) maintains that it will take centuries for the sea level to stop rising from a warming increase; decades for atmospheric GHG concentrations to stabilize once emissions have stabilized; and decades to fully retrofit and/or replace the stock of equipment, vehicles, and technology associated with current anthropogenic emissions.

Society must decide whether to let emission increases continue or to 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). If steps are to be taken, another choice is whether to reduce emissions directly or to reduce them indirectly through the enhancement of sinks.

Agriculture potentially can 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, or CO_2), it is important in the total picture. According to the latest Environmental Protection Agency (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 1970s “energy crisis.” However, in the United States, biofuel production has not proven to be broadly economically feasible without subsidies (in the late 1990s, 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 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.

Here, 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’ net contribution to GHG emissions are measured in terms of net emissions of carbon dioxide, nitrous oxide, and methane. Also, we consider biofuels in comparison with a total suite of agricultural mitigation options rather than independently. Such a comparison allows us to examine the relative desirability of biofuels vis-à-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

- 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;
- nitrous oxide emissions as influenced by fertilization quantity and practices (through increased soil testing, use of denitrification inhibitors, or increased manure substitution);
- methane emissions from rice fields as influenced by total rice acreage and water management; and
- CO_2 emissions from fossil fuels used in production, transport, processing, and input manufacture (U.S. EPA 1999a,b).

In terms of emission absorption, agricultural GHG sinks can be expanded by increasing

- 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; Cole et al.);
- the acreage transformed from cropping usage to grasslands or forests (Sedjo; McCarl); or
- 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 use biofuel-based strategies, as previously discussed, or otherwise produce agricultural commodities, which through their consumption substantially offset emission-intensive nonagricultural 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? We will investigate this question from an economic viewpoint.

Issues in Appraising Economics of Agricultural Emission Reductions

An investigation of emission reductions via agriculture raises several important issues concerning the economic analysis framework. These include use of sectoral level analysis, incorporation of mitigation alternatives, and depiction of multiple gas trade-offs.

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 annually. The Kyoto Protocol, however, contains a U.S. limit on net emissions of 1990 levels less 7 percent for six greenhouse gas categories (United Nations). 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 emissions offsets could not be supplied through cropping agriculture, even if all available cropland were retired.

The previous argument suggests that agriculture may face a high demand for emission offsets if it can verifiably mitigate GHG emissions at relatively low costs. However, large-scale mitigation efforts, which involve a significant amount of the cropland base, would greatly affect the agricultural sector, with accompanying adjustments in production, prices, and welfare. To capture such effects, a sectorwide analysis is appropriate. To pursue 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. 2001.

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 friendly 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 estimated the economic mitigation potential of specific agricultural strategies independently. For example, afforestation has been examined by Stavins and by Moulton and Richards; biofuels have been assessed by Wang, Saricks, and Santini; Mann and Spath; McCarl, Adams, and Alig; and Lal et al., and Babcock and Pautsch have analyzed soil carbon sequestration on U.S. croplands. However, these individual strategy examinations may be biased because alternative mitigation options are left out. 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 various agricultural strategies, it is important that all available options be examined simultaneously.

We tried to accomplish this by including as many strategies as the consistent data would allow. Table 1 provides a summary list of the GHG emission mitigation options included in our model

Multiple Gas Trade-offs

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, and releases methane through enteric fermentation from ruminant animals or as a manure by-product; but it possibly can augment the soil carbon stock by using reduced tillage. Trade-offs between

TABLE 1. Mitigation strategies included in the analysis

Strategy	Basic Nature	Greenhouse Gas Affected CO_2	CH_4	N_2O
Biomass electricity production	Offset	X	X	X
Ethanol production	Offset	X	X	X
Afforestation/timberland management	Sequestration	X		
Crop mix alteration	Sequestration, emission	X	X	X
Crop fertilization alteration	Sequestration, emission	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	

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 changes in the level 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 agricultural sector model (ASM) of McCarl and associates (Chang et al.; McCarl et al. 2001). The ASM was first developed in the mid-1970s and has been used in many economic appraisals of 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 a U.S. agricultural sector model that also incorporates production and trade activity in the rest of the world. It depicts production in 63 U.S. agricultural subregions, 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, agricultural commodity consumption, producer income effects, consumer welfare effects, and various environmental impacts.

