Appendix 1 Pesticide action data

Table S.1 Chemical cost and yield effects on Atrazine treated corn fields

US State	Corn acreage treated with Atrazine (%)	Costs of Atrazine treatment ($/acre)	Costs of using Atrazine substitutes ($/acre)	Yield loss without Atrazine (%)
CO	52	4.15	5.48	2
GA	67	4.85	8.37	5
IA	68	2.90	11.17	1
IL	83	3.89	9.00	3
IN	79	4.31	11.52	5
KS	78	3.41	9.27	0
KY	91	4.66	10.26	2
MI	69	4.27	7.86	5
MN	39	2.49	9.44	1
MO	85	4.18	11.30	10
NC	78	4.43	7.21	3
NY	70	4.79	8.71	4
OH	80	4.02	10.41	4
PA	76	3.92	9.40	3
SD	27	2.55	7.50	3
TX	75	2.90	10.92	10
WI	59	2.90	7.68	1

Table S.2 Chemical cost and yield effects on Pendimethalin treated soybean fields

US State	Soybean acreage treated with Pendimethalin (%)	Costs of Pendimethalin treatment ($/acre)	Costs of using Pendimethalin substitutes ($/acre)	Yield loss without Pendimethalin (%)
AR	18	6.88	7.03	0
GA	3	6.16	18.68	0
IA	19	7.84	10.49	0
IL	32	7.52	13.55	0
IN	22	6.32	13.69	0
KS	15	8.32	9.00	0
KY	16	4.40	13.43	0
MI	10	8.80	10.87	0
MN	5	7.76	12.57	0
MO	27	6.16	13.58	0
MS	30	6.64	7.09	0
NC	28	5.52	8.65	0
OH	22	6.80	13.99	0
SD	1	6.88	6.39	0
WI	0	0.00	0.00	0

Table S.3 Chemical Cost and Yield Effects due to of Boll Weevil Damage

State (Region)	Infested Acreage (%)	Number of Treatments	Treatment Cost ($/Acre)	Yield Loss (%)
Alabama	69.6	2.0	3.13	1.95
Arkansas	90.7	2.2	11.47	1.23
Louisiana	98.1	4.2	17.51	3.51
Missouri	51.8	1.4	4.71	2.09
Mississippi	89.8	2.7	8.49	2.28
Oklahoma	72.9	1.6	7.00	2.51
Tennessee	68.8	2.3	8.31	6.12
TX High Plains	12.6	0.2	0.13	0.25
TX Rolling Plains	91.8	0.7	3.86	3.47
TX Central Blacklands	58.6	1.7	6.97	4.24
TX Coastal Bend	96.5	3.5	19.08	4.29
TX Trans Pecos	41.8	0.7	1.83	1.56
TX South Texas	97.0	3.5	23.76	3.29
TX East Texas	13.4	2.6	2.44	4.35
TX Edward’s Plateau	99.7	1.9	9.47	5.89

APPENDIX 2: Agricultural Sector Model Documentation

Details on the Mathematical Structure of ASMGHG

This section provides a brief summary of the U.S. agricultural sector and mitigation of greenhouse gas model (ASMGHG). The model is an extension of the agricultural sector model (Adams et al., 1985; Chang et al., 1992; Chen and McCarl, 2000). Through a spatially detailed linkage to the biophysical crop growth model EPIC (Jones et al., 1991; Wang et al., 2012; Williams et al., 1989), ASMGHG integrates many crop management adaptation options and several detailed environmental impact accounts. The linked EPIC-ASMGHG modelling system has been used to quantify agricultural greenhouse gas emission mitigation potentials (McCarl and Schneider, 2001; Schneider, 2000; Schneider and McCarl, 2003, 2006; Schneider et al., 2007) and to study the impact of energy, climate, and pesticide policies (Koleva and Schneider, 2010; Schneider and McCarl, 2003, 2005; Shakhramanyan et al., 2013). Concept and mathematical programs of ASMGHG were also used to develop a global agricultural and forest sector model (Boettcher et al., 2013; Havlik et al., 2011; Mosnier et al., 2013; Sauer et al., 2010; Schneider et al., 2011; Valin et al., 2013).

Here, we describe the general model structure, which is not affected by data updates or model expansion toward greater detail. 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 computational limits, sector models cannot provide the same level of detail as do farm level or regional models. Therefore, ASMGHG depicts only representative crop and livestock enterprises in 63 aggregated U.S. production regions rather than individual farms characteristics. International markets and trade relationships are portrayed in 28 international regions.

