The Agricultural Sector and Greenhouse Gas Mitigation Model (ASMGHG)

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The overall objective of ASMGHG is to analyze the potential of U.S. agriculture to mitigate greenhouse gas emissions (GHGE). The Agricultural Sector Model (ASM) hosted at Texas A&M (McCarl et al.) presented a good starting point for meeting this objective. ASM computes the market equilibrium for major agricultural markets in the U.S. Foreign markets for relevant trading partners are also included. Maximization of producer profits and consumer utility yields the equilibrium solution in ASM. The solution provides a detailed picture of the U.S. agricultural sector including information on prices, levels of production, and net exports as well as resource usage, technology adoption, and welfare distribution. However, the original ASM model does not involve a complete GHGE related component.

The fundamental task and method was to augment the ASM model for the analysis of GHGE mitigation. Several basic steps were taken to accomplish this goal. First, a list of potential mitigation strategies was defined. These strategies included available options for all agriculturally relevant GHGs with respect to crop or livestock production, and basic processing.

Second, data were needed on GHGE levels for all feasible mitigation strategies. Emissions data for livestock technologies were based on EPA and IPCC estimates, or derived according to IPCC guidelines. The IPCC and EPA, however, do not provide emissions data on crop production activities. Emissions from crop production are very sensitive to many specific technology parameters and regionally specific weather patterns (Granli and Bøckman). As a result, comprehensive observational data are very costly to obtain and, as of yet, few such data exist. The only way to overcome this lack of data is to use crop growth simulation models. Examples are the EPIC model (Williams et al.)

and the CENTURY model (Parton et al.). All of these models are continuously developed to improve estimation of the complex relationship between agricultural crop management and associated levels of emissions. Here, we used the EPIC model to simulate the relative effects of agricultural management on carbon dioxide and nitrous oxide emissions, and on a variety of other environmental parameters.

Third, agricultural activities in ASM needed to be made compatible to mitigation strategies. For example, nitrous oxide emission mitigation can be achieved through reduced fertilization. The original ASM model, however, has no fertilization alternatives. Given the virtually infinite number of possible management options, this step required choosing a sufficient number of representative alternatives. The limiting factor for the number of examined alternatives is computing time.

Fourth, the mathematical structure of the ASM model needed to be modified. This involved setting up GHG emission and sink accounting equations, validation of baseline emissions and baseline cropping practices, and building a GHG policy module that allows for analysis of various policy scenarios involving payment levels and eligible strategies.

The following sections document and describe the methodological components of this analysis in more detail.

1 DEVELOPING FARM LEVEL GHGE DATA - USE OF THE EROSION PRODUCTIVITY IMPACT CALCULATOR (EPIC)

1.1 Description

The EPIC model was originally developed to assess the impact of cropping practices on crop productivity of various soils (Williams et al.). In later years, the scope of EPIC has been expanded to cover the effect of a variety of land use management decisions on soil, water, nutrient, and pesticide movements and their combined impact on soil loss, water quality, and crop yields. Recent efforts involve greenhouse gas emission related processes such as estimation of denitrification rates and soil carbon accounting. EPIC has been used in more than fifty countries.

The basic geographical scale of EPIC is a field site with homogeneous soil, landscape, weather, and cropping characteristics. Water and associated chemicals, soil, and organic matter move from the edge of the field and from the bottom of root zone. An internal weather generator, based on local weather patterns, generates random probabilistic weather events, which combined with user specified crop management events results in plant growth and all the above-mentioned nutrient, weather, and soil component changes. EPIC is a daily time step model and produces summary output daily, monthly, annually, or by aggregates of these time periods.

EPIC will be used to simulate the effects of alternative crop management strategies on soil organic matter content, nitrous oxide emissions through denitrification or air volatilization, and several other important environmental parameters such as soil erosion, nitrogen, and phosphorous movements. The simulated values will then be integrated in an economic optimization model for the U.S. agricultural sector. A description of this optimization model follows in sections 2 and 3.

1.2 Running EPIC for Alternative Fertilization Options

EPIC was originally built as a site-specific simulation model, which can provide output on hundreds of soil and crop related parameters on a daily basis. Consequently, most previous EPIC studies are site, crop and technology specific. For ASMGHG, we needed EPIC to develop annual, representative parameter values for all major U.S. crops, in all major U.S. production regions, and for many alternative technology specifications. For example, the number of EPIC runs covering one fertilization option with all feasible irrigation and tillage system combinations, for all major crops on all relevant soil types, in all major production regions amounted to about 5,000 individual runs. Thus, the total number of runs equaled the number of individual runs per fertilization option times the number of different fertilization option to be examined.

An individual EPIC run requires three input files. These three files contain local weather and climate data (file extension 'DAT'), soil parameters (file extension 'SOL'), and crop management related parameters (file extension 'OPS'). In an effort to use the EPIC model for large-scale assessments of agricultural practices, a complete set of EPIC input files consistent with 5,000 individual crop management combinations was compiled at the Blackland Research Center and made available for this study.

The EPIC program also contains several parameter files, which allow users to modify specific options. For this study, the following options were modified: a) fertilizer applied through nitrogen stress parameter (contained in file PARM8120.DAT), b) fertilizer type at application time (contained in file ASMFERT1.DAT), and c) denitrification soil-water threshold (contained in file PARM8120.DAT). The nitrogen stress level determines the fraction of growing season days with nitrogen stress. High levels of nitrogen stress imply low levels of nitrogen fertilizer. Possible types of mineral nitrogen fertilizers in EPIC include nitrate, ammonia, and any convex combination between the two. The denitrification soil-water threshold determines the water saturation level, which initiates denitrification of nitrate to atmospheric nitrogen and nitrous oxide. For this study, it was uniformly set to 99 percent.

Table 2-1 summarizes the basic steps of the program developed to run EPIC and to automatically format the output values. Annual EPIC output parameters, which were saved, are listed in Table 2-2. The final EPIC output is directly compatible to the economic optimization model described in sections 2 and 3.

2 THE AGRICULTURAL SECTOR MODEL (ASM)

The economic impacts of greenhouse gas mitigation will be assessed using a mathematical programming model, which is based on the agricultural sector model (ASM). The ASM maximizes the sum of producers' and consumers' surplus subject to resource limitations, government policy, and market supply-demand balances as described in McCarl and Spreen; and Chang, et al.

Table 2-1 Description of Program to Link EPIC to ASMGHG

Step	Description
Step 1 (GAMS)	Define fertilizer alternatives for EPIC runs a) Values of nitrogen stress parameter {20...100} b) Values of denitrification parameter {95,99} c) Values of NH_4/NO_3 ratio {100% NH_4, 0% NH_4} d) Values of simulation period {100 years}
Step 2 (DOS-UTIL)	Create parameter files for alternative fertilizer options a) PARM8120.DAT (nitrogen stress and denitrification options) b) ASMFERT1.DAT (nitrogen fertilizer type) c) Copy parameter file into subdirectory d) Change file name to identify fertilizer alternative Example: After setting nitrogen stress equal to "85" and denitrification equal to "99", save PARM8120.DAT as N8599.PAR in subdirectory "\EPIC8120\FERTALT\". Similarly, after setting NH_4 equal to 100% save ASMFERT1.DAT as N1N0.PAR in subdirectory "\EPIC8120\FERTALT\". e) Repeat Step 2a) - d) until all alternative fertilizer settings have been processed

Step 3 (GAMS)[i]	Scan existing EPIC records If results are complete, Exit program If records are incomplete, Write missing runs in each region to EPICRUN.DAT file, Copy EPICRUN.DAT into respective EPIC regional directory, Go to Step 4
Step 4 (GAMS)[i]	Write executable batch files for missing EPIC runs Go to Step 5
Step 5 (DOS)[i]	Execute EPIC using batch files from Step 4
Step 5a (DOS)[i]	Overwrite fertilizer parameter files in EPIC8120 directory: i) PARM8120.DAT ii) ASMFERT1.DAT Go to Step 5b
Step 5b (DOS)[i]	Copy regional EPIC input files into EPIC8120 directory i) *.NEW (weather data) ii) *.SOL (soil property data) iii) *.OP2 (management data) iv) OPSFILE2.DAT, SOLFILE1.DAT, EPICRUN.DAT
Step 5c (DOS)[i]	Execute EPIC8120 (This executes all EPIC runs which are specified in EPICRUN.DAT for the current region and the current fertilizer setting) Go to Step 5d
Step 5d (DOS)[i]	Copy EPIC output file into data storage directory Change the file name of EPIC output file (EPIC8120.SUM) to identify region and fertilizer settings. Example: Change EPIC8120.sum to TXHI9599.113 (This file would then contain results for Texas High Plains, nitrogen stress 95, denitrification option 99, 100% NH$_4$-nitrogen, nitrification inhibitor, and 100 years simulation Go to Step 5e

Table 2-1 Continued

Step	Description
Step 5e (DOS)[i]	Delete the following files for each completed regions: i) *.NEW (weather data) ii) *.SOL (soil property data) iii) *.OP2 (management data) iv) OPSFILE2.DAT, SOLFILE1.DAT, EPICRUN.DAT Go to Step 5f
Step 5f (GAMS)[i]	If more regions to be processed, Continue with Step 5b for next region If all regions processed, Go to Step 5g
Step 5g (GAMS)[i]	If more fertilizer options to be processed, Continue with Step 5a for next fertilizer alternative If all fertilizer settings processed, Go to Step 6
Step 6 (FORTRAN)[i]	Create aggregated, GAMS compatible EPIC output file a) Copy all regional output files into one file, use GAMS table format b) Add dimension for fertilizer option in each row of new file
Step 7 (GAMS)[i]	Go to Step 3

Table 2-2 Annual EPIC Parameters From Comparative Runs

EPIC-Variable	Description and Unit
Weather data	
PRCP	Precipitation (mm)
PET	Potential evapo-transpiration (mm)
ET	Actual evapo-transpiration (mm)
Crop technology data	
YIELD	Crop yield (t/ha)
HI	Harvest index (crop yield/aboveground biomass)
BIOM	Crop biomass (shoot + root) (t/ha)
RSD	Crop residue (t/ha)
COST	Total production cost ($)
Soil data	
PH	Soil pH
ORG C	Organic carbon content (%)
YOC	Carbon in sediment yield (t/ha)
HUM	Stable organic matter (humus) in profile (t/ha)
TOCI	Initial carbon content in soil in (t/ha)
TOCF	Final carbon content in soil (t/ha)

Table 2-2 Continued

EPIC-Variable	Description and Unit
Nitrogen data	
NS	Nitrogen stress factor in days of vegetation period
FN	Average annual nitrogen fertilizer rate (kg/ha)
FNO3	Average annual NO_3 fertilizer rate (kg/ha)
FNO	Organic nitrogen fertilizer
FNH3	NH_3-N fertilizer (kg/ha)
NFIX	Nitrogen fixation by legumes (kg/ha)
AVOL	Nitrogen volatilization NH_3-N (kg/ha)
DN	Nitrogen loss by denitrification (kg/ha)
PRKN	Mineral nitrogen loss in percolation (kg/ha)
IMN	Nitrogen immobilized by decaying residue (kg/ha)
NITR	Nitrification NH_3-N conversion to NO_3-N (kg/ha)
HMN	Nitrogen mineralized from stable organic matter (kg/ha)
MNN	Nitrogen mineralized (kg/ha)
YON	Organic nitrogen loss with sediment (kg/ha)
YNO3	NO_3-N loss in surface runoff (kg/ha)
SSFN	Mineral nitrogen loss in subsurface flow (kg/ha)

Table 2-2 Continued

EPIC-Variable	Description and Unit
Phosphorous data	
FP	Average annual phosphorous fertilizer rate (kg/ha)
PS	Phosphorus stress in days of vegetation period
YAP	Soluble phosphorous loss in runoff (g/ha)
YP	Phosphorous loss with sediment (kg/ha)
MNP	Phosphorous mineralized
PRKP	Mineral phosphorous loss in percolation
Erosion data	
MUST	Soil loss from water erosion using MUST equation (t/ha)
MUSS	Soil loss from water erosion using MUSS equation (t/ha)
USLE	Soil loss from water erosion using USLE (t/ha)
YW	Soil loss from wind erosion (t/ha)
Water flow data	
IRGA	Irrigation water applied (mm)
Q	Surface runoff (mm)
SSF	Sub-surface flow (mm)
PRK	Percolation below soil profile (mm)

ASM solutions yield estimates of equilibrium prices, quantities, resource usage, and social welfare levels. There are 48 primary and 54 secondary commodities included. Land, labor, and water resources are allocated among ten major production regions and further disaggregated into 63 smaller regions. Production budgets are specified for each region while national level processing budgets are used. Constant elasticity functional forms are defined for domestic consumption and export demand as well as input and import supply. A basic representation of the economic structure in ASM is given in Figure 3-1.

