Leakage and Comparative Advantage Implications of Agricultural Participation in Greenhouse Gas Emission Mitigation

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Abstract

The world is moving toward efforts to reduce net greenhouse gas emissions. Reduction efforts may involve the agricultural sector through options such as planting of trees, altering crop and livestock management, and increasing production of biofuels. However, such options can be competitive with domestic food production. In a free trade arena, reduced domestic food production could stimulate increased production and exports in other countries, which are not pursuing net emission reductions. As a consequence, emission reduction efforts in implementing countries may be offset by production increases stimulated in other countries.

We examine the competitive effects of agriculturally related emission reduction actions on agricultural production and international trade. In doing this we employ the assumption that U.S. emission reduction caused cost increases will also occur in other reducing countries. We consider emission reduction: 1) unilaterally by the U.S., 2) by all Kyoto Protocol Annex B countries, and 3) globally. The results, which are only suggestive of the types of effects that would be observed due to the simplifying cost assumptions, indicate compliance causes supply cutbacks in regulated countries and increases in non-regulated countries. The study results show that producers in regulating countries are likely to benefit and consumers lose due to commodity price increases.

Key words: leakage, international trade, agricultural and forest sector, greenhouse gas, mitigation implementation.

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Society has increasingly become concerned with the potential climate implications of greenhouse gas (GHG) emissions, and GHG atmospheric concentrations. The Intergovernmental Panel on Climate Change, projects that GHG concentrations will cause global average temperature to increase by 1.4 to 5.8°C between 1990 and 2100 (IPPC, 2001). In turn, such warming is predicted to alter agricultural production, raise sea level, change habitat boundaries for many plants and animals, and induce a number of other changes (IPCC, 2001b, USGCRP, National Assessment Team, 2000). Numerous strategies have been proposed to mitigate GHG emissions, a number of which involve agriculture and forestry (McCarl and Schneider, 2000, 2001). In particular, agriculture and forestry may be important players due to emission, sequestration and offset possibilities (IPCC, 2001a)

GHG concentrations and their climate effects are global, thus all countries will share the benefits from GHG emission (GHGE) mitigation, but in the absence of widespread trading and emission caps only countries adopting mitigation measures will directly bear the costs. This implies two things.

- Producers in emitting industries, and users of emission intensive products within countries mitigating GHG emissions are likely to experience increased production costs since mitigation actions are likely to induce increases in fuel, fertilizer and other petrochemical prices. The possibility also exists that producers will incur costs for GHG emissions related to future land use changes as well as fertilizer related nitrous oxide emissions, livestock related methane/nitrous oxide emissions or rice production related methane emissions.

- Competing producers in non-adopting countries may gain advantage and trade market share stimulating both
  - shifts in comparative advantage and
  - expanded GHG emissions reflecting emission leakage into other countries.

This paper reports on a first order examination of the producers' surplus, comparative advantage and leakage impacts of differential GHGE mitigation efforts. Specifically, we examine international production and U.S. agricultural sector implications under: 1) unilateral U.S. GHGE mitigation implementation, 2) developed country implementation (in those countries falling within the Annex B[a] list under the Kyoto Protocol and 3) global implementation.

1. Background

The welfare and leakage effects of agricultural GHGE mitigation have been the subject of a number of studies. Let us review these categorized by the major issues in the bullets above.

1.1 Production cost and producers' surplus

The implications of pursuing agriculturally based GHG mitigation for domestic production cost and farm income has been a concern of producer groups. For example, in 1998 the U.S. Farm Bureau advanced a position that it will not support ratification of the Kyoto

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[a] The Annex B countries are those listed in Annex B of Kyoto Protocol.

Protocol (KP) unless principal international market competitor countries were also covered by the KP terms (Francl, 1997, Francl, Nadler and Bast, 1998). Francl and associates asserted that substantial farm income (up to 84%) would be lost due to increases in fuel prices. However, later analyses that considered factor substitution, product price adjustments and consumer demand reactions (McCarl et al 1997, USDA, 1999, Antle et al., 1999, Konyar and Howitt, 2000, Peters et al., 2001) found producers' surplus reductions but of much smaller magnitudes (generally below 10%). However, none of these studies considered the effects of possible payments to farmers for carbon sequestration or taxes for methane and nitrous oxide emissions from livestock, fertilization, and other sources.

More recent work by McCarl and Schneider, 1999, 2001 examined both the effects of higher input prices and possible payments for agricultural GHGE offsets finding that the aggregate producer group can benefit. Such benefits arise largely due to the combination of direct carbon payments and the market price increasing features associated with a substitution of carbon production for some existing agricultural production. Similarly, Antle et al. 2002 argue that producer incomes will be enhanced by carbon payments but did not consider possible market price changes.

