DOE Project Termination Report for

Supply Curves for Agricultural and Forestry Greenhouse Gas Emissions and their Use in Integrated Assessments: Methodology and Case Development

Funded by Department of Energy Office of Science under Notice 01-22, Integrated Assessment of Global Climate Change Research

By Bruce A. McCarl and Dhazn Gillig

Department of Agricultural Economics
Texas A&M University and Texas Agricultural Experiment Station

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1 *Summary of results:*

The results produced by this project include:

(1). Development of econometrically estimated marginal abatement and associated production curves describing response of agricultural and forestry emissions/sink/offsets enhancements for use in integrated assessments. Curves were developed that reflected agricultural, and forestry production of traditional commodities, carbon and other greenhouse gas offsets and biofuels given signals of general commodity demand, and carbon and energy prices. This work was done jointly with Dr. Ronald Sands at PNNL. A paper from this is forthcoming as follows

> Gillig, D., B.A. McCarl, and R.D. Sands, "Integrating Agricultural and Forestry GHG Mitigation Response into General Economy Frameworks: Developing a Family of Response Functions," Mitigation and Adaptation Strategies for Global Change, forthcoming, 2004.

An additional effort was done involving dynamics and a second paper was prepared that is annex A to this report and is

> Gillig, D., and B.A. McCarl, "Integrating Agricultural and Forestry Response to GHG Mitigation into General Economy Frameworks: Developing a Family of Response Functions using FASOM," 2004.

(2) Integration of the non dynamic curves from (1) into in a version of the PNNL SGM integrated assessment model was done in cooperation with Dr. Ronald Sands at PNNL. The results were reported at the second DOE conference on sequestration in the paper listed just below and the abstract is in Annex B of this report.

> Sands, R.D., B.A. McCarl, and D. Gillig, "Assessment of Terrestrial Carbon Sequestration Options within a United States Market for Greenhouse Gas Emissions Reductions," Presented at the Second Conference on Carbon Sequestration , Alexandria, VA, May 7, 2003.

The results in their latest version show about half of the needed offsets by 2030 can be achieved through agriculture through a mix of sequestration and biofuel options.

(3). Alternative agricultural sequestration estimates were developed in conjunction with personnel at Colorado State University using CENTURY and analyses can operate under the use of agricultural soil carbon data from either the EPIC or CENTURY models.

(4) A major effort was devoted to understanding the possible role and applicable actions from agriculture. Papers have been drafted from this as follows and are in the process of being finalized for publication.

Lee, H.C., and B.A. McCarl, "U.S. Agricultural and Forest Carbon Sequestration Over Time: An Economic Exploration," 2004.

Lee, H.C., B.A. McCarl, and D. Gillig, "The Dynamic Competitiveness of U.S. Agricultural and Forest Carbon Sequestration," 2004.

(5) Results have been presented in front of a number of scientific and policy bodies. These include the CASMGS, Non CO2 Network, Energy Modeling Forum on the science side and the Government of Japan, the Council of Economic Advisors , DOE, USDA and EPA on the policy side. Input has also been provided to the IPCC design of the fourth assessment report.

(6) Work was done with EPA and EIA to update the biofuel data and assumptions resulting in some now emerging results showing the criticality of biofuel assumptions.

2 *Papers and other products created*

Results from this study and its immediate predecessor have been published in Science , Climatic Change, with a number of pending publications in submissions planned. Several presentations have been given to industry, integrated assessment and government groups.

2.1 Journal Articles

Gillig, D., B.A. McCarl, and R.D. Sands, "Integrating Agricultural and Forestry GHG Mitigation Response into General Economy Frameworks: Developing a Family of Response Functions," Mitigation and Adaptation Strategies for Global Change, forthcoming, 2004.

Murray, B.C., B.A. McCarl, and H.C. Lee, "Estimating Leakage From Forest Carbon Sequestration Programs," Land Economics, forthcoming February, 2004.

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Schneider, U.A., and B.A. McCarl, "Economic Potential of Biomass Based Fuels for Greenhouse Gas Emission Mitigation," Environmental and Resource Economics, 24, 291-312, 2003.

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McCarl, B.A., and U.A. Schneider, "The Cost of Greenhouse Gas Mitigation in U. S. Agriculture and Forestry," Science, Volume 294 (21 Dec), 2481-2482, 2001.

2.2 Book Chapters

McCarl, B.A., R.M. Adams, and B. Hurd, "Global Climate Change and It's Impact on Agriculture," in Encyclopedia of Life Support Systems, Edited by C. Chang and C. Huang, Institute of Economics Academia Sinica and UNESCO,Taipai, Taiwan, forthcoming, 2004.

Schneider, U.A., and B.A. McCarl, "Economic Potential of Biomass for Greenhouse Gas Emission Reductions: Comparative role in Agriculture," in Policies for Greenhouse Gases Reduction and Pollution in Asian-Pacific, forthcoming, ed R. Mendelsohn, 2004.

Antle, J.M., and B.A. McCarl, "The Economics of Carbon Sequestration in Agricultural Soils," in Volume VI of the International Yearbook of Environmental and Resource Economics, edited by T. Tietenberg and H. Folmer, published by Edward Elgar., 278-310, 2003.

Marland, G., B.A. McCarl, and U.A. Schneider, "Soil Carbon: Policy and Economics," in Storing Carbon in Agricultural Soils: A Multi-Purpose Environmental Strategy, edited by N.J. Rosenberg and R.C. Izaurralde, Kluwer Academic Publishers, Boston, MA,, 111-117, 2001.

2.3 Govt/Univ/Research Reports

Paustian, K., B.A. Babcock, J. Hatfield, R. Lal, B.A. McCarl, S. McLaughlin, A. Mosier, C. Rice, G.P. Roberton, N.J. Rosenberg, and C. Rosenzweig, Agricultural Mitigation of Greenhouse Gases: Science and Policy Options, Forthcoming CAST Report, 2004.

McCarl, B.A., Written Testimony to Texas House Committee on Agriculture and Livestock Regarding No-till Farming Practices, October 14, 2002.

McCarl, B.A., Testimony on Opportunities for Greenhouse Gas Mitigation in Agriculture and Forestry, Congressional Record, Senate Committee on Agriculture, Nutrition and Forestry, Hearing on Biomass and Environmental Trading, March 29, 2001.

2.4 Unpublished Proceedings

Johnson, D.E., H.W. Phetteplace, A.F. Seidl, U.A. Schneider, and B.A. McCarl, "Management variations for U.S. beef production systems: effects on Greenhouse Gas Emissions and profitability," Presentation at 3rd International Methane & Nitrous Oxide Mitigation Conference, Beijing, China, December, 2003.

Johnson, D.E., H.W. Phetteplace, A.F. Seidl, U.A. Schneider, and B.A. McCarl, "Selected Variations in Management of U.S. Dairy Production Systems: Implications for Whole Farm Greenhouse Gas Emissions and Economic Returns," Presentation at 3rd International Methane & Nitrous Oxide Mitigation Conference, Beijing, China, December, 2003.

McCarl, B.A., "Comments on Integrated Environmental/Economic Modeling and Analysis Effort of the Strategic Policy Branch Agriculture and Agri-food Canada," Presented at the Workshop to Review the Analytical Tools and Analytical Needs of AAFC May 29-30, 2003, Ottawa, 2003.

McCarl, B.A., "On-Farm Carbon Sequestration? Can a farmer make some money at it?," Presented at Purdue Top Farmer Workshop, West Lafayette, IN, July, 2003.

McCarl, B.A., "Panel discussion on Acceptable Error," Presented at Carbon Measurement and Monitoring Forum, Manhattan, KS October 15-17, 2003.

