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Agricultural sector analysis on greenhouse gas mitigation in US agriculture and forestry

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Abstract

Mathematical programming is used to examine the economic potential of greenhouse gas mitigation strategies in US 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 bioenergy generation. Results demonstrate the sensitivity of individual strategy potentials to assumptions about alternative opportunities. Assessed impacts also include market shifts, regional strategy diversity, economic surplus distribution, and environmental co-effects.

Keywords: Abatement function; Agricultural sector model; Carbon sequestration; Economic potential; Greenhouse gas emission; Mathematical programming; Multiple technical change; Policy simulation

1. Introduction

Increasing atmospheric concentrations of greenhouse gases and their projected consequences, in particular global warming, have caused widespread consideration of feasible remedies. Agriculture has been identified as a potential source of low-cost alternatives by some (Plantinga et al., 1999). While US agriculture is a small emitter of the most prevalent greenhouse gas (carbon dioxide – CO_2), it contributes about 7% of total carbon equivalent (CE) emissions releasing about 28% of methane emissions and 73% of nitrous oxide (US EPA, 2004). Furthermore, agriculture has substantial potential for offsetting CO_2 emissions by serving as a sink augmenting carbon absorption through changes in tillage (Antle et al., Pautsch et al.) or conversion of cropland to grassland or forest (Plantinga et al., 1999; 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 (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 major elements of the problem (Table 1). First, mitigation programs are likely to be nation wide and a number of studies take a partial geographic approach. Second,

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Table 1
Characteristics considered in greenhouse gas abatement studies related to US agriculture

Study	Geographic scope	Economic market elements considered			Strategies investigated	Greenhouse gases analyzed		
		Production substitution	Effects on market prices	Effects on international trade		CO_2	CH_4	N_2O
Antle et al. (2001)	Montana	+	+		Changes in crop intensity, crop to grassland	+		
Phetteplace et al. (2001)	Various US states	+			Livestock diet and pasture management	+	+	+
De Cara and Jayet (2000)	12 EU countries	+			Animal feeding, fertilization, crop to grassland, afforestation	+	+	+
Faeth and Greenhalgh (2000)	US	+	+		Tillage, fertilization, crop to grassland	+		+
Lal et al. (1998)	US				Tillage, crop to grassland	+		
Parks and Hardie (1995)	US	+			Afforestation of marginal agricultural land	+		
Pautsch et al. (2001)	Iowa	+			Tillage	+		
Lewandrowski et al. (2004)	US	+	+		Tillage, crop to grassland or forest, and rotation changes	+		
Stavins (1999)	Delta states	+			Afforestation	+		
This study	US	+	+	+	Direct and indirect fossil fuel use, tillage, fertilization, crop to grassland, afforestation, bioenergy, livestock diet, pasture and manure management	+	+	+

large-scale mitigation efforts in the US agriculture are likely to have substitution effects with traditional agricultural production increasing associated commodity prices, land values, and hence increase farmers' opportunity costs of agricultural GHG emission mitigation. Thus impacts on production, market prices, and trade need to be considered. While production substitution is frequently examined prices are usually held exogenous and trade is not considered. Third, a number of studies only examine a very limited strategy set even though simultaneous implementation of multiple strategies can lower costs. Furthermore, interactions between strategies that draw from a common resource base need to be considered. Finally, efforts to lower net emissions of a particular greenhouse gas can enhance or reduce emissions of other greenhouse gases as many agricultural mitigation strategies affect several greenhouse gases simultaneously. This interaction has largely been absent from analytical models.

In this article, we try to consider all of these factors simultaneously and employ a model that can depict a multi-sector, multi-gas, and multi-strategy assessment of agricultural mitigation options taking into account strategy competition, market effects, economic surplus, environmental consequences, and regional heterogeneity. Details on the mathematical programming (MP) model 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.

2. The US agricultural sector and mitigation of greenhouse gas model

This section documents the essential structure of the US 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.

ASMGHG is designed to emulate US 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 production factor markets, agricultural technologies (Table 2), primary and processed commodity markets, 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 representative crop and livestock enterprises in 63 aggregated US production regions rather than trying to depict millions of individual farms. International markets and trade relationships are portrayed through 27 international regions for 8 major crops and through one rest-of-the-world region for 32 other commodities including various crop, livestock and processed products. A brief summary of ASMGHG's spatial resolution is contained in Table 3.

Agricultural technologies in the US are represented through Leontief production possibilities specifying fixed quantities of multiple inputs and multiple outputs.

Table 2
Agricultural management alternatives in ASMGHG

Decision criterium	Available options in ASMGHG
Crop choice	Cotton, corn, soybeans, winter wheat, durum wheat, hard red winter wheat, hard red and other spring wheat, sorghum, rice, barley, oats, silage, hay, sugar cane, sugar beets, potatoes, tomatoes, oranges, grapefruit Switchgrass, Willow, hybrid poplar
Irrigation alternatives	No irrigation Full irrigation
Tillage system choice	Conventional tillage (<15% plant cover) Reduced tillage (15–30% plant cover) Zero tillage (>30% plant cover)
Fertilization choice	Observed nitrogen fertilizer rates Nitrogen fertilizer reduction corresponding to 15% stress Nitrogen fertilizer reduction corresponding to 30% stress
Animal production choice	Dairy, cow-calf, feedlot beef cattle, heifer calves, steer calves, heifer yearlings, steer yearlings, feeder pigs, pig finishing, hog farrowing, sheep, turkeys, broilers, egg layers, and horses
Feed mixing choice	1158 specific processes based on 329 general processes differentiated by 10 US regions
Livestock production choice	Production intensity (cattle, dairy, hogs), liquid manure treatment (dairy and hogs), BST treatment (dairy), pasture management intensities, culling rates (dairy), genotype choice (dairy, cattle), stocking and slaughter schedules (cattle)

