AGRICULTURAL SECTOR ANALYSIS ON GREENHOUSE GAS EMISSION MITIGATION IN THE UNITED STATES

A Dissertation

by

UWE ANDREAS SCHNEIDER

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2000

Major Subject: Agricultural Economics

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ABSTRACT

Agricultural Sector Analysis on Greenhouse Gas Emission

Mitigation in the United States. (December 2000)

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This dissertation analyzes the economic potential of agriculture to participate in greenhouse gas emission mitigation efforts. Major agricultural mitigation strategies are included simultaneously to capture interactions. Results indicate that agriculture's contribution to emission reduction may be substantial, but not sufficient to fulfill the requirements of the Kyoto Protocol, which are estimated to be in the neighborhood of 700 million metric tons (MMT) of carbon equivalents by the year 2010. Even under extreme economic incentives, the annual emission reduction potential from U.S. agriculture does not exceed 300 MMT if including all carbon dioxide related strategies, or 400 MMT if also including carbon equivalent emission reductions of methane and nitrous oxide related strategies.

Production of biomass feedstock for power plants, i.e. switch grass, becomes the dominating mitigation strategy for carbon saving incentives of $80 per ton of carbon equivalent and above. Lower incentives between $5 and $80 per metric ton of carbon equivalent lead to a complex mixture of various mitigation strategies involving reduced

fertilization, tillage, and irrigation; increased afforestation; and improved liquid manure management. In addition to net emission reductions between 25 and 70 MMT of carbon equivalents, low carbon incentives involve substantial environmental gains through less erosion and less nitrogen pollution.

Empirical results from this dissertation show the importance of accounting for interdependencies among mitigation strategies. The savings potential of mitigation strategies examined individually may be considerably higher than it is under a joint analysis. The findings also provide support for a new breed of combined environmental and farm policy, which would replace costly individual programs aimed at various environmental goals or to provide for fair farm incomes.

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1 INTRODUCTION

1.1 Background

Greenhouse gas emissions (GHGE) have increased for centuries due to industrial, agricultural, and household activities, especially those activities that involve fossil fuel use. The first scientific recognition of GHGE and their possible environmental impacts occurred in 1896 by the Swedish chemist Arrhenius. He advanced the theory that carbon dioxide emissions from combustion of coal would enhance earth's greenhouse effect and lead to global warming. About 90 years later in 1987, an ice core from Antarctica analyzed by French and Russian scientists revealed an extremely close correlation between CO_2 concentration and temperature going back more than 100,000 years (Jouzel et al., Barnola et al.). In 1997, the first international agreement to limit emissions was established in Kyoto, Japan.

Since recognition of the GHGE problem, the number of related studies has increased exponentially. This argument may be illustrated through a small experiment using the agricultural database library AGRICOLA. Searching for the keyword "global warming" returns 1 citation between 1970 and 1978, 2 citations between 1979 and 1984, 113 citations between 1985 and 1991, and 629 citations between 1992 and 1997. The

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This dissertation follows the reference style of the *American Journal of Agricultural Economics*.

scientific work on GHGE crosses disciplinary boundaries, involving, among others, biochemical, physical, economic, and ethical studies. One reason for the continued scientific interest is the difficulty of solving the GHGE problem. Difficulties arise because of high cost estimates of emission reductions, the need for international cooperation, and the scientific uncertainty about cause-effect relationships involved with GHGE.

Solving the GHGE problem implies reducing net emissions of GHG and stabilizing atmospheric concentrations at acceptable levels. Substantial changes in human technologies are necessary to accomplish such a goal. However, currently available alternative technologies are expensive and have motivated many economic studies. This dissertation adds yet another study to the economic section of GHGE science.

1.2 Objectives

The main objective of this dissertation is to provide a comprehensive economic assessment of GHGE mitigation through the agricultural sector of the U.S. Agriculture has been discovered as a perhaps cheap alternative for overall emission reduction in the next decades. Potential agricultural strategies are manifold and have been subject to economic analysis (McCarl and Schneider, 1999). However, many important questions have been omitted from previous assessments.

Previous studies have examined specific agricultural mitigation strategies (McCarl, Adams, and Alig; Stavins; Babcock and Pautsch). To estimate the economic implications of a strategy, prior work has assumed independence from some, or all additional mitigation opportunities. The assumption of independence, however, is not very plausible. Most of the crop-management-related mitigation strategies are competitive with one another, because they compete for the common land base. The more cropland converted to grassland, the less cropland available for tree planting, ethanol production, or no-till-management of food crops. Thus, as various U.S. mitigation strategies are implemented simultaneously, the costs for each individual strategy will increase. The analysis in this dissertation will augment previous analyses by accounting for the interactions between GHGE mitigation strategies.

The economic assessment will involve estimation of mitigation costs in agriculture, welfare implications for the agricultural market segments including welfare effects on foreign countries, and agricultural market responses such as price changes and acreage shifts. This study will provide an estimate of the aggregate supply curve for GHGE reductions from the agricultural sector. Knowledge of the aggregate supply curve is an important step toward internalizing the GHGE externality. In addition, the study will estimate the effect of agricultural emission reductions on the level of other externalities such as erosion and fertilizer runoff.

In section 2, U.S. agriculture's potential to participate in GHGE mitigation efforts will be discussed. Available mitigation strategies and existing cost estimates for adoption will be reviewed based on the recent literature. Graphical analysis is used in section 3 to theoretically justify the objective of this dissertation. Emphasis is given to the importance of mitigation-induced interdependencies within the agricultural sector.

Methodology will be outlined in section 4. In section 5, empirical results of the GHGE analysis are summarized. Agricultural impacts from mitigation are estimated using the best possible assessment method, where all possible mitigation strategies are available simultaneously and substitution between gas offsets is possible. Alternative assumptions and assessment methodologies are examined in section 6. Summary and conclusions are presented in section 7.

2 U.S. AGRICULTURE'S ROLE IN A GREENHOUSE GAS EMISSION MITIGATION WORLD: AN ECONOMIC REVIEW AND PERSPECTIVE[1]

Greenhouse gas emissions (GHGE) constitute a global production externality, which is likely to adversely affect climate. The United Nations Framework Convention on Climate Change (UNFCCC) was established to negotiate net GHGE reduction. Actions under that convention yielded the Kyoto Protocol, which represents the first major international agreement towards GHGE reduction. This paper addresses how agriculture may be affected by dealing with four questions.

- What is the reason society might be involved in GHGE reduction?
- How might agriculture participate in or be influenced by GHGE reduction efforts?
- How might an agricultural GHGE reduction role be implemented?
- What characteristics of agriculture might be relevant in formulating GHGE reduction policy?

2.1 What Is the Reason Society Might Be Involved in GHGE Reduction?

Greenhouse gas (GHG) emissions pose a global environmental problem. Their atmospheric concentrations have increased considerably and are projected to continue to do so. According to the Intergovernmental Panel on Climate Change (IPCC), increasing GHG concentrations will cause global mean temperatures to rise by about 0.3 degree Celsius per decade (Houghton, Jenkins, and Ephramus). Global warming in turn is predicted to increase the sea level, change habitat boundaries for many plants and animals, and induce other changes within the complex climate system (Cole et al.). Major agricultural impacts of increased GHGE may include changes of the species composition in a given area, changes in crop yields, changes in irrigation water requirements and supply, and changes in cost of production. Many scientists believe the risks of negative impacts across society outweigh potential benefits (Bruce, Lee, and Haites) and suggest that society reduce net GHGE to insure that future problems do not arise. Currently, many countries are considering policy actions regarding net GHGE emission reductions.

2.1.1 The Kyoto Protocol

In 1992, the UNFCCC was established with the "ultimate objective ... to achieve ... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (p.9). As of October 1998, 176 countries had signed the convention. However, the convention does not specify either GHG concentration targets or emission reduction levels. The Geneva conference in 1996, the Kyoto conference in 1997, the Buenos Aires conference in 1998, and the Bonn conference in 1999 were intended to create more specific targets.

In Kyoto, a first agreement was reached (Bolin). Thirty-eight countries, mainly developed nations in North America, Europe, Asia, and Australia, agreed to reduce emissions of six greenhouse gases [carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydro-fluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride

(SF_6)] to five to eight percent below 1990 levels. U.S. negotiators agreed to reduce emissions by seven percent. The resultant Kyoto protocol requires each participating party to "have made demonstrable progress in its commitments" (p.9) by 2005 and to achieve the emission reductions within the period 2008 to 2012. In addition to emission reductions, the treaty approves offsets through enhancement of sinks, which absorb greenhouse gases.

Agriculture (using a broad definition including rangelands and forestry) is mentioned as both an emitter and a sink in the protocol. Annex A of the Protocol identifies agricultural emission sources such as enteric fermentation[2], manure management, rice cultivation, soil management, field burning, and deforestation. The protocol also lists agriculturally related sinks of afforestation and reforestation. Additional sources and sinks are under consideration.

2.2 How Might Agriculture Participate in or Be Influenced by GHGE Reduction Efforts?

There are at least four ways agriculture may participate in or be influenced by greenhouse gas mitigation efforts.

- Agriculture may need to reduce emissions because it releases substantial amounts of methane, nitrous oxide, and carbon dioxide.
- Agriculture may enhance its absorption of GHGE by creating or expanding sinks through management practices.

- Agriculture may provide products, which substitute for GHGE intensive products displacing emissions.
- Agriculture may find itself operating in a world where commodity and input prices have been altered by GHGE related policies.

We deal with each of these ways by providing cost estimates and literature citations where available. Our treatment of the literature is as global as possible but is undoubtedly biased toward U.S. sources.

2.2.1 Agriculture - A Source of Greenhouse Gases

Agriculture's global share of anthropogenic emissions has been estimated to be about fifty percent of methane, seventy percent of nitrous oxide, and twenty percent of carbon dioxide (see Cole et al., Isermann). Contributions across countries vary with large differences existing between developing and developed countries. Agriculturally based emissions in developing countries largely arise from deforestation and land degradation. Agriculturally based emissions in developed countries are largely caused by fossil fuel based emissions through energy use; reductions in soil carbon through intensive tillage; nitrous oxide emissions through fertilizer applications, livestock feeding, residue management, and tillage (Watson et al.); methane emissions from livestock raising and rice production (Hayhoe). Within livestock production about two thirds of methane emissions emerge from enteric fermentation of ruminant animals, mainly cattle, with the rest from animal waste. Costs of agricultural GHGE reduction strategies have been examined by a number of authors (see Table 2-1 and Table 2-2 for a summary).

2.2.1.1 Methane

Gerbens (1999a, 1999b) reviewed manure management alternatives and dietary changes for enteric fermentation management. The combined additive effect of all enteric fermentation strategies is shown in Figure 2-1. Gibbs estimated the costs of liquid manure management improvements (Figure 2-2) and Adams et al. (1992) examined the effect of reduced high-energy feed rations, and tax induced demand shifts for beef. Gerbens (1999a) asserts that almost all treatments aimed to reduce methane from enteric fermentation would be more profitable than currently used technologies. The studies also indicate that the total reduction potential from enteric fermentation strategies is considerably lower than for livestock manure management.

Seven percent of current methane emissions (the U.S. target level under Kyoto) amounts to 1.5 million metric tons of methane. Both Gerbens (1999b) and Gibbs estimated that liquid manure treatment has the potential to reduce methane emissions by that amount at costs ranging between $100 and $200 per ton carbon equivalent. Adams et al. (1992), at a one million ton reduction level, calculated average costs for methane emission reductions ranging from about $100 (rice) to $700 (beef tax) per ton carbon equivalent.

Table 2-1 Cost Estimates for Methane Emission Reductions

Author	Strategy	Cost in $ per TCE	Reduction in MMT CH_4	Comments
Gerbens (1999a)	Enteric fermentation	-3,700	0.3	Improved feed intake
		273	0.6	BST treatment
Gerbens (1999b)	Liquid manure management	51	0.3	Complete manure removal from liquid/slurry systems
		94	1.6	Large-scale on-farm complete mix digesters
Gibbs	Liquid manure management	0	0.4	See Figure 2-2
		200	2.2	
Adams et.al (1992)	Rice cultivation	103	0.5	50 % fertilization reduction
		116	1.1	100% fertilization reduction
	Altered rations	204	1.1	5% yield decrease (supply shift)
	Herd reduction	730	1.1	5% demand increase (beef tax)

Table 2-2 Cost Estimates for Nitrous Oxide Emission Reductions

Authors	Strategy	Cost in $ per TCE	Reduction in MMT N_2O	Comments
Battye, Werner, and Hallberg	Improved crop nutrient management	-158	0.16	
	Nitrification inhibitors	164	0.13	
	Low protein swine feed	-1,400	0.17	
	Nitrogen reduced poultry feed	1,300	0.67	
Harnisch	Nitrogen fertilizer tax	370	0.02	
	No anhydrous nitrogen fertilizer	46	0.06	
Trachtenberg and Ogg	Improved nutrient management			Total benefits of 473 –624 Mill. $, Estimated excess N-application of 24-32%
Adams et al. (1992)	Nitrogen fertilizer use reduction	56	0.14	

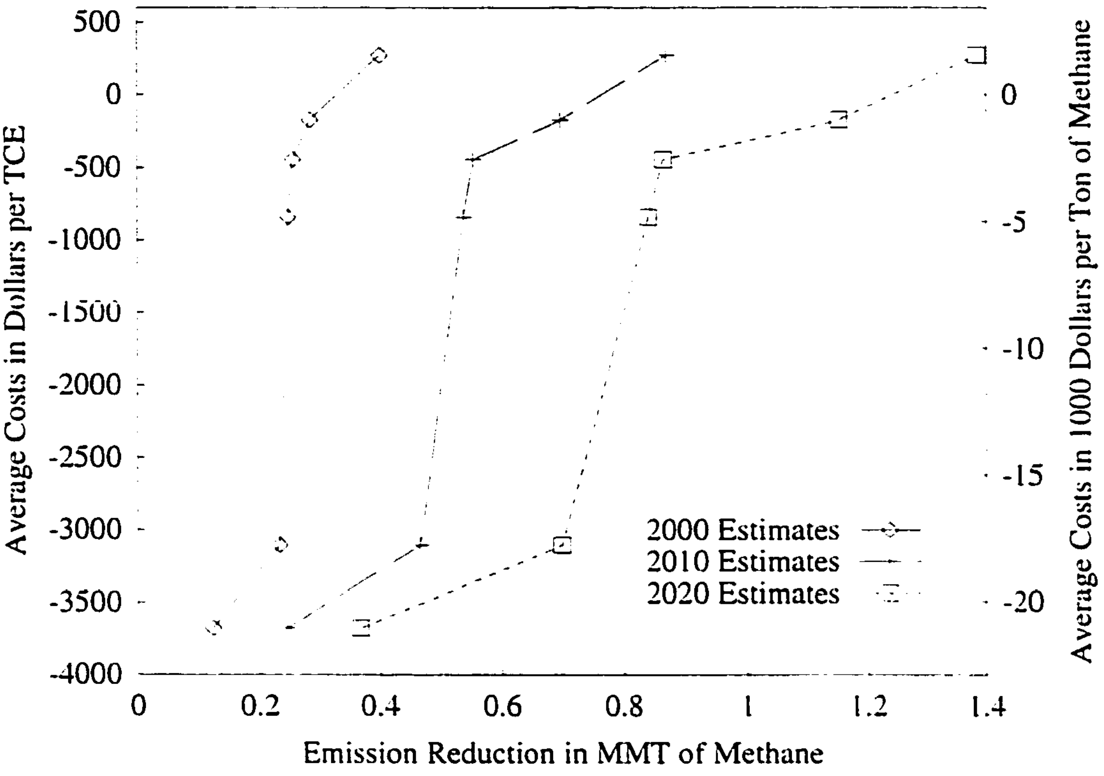

Figure 2-1 Costs of GHGE reductions through enteric fermentation, based on Gerbens (1999a)

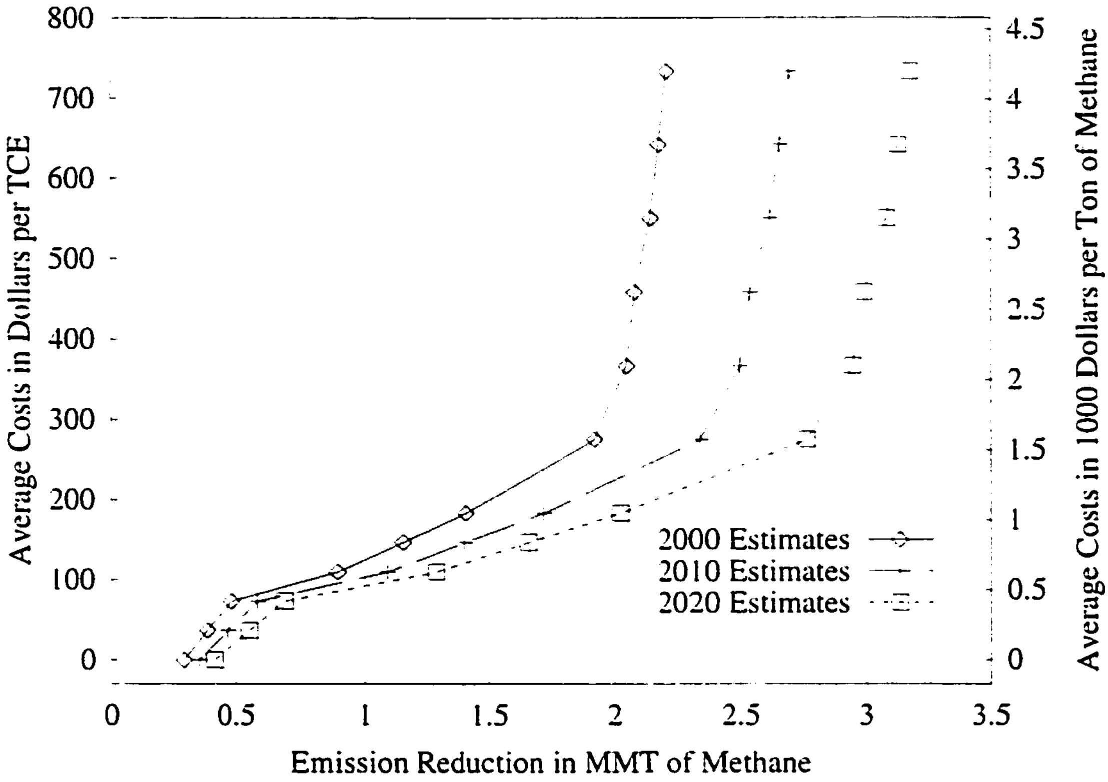

Figure 2-2 Costs of GHGE reductions through livestock manure management, based on Gibbs

2.2.1.2 Nitrous Oxide

Cost estimates for reducing nitrous oxide emissions have been developed assuming relevant strategies are: a) reduced nitrogen fertilizer applications, b) use of nitrification inhibitors, c) improved nitrogen nutrient management, and d) reduced nitrogen content of animal feeds. The cost estimates vary widely in part due to the uncertainty in the magnitudes of emission levels. Battye, Werner, and Hallberg found reduced nitrogen content poultry feed to cost $1,300 per ton carbon equivalent while potential low protein amino acid supplements to swine feed could reduce feeding costs by $1,400 per ton carbon equivalent saved. In addition, Battye, Werner, and Hallberg argue improved nitrogen nutrient management can reduce emissions at cost savings. Average costs for nitrous oxide emissions from reducing anhydrous and total nitrogen fertilizer use were estimated in the neighborhood of $50 per ton carbon (Adams et al. 1992, Harnisch). To meet the Kyoto requirements[3], about 0.13 million metric tons of N_2O emissions need to be reduced.

2.2.1.3 Carbon Dioxide

The volume of CO_2 emission reductions from agriculture is relatively low and thus will receive only brief mention here. Agricultural sources of carbon dioxide emissions from fuel use are minor relative to total societal emissions. U.S. EPA estimated agricultural emissions in 1996 from fossil fuel use to be less than one percent of the U.S. total emissions of 4,900 million metric tons of CO_2.

Soil carbon dioxide emissions have been larger in the past. In the first half of this century, Donigian et al. argue that for the central U.S. land conversion to agriculture decreased soil organic matter (SOM) to about fifty percent of its native level but the land base is not now expanding. While SOM remained relatively stable through 1970 (Allison), it then increased reflecting increased rates of reduced tillage systems (Flach, Barnwell, and Crosson). Similarly, total forestland in the U.S. has been slightly increasing during the last decade (U.S. Forest Service). In countries with large rates of deforestation emissions are important. Houghton estimates that between twenty-five and thirty-one percent of global carbon emissions come from tropical deforestation and subsequent land degradation.

2.2.2 Agriculture - A GHG Sequestering Sink

Another way to reduce net emissions is to increase storage of GHG in ecosystem compartments such as biomass or soil. This strategy is also commonly called carbon or GHG sequestration.

2.2.2.1 Soil Sequestration

Soil organic matter is the largest global terrestrial carbon pool (Post et al.) and exceeds the amount of carbon in living vegetation by a factor of two or three (Schlesinger). Currently, U.S. agricultural soils hold about seven billion metric tons of carbon (Kern). Management practices such as land retirement (conversion to native vegetation), residue management, less disruptive tillage systems, increased use of winter cover crops and perennials, altered forest harvest practices, land use conversion to pasture or forest, and restoration of degraded soils can increase carbon retention. Kern argues that an increase in SOM could absorb 1 to 1.7 billion metric tons. Lal et al. estimate the fifty-year potential at about five billion metric tons. Babcock and Pautsch analyzed the costs of carbon sequestration on cropland through reduced tillage generating estimates ranging from $0 to about $400 per ton of carbon depending on level sequestered (Table 2-3).

Soils also provide sinks for other gases, but much less is known. Estimates indicate that soils take up between ten and twenty percent of methane emissions annually (Reeburgh, Whalen, and Alperin). The soil sink of nitrous oxide is not well understood at the present time (Watson et al.). Studies (Mosier et al.) on grasslands indicate that conversion of grasslands to croplands tends to increase net emissions of nitrous oxide and methane. The net increase of methane emissions is due to a reduction in the capacity of cultivated soils to absorb methane.

2.2.2.2 Forest Sequestration

One management alternative that has been repeatedly examined involves conversion of agricultural lands to tree plantations (Table 2-3). Carbon is subsequently stored in the forest soil, the growing tree and any product, which takes up long-term residence in buildings etc. Adams et al. (1999) recently developed estimates of the average costs of carbon sequestration by tree plantations. Four selected carbon-fixing goals yielded undiscounted average annual costs between $13 and $26 per ton carbon.

