The Potential of U.S. Agriculture and Forestry to Mitigate Greenhouse Gas Emissions: An Agricultural Sector Analysis

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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 prices. 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.

Key words: aggregate supply and demand analysis, environmental management, global warming, greenhouse gas emission mitigation, prices, renewable resources and conservation.

THE POTENTIAL OF U.S. AGRICULTURE AND FORESTRY TO MITIGATE GREENHOUSE GAS EMISSIONS: AN AGRICULTURAL SECTOR ANALYSIS

Increasing atmospheric concentrations of greenhouse gases and their projected consequences, in particular global warming (IPCC 2001), have caused a widespread search for feasible remedies. Agriculture has been identified as potential source of low-cost alternatives for greenhouse gas (GHG) emission mitigation during the next few decades (McCarl and Schneider 2000). While U.S. agriculture is a small emitter of carbon dioxide (CO_2), the most prevalent greenhouse gas, it contributes about 7 percent of total carbon equivalent emissions, releasing about 28 percent of methane emissions and 73 percent of nitrous oxide (US EPA 2001). Furthermore, agriculture has substantial potential for offsetting CO_2 emissions by serving as a sink, augmenting carbon absorption through changes in tillage (Kern 1994; Lal et al. 1998; Antle et al. 2001) or conversion of cropland to grassland or forest (Moulton and Richards 1990; Adams et al. 1993; Plantinga, Mauldin, and Miller 1999; Stavins 1999). Agriculture also can offset GHG emissions by increasing production of energy crops, which can serve either as feedstock for electricity generating power plants (Walsh et al. 1998; Mann and Spath 1997; McCarl et al. 2000; Schneider and McCarl 2002) or as blends/substitutes for fossil fuel based gasoline (Wang, Saricks, and Santini 1999; Wang 1999; Shapouri, Duffield, and Graboski 1995).

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 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

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

		Traditional Agriculture				Analyzed Greenhouse Gases		
Study	**Abatement Region**	**S**[a]	**P**[b]	**T**[c]	**Simultaneous Strategies**	**CO_2**	**CH_4**	**N_2O**
Antle et al. 2001	Montana	+	+	-	Tillage, Crop to grassland	+	-	-
Phetteplace, Johnson, and Seidl 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).

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 costs actually depend on the global warming potential weighted sum of all emissions.

In this paper, we use mathematical programming 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. We develop a model to simulate abatement functions and examine the consequences of omitting alternative strategies.

Generalized Structure of an Agricultural Sector Model

In this section we formulate a general framework for an Agricultural Sector Model similar to the welfare-maximizing models developed by Baumes (1978), Adams, Hamilton, and McCarl (1986), Chang et al. (1992), and McCarl et al. (2000). As a major extension to these models, we integrate multiple GHG mitigation strategies available to crop and livestock producers and establish complete and spatially differentiated accounts on GHG emissions, emission reductions, and other externalities for all agricultural activities in the United States. The framework we develop can be used to assess any policy or research induced multiple technical changes on a national or international scale.

Because of data requirements and computing feasibilities, sector models cannot provide the same detail as do farm-level (Garmhausen 2002) or regional (Schmid 2001) models. Generally, sector models depict representative enterprises for different production regions rather than individual farm characteristics. In each region, discrete technological choices are represented through production budgets. A budget specifies fixed quantities of multiple inputs and multiple outputs. Instead of optimizing the level of each production input or output on a continuous scale, choices are made between different sets of fixed input-output combinations. However, a sufficiently large number of alternative technological opportunities and convex combinations can provide the desired flexibility.

Basic economic theory demonstrates that maximization of the sum of consumers' and producers' surplus yields the competitive market equilibrium. In our framework, input supply and output demand functions are explicitly specified as partial equilibrium CES (constant elasticity of substitution) functions. Input demand and output supply functions, on the other hand, are only implicitly represented through the contained technologies. Consequently, the Marshallian welfare measure of consumer and producer surplus cannot be computed directly in either input or in output markets. However, as shown in McCarl and Spreen (1980), maximization of the sum of the areas underneath the inverse commodity and export demand and curves ($p[\cdot]$) minus the sum of the areas underneath the inverse factor and import supply curves yields equivalent results.