Greenhouse Gas Features

ASMGHG was developed to appropriately analyze major agricultural GHG mitigation opportunities. 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. Baseline emissions are calibrated to match EPA

(1999a) estimates. 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.

Next, we will highlight some important characteristics and assumptions of ASMGHG. A more detailed and technical description is available in Schneider 2000 or by contacting the authors.

Biofuel Feedstock Modeling. The biofuel feedstock components used were adapted from earlier ASM studies (see McCarl, Adams, and Alig). From those studies, 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 2 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 3 and Table 4).

No lifecycle assessments were available for switchgrass-based power plants. We therefore assumed a carbon closure[1] of about 95 percent, similar to poplar-based power plants. The literature suggests both higher (Samson and Duxbury) and lower values of carbon closure for switchgrass-based energy (Mann and Spath). Differences arise from different assumptions about crop management implications, i.e., soil carbon sequestration. For this study we assumed no change in soil organic matter from growing switchgrass.

Afforestation. We used solution information from the forest and agricultural sector optimization model (FASOM) (Adams et al.; Alig et al.) to obtain estimates of tree carbon sequestration for carbon prices ranging from $0 to $400 per ton of carbon equivalent. For each simulated carbon price, we recorded the FASOM-generated land transfer from agriculture to forestry, the carbon sequestration, and the land values. To export dynamic FASOM results into the static equilibrium ASMGHG, we computed

TABLE 2. 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	

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 foregone 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

TABLE 3. 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% 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 1,000 lbs of cornstarch)	79 gallons
Ethanol price	$1.20 per gallon

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 non-saturating 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

TABLE 4. Key parameters for computation of GHG emission offsets from biomass power plants

Region	Processing Costs (in $1,000 per 7 Trillion BTUs) [a]		
	Switchgrass	**Hybrid Poplar**	**Willow**
Northeast	1475.87		1454.56
Lake States	1434.95	1551.79	
Cornbelt	1434.95	1551.79	
Southeast	1332.68	1539.77	
Delta States	1379.56	1621.29	
	Power Plant Requirements (in 1,000 Dry Tons per 7 Trillion BTUs)		
	Switchgrass	**Hybrid Poplar**	**Willow**
All relevant regions	482.76	424.24	424.24
	GHG Emission Offsets (in kg CE per dry ton)		
	Switchgrass	**Hybrid Poplar**	**Willow**
All relevant regions	369.61	420.59	420.59
	Producer Price (in $ per MBTU)		
	Switchgrass	**Hybrid Poplar**	**Willow**
All relevant regions	0.83	0.83	0.83

[a] Seven trillion BTUs is the average annual energy generation of the examined biomass power plants.

systems, crop rotations, and management practices. Numerical specification of a full set of management alternatives requires a detailed and comprehensive data set that gives 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 managerially consistent with ASM dimensions. Through EPIC (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 sequestration, nitrous oxide release, and several other environmental effects (e.g., erosion, nutrient pollution).

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%

Caution was needed in interpreting the EPIC simulation results. We decided not to rely blindly on EPIC's absolute soil organic matter 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 soil organic matter number changes, we made a few aggregate assumptions based on other studies from the existing literature. Lal et al. report 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 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 soil organic matter accumulation from reduced tillage, West et al. 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 Council of Economic Advisers has taken a position that the carbon price will be somewhere in the 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 $300 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 that net emission reductions increase steadily, up to a maximum of about 380 MMTCE. However, for prices in the range of $50 to $100, overall reductions remain between 100 and 200 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, never exceeding a combined total of 50 million metric tons (MMT), even under high reduction incentives.

Figures 2 and 3 provide 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 (Figure 2). As the price level increases above $50 per ton, switchgrass-based biomass comes into production, and above $100 we also encounter willow- and poplar-based biomass (Figure 3).