ASM has been used previously in Baumes; Burton; Burton and Martin; Tyner et al.; Adams, Hamilton, and McCarl; and Adams et al. among others. ASM solution values should be interpreted as intermediate-run equilibrium results. Adjustment costs incurred in the short-run, i.e. for implementing new technologies are not accounted for in ASM.

3 THE AGRICULTURAL SECTOR AND GREENHOUSE GAS MITIGATION MODEL (ASMGHG)

The modeling effort for building ASMGHG involved modifying and expanding the ASM to analyze opportunities of greenhouse gas emission mitigation through the agricultural sector.

3.1 New Crop Management Dimensions in ASMGHG

To examine greenhouse gas mitigation options through agricultural management, sufficient choices with respect to agricultural management had to be made available in ASM.

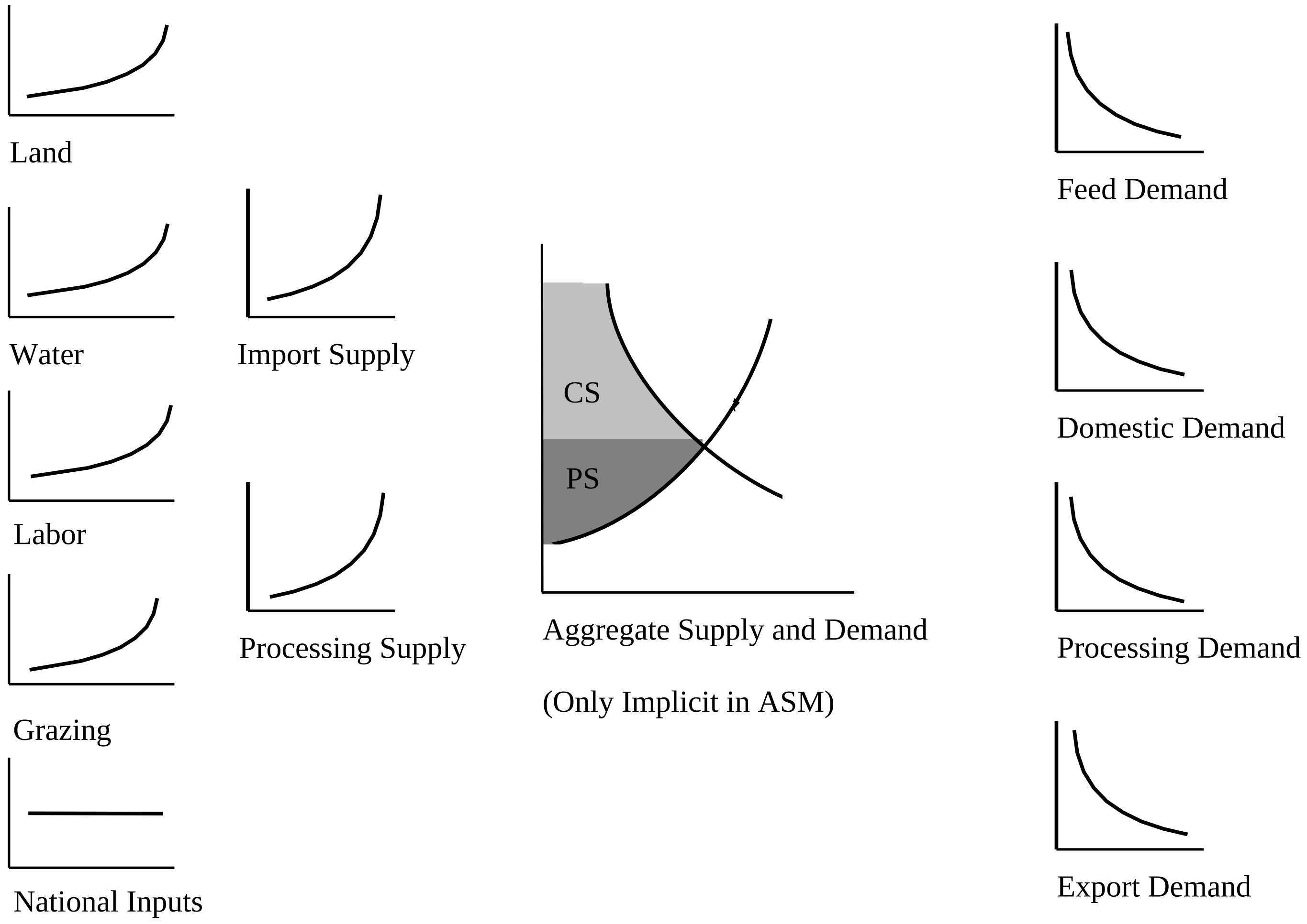

Figure 3-1 Agricultural Sector Model economic structure

Tillage intensity, soil type, and the amount and type of nitrogen fertilizer applications impact both soil organic matter buildup and denitrification rates, and thus, net carbon dioxide and nitrous oxide emissions (Granli and Bøckman). The original ASM for crop enterprises included neither alternative tillage systems, nor different soil types, nor alternative fertilization options.

The complete set of crop enterprise budgets of ASM was replaced by a new data set compiled by USDA NRCS (Benson). The new data set includes information on input requirements, input expenditures, and yields for conventional and alternative tillage systems as classified by the National Conservation and Resource Service (NRCS). In particular, the three tillage categories introduced are conventional tillage, conservation tillage, and zero tillage.

3.2 Linking Farm Level Emissions Data to ASMGHG

EPIC results were used to augment ASMGHG enterprise budgets by two additional dimensions: a fertilization dimension and a land type dimension. Each element of the fertilizer dimension represents a specific type and amount of fertilizer applied (Table 3-1). In addition, the fertilizer dimension identifies whether nitrification inhibitors were used. Soils in each region were subdivided into four classes.

Table 3-1 Nitrogen Fertilizer Choices

N-Scenario	N-Stress Value	N-Type	N-Inhibitor
N50T1I0	50%	100% NH4	No
N75T1I0	25%	100% NH4	No
N85T1I0	15%	100% NH4	No
N92T1I0	8%	100% NH4	No
N95T1I0	5%	100% NH4	No
N98T1I0	2%	100% NH4	No
N00T1I0	0%	100% NH4	No
N50T5I0	50%	50% NH4, 50% NO3	No
N75T5I0	25%	50% NH4, 50% NO3	No
N85T5I0	15%	50% NH4, 50% NO3	No
N92T5I0	8%	50% NH4, 50% NO3	No
N95T5I0	5%	50% NH4, 50% NO3	No
N98T5I0	2%	50% NH4, 50% NO3	No
N00T5I0	0%	50% NH4, 50% NO3	No
N50T0I0	50%	100% NO3	No
N75T0I0	25%	100% NO3	No
N85T0I0	15%	100% NO3	No
N92T0I0	8%	100% NO3	No
N95T0I0	5%	100% NO3	No
N98T0I0	2%	100% NO3	No
N00T0I0	0%	100% NO3	No

Crop budget data for alternative fertilization options and different soil types were developed through adjustment of base technology data. While some of the crop budget data, for example input use, could be assumed to stay at the base level, others needed to be updated. In particular, crop yield, fertilizer use, water use, and associated costs were adjusted for different soil types and fertilization management. The adjustment process required three basic steps and is summarized below.

First, a base level for EPIC parameters was established which had the same dimensions as equivalent parameters in the ASMGHG crop production budgets. The base level for the average land type was calculated for each region using a weighted average of soil types from that region. The base nitrogen level was set equal to the highest fertilization scenario in EPIC. Second, the proportionate change of all EPIC data from the base level was calculated (Equation 1). EPIC data, which are not impacted by nitrogen management and soil type, thus, would have a value of 100 percent.

Third, the adjusted ASMGHG budget item value was calculated as the product of original budget item value times the adjustment for a particular land type and fertilization management (Equation 2). By using a relative adjustment instead of absolute levels, deviations of the base scenarios of the new ASMGHG model from the original were minimized. Environmental parameters such as soil organic matter, erosion, nitrogen and phosphorus percolation were not contained in ASM budgets. There, the absolute EPIC value was assigned to ASM crop budget data.

Equation 1 Percentage Change Calculation of EPIC Parameters

$$E^{EPIC\%}_{R,C,W,L,T,F,E} = \frac{E_{R,C,W,L,T,F,E}}{\sum_{L}\left(\frac{L_{L,R}}{\sum_{L} L_{L,R}} \times E_{R,C,W,L,T,\text{"NBASE"},E}\right)}$$

Equation 2 Augmenting of ASMGHG Budget Items Through Relative Changes of EPIC Parameters

$$BUD^{ASMGHG}_{R,C,W,L,T,F,E} = BUD^{ASM}_{R,C,W,T,E} \times E^{EPIC\%}_{R,C,W,L,T,F,E}$$

Where:

$L_{R,L}$ = Available cropland of land type L in region R,

$E_{R,C,W,L,T,F,E}$ = Simulated value of epic item E, for crop C, in region R, water technology W, land type L, tillage system T, and fertilization alternative F,

$E^{EPIC\%}_{R,C,W,L,T,F,E}$ = Multiplier for adjusting basic ASM budget items to land type L and alternative fertilization alternative F,

$BUD^{ASM}_{R,C,W,T,E}$ = Original ASM budget item E in region R, for crop C, water technology W, tillage system T, and

$BUD^{ASMGHG}_{R,C,W,L,T,F,E}$ = Augmented ASMGHG budget item E in region R, for crop C, water technology W, land type L, tillage system T, and fertilization alternative F.

3.3 ASMGHG Validation

The ASMGHG is specified with 1997 prices and production levels. In addition, cost and yields were calibrated to match the observed use of conservation tillage and irrigation according to 1997 NRI levels. The adjustment of yields is shown below.

First, the acreage allocated to a specific crop, irrigation technology and tillage practice was constrained to match nationally observed levels (Equation 3 through Equation 5). In addition, the acreage allocated to alternative fertilizer options was constrained to be zero (Equation 6). Second, levels of domestic production were determined through ASMGHG (Equation 7). Substituting Equation 7 in Equation 8 yields Equation 9. The final adjustment to yields in ASMGHG is shown in Equation 10.