Applying the McCarl and Spreen (1980) technique, we can formulate a price-endogenous objective function as shown in equation (1):[1]

$$
\begin{aligned}
Max\quad & \sum_{y}\left[\int_{y} p^{y}\left(\sum_{r} DD_{r,y}\right)d\left(\cdot\right)\right] \\
& +\sum_{j,c}\left[\int p^{c}\left(\sum_{r} EX_{j,r,c}\right)d\left(\cdot\right)\right] \\
& -\sum_{j,c}\left[\int p^{c}\left(\sum_{r} IM_{j,r,c}\right)d\left(\cdot\right)\right] \\
& -\sum_{r,s}\left[\int p^{L}_{r,s}\left(\sum_{c,t,w,n,u} a^{L}_{r,c,t,w,n,s,u}\cdot L_{r,c,t,w,n,s,u}+\sum_{k,i} a^{L}_{r,k,i}\cdot LIVE_{r,k,i}+\sum_{f} a^{dL}_{r,f}\cdot dL_{r,f}\right)d\left(\cdot\right)\right] \\
& -\sum_{r}\left[\int p^{LB}_{r}\left(\sum_{c,t,w,n,s,u} a^{LB}_{r,c,t,w,n,s,u}\cdot L_{r,c,t,w,n,s,u}+\sum_{k,i} a^{LB}_{r,k,i}\cdot LIVE_{r,k,i}\right)d\left(\cdot\right)\right] \\
& -\sum_{r}\left[\int p^{W}_{r}\left(\sum_{c,t,w,n,s,u} a^{W}_{r,c,t,w,n,s,u}\cdot L_{r,c,t,w,n,s,u}\right)d\left(\cdot\right)\right] \\
& -\sum_{r}\left[\int p^{AU}_{r}\left(\sum_{k,i} a^{AU}_{r,k,i}\cdot LIVE_{r,k,i}\right)d\left(\cdot\right)\right] \\
& -\sum_{r,inp}\left\{p^{inp}\cdot\left[\sum_{c,t,w,n,s,u}\left(a^{inp}_{r,c,t,w,n,s,u}\cdot L_{r,c,t,w,n,s,u}\right)+\sum_{k,i}\left(a^{inp}_{r,k,i}\cdot LIVE_{r,k,i}\right)+\sum_{h}\left(a^{inp}_{r,h}\cdot PR_{r,h}\right)\right]\right\} \\
& -\sum_{r}\left\{\left[\sum_{y} p^{US}_{r,\tilde{r}}\cdot\sum_{\tilde{r}}\left(US_{r,\tilde{r},y}+US_{\tilde{r},r,y}\right)\right]+\left[\sum_{j,c} p^{IM/EX}\cdot\left(EX_{j,r,c}+IM_{j,r,c}\right)\right]\right\} \\
& -p^{CE}\cdot\sum_{g}\left(EM_{g}-ER_{g}\right).
\end{aligned}
\tag{1}
$$

The first term in equation (1) represents the area underneath the inverse domestic demand curves for all crops, livestock products, and processed commodities (index $y = \{c, q, z\}$). Subsequently, the terms in lines 2 and 3 account for the area underneath the inverse import supply and export demand curves. Terms 4 to 8 integrate the area underneath the endogenously priced factor supply curves of labor, water, land, and animal unit months (AUMS). Explicitly included are changes in sectoral land use (*dL*), that is, conversion of cropland to forest or grassland. The coefficient $a^{dL}_{r,f}$ takes on a value of 1 if the sectoral land shift (index *f*) demands land of land class *s* and –1 if the shift supplies land of land class *s*. Term 9 incorporates exogenously priced inputs (index *inp*) used for crop and livestock production and processing.

Term 10 incorporates transportation costs and term 11, the cost of a basic greenhouse gas policy, where a dollar value (p^{CE}) is placed on carbon equivalent net emissions. While emission-based policies may be impractical for non-point source pollutants, they are useful for estimating a lower bound on abatement cost achievable through practical policies. Practical policies could be based on management. In such a situation, the objective function term $p^{CE} \cdot \sum_{g} \left(EM_g - ER_g \right)$ would be replaced by

$$\sum_{r} \left(\sum_{c,t,w,n,s,u} \left(p^{CE}_{r,c,t,w,n,s,u} \cdot L_{r,c,t,w,n,s} \right) + \sum_{k,i} \left(p^{CE}_{r,k,i} \cdot LST_{r,k,i} \right) + \sum_{h} \left(p^{CE}_{r,h} \cdot PR_{r,h} \right) \right),$$

where $p^{CE}_{r,c,t,w,n,s,u}$, $p^{CE}_{r,k,i}$, and $p^{CE}_{r,h}$ represent the emission prices applied to crop production, livestock production, and processing.