Table 3
Spatial scope of ASMGHG

Region class	Class elements	ASMGHG features
Non-US world regions (27)	Canada, Mexico, Caribbean, West America, East America, Argentina, Brazil, Scandinavia, Islands, Northern Central Europe, Western Europe, Eastern Europe, Former Soviet Union, East Mediterranean, Adriatic, Persian Gulf, Red Sea, North Africa, West Africa, East Africa, West Asia, Southeastern Asia, China, Japan, South Korea, Taiwan, Australia	Excess demand and supply function parameters for 8 major crop commodities; transportation cost data; computation of trade equilibrium
Non-US	Rest of the world	Excess demand and supply function parameters for livestock and processed commodities; computation of trade equilibrium
US	US	Demand function parameters for crop, livestock, and processed commodities
Major US regions (10)	Northeast, Lake States, Corn belt, Northern Plains, Appalachia, Southeast, Delta States, Southern Plains, Mountain States, Pacific States	Feed mixing and other process data; labor endowment data
Minor US regions (63)	Alabama, Arizona, Arkansas, N-California, S-California, Colorado, Connecticut, Delaware, Florida, Georgia, Idaho, N-Illinois, S-Illinois, N-Indiana, S-Indiana, W-Iowa, Central Iowa, NE-Iowa, S-Iowa, Kansas, Kentucky, Louisiana, Maine, Maryland, Massachusetts, Michigan, Minnesota, Mississippi, Missouri, Montana, Nebraska, Nevada, New Hampshire, New Jersey, New Mexico, New York, North Carolina, North Dakota, NW-Ohio, S-Ohio, NE-Ohio, Oklahoma, Oregon, Pennsylvania, Rhode island, South Carolina, South Dakota, Tennessee, TX-High Plains, TX-Rolling Plains, TX-Central Blackland, TX-East, TX-Edwards Plateau, TX-Coastal Belt, TX-South, TX Transpecos, Utah, Vermont, Virginia, Washington, West Virginia, Wisconsin, Wyoming	Crop and livestock production data and activities, land type and water resource data
Land types (6)	Agricultural land: land with wetness limitation, low erodible land (erodibility index (EI) < 8), medium erodible land (8 < EI < 20), highly erodible land (EI < 20); pasture; forest	Land endowments; cost, yield, and emission data adjustment

Producers can choose among several alternative production technologies. Specifically, alternative crop production functions arise from combinations of three tillage alternatives, two irrigation alternatives, and three nitrogen fertilization alternatives specific to each US region, land, and crop type. Alternative livestock production functions reflect different production intensities, various manure treatment schemes, alternative diets, and pasture management for 15 animal production categories and 63 US regions. Processing functions identify first or higher level processing opportunities carried out by producers. Environmental impacts include 35 individual GHG emission accounts and several other environmental indicators related to erosion and nutrient leaching (Table 4).

ASMGHG is setup as mathematical programming model and contains more than 20,000 individual variables and more than 5000 individual equations. These equations and variables are 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 production variables, LUTR = land use transformation, LIVE = livestock production, PROC = processing, and INPS = production factor (input) use variables. Additional variable blocks reflect the disappearance of agricultural products with DOMD = US domestic demand, TRAD = US interregional and international trade, FRXS = foreign region excess supply, FRXD = foreign region excess demand, EMIT = Emissions, and SEQU = Sequestration variables. WELF denotes total agricultural economic surplus from both US and foreign agricultural markets. With the exception of WELF, all variables are restricted to be nonnegative.

ASMGHG contains an objective function, which maximizes total agricultural economic surplus (WELF) and a set of constraining equations, which define the convex feasible region for all variables. The constraining equations include resource limits, supply and demand balances, trade balances, and crop mix constraints. 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 economic surplus, 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' surplus yields the competitive market equilibrium as reviewed by McCarl and Spreen (1980). Thus, the optimal variable levels can be interpreted as equilibrium levels for agricultural activities under given economic, political, and technological conditions and the shadow prices give market clearing prices.

To facilitate understanding of the ASMGHG structure, we will first describe the set of constraining equations and subsequently explain the objective function. Constraint 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 sides may have subscripts indicating indices. In particular, the index c denotes the set of crops, j the crop management alternatives, i the livestock management alternatives, k the animal production types, w the production factors, f the production factors with exogenous prices (subset of index w), n the natural or human resource types (subset of index w), s the soil classes (subset of indexes n and w), h the processing alternatives, y the primary and processed agricultural commodities, l the land transformation alternatives, g the greenhouse gas accounts, r the regions, u the US regions (subset of index r), m the international regions (subset of index r), and t the years.

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 US region through domestic consumption (DOMD), processing (PROC), and exports (TRAD) cannot exceed the total amount of commodities supplied through crop production (CROP), livestock raising (LIVE), or imports (TRAD). Note that the USSH and TRAD variables contain two regional indexes with the first one denoting the exporting region and the second one denoting the importing region. Equation block (1) shows the set of commodity supply and demand balance equations employed in ASMGHG, which is indexed over US regions and commodities.

$$\begin{aligned}
&-\sum_{c,s,j}(a^{\mathrm{CROP}}_{u,c,s,j,y}\cdot \mathrm{CROP}_{u,c,s,j})-\sum_{k,i}(a^{\mathrm{LIVE}}_{u,k,i,y}\cdot \mathrm{LIVE}_{u,k,i})\\
&\quad-\sum_{r}\mathrm{TRAD}_{r,u,y}+\mathrm{DOMD}_{u,y}-\sum_{h}(a^{\mathrm{PROC}}_{u,h,y}\cdot \mathrm{PROC}_{u,h})\\
&\quad+\sum_{r}\mathrm{TRAD}_{u,r,y}\leqslant 0\quad \text{for all } u \text{ and } y. \qquad (1)
\end{aligned}$$

As shown in equation block (1), agricultural commodities can be supplied in each US region u through crop production (if yield $a^{\mathrm{CROP}}_{u,c,s,j,y}>0$), livestock production (if yield