Equation 3 Total Regional Crop Acreage Constraint During Baseline Budget Validation

$$\sum_{W,T,L,F} \tilde{A}^{ASMGHG}_{R,C,W,T,L,F} = A^{USDA}_{R,C}$$

Equation 4 Total Regional Irrigated Crop Acreage Constraint During Baseline Budget Validation

$$\sum_{T,L,F} \tilde{A}^{ASMGHG}_{R,C,\text{"Irrg"},T,L,F} = A^{USDA}_{R,C,\text{"Irrg"}}$$

Equation 5 Total Region, Crop, and Tillage Specific Acreage Constraint During Baseline Budget Validation

$$\sum_{W,L,F} \tilde{A}^{ASMGHG}_{R,C,W,T,L,F} = A^{USDA}_{R,C,T}$$

Equation 6 Zero Upper Limit on Alternative Fertilization Practices During Baseline Budget Validation

$$\tilde{A}^{ASMGHG}_{R,C,W,T,L,F\neq\text{"NBASE"}} = 0$$

Equation 7 Calculation of ASMGHG Baseline Production

$$\tilde{Q}^{ASMGHG}_{R,C} = \sum_{W,T,L,F} \left(Y^{ASMGHG}_{R,C,W,T,L,F} \times \tilde{A}^{ASMGHG}_{R,C,W,T,L,F} \right)$$

Equation 8 Simple Production Level Identity

$$Q^{USDA}_{R,C} = \frac{Q^{USDA}_{R,C}}{\tilde{Q}^{ASMGHG}_{R,C}} \times \tilde{Q}^{ASMGHG}_{R,C}$$

Equation 9 Production Level Identity After Substitution of Equation 7 Into Equation 8

$$Q^{USDA}_{R,C} = \sum_{W,T,L,F}\left(\left(Y^{ASMGHG}_{R,C,W,T,L,F} \times \frac{Q^{USDA}_{R,C}}{\tilde{Q}^{ASMGHG}_{R,C}}\right) \times \tilde{A}^{ASMGHG}_{R,C,W,T,L,F}\right)$$

Equation 10 Yield Adjustment in ASMGHG

$$^{*}Y^{ASMGHG}_{R,C,W,T,L,F} = Y^{ASMGHG}_{R,C,W,T,L,F} \times \frac{Q^{USDA}_{R,C}}{\tilde{Q}^{ASMGHG}_{R,C}}$$

Where:

$\tilde{A}^{ASMGHG}_{R,C,W,T,L,F}$ = Constrained acreage in ASMGHG allocated to crop C in region R using water technology W, tillage system T, fertilization alternative F on land type L,

$A^{USDA}_{R,C}$ = Observed total acreage of crop C in region R,

$A^{USDA}_{R,C,T}$ = Observed total acreage of crop C in region R with tillage system T,

$A^{USDA}_{R,C,\text{"Irrg"}}$ = Observed total irrigated acreage of crop C in region R,

$Y^{ASMGHG}_{R,C,W,T,L,F}$ = Original ASMGHG yields for crop C in region R using water technology W, tillage system T, fertilization alternative F on land type L,

$\tilde{Q}^{ASMGHG}_{R,C}$ = Computed level of domestic production of crop C in region R,

$Q^{USDA}_{R,C}$ = Level of domestic production of crop C in region R, and

$^{*}Y^{ASMGHG}_{R,C,W,T,L,F}$ = Adjusted yields in ASMGHG for crop C in region R using water technology W, tillage system T, fertilization alternative F on land type L.

3.4 Methane Emissions

3.4.1 Livestock Emissions

The first step in modeling greenhouse gas emission mitigation was to specify emission coefficients for currently used technologies. Emission coefficients specifically estimated for the U.S. were available from the EPA web site (U.S. EPA). In addition, the IPCC provides default coefficients, which were used whenever no U.S. specific estimates were available. In applying EPA or IPCC emission coefficients to ASM, several adjustments had to be made. First, the classification of livestock activities in ASMGHG often differed from EPA and IPCC classifications. Annual livestock production values from the ASMGHG model had to be translated into livestock population estimates (Equation 11). This conversion was necessary because emissions do not arise from livestock products (animal flux) but rather from standing animals (animal pool).

Equation 11 Animal Population Constraint

$$\left(\sum_{B} N_{R,A,B} = \sum_{S} P_{R,S} \times (1 - \delta_{R,S})^{-1} \times L_{A,R,S} \times W_{A,R,S}^{-1} \right)_{R,A}$$

Where:

$N_{R,A,B}$ = Average annual total population of animal A, in region R, under enteric fermentation regime B,

$P_{R,S}$ = Annual livestock production in region R for ASMGHG livestock activity S,

$\delta_{R,S}$ = Average death loss in region R for ASMGHG livestock activity S,

$W_{A,R,S}$ = Average live weight or production for animal A in region R under ASMGHG livestock activity S, and

$L_{A,R,S}$ = Average live span of animal A in region R in ASMGHG livestock activity S.

EPA calculates emission coefficients for cattle depending on age. Emissions from beef cattle, for example, are categorized in three stages: stage one covers the first twelve month and has the lowest emission factors, stage two covers the second twelve month, and stage three covers emissions from mature animals beyond an age of two years. Whenever ASMGHG livestock production activities overlap these emission categories, the activity was divided into sub-classes

Anaerobic decomposition of livestock manure leads to production of methane. Emissions are driven by the amount of manure produced, its composition and temperature, and the way the manure is managed (U.S. EPA). Liquid and slurry systems not only generate more methane emissions than dry systems, but their usage in the U.S. is increasing as the trend toward fewer but larger dairy and swine farms continues.

3.4.2 Emission Reductions From Livestock Production

There are three principal ways to mitigate methane emissions from livestock. First, decreasing the numbers of ruminant animals can reduce emissions. Second, improving manure handling can reduce methane emissions. A third way to decrease methane emissions from livestock is to improve the enteric fermentation process in ruminant animals.

3.4.2.1 Manure Handling

Manure management system improvements include covered anaerobic digesters, complete-mix digesters, and plug flow digesters (U.S. EPA), which are all applicable to liquid manure systems for large dairy and hog farms. Dry manure system improvements are not included in this analysis for several reasons. First, large hog farms in the U.S. manage manure almost exclusively with liquid systems (U.S. EPA). Second, methane production is highest in an anaerobic, water-based environment, with a high level of nutrients, warm temperatures, and in a moist climate (U.S. EPA). As a result, dry manure systems produce much less methane than liquid manure systems. Third, data for manure system improvements from dry manure systems were only available from European farms on a very aggregated level.

For both swine and dairy farms, EPA published the break-even herd size for an improvement technology to be economically feasible, the incremental emission reduction contribution in million metric tons of carbon equivalent, and the average value of methane emission reductions in dollars per metric ton of carbon (Table 3-2). Manure management emission reduction involves the following main characteristics. First, costs of emission reduction technologies consist of installation and operating and opportunity costs for all system components. Revenues consist of the value of the electricity produced, the value of emission reductions, and the value of heat recovery. The value of emission reductions equals the product of assumed carbon equivalent value and global warming potential of methane. As the value of carbon equivalent emission reductions increases, so does the price of electricity.

Second, emission reduction costs per animal depend on herd size (U.S. EPA). The larger a herd, the lower are these costs of using methane emission reduction technologies per animal head. Third, it is assumed that operating manure digesters completely eliminates manure emissions from associated swine or dairy herds.

Table 3-2 EPA Data Used for Manure Management Improvement

Value of Emission Reduction in Dollars per TCE	Dairy		Hogs	
	Cumulative Methane Emission Reduction in Percent	Incremental Methane Emission Reduction in MMTCE	Cumulative Methane Emission Reduction in Percent	Incremental Methane Emission Reduction in MMTCE
-30	4	0.23	10	1.23
-20	14	0.52	10	0.00
-10	20	0.33	10	0.00
0	36	0.88	10	0.00
10	41	0.29	10	0.00
20	46	0.27	16	0.79
30	49	0.19	35	2.25
40	52	0.17	46	1.36
50	55	0.14	55	1.10
75	62	0.37	83	3.52
100	68	0.38	88	0.51
125	74	0.31	90	0.25
150	79	0.26	90	0.01
175	83	0.24	90	0.00
200	87	0.21	90	0.00

For modeling manure management in ASMGHG, aggregated EPA data needed to be decomposed to find necessary coefficients on a per animal head basis. First, a share factor was calculated which represents the fraction of animals for which manure management would be profitable (Equation 12 and Equation 13). The value of this fraction depends both on the animal type and the level of the carbon equivalent subsidy.

Equation 12 Emission Reduction Identity for Livestock Manure Management

$$ER^{EPA}_{A,i,\text{"CE"}} = \frac{s_{A,i} \times \sum_{R} (e^{Manr}_{R,A,\text{"CH4"}} \times N^{EPA}_{R,A})}{GWP_{\text{"CH4"}}}$$

Equation 13 Calculation of Animal Population Fraction Under Improved Manure Management for Each Level of Carbon Equivalent Subsidy

$$s_{A,i} = \frac{ER^{EPA}_{A,i,\text{"CE"}} \times GWP_{\text{"CH4"}}}{\sum_{R} (e^{Manr}_{R,A,\text{"CH4"}} \times N^{EPA}_{R,A})}$$

Where:

$ER^{EPA}_{A,i,\text{"CE"}}$ = Total emission reductions in carbon equivalents from animal A at the ith level of a supposed carbon equivalent subsidy (U.S. EPA estimate),

$N^{EPA}_{R,A}$ = Total population of animal A in region R,

$s_{A,i}$ = Fraction of national animal population for which liquid manure management to save methane emissions is profitable,

$e^{Manr}_{R,A,\text{"CH4"}}$ = Annual methane emissions from manure of animal A in region R, and

$GWP_{\text{"CH4"}}$ = Global warming potential of methane.

The calculation of system costs for manure management is shown below. It is assumed that system costs are the same for the equally sized animal herds across all U.S.

regions. As the value of methane emission reductions increases, improved manure management crosses the breakeven point for smaller herd sizes. All emission reduction increments in Table 3-2 represent methane savings from animal herds for which improved manure management has just become profitable. Given small profit margins for those animal herds, total additional abatement costs at each CE price must approximately equal total additional revenues (Equation 14). Thus, dividing total costs by the number of animals added at each incentive level yields an estimate of system costs per animal head (Equation 15).

Equation 14 Total Cost Approximation of Manure Management Improvement

$$C_{A,i} \approx ER^{EPA}_{A,i,"CE"} \times v_{i,"CE"}$$

Equation 15 Deduction of Cost per Animal Head for Improved Manure Management

$$c_{A,i} = \frac{C_{A,i}}{s_{A,i} \times \sum_{R,B} N_{A,R,B}}$$

Where:

$C_{A,i}$ = Total system costs at carbon equivalent value i for animal A,

$v_{i,"CE"}$ = i^th value of carbon equivalent emission reductions, and

$c_{A,i}$ = System cost coefficient at carbon equivalent value i per head of animal A.

As mentioned above, manure management improvements are more cost efficient for larger animal herds. In ASMGHG, animals are not distinguished by herd size. To model increasing system costs as the number of involved animals increases, an additional constraint was introduced (Equation 18). This constraint limits at each value of carbon equivalent emission reduction the number of animals for which manure management improvements is feasible. In addition, the percentage of animals deployed for better manure management in each region is also proportional to the fraction of liquid manure management usage in each region (Equation 19).

Equation 16 Total Methane Emission Reduction Accounting From Improved Livestock Manure Management in ASMGHG

$$ER^{Manr} = \sum_{R,A,i} \left(e_{R,A}^{Manr} \times M_{R,A,i} \right)$$

Equation 17 Total Cost Accounting From Improved Livestock Manure Management in ASMGHG

$$C^{Manr} = \sum_{A,i} \left(c_{A,i} \times \sum_{R} M_{R,A,i} \right)$$

Equation 18 Limit on National Population Under Improved Manure Management

$$\sum_{R} M_{R,A,i} \leq s_{A,i} \times \sum_{R,B} N_{R,A,B}$$

Equation 19 Proportionality Constraint on Improved Manure Management

$$M_{R,A,i} = \frac{Sys_{R,A}^{\%} \times \sum_{R,B} N_{R,A,B}}{\sum_{R} \left(Sys_{R,A}^{\%} \times \sum_{B} N_{R,A,B} \right)} \times \sum_{R} M_{R,A,i}$$

Where:

$M_{R,A,i}$ = The number of animals A in region R added to improved manure management regime, and

$Sys_{R,A}^{\%}$ = The percentage of animals A in region R, which is kept under liquid manure management and is hence eligible for methane reduction measures through improved manure management.