Furthermore, for prices above $170 per ton, bioelectricity offsets dominate the contribution of all other agricultural GHG mitigation strategies. These observations

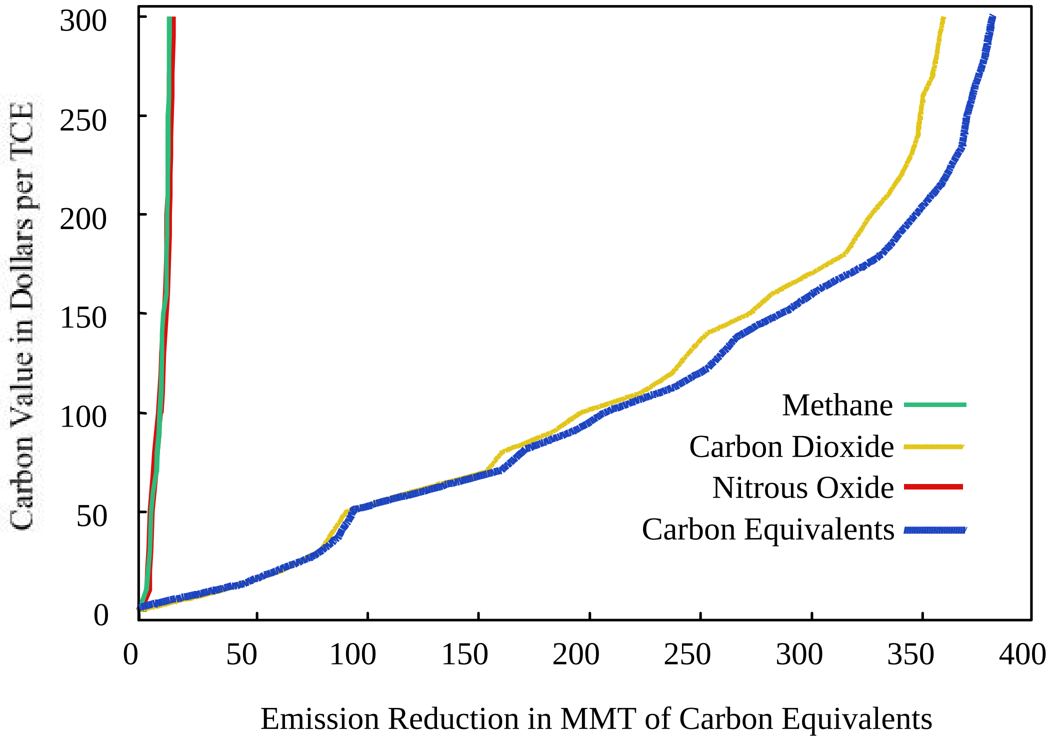

FIGURE 1. Emission abatement supply curve generated by agricultural greenhouse gas components