Table 2-3 Cost Estimates for Carbon Sink Enhancements

Authors	Strategy	Cost in $ per TCE	Reduction in MMTCE	Comments
Winjum et al.	Tree planting	5		Reforestation, only vegetation carbon
		2		Afforestation, only vegetation carbon
Moulton and Richards	Tree planting	12	127	Soil, litter, and vegetation carbon (see Figure 2-3)
		16	255	
		18	382	
Adams et al. (1992)	Tree planting	16	127	Soil, litter, and vegetation carbon and also include land rental costs and forgone costs of less agricultural production (see Figure 2-3)
		23	255	
		30	382	
		62	636	
Adams et al. (1999)	Tree planting	21	43 (annually)	Above and below ground carbon, study analyzed annual carbon flux increase, cost estimates are undiscounted, (see Figure 2-3)
		23	53 (annually)	
		25	63 (annually)	
		26	73 (annually)	

Table 2-3 Continued

Authors	Strategy	Cost in $ per TCE	Reduction in MMTCE	Comments
Dudek and Leblanc	Tree planting	3 to 12	35	
McCarl	Tree planting	Wide range	Wide range	Supply curve up to 40 billion metric tons (see Figure 2-3)
Parks and Hardie	Tree planting	9 to 10	42 (annually)	
Sedjo and Solomon	Tree planting	13 to 21	2600	
Sedjo	Tree planting	3.5	2900	Temperate forests
Stavins	Tree planting	< 66	9	37 U.S. counties in the South
Newell and Stavins	Tree planting	0 to 145	0 to 14 annually	36 counties, econometric model (see Figure 2-3)
Plantinga, Mauldin, and Miller	Tree planting	0 to 110	0 to 5	Maine
		0 to 45	0 to 16	South Carolina
		0 to 75	0 to 60	Wisconsin
Van Kooten et al.	Tree planting	0 to 50	0 to 30	Western Canada, hybrid poplar used for wood products, infinite time horizon, zero percent (upper row) and four percent (lower row) discounting
		0 to 70	0 to 30	
Babcock and Pautsch	Reduced tillage	0	11	
		200	19	
		400	22	

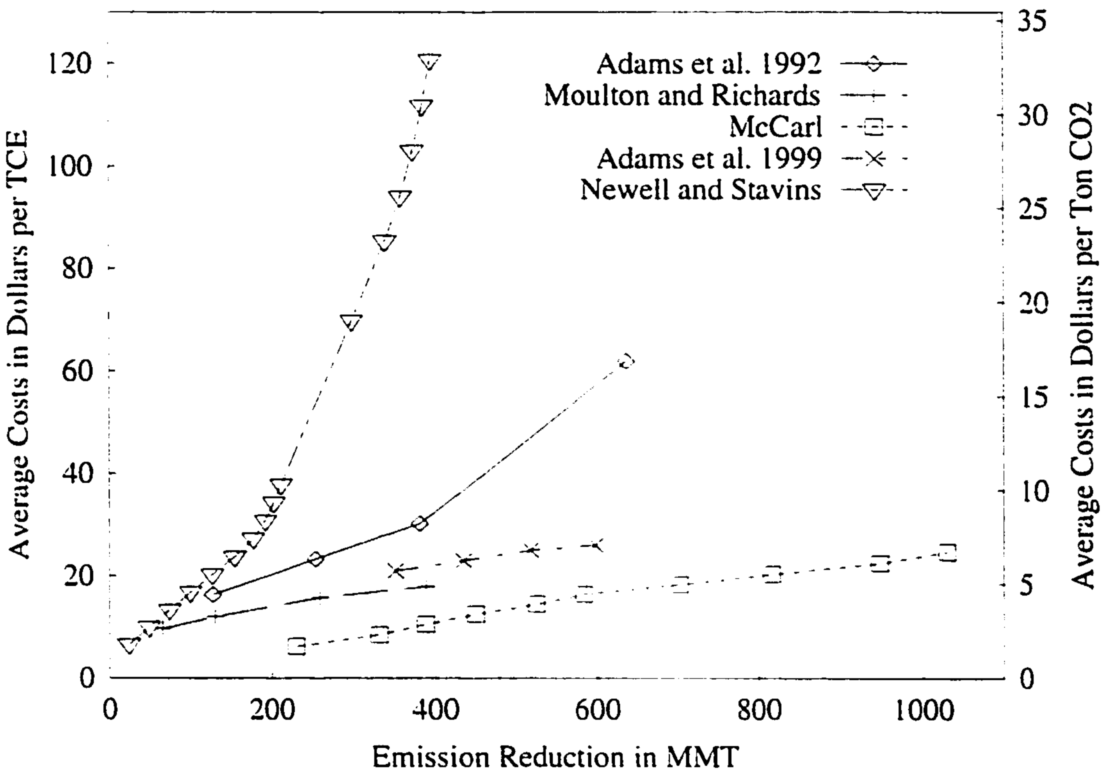

Figure 2-3 Costs of GHGE reductions through tree planting

Their results were consistent with those of a number of previous studies (Winjum et al.; Dudek and Leblanc; Moulton and Richards; Adams et al., 1992; McCarl). Tweeten, Sohngen, and Hopkins list further studies on carbon sequestration in forest ecosystems and tree plantations. Estimates have not been done for the costs via such possible strategies as Conservation Reserve Program (CRP) expansion[4], zero tillage, and forest harvest practice alterations.

2.2.3 Agriculture - A Way of Offsetting Net Greenhouse Gas Emissions

Agriculture could also be involved in providing substitutes for products whose use causes substantial greenhouse gas emissions. In particular, this could occur through use of agricultural commodities as biofuel replacing fossil fuels or through substitution of wood products for more GHGE intensive building materials.

2.2.3.1 Biomass for Power Plants

Substitution for fossil fuels generally involves using agricultural products as feedstock for electrical power plants or inputs to liquid fuel production. The power plant alternative involves burning agricultural biomass in the form of switch grass or short rotation woody crops to offset fossil fuel use for electricity generation. Burning biomass instead of fossil fuel would reduce net CO_2 concentration into the atmosphere because the photosynthetic process involved with biomass growth removes about ninety-five percent of CO_2 emitted when burning the biomass (Kline, Hargrove and Vanderlan) causing a recycling of the emissions. Fossil fuel combustion, however, releases fossil carbon that was fixed as organic matter hundreds of millions of years ago.

A number of studies have examined the costs of biomass fuel substitution (recent ones are summarized in Table 2-4). The cost of CO_2 offsets with biomass-fueled electrical power plants can be computed from the results in McCarl, Adams, and Alig. Dividing their estimates of the extra costs of using biomass as opposed to coal by the difference in carbon dioxide emissions[5] yields an estimate of average abatement costs. McCarl, Adams, and Alig estimates indicate that a million BTUs from biomass will cost $1.45 to $2.16 as opposed to a coal cost of $0.80 (U.S. DOE, 1998a). The corresponding average costs of reducing carbon emissions by one metric ton are between $25 and $55 (Figure 2-4).

2.2.3.2 Liquid Fuel Production - Ethanol

Converting cornstarch or cellulose-laden products into ethanol substituting for petroleum can also offset carbon emissions (Wang, Saricks, and Santini). Again this would recycle the majority of the GHGE from fuel use. The economics of ethanol has been investigated for more than 20 years with almost all results indicating a substantial subsidy is required to make it competitive with petroleum. Tyner et al. investigated the question in the late 70s.

Table 2-4 Cost Estimates of Carbon Emission Reductions Through Fossil Fuel Offsets

Authors	Category	Cost in $ per TCE	Reduction in MMTCE	Comments
McCarl, Adams, and Alig	Bio-fuel for power plants	11 (26)	26	See Figure 2-4, numbers in parentheses are cost estimates if no research progress is assumed
		24 (42)	137	
		53 (73)	560	
Graham et al.	Bio-fuel for power plants	29 to 52	0 to 520	
Walsh et al.	Bio-fuel for power plants	58	23	
		96	110	
Jerko	Ethanol	290	110	See Figure 2-5
		324	800	

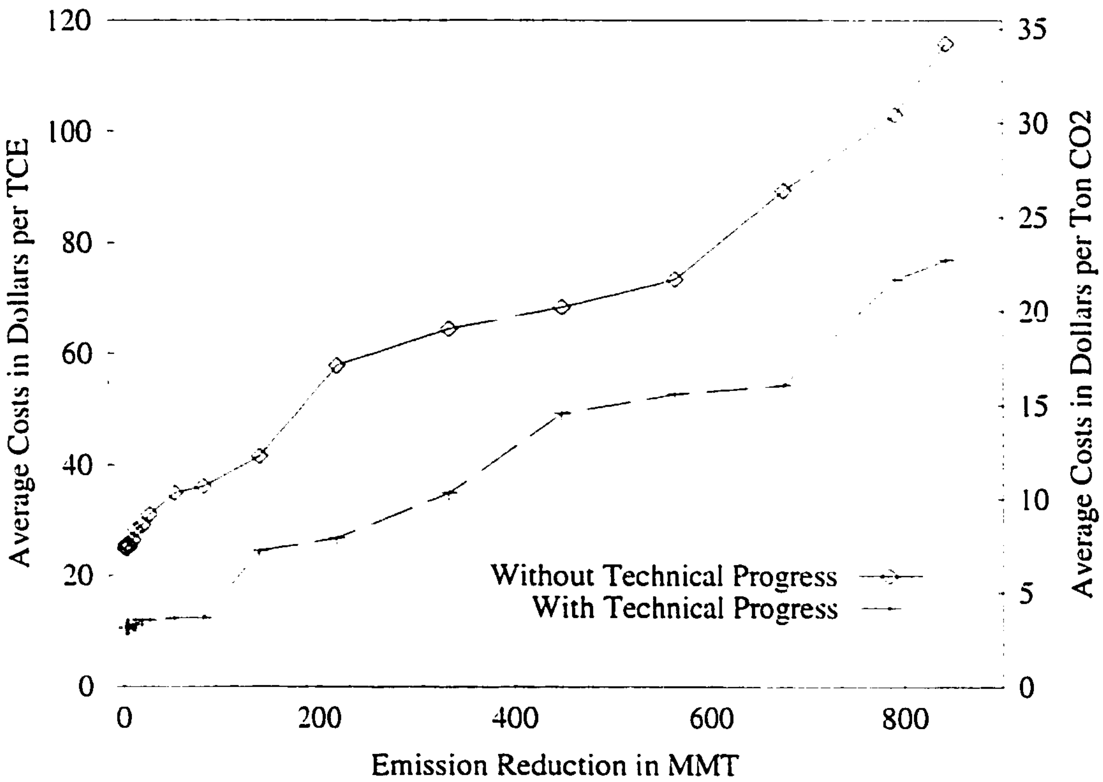

Figure 2-4 Costs of carbon reductions through biofuel for power plants, based on McCarl, Adams, and Alig

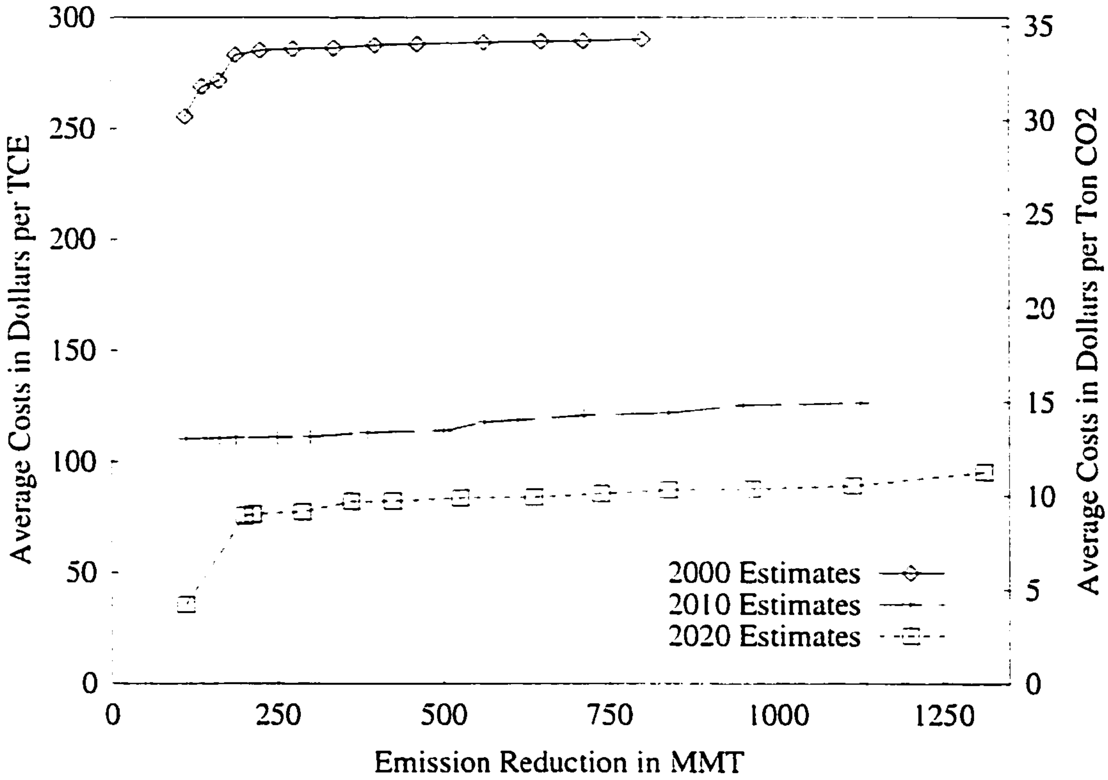

Figure 2-5 Costs of GHGE reductions through ethanol use, based on Jerko

More recently Jerko derived ethanol production costs between $1.20 and $1.35 per gallon. Production of fossil fuel based gasoline costs only about $0.60 per gallon. Using the difference between Jerko's price and the gasoline price and an average carbon content of 0.616 kg carbon per gallon of gasoline (U.S. DOE, 1998b), average abatement costs range between $250 and $330 per ton carbon. Figure 2-5 shows ethanol based carbon emission reduction costs derived using the data in Jerko.

2.2.3.3 Building Products Substitution

Marland and Schlamadinger argue that increased use of wood in construction, while increasing carbon emissions from the forest products industry, reduces net emissions since it creates larger savings through reduced use of fossil fuels in the concrete block or steel industries. The authors, however, do not provide estimates of carbon equivalent costs.

2.2.4 Agriculture - Operating in a Mitigating World

Agriculture could be affected by greenhouse gas reduction policies, which are largely directed toward other sectors. In particular, efforts to reduce emissions are likely to increase fossil fuel prices. For example, sellers of diesel fuel might have to purchase an emissions permit, which would increase fuel prices. Similarly, fuel taxes might be imposed. Such increases would not only influence the cost of petrol-based agricultural chemicals and fuel inputs but also alter off-farm commodity prices.

There have been a few economic examinations[6]. McCarl, Gowen, and Yeats report an analysis where they show that, for example, a $100 per ton carbon tax would result in a 0.5 percent reduction in agricultural induced welfare. Collins and USDA Global Change Program Office studied the same magnitude of tax and reached the same conclusions. Antle et al. simulated economic effects of energy prices on Northern Plain grain producers. For a $110 carbon tax they estimate variable costs to rise between three and thirteen percent. Farm Bureau also did an analysis (Francl; Francl, Nadler, and Bast) in which they concluded that a $110 carbon tax would cause at least a twenty-three percent loss in net farm income for Midwest corn farms. As the estimated effects on farm income differ, so does the scope of the analyses. While McCarl, Gowen, and Yeats treat both agricultural prices and crop acres endogenously, Antle et al. only allow for acreage substitution, holding prices constant. Farm Bureau did not use a complete cost benefit analysis, but based their analysis on simple budgeting, holding both prices and acreage constant. Generally, the results of the more complete studies reveal energy taxes are likely to have little agricultural sector impact.

2.3 How Might a Country Implement GHGE Reduction?

A system of incentives or regulations will be needed to secure participation in GHGE mitigation. The Kyoto Protocol establishes country-specific GHGE reduction targets, but provides flexibility in meeting these targets. It emphasizes "application of market instruments" to achieve the "quantified emission limitations" on a national level. Limits are not placed on individual emitters but rather on the whole country, and it is anticipated that domestic trading systems will be established. However, individual emitters are obligated to account, report, and verify their emissions annually. No provisions have been made yet for emissions trading between time periods, commonly called banking.

2.3.1 Markets for Emissions Trading

Markets for emissions trading should be at the top list of policy options to cost-effectively manage emissions (Sandor and Skees). Several emissions trading programs have been implemented. Examples in the U.S. are the Emissions Credit Trading (1977), the U.S. Lead Phase down (1982), and the Acid Rain Program (1995). Current policy debate on GHGE reduction implementation suggests that an emissions trading system much like the one used for the U.S. acid deposition program will be put in place. This system uses a cap and trade approach and has been successful in bringing down SO_2 emissions (Tietenberg et al.). It permits emitters who bear high costs from emission reductions to buy emission rights from lower cost emitters. The sum of all tradable emission rights equals the emission volume targeted. High penalties for violations and monitoring ensure compliance.

Fischer, Kerr, and Toman highlight features of potential GHGE trading systems. First, they assert that unlike SO_2 emissions, GHGE will have to be controlled upstream because control of GHGE at the point of billions of emission sources is too expensive. Fortunately, fossil fuel use is almost perfectly related to CO_2 emissions and much cheaper to account for. Also, Post et al. argue that keeping track of land management can provide reasonable estimates of agricultural sinks, as well as, methane and nitrous oxide emissions.

Second, Fischer, Kerr, and Toman assert that permits should be auctioned arguing that auctioning would substantially raise governmental revenue compared to gratis allocations such as grandfathering. The revenue then could be used to alleviate adverse effects, finance technological research and adaptation to climate change, and benefit taxpayers through reductions in other taxes. With grandfathering, permits are allocated to emission sources according to their relative historical share on total. Thus, two additional weaknesses of grandfathering are that the system may be biased against new sources and that the beneficiaries of the initial allocation may not be the same who face the most adverse economic effects from emission control policies.

Third, credits for early emission reductions (commonly called emissions banking) would considerably lower compliance cost to the Kyoto Protocol. Burtraw, Palmer, and Paul estimate mitigation costs in the U.S. electricity sector to achieve reductions equivalent to a full year's obligation during the commitment period from 2008 to 2012. Their study shows average costs in the neighborhood of $25 per metric ton of carbon if emission credits were applicable over the next decade, i.e. from 2000 to 2009. According to a similar EIA study (US DOE, 1998b), the same emission reduction volume enforced in 2010 alone would cost on average $350 per metric ton of carbon.

2.3.2 Taxation or Subsidization

In addition to emissions trading, the Kyoto Protocol leaves open the possibility of taxes and subsidies. The non-point source nature of greenhouse gas emissions would again likely make it necessary to tax or subsidize inputs rather than emissions. Fossil fuel taxes may be employed because they have low transaction costs and yield revenues that can be used to finance other mitigation policies. Increased fossil fuel prices can also create a considerable economic incentive for emission saving technologies.

2.3.3 Trading Across Gases

Trading may be allowed across the spectrum of greenhouse gases. To place the gases on an equal footing, the IPCC developed the concept of global warming potential (GWP) which compares greenhouse gas ability to trap heat in the atmosphere (Cole et al.). The IPCC uses carbon dioxide as a reference gas and calculates GWPs for three reference time horizons: 20, 100, and 500 years. For example, over a 100-year time horizon, one metric ton of methane and 21 metric tons of carbon dioxide trap an equal amount of heat in the atmosphere so the GWP of methane is 21. Similarly, the GWP of nitrous oxide is 310. The other gases (HFCs, PFCs, and SF_6) each have GWPs of several thousand.

2.3.4 Trading Across Countries

Four international implementation mechanisms are authorized. These include bubbles, emission trades, joint implementation, and the Clean Development Mechanism (CDM). The bubble approach permits groups of Annex B[7] countries of the Kyoto Protocol to merge their emissions compliance, setting few restrictions on trading within those country groups. The U.S. has reached a conceptual agreement with Australia, Canada, Japan, New Zealand, Russia and Ukraine to pursue a bubble group (U.S. Department of State). Bubbles reduce the incentive for non-compliance through the joint responsibility of both the individual members and the regional organization. However, bubbles may result in efficiency losses compared to emissions trading for they restrict permit trading within the bubble member countries.

Emissions trading would allow Annex B countries to purchase or sell emission rights to any other such country. Each international transaction must be reported to and approved by the UNFCCC secretariat. The relevant modalities, rules and guidelines for these transactions still need to be defined. In principle, emissions trading could be authorized at the governmental level or at a sub-national entity level. The latter would increase trade efficiency.

Joint implementation (JI) refers to multi-national projects within Annex B countries, where involved parties can receive emission reduction units (ERU). JI can be viewed as supplemental option to emissions trading. Instead of buying emissions allowances from another eligible party, a country can also directly finance and supervise emission reduction projects in that country. This can be more efficient than emissions trading, particularly, when substantial technological differences exist between countries. The importance of JI, however, may be small with respect to the agricultural sector.

Through the Clean Development Mechanism, Annex B countries can secure certified emission reductions (CER) in non-Annex B developing countries, which are not subjected to emission reduction targets. Countries like the U.S. are likely to buy additional emission allowances from outside to meet their national commitment especially favor the Clean Development Mechanism. By integrating low cost emission reduction options in developing countries, this mechanism would result in a lower market price for emission permits.

2.3.5 Monitoring and Verification

A recurring theme in the Kyoto Protocol is the monitoring and verification of carbon emissions and sinks. To have a viable market in credits there needs to be a commodity that can be clearly identified and reliably and consistently measured. Marland, McCarl and Schneider note the possibility that GHG credits could depend on the uncertainty in their measurement.

Implementation of trading systems across gases is likely to involve some type of uncertainty discounting. As argued above emission reductions will have to be estimated upstream, hence uncertainties arise. The degree of these uncertainties, however, seems to differ widely between different GHG mitigation strategies. Nitrous oxide emissions savings from improved fertilizer management, for example, vary to a much higher degree, than do carbon dioxide emissions savings from reduced fossil fuel use. Thus, in a risk adverse society, the value of emission credits from fairly uncertain nitrous oxide reductions should be discounted relative to the value of emission credits from almost perfectly predictable carbon dioxide emission reductions.

Canada has proposed carbon credit adjustments based on confidence intervals of the amount of CE emission reductions (Table 2-5). The resulting adjustment factors can be interpreted as uncertainty discount factors. Two pieces of information would be necessary to make these adjustments.

Table 2-5 Uncertainty Discount Factors for CE Emissions Trading Based on Proposition by Canada

Uncertainty in Emission Estimate (Assuming 95% Confidence and Normal Distribution)	Maximum Allowable Deviation of Actual Emissions from Emission Target (Excess Emission Tolerance)			
	1%	3%	5%	10%
10%	0.93	0.95	0.97	1
20%	0.86	0.88	0.90	0.94
30%	0.81	0.82	0.84	0.88
40%	0.76	0.77	0.79	0.82
50%	0.71	0.73	0.74	0.77
80%	0.60	0.62	0.63	0.66

First, probability distributions for the uncertainty of CE emission reductions from all involved mitigation strategies must be known with 95 percent confidence. Second, a maximum allowed quantity of excess emissions (due to uncertainty) over an emission target must be specified. In Table 2-5, adjustment factors are shown for different levels of uncertainty and different levels of excess emission tolerance.

2.4 What Characteristics of Agriculture Might Be Relevant in Formulating GHGE Mitigation Policy?

Agricultural policies have always been subject to controversial debates. Features of recent U.S. farm programs have been shown to induce changes in agricultural management and resource use. For example, the deficiency payment scheme motivated farmers to produce more. In this section, we will discuss characteristics of agriculture that should be considered in formulating GHGE mitigation policies.

2.4.1 Positive and Negative Externalities

Pursuit of agriculturally based policies limited to carbon sequestration can have both beneficial and detrimental external effects that are unintended. A total weighing of the externalities may be key to policy formation.

2.4.1.1 Potential Positive Externalities

When McCarl, Gowen, and Yeats examined the effects of carbon permit prices, they found that the policy stimulated widespread expansion of conservation tillage and a large reduction in soil erosion. A country bears a number of costs due to erosion in terms of water quality, ecology, sedimentation, etc. that would be reduced by increased use of conservation tillage. Thus, a policy based on carbon emissions or sequestration might benefit a number of erosion-related areas not originally the target of the policy. Other types of positive externalities could occur including:

- Reduced tillage could increase soil organic matter, enlarging soil water-holding capacity and reducing the need for irrigation water;
- Increased soil organic matter could also improve natural soil fertility, thereby decreasing the need for inorganic fertilizers;
- Expanded conversion of agricultural lands to grasslands or forests could provide increased wildlife habitat and protect biodiversity;
- Diminished use of fertilizer could reduce the nutrient content of runoff from agricultural lands, thereby improving water quality and reducing hypoxia of streams, rivers, lakes and aquifers. Such alterations would improve the characteristics of the waters in these regions for use by non-agricultural water consumers;
- Diversion of agricultural lands into energy production to reduce CO_2 emissions might induce technological improvement in agricultural crops, permitting expanded electricity generation at lower cost.

Many other benefits could be cited, but the basic point has been made. The potential clearly exists for positive environmental and economic benefits (externalities) to arise from policies intended to reduce CO_2 accumulation in the atmosphere.

2.4.1.2 Potential Negative Externalities

Along with the possibility of unintended benefits, there is the possibility of unintended costs. Here is a short list of possible negative externalities:

- Adams et al. (1992), and more recently McCarl, show that programs designed to move agricultural lands into forestry could have deleterious effects on the traditional forest sector, leading to either deforestation of traditional parcels or reduced incomes.
- Reduction in intensity of tillage has been found in some cases to require additional use of pesticides for weed, fungus, and insect management. In addition to requiring energy for synthesis, production, and application, these may have deleterious effects on ecological systems, runoff, and water quality.
- Expanded use of agricultural lands for carbon sequestration increases the competition with traditional food and fiber production. The result might well be decreased food and fiber production; increased consumer prices for crops, meat and fiber; and decreased export earnings from agriculture.

