Measuring Abatement Potentials When Multiple Change is Present:

The Case of Greenhouse Gas Mitigation in U.S. Agriculture and Forestry

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Keywords

Abatement Function, Agricultural Sector Model, Carbon Sequestration, Economic Potential, Greenhouse Gas Emission, Mathematical Programming, Multiple Technical Change, Policy Simulation

Abstract

Mathematical programming is used to examine the economic potential of greenhouse gas mitigation strategies in U.S. agriculture and forestry. Mitigation practices are entered into a spatially differentiated sector model and are jointly assessed with conventional agricultural production. Competition among practices is examined under a wide range of hypothetical carbon prices. Simulation results demonstrate a changing portfolio of mitigation strategies across carbon price. For lower prices preferred strategies involve soil and livestock options, higher prices, however, promote mainly afforestation and biofuel generation. Results demonstrate the sensitivity of individual strategy potentials to assumptions about alternative opportunities. Assessed impacts also include market shifts, regional strategy diversity, welfare distribution, and environmental co-effects.

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Increasing atmospheric concentrations of greenhouse gases and their projected consequences, in particular global warming (IPCC, 2001), have caused widespread search for feasible remedies. Agriculture has been identified as potential source of low-cost alternatives for greenhouse gas emission mitigation during the next few decades (McCarl and Schneider, 2000). While U.S. agriculture is a small emitter of the most prevalent greenhouse gas (carbon dioxide - CO2), it contributes about 7 percent of total carbon equivalent emissions releasing about 28 percent of methane emissions and 73 percent of nitrous oxide (U.S. EPA). Furthermore, agriculture has substantial potential for offsetting CO2 emissions by serving as a sink augmenting carbon absorption through changes in tillage [Kern (1994), Lal et al., Antle et al. (2001b), and Pautsch et al.] or conversion of cropland to grassland or forest [Adams et al. (1993); Plantinga (1999), and Stavins (1999)]. Agriculture can also offset greenhouse gas (GHG) emissions by increasing production of energy crops, which can serve either as feedstock for electricity generating power plants [McCarl et al. (2000); Schneider and McCarl (2003)] or as blend/substitute for fossil fuel based gasoline.

Economists and physical scientists have assessed many of the mitigation strategies available to the agricultural sector [see McCarl and Schneider (2000) for a review]. However, previous assessments are limited in scope neglecting at least one of three major economic impacts (Table 1). First, large-scale mitigation efforts in the U.S. agriculture are likely to reduce traditional agricultural production, increase associated commodity prices and land values, and hence increase farmers' opportunity costs of agricultural GHG emission mitigation. Second, simultaneous implementation of strategies, which draw from a common resource base, increases the opportunity cost of individual strategies. Third, efforts to lower net emissions of a particular greenhouse gas can enhance or reduce emissions of other greenhouse gases. Because many agricultural mitigation strategies affect several greenhouse gases simultaneously, their respective net abatement cost actually depends on the Global Warming Potential weighted sum of all emissions.

In this article, we use mathematical programming (MP) for a multi-sector, multi-gas, and multi-strategy assessment of agricultural mitigation options taking into account strategy competition, market, welfare, and environmental consequences, and regional heterogeneity. Details on the MP model structure are given in the next section. Subsequently, we report and discuss results from a simulation exercise, where the model is used to estimate agricultural abatement functions for GHG emissions and also to examine the consequences of omitting alternative mitigation strategy opportunities.

The U.S. Agricultural Sector and Mitigation of Greenhouse Gas Model

This section documents the essential structure of the U.S. agricultural sector and mitigation of greenhouse gas (ASMGHG) model. Here, we focus on the general model structure, which is not affected by data updates or model expansion toward greater detail. Data and a GAMS version of a regionally aggregated ASMGHG version is available on the Internet. The aggregated model can be used to examine and verify the model structure and data and to qualitatively replicate the results presented in this article. In representing ASMGHG's mathematical structure, we will use summation notation because it corresponds very closely to the ASMGHG computer code.

ASMGHG is designed to emulate U.S. agricultural decision making along with the impacts of agricultural decisions on agricultural markets, the environment, and international trade. To accomplish this objective, ASMGHG portrays the following key components: natural and human resource endowments, agricultural factor (input) markets, primary and processed commodity (output) markets, available agricultural technologies, and agricultural policies. Because of data requirements and computing feasibilities, sector models cannot provide the same level of detail as do farm level or regional models. Therefore, ASMGHG depicts only representative crop and livestock enterprises in 63 aggregated U.S. production regions rather than individual farms characteristics. International markets and trade relationships are portrayed in 28 international regions.

Agricultural technologies in the U.S. are represented through Leontief production functions specifying fixed quantities of multiple inputs and multiple outputs. Producers can choose among several alternative production technologies. Specifically, alternative crop production functions arise from combinations of 3 tillage alternatives (conventional tillage, conservation tillage, and zero tillage), 2 irrigation alternatives (irrigation, dryland), 4 alternative conservation measures (none, contour plowing, strip cropping, terracing), and 3 nitrogen fertilization alternatives (current levels, a 15 percent reduction, and a 30 percent reduction) specific to each U.S. region, land, and crop type[1]. Alternative livestock production functions reflect different production intensities, various manure treatment schemes, alternative diets, and pasture management for 11 animal production categories and 63 U.S. regions. Processing functions identify first or higher level processing opportunities carried out by producers.

ASMGHG is setup as mathematical programming model and contains more than 20,000 individual variables and more than 5,000 individual equations. These equations and variables are

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[1] We use representative crop production budgets for 63 U.S. regions, 20 crops (cotton, corn, soybeans, 4 wheat types, sorghum, rice, barley, oats, silage, hay, sugar cane, sugar beets, potatoes, tomatoes, oranges, grapefruits), 6 land classes (low erodible cropland, medium erodible cropland, highly erodible cropland, other cropland, pasture, and forest)

not entered individually but as indexed blocks. All agricultural production activities are specified as endogenous variables and denoted here by capital letters. In particular, the variable block CROP denotes crop management variables, LUTR = land use transformation, LIVE = livestock raising, PROC = processing, and INPS = production factor (input) supply variables. Additional variable blocks reflect the dissemination of agricultural products with DOMD = U.S. domestic demand, TRAD = U.S. interregional and international trade, FRXS = foreign region excess supply, FRXD = foreign region excess demand , EMIT = Emissions, and SEQU = Emission reduction or sequestration variables. WELF denotes total agricultural welfare from both U.S. and foreign agricultural markets. With the exception of WELF, all variables are restricted be nonnegative.

ASMGHG consists of an objective function, which maximizes total agricultural welfare (WELF) and a set of constraining equations, which define a convex feasibility region for all variables. Feasible variable levels for all depicted agricultural activities range from zero to an upper bound, which is determined by resource limits, supply and demand balances, trade balances, and crop rotation constraints[2]. Solving ASMGHG involves the task of finding the "optimal" level for all endogenous variables subject to compliance with all constraining equations. By means of ASMGHG's objective function, optimal levels of all endogenous variables are those levels which maximize agricultural sector based welfare, which is computed as the sum of total consumers surplus, producers surplus, and governmental net payments to the agricultural sector minus the total cost of production, transportation, and processing. Basic economic theory demonstrates that maximization of the sum of consumers' plus producers'

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[2] Crop rotation constraints force the maximum attainable level of an agricultural activity such as wheat production to be equal or below a certain fraction of physically available cropland.

surplus yields the competitive market equilibrium as reviewed by McCarl and Spreen. Thus, the optimal variable levels can be interpreted as equilibrium levels for agricultural activities under given economic, political, and technological conditions.