McCarl, B.A., and M.K. Kim, "Can You Sell All That You Measure?," Presented at the Carbon Measurement and Monitoring Forum, Manhattan, KS October 15-17, 2003.

McCarl, B.A., B.C. Murray, F. de la Chesnaye, and K. Andrasko, "Assessing Economic Potential for GHG Offsets in US Agriculture and Forestry Using FASOMGHG," Presented to Staff of the Council of Economic Advisors and Energy Information Agency, 2003.

McCarl, B.A., H.C. Lee, D. Gillig, and B.C. Murray, "Economic Explorations on the Potential Role of Agriculture and Forestry in Mitigating Greenhouse Gas Emissions: Findings and Research Directions," Presented at 2nd DOE Conference on Carbon Sequestration, May, 2003.

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McCarl, B.A., "Assessment of GHG Mitigation Opportunities in U.S. Forest and Agricultural Sectors," Presented at 1st Agricultural GHG Mitigation Experts Meeting, Non-CO2 Network Project on Agricultural GHG Mitigation, Washington DC, December, 2002.

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Emissions into the Global Trade Analysis Project (GTAP) Data Base, Cambridge, MA, September 5-6,, 2002.

McCarl, B.A., "Including Potential Greenhouse Gas Emission Mitigation from Forests and Agriculture In Integrated Assessment," Presented at EMF -21 Meeting Washington, DC December, 2002.

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McCarl, B.A., and H.C. Lee, "Carbon Sequestration in Forests: An investigation of Economic Potential and Market Design Challenges," Presented at the Taiwan Forestry Research Institute Symposium on Forest Carbon Sequestration and Monitoring, November, 2002.

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McCarl, B.A., "Agriculture, Carbon Sequestration and Policy," Presented at the Carbon Sequestration Conference, Hornsby Bend Water Treatment Plant Conference Room, Austin, TX, July 26, 2001.

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McCarl, B.A., "Discussion of Sohngren, Mendelsohn and Sedjo paper entitled Optimal Forest Carbon Sequestration," Presented at Annual meeting of American Economic Association, New Orleans, January, 2001.

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McCarl, B.A., "Estimating Carbon Sequestration Supply from Forests and Agriculture with an Eye toward Integrated Assessment," Presented at Energy Modeling Forum, Aug, 2001, Snowmass, CO, 2001.

McCarl, B.A., "Remarks on Quantitative Knowledge for Environmental Policy Design," Presented at Conference on Farm Bill and the Environment, Washington, D.C., June 28-29, 2001.

McCarl, B.A., and U.A. Schneider, "An Agricultural Sector Model to Analyze Greenhouse Gas Emission Mitigation from Forests and Agriculture," Presented at the Agricultural Greenhouse Gas Modeling Forum, Shepardstown WV , Oct, 2001.

McCarl, B.A., and U.A. Schneider, "Economic Potential of Greenhouse Gas Emission Reductions: Comparative Role of Strategies in Agriculture," Presented at European Commission Non-CO2 Greenhouse Gases Network Meeting, Brussels, June 14-15, 2001.

McCarl, B.A., B.C. Murray, and U.A. Schneider, "Jointly Estimating Carbon Sequestration Supply from Forests and Agriculture," Paper presented at Western Economics Association Meetings, San Francisco, July 5-8, 2001.

2.5 Seminar Papers

McCarl, B.A., "Economic Explorations on the Potential Role of Agriculture and Forestry in Mitigating Greenhouse Gas Emissions: Findings and Research Directions," Presented at RTI/NC State Environmental Workshop Raleigh, NC January, 2003.

McCarl, B.A., "Economic Explorations on the Potential Role of Agriculture and Forestry in Mitigating Greenhouse Gas Emissions: Findings and Research Directions: Seminar," Presented at Department of Agricultural Economics, Purdue University West Lafayette, IN April, 2003.

McCarl, B.A., "Economic Explorations on the Potential Role of Agriculture and Forestry in Mitigating Greenhouse Gas Emissions: Findings and Research Directions: Seminar," Presented at International Food Policy Research Institute, Washington, D.C., May, 2003.

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2.6 Journal Drafts

Butt, T.A., and B.A. McCarl, "Can Farmers Sell All the Carbon They Sequester?," 2004.

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Elbakidze, L., and B.A. McCarl, "Sequestration Offsets versus Direct Emission Reductions: Consideration of Environmental Externalities," 2004.

Gillig, D., and B.A. McCarl, "Integrating Agricultural and Forestry Response to GHG Mitigation into General Economy Frameworks: Developing a Family of Response Functions using FASOM," 2004.

Lee, H.C., and B.A. McCarl, "U.S. Agricultural and Forest Carbon Sequestration Over Time: An Economic Exploration," 2004.

Lee, H.C., B.A. McCarl, and D. Gillig, "The Dynamic Competitiveness of U.S. Agricultural and Forest Carbon Sequestration," 2004.

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McCarl, B.A., B.C. Murray, and U.A. Schneider, "The Comparative Value of Biological Sequestration versus Emissions Offsets," 2004.

Pattanayak, S.K., B.A. McCarl, A.J. Sommer, B.C. Murray, T. Bondelid, D. Gillig, and B. DeAngelo, "Water Quality Co-effects of Greenhouse Gas Mitigation in US Agriculture," 2004.

Post, W.M., R.C. Izaurralde, J. Jastrow, B.A. McCarl, J. Amonette, V. Bailey, H. Bolton, L. Drinkwater, C. Garten, P. Jardine, G. Marland, R.M. Miller, N.J. Rosenberg, R.D. Sands, J.L. Smith, R. Lal, R. Matamala, P. Puget, T.O. West, and J. Zhou, "Carbon Sequestration Enhancement in Midwest U.S. Soils," 2004.

Schneider, U.A., and B.A. McCarl, "Implications of a Carbon Based Energy Tax for U.S. Agriculture," 2004.

Schneider, U.A., and B.A. McCarl, "Measuring Abatement Potentials When Multiple Change is Present: The Case of Greenhouse Gas Mitigation in US Agriculture and Forestry," 2004.

3 *Annex A* Integrating Agricultural and Forestry Dynamic Response to GHG Mitigation into General Economy Frameworks: Developing a Family of Response Functions*

by

Dhazn Gillig
Research Scientist
Department of Agricultural Economics
Texas A&M University, College Station, TX
dgillig@ag.tamu.edu
(979) 845-3153

Bruce A. McCarl
Regents Professor
Department of Agricultural Economics
Texas A&M University, College Station, TX
mccarl@tamu.edu
(979) 845-1706

Ronald D. Sands
Joint Global Change Research Institute
University of Maryland
College Park, MD , ronald.sands@pnl.gov
(301)-314-6765

Heng-Chi Lee
Lecturer
Department of Economics
The University of Western Ontario, London, Ontario, Canada
hlee43@uwo.ca
(519) 661-2111 Ext. 85452

September 2002

Seniority of authorship is shared by McCarl and Gillig.

* This research was sponsored by funds from the Texas Agricultural Experiment Station and the Department of Energy.

Integrating Agricultural and Forestry Dynamic Response to GHG Mitigation into General Economy Frameworks: Developing a Family of Response Functions using FASOM

3.1.1 Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), buildups in the atmospheric concentrations of GHGs will affect global climate, stimulating warming (IPCC, 2001a and 2001b). In the face of such a development, a number of societal groups are entertaining the possibility of actions directed at reducing concentrations by reducing net emissions. A number of investigators are trying to examine the costs of various options for GHG emission reduction largely structured around the assessment of compliance with the Kyoto Protocol (KP) as typified by the efforts under the Stanford Energy Modeling Forum (Weyant, 1999).