Again, many other cases could be cited, but the basic point has been made. There could be negative environmental externalities arising out of policies intended to reduce emissions or increase carbon sequestration.

2.4.2 Political Will for Public Intervention and Farm Support

Historically, the agricultural sector in many countries has received substantial public subsidies in the form of price and income supports. Today, U.S. farm subsidies have been reduced. However, there is also increasing pressure from farm interests to get back into the farm program business, particularly given low current prices for agricultural commodities. GHGE reductions under the Kyoto Protocol raise new possibilities for income supports. Perhaps a new breed of farm programs could be justified with funding based on energy and GHGE savings.

Also the emergence of a carbon-offset market could reduce the government role. Private agricultural and non-agricultural interests contracting for carbon would provide a new source of private income to farmers.

2.4.3 Demand Characteristics

Most agricultural production is up against an inelastic demand curve. People do not eat a great deal more even if food costs less; so increased production is often matched by declining prices. However, producing biofuel for the energy market would probably place agriculture as a fairly small player producing against an elastic demand curve. The carbon market may have similar characteristics. Such a market would not yield such large price reductions when agricultural carbon credits are included and would yield producer benefits, as opposed to consumer gains as has been the prevalent recent case. Adding such a market would have income distribution implications.

2.4.4 Practical Sectoral Economics

From a practical standpoint when considering both how to garner agricultural participation and how such participation might influence the economics of the agricultural sector, there are a number of important economic questions.

2.4.4.1 Are the Comparative Costs of Agricultural Net GHGE Reductions Low Enough?

Are comparatively cheap emission reductions or sink enhancements available? Will non-agricultural interests buy carbon credits from agricultural interests? Anecdotal evidence seems to suggest that this is the case, but the demand by non-agricultural interests for carbon credits is not clear. The evidence above shows the cost of several agricultural opportunities to be well below $100 per ton of carbon. Recent studies by the President's Council of Economic Advisors (1998), the Energy Information Administration (U.S. Department of Energy), and by economists such as Manne and Richels have produced a wide range of numbers for the cost of carbon emission reductions in other sectors. The range of costs depends very much on program timing and trading regime permitted, i.e. the extent to which emissions credits will be traded internationally and which countries will participate, and when the program is implemented. Many cost estimates exceed $100 per ton of carbon.

2.4.4.2 Will a Carbon Program Disrupt the Traditional Agricultural Sector?

The economic impacts on the traditional agricultural sector participants depend on the intensity of mitigation efforts. The more agriculture enters the GHGE business the less there will be conventional agricultural production. Some mitigation strategies may be competitive (biofuel, ethanol, forestation) and some may be complementary (management alterations) to existing land uses. Competitive strategies will decrease conventional agricultural production and cause prices for food commodities to rise.

However, such rises may induce further innovation and resources into the sector. With inelastic demand curves as often encountered for food commodities, producers are likely to gain but consumers will probably lose. Land prices would likely rise as a consequence of the competition between crops used for food and crops (including trees) used directly for mitigation strategies, such emission sequestration and biofuel generation. The total issue portends shifts in the distribution of income between agricultural producers and consumers. We also need to consider the costs and benefits of the negative and positive program externalities, including, ideally, the costs and benefits of a changing climate.

2.4.5 Will the Farmer Participate?

Many physical scientists have evaluated farmer mitigation strategies and concluded there are "win-win" possibilities available, asserting that the farmer would make money, emissions would be lowered, and there would be positive environmental externalities. However, the adoption of such strategies by farmers is not granted. Farmers do not choose a "winning" strategy from a social or scientific point of view; they choose the "best" winning strategy available to them. Thus the strategy chosen must dominate the other strategies available from farmers' viewpoint. Farmers may not choose a profitable reduced tillage method if a more profitable intensive tillage method is available. In addition, a number of other factors will enter into their decisions. In particular:

- Risk is a consideration. Farmers who switch practices may experience not only a change in net returns but also changes in operational risk. Studies on tillage intensity show that slightly increased net returns under reduced or no-tillage are offset by higher variation in net returns, thus increased risk (Klemme; Mikesell, Williams, and Long; Williams, Llewelyn, and Barnaby; Epplin and Al-Sakkaf). This may imply that the development of insurance programs partially alleviating risk may be desirable to stimulate adoption.

- Management requirements can be more demanding for mitigation related strategies, particularly less tillage-intensive practices. Farmers may be unwilling to adopt practices that require substantially more critical management activities and a long learning time. This may be particularly true of older farmers nearing retirement. Extension efforts and insurance may be needed to facilitate adoption.
- Many farmers are motivated by a stewardship role in terms of the soil and the environment. In that context, one may find that farmers would more easily adopt soil-conserving techniques than would otherwise be the case.
- A number of the mitigation practices, once adopted, must remain in use for a long time if GHGE gains are to be realized. Farmers may be unwilling to assume such long-term commitments, and it may be difficult to pass on the commitment and monitor continued performance when farm ownership changes. Leasing arrangements may also create obstacles.

2.4.6 Incentive Program Design

Incentive programs which capture gains through emission reductions need to be carefully designed with respect to four big issues: 1) preservation of gains over time, 2) discouragement of countervailing actions, 3) avoidance of unintended program expenses (hitting more than the target), and 4) diminution of non-point sink uncertainties.

2.4.6.1 Preservation of Gains Over Time

Many mitigative strategies regarding sinks result in increased absorption of GHGs until a new equilibrium state is reached. Growth rates of both trees and soil carbon accelerate over the first few decades, but decline as trees reach maturity or soils approach new carbon equilibrium (Sprugel). Tillage experiments have shown that the carbon content of agricultural soils increases for up to 30-40 years after tillage alteration (Hendrix). Many sink strategies have three important features. First, they cannot be counted as a recurring annual sink for GHG. Initially, they offset emissions, but later their net emission reduction falls close to zero as the new equilibrium is approached. Second, if after some time the management of the sink changes to a less "friendly" basis such as plowing the land, harvesting the trees, or adopting conventional tillage, then the stored GHGs volatize rapidly. Thus, management alterations must be retained once they are initiated. Third, the ability of soils to sequester carbon in soils may diminish as the climate warms, as there is a negative relationship between higher temperatures and the organic matter content of soils (Kutsch and Kappen).

2.4.6.2 Countervailing Actions

The adoption of certain emission reduction strategies in one economy segment may lead to a substantial offset by countervailing actions in other parts of the economy. For example, McCarl recently found that land converted to forest under a carbon-based subsidy program would revert back to agriculture after one forest rotation unless the program was somehow designed to not let the land be harvested or to make it stay within the forest sector. In addition, he discovered a substantial countervailing movement of land from the traditional forest sector back into the agricultural sector when a carbon subsidy caused large amounts of land to be afforested. A program with a semi permanent ban on harvesting and a non-reversion to agriculture clause might be required to maintain the gain over the long term. This will raise program cost.

2.4.6.3 Hitting More Than the Target

The design of an incentive scheme may pose challenging policy targeting questions and could encounter unintended expenses. Our history of targeting non-point source pollution phenomena in agriculture has been checkered (Malik, Larson, and Ribaudo). The Conservation Reserve Program, for example, helped reduce soil erosion considerably. However, the program most likely incurred unwanted expenses by paying farmers for enrollment of land that was not intended to be cultivated anyway. In the carbon arena, incentives designed to keep land in forestry might end up paying landowners who had no real intention of ever moving land out of forestry.

2.4.6.4 Uncertainty of Non-Point Sinks

Acceptance of agricultural sink strategies implies the establishment of a trading scheme involving land in many diverse areas of the country. Unfortunately, emission savings from some sink enhancements are not perfectly correlated to land management, thus uncertainty results. The widespread nature of possible participants coupled with the uncertainties may dampen the enthusiasm for including such sinks in a national or international emissions trading scheme, and may discourage nonagricultural interests from approaching agriculture for permit trades. Taff and Senjem find that trading schemes' success depends on the non-point sinks' ability to offer remedial practices that are at once visible and whose effectiveness can be predicted within acceptable degrees of certainty.

2.4.7 Property Rights

Programs, which tax or regulate alterations of land-use, will cause private property rights issues to arise. Public discussion of such issues has been observed, for example, when land-use changes have been restricted to preserve endangered species whose habitat is dependent on private property. Consider the following questions

- Will we allow existing forest owners, who are not being compensated in the program, to choose to deforest their lands and move them into agriculture?
- Will harvested forests be taxed in proportion to any carbon released?
- Will farmers who are currently using some form of reduced tillage be allowed to later reverse that decision and use more intensive tillage systems?
- Will landowners who now have land in some form of grass or forested lands and develop that land into tilled agricultural lands have to pay for emissions?
- Will land that is currently rather minimally disturbed in the agriculture or forest sectors but moves into subdivisions or other uses that diminish the carbon storage potential be requiring emission permits?

All of these appear to be major property rights issues.

2.4.8 Trade and Program Participation by Trade Competitors

The concept that not all countries will be treated equally, largely because of their development status, is prominent in the Kyoto protocol with the Annex B etc. country discussion. The Farm Bureau has stated opposition to adoption of the protocol because certain key competitive agricultural countries such as Brazil and Argentina are not covered (Francl). The Bureau's analysts feel U.S. farmers will lose their comparative advantage if they need to obey GHGE regulations while key competitive agricultural producing countries do not. Such an issue may well have to be resolved before countries like the United States ratify the protocol.

2.4.9 Eligibility of Agricultural Sinks

There are a variety of agricultural land-management practices that might enhance sinks or limit emissions. However, only the forestry activities involving afforestation, reforestation and deforestation appear eligible under the current phrasing of the Kyoto Protocol. Article 3.4 leaves the way open to add other items to the list at some future time, but this has not occurred as of yet.

2.5 Concluding Comments -- Agriculture as a Bridge to the Future

Agriculture with the near-term possibilities for changes in tillage and/or forest incidence offers a near-term way of reducing GHGE, which may or may not persist at a future date. The essential question is whether agriculture provides a way of reducing current compliance costs before major nonagricultural technological breakthroughs are available which reduce dependency on fossil fuels and lower future GHGE, such as the long awaited fusion development. Many of the above cost estimates seem low enough that agricultural strategies may have a role at least as a bridge to future nonagricultural technological fixes. In meeting such agreements as the Kyoto Protocol, agricultural participation may be highly desirable, as there are cheap GHGE reductions or offsets. However, the 10 years until the commitment period are short. GHGE offset strategies will be cheapest when trees and soil carbon reach their maximum growth rates, which in the case of trees will not uniformly happen by the critical Kyoto dates. Agriculture certainly will respond if proper incentives or markets are provided as the historic participation in such programs as the U.S. Conservation Reserve Program, farm program and payment in kind programs indicate.

3 GRAPHICAL ANALYSIS AND JUSTIFICATION FOR THE METHODOLOGY USED IN THIS DISSERTATION

This study analyzes simultaneously the multiple mitigation options available to the agricultural sector and captures interdependencies between these options. It treats crop acreage allocation and prices for agricultural products endogenously and assesses the effects of mitigation policies on various agricultural externalities. This section illustrates under which circumstances the use of such a modeling framework is important as opposed to using a more simplistic approach. Note that many assumptions used for the graphical analysis were not applied for the empirical analysis in sections 5 and 6.

3.1 Input Market Interdependencies

Agricultural mitigation strategies are linked because they use a common farm resource, land. In Figure 3-1, the effects of interdependencies in the land market are illustrated graphically. To simplify the graphical analysis, several assumptions are made. First, agricultural production is constrained to involve only three hypothetical choices of crop management practices. These practices include two alternative types of wheat management: no-till wheat production (Strategy A) and conventional-till wheat production (Strategy B), and one type of corn management (Strategy C). The produced corn is processed into ethanol.

Second, introduction of a carbon emission mitigation policy is assumed to affect the profitability of considered cropping alternatives.

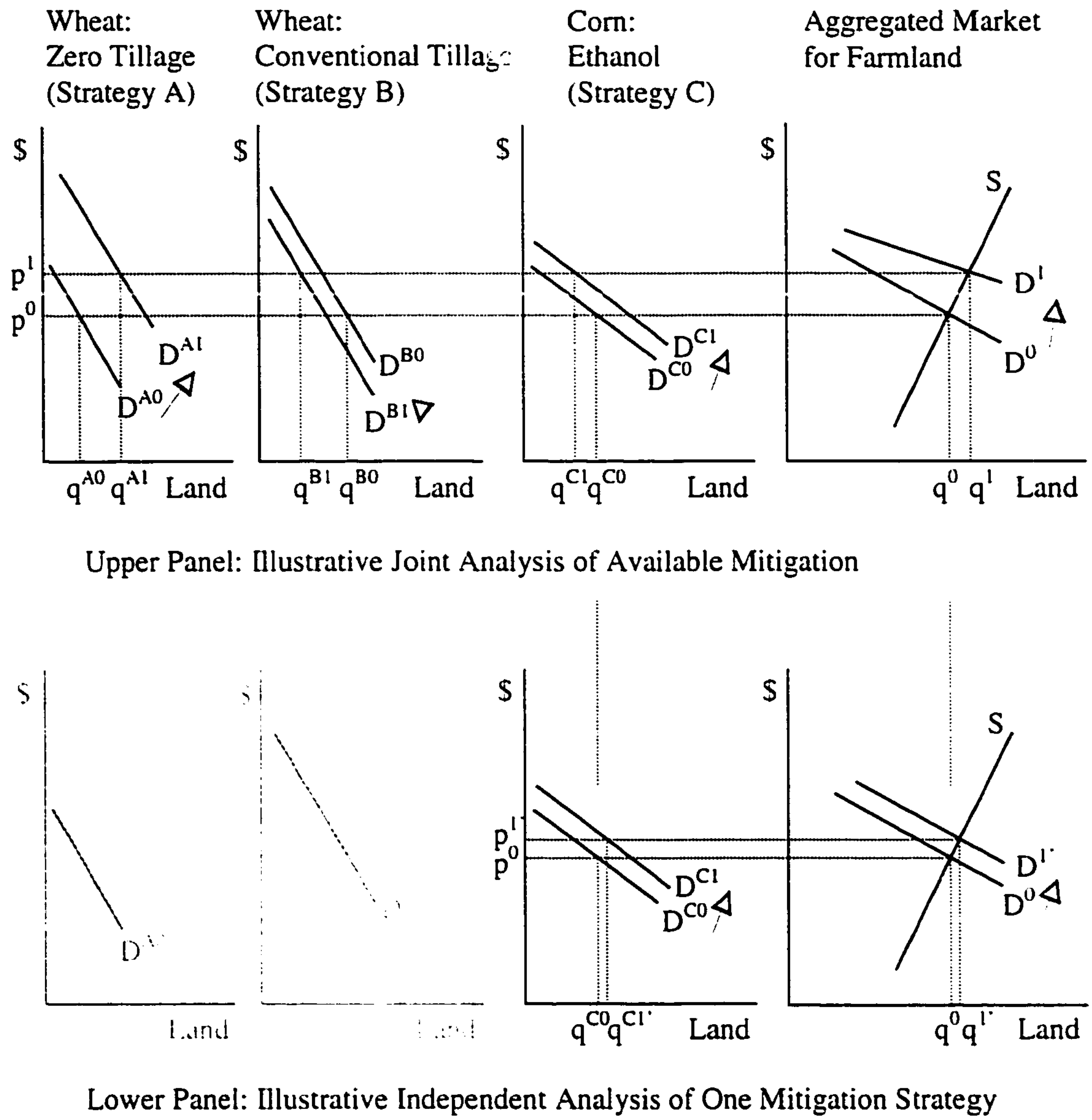

Figure 3-1 Illustrative graphical analysis of potential shifts of demand for farmland after a mitigation policy under joint (upper panel) and independent (lower panel) analysis

The supposed policy is a tax on net emissions of carbon equivalents. If net carbon emissions from a cropping alternative are negative, then the tax becomes a subsidy and net profits increase.

For this qualitative analysis, zero-till wheat and corn-ethanol production are assumed to become more profitable after policy implementation because net carbon emissions are assumed to be negative. The mitigative effect of corn-ethanol relates to its potential to substitute for conventional gasoline. Zero-till wheat production offsets carbon emissions through increases in soil organic matter. In contrast, conventional-till wheat management is assumed to yield positive net carbon emissions, hence, net profits decrease. If net profits from agricultural practices change, demand for farmland will change as well. For demonstrative purpose, it is assumed that farmland demand will increase substantially for zero-till wheat production (D^{A0} to D^{A1}), less substantially for corn-ethanol (D^{C0} to D^{C1}), and decrease for conventional-till wheat production (D^{B0} to D^{B1}).

With no mitigation policy in place, the equilibrium land use occurs at the intersection of aggregate land demand curve (D^0) and land supply curve (S). Demand for land is aggregated over the individual demand curves of all hypothetical cropping activities a farmer may choose from (D^{A0}, D^{B0}, D^{C0}). Farmland is primarily used for conventional wheat production (q^{B0}) and corn-ethanol production (q^{C0}). Demand for zero-till wheat management (D^{A0}) is fairly low and relatively little acreage is allocated to this type of wheat management. At equilibrium, total land amounts to q^0 with the land rental cost equaling p^0.

To illustrate the interdependency between mitigation strategies, two alternative methods for assessing the mitigative potential of cropping practices are compared in Figure 3-1. The first approach involves a joint assessment (upper panel in Figure 3-1), where the supposed mitigation policy simultaneously affects all three hypothetical cropping practices. A second more partial approach involves an independent analysis, where the policy impacts on only one of the available cropping activities (lower panel of Figure 3-1). In particular, this approach considers mitigative effects from corn-ethanol production, but ignores emissions and emission reductions from soil organic matter changes and fossil fuel use of the two hypothetical wheat management practices.

Under a joint assessment, introduction of the mitigation policy will increase equilibrium farmland usage from q^0 to q^1, raising the land rental rate from p^0 to p^1. Zero-till wheat acreage increases (q^{A0} to q^{A1}) while conventional-till wheat acreage decreases (q^{B0} to q^{B1}). Despite increased farmland demand for corn-ethanol production, the actual acreage allocated to corn-ethanol decreases (q^{C0} to q^{C1}). This occurs because the increased marginal revenue from corn-ethanol production does not offset the increased costs, which are rental cost and opportunity cost of land.

Assessing ethanol's mitigation potential independently leads to different results. Such an assessment would not look at demand shifts for farmland from wheat management strategies. The new equilibrium land rental rate ($p^{1'}$) would be higher than originally (p^0) but lower than under the assumption of joint mitigation (p^1, upper panel). Corn-ethanol acreage would increase from q^{C0} to $q^{C1'}$. The relatively high prediction of corn-ethanol acreage ($q^{C1'} > q^{C1}$) would in turn yield a relatively high prediction of the mitigation potential from ethanol-based carbon emission reductions.

The graphical results lead to several implications for the methodology employed in this study. First, independent analysis of individual mitigation strategies can overstate the mitigation potential of that strategy if a) more mitigation strategies are simultaneously available, and b) some of the alternative mitigation strategies have a comparative advantage over the strategy examined. In Figure 3-1, this argument is confirmed through the case of ethanol-based emission reductions.

Second, interdependencies do not only exist among different mitigative strategies but also between mitigative and non-mitigative strategies. As shown in Figure 3-1, non-mitigative strategies such as conventional-till wheat management experience a comparative disadvantage, thus, the equilibrium usage of these activities decreases.

3.2 Output Market Effects

Mitigation policy induced changes of the land market equilibrium will also affect the equilibrium in output markets. A hypothetical example of the aggregate output markets for cropping activities is shown in Figure 3-2. For illustrative purpose, Figure 3-2 is subdivided into three graphs each symbolizing a particular level of market integration. Traditional agricultural markets are represented in the upper diagram. Supply and demand curves are aggregated over all food commodities and other established agricultural products. A potential mitigation market is represented in the lower diagram of Figure 3-2.

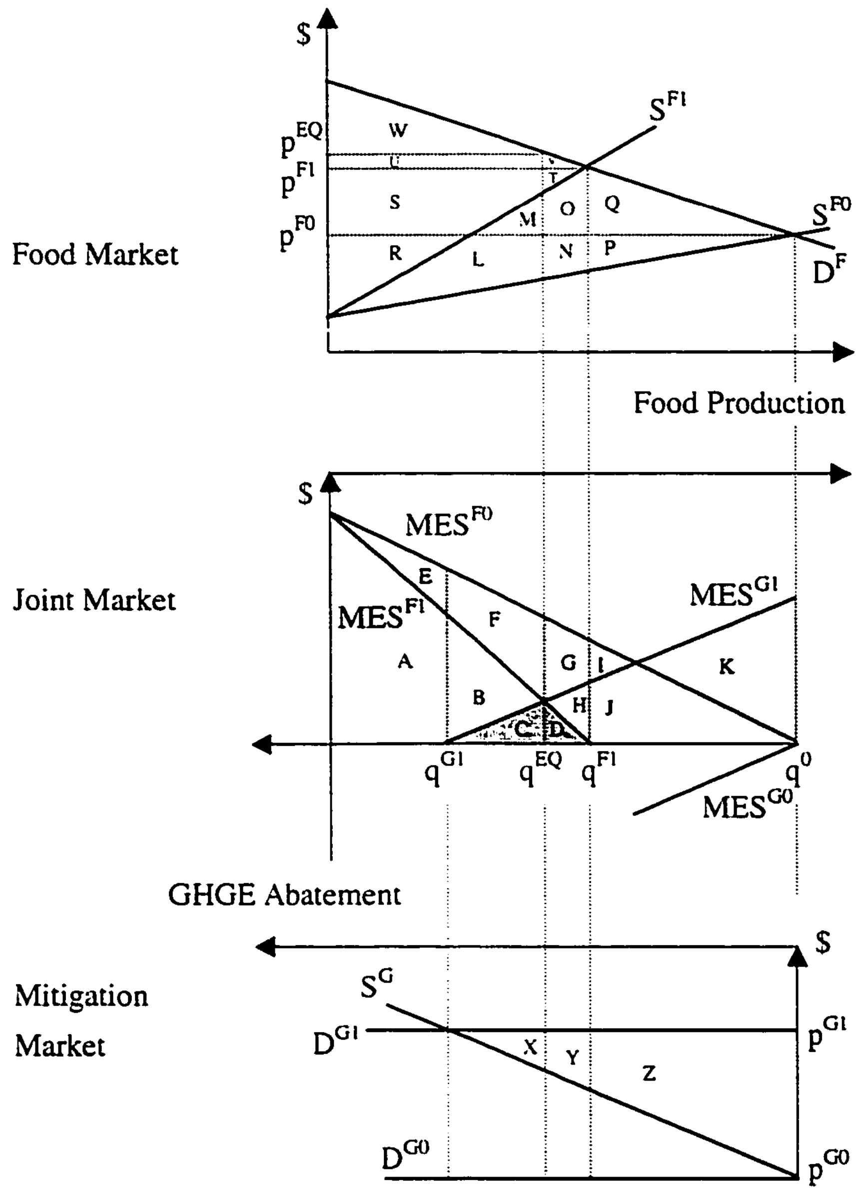

Figure 3-2 Possible responses in agricultural output markets after greenhouse gas emission regulation

Demand for GHGE abatement is positive (D^{G1}) if a mitigation policy has been implemented or zero (D^{G0}) if not. In the middle diagram, food and mitigation market are combined by use of marginal economic surplus (MES) curves. These curves correspond to the difference of demand and supply in the two individual markets.

Some specific assumptions should be noted. First, GHGE abatement is assumed to be negatively correlated with food production. For example, land that is used for tree planting or ethanol production cannot be used to produce food. Similarly, reduced nitrogen fertilizer use abates N_2O emissions but on the expense of lower crop yields. To incorporate the inverse relationship between food production and GHGE abatement into the joint market, the axis indicating GHGE abatement is directed oppositely (right to left) to the axis representing aggregate food production (left to right). The more emissions are abated, the less food can be produced. Thus, at a particular point of production (GHGE abatement), the area underneath the MES curve for food production to the left of that point measures the total economic surplus in the food market. The area underneath the MES for GHGE abatement to the right of the point in question measures the total economic surplus in the mitigation market.