Table 4
Environmental accounts in ASMGHG

Account type	Individual account elements
Carbon dioxide emission accounts	On-farm fossil fuel use for agricultural machinery, energy for irrigation, grain drying, fertilizer manufacture, and pesticide manufacture, feed urea applications, bioelectricity and biofuel generation, soil organic matter changes on crop and pasture lands, afforestation, pasture management
Methane and nitrous oxide emission accounts	Rice cultivation, nitrogen fertilizer applications, nitrification, denitrification, grazing regime, enteric fermentation, animal waste, livestock manure, manure treatment, manure fertilization, bioelectricity and biofuel generation
Other environmental accounts	Soil erosion through wind and water, nitrogen and phosphorous losses from surface runoff, subsurface flow, percolation, immobilization, and other processes

$a^{\text{LIVE}}_{u,k,i,y} > 0$), processing (if yield $a^{\text{PROC}}_{u,h,y} > 0$), and shipments from other US regions $\tilde{u}$ or international region m. On the demand side, commodities can be used as an input for livestock production (if usage rate $a^{\text{LIVE}}_{u,k,i,y} < 0$), processed (if usage rate $a^{\text{PROC}}_{u,h,y} < 0$), directly sold in US region u's market, shipped to other US regions $\tilde{u}$, or exported to international region m.

The constraint coefficients $a^{\text{CROP}}_{u,c,s,j,y}$, $a^{\text{LIVE}}_{u,k,i,y}$, and $a^{\text{PROC}}_{u,h,y}$ can be positive or negative. A negative value indicates that commodity y is an input to production (like livestock feed) and the rate at which it is used, while a positive value indicates outputs. 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), and processing (PROC) activities must be matched by total supply of these factors (INPS) in each region

$$\text{INPS}_{u,w} - \sum_{c,s,j} a^{\text{CROP}}_{u,c,s,j,w} \cdot \text{CROP}_{u,c,s,j} - \sum_{k,i} a^{\text{LIVE}}_{u,k,i,w} \cdot \text{LIVE}_{u,k,i} - \sum_{h} a^{\text{PROC}}_{u,h,w} \cdot \text{PROC}_{u,h} \leqslant 0 \quad \text{for all } u \text{ and } w. \tag{2}$$

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 or supply curves of these private or public resources. In ASMGHG, all agricultural production variables (CROP, LIVE, and PROC) have associated with them resource use coefficients ($a^{\text{CROP}}_{u,c,s,j,n}$, $a^{\text{LIVE}}_{u,k,i,n}$, $a^{\text{PROC}}_{u,h,n}$), which contain the quantity of resources needed per unit of production. 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 can also be inflated by set aside requirements when analyzing farm program features (Chang et al., 1992).

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 endowments $b_{u,n}$. Note that the natural and human resource index n is a subset of the production factor index w. Thus, all $\text{INPS}_{u,n}$ resource use variables are also constrained through equation block (2)

$$\text{INPS}_{u,n} \leqslant b_{u,n} \quad \text{for all } u \text{ and } n \tag{3}$$

In ASMGHG, trade activities ($\text{TRAD}_{u,m,y}$, $\text{TRAD}_{\tilde{m},m,y}$, $\text{TRAD}_{m,u,y}$, $\text{TRAD}_{m,\tilde{m},y}$) 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 an international region's excess demand for an agricultural commodity ($\text{FRXD}_{m,y}$) to not exceed the sum of all import activities into that particular region from other international regions ($\text{TRAD}_{\tilde{m},m,y}$) and from the US ($\text{TRAD}_{u,m,y}$). Similarly, the equations in block (5) force the sum of all commodity exports from a certain international region into other international regions ($\text{TRAD}_{m,\tilde{m},y}$) and the US ($\text{TRAD}_{m,u,y}$) to not exceed the region's excess supply activity ($\text{FRXS}_{m,y}$).

$$-\sum_{u} \text{TRAD}_{u,m,y} - \sum_{\tilde{m}} \text{TRAD}_{\tilde{m},m,y} + \text{FRXD}_{m,y} \leqslant 0 \quad \text{for all } m \text{ and } y \tag{4}$$

$$\sum_{u} \text{TRAD}_{m,u,y} + \sum_{\tilde{m}} \text{TRAD}_{m,\tilde{m},y} - \text{FRXS}_{m,y} \leqslant 0 \quad \text{for all } m \text{ and } y \tag{5}$$

The number of individual equations in blocks (4) and (5) depends on the number of traded commodities and the number of international regions per commodity. Eight major agricultural crop commodities are constrained through spatially explicit multilateral international trade balance equations, where trade is made endogenous not only between the US and international regions but also between different international regions (Takayama and Judge, 1964). For the remaining crop commodities as well as livestock and processed products, the rest of the world is portrayed as a single region.

A fifth set of constraints addresses aggregation related aspects of farmers' decision process. These constraints force producers' cropping activities $\text{CROP}_{u,c,s,j}$ to fall within a convex combination of historically observed choices $h_{u,c,t}$ (Eq. (6)). Based on decomposition and economic duality theory, Onal and McCarl (1991) show that historical crop mixes represent rational choices embodying numerous farm resource constraints, crop rotation considerations, perceived risk reactions, and a variety of natural conditions. In (6), the $h^{\text{CMIX}}_{u,c,t}$ coefficients contain the observed crop mix levels for the past 30 years. $\text{CMIX}_{u,t}$ are positive, endogenous variables indexed by historical year and region, whose level will be determined during the optimization process

$$-\sum_{t} (h^{\text{CMIX}}_{u,c,t} \cdot \text{CMIX}_{u,t}) + \sum_{s,j} \text{CROP}_{u,c,s,j} = 0 \quad \text{for all } u \text{ and } c. \tag{6}$$

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. However, the sum of the CMIX variables over time is not forced to add to unity. 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 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, 1991).