One characteristic across these analyses is a lack of in depth treatment of agricultural and forestry (AF) sector options[1]. In particular, emission mitigation can be achieved through AF efforts by employing sink strategies, biofuel production or emissions management relative to carbon, methane (CH_4) or nitrous oxide (N_2O) – as discussed in McCarl and Schneider, 2000. Agricultural and forestry participation is partially covered in recent work by Babiker et al. (2002) where the sink part only deals with the business as usual allocation in the Kyoto negotiations and the non CO_2 part is treated in a relatively simplistic fashion. Sohngen and Mendelsohn (2001) also cover such issues in a forestry context integrating with the Nordhaus (2001) DICE/RICE model but do not deal with agriculture or biofuels in depth.

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[1] The range of potential options is discussed in McCarl and Schneider (1999 and 2000).

Inclusion of agricultural and forestry (AF) options is a complex endeavor. The saturation and impermanence characteristics of sequestration related strategies portend an uneven dynamic contribution from the AF sectors so the response must be able to vary over time. Furthermore a number of the alternative emission mitigation strategies are directly competitive (for example crop land based strategies like traditional crop conservation tillage adoption, afforestation and biofuel production are mutually exclusive on an acre of land) and are misleading when treated independently. In addition, there are important market interactions that cause interactions between strategies. For example, afforestation of an acre that was producing corn reduces available feed and may stimulate production of feed elsewhere as well as intensification (increased fertilized or irrigation), or reduced livestock herd size all of which have GHG, economic and environmental implications.

Thus, proper inclusion of AF reactions requires a detailed dynamic examination of the underlying sectoral interactions. This study develops response functions from a dynamic AF sector model that embodies many of the complexities of agriculture and forestry for use in more general economy wide exercises. To data from which such functions can be estimated we ran the a dynamic AF sectoral model repeatedly under alternative constant over time levels for the carbon equivalent price, the general level of demand for agricultural commodities and the fuel price to generate data on the simultaneous production of GHG offsets and traditional AF commodities along with information on sectoral performance. Finally, we fit functions to those data to encapsulate the results in a compact form. In turn, these functions are hopefully usable in integrated assessment modeling to reflect the possible role the AF might play and the effects of allowing sinks into the GHG offset accounting system.

3.1.2 Model Used and Data Generation

This study generates data from which response functions can be estimated using the Forest and Agriculture Sector Optimization Model (FASOM - Adams et al), as adapted by Lee to include greenhouse gas management options in both agriculture and forestry. Hereafter the model will be called FASOMGHG. FASOMGHG accounts for accumulation of carbon in: (i) forest ecosystems on existing forest stands, (ii) regenerated and afforested stands, (iii) non-commercial carbon pools after harvest, (iv) harvested timber products, and (v) agricultural lands/sources including methane from livestock and rice and nitrous oxide from fertilization and livestock. The agricultural accounting part in FASOMGHG is based on that in ASMGHG[2] (Schneider, and McCarl and Schneider) accounting for: (i) agricultural lands soil sequestration in agriculture sector as influenced by tillage practice or/and land use shifts, (ii) livestock management, (iii) manure management, (iv) fertilization, (v) rice methane, (vi) fuel related emissions, and (vii) biofuels and a number of other GHG emission possibilities. FASOMGHG explicitly models the dynamic evolution of sequestration with soils and forests saturating

The FASOMGHG output gives simulated levels of GHG emissions and sequestration in both the agricultural and forest sectors. FASOMGHG deals with production and sequestration of three greenhouse gases — carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). All gasses are treated on a carbon equivalent basis allowing FASOMGHG to consider tradeoffs among the gasses. This is a set up using the IPCC (1995) 100-year global warming potentials. In particular, 1, 21, and 310 are used for carbon dioxide, methane, and nitrous oxide, respectively. In turn, all of these items are multiplied by the proportion of carbon in a unit of CO_2 (12/44) to convert to carbon equivalent (CE).

In addition to the GHG emissions and sequestration, FASOMGHG provides information on the U.S. agricultural and forest consumer, producer and rest of the world (ROW) welfare; environmental indicators; agricultural and forestry GHG mitigation practice usage; and commodity prices and production. In terms of dynamics, FASOMGHG simulates outcomes on a decade-by-decade basis over a 100-year time horizon. Additional details on FASOMGHG can be found at http://agecon.tamu.edu/faculty/mccarl/FASOM.html.

3.1.3 Response function estimation

FASOMGHG is a large and complex model containing close to 255,000 variables and 35,000 constraints. As such it is not suitable for direct incorporation into a general economy wide CGE model. Consequently, we decided to run the model under a number of alternative possible signals from the CGE model and generate data on responses then encapsulate that data into a set of response functions that could be incorporated into a CGE. This entailed making four main decisions.

1. Definition of the items that will convey the signals from the CGE.
2. Definition of the levels over which to vary those items.
3. Definition of the items for which response functions are to be estimated.

[2] Additional details on ASMGHG can be found at http://agecon.tamu.edu/faculty/mccarl/asm.html under the title "*Brief Technical Summary of ASMGHG ala 2001*".

4. Selection of functional form.

3.1.3.1 Signals – Independent variables

The signals we chose to use from the rest of the economy that will constitute the independent variables in the estimated functions are carbon and fuel prices plus the level of agricultural demand domestically and internationally. In the regression since we use a log form we enter a one for the zero carbon price case rather than a zero.

3.1.3.2 Levels over which to vary signals

Since the response functions are to be estimated econometrically and in turn used in CGE models a wide range of settings for the signals passed from the general economy is desirable. Specifically, FASOMGHG was used to simulate results under 180 settings (scenarios) of these independent variables including 10 alternative carbon prices ($0, $5, $10, $20, $30, $50, $80, $100, $200, and $300 per ton of CE); 3 levels of fuel prices for ethanol and energy (at 80%, 100%, and 120% of base levels), 3 levels of demand for agricultural products (at 90%, 100%, and 110% of 1997 demand levels), and 2 levels of demand for exports (at 100%, and 110% of 1997 demand levels). In addition to these 180 systematic scenarios, another 15 scenarios were randomly drawn from the ranges above for each of the 4 items to build degrees of freedom for parameters applied to each of the 4 varied factors. Each scenario setting is in fact simulated on a decade time step, with a 100-year time horizon.

While it would be desirable to vary the signals by decade for now we used constants across all decades. This compromises our ability to look at dynamic issues involved with rising carbon prices and the effects of earlier decisions on later outcomes. On the other hand the constant item runs took 5 weeks of computer time and the cases implied by a time phased carbon price would multiply that time substantially. Further work is planned on that issue but for now we are not treating it.

3.1.3.3 Response Functions Estimated

A family of response functions will be estimated from the FASOMGHG data. These fall into a number of classes wherein functions are estimated forecasting the effect of the signals on

1. *Quantity of GHG emissions and sinks* -- CO_2, CH_4, and N_2O emissions, biofuel based offsets and sinks by gas with separate sink and emission functions estimated since these items are expected to move in different directions with respect to carbon price and the net GHG flux goes from positive to negative in some cases.
    a. CO_2 emissions from use of fuel, tillage, fertilizer manufacture, pesticide manufacture, irrigation pumping, grassland conversion to crops, and deforestation with a separate function estimated for each.
    b. CH_4 emissions from enteric fermentation, manure, rice, biomass power plus plants production, and corn ethanol processing.
    c. N_2O emissions from fertilizer use, manure, residue burning, biomass production and use, and corn ethanol processing.
    d. CO_2 offsets from biofuel use in the form of feedstocks for power plants and ethanol as a replacement for gasoline.
    e. CO_2 sinks in forests and agricultural soil. CO_2 sinks in forests result from tree growth, product longevity and afforestation with carbon stored in forest soils, growing trees and harvested forest products. CO_2 sinks in agriculture arise from lessened tillage intensity or conversion to grasslands in the form of soil carbon sequestration.
2. *Commodity production, exports, imports and prices* -- Fisher index number for agricultural and forestry production, exports levels, import levels and prices.