Second, realization of a mitigation policy is assumed to move the aggregated supply curve for food from S^{F0} to S^{F1}. This shift symbolizes additional production cost to farmers because of increased rental rates for farmland (see previous section) and higher expenses on fossil fuel based inputs. On the other hand, implementation of a mitigation policy is assumed to create additional revenue to farmers in the mitigation market. This revenue corresponds to positive demand (D^{G1}) for GHGE abatement[8] established directly through the government via a subsidy or indirectly via emissions trading.

Figure 3-2 can be used to analyze effects of a mitigation policy on the level of food production, prices, GHGE abatement, and on welfare of different market segments. In absence of mitigation regulations, aggregated food demand (D^F) and supply (S^{F0}) determine the autarkic equilibrium level of food production (q^0) and price (p^{F0}). The marginal economic surplus to the agricultural sector as a whole from producing food (MES^{F0}) equals zero at equilibrium (q^0). Since no demand exists for GHGE reductions ($D^{G0} = 0$), GHGE abatement remains at its lowest level (q^0). Total welfare in the agricultural sector equals the sum of producers' surplus (areas R + L + N + P) and consumers' surplus (areas S + M + O + Q + T + U + V + W). The sum of these areas in the food market is exactly identical to the sum of areas A through J in the joint market.

Introduction of GHGE abatement incentives establishes a second market for agricultural enterprises: the mitigation market. The simultaneous equilibrium can be found in the joint market by maximizing total economic surplus from both markets. The maximization condition is met where MES^{F1} and MES^{G1} intersect and results in q^{EQ}. By moving to either side of the equilibrium point (q^{EQ}), additional benefits in one market would be more than offset through losses in the other market. At equilibrium, the sum of consumers' and producers' surplus corresponds to areas A + B + C realized in the food market, and areas D + H + J + K realized in the mitigation market. Note that the level of food production is lower than before implementation of the mitigation policy.

Mitigation policy based welfare losses in the food market total the sum of areas D + E + F + G + H + I + J (joint market). Using the food market diagram, these losses can be decomposed into producers' (areas L + N + P) and consumers' losses (area M + O + Q + V + T). In addition to overall welfare reductions in the food market, welfare will be shifted from consumers to producers because prices in the food market increase (p^{F0} to p^{EQ}). These welfare shifts are represented by the sum of areas S + U. Because producers both gain and lose from mitigation policies, the net effect on producers' welfare is ambiguous and depends on the elasticities of supply and demand curves, and the magnitude of supply shifts as well. Consumers are likely to experience substantial welfare losses in the food market.

While farmers may or may not experience income losses in the food market, they are subject to gains in the mitigation market. In particular, these gains amount to the sum of areas Y + Z, or equivalently, to areas D + H + J + K (joint market). Note that the autarkic equilibrium in the mitigation market would occur at q^{G1}, where marginal cost of emission reductions equals marginal revenue, and MES from GHGE abatement equals zero. However, such equilibrium is purely hypothetical because it assumes no interactions with the food market. If these interactions were taken into account, abating at q^{G1} would reduce total welfare in the food market by the sum of areas C + B + F (joint market) subject to relatively small gains in the mitigation market (area C in joint market representation or area X in mitigation market representation). Such behavior would be inconsistent with profit maximization.

Figure 3-2 can also be used to assess the qualitative impacts of a mitigation policy that does not establish direct revenues from emission reductions. For example, implementation of emission standards with no emissions trading provisions increases cost of food production subject to no monetary gains from complying with the imposed standard. The resulting market equilibrium can be found in the joint market at the intersection of MES^{F1} and MES^{G0}. Effects in the food market are similar as observed before. Production decreases from q^0 to q^{F1} causing substantial welfare losses in the food sector. Increasing prices for food (p^{F0} to p^{F1}) lead to welfare shifts from consumers to producers (areas S + T). Again, while consumers loose, the net effect on farmers' income is ambiguous.

3.3 Effects of Mitigation Policies on Other Agricultural Externalities

The relationship between food production, emissions of greenhouse gases (G), and two other environmental externalities, erosion (E) and nitrogen pollution (N) is shown in Figure 3-3. Two assumptions are made for this hypothetical analysis. First, the marginal social costs of erosion increase as more food is produced. This occurs because highly erodible land is usually more costly to manage. Farmers use the most suitable and less erodible land first, but bring more erodible land into production as demand for food commodities increases.

Second, the marginal social costs of nitrogen pollution are also increasing with respect to food production. High demand for food increases farmers' incentive to maximize yields; hence nitrogen fertilization increases.

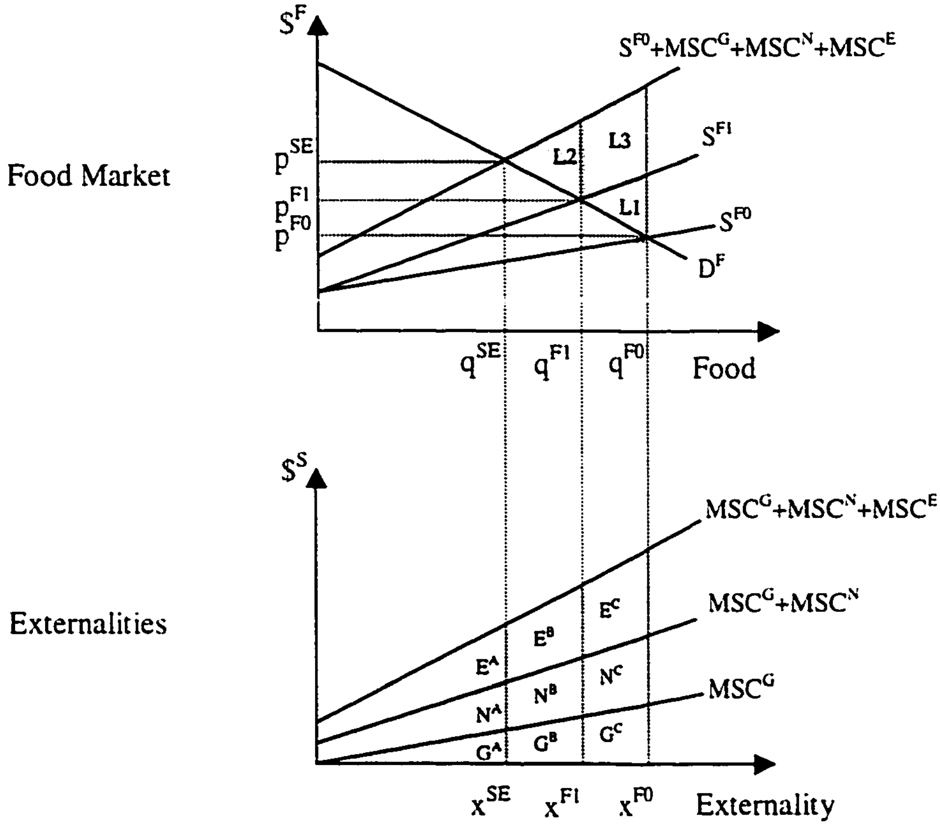

Figure 3-3 Impacts of greenhouse gas emission (G) mitigation efforts on erosion (E) and nitrogen pollution (N)

As nitrogen use increases, so does the probability of causing excess nitrogen, the nitrogen residual left in the soluble portion of the soil after plant uptake. Excess levels of nitrogen increase the amount of nitrogen leaching into the ground water.

Social costs of the described externalities are shown in the lower panel of Figure 3-3, where MSC^G represents marginal social cost of GHGE, MSC^N marginal social cost of nitrogen water pollution, and MSC^E marginal cost of erosion. As argued above and in section 3.2, all externalities are positively correlated with food production, thus the marginal social damage increases as more food is produced.

The food market representation in Figure 3-3 contains one aggregate demand curve (D^F) and three supply curves symbolizing three different levels of social cost accountancy. The supply curve labeled S^{F0} embodies all currently incurred marginal costs of food production in absence of any environmental policy. Internalizing only the GHGE externality generates supply curve S^{F1}. To emphasize the linkage to section 3.2, the two supply curves (S^{F0}, S^{F1}) were named identically to those used in this previous section. Finally, internalizing all marginal social costs of considered externalities and adding these costs to the marginal cost of food production (S^{F0}) yields the total marginal social cost curve ($S^{F0} + MSC^G + MSC^N + MSC^E$).

In absence of any environmental policy, the free market equilibrium would be determined at the intersection of D^F and S^{F0}, corresponding to a relatively high level of food production (q^{F0}). As concluded in section 3.2, the aggregate food price would settle relatively low, at p^{F0}. Unaccounted social costs from above described externalities would be relatively high and equivalent to the sum of areas $G^A + G^B + G^C + N^A + N^B + N^C + E^A + E^B + E^C$.

If all externalities were internalized, the market would move from the free market equilibrium (q^{F0}, p^{F0}) to a new equilibrium (q^{SE}, p^{SE}). Production of food would notably decline and prices for food would go up. Social cost from environmental damages would not be eliminated but considerably reduced. The remaining environmental damage would equal the sum of areas $G^A + N^A + E^A$ (lower diagram of Figure 3-3). The associated social benefits from internalizing the identified externalities can also be recognized in the food market diagram (sum of areas L1 + L2 + L3).

In the previous section, impacts of a GHGE mitigation policy on food markets were analyzed. Particularly, it was argued that internalizing emissions of GHG would shift the aggregate supply curve for food to the left (S^{F0} to S^{F1}). As a result production of food would decrease from q^{F0} to q^{F1} and the price of food would increase from p^{F0} to p^{F1}. The effects of such policy on environmental externalities can be seen in Figure 3-3. As intended, GHGE would be lower (x^{F1}) than without policy (x^{F0}). However, given the above-discussed assumptions are valid, nitrogen pollution and erosion would also be diminished at x^{F1}. Areas $N^C + E^C$ represent those unintended environmental gains.

The unintended environmental side effects are unaccounted for in previous GHGE mitigation studies (see section 2). Although this dissertation will not provide estimates of the marginal social damage from erosion or nitrogen leaching, it can provide a quantitative record of changes in levels of erosion and nitrogen pollution as various mitigation policies are put in place. This represents a major improvement over existing analyses. It will be left to further studies to place monetary values on erosion and nitrogen pollution reductions, and to incorporate likely effects of GHGE reduction policies on additional externalities, for example, on the quality of wild life habitats.

3.4 Efficiency of Mitigation Policies

Summarizing the above arguments, mitigation policies are likely to cause the following main impacts on the agricultural sector. First, limited availability of farmland will force a competition between land used for traditional agricultural production and land used to mitigate greenhouse gas emissions. Second, farmers will select a combination of traditional management and mitigation strategies that maximizes their profit. Third, prices for food commodities are likely to rise. Fourth, farm income may increase due to gains in the mitigation arena. Also, farm income arising from food production may increase because the inelastic demand for food commodities may increase food prices considerably. Fifth, mitigation is likely to reduce the extent of other negative environmental externalities.

Policy makers want to know whether agriculture's mitigation potential justifies implementation of specific farm management related mitigation policies and if so, what specific policies would be efficient. In general, a mitigation policy is efficient if the time stream of net social benefits from this policy is preferred over that from any feasible alternative. Benefits from GHGE mitigation efforts may include reduced levels of greenhouse gas emissions, reduced costs of emission reductions in non-agricultural markets, reduced levels of other agricultural externalities, more governmental revenues, and fairer income distribution in the agricultural sector. Dynamic efficiency gains of, for example, decreased future abatement costs through technological change are important (Jaffe and Stavins). Losses from GHGE mitigation policies involve welfare reductions in the traditional agricultural sector and transaction costs.

The analytical approach of this dissertation enables a more accurate estimation of net benefits from mitigation policies, which in turn enables policy makers to choose efficient policies.

3.5 Transaction Costs

Transaction costs represent a key characteristic of environmental policies. Most environmental externalities exist because the magnitude of these costs outweighs potential gains from creating a market for the external good or bad. Transaction costs include costs of implementation, monitoring, and enforcement of environmental policies. Because of very limited experience with GHGE policies, the magnitude of transaction costs in the mitigation arena is highly uncertain and may differ substantially among emission sources (Crandall).

Taxes on fuel, fertilizer, and energy certainly belong to the low cost category of mitigation policies. They are already used in many countries (Organization for Economic Cooperation and Development survey) even though the actual tax rates are disconnected from GHGE reduction objectives. Adjusting the level of an already implemented policy, therefore, should not considerably increase the costs of monitoring and enforcing this policy. Given that lobbying costs for tax level changes are tolerable, societies would incur relatively little additional expenses from adjusting these tax rates to incorporate emission reduction objectives.

While implementation of fuel taxes may be relatively cheap, some other agricultural mitigation policies are likely to yield higher transaction costs. For example, nitrous oxide emissions from agricultural fields can only be mitigated by upstream policies on certain management practices. The linkage of these practices to actual levels of emissions, however, is not yet well established (see section 2.2.1.2). Hence, inefficiencies result. Similarly, soil carbon emission mitigation policies may relate to high costs from verifying net emission reductions over time.

Costs pertaining to inefficiencies from upstream versus downstream emission regulations will be the only transaction cost item examined in this dissertation. Other items pertaining to costs of implementation, verification, and monitoring of GHGE mitigation policies will be ignored throughout the empirical analysis. The main reason for this rigorous approach is the lack of reliable data. However, not accounting for transaction costs does not entirely reduce the usefulness of empirical results. Since transaction costs are likely to be governmental expenses, their absence or presence does not affect the market equilibrium. Thus, if transaction cost data become available at some future date, the empirical results from this dissertation may be augmented, perhaps without the need for extensive recomputations.

4 METHODOLOGY

The overall objective of this dissertation is to analyze the potential of U.S. agriculture to mitigate 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 of this dissertation 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. For the purpose of this dissertation, 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.

4.1 Developing Farm Level GHGE Data - Use of the Erosion Productivity Impact Calculator (EPIC)

4.1.1 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.

In this dissertation, 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 4.2 and 4.3.

4.1.2 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. The task of this dissertation was to use 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 4-1 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 4-2. The final EPIC output is directly compatible to the economic optimization model described in sections 4.2 and 4.3.

4.2 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 4-1 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)[9]	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)[9]	Write executable batch files for missing EPIC runs Go to Step 5

Table 4-1 Continued

Step	Description
Step 5 (DOS)[9]	Execute EPIC using batch files from Step 4
Step 5a (DOS)[9]	Overwrite fertilizer parameter files in EPIC8120 directory: i) PARM8120.DAT ii) ASMFERT1.DAT Go to Step 5b
Step 5b (DOS)[9]	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)[9]	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)[9]	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 4-1 Continued

Step	Description
Step 5e (DOS)[9]	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)[9]	If more regions to be processed, Continue with Step 5b for next region If all regions processed, Go to Step 5g
Step 5g (GAMS)[9]	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)[9]	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)[9]	Go to Step 3

Table 4-2 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 (S)
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 4-2 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 4-2 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 4-1.

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.

4.3 The Agricultural Sector and Greenhouse Gas Mitigation Model (ASMGHG)

The modeling effort in this dissertation involved modifying and expanding the ASM to analyze opportunities of greenhouse gas emission mitigation through the agricultural sector. Hereafter, the modified ASM shall be referred to as ASMGHG.

4.3.1 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.

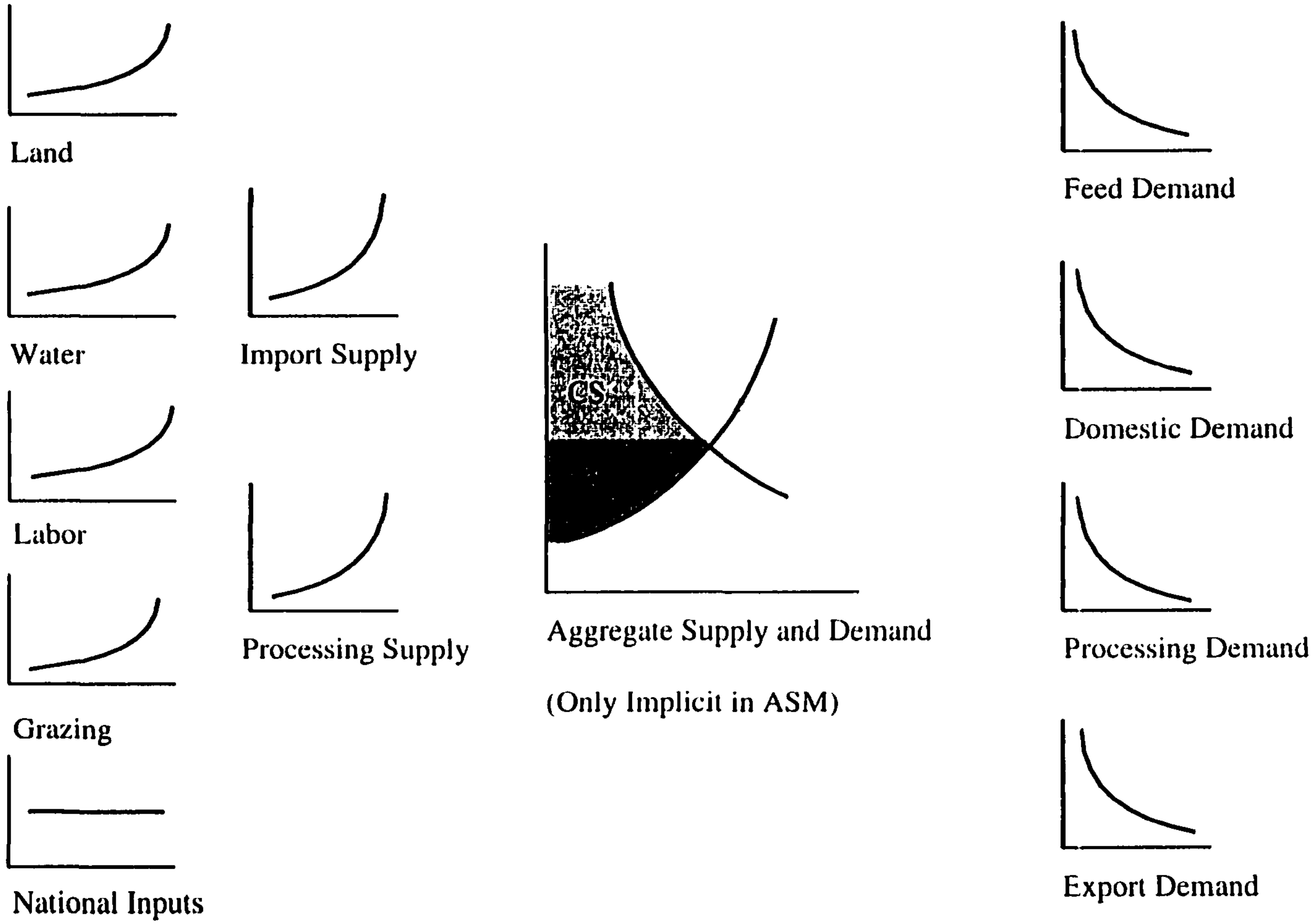

Figure 4-1 Agricultural Sector Model economic structure

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.

In this dissertation, the complete set of crop enterprise budgets 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.

4.3.2 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 4-3). In addition, the fertilizer dimension identifies whether nitrification inhibitors were used. Soils in each region were subdivided into four classes.

Table 4-3 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.

4.3.3 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

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

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

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

4.3.4 Methane Emissions

4.3.4.1 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.

4.3.4.2 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.

4.3.4.2.1 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 4-4). 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 4-4 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 i^{th} 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,

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

$GWP_{\text{"}CH4\text{"}}$ = 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 4-4 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

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

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

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

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.

4.3.4.2.2 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. Results from enteric fermentation related mitigation studies are summarized in section 2.2.1.1 of the dissertation.

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

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

Equation 21 Prediction of Year 2000 Levels of Milk Production

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

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

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

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

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

Where:

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

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

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

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

$\hat{q}^{EPA}_{R,\text{"Milk"},\text{"2000"}}$ = 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

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

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

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

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

$e^{EPA}_{R,\text{"Dairy"},\text{"Ef}_{Base}\text{"},\text{"2000"}}$ = 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

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

Equation 28 True Emission Reduction From BST Use

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

Where:

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

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

ER_i^{bST} = 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 4-5 summarizes the assumptions made for BST treatment.

4.3.4.3 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 4-5 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.

4.3.5 Carbon Dioxide Emissions

4.3.5.1 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.

4.3.5.1.1 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

$$e_{R,C,W,T}^{DirFF} = \sum_{FF} \left(q_{FF,R,C,W,T} \times q_{FF}^{BTU} \times CE_{FF}^{BTU} \right)$$

Where:

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

$q_{FF,C,W,T}$ = 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_{FF}^{BTU} = Average energy content of fossil fuels, and

CE_{FF}^{BTU} = Carbon emission of fossil fuels per unit of energy.

4.3.5.1.2 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

$$pq^{Irrg}_{R,FF} = \frac{pQ^{Irrg}_{R,FF}}{A^{Irrg}_{R} \times w^{Irrg}_{R}}$$

Equation 32 Calculation of Average Fuel Quantities for Irrigation

$$q^{Irrg}_{R,FF} = \frac{pq^{Irrg}_{R,FF}}{p_{FF}}$$

Equation 33 Calculation of Average Carbon Emissions From Irrigation

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

Where:

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

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

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

W^{Irrg}_{R} = 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.

4.3.5.1.3 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.

4.3.5.2 Sink Enhancements

As argued in sections 2.2.2 and 2.2.3, 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.

4.3.5.2.1 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

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

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

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

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

$$\Delta SOM^{EPIC}_{T} = SOM^{EPIC}_{T} - \overline{SOM}^{EPIC}$$

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

Where:

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

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

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

$\overline{SOM}^{EPIC}$ = 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

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

Equation 39 Zero SOM Change for Base Scenario

$$\Delta SOM^{Lit}_{"Base"} = \sum_{T} \left(s^{NRCS}_{T} \times \Delta SOM^{Lit}_{T} \right) = 0$$

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

$$\Delta SOM^{Lit}_{"Vent"} = \sum_{T=\{"Zero","Cons"\}} \left(- s^{NRCS}_{T} \times \Delta SOM^{Lit}_{T} \right) \Big/ s^{NRCS}_{"Vent"}$$

Equation 41 SOM Change Identity

$$\Delta SOM^{Lit}_{T} = k^{SOM}_{T} \times \Delta SOM^{EPIC}_{T}$$

Where:

ΔSOM^{Lit}_{T} = Change in total soil carbon at 100% adoption of tillage system T (based on literature estimates).

s^{NRCS}_{T} = Fraction of tillage system T used in 1997 according to NRCS estimates.

ΔSOM^{EPIC}_{T} = Change in total soil carbon for 100% adoption of tillage system T (based on EPIC), and

k^{SOM}_{T} = 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 4-6.

Equation 42 Augmented SOM Change Identity

$$\Delta SOM_T^{Lit} \overset{!}{=} L^{USDA} \times \sum_{R,C,W,L}\left(\left(\sum_{\bar{T}} s_{R,C,W,L,\bar{T}}^{NRCS}\right) \times \Delta SOM_{R,C,W,T,L,"Nbase"}^{ASMGHG}\right)$$

Equation 43 Identity After Substituting Equation 37 Into Equation 41

$$\Delta SOM_T^{Lit} = k_T^{SOM} \times L^{USDA} \times \sum_{R,C,W,L}\left(\begin{array}{l}\left(\sum_{\bar{T}} s_{R,C,W,\bar{T},L}^{NRCS}\right) \times SOM_{R,C,W,T,L,"Nbase"}^{EPIC} \\ -\sum_{\bar{T}}\left(s_{R,C,W,\bar{T},L}^{NRCS} \times SOM_{R,C,W,\bar{T},L,"Nbase"}^{EPIC}\right)\end{array}\right)$$

Equation 44 Identity After Substituting Equation 42 Into Equation 43

$$\left(\sum_{\bar{T}} s_{R,C,W,L,\bar{T}}^{NRCS}\right) \times \Delta SOM_{R,C,W,T,L,"Nbase"}^{ASMGHG} \overset{!}{=} k_T^{SOM} \times \left(\begin{array}{l}\left(\sum_{\bar{T}} s_{R,C,W,\bar{T},L}^{NRCS}\right) \times SOM_{R,C,W,T,L,"Nbase"}^{EPIC} \\ -\sum_{\bar{T}}\left(s_{R,C,W,\bar{T},L}^{NRCS} \times SOM_{R,C,W,\bar{T},L,"Nbase"}^{EPIC}\right)\end{array}\right)$$

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

$$\Delta SOM_{R,C,W,T,L,"Nbase"}^{ASMGHG} \overset{!}{=} \frac{k_T^{NRCS}}{\left(\sum_{\bar{T}} s_{R,C,W,L,\bar{T}}^{NRCS}\right)} \times \left(\begin{array}{l}\left(\sum_{\bar{T}} s_{R,C,W,\bar{T},L}^{NRCS}\right) \times SOM_{R,C,W,T,L,"Nbase"}^{EPIC} \\ -\sum_{\bar{T}}\left(s_{R,C,W,\bar{T},L}^{NRCS} \times SOM_{R,C,W,\bar{T},L,"Nbase"}^{EPIC}\right)\end{array}\right)$$

Table 4-6 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.