3.4.2.2 Emission Reductions From Altered Enteric Fermentation

Increasing the amount of absorbed energy per unit of foodstuff to reduce rumination per unit of product can reduce methane emissions from enteric fermentation. Potential strategies include genetic improvement (Gerbens, 1999a) or use of feed supplements to increase feed intake (U.S. EPA), dietary changes resulting in a higher energy concentration per unit of foodstuff (Gerbens, 1999a), pasture improvements (Johnson et al.), and vaccination.

In the U.S., not all of the suggested strategies are practical. Intensively managed dairy cattle already receive a high-quality diet, which has a high proportion of concentrates. In addition, a large number of U.S. beef cattle are raised on pasture. For these animals substitution of roughage by concentrates is impractical. Improving the quality of the pasture could reduce methane emissions, however, comprehensive data to quantify both the economic and mitigative effects of such a strategy are not available as of yet.

For above reasons, Bovine somatrophine (bST) use for dairy cows is the only enteric fermentation option currently implemented in ASMGHG. Use of BST impacts livestock production in four ways. First, the milk production of dairy cows increases. Second, feeding intake per cow increases. Third, enteric fermentation per dairy cow also increases. As a result, methane emissions per dairy cow increase as well. Fourth, BST treatment imposes additional cost on dairy farmers. While BST treatment increases the milk production per cow, fewer cows are necessary to produce the same amount of milk. Thus, BST treatment has the potential to mitigate GHGE by decreasing the amount of methane emissions per unit of product.

EPA aggregated data on regional total milk production and dairy populations were used to obtain average regional milk production per dairy cow and to project milk production without BST use for the year 2000 (Equation 20 and Equation 21). The relationship between enteric fermentation per dairy cow and milk production was estimated through ordinary least squares (Equation 23).

Equation 20 Calculation of Milk Yields From EPA Data

$$q^{EPA}_{R,"Milk",t} = \frac{Q^{EPA}_{R,"Milk",t}}{N^{EPA}_{R,"Dairy",t}}$$

Equation 21 Prediction of Year 2000 Levels of Milk Production

$$\hat{q}^{EPA}_{R,"Milk","2000"} = \hat{\alpha}_R + \hat{\beta}_R \times Y_{"2000"}$$

Equation 22 Calculation of Emission Coefficients From Enteric Fermentation for Dairy Cows From EPA Data

$$e^{EPA}_{R,"Dairy","Ef_{Base}",t} = \frac{E^{EPA}_{R,"Dairy","Ef_{Base}",t}}{N^{EPA}_{R,"Dairy",t}}$$

Equation 23 Prediction of Emission Coefficients From Enteric Fermentation for Dairy Cows Beyond EPA Data

$$e^{EPA}_{R,"Dairy","Ef_{Base}",t} = \gamma_R + \varphi_R \times q^{EPA}_{R,"Milk",t} + \varepsilon^{II}_R$$

Where:

$\alpha_R, \beta_R, \gamma_R, \varphi_R$ = Regional OLS regression parameters,

$q^{EPA}_{R,"Milk",t}$ = Computed average regional milk production per dairy cow,

$Q^{EPA}_{R,"Milk",t}$ = Annual total regional milk production,

$N^{EPA}_{R,"Dairy",t}$ = Annual total regional dairy cow population,

$\hat{q}^{EPA}_{R,"Milk","2000"}$ = Projected regional milk production without BST in 2000,

Y_t = Time parameter,

$e^{EPA}_{R,\text{"Dairy"},\text{"}Ef_{Base}\text{"},t}$ = Regional methane emission coefficient from enteric fermentation per dairy cow, and

$E^{EPA}_{R,\text{"Dairy"},\text{"}Ef_{Base}\text{"},t}$ = Regional methane emissions from enteric fermentation of all dairy cows.

Subsequently, a relative adjustment factor for regional enteric fermentation coefficients of dairy cows was calculated (Equation 24 to Equation 26). This factor is an estimate of the percentage increase in methane emissions from enteric fermentation after BST treatment.

Equation 24 Estimation of Year 2000 Emission Coefficients From Enteric Fermentation of Dairy Cows

$$e^{EPA}_{R,\text{"Dairy"},\text{"}Ef_{Base}\text{"},\text{"2000"}} = \hat{\gamma}_R + \hat{\phi}_R \times \hat{q}^{EPA}_{R,\text{"Milk"},\text{"2000"}}$$

Equation 25 Calculation of Emission Coefficients for Enteric Fermentation From BST Treated Dairy Cows

$$e^{EPA}_{R,\text{"Dairy"},B,\text{"2000"}} = \hat{\gamma}_R + \hat{\phi}_R \times \left(\left(1 + \frac{q^{bST(\%)}_{\text{"Milk"}}}{100}\right) \times \hat{q}^{EPA}_{R,\text{"Milk"},\text{"2000"}}\right)$$

Equation 26 Calculation of Enteric Fermentation Coefficient Adjustments for BST Treated Dairy Cows

$$ef^{\%}_{R,\text{"Dairy"},B} = \frac{\left(e^{EPA}_{R,\text{"Dairy"},B,\text{"2000"}} - e^{EPA}_{R,\text{"Dairy"},\text{"}Ef_{Base}\text{"},\text{"2000"}}\right)}{e^{EPA}_{R,\text{"Dairy"},\text{"}Ef_{Base}\text{"},\text{"2000"}}}$$

Where:

$e^{EPA}_{R,\text{"Dairy"},B,\text{"2000"}}$ = Percentage increase in milk production after BST treatment,

$e^{EPA}_{R,\text{"Dairy"},\text{"}Ef_{Base}\text{"},\text{"2000"}}$ = Adjustment factor for enteric fermentation coefficient of BST treated dairy cows,

$e^{EPA}_{R,\text{"Dairy"},B,\text{"2000"}}$ = Projected enteric fermentation coefficient of dairy cows without BST treatment in the year 2000, and

$e^{EPA}_{R,"Dairy","Ef_{Base}","2000"}$ = Projected enteric fermentation coefficient of BST treated dairy cows in the year 2000.

The enteric fermentation coefficients of BST treated dairy cows in ASMGHG were then computed as the product of base enteric fermentation coefficients times the adjustment due to BST treatment (Equation 27). Note that BST treatment only then mitigates methane emissions from enteric fermentation if the number of dairy cows decreases as a result of higher milk production per cow. In ASMGHG this could be examined by solving the model twice for a wide range of methane emission reduction values, with and without the opportunity to use BST treatments (Equation 28).

Equation 27 Methane Emission Coefficient From Enteric Fermentation in ASMGHG

$$e^{EntF}_{R,A,"CH4",B} = e^{EntF}_{R,A,"CH4","Base"} \times (1 + ef^{\%}_{R,A,B})$$

Equation 28 True Emission Reduction From BST Use

$$ER^{bST}_{i} = \left(\sum_{R,A,B} e^{EntF}_{R,A,"CH4",B} \times N_{R,A,B} \right)^{bST}_{i} - \left(\sum_{R,A,B} e^{EntF}_{R,A,"CH4","Base"} \times N_{R,A,B} \right)^{no\,bST}_{i}$$

Where:

$e^{EntF}_{R,A,"CH4",B}$ = ASMGHG enteric fermentation coefficient for animal A with enteric fermentation regime B in region R,

$e^{EntF}_{R,A,"CH4","Base"}$ = ASMGHG enteric fermentation base coefficient for animal A in region R, and

ER^{bST}_{i} = True emission reduction from BST treatment.

The feed intake of BST treated dairy cows was increased proportional for all feed categories according to estimates from Kaestle, Williams, and Gibbs. The treatment costs of BST were entered according to an estimate from Gerbens (1999a). Table 3-3 summarizes the assumptions made for BST treatment.

3.4.3 Rice Production

Besides livestock production, rice agriculture also constitutes a source of methane emissions. In ASMGHG, emission coefficients for rice production were calculated through average emission coefficients (Equation 29) as provided by (U.S. EPA).

Table 3-3 Parameters for Modeling BST-Treatment of Dairy Cows

Parameter	Value
Milk production increase	1,800 lbs./cow/year
Overall feed intake increase	15%
Roughage	15%
Concentrates	15%
Treatment cost	122 $/year/cow
BST base adoption in ASMGHG	10 % (endogenously computed)

The only way in the model to decrease methane emissions from rice is through acreage reduction. Alternative practices may also reduce methane emissions in the future. However, current scientific knowledge about potential savings is limited, and hence, no data were available to quantify the effects of alternative practices on methane emissions.

Equation 29 Methane Emission Coefficients From Rice Cultivation

$$e^{Rice}_{R,L,"CH4"} = \bar{e}^{EPA}_{"Rice","CH4"} \times T^{H_2O}_{"Rice",R}$$

Where:

$e^{Rice}_{R,L,"CH4"}$ = Methane emission coefficient for production of one acre of rice in region R on land type L,

$\bar{e}^{EPA}_{"Rice","CH4"}$ = Average methane emission coefficient per day on flooded rice fields, and

$T^{H_2O}_{"Rice",R}$ = Average flooding time of rice fields in region R in days per year.

3.5 Carbon Dioxide Emissions

3.5.1 Source Emissions

Agricultural carbon emissions are based on direct and indirect use of fossil fuels and on changes in soil organic matter or aboveground biomass. The following section documents the calculations used to retrieve greenhouse gas emission coefficients for a wide range of agricultural practices including specific mitigation strategies. Data sources are provided as well.

3.5.1.1 Direct Carbon Emissions Through Fossil Fuel Use

Fossil fuels, which are directly used in agricultural operations, include diesel, gasoline, electricity, natural gas, and liquefied petroleum gas (LP gas). The new crop enterprise budgets used in ASMGHG contain both quantity and expenditure on above fuel items based on USDA farm surveys. Carbon emission coefficients from direct fossil fuel use were derived as shown in Equation 30.

Equation 30 Calculation of Emission Coefficients From Fossil Fuel Use

$$e^{\mathrm{DirFF}}_{\mathrm{R,C,W,T}} = \sum_{\mathrm{FF}} \left(q_{\mathrm{FF,R,C,W,T}} \times q^{\mathrm{BTU}}_{\mathrm{FF}} \times CE^{\mathrm{BTU}}_{\mathrm{FF}} \right)$$

Where:

$e^{\mathrm{DirFF}}_{\mathrm{R,C,W,T}}$ = Direct carbon emissions from producing one acre of crop C in region R, using water technology W, and tillage system T,

$q_{\mathrm{FF,C,W,T}}$ = Direct quantity of fossil fuel FF from producing one acre of crop C in region R, using water technology W, and tillage system T,

$q^{\mathrm{BTU}}_{\mathrm{FF}}$ = Average energy content of fossil fuels, and

$CE^{\mathrm{BTU}}_{\mathrm{FF}}$ = Carbon emission of fossil fuels per unit of energy.

3.5.1.2 Indirect Carbon Emissions Through Irrigation

Irrigation of agricultural fields can be an energy intensive process. Particularly, in places where water is a scarce resource, pumping and transportation of irrigation water may consume considerable amounts of energy. Since energy sources usually involve fossil fuels, carbon dioxide emissions result and should be accounted for as indirect agricultural carbon emissions.

Ag census data were available on fuel expenditure for irrigation at state level (Farm and Ranch Irrigation Survey). Specification of carbon emission coefficients from irrigation in ASMGHG required three steps. First, the average expenditure on each fuel type for one acre-foot of irrigation water was computed (Equation 31). Second, the average fuel type quantity for an acre-foot of water was calculated dividing average expenditure by national prices for each fuel type (Equation 32). Third, carbon emission coefficients for an acre-foot were estimated using DOE carbon emission coefficients for each fuel type (Equation 33).