To facilitate understanding of the ASMGHG structure, we will start with the description of the set of constraining equations and subsequently explain the objective function. Matrix coefficients and right hand side values are represented by small letters. Demand and supply functions are denoted in italic small letters. Equations, variables, variable coefficients, and right hand sight variables may have subscripts indicating indices with index c denoting the set of crops, f = production factors with exogenous prices (subset of index w), g = greenhouse gas accounts, h = processing alternatives, i = livestock management alternatives, j = crop management alternatives, k = animal production type, l = land transformation alternatives, m = international region (subset of index r), n = natural or human resource types (subset of index w), r = all regions, s = soil classes (subset of index n), t = years, u = U.S. region (subset of index r), w = all production factors, and y = primary and processed agricultural commodities. A list of individual set elements is available on the Internet or from the authors.

Supply and demand balance equations for agricultural commodities form an important constraint set in ASMGHG, which link agricultural activities to output markets. Specifically, the total amount of commodities disseminated in a U.S. region through domestic consumption (DOMD), processing (PROC), and exports (TRAD[3]) cannot exceed the total amount of commodities supplied through crop production (CROP), livestock raising (LIVE), or imports (TRAD). Equation block (1) shows the set of commodity supply and demand balance equations

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[3] While the first index of the USSH and TRAD variables denotes the exporting region or country, the second denotes the importing region or country.

employed in ASMGHG. Note that equation block (1) is indexed over U.S. regions and commodities. Thus, the total number of individual equations equals the product of 63 U.S. regions times the 54 primary agricultural commodities.

$$\text{(1)}\quad \begin{array}{l} -\sum_{c,s,j}\left(a^{CROP}_{u,c,s,j,y}\cdot CROP_{u,c,s,j}\right)-\sum_{k,i}\left(a^{LIVE}_{u,k,i,y}\cdot LIVE_{u,k,i}\right)-\sum_{r}TRAD_{r,u,y} \\ \qquad +DOMD_{u,y}+\sum_{h}\left(a^{PROC}_{u,h,y}\cdot PROC_{u,h}\right)+\sum_{r}TRAD_{u,r,y}\leq 0 \end{array}\quad \text{for all u and y}$$

As shown in equation block (1), agricultural commodities can be supplied in each U.S. region through crop production activities (if cropping activity $CROP_{u,c,s,j} > 0$ with yield $a^{CROP}_{u,c,s,j,y} > 0$), livestock production activities (if activity variable $LIVE_{u,k,i} > 0$ with yield $a^{LIVE}_{u,k,i,y} > 0$), shipments from other U.S. regions (from U.S. region $\tilde{u}$ to u if $TRAD_{\tilde{u},u,y} > 0$), or foreign imports (from foreign region m to U.S. region u if $TRAD_{m,u,y} > 0$). On the demand side, commodities can be used as an input for livestock production (if activity variable $LIVE_{u,k,i} > 0$ and with usage rate $a^{LIVE}_{u,k,i,y} < 0$), processed (if activity variable $PROC_{u,h} > 0$ with usage rate $a^{PROC}_{u,h,y} < 0$), directly sold in U.S. region u's market (if $DOMD_{u,y} > 0$), shipped to other U.S. regions (if $TRAD_{u,\tilde{u},y} > 0$), or exported to foreign markets (if $TRAD_{u,m,y} > 0$).

The coefficients $a^{CROP}_{u,c,s,j,y}$, $a^{LIVE}_{u,k,i,y}$, and $a^{PROC}_{u,h,y}$ are unrestricted in sign. While negative signs indicate that commodity y is an input for an activity, positive signs indicate outputs. The magnitude of these coefficients along with their sign identify either input requirements or output yields per unit of activity. The structure of equation block (1) allows for production of multiple products and for multi level processing, where outputs of the first process become inputs to the next process. All activities in (1) can vary on a regional basis.

Supply and demand relationships are also specified for agricultural production factors linking agricultural activities to production factor markets. As shown in equation block (2), total use of production factors by cropping (CROP), livestock (LIVE), land use change (LUTR), and processing (PROC) activities must be matched by total supply of these factors (INPS) in each region.

$$(2)\quad \begin{aligned} &\mathrm{INPS}_{u,w} - \sum_{c,s,j} a^{\mathrm{CROP}}_{u,c,s,j,w} \cdot \mathrm{CROP}_{u,c,s,j} - \sum_{l} a^{\mathrm{LUTR}}_{u,l,w} \cdot \mathrm{LUTR}_{u,l} \\ &\quad - \sum_{k,i} a^{\mathrm{LIVE}}_{u,k,i,w} \cdot \mathrm{LIVE}_{u,k,i} - \sum_{h} a^{\mathrm{PROC}}_{u,h,w} \cdot \mathrm{PROC}_{u,h} \le 0 \end{aligned} \qquad \text{for all u and w}$$

The most fundamental physical constraints on agricultural production arise from the use of scarce and immobile resources. Particularly, the use of agricultural land, family labor, irrigation water, and grazing units is limited by given regional endowments of these private or public resources. In ASMGHG, all agricultural activity variables (CROP, LUTR, LIVE, and PROC) have associated with them resource use coefficients ($a^{\mathrm{CROP}}_{u,c,s,j,n}$, $a^{\mathrm{LUTR}}_{u,l,n}$, $a^{\mathrm{LIVE}}_{u,k,i,n}$, $a^{\mathrm{PROC}}_{u,h,n}$), which give the quantity of resources needed for producing one unit of that variable. For example, most crop production activity variables have a land use coefficient equaling 1. However, land use coefficients are greater than 1 for some wheat production strategies, where wheat is preceded by fallow. Land use coefficients were also inflated by set aside requirements when analyzing previous features of the farm bill.

The mathematical representation of natural resource constraints in ASMGHG is straightforward and displayed in equation block (3). These equations simply force the total use of natural or human resources to be at or below given regional resource endowments $b_{u,n}$. Note that the natural and human resource index n is a subset of the production factor index w. Thus, all $\mathrm{INPS}_{u,n}$ resource supplies also fall into constraint set (2). The number of individual equations in (3) is given by the product of 63 U.S. regions times the number of relevant natural resources per region.

(3) $\mathrm{INPS}_{u,n} \le b_{u,n}$ for all u and n

In ASMGHG, trade activities ($\mathrm{TRAD}_{u,m,y}$, $\mathrm{TRAD}_{\tilde{m},m,y}$, $\mathrm{TRAD}_{m,u,y}$, $\mathrm{TRAD}_{m,\tilde{m},y}$) by international region of destination or origin are balanced through trade equations as shown in equation blocks (4) and (5). The equations in block (4) force a foreign region's excess demand for an agricultural commodity ($\mathrm{FRXD}_{m,y}$) to not exceed the sum of all import activities into that particular region from other international regions ($\mathrm{TRAD}_{\tilde{m},m,y}$) and from the U.S. ($\mathrm{TRAD}_{u,m,y}$). Similarly, the equations in block (5) force the sum of all commodity exports from a certain international region into other international regions ($\mathrm{TRAD}_{m,\tilde{m},y}$) and the U.S. ($\mathrm{TRAD}_{m,u,y}$) to not exceed the region's excess supply activity ($\mathrm{FRXS}_{m,y}$).

(4) $-\sum_{u} \mathrm{TRAD}_{m,u,y} - \sum_{\tilde{m}} \mathrm{TRAD}_{m,\tilde{m},y} + \mathrm{FRXD}_{m,y} \le 0$ for all m and y

(5) $\sum_{u} \mathrm{TRAD}_{u.m,y} + \sum_{\tilde{m}} \mathrm{TRAD}_{\tilde{m},m,y} - \mathrm{FRXS}_{m,y} \le 0$ for all m and y

The number of individual equations in blocks (4) and (5) equals the product of the number of traded commodities times the number of international regions per commodity. Because of data limitations only 8 major agricultural commodities are constraint through international trade balance equations. More details can be found in Chen and in Chen and McCarl.