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 $E[\sum_{s,j}\mathrm{LAND}_{u,c,s,j}/\sum_{c,s,j}\mathrm{LAND}_{u,c,s,j}] > \mathrm{Max}_t(h^{\mathrm{CMIX}}_{u,c,t}/\sum_c h^{\mathrm{CMIX}}_{u,c,t})$, then these crops are not part of the crop mix equations. In ASMGHG, the energy crops of switchgrass, poplar and willow fall into this category.

The mix of livestock production is constrained in a similar way as crop production (Eq. (7)). Particularly, the regionally produced livestock commodities are constrained to fall in a convex combination of historically observed livestock product mixes ($h^{\mathrm{LMIX}}_{u,y,t}$). $\mathrm{LMIX}_{u,t}$ are positive, endogenous variables indexed by historical year and region, whose level will be determined during the optimization process.

$$-\sum_t(h^{\mathrm{LMIX}}_{u,y,t}\cdot\mathrm{LMIX}_{u,t})+\sum_{k,i}(a^{\mathrm{LIVE}}_{u,k,i,y}\cdot\mathrm{LIVE}_{u,k,i})=0 \quad \text{for all } u \text{ and } y. \tag{7}$$

Agricultural land owners not only have a choice between different crops and different crop management strategies, they can also abandon traditional crop production 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 (8), 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 (8) is not enforced. In such a case, land use transformations would only be constraint through constraint set (3).

$$\mathrm{LUTR}_{u,l}\leqslant d_{u,l}|_{d_{u,l}\geqslant 0} \quad \text{for all } u \text{ and } l. \tag{8}$$

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 (9) and (10). For each land management ($\mathrm{CROP}_{u,c,s,j}$ and $\mathrm{LUTR}_{u,l}$), livestock ($\mathrm{LIVE}_{u,k,i}$), or processing ($\mathrm{PROC}_{u,h}$) activity, environmental impact coefficients ($a^{\mathrm{LAND}}_{u,c,s,j,g}$, $a^{\mathrm{LUTR}}_{u,l,g}$, $a^{\mathrm{LIVE}}_{u,k,i,g}$, $a^{\mathrm{PROC}}_{u,h,g}$) 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)

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

$$\begin{aligned}\mathrm{SEQU}_{u,g}=&\sum_{c,s,j}(a^{\mathrm{CROP}}_{u,c,s,j,g}\cdot\mathrm{CROP}_{u,c,s,j})|_{a^{\mathrm{LAND}}_{u,c,s,j,g}<0}\\&+\sum_l(a^{\mathrm{LUTR}}_{u,l,g}\cdot\mathrm{LUTR}_{u,l})|_{a^{\mathrm{LUTR}}_{u,l,g}<0}\\&+\sum_{k,i}(a^{\mathrm{LIVE}}_{u,k,i,g}\cdot\mathrm{LIVE}_{u,k,i})|_{a^{\mathrm{LIVE}}_{u,k,i,g}<0}\\&+\sum_h(a^{\mathrm{PROC}}_{u,h,g}\cdot\mathrm{PROC}_{u,h})|_{a^{\mathrm{PROC}}_{u,h,g}<0}\\&\text{for all } u \text{ and } g.\end{aligned}\tag{10}$$

While the structure of equation blocks (9) and (10) can be used to account for many different environmental impacts, special focus was placed in ASMGHG on greenhouse gases. GHG emissions and emission reductions (index g) are accounted for all major sources, sinks and offsets from agricultural activities, for which data were available or could be simulated. Particularly, ASMGHG considers (a) 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), (b) indirect carbon emissions from fertilizer and pesticide manufacturing, (c) carbon savings from increases in soil organic matter (reduced tillage intensity and conversion of arable land to grassland) and from afforestation, (d) carbon offsets from bioenergy production (ethanol and power plant feedstock via production of corn, switchgrass, poplar, and willow), (e) nitrous oxide emissions from fertilizer usage, livestock manure, herd size and feeding adjustments, (f) methane emissions from enteric fermentation, livestock manure, herd size and feeding adjustments, and rice cultivation, (g) methane savings from changes in manure management, grazing management and bovine somatrophine, and (h) methane and nitrous oxide emission changes from biomass power plants. Afforestation data are based on simulation results from the Forest and Agricultural Sector Optimization Model (Alig et al., 1998) for corresponding carbon price scenarios.

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 price endogenous approach as reviewed in McCarl and Spreen (1980), we use an economic surplus based objective function. This equation is shown in (11). Note that 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.

The left-hand side of Eq. (11) contains the unrestricted total agricultural surplus variable (WELF), which is to be maximized. The right-hand side of Eq. (11) contains several major terms, which will be explained in more detail below. The first term $\sum_{u,y}[\int_y p_{u,y}^{\mathrm{DOMD}}(\mathrm{DOMD}_{u,y})\,\mathrm{d}(\cdot)]$ adds the sum of the areas underneath the inverse US domestic demand curves over all crops, livestock products, and processed commodities. ASMGHG can employ three types of non-zero demand specifications: (a) downward sloping demand curves, (b) horizontal or totally elastic demand implying constant prices, and (c) vertical demand implying fixed demand quantities.

$$\begin{aligned}\text{Max WELF} = {} & \sum_{u,y}\left[\int_y p_{u,y}^{\mathrm{DOMD}}(\mathrm{DOMD}_{u,y})\,\mathrm{d}(\cdot)\right] \\ & - \sum_{u,n}\left[\int_n p_{u,n}^{\mathrm{INPS}}(\mathrm{INPS}_{u,n})\,\mathrm{d}(\cdot)\right] \\ & + \sum_{m,y}\left[\int_y p_{m,y}^{\mathrm{FRXD}}(\mathrm{FRXD}_{m,y})\,\mathrm{d}(\cdot)\right] \\ & - \sum_{m,y}\left[\int_y p_{m,y}^{\mathrm{FRXS}}(\mathrm{FRXS}_{m,y})\,\mathrm{d}(\cdot)\right] \\ & - \sum_{u,f}(p_{u,f}^{\mathrm{INPS}}\cdot \mathrm{INPS}_{u,f}) \\ & - \sum_{r,\tilde{r},y}(p_{r,\tilde{r},y}^{\mathrm{TRAD}}\cdot \mathrm{TRAD}_{r,\tilde{r},y}). \end{aligned} \tag{11}$$