Equation 31 Calculation of Average Fuel Expenditure for Irrigation

$$pq_{R,FF}^{Irrg} = \frac{pQ_{R,FF}^{Irrg}}{A_R^{Irrg} \times w_R^{Irrg}}$$

Equation 32 Calculation of Average Fuel Quantities for Irrigation

$$q_{R,FF}^{Irrg} = \frac{pq_{R,FF}^{Irrg}}{p_{FF}}$$

Equation 33 Calculation of Average Carbon Emissions From Irrigation

$$e_{R,"CE"}^{Irrg} = q_{R,FF}^{Irrg} \times \bar{e}_{FF,"CE"}$$

Where:

$pq_{R,FF}^{Irrg}$ = Average expenditure on fossil fuel type FF from irrigation of one acre by one foot of water in region R,

$pQ_{R,FF}^{Irrg}$ = Total expenditure on fossil fuel type FF for irrigation in region R,

A_R^{Irrg} = Total irrigated acreage in region R,

W_R^{Irrg} = Total annual amount of irrigation water used in region R,

$q^{Irrg}_{R,FF}$ = Average quantity of fossil fuel type FF needed from irrigation of one acre by one foot of water in region R,

p_{FF} = Average national price of fossil fuel type FF at farm gate,

$e^{Irrg}_{R,"CE"}$ = Regional carbon emission coefficient for irrigation of one acre with one foot of water, and

$\bar{e}_{FF,"CE"}$ = The average carbon emission coefficient for fossil fuel type FF.

Currently, the only option to reduce carbon emissions from irrigation in ASMGHG is to reduce the amount of irrigated acreage. In the real world, Farmers also have the option to reduce the amount of water applied on irrigated fields. However, modeling this option in ASMGHG would require additional data that were not available at this point.

3.5.1.3 Indirect Carbon Emissions Through Fertilizer Use

Fertilizer manufacturing is also an energy intensive process in which a large amount of fossil fuel is combusted. Thus, the more fertilizer is applied, the more carbon is indirectly emitted through agriculture. In ASMGHG, emission coefficients per acre and per mass unit of fertilizer were established through use of input-output direct multipliers, total energy equivalents of fertilizer, emission coefficients of fossil fuels as reported by DOE, and EPIC results (Equation 34). Note that using input-output direct multipliers implies fixed proportions of various fuel types in manufacturing fertilizers. However, as the value of emission reductions increases, substitution of emission intensive fossil fuel types by less emission intensive fossil fuel types or other energy sources is likely. For the purpose of this study, the expected marginal improvement in assessment accuracy did not justify the marginal cost of gathering relevant information to relax this assumption. Emission coefficients were also adjusted for the four soil types and various nitrogen fertilizer management options.

Equation 34   Calculation of Indirect Carbon Emissions From Fertilizer Manufacturing

$$e^{Fert}_{R,C,W,T,L,F,NU} = q^{Fert}_{R,C,W,T,NU} \times \sum_{FF} \left(s^{BTU\%}_{FF,NU} \times en^{BTU}_{NU} \times e^{BTU}_{FF} \right) \times E^{EPIC\%}_{R,C,W,T,L,F,NU}$$

Where:

$e^{Fert}_{R,C,W,T,L,F,NU}$ = Indirect nutrient fertilizer emissions of CO_2 from producing one acre of crop C in region R, using water technology W, and tillage system T, fertilization alternative F on land type L,

$q^{Fert}_{R,C,W,T,NU}$ = Quantity of nutrient fertilizer NU applied to one acre of crop C, using water technology W, tillage system T in region R,

$s^{BTU\%}_{FF,NU}$ = Relative energy share of fossil fuel type FF in manufacturing nutrient fertilizer NU,

en^{BTU}_{NU} = Total energy input to produce one mass unit of nutrient fertilizer NU, and

$E^{EPIC\%}_{R,C,W,T,L,F,NU}$ = Emission coefficient adjustment factor from EPIC for nitrogen fertilizer for soil types and fertilizer management.

3.5.2 Sink Enhancements

Agriculture could offset fossil fuel based emissions through production of alternative energy sources and through carbon sequestration. Sequestration involves the buildup of soil organic matter through reduced tillage intensity or increased soil cover, and buildup of aboveground organic matter by planting trees on agricultural land.

3.5.2.1 Soil Carbon Emission Sink/Source

EPIC simulations provided the absolute Soil Organic Matter (SOM) equilibrium levels for each region, soil, and crop management. In converting the EPIC-based SOM equilibrium levels to ASMGHG coefficients, caution was necessary. SOM level calculations are new features in EPIC, which have not been verified or compared extensively to observed SOM behavior in natural soils. Thus, absolute EPIC-based SOM values were likely to over- or understate the true carbon sequestration potential.

To minimize EPIC bias, it was desirable that the total potential to sequester carbon through reduced tillage of agricultural soils in ASMGHG concurs to existing estimates from the literature (Lal, Kern). To meet this objective, EPIC-based SOM values were calibrated. Through this calibration, absolute SOM levels between different tillage intensities were adjusted but management specific differences within a tillage category were proportionally preserved. Below this process is described in detail.

As a first step in calibrating EPIC-based SOM estimates, total changes in SOM were calculated for each tillage system. Throughout the entire calculation, crop and irrigation acreage for each crop in each region were held constant at 1997 levels. The SOM base level was computed using the 1997 tillage mix and EPIC-based total SOM values (Equation 35). In Equation 36, EPIC-based total SOM levels for each tillage system are computed assuming that the respective tillage is used on all U.S. cropland. The net effect of exclusively using a particular tillage system throughout the U.S. on the change in total SOM is the difference between the total SOM levels using only the particular tillage system minus the 1997 total SOM level (Equation 37)

Equation 35 Total SOM Account Using EPIC Factors and USDA Tillage System Data

$$\overline{\text{SOM}}^{\text{EPIC}} = \text{L}^{\text{USDA}} \times \sum_{\text{R,C,W,L}} \sum_{\text{T}} \left(\text{s}^{\text{NRCS}}_{\text{R,C,W,T,L}} \times \text{SOM}^{\text{EPIC}}_{\text{R,C,W,T,L,"Nbase"}} \right)$$

Equation 36 Theoretical SOM Level of Each Tillage System Assuming 100 Percent Adoption

$$\text{SOM}^{\text{EPIC}}_{\text{T}} = \text{L}^{\text{USDA}} \times \sum_{\text{R,C,W,L}} \left(\left(\sum_{\tilde{\text{T}}} \text{s}^{\text{NRCS}}_{\text{R,C,W,}\tilde{\text{T}}\text{,L}} \right) \times \text{SOM}^{\text{EPIC}}_{\text{R,C,W,T,L,"Nbase"}} \right)$$

Equation 37 Total SOM Change of Each Tillage System Assuming 100 Percent Adoption

$$\begin{aligned} \Delta\text{SOM}^{\text{EPIC}}_{\text{T}} &= \text{SOM}^{\text{EPIC}}_{\text{T}} - \overline{\text{SOM}}^{\text{EPIC}} \\ &= \text{L}^{\text{USDA}} \times \sum_{\text{R,C,W,L}} \left(\begin{array}{l} \left(\sum_{\tilde{\text{T}}} \text{s}^{\text{NRCS}}_{\text{R,C,W,}\tilde{\text{T}}\text{,L}} \right) \times \text{SOM}^{\text{EPIC}}_{\text{R,C,W,T,L,"Nbase"}} \\ - \sum_{\tilde{\text{T}}} \left(\text{s}^{\text{NRCS}}_{\text{R,C,W,}\tilde{\text{T}}\text{,L}} \times \text{SOM}^{\text{EPIC}}_{\text{R,C,W,}\tilde{\text{T}}\text{,L,"Nbase"}} \right) \end{array} \right) \end{aligned}$$

Where:

L^{USDA} = Total cropland according to USDA estimates,

$\text{SOM}^{\text{EPIC}}_{\text{R,C,W,T,L,"Nbase"}}$ = Absolute soil organic matter per acre based on EPIC in region R, for crop C, water technology W, land type L and basic fertilization,

$\text{s}^{\text{NRCS}}_{\text{R,C,W,T,L}}$ = Relative share of tillage system T, water technology T, in region R, for crop C, on land type L, and

$\overline{\text{SOM}}^{\text{EPIC}}$ = Total soil carbon in U.S. cropland based on EPIC estimates and aggregated using 1997 NRCS observed tillage mix.

As a second step, target levels of total SOM changes under each tillage system were developed. These levels represent maximum changes in total SOM after a complete adoption of a particular tillage system. Lal has estimated the total potential from using zero tillage to be around one billion metric tons of carbon. Thus, this estimate was used as target level for zero tillage. Conservation tillage leads to slightly lower gains than zero tillage. Based on EPIC results, the total carbon sequestration potential of conservation tillage was assumed to be 80 percent of the potential from zero tillage (Equation 38). The expected total SOM change from applying conventional tillage on all fields (Equation 40) was deducted using the total potential of conservation and zero tillage, the proportions of current tillage system usage, and an additional assumption shown in Equation 39. In particular, it is assumed that maintaining the current proportions of tillage system use will not change the SOM levels. The proportionate deviation of EPIC estimates of the potential to sequester carbon from target levels was captured through an adjustment factor k_T^{SOM} (Equation 41).

Equation 38 Specification of Maximum SOM Change Under Complete Switch to Conservative Tillage

$$\Delta SOM_{\text{"Cons"}}^{Lit} = 80\% \times \Delta SOM_{\text{"Zero"}}^{Lit}$$

Equation 39 Zero SOM Change for Base Scenario

$$\Delta SOM_{\text{"Base"}}^{Lit} = \sum_{T} \left(s_T^{NRCS} \times \Delta SOM_T^{Lit} \right) \overset{!}{=} 0$$

Equation 40 Calculation of SOM Change at 100 Percent Conventional Tillage System Adoption

$$\Delta SOM_{\text{"Vent"}}^{Lit} = \sum_{T=\{\text{"Zero"},\text{"Cons"}\}} \left(- s_T^{NRCS} \times \Delta SOM_T^{Lit} \right) \Big/ s_{\text{"Vent"}}^{NRCS}$$

Equation 41 SOM Change Identity

$$\Delta SOM_T^{Lit} = k_T^{SOM} \times \Delta SOM_T^{EPIC}$$

Where:

$\Delta \mathrm{SOM}_T^{Lit}$ = Change in total soil carbon at 100% adoption of tillage system T (based on literature estimates),

s_T^{NRCS} = Fraction of tillage system T used in 1997 according to NRCS estimates,

$\Delta \mathrm{SOM}_T^{EPIC}$ = Change in total soil carbon for 100% adoption of tillage system T (based on EPIC), and

k_T^{SOM} = Scaling factor to adjust EPIC values.

For SOM changes in ASMGHG to be consistent with NRCS survey based estimates, Equation 42 needed to be satisfied. Substituting Equation 37 in Equation 41 yields Equation 43. Combining Equation 42 and Equation 43 in turn leads to Equation 44. This equality can be solved explicitly ASMGHG SOM level changes as a function of EPIC-based SOM estimates (Equation 45).

SOM coefficient adjustments are summarized in Table 3-4.