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

ASMGHG is setup as mathematical programming model and contains more than 100,000 individual variables and more than 10,000 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 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 =

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

Emissions, and SEQU = Emission reduction or sequestration variables. WELF denotes total agricultural welfare from both U.S. and foreign agricultural markets. With the exception of WELF, all variables are restricted be nonnegative.

ASMGHG consists of an objective function, which maximizes total agricultural welfare (WELF) and a set of constraining equations, which define a convex feasibility region for all variables. Feasible variable levels for all depicted agricultural activities range from zero to an upper bound, which is determined by resource limits, supply and demand balances, trade balances, and crop rotation constraints[2]. Solving ASMGHG involves the task of finding the "optimal" level for all endogenous variables subject to compliance with all constraining equations. By means of ASMGHG's objective function, optimal levels of all endogenous variables are those levels which maximize agricultural sector based welfare, which is computed as the sum of total consumer surplus, producer surplus, and governmental net payments to the agricultural sector minus the total cost of production, transportation, and processing. Basic economic theory demonstrates that maximization of the sum of consumers' plus producers' surplus yields the competitive market equilibrium as reviewed by (McCarl and Spreen, 1980). Thus, the optimal variable levels can be interpreted as equilibrium levels for agricultural activities under given economic, political, and technological conditions.

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 exogenous 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

---

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

alternatives, j = crop management alternatives, k = animal production type, l = land transformation alternatives, m = international region (subset of index r), n = natural or human resource types (subset of index w), r = all regions, s = soil classes (subset of index n), t = years, u = U.S. region (subset of index r), w = all production factors, and y = primary and processed agricultural commodities. A list of individual set elements is available on the Internet or from the authors.

Supply and demand balance equations for agricultural commodities form an important constraint set in ASMGHG, which link agricultural activities to output markets. Specifically, the total amount of commodities disseminated in a U.S. region through domestic consumption (DOMD), processing (PROC), and exports (TRAD[3]) cannot exceed the total amount of commodities supplied through crop production (CROP), livestock raising (LIVE), or imports (TRAD). Equation block (1) shows the set of commodity supply and demand balance equations 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) $$\begin{aligned}&-\sum_{c,s,j}\left(a^{CROP}_{u,c,s,j,y}\cdot CROP_{u,c,s,j}\right)-\sum_{k,i}\left(a^{LIVE}_{u,k,i,y}\cdot LIVE_{u,k,i}\right)-\sum_{r}TRAD_{r,u,y}\\&+DOMD_{u,y}+\sum_{h}\left(a^{PROC}_{u,h,y}\cdot PROC_{u,h}\right)+\sum_{r}TRAD_{u,r,y}\le 0\end{aligned}$$ **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

[3] The first and second regional indexes of the TRAD variables denote the exporting region and importing region, respectively.

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)
$$\begin{aligned} INPS_{u,w} &- \sum_{c,s,j} a^{CROP}_{u,c,s,j,w} \cdot CROP_{u,c,s,j} - \sum_{l} a^{LUTR}_{u,l,w} \cdot LUTR_{u,l} \\ &- \sum_{k,i} a^{LIVE}_{u,k,i,w} \cdot LIVE_{u,k,i} - \sum_{h} a^{PROC}_{u,h,w} \cdot PROC_{u,h} \leq 0 \end{aligned}$$
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 ($a^{CROP}_{u,c,s,j,n}$, $a^{LUTR}_{u,l,n}$, $a^{LIVE}_{u,k,i,n}$, $a^{PROC}_{u,h,n}$), 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) $$INPS_{u,n} \le b_{u,n}$$ **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) $$-\sum_{u} TRAD_{m,u,y} - \sum_{\tilde{m}} TRAD_{m,\tilde{m},y} + FRXD_{m,y} \le 0$$ **for all m and y**

(5) $$\sum_{u} TRAD_{u.m,y} + \sum_{\tilde{m}} TRAD_{\tilde{m},m,y} - FRXS_{m,y} \le 0$$ **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 (2000) and in Chen and McCarl (2000).

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, 1982; Önal and McCarl, 1991), 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 $h^{\mathrm{CMIX}}_{u,c,t}$ 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) $$-\sum_{t}\left(h^{\mathrm{CMIX}}_{u,c,t}\cdot \mathrm{CMIX}_{u,t}\right)+\sum_{s,j}\mathrm{CROP}_{u,c,s,j}=0$$ **for all u and c**

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

Crop mix constraints are not applied to crops, which under certain policy scenarios are expected to expand far beyond the upper bound of historical relative shares. Particularly, if $E\left[\sum_{s,j} LAND_{u,c,s,j} \Big/ \sum_{c,s,j} LAND_{u,c,s,j}\right] > \underset{t}{Max}\left(h^{CMIX}_{u,c,t} \Big/ \sum_{c} h^{CMIX}_{u,c,t}\right)$, 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.