Balance equations are needed to link agricultural production technologies to both input and output markets. Equation (2) shows a simplified output balance equation for primary crop and livestock product y in region r:

$$\begin{aligned} & - \sum_{t,w,n,s,u,c} a^{CROP}_{r,c,t,w,n,s,u,y} \cdot L_{r,c,t,w,n,s,u} - \sum_{k,i} a^{LIVE}_{r,k,i,y} \cdot LIVE_{r,k,i} \\ & + \sum_{h} a^{PR}_{r,c,h} \cdot PR_{r,h} + DD_{r,y} \\ & - \sum_{\tilde{r}} US_{\tilde{r},r,y} + \sum_{\tilde{r}} US_{r,\tilde{r},y} - \sum_{j} IM_{j,r,y} + \sum_{j} EX_{j,r,y} \le 0. \end{aligned} \tag{2}$$

Total regional crop production is calculated as management-specific yield $a^{CROP}_{r,c,t,w,n,s,u,y}$ times the corresponding crop acreage $L_{r,c,t,w,n,s,u}$ and is summed over all available management options. Alternative crop management differs in terms of tillage (index t), irrigation (index w), nitrogen fertilization (index n), and conservation practice (index u) for different land classes (index s). Similarly, total regional livestock production is computed as livestock activity yield $a^{LIVE}_{r,k,i,y}$ times the total employment of activity $LIVE_{r,k,i}$ and is summed over all animal types k and management alternatives i.

Primary crop or livestock commodities can be consumed domestically (variable *DD*), shipped to or from other domestic regions (variable *US*), exported (variable *EX*) or imported (variable *IM*) to foreign countries (index *j*), processed (variable *PR*), or directly fed to animals (variable *LIVE*). The coefficient $a_{r,y,h}^{PR}$ identifies the amount of commodity *y* needed for process *h* in region *r,* and $a_{r,k,i,y}^{LIVE}$ is the amount of commodity *y* required to employ one unit of livestock activity $LIVE_{r,k,i}$. If $a_{r,k,i,y}^{LIVE} < 0$, then *y* is an input to activity $LIVE_{r,k,i}$; otherwise, *y* symbolizes an output of that activity.

Technical or policy-induced changes in the agricultural sector of a large country such as the United States may affect not only imports and exports between the United States and foreign countries but also trade among foreign countries. To model trade relationships between foreign countries explicitly, foreign country specific trade balance equations can be specified as shown in equations (3) and (4):

$$-\sum_{r} EX_{j,r,y} - \sum_{\tilde{j}} EX_{j,\tilde{j},y} + FD_{j,y} \leq 0; \tag{3}$$

$$\sum_{r} IM_{j,r,y} + \sum_{\tilde{j}} IM_{\tilde{j},j,y} - FS_{j,y} \leq 0. \tag{4}$$

These equations ensure that a foreign country's demand for an agricultural commodity $(FD_{j,y})$ is matched by the sum of all other countries' commodity exports. Similarly, the sum over all commodity imports from a certain country must be matched by that country's supply $(FS_{j,y})$.

Agricultural enterprises not only produce raw commodities but also engage in certain processing activities (variable *PR*). An efficient way of incorporating numerous first- and higher-level processing relationships is displayed in equation (5):

$$\sum_{h} a_{r,z,h}^{PR} \cdot PR_{r,h} + DD_z + \sum_{r,k,i} a_{r,k,i,z}^{LIVE} \cdot LIVE_{r,k,i} + EX_z - IM_z \leq 0. \tag{5}$$

Processed commodities can be sold domestically, exported, used as inputs for further processing, or fed to animals. A negative sign of $a_{r,z,h}^{PR}$ identifies commodity *z* as an input while a positive sign identifies *z* as an output of process *h*.

The assessment of environmental impacts from agricultural production involves two steps. First, for each crop ($L_{r,c,t,w,n,s,u}$, $dL_{r,f}$), livestock ($LIVE_{r,k,i}$), or processing ($PR_{r,h}$)

activity, relevant environmental impacts (coefficients $e_{r,c,t,w,n,s,u,g}$, $e_{r,f,g}$, $e_{r,k,i,g}$, $e_{r,h,g}$) must be established. Second, impact-specific accounting constraints for emissions (*EM*) and emission reductions (*ER*) of environmental pollutants (index *g*) are separately entered (equations [6] and [7]). The explicit use of equality constraints facilitates simulation of environmental policies and allows computation of the pollutant's shadow price. The latter feature is especially useful in determining the marginal costs of quantity-based policy instruments such as emission standards.