Downward sloping demand curves are specified as constant elasticity functions. 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 ($\mathrm{DOMD}_{u,y}^{\mathrm{TF}}$) and downward sloping for demand quantities above $\mathrm{DOMD}_{u,y}^{\mathrm{TF}}$. In particular, the truncated inverse demand curve for commodity y and region u becomes $p_{u,y}^{\mathrm{DOMD}}(\mathrm{DOMD}_{u,y}) = \{\hat{p}_{u,y}\times(\frac{\mathrm{DOMD}_{u,y}^{\mathrm{TF}}}{\mathrm{DOMD}_{u,y}^{\wedge}})^{1/\varepsilon_{u,y}}$ for all $\mathrm{DOMD}_{u,y} < \mathrm{DOMD}_{u,y}^{\mathrm{TF}}$ and $\hat{p}_{u,y}\cdot(\frac{\mathrm{DOMD}_{u,y}}{\mathrm{DOMD}_{u,y}^{\wedge}})^{1/\varepsilon_{u,y}}$ for all $\mathrm{DOMD}_{u,y} \geqslant \mathrm{DOMD}_{u,y}^{\mathrm{TF}}\}$, 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.

The second right-hand side term $-\sum_{u,n}[\int_n p_{u,n}^{\mathrm{INPS}}(\mathrm{INPS}_{u,n})\,\mathrm{d}(\cdot)]$ 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 $p_{u,y}^{\mathrm{INPS}}(\mathrm{INPS}_{u,n}) = \hat{p}_{u,n}^{\mathrm{INPS}}\times(\frac{\mathrm{INPS}_{u,n}}{\mathrm{INPS}_{u,n}^{\wedge}})^{1/\varepsilon_{u,n}}$. Note that the $\mathrm{INPS}_{u,n}$ supply variables are constrained 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 $+\sum_{m,y}[\int_y p_{m,y}^{\mathrm{FRXD}}(\mathrm{FRXD}_{m,y})\,\mathrm{d}(\cdot)]$ and $-\sum_{m,y}[\int_y p_{m,y}^{\mathrm{FRXS}}(\mathrm{FRXS}_{m,y})\,\mathrm{d}(\cdot)]$ 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 consumers' plus producers' surplus economic of foreign regions.

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

3. 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 induced by policy, research, environmental change or other factors. We chose to examine the national greenhouse gas abatement potential of US 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 US agriculture did not fully incorporate the needed market, and strategy richness that we mention above.

3.1. Mitigation policy simulation in the agricultural sector

Agricultural greenhouse mitigation policies can be designed in many different ways with varying levels of severity. We decided to use a tax/subsidy hybrid system for internalizing emissions. In particular, we assumed that farmers pay a tax on emissions equal to $\mathrm{ep}_{\mathrm{g}}^{\mathrm{EMIT}}$ and receive a subsidy for sequestration equal to $\mathrm{ep}_{\mathrm{g}}^{\mathrm{SEQU}}$. We assumed that the carbon price arises exogenously to the agricultural sector. To implement this policy in ASMGHG, we expanded the objective function (Eq. (11)) by adding the terms $-\sum_{u,g}(\mathrm{ep}_{\mathrm{g}}^{\mathrm{EMIT}}\cdot \mathrm{EMIT}_{u,g})$ and $+\sum_{u,g}(\mathrm{ep}_{\mathrm{g}}^{\mathrm{SEQU}}\cdot \mathrm{SEQU}_{u,g})$.

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 address uncertainties about a future carbon price, we picked a wide range of hypothetical price levels between zero and $500 per megagram carbon equivalent (MgCE). For each carbon price level, we computed the $\mathrm{ep}_{\mathrm{g}}^{\mathrm{SEQU}}$ and $\mathrm{ep}_{\mathrm{g}}^{\mathrm{EMIT}}$ coefficients using $\mathrm{ep}_{\mathrm{g}}^{\mathrm{SEQU}} = \upsilon_{\mathrm{g}}^{\mathrm{SEQU}}\cdot\frac{12}{44}\cdot\mathrm{cp}$ and $\mathrm{ep}_{\mathrm{g}}^{\mathrm{EMIT}} = \upsilon_{\mathrm{g}}^{\mathrm{EMIT}}\cdot\frac{12}{44}\cdot\mathrm{cp}$, where $\upsilon_{\mathrm{g}}^{\mathrm{SEQU}}$ and $\upsilon_{\mathrm{g}}^{\mathrm{EMIT}}$ and are greenhouse gas account specific multipliers based on the 100 year global warming potential. Particularly, $\upsilon_{\mathrm{g}}^{\mathrm{EMIT}} = 1$ for carbon emission accounts, $\upsilon_{\mathrm{g}}^{\mathrm{EMIT}} = 23$ for methane emission accounts, and $v_g^{EMIT} = 298$ for nitrous oxide emission accounts. GHG sequestration accounts in ASMGHG involve only carbon. Reflecting different permanence and saturation characteristics, we assigned $v_g^{SEQU} = 1$ for bioenergy 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. Details on the derivation of these coefficients are available in McCarl et al. (2005).

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 with a carbon price imposed (a) on all GHG accounts, (b) on the afforestation carbon account only, (c) on the bioenergy carbon account only, and (d) on the soil carbon account only. The last three scenarios were chosen to illustrate the difference between the single strategy economic potential and the competitive economic potential, where different strategies can be used simultaneously.

To simulate the above described mitigation policy scenarios, we generate abatement supply curves over all carbon price levels under each policy scope scenario. For each price and policy, we solved ASMGHG, computed and reported relevant solution information.