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

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

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

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) $$LUTR_{u,l} \le d_{u,l}\Big|_{d_{u,l} \ge 0}$$ **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).

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

(10) $$\begin{aligned} SEQU_{u,g} = & \sum_{c,s,j}\left(a^{CROP}_{u,c,s,j,g} \cdot CROP_{u,c,s,j}\right)\Big|_{a^{LAND}_{u,c,s,j,g}<0} \\ & + \sum_{l}\left(a^{LUTR}_{u,l,g} \cdot LUTR_{u,l}\right)\Big|_{a^{LUTR}_{u,l,g}<0} \\ & + \sum_{k,i}\left(a^{LIVE}_{u,k,i,g} \cdot LIVE_{u,k,i}\right)\Big|_{a^{LIVE}_{u,k,i,g}<0} \\ & + \sum_{h}\left(a^{PROC}_{u,h,g} \cdot PROC_{u,h}\right)\Big|_{a^{PROC}_{u,h,g}<0} \end{aligned}$$ **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),
- N_2O emissions from fertilizer usage and livestock manure,
- CH_4 emissions from enteric fermentation, livestock manure, and rice cultivation,
- CH_4 savings from changes in manure and grazing management changes, and
- CH_4 and N_2O 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)[5].

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

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

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

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

The second right hand side term $-\sum_{u,n}\left[\int_{n} p_{u,n}^{INPS}\left(\text{INPS}_{u,n}\right)d(\cdot)\right]$ subtracts the areas underneath the endogenously priced input supply curves for hired labor, water, land, and animal grazing units. Supply curves for these inputs are specified as upward sloping constant elasticity functions with $p_{u,y}^{INPS}\left(\text{INPS}_{u,n}\right) = \hat{p}_{u,n}^{INPS}\times\left(\frac{\text{INPS}_{u,n}}{\text{INPS}_{u,n}^{\wedge}}\right)^{1/\varepsilon_{u,n}}$. Note that the $\text{INPS}_{u,n}$ 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 $+\sum_{m,y}\left[\int_{y} p_{m,y}^{FRXD}\left(\text{FRXD}_{m,y}\right)d(\cdot)\right]$ and $-\sum_{m,y}\left[\int_{y} p_{m,y}^{FRXS}\left(\text{FRXS}_{m,y}\right)d(\cdot)\right]$ account for the areas underneath the foreign inverse excess demand curves minus the areas underneath the foreign inverse excess supply curves. Together these two terms define the total trade based Marshallian consumer plus producer surplus economic of foreign regions.

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

Agricultural management alternatives in ASMGHG

Decision parameter	Available options in ASMGHG
Crop choice (index c)	Cotton, Corn, Soybeans, Winter wheat, Durum wheat, Hard red winter wheat, Hard red and other spring wheat, Sorghum, Rice, Barley, Oats, Silage, Hay, Sugar Cane, Sugar Beets, Potatoes, Tomatoes, Oranges, Grapefruit Switchgrass, Willow, Hybrid poplar
Irrigation alternatives[7]	No irrigation Full irrigation
Tillage system alternatives[7]	Conventional tillage (<15% plant cover) Reduced tillage (15-30% plant cover) Zero tillage (>30% plant cover)
Fertilization alternatives[7]	Observed nitrogen fertilizer rates Nitrogen fertilizer reduction corresponding to 15% stress Nitrogen fertilizer reduction corresponding to 30% stress
Animal production choice	Dairy, cow-calf, feedlot beef cattle, heifer calves, steer calves, heifer yearlings, steer yearlings, feeder pigs, pig finishing, hog farrowing, sheep, turkeys, broilers, egg layers, and horses
Feed mixing choice	1158 specific processes based on 329 general processes differentiated by 10 US regions
Livestock production alternatives	Four different intensities (feedlot beef), two different intensities (hog operations), liquid manure treatment option (dairy and hog operations), BST treatment option (dairy)