Equation 42 Augmented SOM Change Identity

$$\Delta \mathrm{SOM}_T^{Lit} \overset{!}{=} L^{USDA} \times \sum_{R,C,W,L} \left(\left(\sum_{\tilde{T}} s^{NRCS}_{R,C,W,L,\tilde{T}} \right) \times \Delta \mathrm{SOM}^{ASMGHG}_{R,C,W,T,L,\text{"Nbase"}} \right)$$

Equation 43 Identity After Substituting Equation 37 Into Equation 41

$$\Delta \mathrm{SOM}_T^{Lit} = k_T^{SOM} \times L^{USDA} \times \sum_{R,C,W,L} \left(\begin{array}{c} \left(\sum_{\tilde{T}} s^{NRCS}_{R,C,W,\tilde{T},L} \right) \times \mathrm{SOM}^{EPIC}_{R,C,W,T,L,\text{"Nbase"}} \\ - \sum_{\tilde{T}} \left(s^{NRCS}_{R,C,W,\tilde{T},L} \times \mathrm{SOM}^{EPIC}_{R,C,W,\tilde{T},L,\text{"Nbase"}} \right) \end{array} \right)$$

Equation 44 Identity After Substituting Equation 42 Into Equation 43

$$\left(\sum_{\tilde{T}} s^{NRCS}_{R,C,W,L,\tilde{T}}\right) \times \Delta SOM^{ASMGHG}_{R,C,W,T,L,"Nbase"} \overset{!}{=} k^{SOM}_{T} \times \begin{pmatrix} \left(\sum_{\tilde{T}} s^{NRCS}_{R,C,W,\tilde{T},L}\right) \times SOM^{EPIC}_{R,C,W,T,L,"Nbase"} \\ - \sum_{\tilde{T}} \left(s^{NRCS}_{R,C,W,\tilde{T},L} \times SOM^{EPIC}_{R,C,W,\tilde{T},L,"Nbase"} \right) \end{pmatrix}$$

Equation 45 SOM Difference Between New Management Equilibrium and Average Current SOM Level

$$\Delta SOM^{ASMGHG}_{R,C,W,T,L,"Nbase"} \overset{!}{=} \frac{k^{NRCS}_{T}}{\left(\sum_{\tilde{T}} s^{NRCS}_{R,C,W,L,\tilde{T}}\right)} \times \begin{pmatrix} \left(\sum_{\tilde{T}} s^{NRCS}_{R,C,W,\tilde{T},L}\right) \times SOM^{EPIC}_{R,C,W,T,L,"Nbase"} \\ - \sum_{\tilde{T}} \left(s^{NRCS}_{R,C,W,\tilde{T},L} \times SOM^{EPIC}_{R,C,W,\tilde{T},L,"Nbase"} \right) \end{pmatrix}$$

Table 3-4 Calibration of Soil Carbon Net Emission Coefficients

Criterion	Tillage System			
	1997 Mix	Conventional	Conservation	Zero
National system adoption in 1997	100 %	72.2 %	18.7 %	9.2 %
Assumed total organic matter change in million metric tons of carbon at 100% system adoption	0	Endogenous	600	1,000
Calculated final soil organic matter level in million metric tons of carbon at 100% system adoption (EPIC)	2,205	2,184	2,242	2,303
Calculated total soil organic matter change in million metric tons of carbon at 100% system adoption (EPIC)	0	-21	37	98
Calculated total soil organic matter change in million metric tons of carbon at 100% system adoption (ASMGHG)	0	-282	600	1,000
Adjustment factor (k_T^{SOM})	N/A	13.5	16.3	10.2

Where:

$\Delta SOM^{ASMGHG}_{R,C,W,T,L,F}$ = Change in SOM equilibrium of tillage system T relative to tillage mix weighted average in region R, for crop C, water technology W, land type L, and fertilization alternative F.

The change in SOM as computed through Equation 45 represents the maximum gain or loss of carbon from a particular strategy relative to the average current SOM level for that region, crop, and soil type. The average annual net emission coefficient then equals the maximum SOM change divided by the number of years it takes to reach the new equilibrium (Equation 46). For this study we assumed that it would take 30 years for the soil organic matter to adjust to a different tillage system and that the soil carbon changes linearly within this 30-year period.

Equation 46 Annual Soil Carbon Emission Coefficients in ASMGHG

$$e^{Soil}_{R,C,W,T,L,F} = \frac{\Delta SOM^{ASMGHG}_{R,C,W,T,L,F}}{T^{EquAdj}}$$

Where:

$e^{Soil}_{R,C,W,T,L,F}$ = Annual net emissions through changes in soil organic matter from production of one acre of crop C, in region R, using water technology W, tillage system T, and fertilization alternative F on land type L, and

T^{EquAdj} = Time span necessary to reach new soil carbon equilibrium after a change in management strategies.

3.5.2.2 Production of Fossil Fuel Substitutes

Biofuel and ethanol are agriculturally produced commodities, which can offset carbon emissions from fossil fuel based power plants, or fossil fuel based gasoline. Contrary to soil carbon sequestration through tillage reduction, these carbon emission mitigation options compete with the production of traditional agricultural commodities.

To implement biofuel generation in ASMGHG, production budgets for switch grass, hybrid poplar, and willow were obtained from the Oakridge National Laboratory (Walsh et al., see Table 3-5). While production of traditional agricultural crops is constrained to fall in a convex combination of historically observed crop mixes, no such constraint was enforced on biofuel crops. Mitigation policies are likely to directly or indirectly encourage growing these crops beyond historically observed limits.

Net emission reductions from cultivating and processing biofuel crops were calculated as shown in Equation 47. Data were available on production of energy units per mass unit of biofuel crop (Table 3-5) and on the average GHGE coefficients of electrical power plants per unit of energy (U.S. DOE, see Table 3-6). All power plant emission parameters refer to average annual emission coefficients obtained through a life cycle assessment (Mann and Spath).

Table 3-5 Regional Assumptions on Biomass Productivity and Resulting Net Emission Values

Biomass Crop	Region	Yield (Dry Tons per Acre)	Net Emissions (KG CE per Acre)		
			CO2	CH4	N2O
Willow	North East	4.21	-2,003	-86	3.4
Switch grass	North East	3.21	-1,342	-58	2.3
Switch grass	Lake States	3.64	-1,522	-66	2.6
Switch grass	Corn Belt	3.64	-1,522	-66	2.6
Switch grass	South East	5.16	-2,157	-93	3.6
Switch grass	Delta States	4.36	-1,823	-79	3.1
Hybrid poplar	Lake States	3.11	-1,480	-64	2.5
Hybrid poplar	Corn Belt	3.11	-1,480	-64	2.5
Hybrid poplar	South East	3.22	-1,532	-66	2.6
Hybrid poplar	Delta States	2.57	-1,223	-53	2.1

Table 3-6 Data and Assumptions for Calculating Emission Offsets From Biomass Power Plants

Parameter of 100 MW Power Plant	Feedstock	
	Biomass	Coal
Carbon dioxide emissions (g/KWH)	4.95 E+1	1.02 E+3
Methane emissions (g/KWH)	5.07 E-3	2.00
Nitrous oxide emissions (g/KWH)	9.54 E-3	4.30 E-3
Average heat rate (BTU/KWH)	9,179	10,318
Average net plant efficiency[ii] (%)	37.2	33.1

	Biomass Feedstock		
	Switch Gras	Willow	Hybrid Poplar
Annual feedstock input (1000 tons)	482.76	424.24	424.24

Equation 47 Net GHG Emission Coefficients of Biomass Production in ASMGHG

$$e^{\text{BioF}}_{\text{R,BF,L,G}} = y^{\text{DM}}_{\text{R,BF,L}}\left[\frac{\text{Dry Ton}}{\text{Acre}}\right] \times en^{\text{BTU}}_{\text{BF}}\left[\frac{\text{MBTU}_{\text{BF}}}{\text{Dry Ton}}\right] \times eff^{\text{ BioPP}}\left[\frac{\text{MBTU}_{\text{GRID}}}{\text{MBTU}_{\text{BF}}}\right]$$

$$\times \frac{1000}{3.4147}\left[\frac{\text{KWH}_{\text{GRID}}}{\text{MBTU}_{\text{GRID}}}\right] \times \left(E^{\text{BioPP}}_{\text{G}} - E^{\text{CoalPP}}_{\text{G}}\right)\left[\frac{\text{KG}}{\text{KWH}_{\text{GRID}}}\right]$$

Where:

$e^{\text{BioF}}_{\text{R,BF,L,G}}$ = Net emission of greenhouse gas G from using one acre in region R to produce biomass crop BF on land type L,

$y^{\text{DM}}_{\text{R,BF,L}}$ = Dry mass yield of one acre of biomass crop BF in region R on land type L,

$en^{\text{BTU}}_{\text{BF}}$ = Average energy yield for biomass crop BF,

$eff^{\text{ BioPP}}$ = Net plant efficiency of biomass fueled power plants,

$E^{\text{BioPP}}_{\text{G}}$ = Net emission of greenhouse gas G from using a biomass fueled power plant, and

$E^{\text{CoalPP}}_{\text{G}}$ = Net emission of greenhouse gas G from using a coal fired power plant.

Emission coefficients of ethanol production were obtained (Equation 48) in a similar fashion. Since ethanol can be used as gasoline, the carbon emission reduction corresponds to the amount of carbon otherwise released when combusting fossil fuel based gasoline.

Equation 48 Carbon Emission Coefficients From Ethanol Production

$$e^{\text{ET}}_{\text{P,R,C}^{\text{ET}}\text{,W,T,L,F}} = y^{\text{ET}}_{\text{P,C}^{\text{ET}}} \times \overline{\text{CE}}^{\text{GL}} \times y_{\text{R,C}^{\text{ET}}\text{,W,T,L,F}} \times \left(1 - \frac{L^{\%}_{\text{ET}}}{100}\right)$$

Where:

$e^{ET}_{P,R,C^{ET},W,T,L,F}$ = Carbon emission reduction from production of ethanol through process P using crop C^{ET} produced on one acre in region R with water technology W, tillage system T, fertilization alternative F on land type L,

$y^{ET}_{P,C^{ET}}$ = Ethanol yield of process P using commodity C^{ET},

$\overline{CE}^{GL}$ = Average carbon emission of fossil fuel based gasoline,

$y_{R,C^{ET},W,T,L,F}$ = Yield of one acre of ethanol crop C^{ET} produced with water technology W, tillage system T, fertilization alternative F on land type L, and

$L^{\%}_{ET}$ = Relative loss factor which accounts for carbon emissions from producing and processing ethanol.

3.5.2.3 Conversion of Agricultural Land Into Forestry

Planting trees on agricultural land is perhaps the most referred carbon sink on agricultural lands. Stavins estimated the national potential to sequester carbon from planting pines on agricultural lands as a function of carbon subsidies. His results are listed in Table 3-7 and were used in ASMGHG.

Table 3-7 Data on Potential, Costs, and Carbon Sequestration From Planting Trees on Agricultural Lands (After Stavins)

Scenario	Land Planted With Pines in 1000 Acres	Average Cost in $ per TCE	Carbon Sequestered Annually in 1000 Metric Tons
1	0	0	0
2	4653	57.32	7045
3	6579	105.63	9961
4	7484	129.15	11332
5	7897	142.25	11957
6	8212	155.98	12434
7	8470	169.22	12825
8	8689	182.74	13156
9	8874	195.72	13437
10	9038	208.21	13685
11	9178	219.53	13897

Each estimation point from Stavins was used to approximate the underlying marginal cost function for planting trees on agricultural land in a stepwise linear fashion. Total emission reductions and associated total costs as calculated in ASMGHG are shown in Equation 49 and Equation 50. Emission reductions were included in the sink account (Equation 55), while costs were made part of the objective function. Land used for planting trees was included in the land balance equation of ASMGHG. Equation 51 restricts the step variables to sum up to unity. This forces a convex combination.