In interpreting our results, a few characteristics 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. According to Mooney et al. (2004), the maximum cost for soil carbon monitoring and measurement range between 3% and 11% of the assumed carbon price. Third, carbon and energy prices are exogenous to ASMGHG. Fourth, increased utility from reduced levels of GHG is not included. Fifth, all results portray the new, intermediate run equilibrium after adjustment to the GHG mitigation policy change.

3.2. Mitigation strategy adoption

The contribution of major agricultural GHG emission mitigation strategies is graphically summarized in Fig. 1 through abatement curves and also listed in Table 5. 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 of total abatement is provided by two mitigation strategies: soil carbon sequestration and emission offsets from bioenergy generation. At low carbon prices, soil carbon sequestration dominates but when carbon prices increase above $50 per MgCE, bioenergy becomes the most important mitigation option. GHG emissions reductions through livestock technologies and afforestation also reach noteworthy levels.

Soil carbon sequestration increases for carbon prices up to $50 per MgCE but decreases for higher prices. This occurs for two major reasons: (a) for prices above $50 per MgCE, substantial amounts of cropland are either

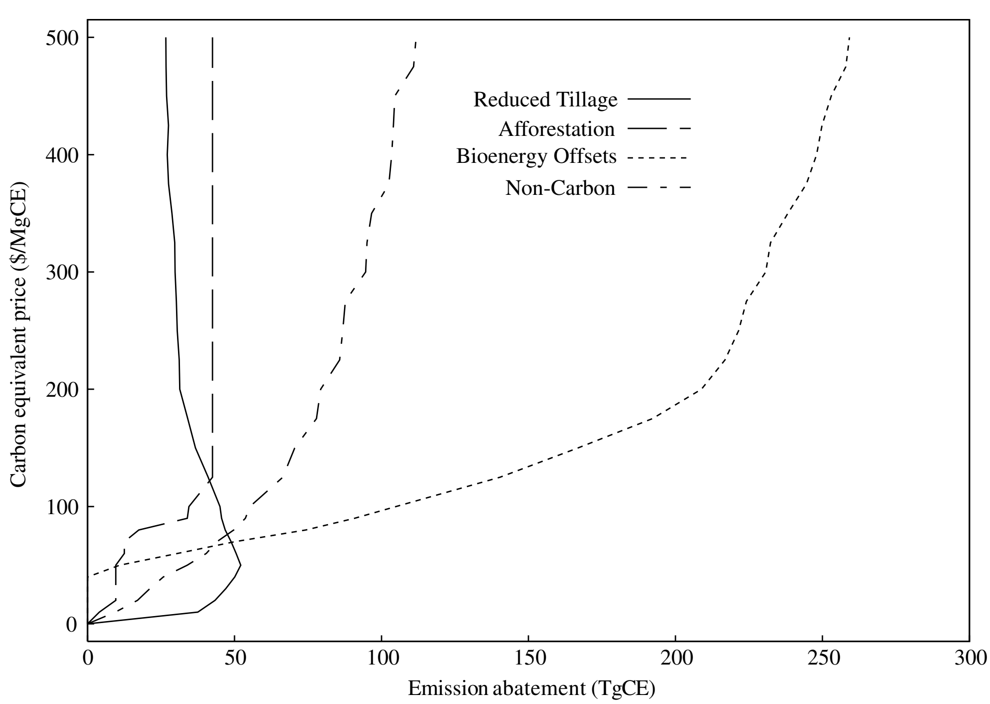

Fig. 1. Multi-strategy, economic potential of major agricultural greenhouse gas emission mitigation strategies in the US at $0 to $300 per teragram carbon equivalent.

Table 5
Environmental abatement effects at selected carbon price scenarios

Category	Carbon price in $ per MgCE						
Sub-category	0	10	20	50	100	200	500
GHG abatement by individual strategy (TgCE)							
Soil carbon storage	0.0	37.5	43.4	52.1	45.1	31.4	26.7
Afforestation	0.0	4.0	9.6	9.6	34.5	42.5	42.5
Bioenergy offsets	3.2	3.2	3.2	14.1	108.1	212.0	259.6
Reduced fossil fuel inputs	0.0	4.9	6.2	10.3	16.2	20.8	26.5
Livestock technologies	0.0	7.6	15.1	31.2	47.2	65.6	94.5
Crop non-carbon strategies	0.0	1.9	1.9	2.3	3.7	4.8	6.4
Total GHG emission abatement (TgCE)							
Carbon dioxide	0.0	46.4	59.2	82.5	196.1	294.4	341.0
Methane	0.0	5.7	11.4	24.3	40.8	60.2	84.9
Nitrous oxide	0.0	3.8	5.6	9.7	14.4	19.1	26.9
Total	0.0	55.9	76.2	116.5	251.3	373.7	452.7
Changes in non-GHG environmental externalities on traditional cropland (% per ha)							
Erosion	0.0	−25.9	−30.4	−34.5	−37.2	−44.2	−43.5
Nitrogen percolation	0.0	−9.9	−10.7	−14.2	−18.2	−19.7	−18.9
Nitrogen subsurface flow	0.0	−11.2	−12.2	−14.6	−12.8	−11.9	−11.7
Phosphorous loss in sediment	0.0	−33.4	−40.0	−46.9	−49.7	−49.4	−49.8

diverted to generate alternative energy crops or afforested. While these land uses will also increase soil carbon, associated net emission savings are allocated to the afforestation and bioenergy accounts; 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 usually less than 1 MgCE per hectare and year, while growing forests or energy crop plantations can mitigate above 2 MgCE per hectare and year. Thus, for high carbon price levels it may 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 $125 per MgCE. Higher incentives up to $500 per MgCE result in no additional gains. Energy crops are not planted for carbon price levels below $50 per MgCE 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 noteworthy but below the contribution of carbon strategies. 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 ecosystem capacity 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 MgCE incentive, only about 56 teragrams of carbon equivalent (TgCE) can be saved through the agricultural and forest sectors. This amount equals about three percent of the combined 1990 US emissions of carbon dioxide, methane, and nitrous oxide (US EPA, 2004). As carbon prices increase, so do marginal abatement costs. For example, an increase to $20 per MgCE adds 20 TgCE or about 36% of the $10 per MgCE contribution. It takes extremely high incentives to bring agriculture's annual contribution above 400 TgCE (Table 5).