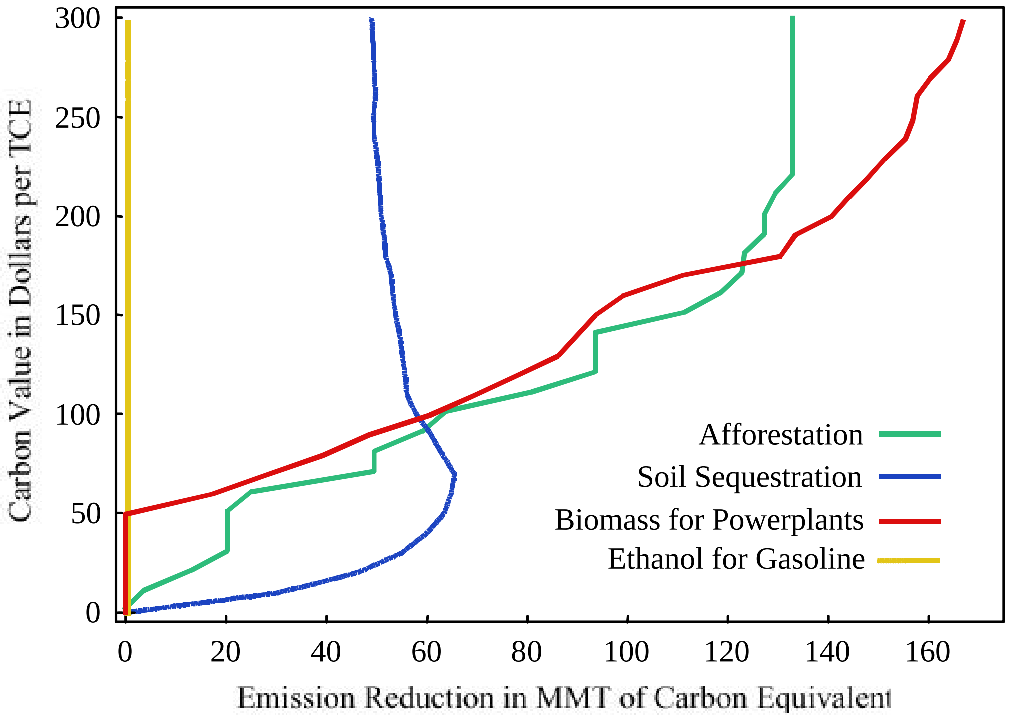

FIGURE 2. Total amount of carbon emissions abated, by major strategy

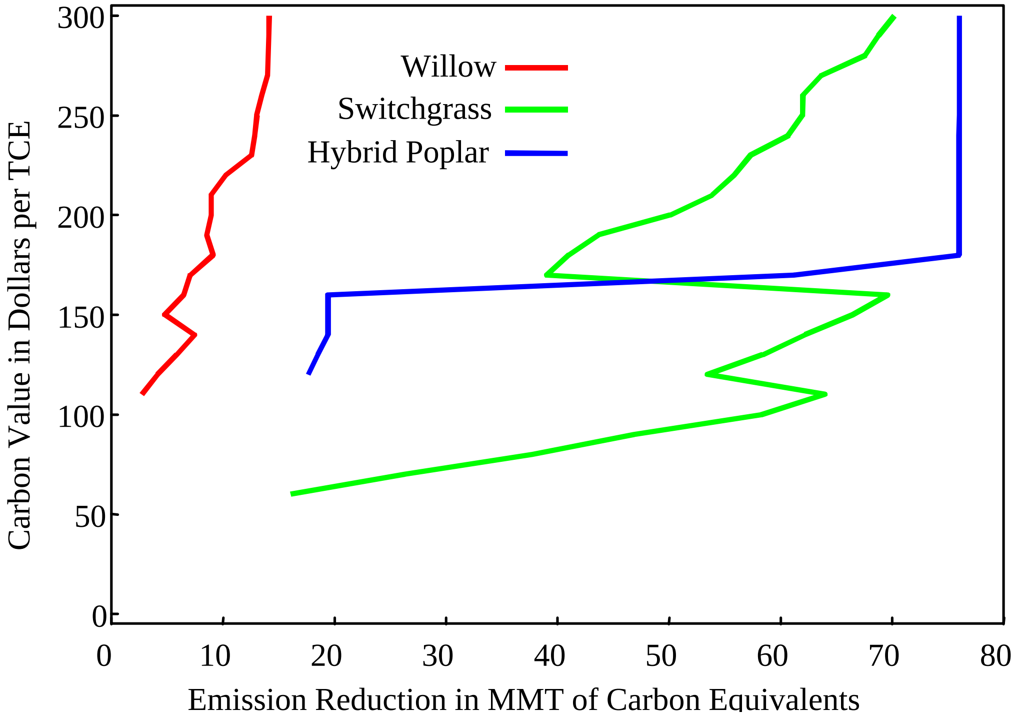

FIGURE 3. Carbon emission offsets by energy crop

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 a 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 feedstocks, 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. Because we did not have accurate cost data for this process, we conducted a sensitivity analysis over a wide range of cost assumptions. For processing costs above $0.50 per gallon of ethanol, no cellulose-based ethanol was generated. Processing costs between $0 and $0.50 yielded emission offsets up to 3.6 MMTCE for carbon prices between $0 and $100 per ton. Under higher carbon prices, switchgrass, poplar, and willow were used to generate electricity in favor of ethanol. In summary, both cornstarch- and cellulose-based ethanol offer limited potential to mitigate GHG within the total spectrum of agricultural mitigation strategies.

Mitigation-Induced Welfare Effects

ASMGHG computes welfare effects on producers, consumers, and foreign trading partners in the agricultural sector. As mitigation incentives increase, total welfare decreases monotonically (Figure 4). This decrease can be identified as deadweight 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 emissions-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