$$\begin{aligned} EM_g = & \sum_{r,c,t,w,n,s,u} \left(e_{r,c,t,w,n,s,u,g} \cdot L_{r,c,t,w,n,s,u} \right)\Big|_{e_{r,c,t,w,n,s,u,g}>0} \\ & + \sum_{r,f} \left(e_{r,f,g} \cdot dL_{r,f} \right)\Big|_{e_{r,f,g}>0} \\ & + \sum_{r,k,i} \left(e_{r,k,i,g} \cdot LIVE_{r,k,i} \right)\Big|_{e_{r,k,i,g}>0} \\ & + \sum_{r,h} \left(e_{r,h,g} \cdot PR_{r,h} \right)\Big|_{e_{r,h,g}>0} . \end{aligned} \tag{6}$$

$$\begin{aligned} ER_g = & \sum_{r,c,t,w,n,s,u} \left(-e_{r,c,t,w,n,s,u,g} \cdot L_{r,c,t,w,n,s,u} \right)\Big|_{e_{r,c,t,w,n,s,u,g}<0} \\ & + \sum_{r,f} \left(-e_{r,f,g} \cdot dL_{r,f} \right)\Big|_{e_{r,f,g}<0} \\ & + \sum_{r,k,i} \left(-e_{r,k,i,g} \cdot LIVE_{r,k,i} \right)\Big|_{e_{r,k,i,g}<0} \\ & + \sum_{r,h} \left(-e_{r,h,g} \cdot PR_{r,h} \right)\Big|_{e_{r,h,g}<0.} \end{aligned} \tag{7}$$

While most input markets can be represented and constrained through supply curves, some physically immobile resources must be restricted further. For example, the total amount of land, unregulated irrigation water, and family labor cannot exceed given endowments (index *ED*={Land, Water, Family Labor}) of these resources in each region, as shown in equation (8):

$$\sum_{c,t,w,n,s,u} \left(a^{ED}_{r,c,t,w,n,s,u} \cdot L_{r,c,t,w,n,s,u} \right) + \sum_{k,i} \left(a^{ED}_{r,k,i} \cdot LIVE_{r,k,i} \right) + \sum_{h} \left(a^{ED}_{r,h} \cdot PR_{r,h} \right) \le b^{ED}_{r} . \tag{8}$$

Non-profit related aspects of farmers' decision processes can be addressed by constraining producers' crop choice $L_{r,c,t,w,n,s}$ to fall within a convex combination of historically observed choices $h_{r,c,year}$, as shown in equation (9):

$$\sum_{t,w,n,s,u} L_{r,c,t,w,n,s,u} - h_{r,c,year} \cdot MIX_{r,year} = 0. \tag{9}$$

Using duality theory, we assume that observed historical crop mixes represent rational choices subject to crop rotation considerations, perceived risk, and a variety of natural conditions. Thus, constraining crop choices implicitly integrates many unobservable constraints faced by agricultural producers. Second, crop choice constraints also preserve regionally specific crop rotations. If the sum of the regionally specific mix variables over time ($\sum_{year} MIX_{r,year}$) is not forced to add to unity, only relative crop shares are restricted, therefore 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. A common problem for large linear programming (LP) models is that the number of variables by far exceeds the number of constraints. Because an optimal LP solution will always occur at an extreme point, the number of non-zero 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).

Crop mix constraints should not be enforced for crops, which are expected to expand under certain policies far beyond the upper bound of historical relative shares. Particularly, if

$$E\left[\sum_{t,w,n,s,u} L_{r,c,t,w,n,s,u} \Big/ \sum_{c,t,w,n,s,u} L_{r,c,t,w,n,s,u}\right] > \underset{year}{Max}\left(h_{r,c,year} \Big/ \sum_{c} h_{r,c,year} \right),$$

then these crops should not be part of the crop mix equations. Structurally equivalent constraints as in equation (9) can be applied to livestock production.

Greenhouse Gas Abatement Potential: An Application

In this section, we apply the general framework previously described to assess GHG abatement potential for the agricultural sector in the United States. A block tableau of the resulting model—hereafter referred to as ASMGHG—is shown in Figure 1. To improve the readability of the tableau, we do not show equations and variables associated with the stepwise approximation of non-linear supply and demand functions. We use representative crop production budgets for 63 U.S. regions, 20 crop types, three tillage intensities (conventional tillage, conservative tillage, zero tillage), two irrigation alternatives (irrigation, no irrigation), five land classes (low erodible cropland, medium erodible cropland, highly erodible cropland, other cropland, pasture), four alternative conservation measures (none, contour plowing, strip cropping, terracing), and several nitrogen fertilization alternatives (standard, -15 percent, -30 percent). Livestock production budgets describe technologies for 11 animal types in 63 U.S. regions with alternative diets, grazing, and manure management strategies. Processing budgets identify numerous first- or higher-level processing opportunities carried out by producers.