Across all of the studies mentioned above, the assumption of constant agricultural conditions on behalf of international trading partners was made[b]. However, GHGE mitigation will be wider in scope than a unilateral U.S. effort and there may be actions on behalf of other participants in the world agricultural commodity markets. Thus, when there are mitigative

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[b] This is mentioned on page 41-42 of the USDA(1999) report but is not quantitatively explored.

actions either unilaterally or globally, this may have important implications for the implementing and non-implementing countries and for net GHGE reductions after leakage. This will be investigated in this paper.

1.2 Shifts in Comparative Advantage

A rich literature has emerged on shifts in comparative advantage as caused by environmental regulation. The fundamental argument is that regulations in one country may shift production to other countries (Pethig, 1976). The overall literature on this topic was reviewed by Jaffe et al who concluded "… regulation clearly imposes large direct and indirect costs on society…" (pg 159) but they also indicated "there is relatively little evidence … that environmental regulations have had a large adverse effect on competitiveness" (page 157). This suggests that adjustments in production patterns may help mitigate the effects of regulations as found in the carbon tax related studies reviewed just above.

1.3 Leakage

Leakage occurs in a GHGE context when actions to offset emissions in one country stimulate additional production and consequent emissions in other countries. Several papers have examined the potential empirical magnitude of leakage when GHGE abatement actions (e.g., emissions limits, carbon taxes, or tradable permits) are applicable to only a subset of the world's countries mainly in an energy context (e.g., Oliveira-Martins et al., 1992; Smith, 1998; Bernstein et al., 1999; Barker, 1999; Babiker, 2001). These leakage estimates range from negligible (Barker, 1999) to substantial (Felder and Rutherford, 1993), but typically are in the range of 10-20 percent of targeted country emission reductions.

Agricultural and forestry related leakage studies have also been done. Wu (2000) examined leakage of about 20% relative to the US Conservation Reserve Program (CRP), which pays farmers to retire land from crop production, but international leakage was not considered. Leakage has also been found to occur with participation in U.S. crop commodity programs (Brooks et al., 1992; Hoag et al., 1993). Alig et al. (1997) examined leakage in a forestry context and found cases where the leakage rate for carbon sequestration projects exceeds 100%. Sedjo and Sohngen (2000) examine international leakage resulting from the establishment of large-scale forest carbon plantations using a model of the global timber market and found leakage rates up to 40%.

None of these investigations examined the international agricultural effects which we will attempt herein.

2. Scope of GHGE Reduction Implementation

In this paper we will examine the leakage and comparative advantage implications of three different international implementation and trading cases.

1. Case I – Unilateral implementation where a country or a group of countries decides to unilaterally implement GHGE mitigation. This might happen today if the Kyoto Protocol is implemented internationally without U.S. participation or if the U.S. implements the President's Clear Skies Initiative and the rest of the world fails to implement the KP. In these cases, one would expect the implementing countries to experience higher costs of domestic production yielding lower domestic production and exports, and higher prices. Simultaneously, non-implementing countries would

be expected to increase domestic production and world market share thereby offsetting some of the GHG emission gains in implementing countries.

2. Case II – Partial global implementation where a relatively large group of countries implement GHGE mitigation policies. This might have happened if the KP was implemented as originally envisioned but the Clean Development Mechanism (CDM) turned out to be an ineffective way of drawing in other countries. In such a case, the Annex B countries would be collectively expected to lose comparative advantage relative to non-Annex B countries. The net impacts on individual Annex B countries and magnitude of emission leakage, however, might be different from Case I.
3. Case III – Global implementation where all countries implement a mitigation policy. This might have happened if the world would have implemented the KP and all non-Annex B countries were involved through mechanisms such as the CDM. In this setting, all countries would experience higher costs of production.

3. Modeling

The cases mentioned above will be evaluated herein. To do that we need a model that portrays global agricultural trade and simultaneously allows examination of detailed GHGE mitigation possibilities within implementing countries. A model with such global scope and regional detail was not available or practical to construct for this investigation. Thus, we used a model that satisfies some of the needed characteristics and combined it with an assumption laden analytical approach.

Specifically we used the greenhouse gas version of the U.S. Agricultural Sector Model (ASMGHG) developed by Schneider (2000) and McCarl and Schneider (2001). This model arose from the base ASM as described in McCarl et al. (2001) and Chang et al. (1992) with the addition of details on soil type dependent production (developed in conjunction with USDA NRCS) and a global trade representation via spatial equilibrium models for eight commodities as developed by Chen and McCarl (2000) and Chen (1999). The combined ASMGHG model considers agricultural production, consumption, and trade in developed and developing countries simultaneously. Overall characteristics of the model are discussed below and a mathematical explanation occurs in the appendix.