A fifth set of constraints addresses aggregation related aspects of farmers' decision process. These constraints force producers' cropping activities $\mathrm{CROP}_{u,c,s,j}$ to fall within a convex combination of historically observed choices $h_{u,c,t}$ [equation (6)]. Based on decomposition and economic duality theory (McCarl, Onal and McCarl), it is assumed that observed historical crop mixes represent rational choices subject to weekly farm resource constraints, crop rotation considerations, perceived risk, and a variety of natural conditions. In (6), the $h_{u,c,t}$ coefficients contain the observed crop mix levels for the past 30 years. $CMIX_{u,t}$ are positive, endogenous variables indexed by historical year and region, whose level will be determined during the optimization process.

(6) $-\sum_{t}\left(h_{u,c,t} \cdot CMIX_{u,t}\right)+\sum_{s,j} CROP_{u,c,s,j}=0$ for all u and c The utilization of (6) has several important implications. First, many diverse constraints faced by agricultural producers are implicitly integrated. Second, crop choice constraints impose an implicit cost for deviating from historical crop rotations. Note that the sum of the CMIX variables over time is not forced to add to unity. Therefore, only relative crop shares are restricted, allowing the total crop acreage to expand or contract. Third, crop choice constraints prevent extreme specialization by adding a substantial number of constraints in each region and mimicking what has occurred in those regions. A common problem to large linear programming (LP) models is that the number of activity variables by far exceeds the number of constraint equations. Because an optimal LP solution will always occur at an extreme point[4] of the convex feasibility region, the number of non-zero activity variables cannot exceed the number of constraints. Fourth, crop choice constraints are a consistent way of representing a large entity of small farms by one aggregate system [Dantzig and Wolfe (1961), Onal and McCarl (1989, 1991)].

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[4] Suppose we have a convex set. A point in this set is said to be an extreme point if it can not be represent as a convex combination of any two other points in this set.

Crop mix constraints are not applied to crops, which under certain policy scenarios are expected to expand far beyond the upper bound of historical relative shares. Particularly, if $E\left[\sum_{s,j} LAND_{u,c,s,j} \Big/ \sum_{c,s,j} LAND_{u,c,s,j}\right] > \underset{t}{Max}\left(h_{u,c,t} \Big/ \sum_{c} h_{u,c,t}\right)$, then these crops should not be part of the crop mix equations. In ASMGHG, the biofuel crops of switchgrass, poplar and willow fall into this category.

Agricultural land owners do not only have a choice between different crops and different crop management strategies, they can also abandon traditional crop production altogether in favor of establishing pasture or forest. Equivalently, some existing pasture or forest owners may decide to convert suitable land fractions into cropland. In ASMGHG, land use conversions are portrayed by a set of endogenous variables LUTR. As shown in (7), certain land conversion can be restricted to a maximum transfer $d_{u,l}$, whose magnitude was determined by GIS data on land suitability. If $d_{u,l} = 0$, then constraint (7) is not enforced. In such a case, land use transformations would only be constraint through constraint set (3).

$$(7) \quad LUTR_{u,l} \leq d_{u,l}\Big|_{d_{u,l} \geq 0} \qquad \text{for all u and l}$$

The assessment of environmental impacts from agricultural production as well as political opportunities to mitigate negative impacts is a major application area for ASMGHG. To facilitate this task, ASMGHG includes environmental impact accounting equations as shown in (8) and (9). For each land management ($CROP_{u,c,s,j}$ and $LUTR_{u,l}$), livestock ($LIVE_{u,k,i}$), or processing ($PROC_{u,h}$) activity, environmental impact coefficients ($a^{LAND}_{u,c,s,j,g}$, $a^{LUTR}_{u,l,g}$, $a^{LIVE}_{u,k,i,g}$, $a^{PROC}_{u,h,g}$) contain the absolute or relative magnitude of those impacts per unit of activity. Negative values of greenhouse gas account coefficients, for example, indicate emission reductions. A detailed description of environmental impact categories and their data sources is available in Schneider (2000).

$$\begin{aligned} \mathrm{EMIT}_{u,g} = & \sum_{c,s,j} \left(a^{\mathrm{CROP}}_{u,c,s,j,g} \cdot \mathrm{CROP}_{u,c,s,j} \right)\Big|_{a^{\mathrm{LAND}}_{u,c,s,j,g}>0} \\ & + \sum_{l} \left(a^{\mathrm{LUTR}}_{u,l,g} \cdot \mathrm{LUTR}_{u,l} \right)\Big|_{a^{\mathrm{LUTR}}_{u,l,g}>0} \\ & + \sum_{k,i} \left(a^{\mathrm{LIVE}}_{u,k,i,g} \cdot \mathrm{LIVE}_{u,k,i} \right)\Big|_{a^{\mathrm{LIVE}}_{u,k,i,g}>0} \\ & + \sum_{h} \left(a^{\mathrm{PROC}}_{u,h,g} \cdot \mathrm{PROC}_{u,h} \right)\Big|_{a^{\mathrm{PROC}}_{u,h,g}>0} \end{aligned} \qquad \text{for all u and g} \tag{8}$$

$$\begin{aligned} \mathrm{SEQU}_{u,g} = & \sum_{c,s,j} \left(a^{\mathrm{CROP}}_{u,c,s,j,g} \cdot \mathrm{CROP}_{u,c,s,j} \right)\Big|_{a^{\mathrm{LAND}}_{u,c,s,j,g}<0} \\ & + \sum_{l} \left(a^{\mathrm{LUTR}}_{u,l,g} \cdot \mathrm{LUTR}_{u,l} \right)\Big|_{a^{\mathrm{LUTR}}_{u,l,g}<0} \\ & + \sum_{k,i} \left(a^{\mathrm{LIVE}}_{u,k,i,g} \cdot \mathrm{LIVE}_{u,k,i} \right)\Big|_{a^{\mathrm{LIVE}}_{u,k,i,g}<0} \\ & + \sum_{h} \left(a^{\mathrm{PROC}}_{u,h,g} \cdot \mathrm{PROC}_{u,h} \right)\Big|_{a^{\mathrm{PROC}}_{u,h,g}<0} \end{aligned} \qquad \text{for all u and g} \tag{9}$$

While the structure of equation blocks (8) and (9) can be used to account for many different environmental impacts, special focus was placed in ASMGHG on greenhouse gases. GHG emissions and emission reductions are accounted for all major sources, sinks and offsets from agricultural activities, for which data were available or could be simulated. Generally, ASMGHG considers:

- Direct carbon emissions from fossil fuel use (diesel, gasoline, natural gas, heating oil, LP gas) in tillage, harvesting, or irrigation water pumping as well as altered soil organic matter (cultivation of forested lands or grasslands),
- Indirect carbon emissions from fertilizer and pesticide manufacturing,
- Carbon savings from increases in soil organic matter (reduced tillage intensity and conversion of arable land to grassland) and from tree planting,

- Carbon offsets from biofuel production (ethanol and power plant feedstock via production of switchgrass, poplar, and willow),
- Nitrous oxide emissions from fertilizer usage and livestock manure,
- Methane emissions from enteric fermentation, livestock manure, and rice cultivation,
- Methane savings from changes in manure and grazing management changes, and
- Methane and nitrous oxide emission changes from biomass power plants.

All equations described so far have defined the convex feasibility region for the set of agricultural activities. Let us now turn to the objective function. The purpose of this single equation is to determine the optimal level of all endogenous variables within the convex feasibility region. Applying the McCarl and Spreen (1980) technique, we use a price-endogenous, welfare based objective function. This equation is shown in (10)[5].