4.3.5.2.2 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 4-7). 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 4-7) and on the average GHGE coefficients of electrical power plants per unit of energy (U.S. DOE, see Table 4-8). All power plant emission parameters refer to average annual emission coefficients obtained through a life cycle assessment (Mann and Spath).

Table 4-7 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 4-8 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[10] (%)	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

$$e^{BioF}_{R,BF,L,G} = y^{DM}_{R,BF,L}\left[\frac{\text{Dry Ton}}{\text{Acre}}\right] \times en^{BTU}_{BF}\left[\frac{MBTU_{BF}}{\text{Dry Ton}}\right] \times eff^{BioPP}\left[\frac{MBTU_{GRID}}{MBTU_{BF}}\right]$$
$$\times \frac{1000}{3.4147}\left[\frac{KWH_{GRID}}{MBTU_{GRID}}\right] \times \left(E^{BioPP}_{G} - E^{CoalPP}_{G}\right)\left[\frac{KG}{KWH_{GRID}}\right]$$

Where:

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

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

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

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

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

E^{CoalPP}_{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

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

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.

4.3.5.2.3 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 4-9 and were used in ASMGHG.

Table 4-9 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.

4.3.6 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 4-10.

Equation 53 Calibration of Nitrous Oxide Emission Coefficients

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

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.

4.3.7 Emissions Accounting in ASMGHG

4.3.7.1 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 4-10 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

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

Where:

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

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

$A_{P^{ET},R,C^{ET},W,T,L,F}^{Ethl}$ = 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}.

4.3.7.2 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

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

4.3.8 Mitigation Policies

4.3.8.1 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 4.3.7.1, 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

greenhouse gas sources (Equation 58) and sinks (Equation 60) are identical to Equation

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 4.3.8.2.

Equation 58 Active Emission Sources Accounting Constraint in ASMGHG

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

Equation 59 Fixation of Ignored Emission Sources at Baseline Level

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

Equation 60 Active Emission Sinks Accounting Constraint in ASMGHG

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

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.

4.3.8.2 Policy Equations

4.3.8.2.1 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.

4.3.8.2.2 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

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

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.

4.3.8.2.3 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

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

Where:

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

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

4.3.8.2.4 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. It is beyond the scope of this dissertation to examine a complete list of these policies. However, an example is given in Equation 70 of how to implement a tax or subsidy on different forms of tillage management.

Equation 70 Total Tax Value in the Agricultural Sector

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

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.

4.3.9 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.

4.3.10 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[11]. A simplified version of the ASMGHG tableau is provided in Figure 4-2.

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 4-2 is shown as implicit identity, where the unrestricted variable 'Consumer plus Producer Surplus' denotes the variable to be maximized during the optimization algorithm.

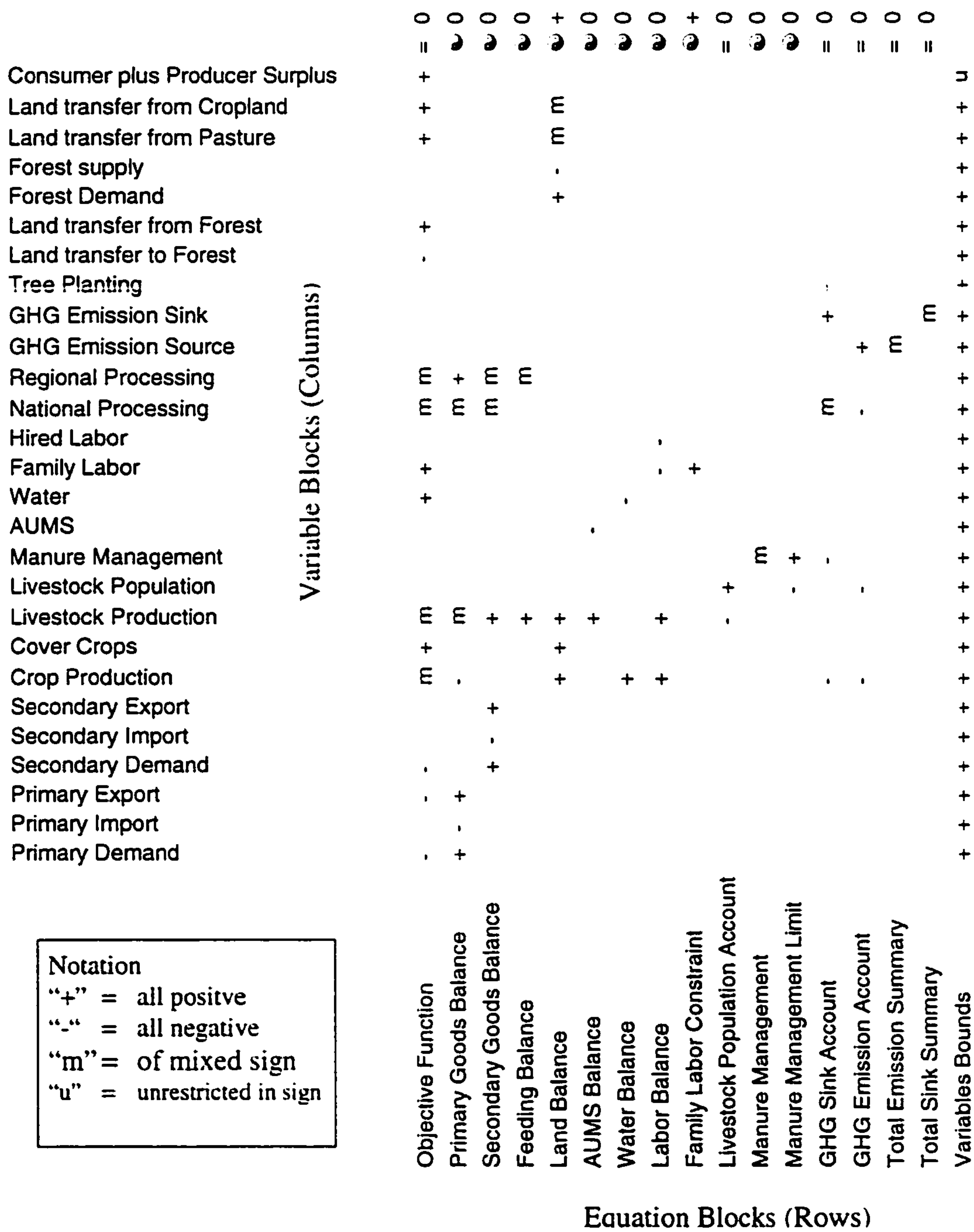

Figure 4-2 Simplified ASMGHG tableau

5 EMPIRICAL RESULTS FROM JOINT GHGE MITIGATION ANALYSIS

This section describes quantitative effects of GHGE mitigation efforts in the U.S. agricultural sector based on empirical results from joint GHGE mitigation scenarios examined with ASMGHG. Mitigation efforts were stimulated through economic incentives placed on CE emission reductions and economic disincentives placed on CE emissions. Each incentive level corresponds to a particular ASMGHG solution. To examine the behavior of parameters of interest for a certain range of incentives, ASMGHG was solved repeatedly each time altering the incentive level. In particular, the incentive level was increased in increments of \$2 for CE values between \$0 and \$50 per TCE, in increments of \$20 for CE values between \$50 and \$500 per TCE, and in increments of \$200 for CE values between \$500 and \$5000 per TCE. While CE values over \$200 per TCE are certainly not practical, they are useful for illustrative purposes, i.e. for finding the overall capacity limit of agricultural mitigation activities.

The mitigation policy design used here can be described as perfect emissions tax or, equivalently, as perfect emission reduction subsidy. Costs for implementing, monitoring, and enforcing this policy were assumed to be zero. In addition, the design allowed for unrestricted tradeoffs between different GHG on the basis of the GWP. For example, the reduction of one metric ton of methane has the same objective function value as a 21 metric ton emission reduction of carbon dioxide.

Taking into account the underlying assumption, the emission reduction values for the mitigation incentive design described above should be interpreted as upper bound.

As such these values provide points of reference for alternative mitigation policies. For example, transaction costs for an alternative policy setup can be approximated through the cost difference between alternative policies and the policy examined here for corresponding levels of emission reduction.

5.1 Overall Contribution of Agriculture to Greenhouse Gas Abatement

The economics of greenhouse gas mitigation can be efficiently summarized through abatement curves (Norton). Abatement curves show potential GHGE reduction at a given cost or, alternatively, what price has to be paid to achieve a certain level of emission reduction. Figure 5-1 through Figure 5-3 show agriculture's potential to mitigate greenhouse gases for low, high, and extremely high CE incentive levels. The net contribution of each greenhouse gas category to the emission reduction is also shown.

Emission reductions were calculated for each incentive level as the difference between actual emissions and baseline emissions. The slope of the marginal abatement curves in Figure 5-1 through Figure 5-3 indicates how much each greenhouse gas can be reduced at a given incentive level. For a $20 per TCE incentive, approximately 50 MMT of carbon equivalents can be saved through the agricultural sector. This amount equals about three percent of the combined 1990 U.S. emissions of carbon dioxide, methane, and nitrous oxide (U.S. EPA). Even under extreme incentives, agriculture's annual contribution does not exceed 400 MMT (Figure 5-1).

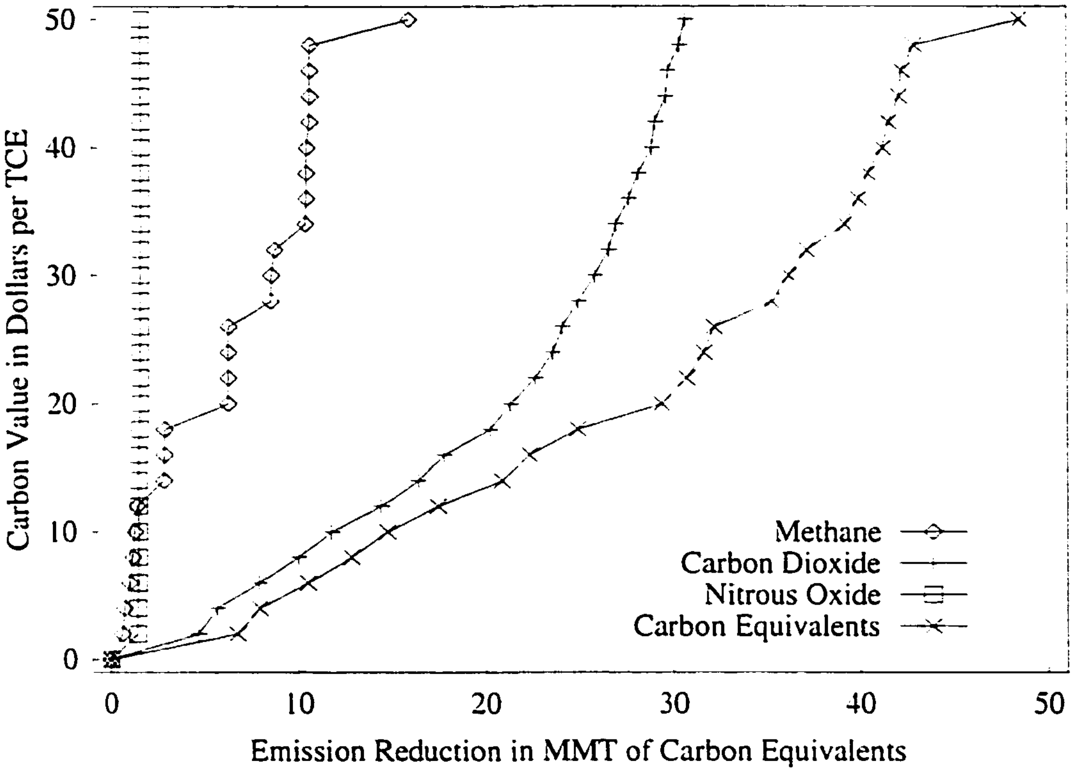

Figure 5-1 Effect of low carbon prices on joint emission reduction of greenhouse gases and contribution of individual gas categories

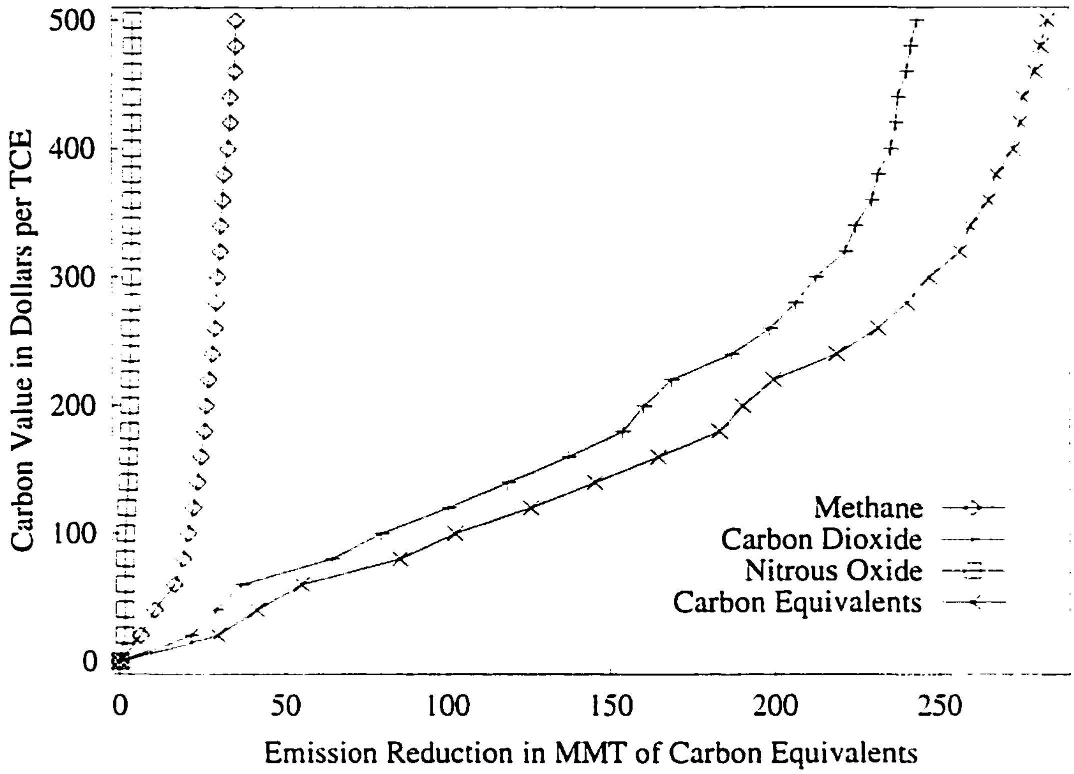

Figure 5-2 Effect of high carbon prices on joint emission reduction of greenhouse gases and contribution of individual gas categories

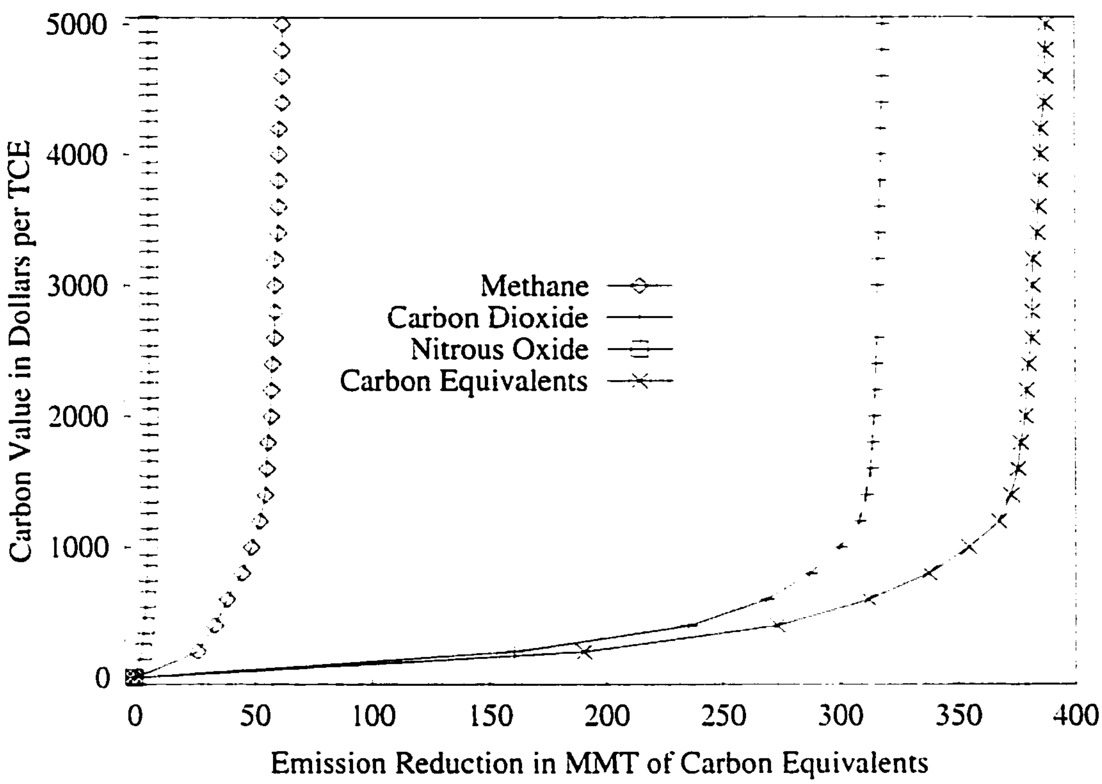

Figure 5-3 Effect of extremely high carbon prices on joint emission reduction of greenhouse gases and contribution of individual gas categories

The low initial slope of the emission reduction supply curve can be attributed to the fact that unregulated externalities involve many production inefficiencies. For example, some farmers may be economically indifferent between two management options, which yield about the same economic profit but result in different levels of emissions. With no incentive in place, these farmers may adopt or continue using the high emitting strategy for various non-economic reasons. However, the introduction of a small incentive will capture all "easy" reductions.

Between $20 and $60 per TCE, the slope of the abatement curve is visibly higher indicating increasing marginal cost of emission reductions. As noted before, marginal abatement curves do not incorporate transaction costs of implementing mitigation policies. From $60 per TCE onwards, the gap between carbon dioxide emission reductions and the other two greenhouse gas emission reductions widens greatly. As shown in Figure 5-1 through Figure 5-3, nitrous oxide emission reductions have the least effect on overall emission reductions.

5.2 Mitigation Contribution of Individual Strategies

The contribution of individual GHGE mitigation components at each emission reduction value is shown in Figure 5-4 through Figure 5-7. Carbon dioxide emission reductions arise mainly from increases in soil organic matter and production of biomass feedstock for electrical power plants (Figure 5-5). The latter option dominates clearly for carbon equivalent taxes of 100 dollars per metric ton or higher.