3.3. 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 (Fig. 3). In ASMGHG, the technical potential can be obtained by maximizing mitigation instead of economic surplus subject to all resource and technological constraints. The total technical potential of soil carbon sequestration is 148 TgCE annually (Fig. 3a).

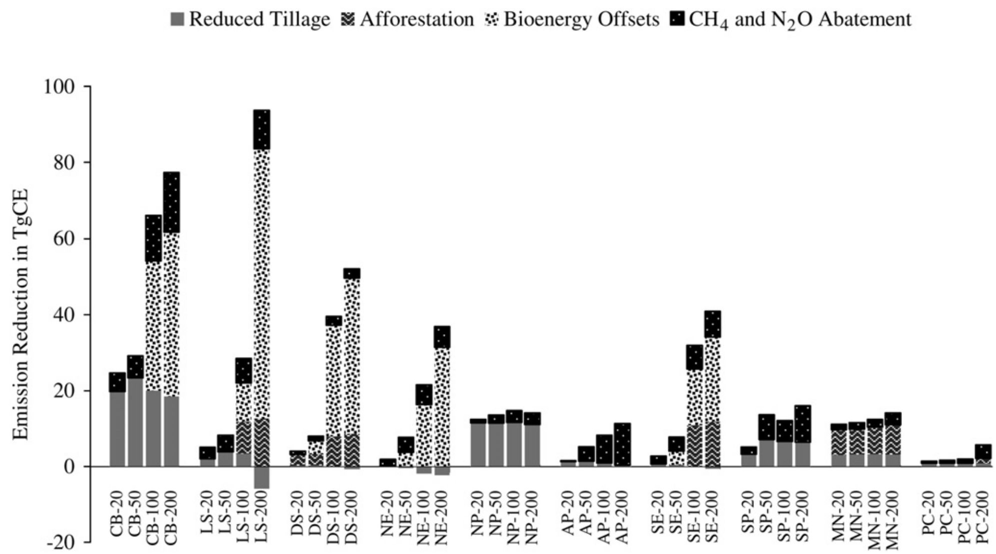

Fig. 2. Differences in regional strategy adoption (LS = Lake states, SE = South east states, CB = Cornbelt, NE = North east states, MN = Mountain states, DS = Delta states, NP = Northern plain states, AP = Appalachian states, SP = Southern plain states, PC = Pacific states) of major agricultural mitigation strategies for selected carbon prices (20, 50, 100, and 200 $ per MgCE).

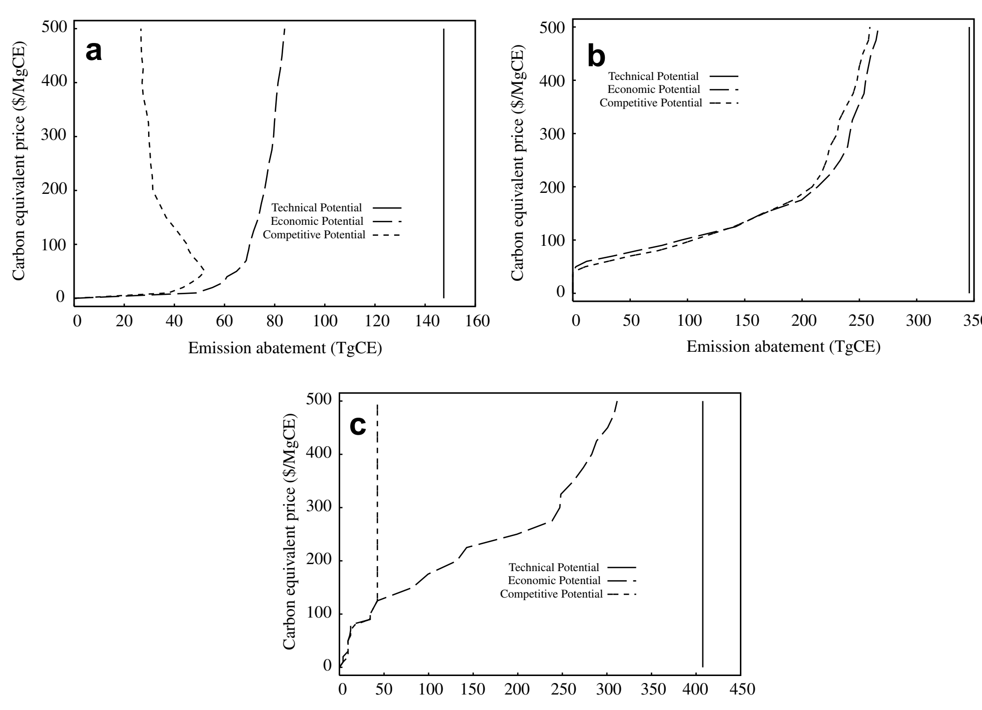

Fig. 3. Technical, sole source economic, and competitive multi-strategy economic potentials for (a) soil carbon Sequestration on US cropland including conversion of cropland into pastureland, (b) biofuel and bioelectricity based emission offsets, and (c) afforestation of US croplands.

However, this potential is not economically feasible even under sole reliance on this strategy and prices as high as $500 per MgCE. Even at such a high price, carbon gains remain about 64 TgCE or 43% short of the technical potential. At lower prices substantially less soil carbon is sequestered. Furthermore, when agricultural soil carbon strategies are considered simultaneously with other strategies, the carbon policy stimulates at most 52 TgCE or 35% of the technical potential with sequestration falling to 31 TgCE (21%) at a $200 price because other strategies are more efficient at higher payment level.