[7] Irrigation, tillage, and fertilization alternatives are contained in index j

Spatial Scope of ASMGHG

Region class	Class Elements	Associated ASMGHG Features
Non-US world regions[8]	Canada, East Mexico, West Mexico, Caribbean, Argentina, Brazil, Eastern South America, Western South America, Scandinavia, European Islands, Northern Central Europe, Southwest Europe, France, East Mediterranean, Eastern Europe, Adriatic, former Soviet Union, Red Sea, Persian Gulf, North Africa, West Africa, South Africa, East Africa, Sudan, West Asia, China, Pakistan, India, Bangladesh, Myanmar, Korea, South East Asia, South Korea, Japan, Taiwan, Thailand, Vietnam, Philippines, Indonesia, Australia	Excess demand and supply function parameter for 8 major crop commodities; transportation cost data; Computation of trade equilibrium
US	US	Demand function parameters for crop, livestock, and processed commodities
US macro regions (10)	Northeast, Lake States, Corn belt, Northern Plains, Appalachia, Southeast, Delta States, Southern Plains, Mountain States, Pacific States	Feed mixing and other process data; labor endowment data;
US minor regions (63)	Alabama, Arizona, Arkansas, N-California, S-California, Colorado, Connecticut, Delaware, Florida, Georgia, Idaho, N-Illinois, S-Illinois, N-Indiana, S-Indiana, W-Iowa, Central Iowa, NE-Iowa, S-Iowa, Kansas, Kentucky, Louisiana, Maine, Maryland, Massachusetts, Michigan, Minnesota, Mississippi, Missouri, Montana, Nebraska, Nevada, New Hampshire, New Jersey, New Mexico, New York, North Carolina, North Dakota, NW-Ohio, S-Ohio, NE-Ohio, Oklahoma, Oregon, Pennsylvania, Rhode island, South Carolina, South Dakota, Tennessee, TX-High Plains, TX-Rolling Plains, TX-Central Blackland, TX-East, TX-Edwards Plateau, TX-Coastal Belt, TX-South, TX Transpecos, Utah, Vermont, Virginia, Washington, West Virginia, Wisconsin, Wyoming	Crop and livestock production data and activities, land type and water resource data
Land types (6)	Agricultural Land: Land with wetness limitation, Low erodible land (Erodibility Index (EI) < 8), Medium erodible land (8 < EI < 20), Highly erodible land (EI < 20); Pasture; Forest	Land endowments; Cost, yield, and emission data adjustment

[8] The international regional resolution differs across the 8 traded crops. For livestock and processed crop commodities one rest of the world region is used.

Environmental Accounts in ASMGHG

Account type	Account elements
Greenhouse gas emission accounts affected by energy tax policy (index g)	Carbon emissions from on-farm fossil fuel use for agricultural machinery (fuelc), carbon emissions from irrigation (irrgc), carbon emissions from grain drying (drygc), carbon emissions from fertilizer manufacture (fertc), carbon emissions from pesticide manufacture (pestc), greenhouse gas emission offsets from bioenergy
Greenhouse gas emission accounts not affected by energy tax policy	Soil carbon changes, carbon sequestration from afforestation, methane emission from rice cultivation, nitrous oxide emissions from nitrogen applications, methane emissions from ruminant animals, methane emissions from livestock manure, nitrous oxide emissions from livestock manure, methane emission savings from livestock manure digestion
Other environmental accounts not affected by energy tax policy	Soil erosion through wind and water, nitrogen and phosphorous losses from surface runoff, subsurface flow, percolation, immobilization, and other processes

References

Adams, R. M., Hamilton, S. A., and Mccarl, B. A. (1985). An Assessment of the Economic-Effects of Ozone on United-States Agriculture. *Journal of the Air Pollution Control Association* **35**, 938-943.

Boettcher, H., Frank, S., Havlik, P., and Elbersen, B. (2013). Future GHG emissions more efficiently controlled by land-use policies than by bioenergy sustainability criteria. *Biofuels Bioproducts & Biorefining-Biofpr* **7**, 115-125.

Chang, C. C., McCarl, B. A., Mjelde, J. W., and Richardson, J. W. (1992). Sectoral Implications of Farm Program Modifications. *American Journal of Agricultural Economics* **74**, 38-49.

Chen, C.-C. (2000). Development and Application of Linked Global Trade-Detailed U. S. Agricultural Sector Analysis System. Ph.D. Dissertation, Texas A&M University, College Station, Texas.

Chen, C. C., and McCarl, B. A. (2000). The value of ENSO information to agriculture: Consideration of event strength and trade. *Journal of Agricultural and Resource Economics* **25**, 368-385.

Dantzig, G. B., and Wolfe, P. (1961). The Decomposition Algorithm for Linear Programs. *Econometrica* **29**, 767-778.