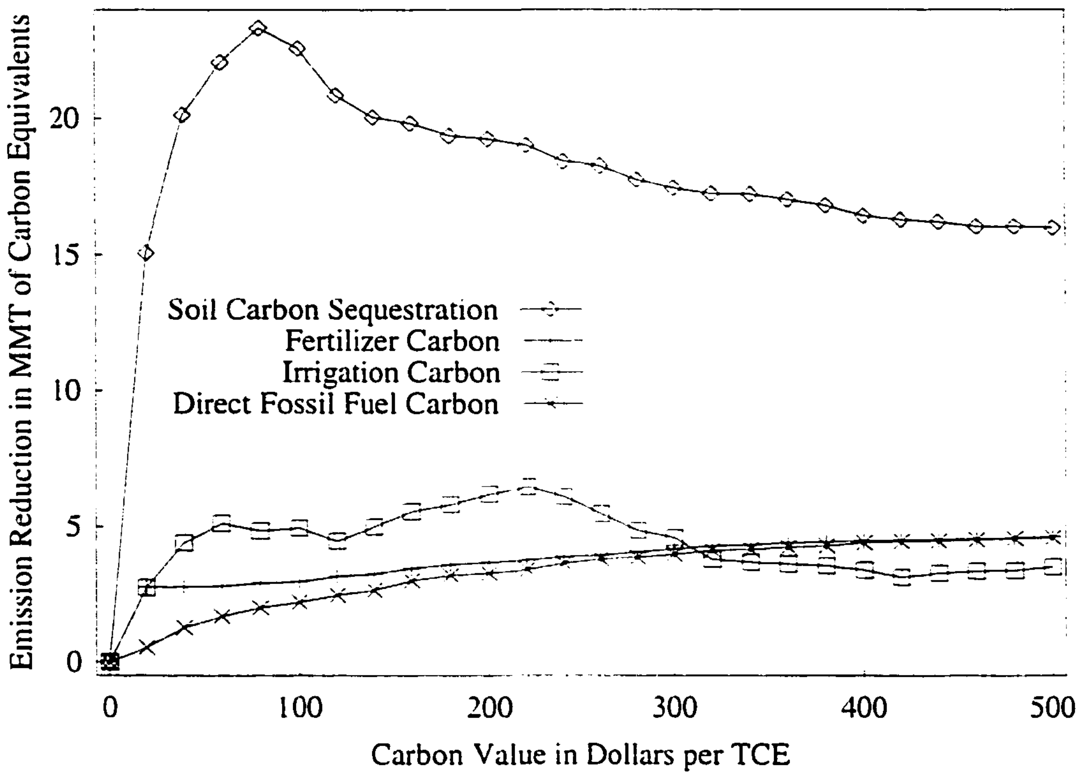

Figure 5-4 Effects of carbon prices on agricultural carbon source reductions

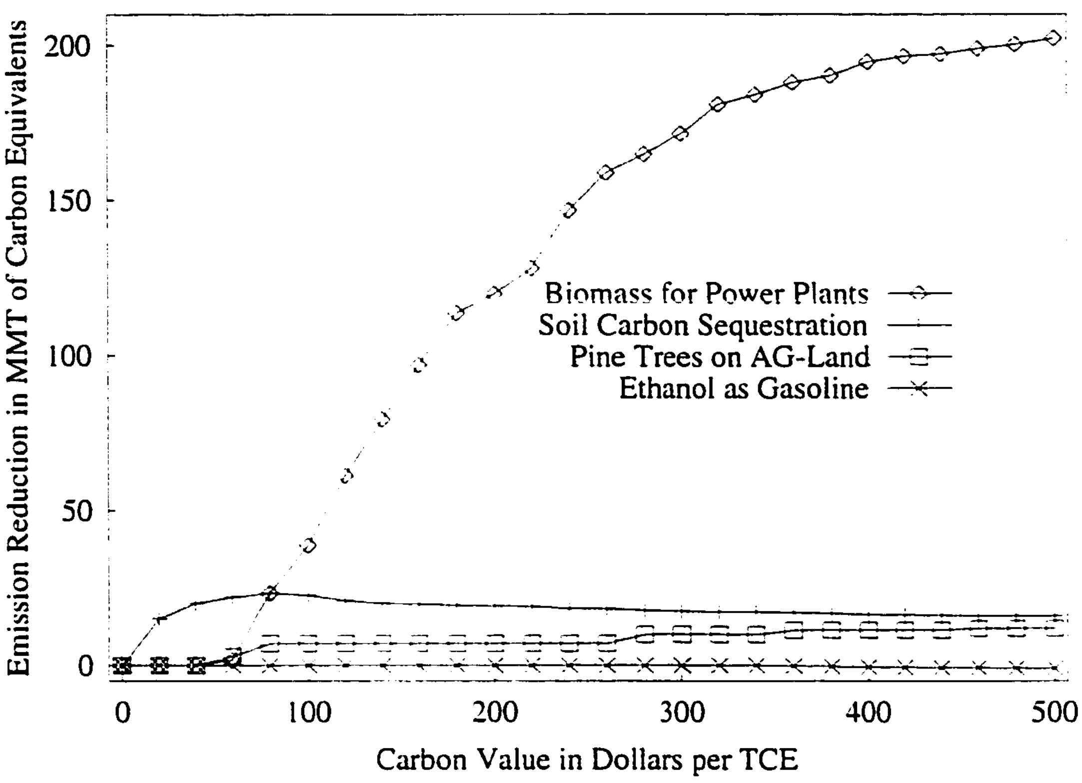

Figure 5-5 Effects of carbon prices on agricultural carbon sinks

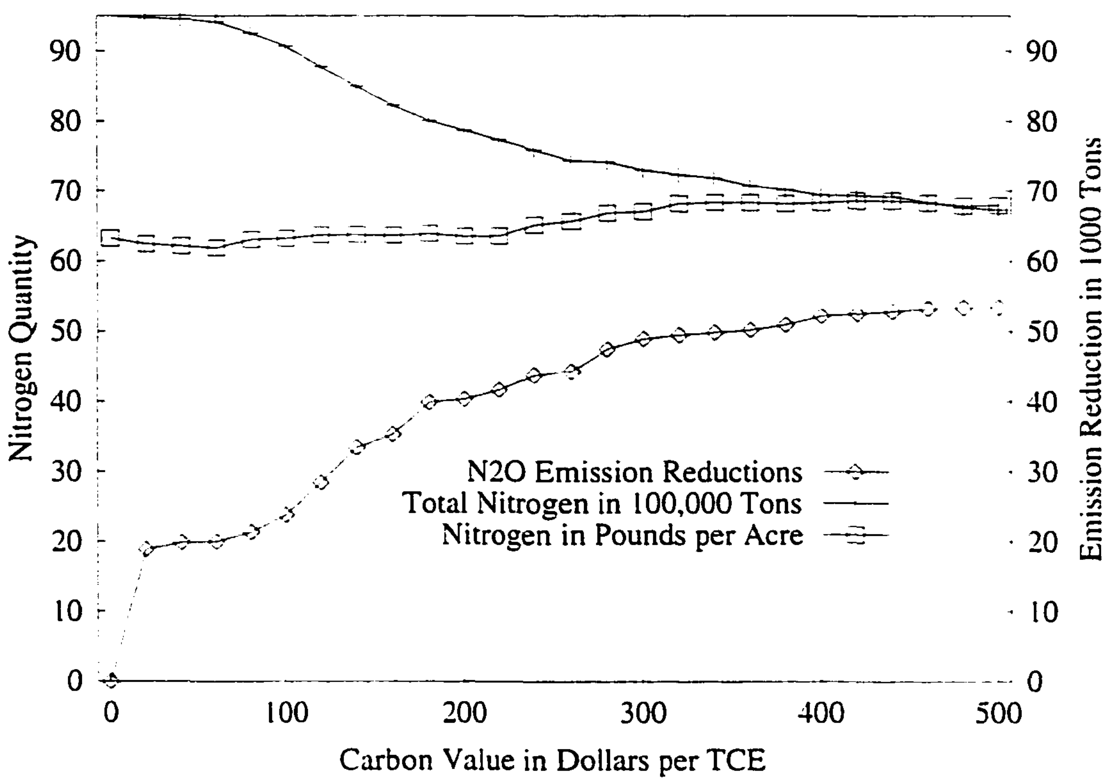

Figure 5-6 Effects of carbon prices on nitrous oxide emission reductions and nitrogen use

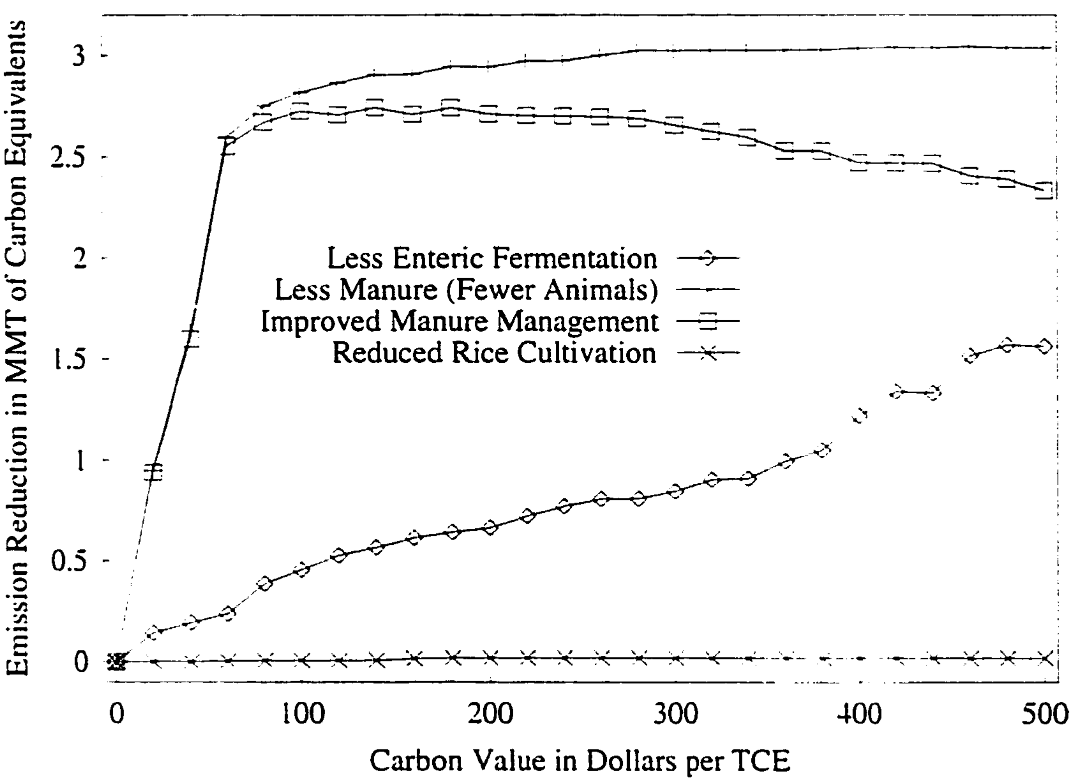

Figure 5-7 Effects of carbon prices on methane emission reduction components

Carbon emissions from direct fossil fuel use and from fertilizer application decrease steadily as emission reductions become more valuable (Figure 5-4). However, these emission reductions embody only reductions from conventional crop production and do not include source reductions from new alternatives such as biomass production.

Agricultural methane emissions are mainly reduced through keeping of fewer animals and through improved liquid manure management. Diminished rice cultivation has only little impact on overall methane emission reductions. Nitrous oxide emission savings from reduced denitrification contribute relatively little to overall emission mitigation.

5.3 Welfare Implications of Mitigation to Agricultural Sector Participants

Welfare impacts of mitigation on agricultural sector participants are shown in Figure 5-8 and Figure 5-9. These impacts represent intermediate run results, which are equilibrium results after adjustment. Thus, producers' welfare does not include adjustment costs, which might be incurred in the short run after implementation of a mitigation policy. Total welfare in the agricultural sector decreases by about 20 billion dollars for every 100 dollars of tax increase on carbon equivalents. In contrast, producers' welfare increases continuously as emission reduction become more valuable. This increase in producers' welfare is due to large welfare shifts from consumers. Consumers' welfare decreases because of higher food prices.

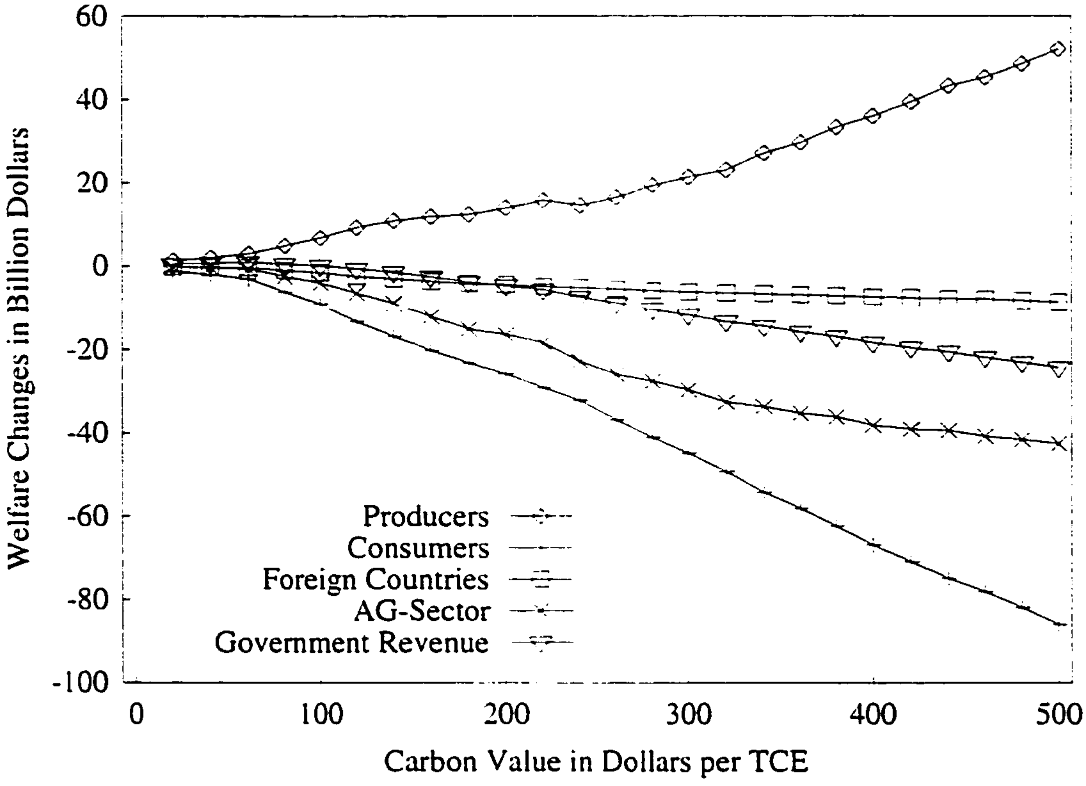

Figure 5-8 Effects of high carbon prices on welfare in the agricultural sector

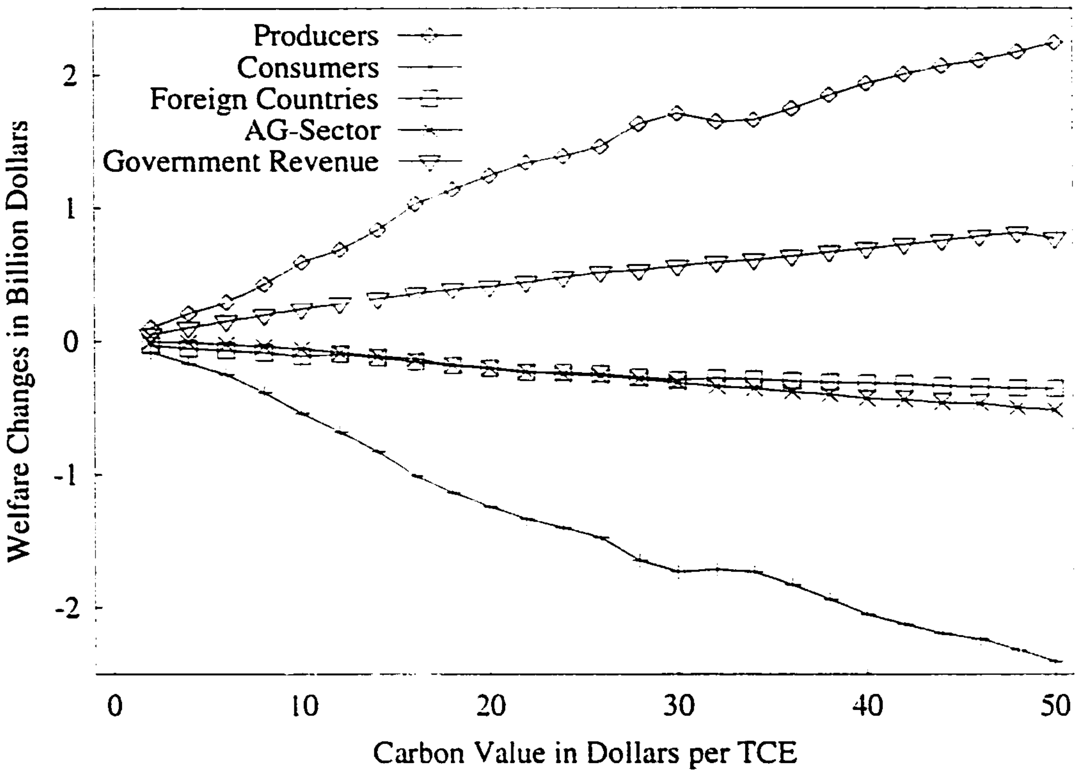

Figure 5-9 Effects of low carbon prices on welfare in the agricultural sector

Foreign countries' welfare decreases as well; however, the reduction is not as large as for domestic consumers. While foreign consumers suffer from higher food prices due to lower U.S. exports, foreign producers benefit from less U.S. food production. Since foreign welfare is aggregated over both foreign consumers and producers, the two effects can offset each other somewhat. The policy setup employed in this section yields positive governmental revenues as long as net emissions of carbon equivalents are positive as well. At tax levels beyond $150 per TCE, net emissions from the agricultural sector become negative and so do governmental revenues. Note that the above welfare accounting does not include social costs or benefits related to diminished or enhanced levels of the greenhouse gas emission externality, and other externalities such as erosion and nitrogen pollution.

5.4 Mitigation Impacts on Traditional Agricultural Markets

Mitigation efforts in the agricultural sector impact both production technologies and production intensities. New economic incentives and disincentives stimulate farmers to abandon emission intensive technologies, increase the use of mitigative technologies, and consider production of alternative products such as biofuel crops. Below, the mitigation impacts on traditional markets are summarized. Most results are provided at the national level to keep the output at reasonable size.

5.4.1 Management Changes

This section summarizes the effects of a mitigation policy on agricultural management strategies. On cropland, reducing tillage intensity is one of the considered actions to reduce net carbon dioxide emissions. ASMGHG explicitly models three different tillage intensities: conventional, conservation, and zero tillage. The national response of tillage system adoption for conventional crop production to various levels of carbon prices is shown in Figure 5-10 and Figure 5-11. Most changes in the adoption of available tillage systems occur between carbon prices of $0 and $100 per metric ton. Zero tillage reaches maximum usage at a carbon price of $80 per ton, but then declines as a result of the overall acre reduction for conventional crop production. Conservation tillage increases relative to the baseline usage only for low carbon prices around $20 per metric ton (Figure 5-11). Conventional (intensive) tillage decreases strongly up to $100 per ton of carbon. Associated emission reductions from increased soil organic matter are also shown in Figure 5-10.

Irrigation use leads to carbon dioxide emissions, the magnitude mainly depending on fossil fuel requirements for water pumping and the amount of water applied to irrigate fields. The relationship between carbon prices, irrigated acreage, and water usage is shown in Figure 5-12. For relatively low values of carbon up to $60 per metric ton of carbon, irrigation decreases. Higher carbon values, however, produce mixed effects on irrigation. A probable explanation is that irrigated crops return higher yields. Starting at carbon prices of $60 per metric ton, production of biomass becomes attractive. Since biomass production has a high mitigative potential, irrigation can free more cropland for biomass production.

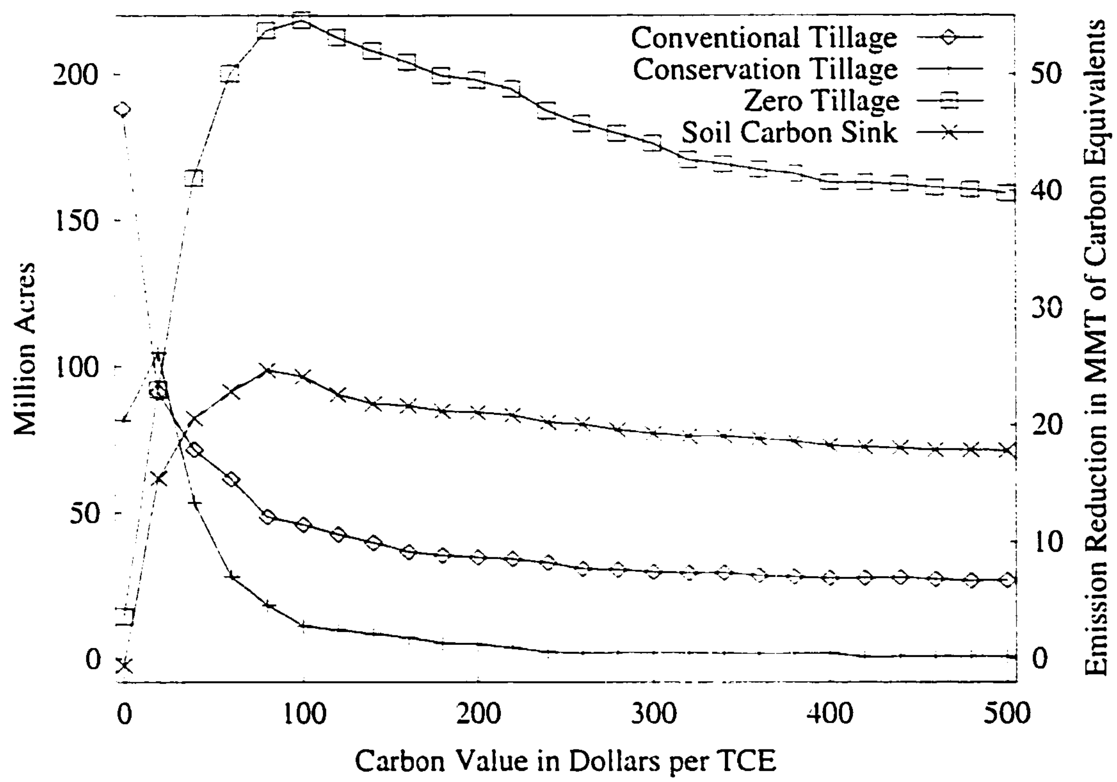

Figure 5-10 Effect of high carbon prices on tillage system use

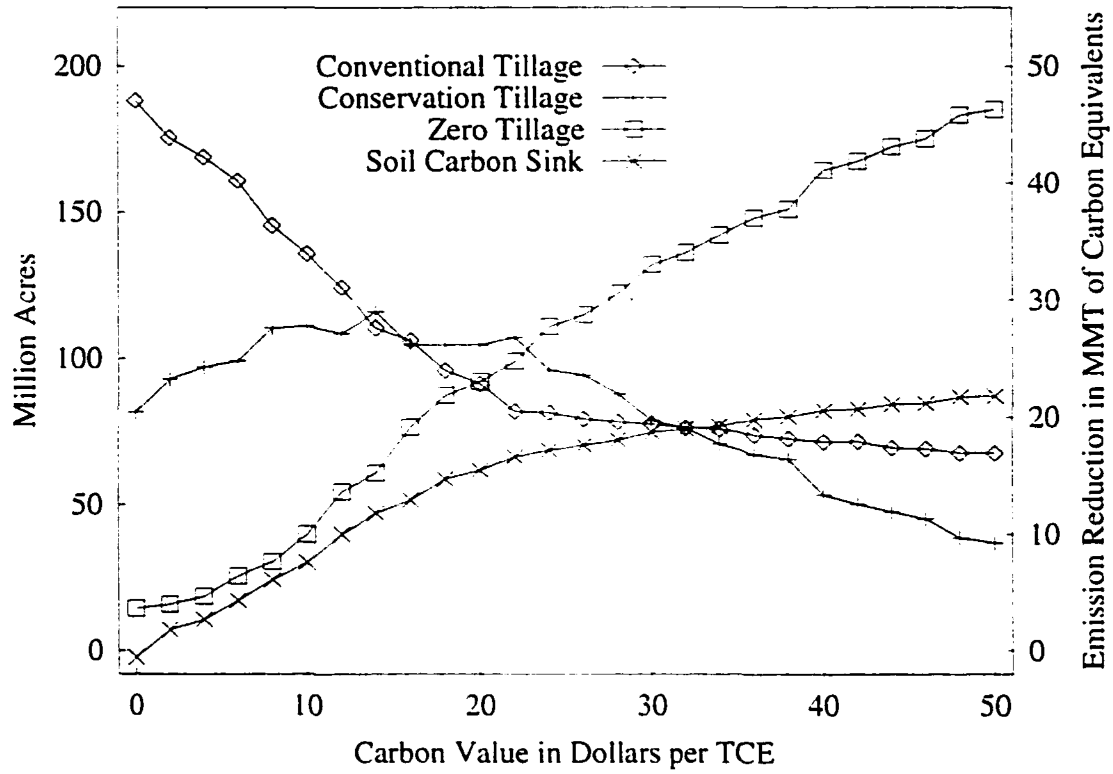

Figure 5-11 Effect of low carbon prices on tillage system use

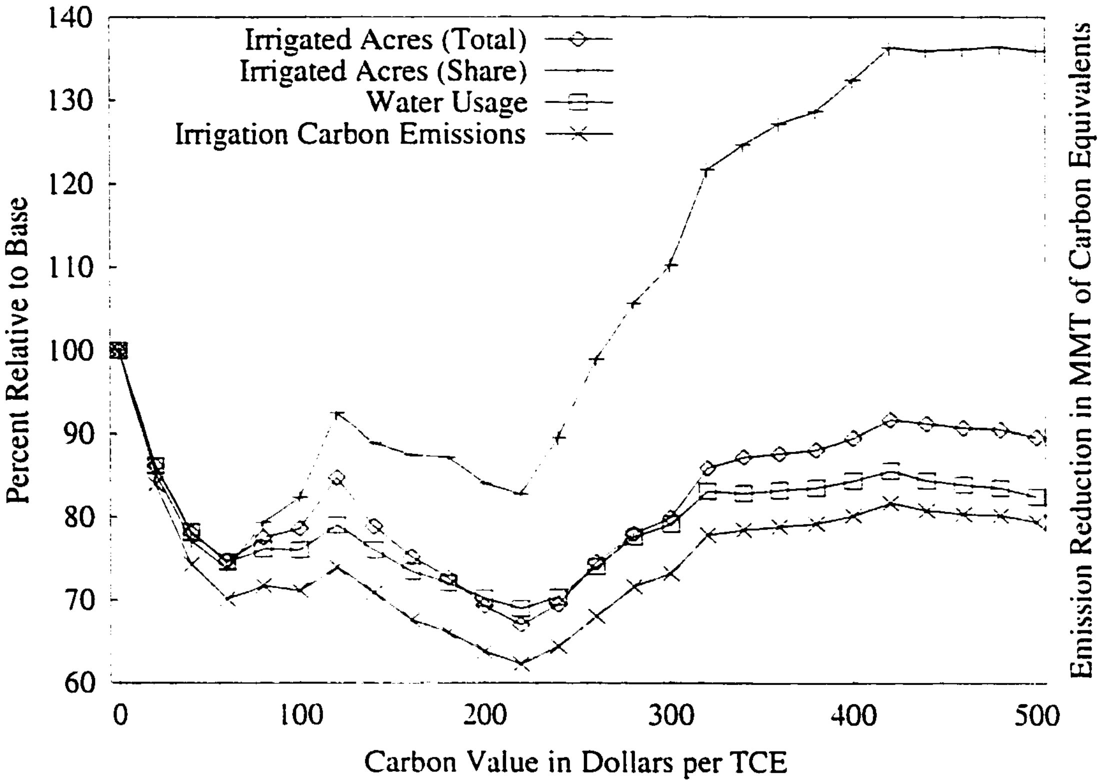

Figure 5-12 Effects of high carbon prices on irrigation of conventional crops and related emissions

Alternative fertilizer management impacts both carbon dioxide emissions and nitrous oxide emissions. In Figure 5-6, changes of nitrogen fertilizer application rates are shown in response to increasing carbon prices. At first, the nitrogen fertilization intensity for traditional crops decreases a little. However, if the price for carbon savings surpasses $80 per TCE, average nitrogen application rates are on the rise again. Analyzing Figure 5-6, it becomes clear that nitrous oxide emission reductions occur because the total amount of nitrogen fertilizer applied to traditional crops decreases. Considering the fact that per acre application rates of nitrogen fertilizer remain relatively unchanged, nitrous oxide emission reductions must result from less acreage allocated to the traditional crop sector.