The left hand side of equation (10) contains the unrestricted total agricultural welfare variable (WELF), which is to be maximized. The right hand side of equation (10) contains several major terms, which will be explained in more detail below. The first term $\sum_{\mathrm{u,y}}\left[\int_{\mathrm{y}} p_{u,y}^{DOMD}\left(\mathrm{DOMD}_{\mathrm{u,y}}\right)\mathrm{d}\left(\cdot\right)\right]$ adds the sum of the areas underneath the inverse U.S. domestic demand curves over all crops, livestock products, and processed commodities. ASMGHG can employ four types of demand specifications: a) downward sloping demand curves, b) horizontal

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[5] In displaying the objective function, several modifications have been made to ease readability: a) the integration terms are not shown explicitly, b) farm program terms are omitted, and c) artificial variables for detecting infeasibilities are omitted. A complete representation of the objective function is available on the Internet or from the authors.

or totally elastic demand implying constant prices, c) vertical demand implying fixed demand quantities, and d) zero demand. Downward sloping demand curves are specified as constant elasticity function[6]. To prevent integrals underneath a constant elasticity function and thus consumers' surplus reach infinity, we use truncated demand curves. A truncated demand curves is horizontal between zero and a small quantity ($\mathrm{DOMD}_{u,y}^{TF}$) and downward sloping for quantities above $\mathrm{DOMD}_{u,y}^{TF}$. In particular, the truncated inverse demand curve for commodity y and region u becomes $p_{u,y}^{DOMD}\left(\mathrm{DOMD}_{u,y}\right) = \{\, \hat{p}_{u,y} \times \left(\frac{\mathrm{DOMD}_{u,y}^{TF}}{\mathrm{DOMD}_{u,y}^{\wedge}}\right)^{1/\varepsilon_{u,y}}$ for all $\mathrm{DOMD}_{u,y} < \mathrm{DOMD}_{u,y}^{TF}$ and $\hat{p}_{u,y} \cdot \left(\frac{\mathrm{DOMD}_{u,y}}{\mathrm{DOMD}_{u,y}^{\wedge}}\right)^{1/\varepsilon_{u,y}}$ for all $\mathrm{DOMD}_{u,y} \geq \mathrm{DOMD}_{u,y}^{TF}\,\}$, where $\hat{p}_{u,y}$ and $\mathrm{DOMD}_{u,y}^{\wedge}$ denote an observed price quantity pair and $\varepsilon_{u,y}$ denotes the own price elasticities of demand.

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[6] The GAMS version of ASMGHG contains a nonlinear and a stepwise linear representation of constant elasticity supply and demand functions both of which can be used.

$$
\begin{aligned}
\text{(10)}\qquad \text{Max WELF} = &\sum_{\mathrm{u,y}}\left[\int_{\mathrm{y}} p_{u,y}^{DOMD}\left(\mathrm{DOMD}_{\mathrm{u,y}}\right)\mathrm{d}(\cdot)\right] \\
&-\sum_{\mathrm{u,n}}\left[\int_{\mathrm{n}} p_{u,n}^{INPS}\left(\mathrm{INPS}_{\mathrm{u,n}}\right)\mathrm{d}(\cdot)\right] \\
&+\sum_{\mathrm{m,y}}\left[\int_{\mathrm{y}} p_{m,y}^{FRXD}\left(\mathrm{FRXD}_{\mathrm{m,y}}\right)\mathrm{d}(\cdot)\right] \\
&-\sum_{\mathrm{m,y}}\left[\int_{\mathrm{y}} p_{m,y}^{FRXS}\left(\mathrm{FRXS}_{\mathrm{m,y}}\right)\mathrm{d}(\cdot)\right] \\
&-\sum_{\mathrm{u,f}}\left(\mathrm{p}_{\mathrm{u,f}}^{\mathrm{INPS}}\cdot\mathrm{INPS}_{\mathrm{u,f}}\right) \\
&-\sum_{\mathrm{r},\tilde{\mathrm{r}},\mathrm{y}}\left(\mathrm{p}_{\mathrm{r},\tilde{\mathrm{r}},\mathrm{y}}^{\mathrm{TRAD}}\cdot\mathrm{TRAD}_{\mathrm{r},\tilde{\mathrm{r}},\mathrm{y}}\right)
\end{aligned}
$$

The second right hand side term $-\sum_{\mathrm{u,n}}\left[\int_{\mathrm{n}} p_{u,n}^{INPS}\left(\mathrm{INPS}_{\mathrm{u,n}}\right)\mathrm{d}(\cdot)\right]$ subtracts the areas underneath the endogenously priced input supply curves for hired labor, water, land, and animal grazing units. Supply curves for these inputs are specified as upward sloping constant elasticity functions with $p_{u,y}^{INPS}\left(\mathrm{INPS}_{\mathrm{u,n}}\right) = \hat{\mathrm{p}}_{\mathrm{u,n}}^{\mathrm{INPS}} \times \left(\frac{\mathrm{INPS}_{\mathrm{u,n}}}{\mathrm{INPS}^{\wedge}_{\mathrm{u,n}}}\right)^{1/\varepsilon_{\mathrm{u,n}}}$. Note that the $\mathrm{INPS}_{\mathrm{u,n}}$ supply variables are constraint by physical limits in equation block (3). Thus, when the physical limit is reached, the inverse supply curve becomes effectively vertical.

The following two terms $+\sum_{\mathrm{m,y}}\left[\int_{\mathrm{y}} p_{m,y}^{FRXD}\left(\mathrm{FRXD}_{\mathrm{m,y}}\right)\mathrm{d}(\cdot)\right]$ and $-\sum_{\mathrm{m,y}}\left[\int_{\mathrm{y}} p_{m,y}^{FRXS}\left(\mathrm{FRXS}_{\mathrm{m,y}}\right)\mathrm{d}(\cdot)\right]$ account for the areas underneath the foreign inverse excess demand curves minus the areas underneath the foreign inverse excess supply curves. Together these two terms define the total trade based Marshallian consumer plus producer surplus economic of foreign regions.

Finally, the terms $-\sum_{u,f}\left(p^{INPS}_{u,f}\cdot INPS_{u,f}\right)$ and $\sum_{r,\tilde{r},y}\left(p^{TRAD}_{r,\tilde{r},y}\cdot TRAD_{r,\tilde{r},y}\right)$ subtract the costs of exogenously priced production inputs and the costs for domestic and international transportation, respectively.

Greenhouse Gas Abatement Potential – An Application

The ASMGHG model can be applied to assess the economic and environmental impacts of multiple technical changes to the agricultural sector, which may be policy, research, environmental change or otherwise induced. We chose to examine the national greenhouse gas abatement potential of U.S. agriculture for several reasons. First, greenhouse gas emissions represent a global externality. Thus, mitigation policies are likely to be implemented in the whole agricultural sector instead of smaller localities. Second, we had access to environmental impact data across the nation simulated for various alternative crop and livestock management strategies. Third, existing estimates of greenhouse gas abatement potential in U.S. agriculture did not fully incorporate opportunity costs arising from multiple strategy implementation and conventional agricultural activities.

Mitigation policy simulation in the agricultural sector

Agricultural greenhouse mitigation policies can be designed in many different ways and levels of severity. We decided to use an emissions based hybrid approach between tax and subsidy. In particular, we assumed that farmers in each U.S. region would have to pay a tax for emissions equal to ep^{EMIT}_{g} and receive a subsidy for sequestration equal to ep^{SEQU}_{g}. To implement this policy in ASMGHG, we expanded the objective function [equation (10)] by adding the terms $-\sum_{u,g}\left(ep^{EMIT}_{g}\cdot EMIT_{u,g}\right)$ and $+\sum_{u,g}\left(ep^{SEQU}_{g}\cdot SEQU_{u,g}\right)$.