3.1 General Structure of the U.S. Agricultural Sector Model

ASMGHG is a price-endogenous mathematical program following the market equilibrium and welfare optimization concept developed in Samuelson (1952), and Takayama and Judge (1971). ASMGHG assumes individual producers and consumers cannot influence commodity or input market prices. Production and use of farming inputs are portrayed in 63 regions in the U.S. and for 28 foreign regions. Data on currently observed trade quantities, prices, transportation costs, and supply and demand elasticities were obtained from Fellin and Fuller (1997, 1998), USDA statistical sources (1994a, b, c; annual), and the USDA, SWOPSIM model (Roningen, 1991).

3.2 Modeling Greenhouse Gas Emissions and Mitigation Strategies

Schneider (2000) added a GHGE mitigation component to the United States part of ASM. This component introduces production alternatives and GHG net emission accounting to reflect the GHGE consequences of changes in crop mix, tillage, irrigation, fertilization, afforestation, biofuel production and livestock management. Livestock management options involve: 1) herd size, 2) liquid manure system alterations on dairy and hog farms, 3) enteric fermentation management involving use of growth hormones for dairy cows, and 4) stocker/feedlot production system adoption. A detailed technical description of all considered mitigation strategies is contained in Schneider (2000). In terms of GHGE accounting ASMGHG considers:

- Direct carbon emissions from fossil fuels (diesel, gasoline, natural gas, heating oil, and LP gas) used in tillage, harvesting, or irrigation water pumping.
- Carbon emissions or sequestration arising from altered soil organic matter stimulated by adopted tillage system or land use change to and from croplands, forestlands, and grasslands.
- Indirect carbon emissions from manufacture of fossil fuel intensive inputs (fertilizers and pesticides).
- Carbon offsets from biofuel production (ethanol, power plant feedstock via production of switchgrass, poplar, and willow) as well as associated methane and nitrous oxide emission changes from biomass combustion.
- Nitrous oxide emissions from fertilizer usage.
- Methane emissions from enteric fermentation and rice cultivation.
- Methane savings from manure management changes as well as both methane and nitrous oxide emission alterations from herd size alterations.

Individual emissions were converted to carbon equivalent measures using global warming potential from the IPCC (1996) report (21 for methane and 310 for nitrous oxide).

ASMGHG only examines detailed emission management possibilities in the U.S. but not in the rest of the world. Thus, global adjustment to GHGE mitigation incentives cannot be simulated accurately outside the U.S. but instead can only be approximated using simplifying assumptions as will be done in the remainder of the analysis.

4. Experimental Results and Implications

Three alternative mitigation implementation scenarios are simulated. The first scenario assumes unilateral mitigation efforts in U.S. agriculture only. The second corresponds to a KP like situation with simultaneous implementation in all Annex B countries. The third involves worldwide implementation. Since we do not model the whole economy we simulate agricultural actions in terms of an exogenous carbon equivalent (CE) price that would obviously be set in a general equilibrium setting generating the supply curve of agricultural offsets. All scenarios are analyzed over a range of exogenously set CE prices ranging from 0 to 500 dollars per ton.

4.1 Unilateral Implementation in Just the United States

The U.S. agricultural sector effects of a unilateral U.S. emission policy implementation over a range of CE prices are listed in Table 1 and 2, which show percentage changes from a zero CE price. Total GHG emissions decline steadily as the price rises. At $100 per ton, net emissions from U.S. agriculture are about zero with the realized levels of carbon sequestration from carbon sinks offsetting all agricultural emissions.

The results in Tables 1 and 2 confirm that emission reductions are obtained at the expense of conventional crop production. Increasing CE prices cause decreases in U.S. production and exports along with increases in prices for conventional agricultural commodities. In addition, since the U.S. is a major trading country, production in other countries is influenced and comparative advantage shifts partially to those countries. Across the range of prices substantial leakage can be observed. For example, at a $100 price total U.S. production falls by 2.5% with traded production falling by 6.5% but global production only falls by 0.40% and production in non-U.S. Annex B and non-Annex B countries expands by 2.66% and 12.22% respectively.