In Figure 5-13, the effects of increasing carbon prices on dairy management and production are shown. Several responses can be observed. First, mitigation efforts are negatively correlated with total dairy cow population and milk production. Higher carbon prices lead to less milk production and fewer animals. However, milk production decreases at smaller rates than animal population. This can be explained by increasing numbers of BST treated animals. The number of cows under improved manure management increases as well.

According to EPA estimates, livestock manure management has the highest methane emission reduction potential among agricultural mitigation strategies. This assertion could be confirmed by ASMGHG results. Emission reductions from methane mitigation options for dairy cows are shown in Figure 5-14.

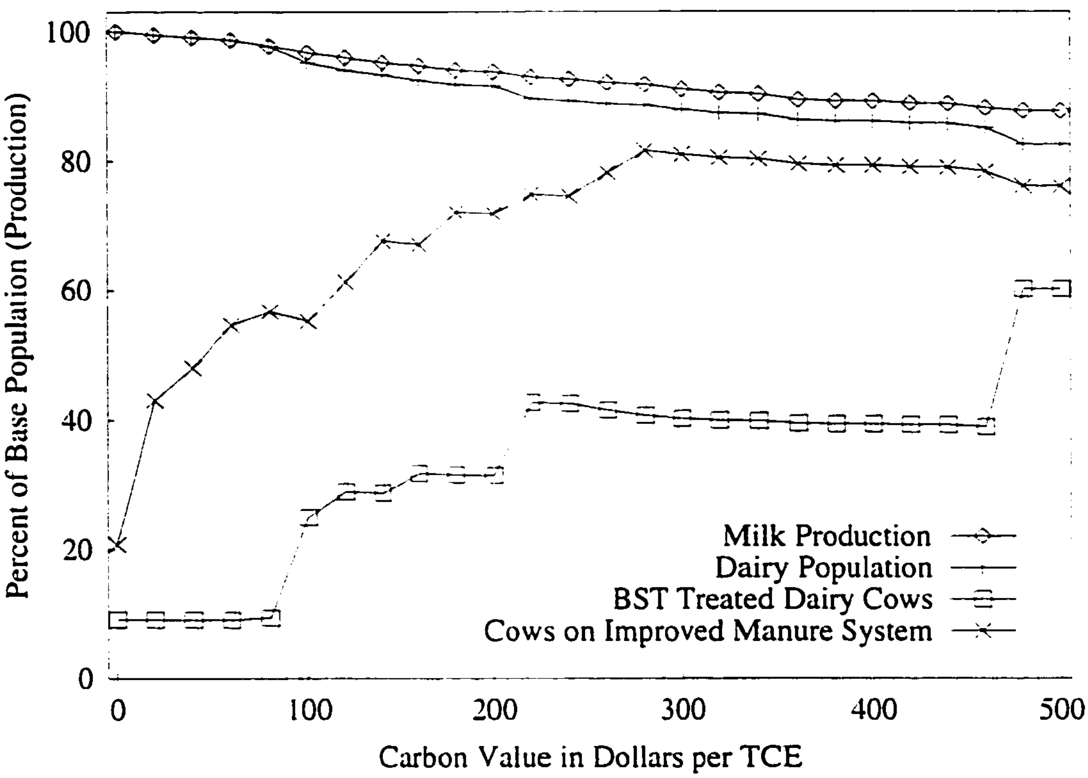

Figure 5-13 Effects of high carbon prices on dairy management and output

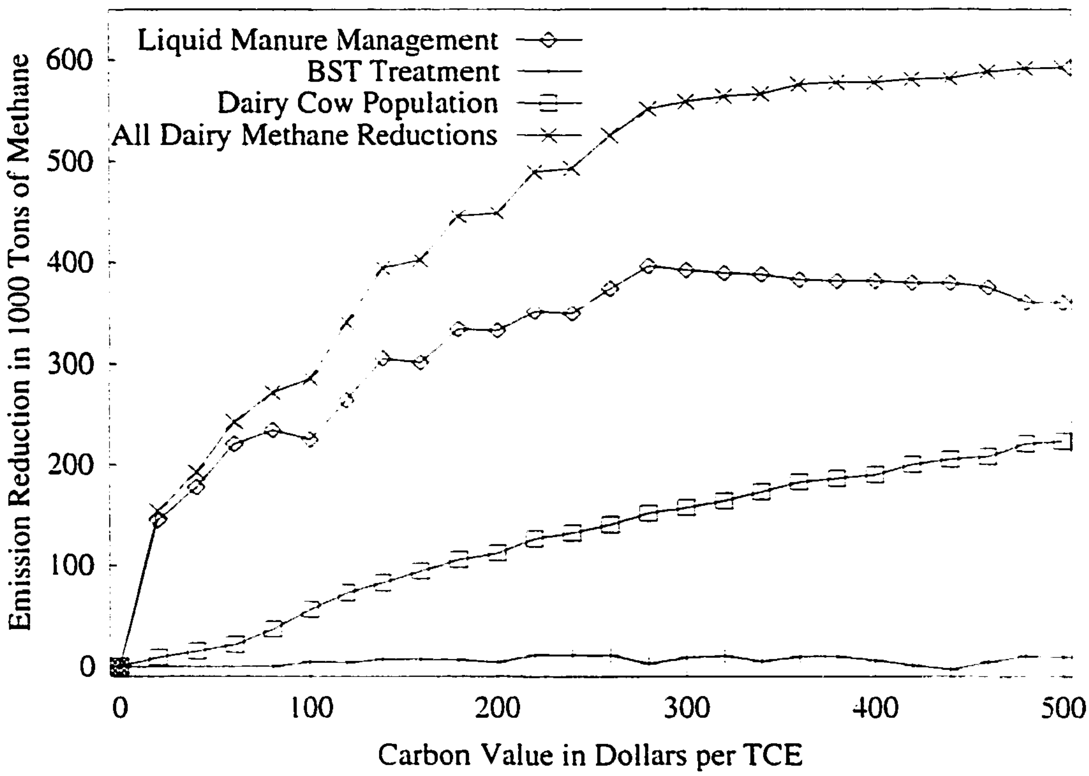

Figure 5-14 Effects of high carbon prices on methane emission reduction components from dairy cows

Liquid manure management appears to be the most cost efficient mitigation option for dairy cows. Note that emissions saving manure management technologies are constrained by the currently observed usage of manure management systems and the currently observed herd size distribution. Subsequently, reducing the number of animals leads to fairly constant increases of methane emission reduction in response to increasing levels of carbon payments. The effect of BST treatments on emission reduction is relatively small.

5.4.2 Market Indicators

This section summarizes agricultural market responses to mitigation policies reflected by changes in market prices, production, exports, and imports. In section 3.1, graphical analysis was used to show that mitigation policies are likely to raise land values. The results from the graphical analysis are confirmed by the empirical results obtained from ASMGHG. Land values of ASMGHG land classes increase considerably as greenhouse gas mitigation becomes more valuable (Figure 5-15).

Agricultural product markets respond in various ways to mitigation policies. Higher costs of production (emission tax, opportunity costs, land rental costs) for conventional crop management strategies and higher incentives for alternatives cause farmers to shift more land to mitigative products. Production of conventional crops may change both due to altered crop yields and acreage shifts. The impact of carbon prices on production of traditional agricultural products is shown in Figure 5-16 and Figure 5-17.

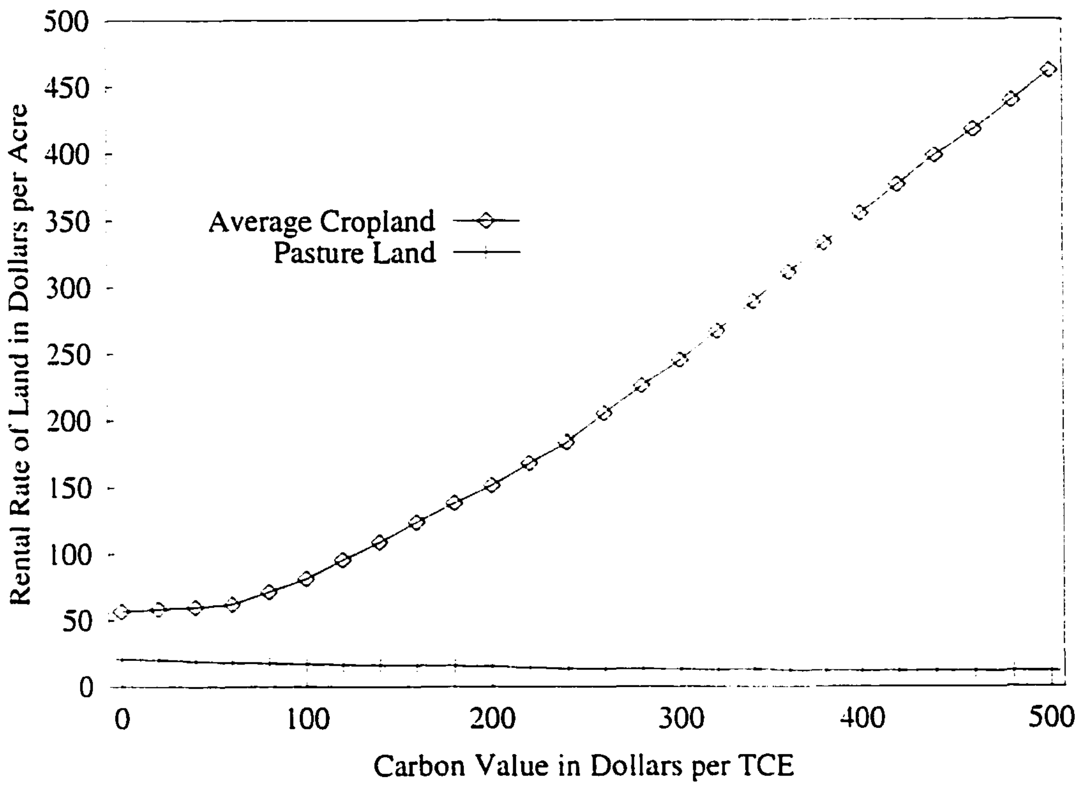

Figure 5-15 Effect of high carbon prices on land values

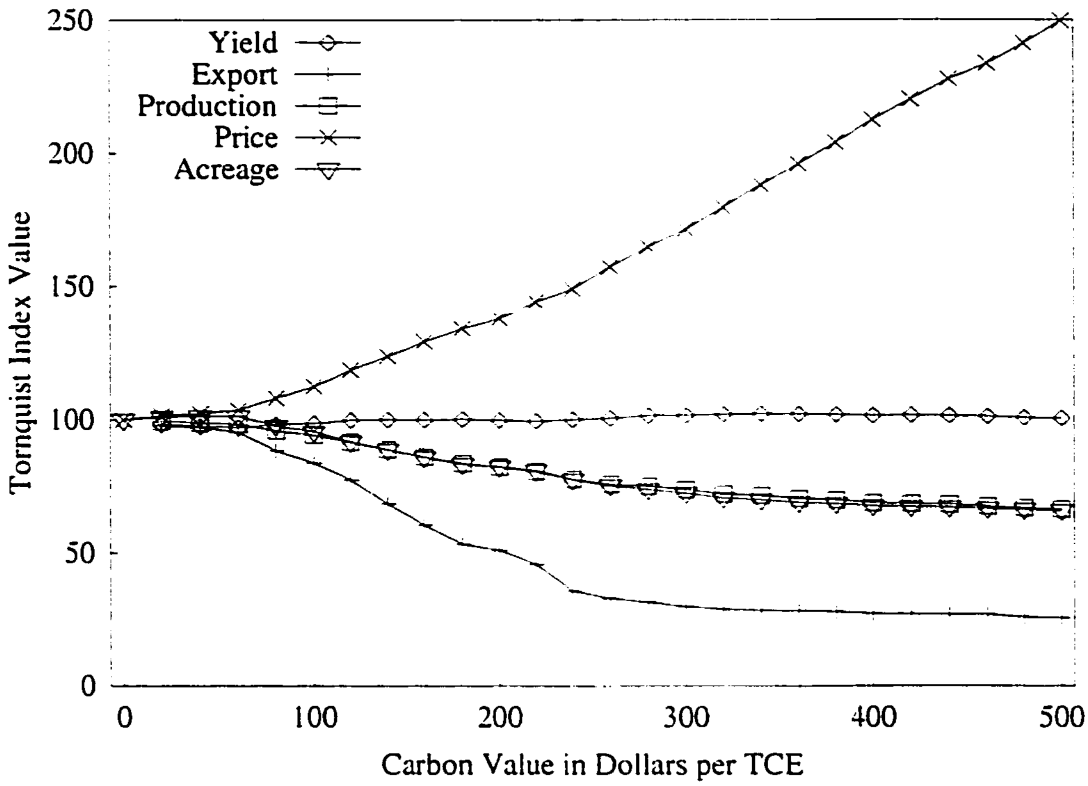

Figure 5-16 Effects of high carbon prices on conventional crop production

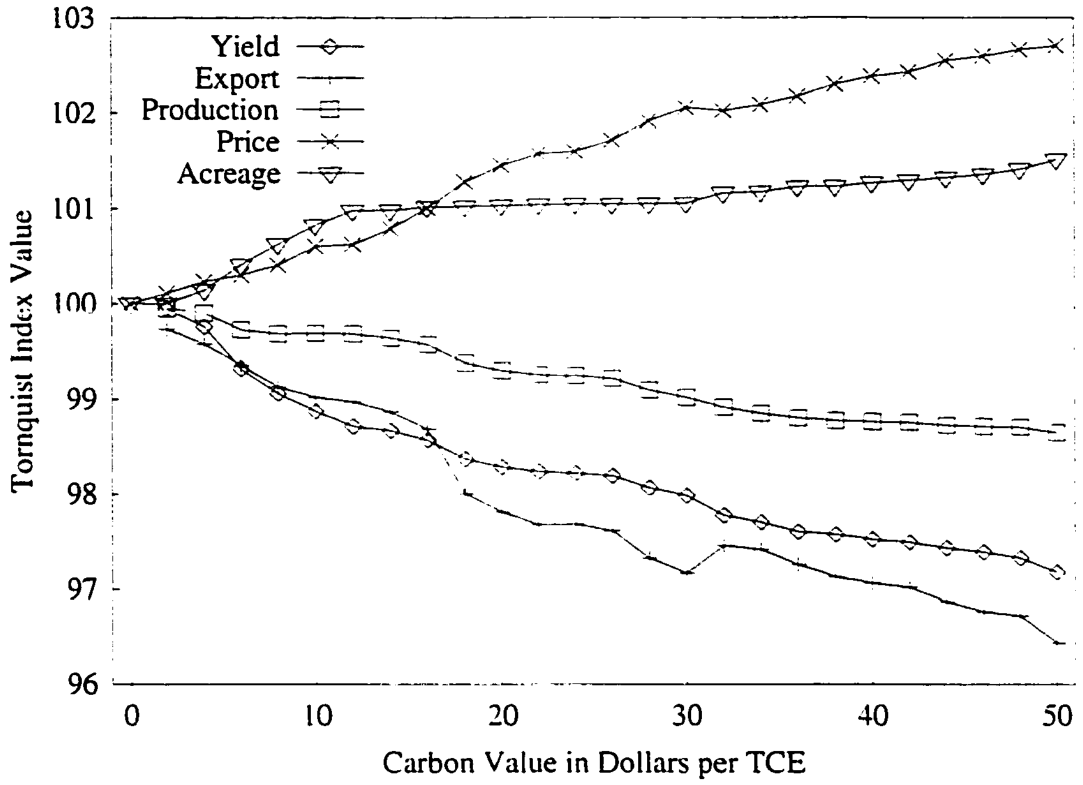

Figure 5-17 Effects of low carbon prices on conventional crop production

Declining crop production is mainly due to less acreage allocated to traditional food crops. The computed Tornquist index reveals only a small response of crop yields to mitigation (Figure 5-16). Initially, yields decline slightly due to less irrigation and less fertilization. Subsequently at higher carbon prices, average crop yields go up again. For prices above $100 per TCE substantial amounts of cropland are diverted to trees and biofuel crops (see section 5.5). In ASMGHG, tree and biomass yields are not sensitive to cropland quality; hence the marginal cropland is diverted first increasing average yields on the remaining acreage for conventional crops. Less U.S. domestic food production coupled with higher prices in U.S. agricultural markets induce foreign countries to increase their net exports into the U.S.

Livestock production decreases as a result of higher costs from mitigative management. Lower levels of production of traditional agricultural products in turn affect the market price of these products (Figure 5-18 and Figure 5-19). In particular, prices change considerably if the product is emission intensive, if it has a low elasticity of demand, and if the U.S. is a major producer.

5.5 Diversion of Agricultural Land to Different Uses

With mitigation incentives in place, farmers may choose to divert cropland to alternative uses. Growing biofuel crops to yield emission offsets or afforestation to sequester carbon emissions are among the considered options. The potential acreage diversion of traditional agricultural land to other uses is shown in Figure 5-20.

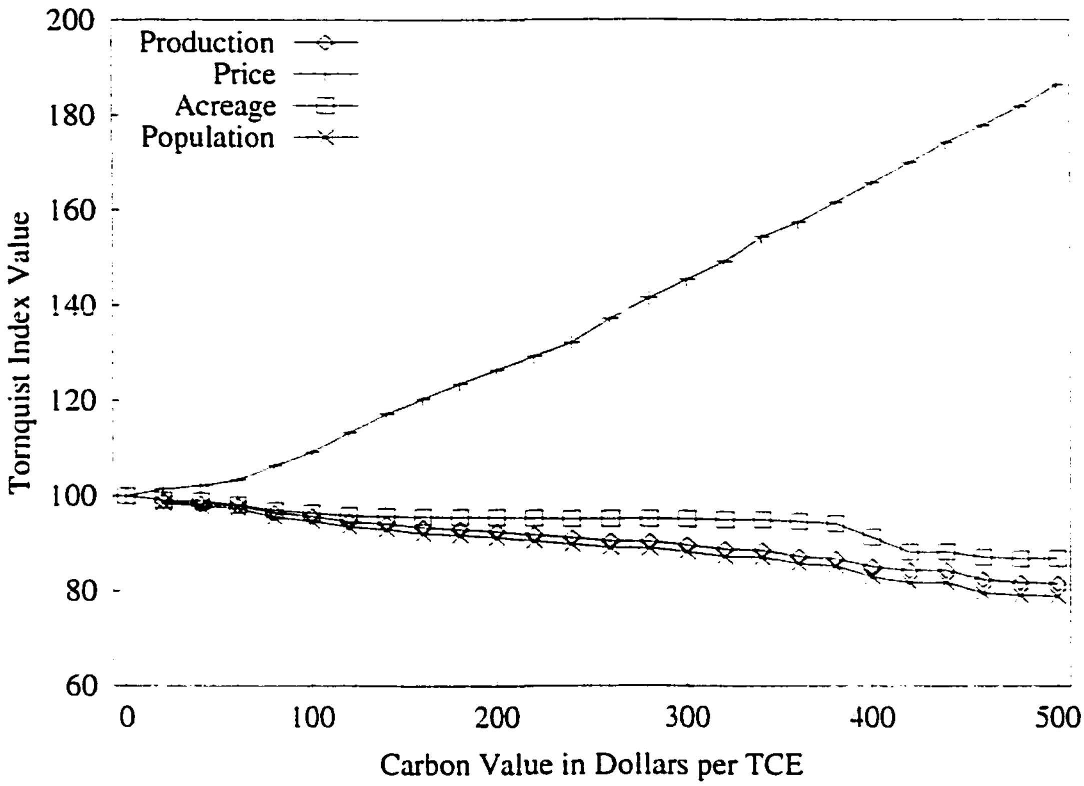

Figure 5-18 Effects of high carbon prices on overall livestock production

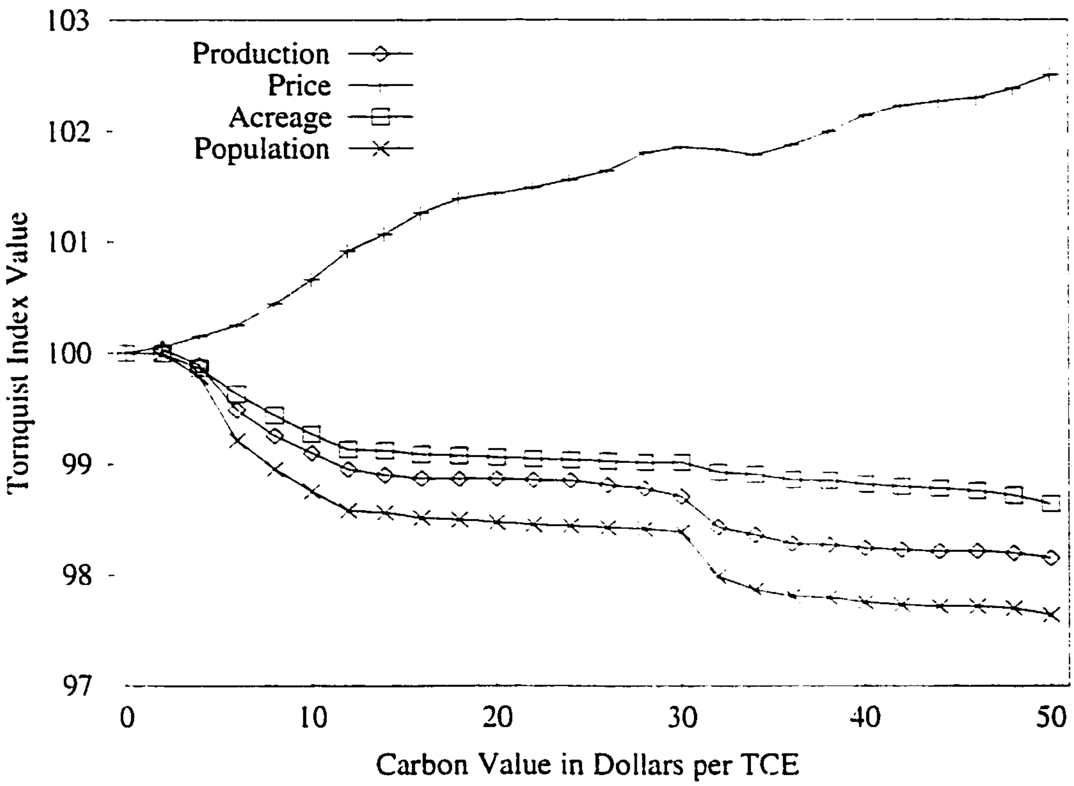

Figure 5-19 Effects of low carbon prices on livestock production

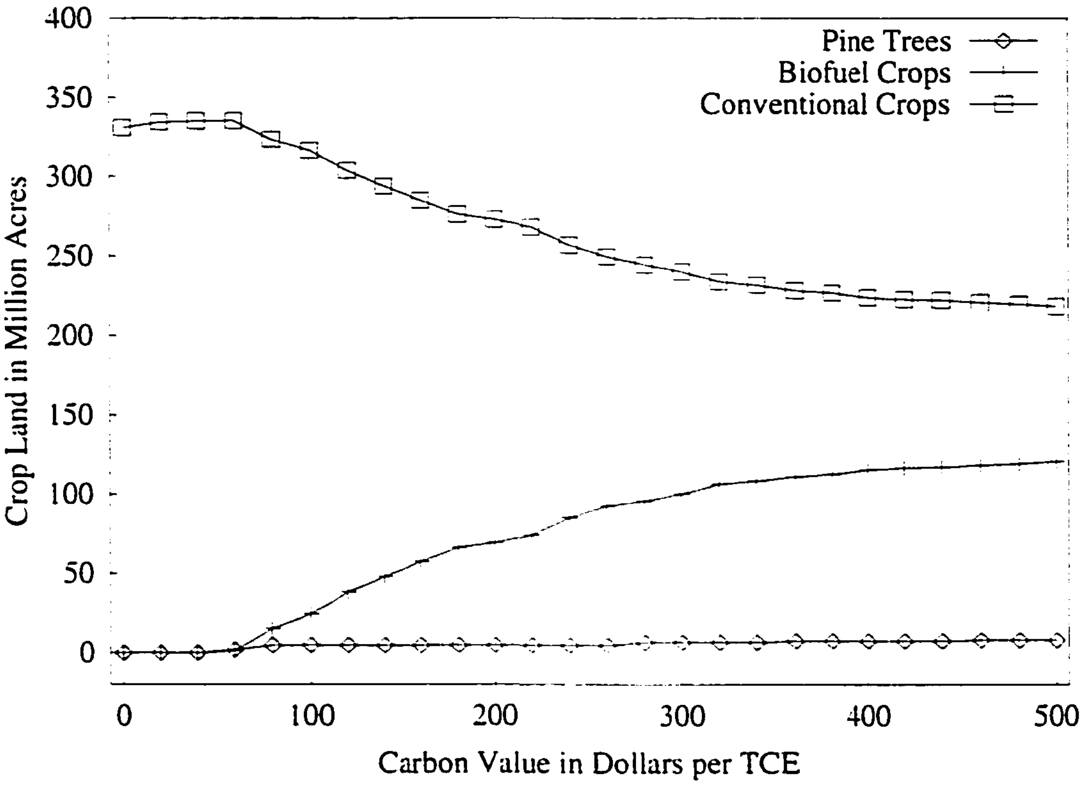

Figure 5-20 Effect of high carbon prices on land use

The acreage afforested with pine trees remains relatively small and reaches only about eight million acres at the highest carbon prices, which is still about five million acres short of the imposed afforestation limit on cropland. Note that tree carbon coefficients do not integrate any specific nonlinear dynamics of tree carbon sequestration over time. Biofuel crop acreage increases from zero to more than one third of the available cropland as the carbon value increases up to $500 per TCE (Figure 5-20).