3. *Land Use, allocation and valuation* -- Total land use for crops, biofuels, pasture and forest along with land rental rates and choice of tillage practices.
4. *Welfare distribution* --Agricultural and forest sector welfare for consumers', producers', and foreign interests.
5. *Environmental indicators*. Levels of irrigated crop land, irrigation water; nitrogen, phosphorus, potassium, pesticides, and fossil fuels along with levels of water and wind erosion.

Definitions of the dependent and independent variables are presented in

Table 1.

3.1.3.4 Functional Form

The general estimation approach involves 2 parts — a base functional form choice and accompanying model specification and a set of procedures for incorporation of dynamics.

The response functions are conceptually specified as:

$$\mathbf{Y} = f(\mathbf{x}, \varepsilon),$$

where **Y** is a vector of dependent variables, **x** is a vector of independent variables, and ε is a vector of error terms. All functions are estimated with a multiplicative functional form,

$$\mathrm{Y}_{\mathrm{kt}} = \mathrm{A}_{\mathrm{k}}\, e^{\alpha_t D_t} \prod_i \mathrm{x}_{\mathrm{i}}^{\beta_{ki}} \varepsilon_k$$

where A_k is the intercept term associated with the *k*th response function and β_{ki} is a vector of estimated parameters associated the vector **x** of signals.

A few words are in order about the dynamic specification. We have been asked by a number of modelers hoping to use these functions about how saturation causes the

GHG offsets to drop off over time. We decided to employ a multiplicative shifter for time period. In general, we expect the sequestration items to raise then fall as practices are adopted and then saturation occurs. In turn D_t is a decadal dummy variable where α_t represents the multiplicative shift in the dependent variable attributed when we are in decade t where t = years 2010-9 is designated as the base and D_t = 2, 3, 4, 5, 6, and 7 represents years 2020-9, 2030-9, 2040-9, 2050-9, 2060-9, 2070-9, respectively. The base functions are for a year during 2010-2019 with all of the independent variables held at the base level (0 for carbon price and 100 for the others) depict the FASOMGHG output under a zero carbon price with 1997 energy price, domestic demand, and export demand levels.

3.1.4 Results

A total of 46 response functions were estimated using an ordinary least squares estimation procedure. The full set of econometric results is reported in the Tables 2.[3] The volume of quantitative results is large. Consequently, only general statements about the overall results will be made. In general, the regressions had good structural fits according to the goodness-of-fit statistic (R^2) with the exception of those for land values and use of tillage methods. The few poor fits are likely caused by functional form choice (McCarl and Schneider, 2000 show that tillage use rises then falls as more land is diverted out of the sector to biofuels and forestry and a multiplicative functional form cannot replicate such behavior). Fortunately, the functions critical for inclusion into a CGE economy wide framework exhibited better structural fits (emissions, sequestration, total production and commodity price). In addition, a 4th order polynomial function was

[3] These are also available in a spreadsheet form from the author's web site.

used to estimate the agricultural soil carbon sequestration (ASC). This functional form is considered more reasonable given that the ASC increases with the carbon prices to a maximum, but then decreases (Figure 1).

Results show that a rise in the carbon price leads to expected decreases in emissions and increases in sinks. Agricultural production is negatively affected, as are exports while agricultural prices and imports are positively affected. Similarly, forest production is negatively affected while forest prices, exports, and imports are positively affected. Crop and pasture land use falls with higher carbon prices while biofuel and tree acreage rises as do land values. Conservation tillage tends to fall with no-tillage and convention tillage rising. A rise in the carbon price encourages a better forest management intensify and increases an average national rotation. Both agricultural and forest welfare are increased for producers but decreased for consumers and overseas interests. Finally, all of the environmental accounts show improvement with reductions in total crop land, irrigated land and chemical use.

Responses to demand shifts depend in part on their source. Shifts in domestic demand have larger effects as the majority of the consumption is domestic and a demand shift of our demand index (set at 100) depicts a larger underlying quantity shift. Export results also reflect the grain dominated export mix and thus act differently from the domestic mix which also contains fruit, vegetable and livestock products. The domestic demand shift tends to increase GHG emissions and decrease sinks. This occurs as crop land use goes up and does production and prices with exports fall. All the environmental indices rise, except for the nitrogen fertilizer.

Export increases tend to increase nitrous oxide levels and sinks again reflecting land competition and increased grain demand. The livestock related methane account goes down some reflecting feed competition and a smaller herd. Production and prices rise as does the producer welfare but the consumer welfare falls. The environmental impact indices all rise, except for the nitrogen fertilizer. Responses to an increase in fuel price increase agricultural prices and producer welfare. CO_2 emissions and sinks respond to fuel prices positively but the magnitude of the effect on sinks is larger than that on emissions.

3.1.4.1 Dynamic Effects

The time dependent shift in GHG reductions is captured through the use of the decade dummy variables. Figure 2 shows the levels of the predicted GHG emission reductions by decade. The quantity of GHG offset from all sources consistently grows over time. Figure 3 shows the total emission reductions disaggregated by major GHG component by decade and carbon equivalent prices. While agricultural soil sequestration plays a key role in obtaining GHG reductions in the early decades, biofuel offsets are the primary factors driving GHG reductions in the later decades. Agricultural soil sequestration is essentially saturated after the third decade. At carbon prices below $50 per ton of CE the emission offsets in the first four decades largely come from forest and agricultural soil sequestration. At higher carbon prices the emission offsets are largely composed from biofuel offsets and afforestation. Furthermore, after the third decade the emission reductions from biofuel offsets increase substantially with afforestation emission reductions decreasing. This result is due to the technological improvement on the biofuel productions making it a cheaper source of mitigation.

3.1.5 Conclusions

This study estimates a dynamic family of response functions summarizing agricultural and forest response to GHG mitigation efforts for inclusion into general economy wide studies. Namely, functions predict the effects of the carbon prices, fuel prices, domestic agricultural demands, and foreign agricultural demand on GHG emission reductions and sequestration, agricultural production, and prices, mitigation practices employed, sectoral welfare and environmental indicators. The functions indicate that sinks will increase and emissions decrease as a carbon market develops. It is also shown that time has a significant effect on the composition of the GHG emissions and sequestration portfolio with sequestration being more important early on and biofuels dominating later. The analysis also indicates that the rest of the sector is influenced by carbon policies with total production and consumer welfare being negatively correlated with prices, environmental indicators and producer welfare being positively correlated.