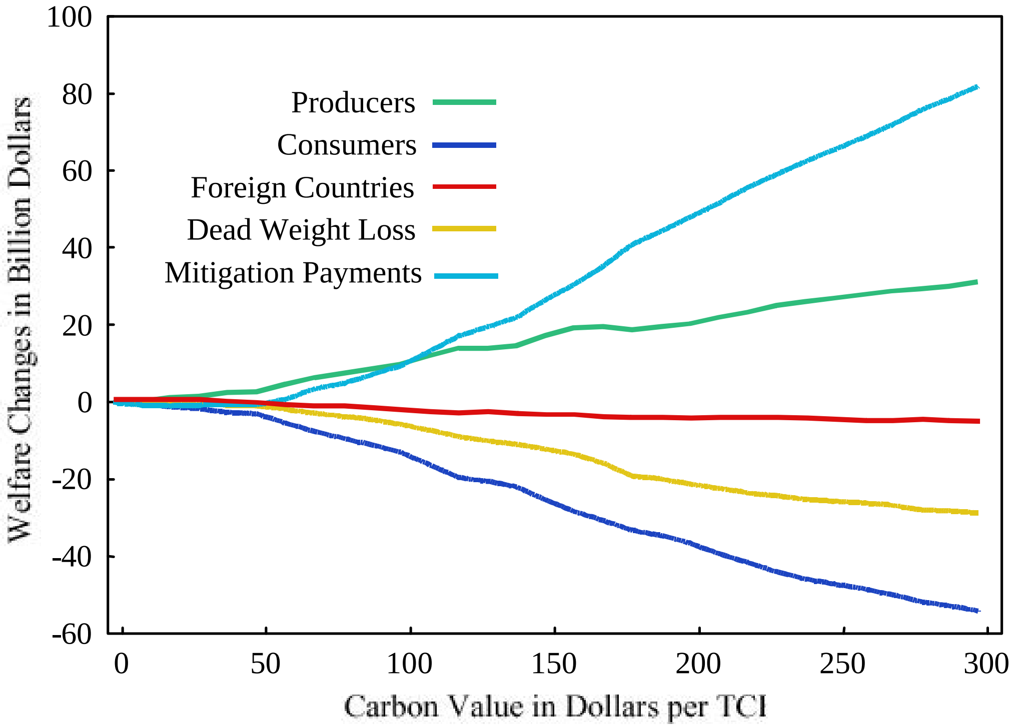

FIGURE 4. Welfare effects of agricultural sector in response to carbon prices

losses arising from using 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 4, the net effect on producers' welfare is positive. The welfare of domestic and foreign consumers, on the other hand, decreases. The loss in domestic agricultural consumers' surplus is due to both higher prices and lower consumption.

Effects on Traditional Agricultural Product Markets

Large-scale production of emissions offsets decreases the amount of land that is available for traditional agricultural practices (Figure 5). The resulting competition affects agricultural product markets. A summary of the effects of increased biofuel production on traditional agricultural production is given in Figure 6. First, agricultural commodity prices are sensitive to carbon prices. For example, corn prices rise by 21 percent when the carbon price goes from $0 to $100 per ton. Commodity prices go up because of increased land rental costs and increased costs of emission-intensive key