A second aspect of GHG mitigation policies involves the level of severity, i.e. the carbon price (cp) level. Carbon prices can be dictated directly by the government or emerge from a carbon market, which involves many sectors of the economy. To overcome uncertainties about a future carbon price, we picked a wide range of hypothetical price levels between zero and \$500 per ton of carbon equivalent. For each carbon price level, we computed the ep_g^{SEQU} and ep_g^{EMIT} coefficients using $ep_g^{SEQU} = v_g^{SEQU} \cdot \frac{12}{44} \cdot cp$ and $ep_g^{EMIT} = v_g^{EMIT} \cdot \frac{12}{44} \cdot cp$, where v_g^{EMIT} and v_g^{EMIT} and are greenhouse gas account specific multipliers. Particularly, $v_g^{EMIT} = 1$ for carbon emission accounts, $v_g^{EMIT} = 23$ for methane emission accounts, and $v_g^{EMIT} = 298$ for nitrous oxide emission accounts[7]. GHG sequestration accounts in ASMGHG involve only carbon. Reflecting different permanence and saturation characteristics, we assigned $v_g^{SEQU} = 1$ for biofuel based carbon offset accounts, $v_g^{SEQU} = 0.75$ for afforestation based carbon accounts, and $v_g^{SEQU} = 0.50$ for reduced tillage based soil carbon sequestration accounts[8].

A third aspect of agricultural mitigation policies concerns their strategy scope. Which activities are eligible for carbon credits? Will it be just afforestation or will it be a comprehensive set of agricultural activities. We decided to analyze four policy scope scenarios, where the carbon price imposed a) on all GHG accounts, b) on the afforestation carbon account only, c) on the biofuel carbon account only, and d) on the soil carbon only. The last three scenarios were also chosen to illustrate the difference between the single strategy economic potential and the competitive economic potential, where different strategies can be used simultaneously.

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[7] These values reflect the 100-year global warming potential of carbon dioxide, methane, and nitrous oxide.

[8] The derivation of the carbon sequestration multipliers is available from the authors.

To simulate the above described mitigation policy scenarios, we set up a loop over all carbon price levels and over all policy scope scenarios. Inside this loop, we first assigned the scenario specific values of ep_g^{SEQU} and ep_g^{EMIT}, solved ASMGHG, computed and reported relevant solution information for each scenario, and then continued with the next scenario.

In interpreting our simulation results, a few qualities must be noted. First, the current situation is represented by the baseline scenario with all ep_g^{SEQU} and ep_g^{EMIT} values equal to zero. Second, all carbon price based abatement cost identify lower bounds because transaction costs of policy implementation, monitoring, and enforcement are not taken into account. Third, carbon prices are completely exogenous to ASMGHG. Fourth, increased utility from reduced levels of GHG is not included. Fifth, the same results that we obtained by using a hybrid tax subsidy approach on GHG net emissions could have been achieved by using a range of GHG emissions targets.

Mitigation Strategy Adoption

The contribution of major agricultural GHG emission mitigation strategies is graphically summarized in Figure 1 through abatement curves and also listed in Table 2. Net emission reductions from each strategy were calculated at each incentive level as the difference between actual emissions and baseline emissions. Results show that the highest share on total abatement is provided by three basic carbon mitigation strategies: soil carbon sequestration, afforestation, and production of perennial energy crops for electricity generation. However, each of these strategies appears attractive at different carbon price ranges.

Soil carbon sequestration increases for carbon prices up to \$50 per metric ton of carbon equivalent (tce) but decreases for higher prices. This occurs for two major reasons: a) for prices above \$50 per tce, substantial amounts of cropland are either afforested or diverted to generate alternative biofuels. Even though these land uses will also increase soil carbon, the net emission savings are allocated to the afforestation account and biofuel account and not to the agricultural soil carbon account (to avoid double counting); and b) As carbon prices increase so do prices for traditional food and fiber commodities. This trend also increases farmers' incentive to produce higher yields even at the expense of increased emissions. For example, adoption of zero tillage on existing cropland sequesters less than 0.5 tce per acre and year, while growing forests or energy crop plantations mitigate above 1 tce per acre and year. Thus, for high carbon price levels it can be more efficient to increase traditional crop yields and thus make more cropland available for afforestation and renewable energy. If conventional tillage produces a higher crop yield, high carbon prices may lead to a partial reversion of reduced tillage back to more conventional tillage.

Afforestation of traditional cropland increases steadily for carbon price levels between $0 and $160 per tce. Higher incentives up to $390 per tce result in no additional gains. Energy crop plantations are not implemented for carbon price levels below $40 per tce but rise quickly in importance at higher carbon prices. The contribution of energy crop plantations and permanent forests illustrates the problem of direct strategy competition. Landowners must choose between afforestation and energy crop plantations but cannot implement both options on the same piece of land. Thus, while the sum of the two abatement categories increases relatively smoothly, the individual abatement curves display non-monotonic behavior.

Net emission reductions via nitrous oxide and methane mitigation strategies are relatively small. However, ASMGHG only contains strategies for which data are available. Introduction of new technologies may alter this picture and increase the total contribution of non-CO_2 strategies. Over time, methane and nitrous oxide emission abatement may also become more important because they are not subject to saturation as are soil sequestration and afforestation.

Agriculture's total contribution to GHG emission mitigation is price sensitive as are the contributions of individual strategies. For a $10 per tce incentive, only about 50 million metric tons of carbon equivalents (mmtce) can be saved through the agricultural and forest sectors. This amount equals about three percent of the combined 1990 U.S. emissions of carbon dioxide, methane, and nitrous oxide (U.S. EPA). As carbon prices increase, so do marginal abatement costs. For example, an increase to $20 per tce adds 25 mmtce or about 50 percent of the $10 per tce contribution. It takes extremely high incentives in the neighborhood of $500 per tce to bring agriculture's annual contribution above 400 mmtce (Table 2).

Measures of Potentials

Many estimates for the emission abatement potential of selected strategies ignore cost and resource competition. Lal et al. (1998), for example assess the total agricultural soil carbon sequestration potential, but do not specify the cost of achieving such a potential level of sequestration. To demonstrate the importance of economic considerations, we use our model to compute and compare the technical, economic, and competitive economic potential for major agricultural strategies (Figure 3). The total technical potential of soil carbon sequestration[9] is 125 mmtce annually (Panel A). However, this potential is not economically feasible even under sole reliance on this strategy and prices as high as $500 per ton. Even at such a high price, carbon gains remain about 20 mmtce or 16 percent short of the maximum potential. At lower prices substantially less soil carbon is sequestered. Furthermore, when agricultural soil carbon strategies are considered simultaneously with other strategies, the carbon price stimulates at most

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[9] The technical potential was computed by replacing ASMGHG's economic surplus maximizing objective function with a function that maximizes soil carbon.

70 mmtce or 56 percent of maximum potential with sequestration falling to 53 mmtce (42 percent) at a $200 price because other strategies are more efficient at higher payment level.

Similar observation can be made for other agricultural GHG mitigation strategies. At a carbon price of $200 per tce, the single strategy economic potential of biofuel carbon offsets (Panel B) is about two third of its technical potential while the competitive economic potential amounts to less than 50 percent. The economic potential of mitigation from afforestation (Panel C) achieves at $200 per tce achieves about three quarters of its technical potential under a single strategy assessment and about 50 percent under multi-strategy assessment.