3.1.6 References

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Table 1. Variable definitions and magnitudes

Variable	Definition	Unit	Average
---------- **Dependent** ----------			
GHG Emissions:			
CO_2	CO_2 emissions	MMTCE	60.82
CH_4	CH_4 emissions	MMTCE	36.93
N_2O	N_2O emissions	MMTCE	30.47
GHG Sequestration in Sinks:			
CO_2	CO_2 sequestration	MMTCE	701.1
Agricultural Market conditions:			
Agricultural Price Index	U.S. all goods including crop and livestock prices	Fisher index	137.71
Agricultural Production Index	U.S. all goods including crop and livestock production	Fisher index	72.532
Agricultural Exports Index	U.S. all goods including crop and livestock exports	Fisher index	49.231
Agricultural Imports Index	U.S. all goods including crop and livestock imports	Fisher index	105.37
Forest Market conditions:			
Timber Price	Timber including sawlogs, pulpwood, and fuelwood for both softwoods and hardwoods	Fisher index	109.18
Timber Production		Fisher index	99.30
Timber Exports		Fisher index	105.16
Timber Imports		Fisher index	162.42
Forest Management Intensity Class:			
Afforestation		1000 acres	2.65
Reforestation		1000 acres	3.10
Average Rotation:			

Existing Forest		1000 acres	74.99
Afforestation		1000 acres	27.84
Reforestation		1000 acres	23.79
Agricultural and Forestry Land related data:			
Crop land	Crop land farmed	10^6 acres	276.79
Crop land rent	National average Crop land rental rate	$/acre	710.09
Pasture land	Pasture land used	10^6 acres	313.90
Pasture land rent	National average Pasture land rental rate	$/acre	101.91
Forest land	Acres afforested	10^6 acres	0.33
Biofuel crop land	Acres devoted to biofuel crops	10^6 acres	37.59
Conventional tillage	Crop acres treated with conventional tillage	10^6 acres	120.70
Conservation tillage	Crop acres treated with conservation tillage	10^6 acres	104.69
No-tillage	Crop acres treated with no-till practices	10^6 acres	89.01
Agricultural Welfare:			
Producer Welfare	U.S. producer welfare	Million $	644.33
Consumer Welfare	U.S. consumer welfare	Million $	1189.3
Rest of the World	The rest of the world welfare	Million $	311.47
Forest Welfare:			
Producer Welfare	U.S. producer welfare	Billion $	349.83
Consumer Welfare	U.S. consumer welfare	Billion $	1238.10
Rest of the World	The rest of the world welfare	Billion $	3.23
Environmental Indicators:			
Irrigated land	Total area of irrigated land	10^6 acres	106.36
Irrigation water use	Total irrigation water use	10^6 acre-ft	122.17
Pesticide	Total pesticide use	10^6 dollars	10139.
Fossil fuel	Total Fossil fuel use	10^6 dollars	2513.6
Nitrogen fertilizer	Total nitrogen fertilizer use	10^6 tons	13.817
Phosphorus fertilizer	Total phosphorus fertilizer use	10^6 tons	2.1750

Potassium fertilizer	Total potassium fertilizer use	10^6 tons	3.1867
Erosion	Water and wind erosion	10^6 tons	1079.5

-- **Independent** --

Carbon Price	Carbon price in $/ton of CE representing a tax on emissions and a subsidy on sequestration
Fuel Price	Fuel price in percent relative to the 1997 base price
Agriculture Demand	Quantity of domestic agricultural demand in percent relative to the 1997 base demand. This represents a demand curve shifter i.e. demand is higher by 10%, in turn FASOMGHG determines the exact demand and price level some where on the shifted demand curve.
Exports	Quantity of excess demand (ROW demand) in percent relative to the 1997 base demand

Table 2. Scenario Estimate Parameters

Dependent Variables	2010	2020	2030	2040	2050	2060	2070	Carbon Price	Ag Demand	Fuel Price	Exports	R^2
GHG Accounts:												
CO2 other source emissions[a]	581.41	567.06	571.78	556.99	533.88	512.01	495.77	-0.122	0.054	-0.557	0.013*	0.765
CO2 soil and grass emissions[b]	21.17	22.95	12.75	37.72	39.27	39.92	22.10	-0.037	0.026*	-0.357	0.184*	0.629
CH4 source emissions	322.67	314.70	317.32	309.11	296.29	284.15	275.14	-0.105	0.048	-0.435	0.011*	0.722
N2Osource emissions	5.98	5.91	6.23	6.54	6.66	6.63	6.64	-0.127	0.075	0.345	0.021*	0.687
CO2 offset from biofuel	0.19	0.25	0.38	0.59	0.82	1.11	1.44	0.355	-0.466	1.336	0.261	0.678
Tree carbon sequestration	2.38	1.61	0.54	0.47	0.22	0.12	0.05	0.224	-0.094*	1.101	-0.143*	0.592
AgSoil carbon sequestration[c]	66.23	68.93	73.06	23.87	17.56	11.25	10.52	0.022	-0.007*	-0.086	0.029*	0.932
Emission reductions[d]	18.99	21.91	22.88	29.28	36.10	47.73	63.00	0.358	-0.345	0.771	-0.100*	0.770
Agricultural Prices and Production:												
Price	8.32	9.51	9.80	9.26	8.40	9.08	8.183	0.109	0.001*	0.494	0.007*	0.814
Production	127.67	109.13	97.84	93.87	93.99	94.74	99.824	-0.129	0.077	-0.076	0.026*	0.752
Exports	1632.39	1607.20	1942.42	2181.68	2231.55	1975.98	2077.33	-0.210	-0.123	-1.834	1.291	0.749
Imports	13.07	13.51	13.74	13.62	13.63	13.82	14.505	0.012	0.284	0.135	0.014*	0.806
Forest Prices and Production:												
Price	121.44	109.74	95.40	93.18	82.96	76.50	71.85	0.051	-0.026*	0.063	-0.046*	0.701
Production	88.45	96.34	99.84	102.06	102.97	106.70	103.04	-0.017	0.011*	-0.027	0.028*	0.463
Exports	65.79	65.00	69.78	74.96	73.80	72.45	75.46	0.001*	0.016*	-0.009*	0.075*	0.204
Imports	67.29	53.95	37.05	26.78	19.79	23.85	23.51	0.127	-0.061*	0.120	0.144*	0.457
Forest Management Intensity Class:												
Afforestation	2.62	2.67	2.94	2.80	2.80	2.55	2.59	0.031	-0.001*	-0.013*	-0.017*	0.255
Reforestation	3.16	3.16	3.04	3.09	3.03	3.18	3.11	0.021	-0.018*	0.025	-0.025*	0.270
Average Rotation:												
Existing Forest	60.75	61.02	66.13	72.64	74.23	80.90	84.91	0.033	-0.008	-0.010	0.001	0.895
Afforestation	0.89	17.75	22.87	25.27	28.04	37.53	39.75	0.066	-0.018	-0.040	0.029	0.994
Reforestation	1.04	1.51	21.03	25.69	33.45	47.36	37.70	0.004	0.055	0.200	-0.264	0.922
Agricultural Welfare:												
U.S. Producer Welfare	16.19	18.91	22.43	26.87	32.21	38.77	46.42	0.078	0.102	0.565	-0.057*	0.955