Similar observations can be made for other agricultural GHG mitigation strategies. At a carbon price of $200 per MgCE, the single strategy economic potential of bioenergy carbon offsets (Fig. 3b) is not even two third of its technical potential. The economic potential of mitigation from affor-

Table 6
Production, market and economic surplus effects in US agriculture at selected carbon price scenarios

Category	Unit	Carbon price in \$ per MgCE						
Sub-category		0	10	20	50	100	200	500
Agricultural production								
Pasture	Million ha	164.2	160.6	157.3	153.4	146.4	133.3	114.9
Traditional crops	Million ha	129.5	131.3	132.9	132.3	118.4	102.0	90.1
Energy crops	Million ha	0.0	0.0	0.0	4.9	48.6	96.0	123.8
New forests	Million ha	0.0	0.0	2.6	2.6	8.7	9.8	9.8
Reduced tillage	Percent	33.7	41.7	45.7	53.1	55.4	47.3	44.4
Irrigation	Percent	25.2	23.9	22.2	19.7	18.8	18.1	17.3
Nitrogen fertilizer	Tg N	9.4	8.2	8.2	8.0	7.2	6.5	5.5
Agricultural market shifts								
Crop production	Fisher index	100.0	100.5	100.9	99.9	89.9	77.7	66.3
Crop prices	Fisher index	100.0	98.6	97.9	99.0	120.9	167.3	310.4
Crop net exports	Fisher index	100.0	100.8	101.2	90.9	57.2	21.3	12.3
Livestock production	Fisher index	100.0	97.9	95.8	91.8	85.6	76.8	60.0
Livestock prices	Fisher index	100.0	100.1	100.4	104.8	126.8	166.4	284.4
Changes in agricultural economic surplus								
Ag-Sector welfare	Billion \$	0.0	−0.5	−1.1	−4.0	−16.4	−40.0	−85.3
Producers welfare	Billion \$	0.0	−3.0	−5.1	−8.4	7.4	45.7	172.4
Consumers welfare	Billion \$	0.0	0.4	0.3	−2.6	−23.0	−58.9	−150.7
Foreign welfare	Billion \$	0.0	0.1	0.1	−0.1	−1.5	−3.6	−9.6

estation (Fig. 3) achieves at \$200 per MgCE achieves about one third of its technical potential under a single strategy assessment and only 11% under multi-strategy assessment.

3.4. Regional effects

While results presented so far concentrated at the national level, ASMGHG output can also be used to examine regional differences (Fig. 2). Particularly, soil carbon sequestration is dominant in the Northern Plains States, important in the Cornbelt and Southern Plains States but negligible in the Delta and Southeastern States. Renewable energy strategies appear attractive at higher carbon prices in the Cornbelt, Lake, Delta, Northeastern, and Southeastern States. Note that the relatively high bioenergy impacts at \$200 per MgCE in the Lake and Northeastern States go with increased soil carbon emissions on traditional cropland. Furthermore, afforestation dominates mitigation efforts in the Mountain States, reaches notable levels in the Lake, Delta, and Southeastern States but does not appear in the Cornbelt, Northeastern, Northern Plains, Appalachian, and Southern Plains States. Finally, while CH_4 and N_2O strategies play a major role in the Appalachian and Southern Plain States, considerably smaller shares are observed in other regions.

Regional differences in strategy adoption arise from and reflect the heterogeneous agricultural and forest production conditions characterized by regionally specific cost, yield, and environmental impact data. The results in Fig. 2 should be interpreted with caution because ASMGHG is calibrated at the national level and may not perform as accurately in individual regions. However, regional deviations show that different mitigation strategies are optimal for different locations and mitigation incentives.

3.5. Income impacts

Income impacts of mitigation on agricultural sector participants are listed in Table 6. Again, these impacts represent intermediate run results, which are equilibrium results after adjustment. Thus, producers' income changes do not include adjustment costs, which might be incurred in the short run after implementation of a mitigation policy. Total economic surplus in the agricultural sector decreases notably once the carbon price passes \$100 per MgCE. Similarly, stronger mitigation policies decrease consumers' economic surplus by roughly 30 billion dollars per \$100 per MgCE carbon price increase because of higher commodity prices. In contrast, producers' surplus decreases somewhat under modest mitigation incentives but increases as emission reductions value more than \$90 per MgCE. The increase in producers' surplus is due to large surplus shifts from consumers. Foreign countries' surplus 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 US exports, foreign producers benefit from less US production. Since foreign surplus is aggregated over both foreign consumers and producers, the two effects offset each other somewhat. The above described measures of surplus do not provide a complete picture of economic surplus impacts because they do not internalize 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.

3.6. 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 energy crops (see Table 6). 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 6. 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 6). 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 MgCE substantial amounts of cropland are diverted to trees and energy 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 US domestic food production coupled with higher prices in US agricultural markets induce foreign countries to increase their net exports into the US. 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 6). In particular, prices change considerably if the product is emission intensive, if it has a low elasticity of demand, and if the US is a major producer.

3.7. Other externalities

Many of the GHG emission coefficients for crop production were simulated with the Environmental Policy Integrated Climate (EPIC) system. This complex biophysical simulation model simultaneously reports soil carbon changes, nutrient, pesticide, and sediment emissions from soils, and many other environmental impacts. 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 Tables 5 and 6. The average per hectare emissions of the other externalities decrease notably as carbon prices increase from $0 and $100 dollars per MgCE with little or no additional reductions at higher prices.

4. 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 US agriculture can contribute to greenhouse gas mitigation, but total abatement potential is price sensitive. For low GHG 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% of the original US Kyoto Protocol target. At higher carbon prices, most of the emission abatement comes from 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 US 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, depending on the carbon price, farmers may experience higher earnings. The financial losses due to an overall reduction in production caused by the competitive nature of many mitigation strategies with conventional production can be more than offset by financial gains due to market price effects and GHG credit revenues.

The findings provide support for altered 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 and uncertainties to this research should be noted. 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 certainty of the estimates presented here depends on the quality of these models and the certainty of associated simulation model input data. 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., 2001; 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. Finally, all simulated results are derived from the optimal solution of the mathematical program and as such constitute point estimates without probability distribution.

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