GHG emissions and emission reductions are accounted for for all major sources, sinks, and offsets from agricultural activities for which data were available or could be generated. For a detailed description of the derivation of the GHG emission coefficients, see Schneider 2000. Generally, ASMGHG considers the following:

- 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 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, 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
- Methane and nitrous oxide emission changes from biomass power plants

	Consumer + Producer Surplus	Primary Good US Demand	Primary Good Shipments Within US	Primary Good US Regional Import	Primary Good US Regional Export	Primary Good Foreign Country Demand	Primary Good Foreign Country Supply	Primary Good Foreign Country Trade	Crop Production	Cropland Conversion to Pasture	Afforestation	Pasture Conversion to Cropland	Livestock Production	Livestock Population	Public AUMS	Private AUMS	Fixed Price Water	Additional Water From Market	Family Labor	Hired Labor	Crop Mix	Livestock Mix	Processed Good US Demand	Processed Good US Import	Processed Good US Export	National Processing	Regional Processing	GHG Emission Source	GHG Emission Sink	(In)equality Sign	Right Hand Side Value
Objective Function	+	-	+	+	-	-	+	+	+	+	+	+	+		+		+	+	+	+			-	+	-	+	+	(+)	(-)	E	0
Primary Good Regional Balance		+	m	-	+				-				+														+			L	0
Processed Good National Balance													+										+	-	+	m	m			L	0
Processed Feed Regional Balance													+														m			L	0
Foreign Country Export Balance				+			-	+																						L	0
Foreign Country Import Balance					-	+		-																						L	0
Land Constraint									+	m	+	m	+																	L	+
Pasture Constraint												+																		L	+
AUMS Balance													+		-	-														L	0
Public AUMS Constraint															+															L	+
Water Market Balance									+								-	-												L	0
Fixed Price Water Constraint																	+													L	+
Labor Balance									+				+						-	-										L	0
Family Labor Constraint																			+											L	+
Crop Mix Constraint									+												-									E	0
Livestock Production Mix Constraint													+									-								E	0
Livestock Population Account													-	+																E	0
GHG Sink Account									-	-	-															-	-		+	E	0
GHG Emission Account									-			-		-												-	-	+		E	0
Variable type	u	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		

+ positive, - negative, m mixed, u unrestricted coefficients or variables

FIGURE 1. ASMGHG block tableau

To trace out emission abatement cost curves, we subjected ASMGHG to a wide range of hypothetical carbon prices. The simulated estimates represent least-cost results because transaction costs of policy implementation, monitoring, and enforcement are not taken into account but are left for further analysis.

Mitigation Strategy Adoption

The contribution of major agricultural GHG emission mitigation strategies is summarized in Figure 2 through abatement curves (Norton 1984) 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 of total abatement is provided by three basic carbon mitigation strategies: soil carbon sequestration, afforestation, and production of perennial energy crops for