U.S. Consumer Welfare	919.22	970.69	1035.73	1112.91	1203.79	1318.50	1450.45	-0.022	0.158	-0.127	-0.005*	0.977
Rest of the World Welfare	38.19	39.24	40.85	42.60	45.18	47.10	51.58	-0.016	-0.007*	-0.088	0.530	0.956
Forest Welfare:												
U.S. Producer Welfare	10782.2	9186.4	6289.0	6205.0	5275.7	4963.2	1557.4	0.250	0.206*	0.760	-0.519*	0.251
U.S. Consumer Welfare	80931.6	111468.8	135124.2	137421.8	138479.8	139343.9	138801.5	-0.027	0.011*	-0.020	0.018*	0.898
Rest of the World Welfare	285.4	302.3	316.3	328.7	331.5	334.6	339.6	-0.008	0.022*	-0.009*	-0.004*	0.472
Agricultural and Forestry Practices:												
Crop land	64.16	59.30	59.17	59.87	59.02	56.74	55.55	-0.172	0.144	0.236	0.088*	0.612
Crop land rent	0.12	0.19	0.28	0.40	0.56	0.77	1.03	0.193	-0.027*	1.432	0.010*	0.938
Pasture land	267.24	253.47	247.41	241.47	237.60	236.31	234.94	-0.028	0.016	0.065	-0.004*	0.805
Pasture land rent	118.70	237.30	309.48	379.87	466.47	529.31	534.45	0.245	-0.183	-0.147	-0.172*	0.749
Forest land	0.76	0.74	0.69	0.67	0.65	0.64	0.62	0.040	-0.014*	-0.034	-0.135	0.405
Biofuel crop land	299114	258076	239010	231459	219040	223937	213542	1.361	-0.792	-1.884	-0.739*	0.734
Conventional tillage	731.24	708.41	764.19	937.53	935.11	1018.00	1062.40	0.049	-0.135	-0.177	-0.167*	0.269
Conservation tillage	1.20	0.53	0.85	2.15	2.19	2.23	2.06	-0.570	0.317*	0.949	0.051*	0.425
No-tillage	45.89	43.13	39.79	26.17	24.52	18.83	17.38	0.103	0.240	-0.272	0.165*	0.726
Environmental Indicators:												
Irrigated land	2.15	2.54	2.77	2.95	3.09	3.12	3.11	-0.094	0.094	0.656	0.112	0.761
Irrigated water use	15.53	17.89	19.26	20.17	20.70	20.58	20.18	-0.074	0.068	0.293	0.101	0.766
Pesticide	2899.52	2795.79	2855.32	2980.99	3004.42	2907.45	2876.27	-0.193	0.219	0.154	0.047*	0.544
Fossil fuel	433.67	407.50	413.82	445.17	442.35	432.59	425.63	-0.223	0.174	0.291	0.091*	0.648
Nitrogen fertilizer	6.41	6.51	6.92	7.21	7.16	7.11	6.97	-0.012	-0.023	0.244	-0.061	0.534
Phosphorus fertilizer	0.23	0.22	0.23	0.25	0.25	0.24	0.23	-0.194	0.108	0.470	0.054*	0.609
Potassium fertilizer	0.02	0.02	0.02	0.02	0.02	0.02	0.02	-0.338	0.423	0.647	0.258*	0.520
Erosion	484.68	451.25	457.26	524.93	528.90	547.59	557.19	-0.243	0.112	0.207	0.032*	0.756

[*] Asterisk indicates insignificant from zero at a 0.10 significant level based on a one-tail test.

[a] CO_2 source emissions arise from the use of fuel, fertilizer manufacture, pesticide manufacture, and irrigation pumping.

[b] CO_2 source emissions arise from more intense tillage and changes in soil organic matter, and grassland development.

[c] The 4th order polynomial function is used to estimate the agricultural soil carbon sequestration (ASC) which is more reasonable given that the ASC increases as the carbon prices, but then decreases (in our case the cut off point is about $100 per ton of CE). The carbon price parameter represents a carbon price elasticity evaluated at the mean. The completed estimated parameter for this function is

$ASC = CON_t + 0.2012*\text{Carbon Price} - 0.1463E\text{-}02*(\text{Carbon Price})^2 + 0.3107E\text{-}05*(\text{Carbon Price})^3$

$-0.1804E\text{-}08*(\text{Carbon Price})^4 - 0.007*\text{Agricultural Demand} + 0.029*\text{Exports} - 0.086*\text{Fuel Price}.$

where CON_t represents intercept for each decade, If t = 2010 then Intercept = 66.23

If t = 2020 then Intercept = 68.93 If t = 2030 then Intercept = 73.06

If t = 2040 then Intercept = 23.87 If t = 2050 then Intercept = 17.56

If t = 2060 then Intercept = 11.25 If t = 2070 then Intercept = 10.52

[d] This refers to emission reductions aggregated across CO_2, CH_4, and N_2O expressed in terms of carbon equivalent.

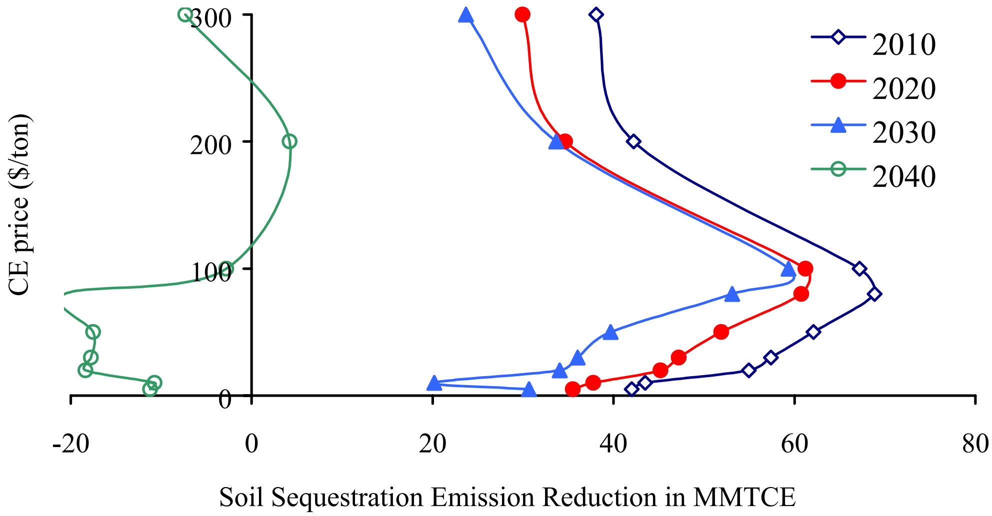


Figure 1. Soil sequestration emission reductions in MMTCE by decade.

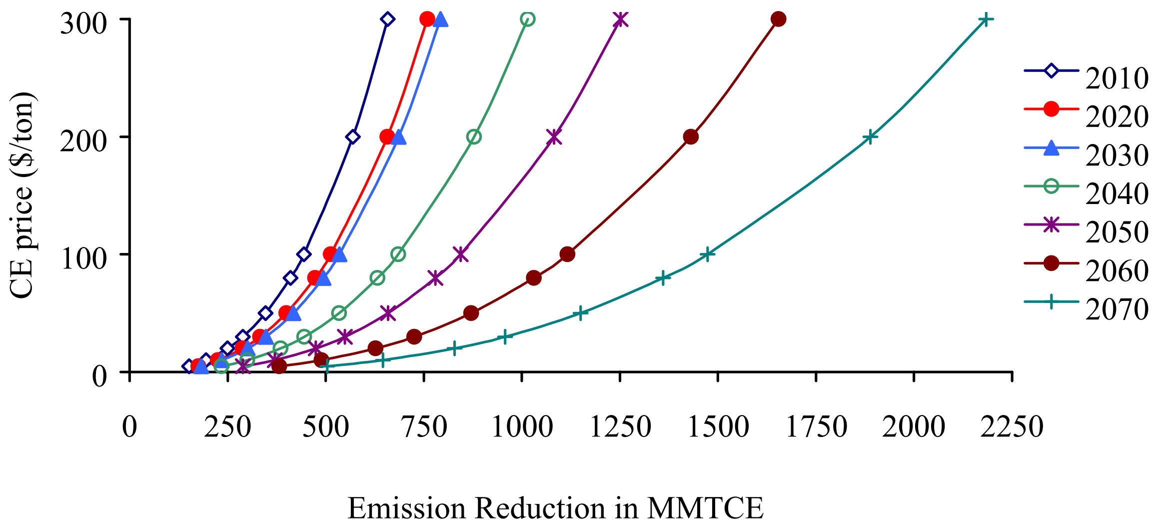
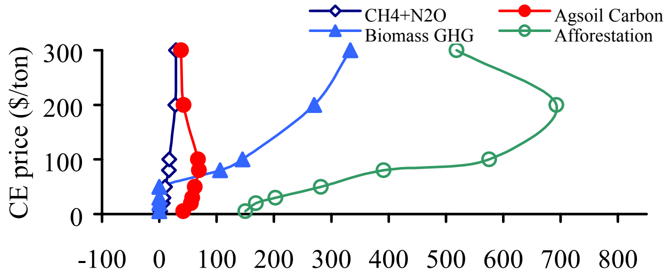
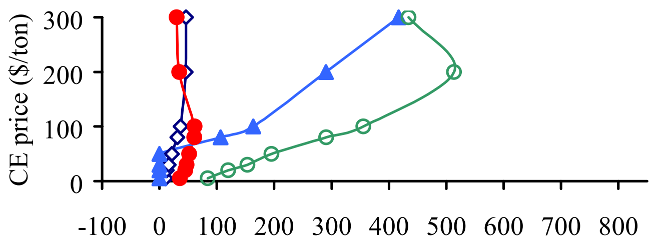