Welfare impacts for unilateral implementation of GHGE mitigation efforts in the U.S. are listed in Table 2. U.S. consumers' surplus decreases monotonically with CE-price increases. Producers' surplus on the other hand is only reduced for CE-prices below $55 per ton but increases above that level. The change in producers' surplus arises from both the traditional commodities markets and the CE-price induced GHG payments/charges. These payments/charges include: 1) charges at the CE-price level for emissions from land use change, fuel use, livestock, rice, fertilization, and other emissions; 2) higher costs for fertilizer and other inputs due to the embodied emissions in their manufacture; 3) sequestration payments for increased soil, grassland, and forest carbon storage; and 4) payments for the production of biofuels. In the U.S. only implementation case, producer gains from higher commodity prices more than offset losses from lower levels of domestic production. GHGE accounting results in a net cost if emissions charges outweigh sequestration and biofuel payments. For prices below $100 per ton, net emissions are positive resulting in additional sectoral cost. Above this price, the amount of carbon sequestration and biofuel related carbon offsets exceed emissions and thus provide additional sectoral revenue. The results also differ from the pure carbon tax studies showing larger total welfare impacts than the most comparable USDA (1999) and McCarl et al (1997) studies as the emissions effects on non CO2 gasses cause larger cutbacks and bigger welfare effects. They also show consideration of international adjustment is also relevant.

Trade surplus measures the welfare of consumers and producers in non-U.S. countries attributable to trade of agricultural commodities. If the U.S. alone implements agricultural provisions for mitigation, the impact on welfare in other countries is negative with the magnitude getting bigger as the CE-price increases.

The results are also suggestive of what would happen under a rest of the world implementation of KP without U.S. participation. Namely one would expect the mirror image of the findings here with market share flowing to the U.S. and a leakage effect. On the other hand recent analyses by integrated assessment groups (i.e. Babicker et al., 2002) show that under such circumstances it is likely that carbon prices will be very low in the $3 to $10 range when KP implementation is combined with the U.S. 18% greenhouse gas intensity reduction climate change strategy.

4.2 Representing Mitigation Induced Shifts in ROW Countries

Mitigation efforts in regions outside of the U.S. could not be modeled explicitly because we did not have detailed data of production technologies in foreign regions, rather having excess supply curves. Thus, a simplifying assumption was made to depict the supply shifts in foreign countries. Namely, the average price increase and production decrease observed for each traded commodity in U.S. agriculture was assumed to proportionally apply to agricultural production in other countries. Thus, if for a given CE price average U.S. prices for rice went up by x percent and production down by y percent, the same shift was applied to rice supply in foreign regions in all implementing countries. We used this crude approximation because alternative reasonable assumptions were not available[c]. Empirical results derived from supply shifts in non-U.S. countries should therefore be considered illustrative but not definitive. In presenting our empirical results we will focus on a comparison between the various implementation scenarios examined.

4.3 Full Annex B Implementation

The results for full Annex B country implementation are shown in Table 1. U.S. agricultural production and exports decline but not as much as in the unilateral case. This diminished response reflects the fact that only the non-Annex B countries now have comparative advantage over U.S. agriculture. Leakage occurs in non-Annex B countries whose production expands by 20 percent at a $100 CE price. Prices of traded agricultural commodities increase slightly more under full Annex B implementation. The welfare results show overall U.S. welfare is reduced less but consumers lose even more than under unilateral implementation. On the other hand, U.S. producers always gain.

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[c] It is also not clear if the cost increases elsewhere would be bigger or smaller as expansions elsewhere may involve new land development which could be subject to substantial carbon taxes.

Annex B countries' net exports are highest under U.S. unilateral implementation but lowest if all Annex B countries are subjected to agricultural mitigation policies. Equivalently, non-Annex B countries' net exports are highest under full Annex B country implementation. All of these observed changes become larger the more the CE-price increases. Note that the Annex B accounts displayed in all figures do not involve the U.S. to avoid double counting.

Total emission reductions from U.S. agriculture are almost identical for all scenarios up to CE-prices of $55 per ton (Figure 1). Above $85 additional emission reductions become smaller under full Annex B country implementation. For example, at a price of $100 per ton, emission reductions are about 11 percent lower than for U.S. alone implementation. U.S. emissions rise because higher commodity prices lead to more intensive production and less adoption of sequestration and emission control activities. This would be offset by emission reductions in the Annex B agriculture but we cannot quantitatively represent that in our model as we do not have model components depicting emissions in those countries and extrapolation of U.S. rates would involve even more heroic assumptions than we are now making.

4.4 Global GHGE Mitigation Implementation

Provisions in the KP permit emissions credits where GHGE emission reductions from projects in non-Annex B countries may be counted as part of the emission reduction obligation for project sponsors in Annex B countries. If such provisions were implemented, low cost activities in agriculture could be exploited globally. This situation is represented by the last scenario, where production globally is shifted using the U.S. average price and cost shift assumptions as explained above. Tables 1 and 2 list the main impacts. We find increased U.S.

market shares at the expense of foreign countries, particularly the non-Annex B ones. Leakage is contained with all regions decreasing aggregate production. Prices rise more than in the U.S. unilateral or KP cases. Note this is a property of the assumptions as we have successively shifted more and more of the total model supply curve.