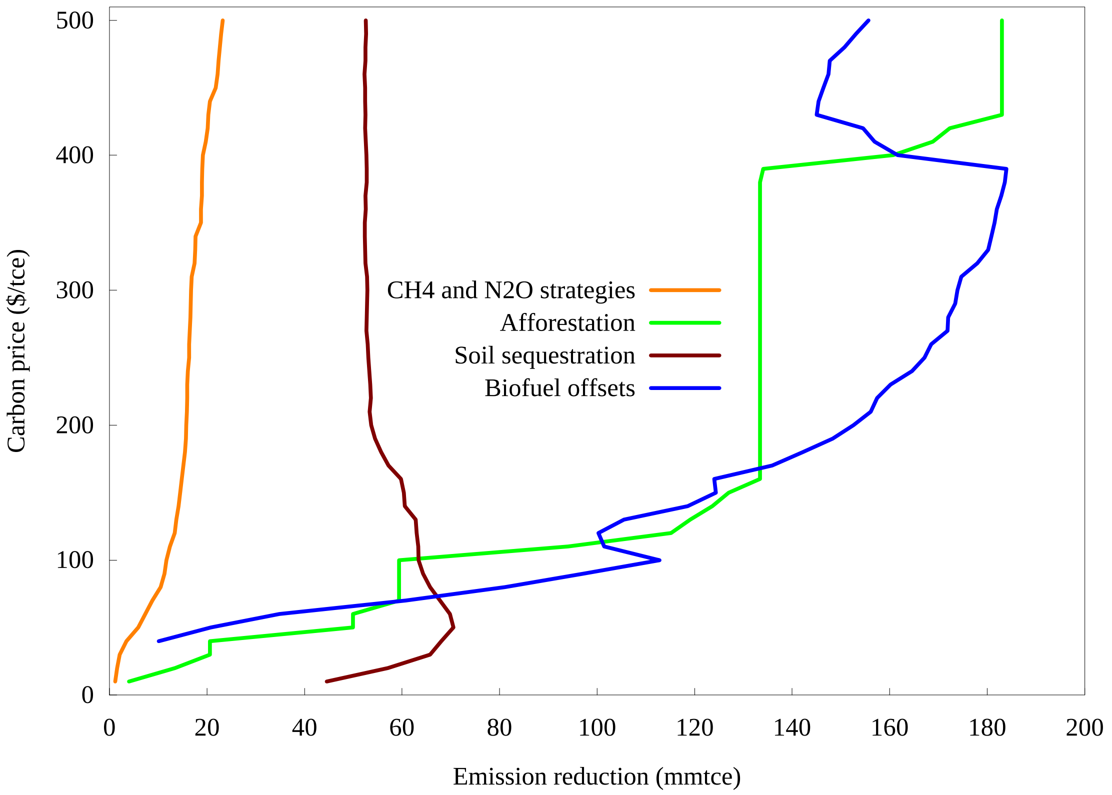


FIGURE 2. Multi-strategy, economic potential of major agricultural greenhouse gas emission mitigation strategies in the United States at $0 to $500 per ton carbon equivalent prices

TABLE 2. Environmental abatement effects at selected carbon price scenarios

Category	Carbon Equivalent Price in $/Metric Ton Carbon						
	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

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 ton of carbon equivalent (tce) but decreases for higher prices. This occurs for two major reasons. First, 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. Second, 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 metric tons of carbon per acre per year, while growing forests or energy crop plantations mitigates more than 1 metric ton of carbon per acre per 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 emissions abatement strategies 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 mmtce (million metric tons of carbon equivalent) can be saved through the agricultural and forest sectors. This amount equals about 3 percent of the combined 1990 U.S. emissions of carbon dioxide, methane, and nitrous oxide (US EPA 2001). 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 to above 400 mmtce (Table 2).

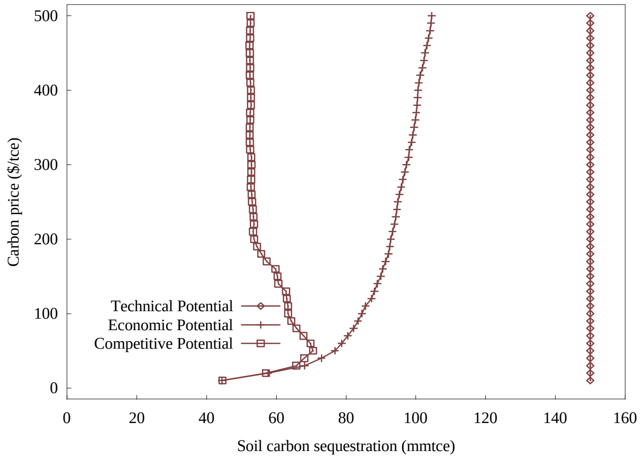
Measures of Potentials

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[2] is 125 mmtce annually (Panel A). However, this potential is not economically feasible even under sole reliance on this strategy and with 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 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 levels.

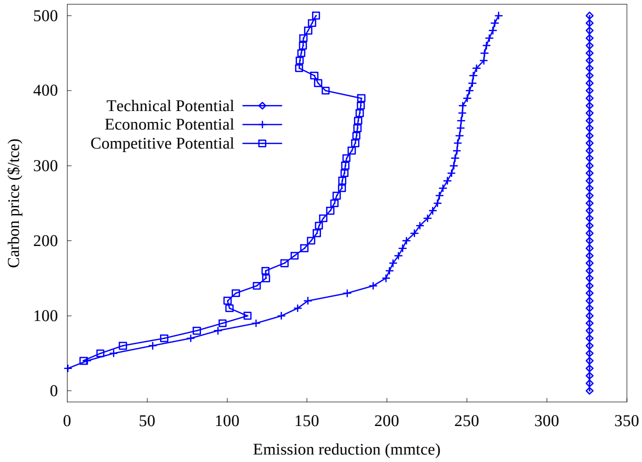
Similar observations can be made for other agricultural GHG mitigation strategies. At a carbon price of $200 per tce, the single strategy economic potential of biofuel carbon offsets (Panel B) is about two-thirds of its technical potential while the competitive economic potential amounts to less than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