Regional Effects

While results presented so far concentrated at the national level, ASMGHG output can also be used to analyze regional effects (Figure 2). Soil carbon sequestration is dominant in the Cornbelt, the Northern Plain States, and to some extent in the Mountain States. For low carbon prices, the Lakes States also indicate soil carbon as the preferred option. However, for higher carbon prices, the Lake States offer the most cost efficient energy crop production. Between $60 and $120 per tce, renewable fuels are produced almost exclusively in these states. Subsequently, the North East, Delta State, and South East regions take part. The Corn Belt region becomes profitable for perennial energy crops only for carbon price above $220 per tce. Possible reasons for such behavior may include higher opportunity cost in the agriculturally productive Corn Belt region. Afforestation takes place in predominantly in the Delta States but also in the North East States. In some regions, incentive levels above $50 per tce are needed to make afforestation profitable.

Welfare Impacts

Welfare impacts of mitigation on agricultural sector participants are listed in Table 3. These impacts represent intermediate run results, which are equilibrium results after adjustment. Thus, producers' welfare does not include adjustment costs, which might be incurred in the short run after implementation of a mitigation policy. Total welfare in the agricultural sector decreases by roughly 8 billion dollars for every 100 dollars per tce tax increase. Moreover, consumers' welfare decreases about 20 billion dollars per 100 dollars per tce tax increase because of higher commodity prices. In contrast, producers' welfare increases continuously as emission reductions become more valuable. This increase in producers' welfare is due to large welfare shifts from consumers. Foreign countries' welfare decreases as well; however, the reduction is not as large as for domestic consumers. While foreign consumers suffer from higher commodity prices due to lower U.S. exports, foreign producers benefit from less U.S. production. Since foreign welfare is aggregated over both foreign consumers and producers, the two effects offset each other somewhat. Note that the above welfare accounting does not include social costs or benefits related to diminished or enhanced levels of the GHG emission externality, and other externalities such as erosion and fertilizer nutrient pollution.

Agricultural Production Sector Effects

Mitigation efforts in the agricultural sector impact production technologies and production intensities. New economic incentives and disincentives stimulate farmers to abandon emission intensive technologies, increase the use of mitigative technologies, and consider production of alternative products such as biofuel crops (Table 3). Higher costs of production (emission tax, opportunity costs, land rental costs) for conventional management strategies and higher incentives for alternatives cause farmers to shift more land to mitigative products.

Production of conventional crops may change both due to altered crop yields and acreage shifts. The impact of carbon prices on production of traditional agricultural products is shown in Table 3. Declining crop production is mainly due to less acreage allocated to traditional food crops. The computed Fisher Ideal Index reveals only a small response of crop yields to mitigation (Table 3). Initially, yields decline slightly due to less irrigation and less fertilization. Subsequently at higher carbon prices, average crop yields go up again. For prices above $100 per tce substantial amounts of cropland are diverted to trees and biofuel crops. In ASMGHG, tree and energy crop yields are not sensitive to cropland quality; hence the marginal cropland is diverted first increasing average yields on the remaining acreage for conventional crops. Less U.S. domestic food production coupled with higher prices in U.S. agricultural markets induce foreign countries to increase their net exports into the U.S. Livestock production decreases as a result of higher costs from mitigative management. Lower levels of production of traditional agricultural products in turn affect the market price of these products (Table 3). In particular, prices change considerably if the product is emission intensive, if it has a low elasticity of demand, and if the U.S. is a major producer.

Other Externalities

Many of the GHG emission coefficients for crop production were simulated with the Environmental Policy Integrated Climate (EPIC) system. The complex nature of this biophysical simulation modeling system makes it an inexpensive task to simultaneously report other emission coefficients along with those for GHGs. Here, we analyzed the effects of agricultural GHG emissions mitigation programs on water quality related externalities. Expert opinion suggests a possible "win-win" situation, where greenhouse gas emission mitigation also leads to a reduction in both soil erosion and water pollution. Simulated results from this study are listed in Table 2 and Table 3. The average per acre values of the other externalities decrease notably as carbon prices increase from $0 and $100 dollars per tce with little or no additional reductions at higher prices.

Summary and Conclusions

We examine the potential role of agricultural GHG mitigation efforts considering the possible implementation of a variety of agricultural practices. Results show that U.S. agriculture can contribute to greenhouse gas mitigation, but total abatement potential is price sensitive. For low carbon equivalent prices prevalent strategies are reduced tillage systems, reduced fertilization, improved manure management, and some afforestation. The abatement levels being generated are in modest quantities relative to Kyoto Protocol like levels. As carbon equivalent prices increase, the abatement potential rises to about 50 percent of the original U.S. Kyoto Protocol target. At higher carbon prices, most of the emission abatement arises from afforestation/forest management and energy crop plantations diverting substantial amounts of cropland away from traditional commodity production.

Overall, a portfolio of strategies seems to be appropriate and may well bolster the political acceptability of mitigation efforts as the pool of potential participants widens. Moreover, a multi-strategy approach may facilitate the acceptance of agricultural mitigation policies across a regionally diverse U.S. agriculture. When comparing estimates of abatement potential we find substantial differences between different measures. Technical potential estimates such as in those in Lal et al. (1998) far overstate the economic potential of strategies like agricultural soil actions. Economic assessment of single strategies deviates from estimates of competitive economic potential especially if GHG saving incentives are high.

Some agriculturists oppose Kyoto Protocol like, environmental policies, arguing that farmers would be subjected to substantial economic losses. The results presented here do not justify this perspective. On the contrary, farmers are likely to experience higher earnings specifically in the intermediate run after adoption of mitigation technologies and market adjustment. The revenue losses due to an overall reduction in production caused by the competitive nature of many mitigation strategies with conventional production are more than offset by revenue gains due to market price effects.

The findings from this paper provide support for expanded environmental aspects of farm policies. Traditionally, considerable taxpayer money has been used to support incomes, stabilize prices at "fair" levels via farm program, and accomplish certain environmental goals via programs such as CRP. Perhaps a joint GHG offset, farm income support program could be crafted that would give incentives to farmers for adoption of environmentally friendly management but also be perceived as contributing to the economy wide GHG offset program.

Several important limitations to this research should be noted which could be subject to improvement. First, the findings presented here reflect technologies for which data were available to us. Second, most of the greenhouse gas emission data from the traditional agricultural sector are based on biophysical simulation models. Thus, the accuracy of the estimates presented here depends on the quality of these models and the origin of associated simulation model input data [Antle (2001a)]. Third, not monetarized in this analysis were transaction costs of mitigation policies, costs or benefits from reduced levels of other agricultural externalities, and costs or benefits of changed income distribution in the agricultural sector. Fourth, we operate at a 63-region level while others [Antle et al. (2001b, 2002), Pautsch et al.

(2001)] operate in regions over thousands of points. Insights gained from those studies could be integrated into more aggregate multi-strategy appraisals to expand overall results reliability.