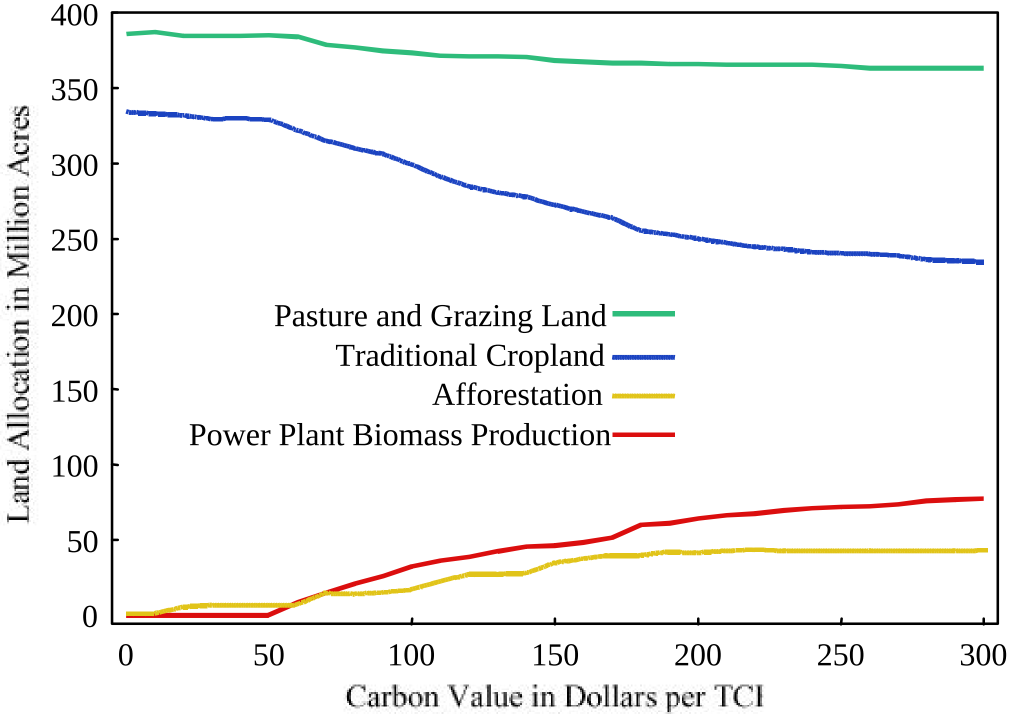

FIGURE 5. Effects of GHGE mitigation incentives on land use

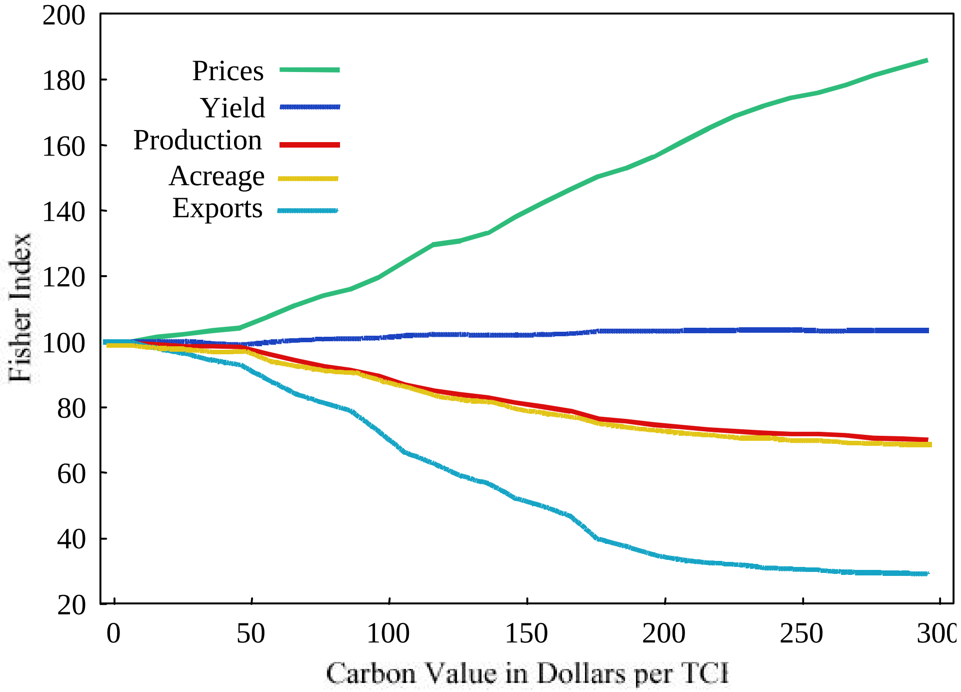

FIGURE 6. Effects of agricultural mitigation efforts on traditional agricultural production

inputs like fertilizer and fuel. For carbon prices between $0 and $50 per ton, average agricultural crop prices increase only by 1 percent per $10 carbon price increment. Higher carbon price levels, however, accelerate price changes. Particularly, between $50 and $300 per ton, average crop prices rise by about 3 percent for every $10 incremental increase in the price of carbon.

Note again that at $50 per ton of carbon, the dominance of biofuel-based mitigation begins. Below that price the mitigation options do not markedly reduce traditional agricultural commodity supply. Strategies such as reduced tillage in some cases increase 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. Switchgrass and short-rotation tree production, though, are unambiguously competitive with food production, causing prices to rise faster.

Figure 6 also displays changes in acreage, yields, production, and net exports of agricultural commodities. Yields remain relatively unaffected but decrease slightly for carbon prices below $50. As biofuel production initiates, average yields on the remaining food crop acreage start going up again and reach original values at a carbon price of about $120 per ton. Total exports of traditional agricultural products decline monotonically. At a carbon price of $50 per ton, food exports decline by a total of 6 percent relative to the base situation. However, carbon incentives between $50 and $200 per ton decrease food exports by 4 percent for every $10 increase.