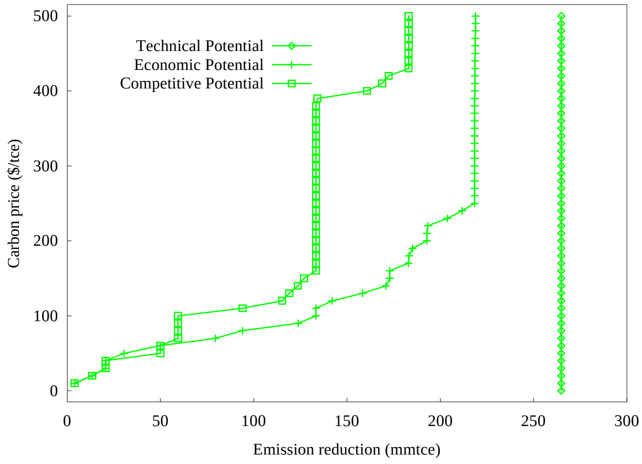
While results presented so far were concentrated at the national level, ASMGHG output can also be used to analyze regional effects (Figure 4). Soil carbon sequestration is dominant in the Corn Belt, the Northern Plains States, and, to some extent, in the Mountain States. For low carbon prices, the Lakes States also indicate soil carbon as the preferred option. However, for higher carbon prices, the Lakes 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 Northeast, Delta, and Southeast regions take part. The Corn Belt region becomes profitable for perennial energy crops only for carbon prices above $220 per tce. Possible reasons for such behavior may include higher opportunity costs in the agriculturally productive Corn Belt region. Afforestation takes place predominantly in the Delta States but also in the



PANEL A
Mitigation potentials of soil carbon sequestration on U.S. cropland including conversion of cropland into pastureland

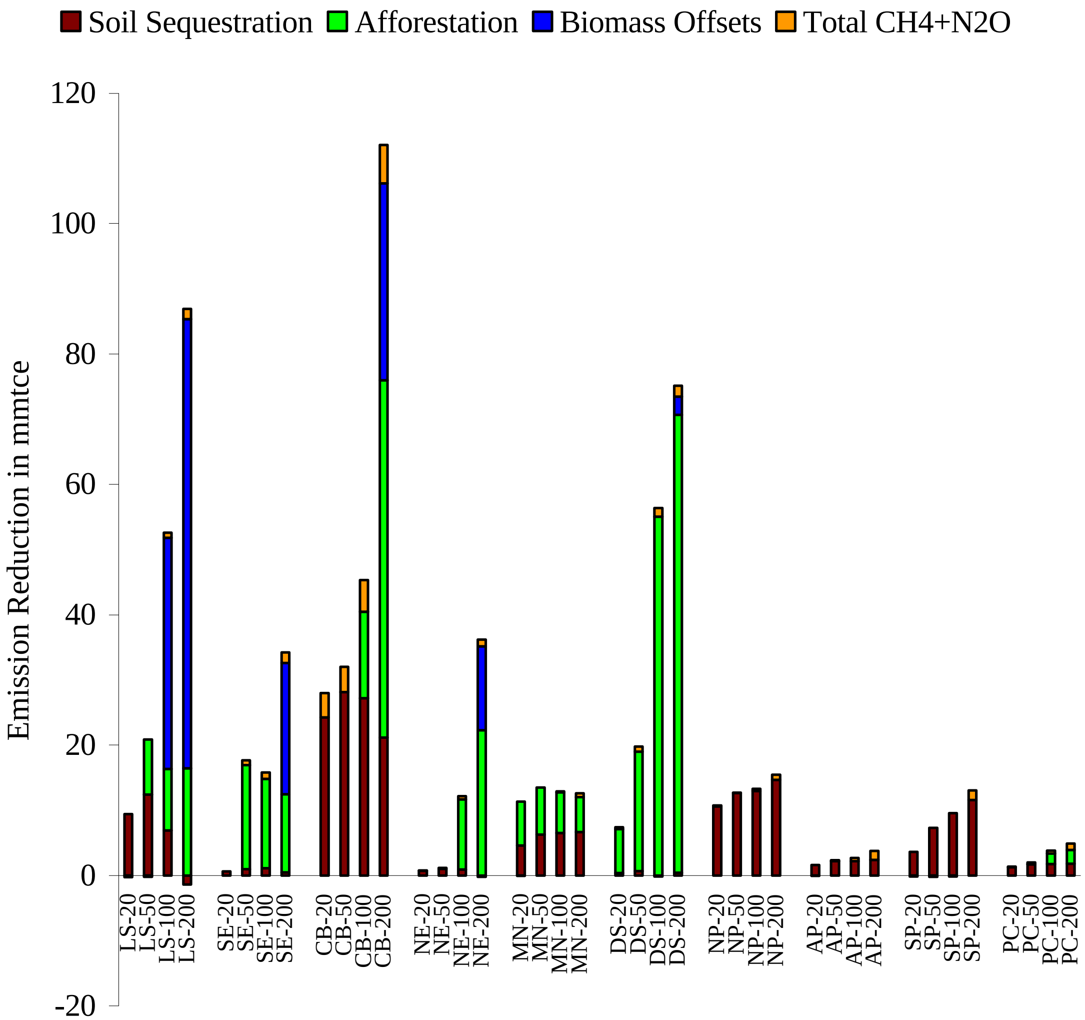


PANEL B
Mitigation potentials of biofuels used as feedstock in electrical power plants thereby offsetting emissions from fossil fuel based power plants