U.S. producers' surplus gains are highest in such a situation and consumers' losses the smallest. Global mitigation efforts affect the level of emissions. The more countries implement GHGE mitigation policies, the smaller are net emission reductions from U.S. agriculture. For example, at a CE-price of $100 per ton, emissions offsets are about 21 percent lower than for U.S. unilateral implementation.

5. Conclusions

The prospect of greenhouse gas emission mitigation policies has stimulated a wide search for cost-efficient emission reduction methods. Agriculture including forestry has been proposed as a relatively cheap source of net emission reductions. However, concerns have been expressed about agricultural abatement policies being hosted in only a subset of all countries. The comparative advantage gained in the agricultural sectors of non-host countries could distort trade patterns, harm domestic agricultural producers in host countries, and lead to increased emissions in non-host countries. Our investigation in the context of the U.S. agricultural sector, confirms tradeoffs between agricultural emission reductions and supply of traditional food and fiber commodities. In particular, the two most important carbon abating strategies, afforestation and production of biofuels, cause the greatest decline in traditional agricultural production. If the positive relationship between agricultural production and agricultural emissions also holds in foreign countries, then our results imply increased greenhouse gas emissions in non-host countries. The consequences of such emission leakage would not necessarily be incurred by non-host countries but by those countries, which are most vulnerable to climate change.

The findings of this paper have several implications for policy makers. First, if national agricultural greenhouse gas mitigation policies are not synchronized with foreign greenhouse gas emission policies, substantial leakage may occur. For example, if an international treaty like the Kyoto Protocol were implemented, emission reductions in Annex B countries would most likely be accompanied by emission increases in non-Annex B (developing) countries.

Second, U.S. farmers' would benefit from a larger number of countries hosting greenhouse gas emission mitigation policies. The more countries abate greenhouse gas emissions through the agricultural sector, the higher agricultural commodity prices would be. Income support has been a longtime objective of American farm bills and carbon payments/taxes contribute to farm income support but at the expense of consumers. The unanswered general equilibrium question is whether the consumer is better off if GHGE mitigation is carried out in agriculture as opposed to elsewhere in the economy but this is beyond the scope of this study. If the U.S. and other potential host countries would financially support Clean Development Mechanism initiatives in non-host countries, i.e. non-Annex B countries, a portion of that expenditure could pay back because higher agricultural prices eliminate the need for expensive farm bills.

Third, credits for agricultural emission abatement could be discounted to reflect likely emission leakage through agricultural sectors in non-host countries. This adjustment would imply higher discount factors for agricultural mitigation strategies, which divert farmland. Such strategies are afforestation and biofuel production. However, strategies, which are complementary to traditional food and fiber production, such as reduced tillage, would remain eligible for full credit. A differential treatment of agricultural mitigation strategies would then increase the relative adoption of complementary strategies and thus reduce leakage.

Fourth, consumers of agricultural products incur higher expenses due to price increases. The more countries participate in mitigation efforts, the higher are losses to both domestic and foreign consumers. Consequently, more people may become dependant on governmental aid to ensure sufficient food consumption.

There are also implications for modelers. Our results show deviation from the results of previous studies, which only looked at fossil fuel based carbon emission taxes. Consideration of emissions from other sources such as methane, nitrous oxide, and land related carbon releases are also important and should be considered in future studies. The results also show international adjustments and potential leakage are important modeling concerns.

The quantitative effects presented in this study reflect several simplifying assumptions and uncertain data, and should therefore be considered preliminary. While efforts will continue to improve the underlying data, the basic nature of our findings is unlikely to change. Possible extensions to our work could also involve a general equilibrium analysis.