Equation 49 National Annual Emission Reduction From Afforestation of Cropland

$$ER^{ASMGHG}_{"Tree","CE"} = \sum_i \left(Z_i \times ER^{Stavins}_{"Tree","CE",i} \right)$$

Equation 50 Total Costs of Afforestation

$$C^{ASMGHG}_{"Tree"} = \sum_i \left(Z_i \times ER^{Stavins}_{"Tree","CE",i} \times C^{Stavins}_{"Tree",i} \right)$$

Equation 51 Convexity Constraint for Afforestation Variable in ASMGHG

$$\sum_i Z_i = 1$$

Where:

$ER^{ASMGHG}_{"Tree","CE"}$ = Total annual emission reduction in ASMGHG from planting trees on agricultural lands,

$ER^{Stavins}_{"Tree","CE",i}$ = Annual emission reduction in ASMGHG from planting trees on agricultural lands by step,

$C^{ASMGHG}_{"Tree"}$ = Total annual costs incurred from planting trees,

$C^{Stavins}_{"Tree",i}$ = Average annual cost of planting trees per ton of carbon sequestered, and

Z_i = Step variable.

3.6 Nitrous Oxide Emissions

Nitrous oxide constitutes perhaps the least understood greenhouse gas among all agriculturally relevant gases. However, a few measures correlate the amount of nitrous oxide emitted from agricultural soils or livestock to specific management practices. In particular, fertilizer management strategies impact the amount of nitrogen that is denitrified (Granli and Bøckman) Denitrified nitrogen, then, enters the atmosphere either as atmospheric nitrogen (N_2) or as nitrous oxide (N_2O). The ratio of nitrous oxide emissions to total nitrogen emissions from denitrification varies depending on environmental conditions (Changsheng, Narayanan, and Harriss). Depending on the annual average temperature, precipitation, and nitrogen content in rainfall, between 19 and 33 percent of the total denitrified nitrogen are estimated to be N_2O-nitrogen. Thus, with respect to soils, estimates of denitrification rates and nitrogen air volatilization may provide proxies of N_2O emissions.

Management strategies to decrease N_2O emissions aim at decreasing the denitrification rate. Included in the analysis was substitution of anhydrous ammonia fertilizer, use of nitrification inhibitors, and reduced nitrogen fertilizer application. Again EPIC was used to simulate the effects of changed fertilization management on yields and variable costs.

Equation 52 Calculation of Nitrous Oxide Emission Coefficients From Crop Production

$$e^{N_2O}_{R,C,W,T,L,F} = \left(dn^{EPIC}_{R,C,W,T,L,F} + av^{EPIC}_{R,C,W,T,L,F}\right) \times \left(\frac{r^{N_2O/N_2}}{1 + r^{N_2O/N_2}}\right)$$

Where:

$e^{N_2O}_{R,C,W,T,L,F}$ = Nitrous oxide emission coefficient from producing one acre of crop C in region R using water technology W, tillage system T, fertilization alternative F on land type L,

$dn^{EPIC}_{R,C,W,T,L,F}$ = Denitrification rate from producing one acre of crop C in region R using water technology W, tillage system T, fertilization alternative F on land type L (EPIC parameter),

r^{N_2O/N_2} = Ratio of nitrous oxide to atmospheric nitrogen from denitrification, and

$av^{EPIC}_{R,C,W,T,L,F}$ = Air volatilization rate from producing one acre of crop C in region R using water technology W, tillage system T, fertilization alternative F on land type L (EPIC parameter).

To minimize the bias of nitrous oxide emission coefficients, all EPIC values were adjusted in absolute magnitude; however, relative differences between different management were preserved. The validation process was based on the assumption that nitrous oxide emission under full fertilization amount to about one percent of the amount of nitrogen fertilizer applied (Equation 53). Results of emission coefficient validation are listed in Table 3-8.

Equation 53 Calibration of Nitrous Oxide Emission Coefficients

$$\tilde{e}^{N_2O}_{R,C,W,T,L,F} = e^{N_2O}_{R,C,W,T,L,F} \times \frac{0.01 \times \sum_{R,C,W,T,L,F}\left(f^{N}_{R,C,W,T,L,\text{"NBase"}} \times A^{Base}_{R,C,W,T,L,F}\right)}{\sum_{R,C,W,T,L,F}\left(e^{N_2O}_{R,C,W,T,L,\text{"NBase"}} \times A^{Base}_{R,C,W,T,L,F}\right)}$$

Where:

$\tilde{e}^{N_2O}_{R,C,W,T,L,F}$ = Adjusted nitrous oxide emission coefficient,

$f^{N}_{R,C,W,T,L,\text{"NBASE"}}$ = Amount of nitrogen fertilizer applied to crop C, in region R, when using water technology W, tillage system T, land type L, and basic fertilization, and

$A_{R,C,W,T,L,F}$ = Total acreage allocated to crop C in region R using water technology W, tillage system T, and fertilization alternative F on land type L.

3.7 Emissions Accounting in ASMGHG

3.7.1 Individual Emission Sources and Sinks

Emission accounting in ASMGHG takes place on the national level. Source emissions are summed over emissions from crop and livestock production, land transfer, and from processing (Equation 54).

Table 3-8 Assumptions for Nitrous Oxide Emission Coefficient Calculation and Validation

Parameter	Value
Total nitrogen fertilizer application in 1995 (USDA), in MMT	11.7
Total nitrogen fertilizer application of ASMGHG base solution (in MMT)	9.6
ASMGHG basic nitrous oxide emissions assuming emissions equal 1 percent of nitrogen fertilizer (in thousand metric tons)	96.0
Assumed denitrification water threshold level for all EPIC runs	99%
Assumed N2O/(N2O+N2) ratio of denitrification for calculating nitrous oxide emission coefficients from denitrification rates	0.22
ASMGHG basic nitrous oxide emissions using EPIC coefficients (in thousand metric tons)	20,495
Adjustment multiplier for original EPIC coefficients	4.68 E-3

Crop emission coefficients vary by crop, water technology, tillage system, soil type, fertilizer management, and region. Livestock emission coefficients are specific by region, animal, and methane reduction technology.

Equation 54 All Emission Sources Accounting Constraint in ASMGHG

$$
\begin{aligned}
E_G = & \sum_{R,C,W,T,L,F} \left(e^{Crop}_{R,C,W,T,L,F,G} \times A_{R,C,W,T,L,F} \right) \Big|_{e^{C}_{R,C,W,T,L,F,G} > 0} \\
& + \sum_{R,A,B} \left(\left(e^{Manr}_{R,A,G} + e^{EntF}_{R,A,G,B} \right) \times N_{R,A,B} \right) \\
& - \sum_{R,L} \left(e^{Pasture}_{R,L,G} \times L^{Pasture->Crop}_{R,L} \right) \\
& + \sum_{P} \left(e^{PowP}_{P,G} \times BP^{PowP}_{P} \right)
\end{aligned}
$$

Where:

$e^{Crop}_{R,C,W,T,L,F,G}$ = Emissions of greenhouse gas G from production of one acre of crop C in region R using water technology W, tillage system T, fertilization alternative F, on land type L, and

$e^{Manr}_{R,A,G}$ = Emissions of greenhouse gas G from production of one animal unit A in region R.

A second block of equations calculates greenhouse gas sinks (Equation 55). Currently, there are three sinks included for carbon dioxide emission reduction and one sink for methane emission reduction. Note that sink here refers to all management options, which lead to a decrease in net emissions relative to the base scenario.

Equation 55 All Emission Sinks Accounting Constraint in ASMGHG

$$
\begin{aligned}
S_G = & \sum_P \left(e^{PowP}_{P,G} \times BP^{PowP}_P\right)\Big|_{e^{PowP}_{P,G}>0} \\
& + \sum_P \left(e^{Ethl}_P \times EP^{Ethl}_P\right) \\
& + \sum_i \left(C^{Pine}_i \times \lambda_i\right) \\
& - \sum_{R,L} \left(e^{Pasture}_{R,L} \times L^{Cropland->Pasture}_{R,L}\right) \\
& + \sum_{R,A,i} \left(e^{Manr}_{R,A} \times M_{R,A,i}\right) \\
& - \sum_{R,C,W,T,L,F} \left(e^{SoilC}_{R,C,W,T,L,F} \times A_{R,C,W,T,L,F}\right)\Big|_{e^{SoilC}_{R,C,W,T,L,F}<0}
\end{aligned}
$$

Where:

C^{Pine}_i = Amount of carbon sequestered nationally at carbon equivalent value i,

$A^{BioF}_{R,BF,L}$ = Acreage allocated to production of biofuel crop BF in region R on land type L, and

$A^{Ethl}_{P^{ET},R,C^{ET},W,T,L,F}$ = Acreage allocated to crop C^{ET} from region R, water technology W, tillage system T, fertilization alternative F on land type L to produce ethanol through process P^{ET}.

3.7.2 Aggregated Emissions

The emission accounting equations described above do not provide emission estimates in Kyoto Protocol defined greenhouse gas categories such as methane, nitrous oxide, or carbon dioxide. Instead, the variables E_G and S_G contain total emissions from individual emission sources such as methane emissions from enteric fermentation or total emission reductions from individual sinks such as carbon sequestration from tree planting. Kyoto Protocol defined greenhouse gas categories are calculated through Equation 56 and Equation 57. The two-dimensional mappings, Emap (KG, G) and Smap (KG, G), ensure an appropriate summation of source emissions and sink emission reductions into the three relevant greenhouse gas categories.

Equation 56 Summation of Individual Emission Sources

$$E_{KG} = \sum_{Emap(KG,G)} E_G$$

Equation 57 Summation of Individual Emission Sinks

$$S_{KG} = \sum_{Smap(KG,G)} S_G$$

3.8 Mitigation Policies

3.8.1 Dual Emission Accounting

Mitigation policies may or may not affect all agricultural greenhouse gas sources and sinks. High transaction costs combined with relatively low expected emission reductions may induce policy makers to not police each and every emission source or sink. Nevertheless, those "ignored" sources and sinks will continue to exist and will continue to emit or absorb greenhouse gases. To distinguish between regulated and unregulated sources and sinks, a dual emission accounting system of equations was introduced in ASMGHG. Contrary to the accounting scheme described in section 3.7.1, the dual equations will only account for selected emission sources and sinks.

The mathematical structure of the dual emission accounting scheme is shown in Equation 58 through Equation 63. The dual accounting equations of "active" individual greenhouse gas sources (Equation 58) and sinks (Equation 60) are identical to Equation 54 and Equation 55. For "non-active" sources and sinks, the dual accounting values equal baseline emissions (Equation 59) and baseline sequestration (Equation 61), respectively. The reason for setting ignored emission sources and sinks equal to their baseline value will be explained in section 3.8.2.