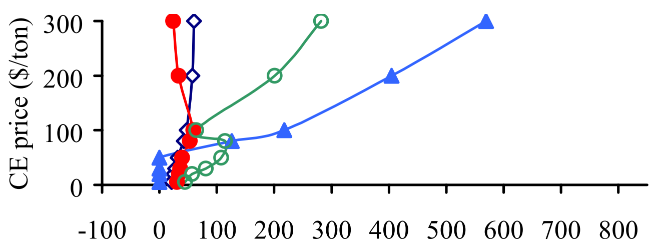
Figure 2. Net predicted emission reductions in million metric ton of carbon equivalent by decade.



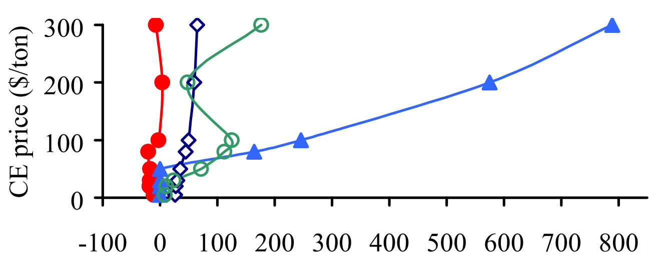
(a) Emission Reduction in MMTCE for 2010



(b) Emission Reduction in MMTCE for 2020



(c) Emission Reduction in MMTCE for 2030



(d) Emission Reduction in MMTCE for 2040

Figure 3. Major GHG components in million metric ton of carbon equivalent by decade.

4 Annex B Assessment of Terrestrial Carbon Sequestration Options within a United States Market for Greenhouse Gas Emissions Reductions

Ronald D. Sands
Joint Global Change Research Institute
Battelle – Pacific Northwest National Laboratory – University of Maryland
8400 Baltimore Ave., Suite 201
College Park, MD 20740-2496
(ronald.sands@pnl.gov, 301-314-6765 phone, 301-314-6719 fax)

Bruce A. McCarl
Regents Professor
Department of Agricultural Economics
Texas A&M University
College Station, TX 77843-2124
(mccarl@tamu.edu, 979-845-1706 phone, 979-862-3977 fax)

Dhazn Gillig
Research Scientist in Agricultural Economics
Texas A&M University
College Station TX 77845-2124
dgillig@ag.tamu.edu
voice 979 845 3153
fax 979 862 3977

ABSTRACT (100 words maximum)

Greenhouse gas mitigation and the potential for carbon sequestration actions is an economy wide phenomenon. No single model can adequately simulate all the activities and processes that might be involved. However, detailed models for various activities, including agriculture and forestry, can be used to inform national and global decisions. We couple results from the a Forestry and Agricultural Sector Optimization Model with the Second Generation Model (SGM), a national and global model of energy and economic processes, to examine the appropriate role of sequestration and other actions in terrestrial ecosystems. This study pays particular attention to the dynamics of carbon sequestration in soils and forests.

5 *Annex C U.S. Agricultural and Forest Carbon Sequestration Over Time: An Economic Exploration*

Heng-Chi Lee and Bruce A. McCarl [4]

The majority of U.S. greenhouse gas emissions (GHGE) come from energy use with electricity generation and petroleum usage each generating about 40% of the total. Thus a large emission cut would require either a large cut in energy use, reducing dependence on fossil fuel sources, development of new technologies, which could be time consuming, or development of some form of offset.

Agriculture and forestry may be able to provide low-cost, near term GHGE reduction strategies, buying time for technological development. Specifically, known management manipulations may be employed to enhance sequestration by removing carbon from the atmosphere and storing it in trees or soils (1).

When considering agricultural and forest carbon sequestration, one needs to recognize that the capacity to sequester is limited and that an ecological equilibrium will be approached effectively saturating the ecosystems ability to hold carbon (2). In addition, while agricultural and forestry carbon sequestration activities increase ecosystem carbon storage, such activities, if discontinued, result in the return of the sequestered carbon to the atmosphere and a rapid approach to a lower carbon equilibrium. Thus, the permanence of sequestered carbon and the need for possible maintenance of non accumulating stocks must be considered.

Previous studies examining the role of agricultural and forest sector carbon sequestration have generally ignored permanence characteristics (3, 4, 5, 6, and 7). Such analyses likely overestimate the long run mitigation potential of agricultural and forestry sequestration programs. This study examines the dynamic role of agricultural and forestry carbon sequestration activities considering permanence related issues.

5.1 Modeling

To examine the dynamic role of agriculture and forest carbon sequestration we used modeling. Specifically we expanded an existing intertemporal, price-endogenous, spatial equilibrium, forest and agricultural sector model (8) to include a full set of greenhouse gas (GHG) management alternatives (9, 10). The model (FASOMGHG) depicts land transfers between the U.S. agricultural and forest sectors and portrays a multi-period. The results yield a simulation of prices, production, management, and consumption under the scenario depicted in the model data.

FASOMGHG considers the level and potential alteration of nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2) emissions from agricultural activities. In addition, the possibility of enhancing carbon sequestration through tillage change, land use change namely conversion of croplands to grasslands or forests and conversion of grasslands to

[4] H. Lee is in Department of Economics, University of Western Ontario, London, Ontario, Canada. B.A. McCarl is in Department of Agricultural Economics, Texas A&M University, College Station, TX 77843-2124.

forests, and avoided deforestation is also depicted. Likewise, additional costs associated with mitigation activities are included. Furthermore, permanence concerns and the approach to a new equilibrium for sequestration are incorporated.

5.2 Model Experimentation

To examine the dynamic portfolio of agriculture and forestry GHG offsets, FASOMGHG is used to simulate the strategies chosen for carbon equivalent (CE) prices ranging from $0 to $100 per. The CE price is applied to CO_2, CH_4, and N_2O emissions/offsets converted to CE using the 100 year Global Warming Potential (GWP). Offset estimates are computed on a total U.S. basis relative to responses under a business as usual (BAU)-zero carbon price scenario and are thus only those additionally stimulated by carbon prices plus account for all domestic leakage..

5.3 Results

Figures 1 to 3 present the accumulated GHG mitigation credits from the model chosen portfolio including forest sequestration, agricultural soil sequestration, powerplant feedstock biofuel offsets, and non-CO_2 strategies.

At low prices (below $25 with $10 portrayed in Figure 1) and in the near term, the carbon stock on agricultural soil grows rapidly initially and is the dominant strategy. However the offset quantity later diminishes and becomes stable with a new equilibrium setting in after 30 years. Carbon stocks in the forest grow over time at low prices and non-CO_2 strategies continually grow throughout the whole time period. Biofuel is not a factor as it is too expensive.

When the prices are higher ($50 to $100 per tonne portrayed in Figure 2 and 3), the forest carbon stock increases first then diminishes and becomes stable; the agricultural soil carbon stock is much less important especially in the later decades; non-CO_2 mitigation credit grows over time but is not a very large player. Powerplant feedstock biofuel potential grows dramatically (ethanol is not used) over time and becomes the dominant strategy in the later decades.