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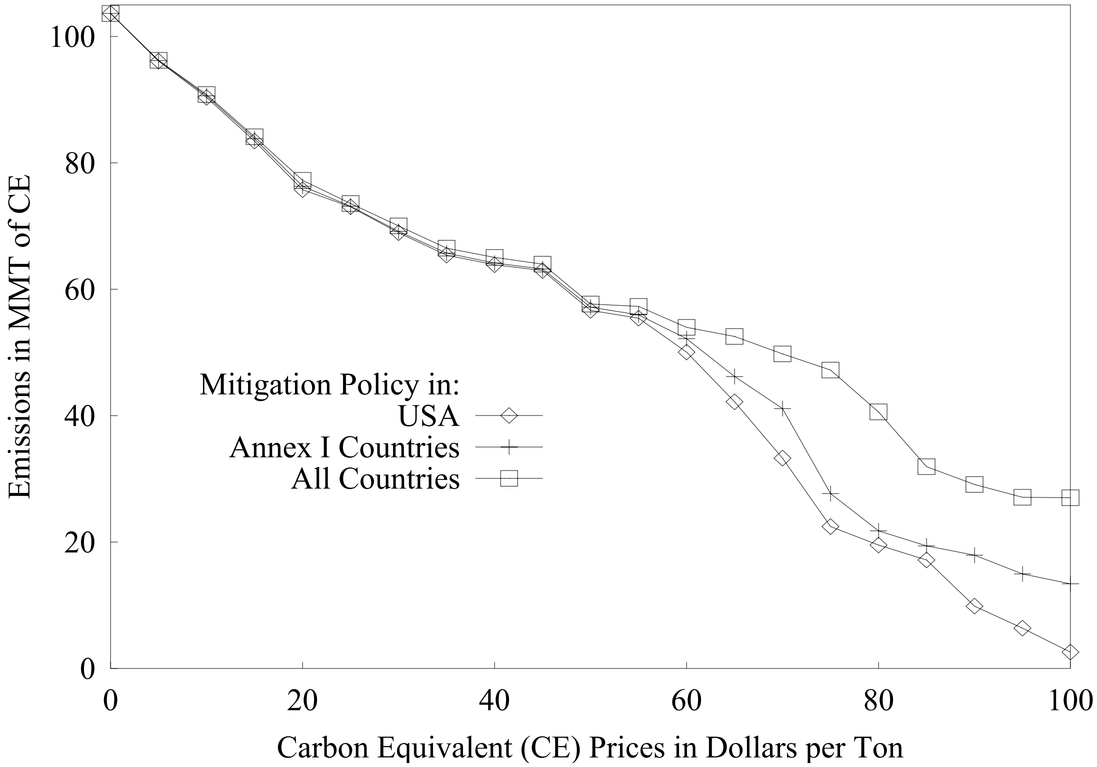

Figure 1 Carbon Equivalent Prices and Net Carbon Emissions from U.S. Agriculture

Table 1 Impacts of Carbon Equivalent Prices on Fisher Ideal Price and Quantity Indices of Production, and Trade[d]

	Mitigation Policy in								
	US Only			US and Annex B Countries			All Countries		
	$10	$20	$100	$10	$20	$100	$10	$20	$100
U.S.									
Production of Traded Crops	99.60	99.09	93.47	99.87	99.64	97.09	100.52	100.59	105.11
All Production	99.33	99.04	97.53	99.93	99.16	97.43	99.47	99.32	98.59
Overall Agricultural Product Prices	100.57	101.42	110.60	100.76	101.82	113.44	101.22	102.28	121.68
Exports	98.84	97.44	81.77	99.93	99.50	97.65	102.19	103.28	126.92
Production of traded commodities in rest of world									
Global production	99.96	99.93	99.60	99.95	99.91	99.44	99.98	99.94	99.71
Annex B Countries (excluding U.S.)	100.36	100.69	102.66	99.51	98.81	92.31	99.61	99.94	99.25
Non-Annex B Countries	100.32	100.93	112.22	100.49	102.15	120.13	96.89	93.85	57.60

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[d] Note: Trading crops production includes the production for corn, soybeans, sorghum, rice, and four kind of wheat defined previous; all production includes production for all primary products (crops and livestock) defined in the model.

Table 2 Impacts of Carbon Equivalent Prices on Agricultural Sector Welfare (Million Dollars) and U.S. Emissions (MMT)[e]