Effects on Other Environmental Matters

Emissions of GHGs constitute just one of many environmental externalities linked to agricultural production. For this study, we examined the effects of mitigation incentives on nitrogen and phosphorous pollution and erosion (Figure 7). Our analysis is limited to pollution impacts on traditional crop production because we did not have adequate EPIC input data for perennial biofuel crops or trees.

Figure 7 shows decreasing levels of soil erosion and phosphorous pollution on traditional cropland as carbon prices take on low levels between $0 and $50 per ton. Thus, most of the gains occur at carbon prices where mitigation does not involve biofuel

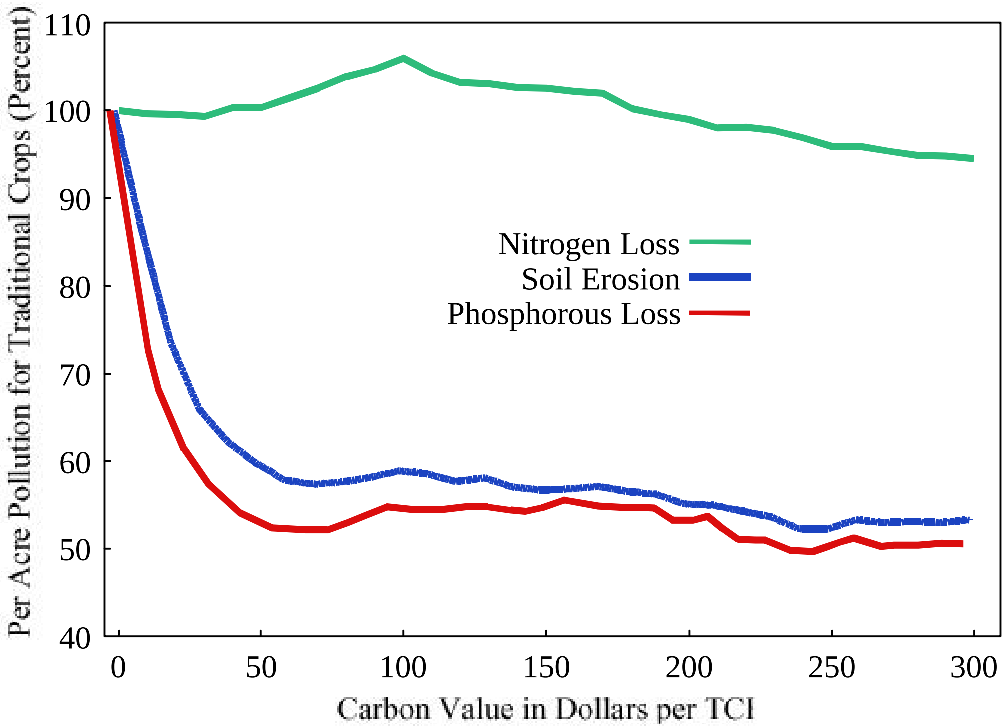

FIGURE 7. Effects of agricultural mitigation efforts on environmental accounts

production. As the biofuels begin to dominate (carbon price > $70 per ton), some externalities begin to increase. For example, phosphorous losses increase slightly for carbon prices between $70 and $160, offsetting about 10 percent of the initial 50 percent loss reduction. Nitrogen losses are highest at carbon prices of $100 per ton. This behavior indicates 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 reduce net GHG emissions by creating a market that values emission reductions. Biofuels could play an important part in such a market, provided the carbon equivalent price was somewhere above $50 per metric ton. At prices below that level, the opportunity cost of resources used in biofuel production are in excess of the value of the feedstock plus the carbon offset generated. Only the ability to collect additional benefits from carbon savings makes the biofuels competitive. The competitiveness of the biofuel prices above $50 arise because biofuels continually offset fossil-fuel-based emissions and fare well in comparison to, for example, changing tillage system use, which 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.

Biofuels thus may face a brighter future than that portended by previous economic analyses, but the big question is whether society will 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.

Several important limitations to this research should be noted. First, the findings presented here reflect currently feasible technologies for which data were available. Introduction of new, more efficient, or missing technologies may affect the competitive equilibrium in our model and change the relative importance of biofuels. Second, most of the greenhouse gas emission data from the traditional agricultural sector are based on simulation models and may not always accurately reflect reality. Third, ASMGHG solutions represent the static, intermediate-term equilibrium in the agricultural sector. Short-term adjustment costs from changing agricultural management are currently not accounted for.

Endnotes

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

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.

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