Equation 58 Active Emission Sources Accounting Constraint in ASMGHG

$$
{}^{D}E_{G} = \left. \left(\begin{array}{l} \displaystyle \sum_{R,C,W,T,L,F} \left(e^{Crop}_{R,C,W,T,L,F,G} \times A_{R,C,W,T,L,F} \right) \Big|_{e^{C}_{R,C,W,T,L,F,G} > 0} \\ \displaystyle + \sum_{R,A,B} \left(\left(e^{Manr}_{R,A,G} + e^{EntF}_{R,A,G,B} \right) \times N_{R,A,B} \right) \\ \displaystyle - \sum_{R,L} \left(e^{Pasture}_{R,L,G} \times L^{Pasture->Crop}_{R,L} \right) \\ \displaystyle + \sum_{P} \left(e^{PowP}_{P,G} \times BP^{PowP}_{P} \right) \end{array} \right) \right|_{G \in G^{Active}}
$$

Equation 59 Fixation of Ignored Emission Sources at Baseline Level

$$
{}^{D}E_{G} = \hat{E}^{Base}_{G} \Big|_{G \notin G^{Active}}
$$

Equation 60 Active Emission Sinks Accounting Constraint in ASMGHG

$$
{}^{D}S_{G} = \left. \left(\begin{array}{l} \displaystyle \sum_{P} \left(e^{PowP}_{P,G} \times BP^{PowP}_{P} \right) \Big|_{e^{PowP}_{P,G} > 0} \\ \displaystyle + \sum_{P} \left(e^{Ethl}_{P} \times EP^{Ethl}_{P} \right) \\ \displaystyle + \sum_{i} \left(C^{Pine}_{i} \times \lambda_{i} \right) \\ \displaystyle - \sum_{R,L} \left(e^{Pasture}_{R,L} \times L^{Cropland->Pasture}_{R,L} \right) \\ \displaystyle + \sum_{R,A,i} \left(e^{Manr}_{R,A} \times M_{R,A,i} \right) \\ \displaystyle - \sum_{R,C,W,T,L,F} \left(e^{SoilC}_{R,C,W,T,L,F} \times A_{R,C,W,T,L,F} \right) \Big|_{e^{SoilC}_{R,C,W,T,L,F} < 0} \end{array} \right) \right|_{G \in G^{Active}}
$$

Equation 61 Fixation of Ignored Emission Sinks at Baseline Level

$$
{}^{D}S_{G} = \hat{S}^{Base}_{G} \Big|_{G \notin G^{Active}}
$$

Equation 62 Calculation of Total Emission Sources

$$ {}^{D}E_{KG} = \sum_{Emap(KG,G)} \left({}^{"a"}E_{G} + {}^{"na"}E_{G} \right) $$

Equation 63 Calculation of Total Emission Sinks

$$ {}^{D}S_{KG} = \sum_{Smap(KG,G)} \left({}^{"a"}S_{G} + {}^{"na"}\hat{S}_{G} \right) $$

Where:

G^{Active} = Active emission source or sink.

The dual emission accounting system allows analysis of both different policy designs and different assumptions about the availability of mitigation strategies in the agricultural sector. It is also valuable to multi gas side effects of policies, which do not cover all GHGs or mitigation strategies.

3.8.2 Policy Equations

3.8.2.1 Emission Standards

Emission standards place an upper limit on allowable net emissions of greenhouse gas categories as defined by the Kyoto Protocol (Equation 64). Two additional non-negative variables - a slack and a surplus variable - capture positive and negative deviations from the imposed standard. With a simple standard, net emission savings have no value; however, net emissions above the standard are penalized (Equation 65).

Equation 64 Implementation of Emission Standards in ASMGHG

$$ \left({}^{D}E_{KG} - {}^{D}S_{KG} + SAV_{KG} - SUR_{KG} = Z_{KG} \right)\Big|_{\text{If } Z_{KG}>0} $$

Equation 65 Costs of Excess Emissions Above Specified Standard

$$ C^{Ag} = \sum_{KG} \left(FINE_{KG} \times SUR_{KG} \right)\Big|_{\text{If } Z_{KG}>0} $$

Where:

C^{Ag} = Total penalty paid from the AG-sector for excess emissions,

SAV_{KG} = GHG Emissions below target (saved emissions),

SUR_{KG} = GHGE above target (emissions surplus),

Z_{KG} = GHGE target, and

$FINE_{KG}$ = Penalty on excess emissions of Kyoto Protocol defined GHG.

In ASMGHG, Equation 64 is only enforced if the standard for a particular greenhouse gas is strictly positive. Similarly, fines on excess emissions are only computed for greenhouse gas categories with a strictly positive standard (Equation 65). To analyze the effect of an overall standard on carbon equivalent net emissions, the individual methane, nitrous oxide, and carbon dioxide standards are set to zero leaving only the carbon equivalent standard active at the appropriate positive level.

3.8.2.2 Emissions Trading

Emissions trading constitutes a mitigation policy, which directly regulates the quantity of emissions. However, entities have more flexibility in meeting the standard through trade of emission permits with other entities. Emissions trading systems can be designed in many ways (Tietenberg, et al.). At this time, no decision has been made as to which types of emissions trading will be allowed. Consequently, the setup described in this section may have to be modified whenever more information becomes available.

In the simplest setup, the agricultural sector is treated as one entity, which could sell emission permits to and buy emission permits from other entities such as the electricity sector (Equation 66). Trading of emission permits is assumed to be perfect within the agricultural sector. Trading between the agricultural and other sectors is based on a given price. Cost and revenue calculations under this type of emissions trading are shown in Equation 67 and Equation 68.

Equation 66 Implementation of Emissions Trading in ASMGHG

$$\left({}^{D}E_{KG} - {}^{D}S_{KG} + \sum_{ENT} BUY_{ENT,KG} - \sum_{ENT} SELL_{ENT,KG} + SAV_{KG} - SUR_{KG} = Z_{KG} \right)\Bigg|_{\text{If } Z_{KG}>0}$$

Equation 67 Total Cost From Emissions Trading to Agricultural Sector in ASMGHG

$$C^{Ag} = \sum_{KG} \left(FINE_{KG} \times SUR_{KG} + \sum_{ENT} \left(p_{ENT,KG} \times BUY_{ENT,KG} \right) \right)_{\text{If } Z_{KG}>0}$$

Equation 68 Total Benefits From Emissions Trading to Agricultural Sector in ASMGHG

$$V^{Ag} = \sum_{KG} \sum_{ENT} \left(p_{ENT,KG} \times BUY_{ENT,KG} \right)$$

Where:

$\sum_{ENT} BUY_{ENT,KG}$ = Total volume of GHG emission credits purchased by entity ENT from the agricultural sector,

$SELL_{ENT,KG}$ = Total volume of GHG emission credits sold by entity ENT to the agricultural sector,

V^{Ag} = Total value of marketed emission credits in the agricultural sector, and

$p_{ENT,KG}$ = Market price for tradable emission credits.

3.8.2.3 Emission Taxes and Sequestration Subsidies

Taxes and subsidies can impact agricultural operations both directly and indirectly. A direct emissions tax or sequestration subsidy is shown in Equation 69. This equation assumes perfect monitoring and enforceability of agricultural emission sources and sinks. Given the non-point source nature of these emissions, this assumption is rather unrealistic. However, it is a useful theoretical assumption for finding the upper boundary of marginal abatement of greenhouse gas emissions. It can also be interpreted as least cost estimation of greenhouse gas emission mitigation.

Equation 69 Emission Taxation in ASMGHG

$$\mathrm{TAX}^{AG} = \sum_{KG} \left(t_{KG} \times \left({}^{D}E_{KG} - {}^{D}S_{KG} \right) \right) \Big|_{t_{KG}>0}$$

Where:

t_{KG} = Tax rate on Kyoto Protocol defined GHG net emissions, and

TAX^{AG} = Total tax payment from the agricultural sector.

3.8.2.4 Special Greenhouse Gas Emission Related Tax or Subsidy Policies

The non-point source nature of greenhouse gas emissions suggests emissions taxing upstream at the input level rather than downstream. ASMGHG provides manifold opportunities to examine upstream tax or subsidy policies. Examples are a carbon emission tax imposed on fossil fuel use, a carbon subsidy paid for land use changes, a methane emission tax imposed on certain types of livestock management, or various combinations of those policies. Equation 70 gives an example of how to implement a tax or subsidy on different forms of tillage management.

Equation 70 Total Tax Value in the Agricultural Sector

$$\mathrm{TAX}^{AG} = \sum_{T,L} \left(t_{T,L} \times \sum_{R,C,W,F} A_{R,C,W,T,L,F} \right)$$

Where:

$A_{R,C,W,T,L,F}$ = Acreage in region R, on land type L, allocated to crop C, water technology W, tillage system T, and fertilization alternative F, and

$t_{T,L}$ = Tillage and land type specific tax.

3.9 Scenario Analysis in ASMGHG

ASMGHG provides four sets of scenario specifications, which can be used to examine the effects of GHGE mitigation policies under various assumptions. The first scenario set (POLICY) contains all policies to be analyzed. The set includes greenhouse gas emission taxes, emission reduction subsidies, emission standards, and others. The second scenario set (INTENSITY) contains the levels of intensity for the policies activated in scenario set one. Thus, if a policy consists of a tax or subsidy, scenario set two contains all desired tax or subsidy levels. If the policy is a standard, scenario set two will contain all desired levels of the standard.

The third scenario set (STRATEGY) specifies which mitigation options are active in ASMGHG. This set is used to find the assessment bias from not modeling mitigation options simultaneously. Finally, scenario set four (SCOPE) in ASMGHG allows researchers to specify different assumptions about the economic scope of the analysis. For the purpose of this study, only the highest economic scope setting was used, where prices, domestic production, and imports from and exports to other countries are endogenous. To estimate the impact of specific assumptions one could specify and analyze different settings in scenario set four. Alternative settings may include use of exogenous prices, exogenous crop acreage allocation, or zero trade restrictions.

Multiple specifications of the four scenario sets can yield substantial combination of model runs. To avoid redundant, senseless, or undesired scenario combinations, model runs are controlled and by a four-dimensional set. For example, it would be senseless to examine a tax policy on nitrous oxide emissions if no nitrous oxide emission mitigation option is active.

3.10 ASMGHG Tableau

Linear programming models can be efficiently summarized through tableaus, which display equations as rows and variables as columns. The base model of ASMGHG contains 5,248 equations, 88,057 variables and 557,615 non-zero coefficients[iii]. A simplified version of the ASMGHG tableau is provided in Figure 3-2. Structurally similar equations and variables are combined in blocks. For example, the equation block "Primary Goods Balance" represents 54 individual equations, one equation for each of the 54 primary agricultural commodities contained in ASMGHG. The objective function in Figure 3-2 is shown as implicit identity, where the unrestricted variable ‘Consumer plus Producer Surplus’ denotes the variable to be maximized during the optimization algorithm.

Variable Blocks (Columns)	Objective Function	Primary Goods Balance	Secondary Goods Balance	Feeding Balance	Land Balance	AUMS Balance	Water Balance	Labor Balance	Family Labor Constraint	Livestock Population Account	Manure Management	Manure Management Limit	GHG Sink Account	GHG Emission Account	Total Emission Summary	Total Sink Summary	Variables Bounds
	0	0	0	0	+	0	0	0	+	0	0	0	0	0	0	0	
	=	≤	≤	≤	≤	≤	≤	≤	≤	=	≤	≤	=	=	=	=	
Consumer plus Producer Surplus	+																u
Land transfer from Cropland	+				m												+
Land transfer from Pasture	+				m												+
Forest supply					-												+
Forest Demand					+												+
Land transfer from Forest	+																+
Land transfer to Forest	-																+
Tree Planting													-				+
GHG Emission Sink													+			m	+
GHG Emission Source														+	m		+
Regional Processing	m	+	m	m													+
National Processing	m	m	m										m	-			+
Hired Labor								-									+
Family Labor	+							-	+								+
Water	+						-										+
AUMS						-											+
Manure Management											m	+	-				+
Livestock Population										+		-		-			+
Livestock Production	m	m	+	+	+	+		+		-							+
Cover Crops	+				+												+
Crop Production	m	-			+		+	+					-	-			+
Secondary Export			+														+
Secondary Import			-														+
Secondary Demand	-		+														+
Primary Export	-	+															+
Primary Import		-															+
Primary Demand	-	+															+

Equation Blocks (Rows)

Notation

“+” = all positive
“-“ = all negative
“m” = of mixed sign
“u” = unrestricted in sign

Figure 3-2 Simplified ASMGHG tableau

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Endnotes:

[i] This procedure is done automatically through a program.

[ii] The power plant efficiency is defined in the traditional sense as the energy delivered to the grid (3414.7 BTU per kWh) divided by the energy in the power plant feedstock. For coal fired power plants, an estimate for the efficiency was obtained from the Electric Power Annual for 1998. Mann and Spath provided an estimate for the efficiency of biomass power plants.

[iii] Note that these values were computed for a setup with three fertilization alternatives. Increasing the number of alternative management options, i.e., allowing for more alternative fertilization options will also increase the ASMGHG model size, in particular the number of contained variables.