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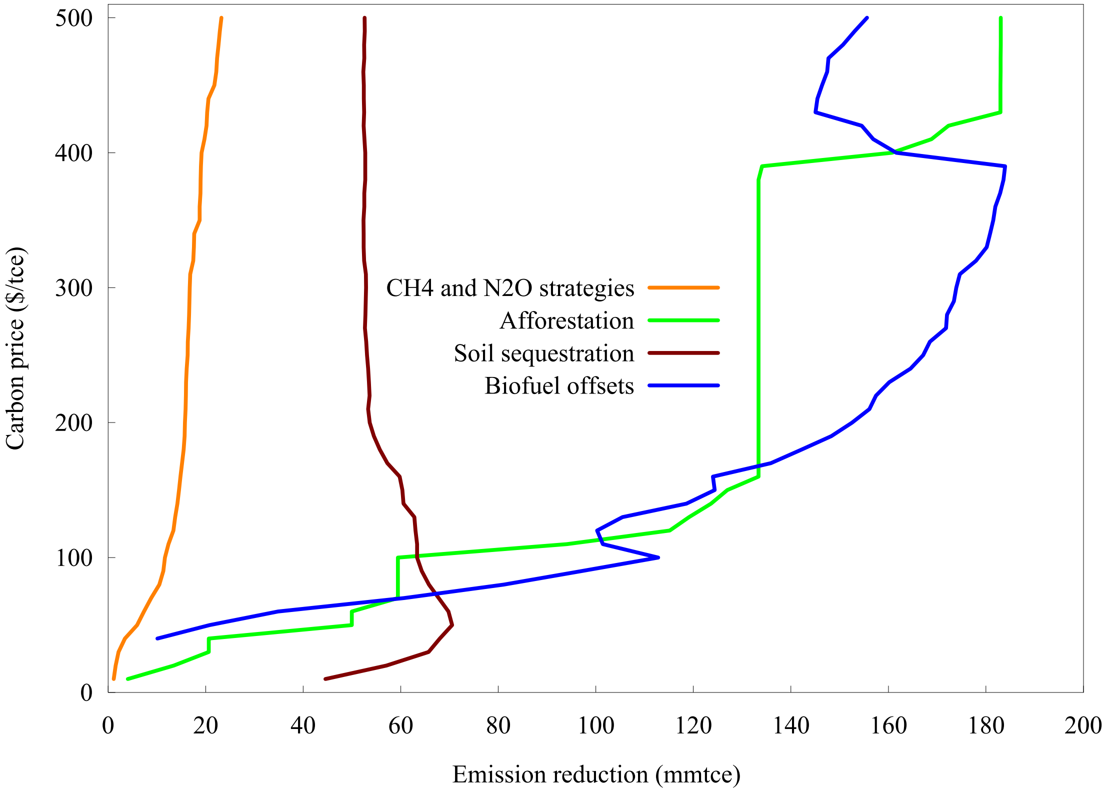


Figure 1 Multi-Strategy, Economic Potential of Major Agricultural Greenhouse Gas Emission Mitigation Strategies in the U.S. at $0 to $300 per Ton Carbon Equivalent Prices

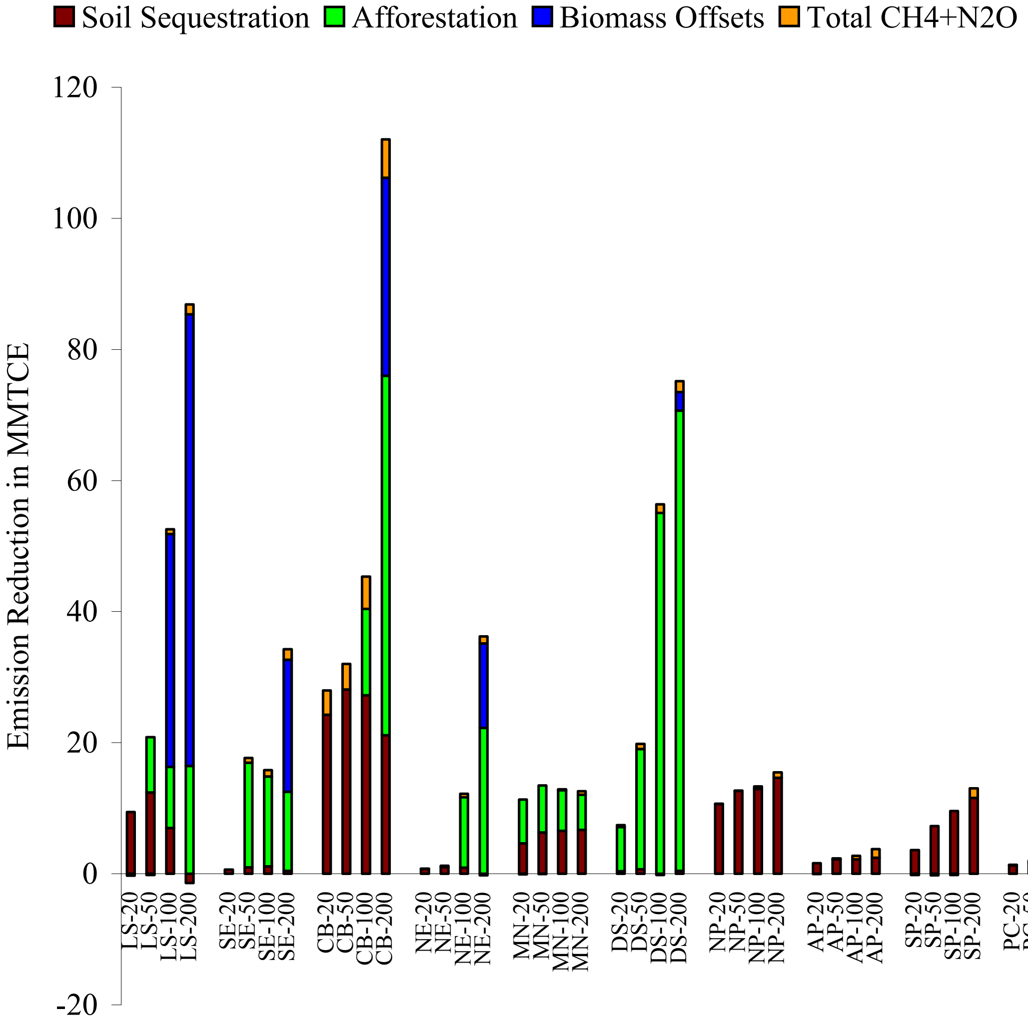
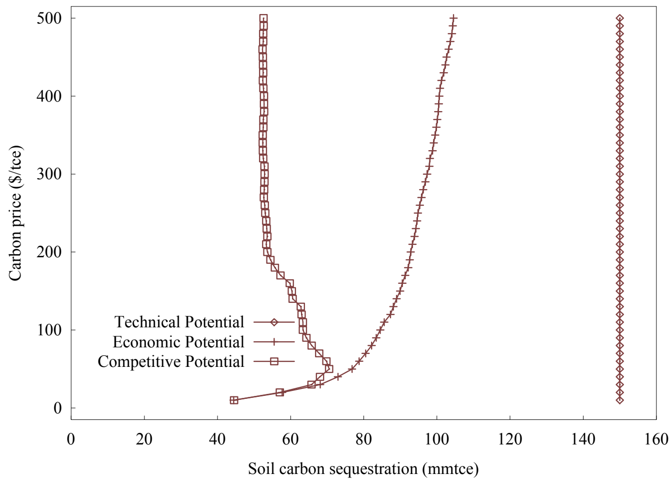
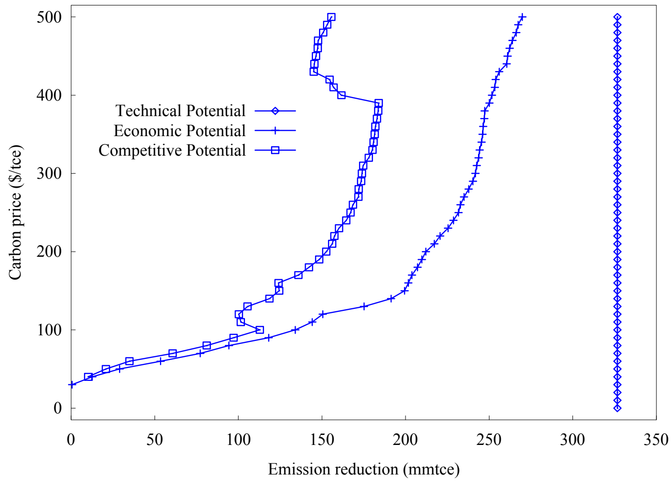


Figure 2 Differences in Regional Strategy Adoption (LS=Lake States, SE=South East States, CB=Cornbelt, NE=North East States, MN=Mountain States, DS=Delta States, NP=Northern Plain States, AP=Appalachian States, SP=Southern Plain States, PC=Pacific States) of Major Agricultural Mitigation Strategies for Selected Carbon Prices (20, 50, 100, and 200 Dollars per Ton of Carbon Equivalent).