	Mitigation Policy in								
	USA Only			Annex B Countries			All Countries		
	$10	$20	$100	$10	$20	$100	$10	$20	$100
U.S. Consumers' Surplus	-540 (-0.05)	-1,240 (-0.10)	-9,159 (-0.77)	-607 (-0.05)	-1,536 (-0.13)	-11,355 (-0.96)	-749 (-0.06)	-1,976 (-0.17)	-17,607 (-1.49)
Net U.S. Producers' Surplus with GHG tax/pay	-207.32 (-0.46)	-161.70 (-0.36)	7,430 (16.35)	-71.61 (-0.16)	449 (0.99)	13,037 (28.69)	264.39 (0.58)	1,479 (3.26)	27,336 (60.15)
Ag Producers' Surplus without GHG Pay	696 (1.53)	1,353 (2.98)	7,689 (16.92)	835 (1.84)	1,976 (4.35)	14,380 (31.64)	1172 (2.58)	3,024 (6.65)	30,037 (66.10)
Total Welfare without GHG Pay	156 (0.01)	113 (0.01)	-1,471 (-0.12)	228 (0.02)	440 (0.04)	3,025 (0.25)	424 (0.03)	1,048 (0.09)	12,430 (1.01)
Total GHG payments to agriculture	-903	-1,514	-259	-907	-1,526	-1,342	-908	-1,545	-2,701
Net Welfare	-748 (-0.06)	-1,402 (-0.11)	-1,730 (-0.14)	-678 (-0.06)	-1,087 (-0.09)	1,683 (0.14)	-484 (-0.04)	-497 (-0.04)	9,728 (0.79)
Foreign Country Surplus	-210 (-0.09)	-395 (-0.16)	-3,516 (-1.45)	1012 (0.42)	2,140 (0.89)	17,902 (7.40)	2557 (1.06)	5,360 (2.22)	42,156 (17.44)
Global Agric. Welfare	-54 (-0.003)	-282 (-0.02)	-4,986 (-0.34)	1240 (0.08)	2,579 (0.18)	20,928 (1.42)	2981 (0.2)	6,408 (0.44)	54,586 (3.71)
U.S. Agricultural GHG Emissions	90.37	76.74	2.58	90.61	76.32	13.40	90.81	77.23	27.01

Note: US consumers' surplus is the area below the demand curve less consumer expenditures for all commodities.

Net U.S. Producers' Surplus with GHG tax (payment) is producer revenue less the area below the supply curve minus (plus) GHG tax (payment) where GHG tax occurs when net emission is positive and GHG payment occurs when net GHG emission is negative.

Foreign country surplus represents the area under the excess demand curves above the price line and above the excess supply curves but below their price line for all the traded commodities.

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[e] The numbers in parentheses give the percentage change with respect to the zero CE-price scenarios.

Gross welfare items exclude GHGE charges/payments.

Appendix

Details on the Mathematical Structure of ASMGHG

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

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

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

ASMGHG is setup as mathematical programming model and contains more than 20,000 individual variables and more than 5,000 individual equations. These equations and variables are not entered individually but as indexed blocks. All agricultural production activities are specified as endogenous variables and denoted here by capital letters. In particular, the variable block CROP denotes crop management variables, LUTR = land use transformation, LIVE = livestock

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

raising, PROC = processing, and INPS = production factor (input) supply variables. Additional variable blocks reflect the dissemination of agricultural products with DOMD = U.S. domestic demand, TRAD = U.S. interregional and international trade, FRXS = foreign region excess supply, FRXD = foreign region excess demand, EMIT = Emissions, and SEQU = Emission reduction or sequestration variables. WELF denotes total agricultural welfare from both U.S. and foreign agricultural markets. With the exception of WELF, all variables are restricted be nonnegative.

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

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

optimal variable levels can be interpreted as equilibrium levels for agricultural activities under given economic, political, and technological conditions.

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

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

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

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

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

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

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

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

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

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

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

(3) $$INPS_{u,n} \le b_{u,n} \quad \text{for all u and n}$$

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

(4) $$-\sum_{u} TRAD_{m,u,y} - \sum_{\tilde{m}} TRAD_{m,\tilde{m},y} + FRXD_{m,y} \le 0 \qquad \text{for all m and y}$$

(5) $$\sum_{u} TRAD_{u.m,y} + \sum_{\tilde{m}} TRAD_{\tilde{m},m,y} - FRXS_{m,y} \le 0 \qquad \text{for all m and y}$$

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

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

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

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

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

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

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

(7) $$-\sum_{t}\left(h^{LMIX}_{u,y,t}\cdot LMIX_{u,t}\right)+\sum_{k,i}\left(a^{LIVE}_{u,k,i,y}\cdot LIVE_{u,k,i}\right)=0 \quad \text{for all u and y}$$

Agricultural land owners do not only have a choice between different crops and different crop management strategies, they can also abandon traditional crop production altogether in favor of establishing pasture or forest. Equivalently, some existing pasture or forest owners may decide to convert suitable land fractions into cropland. In ASMGHG, land use conversions are portrayed by a set of endogenous variables LUTR. As shown in (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).