Our results show that the agricultural and forest sectors offer substantial potential to mitigate GHG emissions, offsetting 3.5 to 39 percent of U.S. projected GHG emissions by 2010 for a CE price ranging from $10 to $100. The optimal mitigation portfolio to achieve such offsets changes dynamically depending on price and time. Carbon sequestration is the primary mitigation strategy implemented in the early decades and at low prices (below $25 per ton) but then stabilizes and even becomes a source after 20 to 40 years. Agricultural soil carbon sequestration is the strategy employed at low carbon prices ($10 and below) and forest carbon sequestration is dominant at prices in the $25 range. On the other hand, power plant feedstock biofuel activities become more important in the longer run or at higher prices

This study incorporates the permanence and approach to an equilibrium characteristics of agricultural soil carbon sequestration. In a joint mitigation implementation program, FASOMGHG results generally show that after 30 years of sequestration programs, the net emissions increase from cropland compared with the BAU scenario.

A model analysis was done on the consequences of ignoring the fact that agricultural sequestration gains only persist until a new equilibrium is reached. Namely we assumed that the gains from changing tillage management continued adding carbon at the same rate for 100 years. In that case agricultural soil carbon sequestration takes on a larger share at the expense of mainly biofuels and forestry. Clearly neglecting saturation overestimates the role of cropland sequestration.

5.4 Conclusions

Permanence and approach to a carbon equilibrium with gains ceasing are important characteristics of agricultural and forestry related sequestration strategies. In a dynamic setting are agricultural and forestry sequestration strategies can be counted upon to develop carbon increments for about 30 years after which they stabilize. In spite of that they may play an important role in providing more time to find long-run solutions such as new technologies to halt the increasing ambient greenhouse gas concentration as discussed in (11). Biofuels and non-CO2 strategies exhibit long run sustainability but biofuels only take a role at carbon prices above $50 per ton.

5.5 References and Notes

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12. The work underlying this paper was supported by USEPA, USDOE, SANREM and the Texas Agricultural Experiment Station.

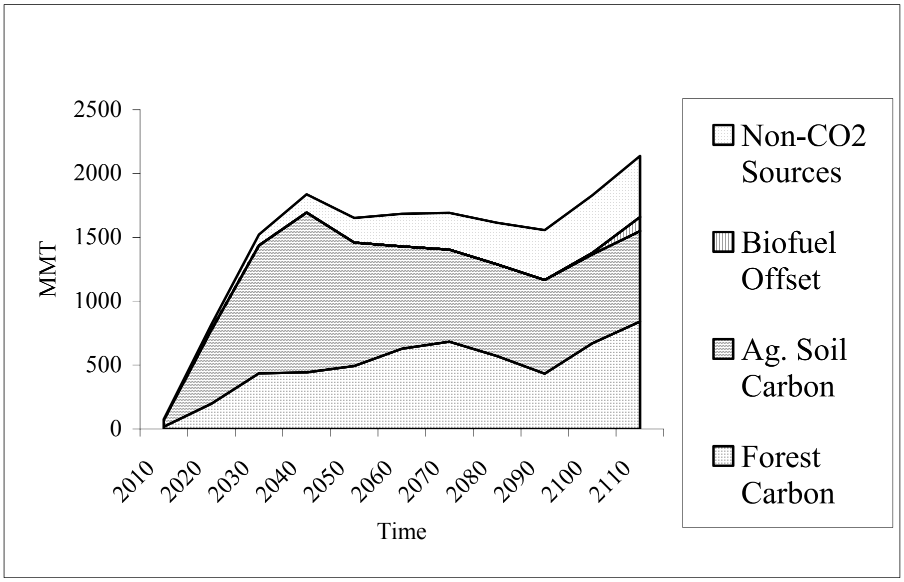

Figure 1. Cumulative mitigation contributions from major strategies at a $10 carbon equivalent price

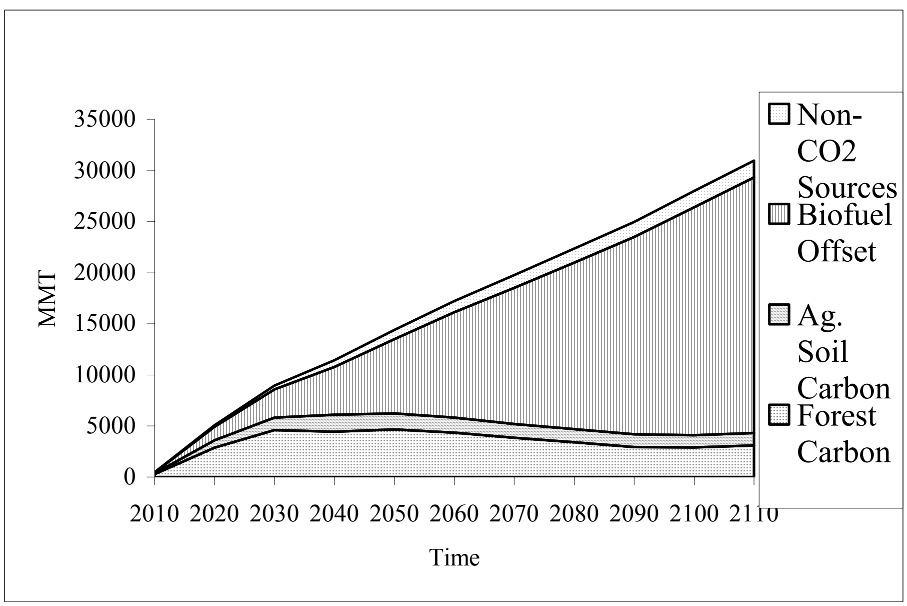

Figure 2. Cumulative mitigation contributions from major strategies at a $50 carbon equivalent price

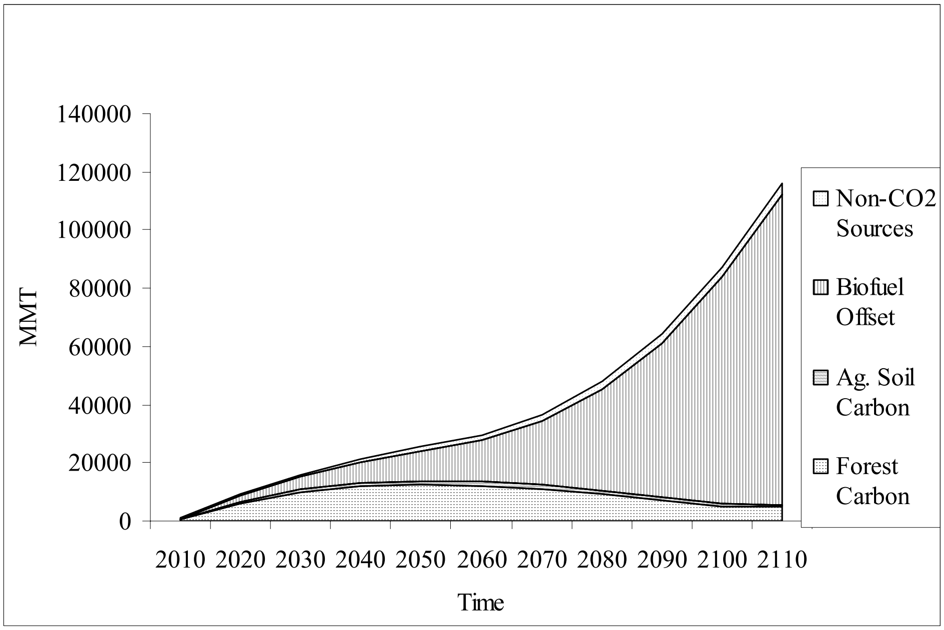

Figure 3. Cumulative mitigation contributions from major strategies at a $100 carbon equivalent price