Havlik, P., Schneider, U. A., Schmid, E., Bottcher, H., Fritz, S., Skalsky, R., Aoki, K., De Cara, S., Kindermann, G., Kraxner, F., Leduc, S., McCallum, I., Mosnier, A., Sauer, T., and Obersteiner, M. (2011). Global land-use implications of first and second generation biofuel targets. *Energy Policy* **39**, 5690-5702.

Jones, C. A., Dyke, P. T., Williams, J. R., Kiniry, J. R., Benson, V. W., and Griggs, R. H. (1991). EPIC - AN OPERATIONAL MODEL FOR EVALUATION OF AGRICULTURAL SUSTAINABILITY. *Agricultural Systems* **37**, 341-350.

Koleva, N. G., and Schneider, U. A. (2010). The impact of climate change on aquatic risk from agricultural pesticides in the US. *International Journal of Environmental Studies* **67**, 677-704.

McCarl, B. A. (1982). Cropping Activities in Agricultural Sector Models - a Methodological Proposal. *American Journal of Agricultural Economics* **64**, 768-772.

McCarl, B. A., and Schneider, U. A. (2001). Climate change - Greenhouse gas mitigation in US agriculture and forestry. *Science* **294**, 2481-2482.

McCarl, B. A., and Spreen, T. H. (1980). Price Endogenous Mathematical-Programming as a Tool for Sector Analysis. *American Journal of Agricultural Economics* **62**, 87-102.

Mosnier, A., Havlik, P., Valin, H., Baker, J., Murray, B., Feng, S., Obersteiner, M., McCarl, B. A., Rose, S. K., and Schneider, U. A. (2013). Alternative US biofuel mandates and global GHG emissions: The role of land use change, crop management and yield growth. *Energy Policy* **57**, 602-614.

Önal, H., and McCarl, B. A. (1989). Aggregation of heterogeneous firms in mathematical programming models. *European Review of Agricultural Economics* **16**, 499-513.

Önal, H., and McCarl, B. A. (1991). Exact Aggregation in Mathematical-Programming Sector Models. *Canadian Journal of Agricultural Economics-Revue Canadienne D Economie Rurale* **39**, 319-334.

Sauer, T., Havlik, P., Schneider, U. A., Schmid, E., Kindermann, G., and Obersteiner, M. (2010). Agriculture and resource availability in a changing world: The role of irrigation. *Water Resources Research* **46**.

Schneider, U. A. (2000). Agricultural Sector Analysis on Greenhouse Gas Emission Mitigation in the U.S. Ph.D. dissertation, Texas A&M University, College Station, Texas.

Schneider, U. A., Havlik, P., Schmid, E., Valin, H., Mosnier, A., Obersteiner, M., Bottcher, H., Skalsky, R., Balkovic, J., Sauer, T., and Fritz, S. (2011). Impacts of population growth, economic development, and technical change on global food production and consumption. *Agricultural Systems* **104**, 204-215.

Schneider, U. A., and McCarl, B. A. (2003). Economic potential of biomass based fuels for greenhouse gas emission mitigation. *Environmental & Resource Economics* **24**, 291-312.

Schneider, U. A., and McCarl, B. A. (2005). Implications of a carbon-based energy tax for U.S. agriculture. *Agricultural and Resource Economics Review* **34**, 265-279.

Schneider, U. A., and McCarl, B. A. (2006). Appraising agricultural greenhouse gas mitigation potentials: effects of alternative assumptions. *Agricultural Economics* **35**, 277-287.

Schneider, U. A., McCarl, B. A., and Schmid, E. (2007). Agricultural sector analysis on greenhouse gas mitigation in US agriculture and forestry. *Agricultural Systems* **94**, 128-140.

Shakhramanyan, N. G., Schneider, U. A., and McCarl, B. A. (2013). US agricultural sector analysis on pesticide externalities - the impact of climate change and a Pigovian tax. *Climatic Change* **117**, 711-723.

Valin, H., Havlik, P., Mosnier, A., Herrero, M., Schmid, E., and Obersteiner, M. (2013). Agricultural productivity and greenhouse gas emissions: trade-offs or synergies between mitigation and food security? *Environmental Research Letters* **8**.

Wang, X., Williams, J. R., Gassman, P. W., Baffaut, C., Izaurralde, R. C., Jeong, J., and Kiniry, J. R. (2012). EPIC AND APEX: MODEL USE, CALIBRATION, AND VALIDATION. *Transactions of the Asabe* **55**, 1447-1462.

Williams, J. R., Jones, C. A., Kiniry, J. R., and Spanel, D. A. (1989). THE EPIC CROP GROWTH-MODEL. *Transactions of the Asae* **32**, 497-511.