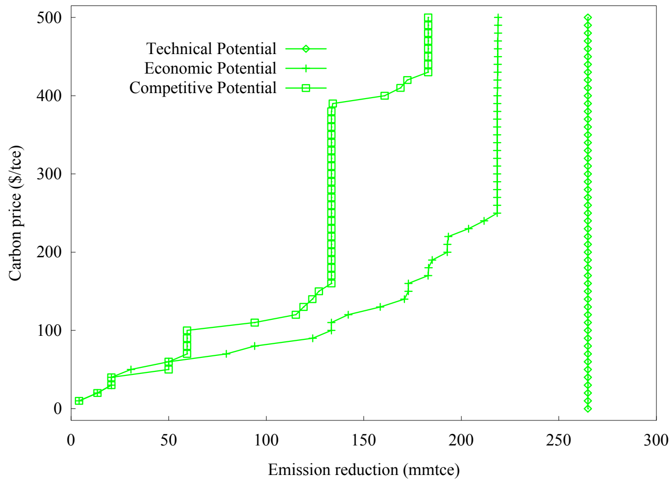
Panel A

Mitigation Potentials of Soil Carbon Sequestration on U.S. Cropland Including Conversion of Cropland into Pastureland



Panel B

Mitigation Potentials of Biofuels Used as Feedstock in Electrical Power Plants Thereby Offsetting Emissions from Fossil Fuel Based Power Plants



Panel C

Mitigation Potentials of Afforestation of U.S. Croplands Based on Data from Dynamic Forest and Agricultural Sector Optimization Model (FASOM)

Figure 3 Technical, Sole Source Economic, and Competitive Multi-Strategy Economic Potentials of Major Agricultural Greenhouse Gas Mitigation Strategies

Table 1 Assessment scope of greenhouse gas abatement studies related to U.S. agriculture

Study	Abatement Region	Traditional Agriculture			Simultaneous Strategies	Analyzed Greenhouse Gases		
		S[a]	P[b]	T[c]		CO_2	CH_4	N_2O
Antle et al. (2001b)	Montana	+	+	-	Tillage, Crop to grassland	+	-	-
Phetteplace et al. (1999)	Various U.S. states	+	-	-	Livestock diet and pasture Management	+	+	+
De Cara and Jayet (2000)	12 EU countries	+	-	-	Animal feeding, Fertilization, Crop to grassland, Afforestation	+	+	+
Faeth and Greenhalgh (2001)	U.S.	+	+	-	Tillage, Fertilization, Crop to grassland	+	-	+
Lal et al. (1998)	U.S.	-	-	-	Tillage, Crop to grassland	+	-	-
Parks and Hardie (1995)	U.S.	+	-	-	Afforestation of marginal agricultural land	+	-	-
Pautsch et al. (2001)	Iowa	+	-	-	Tillage	+	-	-
Peters et al. (2001)	U.S.	+	+	-	Tillage, Crop to grassland	+	-	-
This study	U.S.	+	+	+	Direct and indirect fossil fuel use, Tillage, Fertilization, Crop to grassland, Afforestation, Biofuels, Livestock diet, Pasture and Manure management,	+	+	+

[a] Substitutability of products (+ substitutable products, - fixed level of production)
[b] Commodity prices (+ endogenous, - exogenous)
[c] Trade with regions outside abatement regions (+ yes, - no)

Table 2 Environmental Abatement Effects at Selected Carbon Price Scenarios

Category Sub-Category	Carbon Equivalent price in $/metric ton C						
	0	10	20	50	100	200	500
GHG Abatement by Individual Strategy (Thousand Metric Tons of Carbon Equivalents)							
Permanent Afforestation	0	4,028	13,445	49,957	59,407	133,380	183,040
Soil Carbon Storage	0	44,550	57,061	70,524	63,356	53,638	52,587
Biomass for Power Plants	0	0	0	20,799	112,790	152,544	155,625
Reduced Fossil Fuel Inputs	0	2,637	3,910	5,387	7,026	8,302	9,934
Livestock Technologies	0	37	254	4,181	8,730	11,614	17,910
Crop Non-Carbon Strategies	0	1,129	1,302	1,747	2,920	4,148	5,308
Total GHG Emission Abatement (Million Metric Tons of Carbon Equivalents)							
Methane	0	0.17	0.38	4.55	12.21	16.16	20.97
Carbon Dioxide	0	51.21	74.42	145.8	237.91	341.64	394.9
Nitrous Oxide	0	1	1.18	2.24	4.11	5.83	8.54
Total Carbon Equivalents	0	52.38	75.97	152.6	254.23	363.63	424.4
Changes in Non-GHG Environmental Externalities on Traditional Cropland (Percent per Acre)							
Erosion	0	-24.9	-32.27	-42.9	-45.09	-51.62	-50.31
Nitrogen Percolation	0	-6.91	-9.42	-15.54	-19.07	-18.61	-11.99
Nitrogen Subsurface Flow	0	-7.13	-8.29	-10.72	-8.58	-5.24	-3.53
Phosphor Loss in Sediment	0	-32.58	-40.66	-50.35	-49.53	-52.07	-51.61

Table 3 Production, Market and Welfare Effects in U.S. Agriculture at Selected Carbon Price Scenarios

Category Sub-Category	Unit	Carbon Equivalent price in $/metric ton C						
		0	10	20	50	100	200	500
Agricultural Production								
Traditional Crops	Million Acres	325.6	323.9	320.2	307.0	270.9	229.1	191.6
Pasture	Million Acres	395.4	397.2	397.2	391.9	382.6	377.1	351.4
Perennial Energy Crops	Million Acres	0.0	0.0	0.0	9.6	53.9	72.8	76.0
New Permanent Forests	Million Acres	0.0	0.0	3.6	12.5	13.6	42.1	65.0
Reduced Tillage	Percent	32.71	68.04	72.73	81.05	81.43	80.96	80.02
Irrigation	Percent	18.69	18.32	17.82	18.33	20.29	25.83	31.02
Nitrogen Fertilizer	Million Tons	10.53	10.45	10.34	10.01	9.24	8.22	7.15
Agricultural Market Shifts								
Crop Prices	Fisher Index	100.00	100.75	101.98	108.08	129.14	173.78	288.64
Crop Production	Fisher Index	100.00	99.20	98.47	95.73	86.28	73.71	62.31
Crop Net Exports	Fisher Index	100.00	97.40	94.83	87.05	59.22	29.11	20.28
Livestock Production	Fisher Index	100.00	100.27	100.12	97.42	92.86	87.93	77.87
Livestock Prices	Fisher Index	100.00	100.11	100.46	104.81	119.05	146.08	207.63
Changes in Agricultural Welfare								
Ag-Sector Welfare	Billion $	0.00	-0.22	-0.51	-2.11	-8.78	-19.65	-36.48
Producers Welfare	Billion $	0.00	0.41	0.98	4.49	13.91	32.34	79.97
Consumers Welfare	Billion $	0.00	-0.44	-1.08	-5.38	-19.16	-46.71	-108.76
Foreign Welfare	Billion $	0.00	-0.19	-0.41	-1.21	-3.52	-5.29	-7.69