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 GHG mitigation strategies



LS=Lake States, SE=Southeast States, CB=Corn Belt, NE=Northeast States, MN=Mountain States, DS=Delta States, NP=Northern Plains States, AP=Appalachian States, SP=Southern Plains States, PC=Pacific States

Figure 4. Differences in regional strategy adoption of major agricultural mitigation strategies for selected carbon prices ($20, $50, $100, and $200 per ton of carbon equivalent)

Northeast 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 for every $100 per tce tax increase. Moreover, consumers' welfare decreases about $20 billion per $100 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. Because foreign welfare is aggregated over both foreign consumers and producers, the two effects offset each other

TABLE 3. Production, market and welfare effects in U.S. agriculture at selected carbon price scenarios

		Carbon Equivalent Price in $/Metric Ton Carbon						
Category	**Unit**	**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

somewhat. Note that this welfare accounting does not include social costs or benefits related to diminished or enhanced levels of the GHG emission externality or other externalities such as erosion and fertilizer nutrient pollution.

Agricultural Production Sector Effects

Mitigation policies impact production technologies in the agricultural sector. New economic incentives 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). In particular, higher costs of production (emission taxes, opportunity costs, land rental costs) for conventional management strategies and higher incentives for alternatives cause farmers to shift more land to mitigative products. The impact of carbon prices on production of traditional agricultural products is shown in Table 3. Declining overall crop production is mainly due to less acreage allocated to traditional food crops (Table 3). For prices above $100 per tce, substantial amounts of cropland are diverted to trees and biofuel crops. Less U.S. domestic food production, coupled with higher prices in U.S. agricultural markets, induces foreign countries to increase their net exports into the United States. 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 United States is a major producer.

Other Externalities

GHG emission parameters were simulated with the Environmental Policy Integrated Climate (EPIC, Williams 1989) system. The complex nature of this biophysical simulation model makes it possible to simultaneously predict other environmental parameters along with those for greenhouse gases. Here, we analyzed the effects of agricultural GHG emissions mitigation programs on soil and water quality related externalities (Tables 2 and 3). The average per acre values of these externalities decrease notably as carbon prices increase from $0 and $100 dollars per tce with little or no additional reductions at higher prices. This confirms “win-win” arguments, where greenhouse gas emission mitigation also leads to a reduction in both soil erosion and water pollution.

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 GHG 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 the levels sought in the Kyoto Protocol. As carbon equivalent prices increase, the abatement potential rises to about 50 percent of the original U.S. Kyoto Protocol target. At relatively high carbon prices, most of the emission abatement comes from afforestation/forest management and energy crop plantations diverting substantial amounts of cropland 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. agricultural sector. When comparing estimates of abatement potential, we find substantial differences between different measures. Technical potential estimates such as those in Lal et al. (1998) far overstate the economic potential of strategies such as agricultural soil actions. Economic assessment of single strategies deviates from estimates of competitive economic potential especially if GHG-saving incentives are high.

Some agriculturists (e.g., Francl, Nadler, and Bast 1998) oppose environmental policies like the Kyoto Protocol, 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 receive higher revenues 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 and stabilize prices at “fair” levels through farm programs. Additional money has been spent on environmental programs such as the Conservation Reserve Program. Perhaps a more cost efficient program could be crafted that combined GHG offset intiatives and farm income support. This could give incentives to farmers for adoption of environmentally friendly management practices but also would be perceived as contributing to the economywide 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. Second, most of the GHG emission data from the traditional agricultural sector are based on biophysical simulation models. Thus, the accuracy of our estimates depends on the quality of these models and the origin of associated data (Antle and Capalbo 2001). Third, 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 were not monetarized in this analysis. Fourth, we operate at a 63-region level while others (Antle et al. 2001, 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 the reliability of the overall results.

Endnotes

1. In displaying the objective function, several modifications have been made to ease readability and limit the number of equations: (*a*) the integration terms are not shown explicitly (both nonlinear and stepwise linear specification can be used, (*b*) the input supply balance equations have been substituted into the objective function, (*c*) farm program terms are omitted, and (*d*) artificial variables for detecting infeasibilities are omitted. A complete description of the objective function is available from the authors.

2. The technical potential was computed by replacing ASMGHG's economic surplus maximizing objective function with a function that maximizes soil carbon on crop and pasture lands.

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