(8) $$LUTR_{u,l}\le d_{u,l}\Big|_{d_{u,l}\ge 0} \quad \text{for all u and l}$$

The assessment of environmental impacts from agricultural production as well as political opportunities to mitigate negative impacts is a major application area for ASMGHG. To facilitate this task, ASMGHG includes environmental impact accounting equations as shown in (9) and (10). For each land management ($CROP_{u,c,s,j}$ and $LUTR_{u,l}$), livestock ($LIVE_{u,k,i}$), or processing ($PROC_{u,h}$) activity, environmental impact coefficients ($a^{LAND}_{u,c,s,j,g}$, $a^{LUTR}_{u,l,g}$, $a^{LIVE}_{u,k,i,g}$, $a^{PROC}_{u,h,g}$) contain the absolute or relative magnitude of those impacts per unit of activity. Negative values of greenhouse gas account coefficients, for example, indicate emission reductions. A detailed description of environmental impact categories and their data sources is available in Schneider (2000).

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

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

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 are accounted for all major sources, sinks and offsets from agricultural activities, for which data were available or could be simulated. Generally, ASMGHG considers:

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

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

All equations described so far have defined the convex feasibility region for the set of agricultural activities. Let us now turn to the objective function. The purpose of this single equation is to determine the optimal level of all endogenous variables within the convex feasibility region. Applying the McCarl and Spreen (1980) technique, we use a price-endogenous, welfare based objective function. This equation is shown in (11)[j].

The left hand side of equation (11) contains the unrestricted total agricultural welfare variable (WELF), which is to be maximized. The right hand side of equation (11) contains several major terms, which will be explained in more detail below. The first term $\sum_{\mathrm{u,y}}\left[\int_{\mathrm{y}} p_{u,y}^{DOMD}\left(\mathrm{DOMD}_{\mathrm{u,y}}\right)\mathrm{d}\left(\cdot\right)\right]$ adds the sum of the areas underneath the inverse U.S. domestic

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

demand curves over all crops, livestock products, and processed commodities.

ASMGHG can employ four types of demand specifications: a) downward sloping demand curves, b) horizontal or totally elastic demand implying constant prices, c) vertical demand implying fixed demand quantities, and d) zero demand. Downward sloping demand curves are specified as constant elasticity function[k]. 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 ($\mathrm{DOMD}^{\mathrm{TF}}_{\mathrm{u,y}}$) and downward sloping for quantities above $\mathrm{DOMD}^{\mathrm{TF}}_{\mathrm{u,y}}$. In particular, the truncated inverse demand curve for commodity y and region u becomes $p_{u,y}^{DOMD}\left(\mathrm{DOMD}_{\mathrm{u,y}}\right) = \{\, \hat{\mathrm{p}}_{\mathrm{u,y}} \times \left(\frac{\mathrm{DOMD}^{\mathrm{TF}}_{\mathrm{u,y}}}{\mathrm{DOMD}^{\wedge}_{\mathrm{u,y}}}\right)^{1/\varepsilon_{\mathrm{u,y}}}$ for all $\mathrm{DOMD}_{\mathrm{u,y}} < \mathrm{DOMD}^{\mathrm{TF}}_{\mathrm{u,y}}$ and $\hat{\mathrm{p}}_{\mathrm{u,y}} \cdot \left(\frac{\mathrm{DOMD}_{\mathrm{u,y}}}{\mathrm{DOMD}^{\wedge}_{\mathrm{u,y}}}\right)^{1/\varepsilon_{u,y}}$ for all $\mathrm{DOMD}_{\mathrm{u,y}} \geq \mathrm{DOMD}^{\mathrm{TF}}_{\mathrm{u,y}}\,\}$, where $\hat{\mathrm{p}}_{\mathrm{u,y}}$ and $\mathrm{DOMD}^{\wedge}_{\mathrm{u,y}}$ denote an observed price quantity pair and $\varepsilon_{\mathrm{u,y}}$ denotes the own price elasticities of demand.

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

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

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

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

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

Mitigation Strategies in ASMGHG

Mitigation Strategy	Data Source/Reference	Greenhouse Gas Emission Effect		
		CO_2	CH_4	N_2O
Afforestation/timberland	FASOM	-		
Biofuel production	POLYSIS analysis, GREET model, EPIC model	-	-	+
Crop mix alteration	EPIC model	+/-		+/-
Rice acreage reduction	EPA		-	
Crop fertilizer rate reduction	EPIC model, IMPLAN software	+/-		-
Other crop input alteration	USDA data	+/-		
Crop tillage alteration	EPIC model	+/-		+/-
Grassland conversion	EPIC model	-		
Irrigated/dry land conversion	Ag-Census	+/-		+/-
Livestock management	EPA data, IPCC		+/-	
Livestock herd size alteration	EPA data, IPCC		+/-	+/-
Livestock production system substitution	EPA data, IPCC		+/-	+/-
Liquid manure management	EPA data, IPCC		-	

"+" = positive emissions, "-" = negative emissions, "+/-" = mixed emissions, "" = zero emissions