Three different crops were considered for providing biomass as feedstock to power plants: switch grass, willow and hybrid poplar. The relative importance of these crops is shown in Figure 5-21. Switch grass production accounts for the bulk of emission offsets from biomass power plants. It becomes a competitve mitigation strategy for carbon prices above $60 per TCE. Willow is used to a smaller extent starting from $120 per TCE. Emission offsets from willow increase up to a carbon price of $280 per TCE. Hybrid poplar is never brought into production at any incentive level.

While most results presented so far stayed at the national level, ASMGHG output can also be used to analyze regional effects. With respect to biomass production, this is done so in Figure 5-22. The Lake States offer the most cost efficient biomass production. Between $60 and $120 per TCE, biomass is produced almost exclusively in these states. Subsequently, the North East, Delta State, and South East regions take part. The Corn Belt region becomes profitable for biomass production only for carbon price above $220 per TCE. Possible reasons for such behavior may include high opportunity cost in the agriculturally productive Corn Belt region.

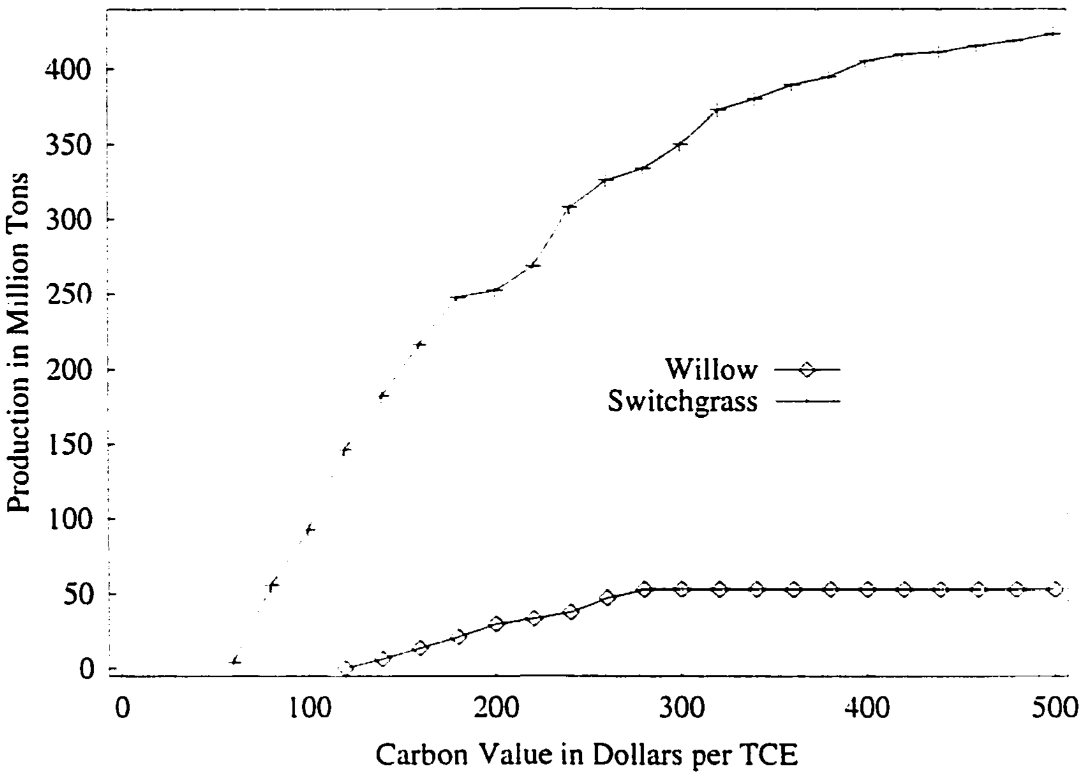

Figure 5-21 Effect of high carbon prices on production of biofuel

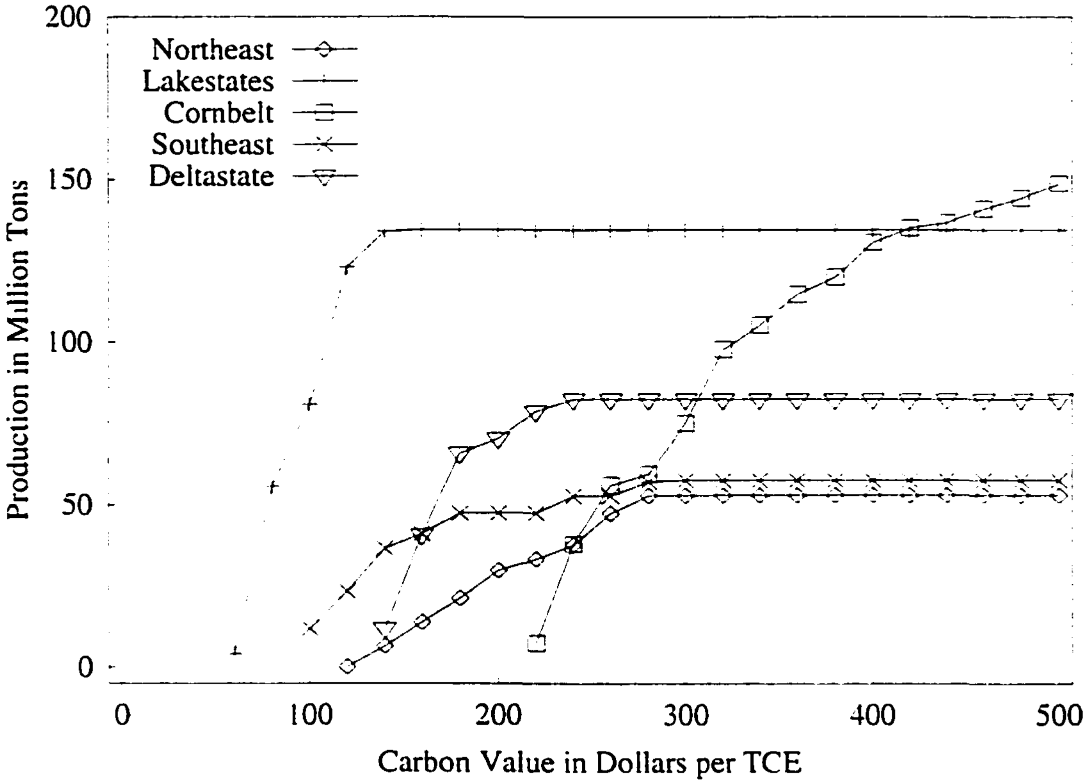

Figure 5-22 Effect of high carbon prices on regional biofuel production

5.6 Mitigation Impacts on Other Agricultural Externalities

The complex nature of EPIC results makes it possible to simultaneously analyze the effects of agricultural management on greenhouse gas emissions and on other important agricultural externalities. In section 3.3, graphical analysis suggested a "win-win" situation, where greenhouse gas emission mitigation also leads to a reduction in both soil erosion and water pollution. The sign and magnitude of EPIC coefficients do not automatically ensure the direction of change for non-greenhouse gas external effects in ASMGHG. For example, average EPIC coefficients of soil erosion decrease as tillage intensity decreases, but increase as nitrogen fertilization decreases. Empirical results from ASMGHG are shown in Figure 5-23 and in Figure 5-24. The average per acre values of the other externalities decrease considerably for a carbon equivalent price between $0 and $100 dollars per metric ton and stays at levels around 65 percent of the baseline value for higher prices. Thus, carbon prices beyond $100 per metric ton do not result in additional gains with respect to the other externalities.

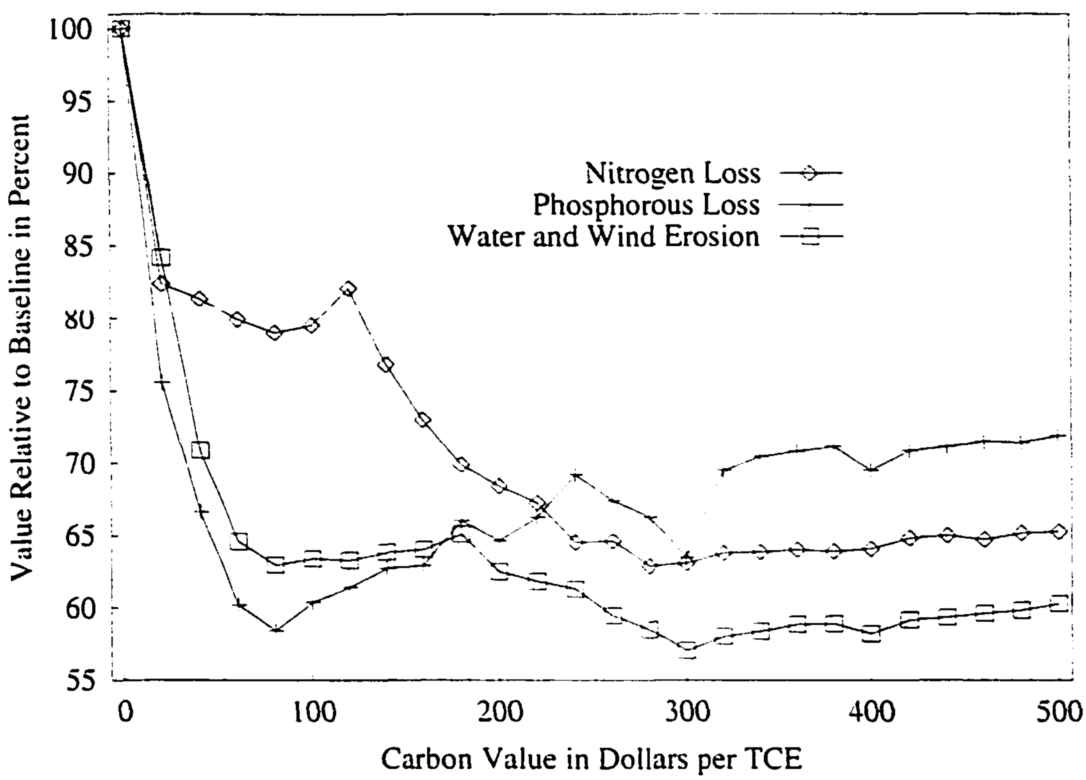

Figure 5-23 Effects of high carbon prices on other agricultural externalities

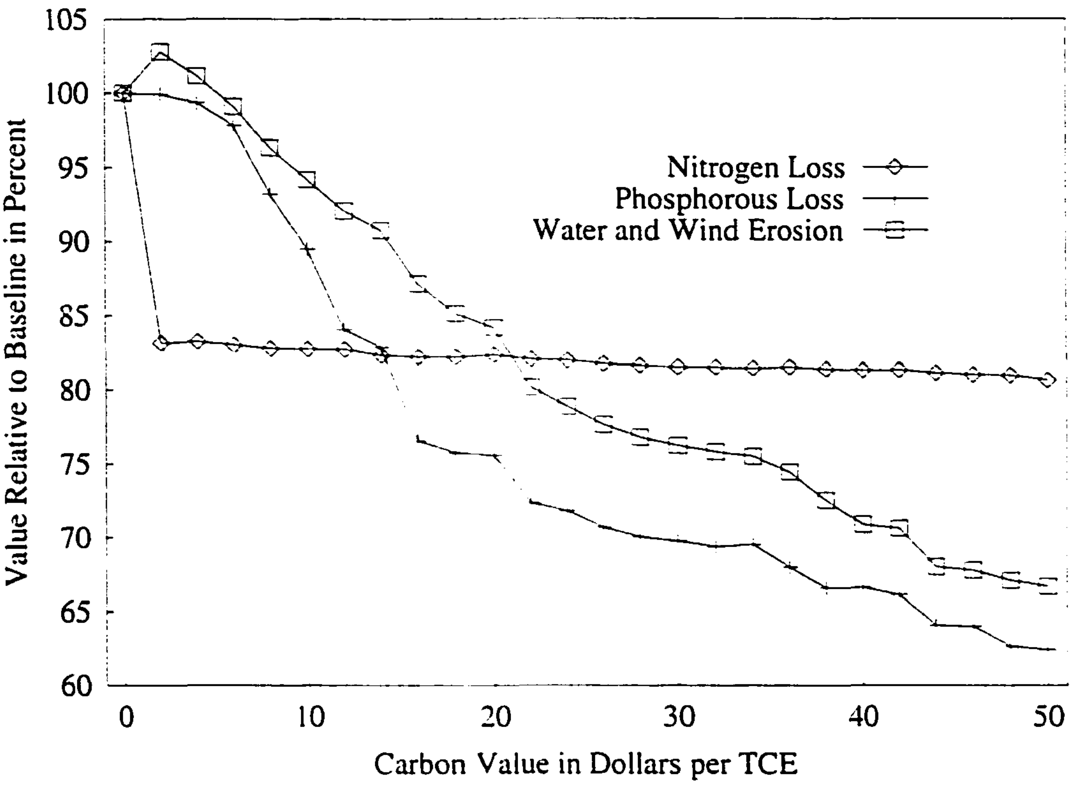

Figure 5-24 Effects of low carbon prices on other agricultural externalities

6 EXAMINATION OF ALTERNATIVE ASSUMPTIONS

In the previous section, ASMGHG was used to estimate the total GHGE mitigation potential from agriculture and related effects on management, markets, and the environment. Throughout section 5, it was assumed that all mitigation options were available simultaneously, emission coefficients were known with certainty, and that policy transaction costs were zero. While these assumptions facilitate the analysis, they are not always accurate or useful. For example, independent analysis of mitigation strategies may be preferred over joint analysis when examining policies, which target only a few specific mitigation strategies. Second, many emission coefficients were derived from simulation models with little experimental validation. Hence, a sensitivity analysis for these coefficients is desirable. Finally, downstream emission pricing policies as assumed in section 5 may not be practical for non-point source pollutants (Fischer, Kerr, and Toman).

In this section, ASMGHG will be used to relax above-mentioned assumptions and to examine the effects of the resulting modifications on GHGE mitigation. The objective of this section is to provide insight in the type of assumptions that can be modified through a few examples. Given the large number of possible cases, an exhaustive analysis of the effects of all assumptions is currently neither feasible nor desirable.

6.1 Joint Versus Independent Analysis of Agricultural Mitigation Options

Independent analysis of individual agricultural mitigation options has been used in many previous studies (see section 2) because of a single strategy focus and/or the fact that tools or resources for a joint analysis were not available. The individual assessment of mitigation strategies may be preferred under at least two circumstances. First, national or international policy makers may consider only one or a few specific agricultural strategies to be acceptable for emission reduction credits. Joint analysis of all possible strategies would then overstate agriculture's potential. Second, comparison of joint and individual analysis can reveal the assessment bias from excluding additional potential mitigation strategies.

The first point is illustrated in Figure 6-1. Emission reduction supply curves are shown for different assumptions about the availability of agricultural mitigation strategies. The more strategies are available the higher becomes the total emission reduction potential. For example, at a price of $100 per TCE, the achieved reductions in GHGE amount to 103 MMT (all AG-mitigation strategies), 50 MMT (biofuel carbon offsets), 32 MMT (non-biofuel carbon sinks), 18 MMT (methane strategies only), 8 MMT (carbon source reductions only), and 2.5 MMT (nitrous oxide strategies only). Alternatively, to get a total reduction volume of 20 MMT, carbon equivalent emission reductions cost on average $14 per TCE (all AG-mitigation strategies), $40 per TCE (non-biofuel carbon sinks), $72 (biofuel carbon offsets), $180 per TCE (methane strategies only)[12], and more than $500 per TCE (carbon source reductions only).

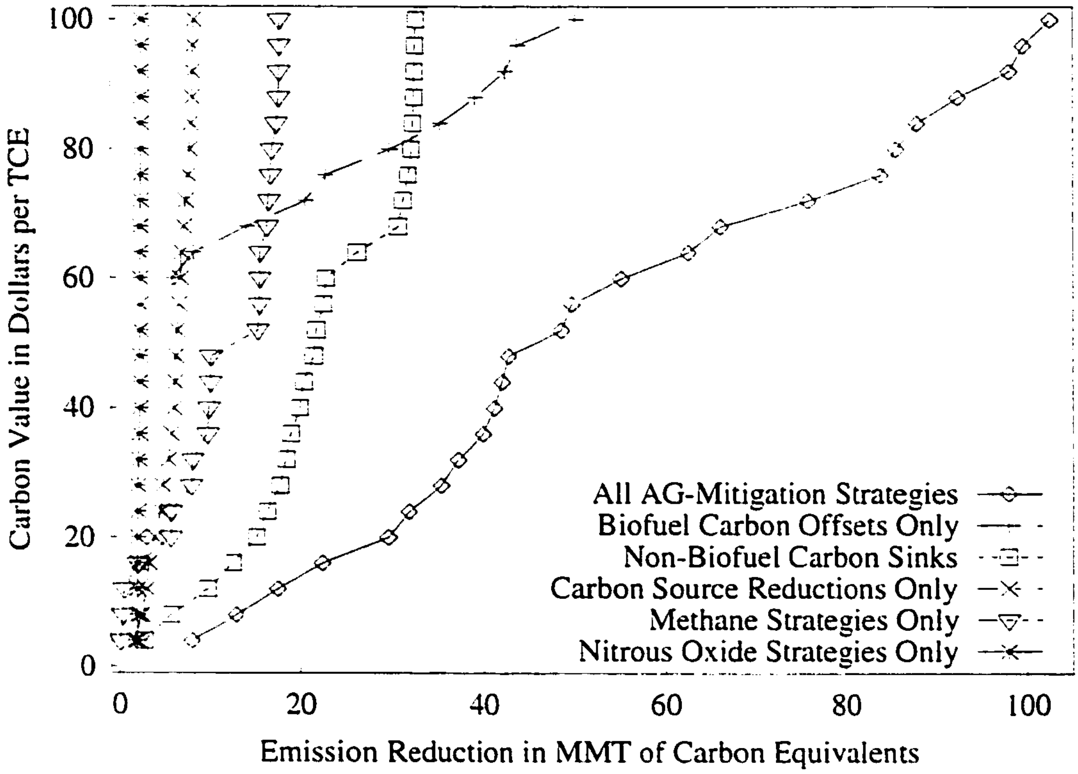

Figure 6-1 Total GHGE reduction potential under different assumptions about implementation of available mitigation strategies

Carbon sink strategies yield the highest individual mitigation potentials. Nitrous oxide emission mitigation appears little attractive, however, results are based on calibrated emission coefficients derived from the EPIC model. The original EPIC coefficients were scaled down (see Equation 53 in section 4.3.6) and hence, may be conservative estimates. Similarly, methane emission reduction supply curves reflect only application of well-documented mitigation options. Intensive research on additional methane emission reduction strategies is currently underway (see section 2.2.1.1) and may provide data for more effective mitigation options in the near future.

The assessment bias of individual mitigation appraisals can be quantified for both individual and aggregate emission reduction supply curves. The first case is illustrated for carbon emission offsets from ethanol production (Figure 6-2).

Pictured in Figure 6-2 are carbon emission abatement curves from ethanol use under different assumptions about simultaneous availability of other mitigation strategies. The scenario labeled "All Options" stands for a joint assessment of all mitigation options. "No Biomass" also represents a joint analysis with biomass production to fuel electrical power plants being the only mitigation option suppressed. In scenario "Ethanol + CH4", only methane mitigation options are enabled in addition to ethanol emission offsets. Finally, in scenario "Ethanol Only" all mitigation options are eliminated except for ethanol.

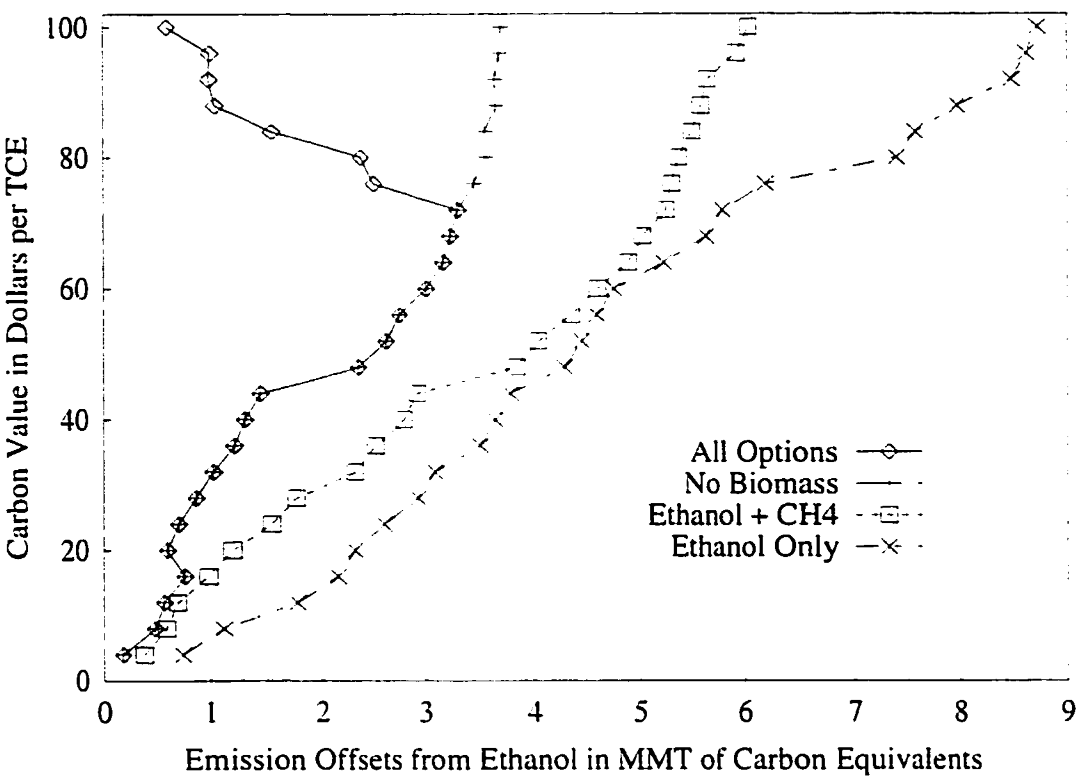

Figure 6-2 Carbon emission offsets from ethanol use under different assumptions about implementation of available mitigation strategies (ethanol price = $1.20/gallon)

The data graphed in Figure 6-2 verify the theoretical findings from section 3.1. Several things can be observed. First, the emission reduction potential from ethanol is highest when ethanol is the only mitigation strategy permitted. If more options are included in the analysis, ethanol emission reductions are smaller because other strategies are more cost effective. Second, the decline in ethanol emission reductions depends on the competitiveness of simultaneously included mitigation strategies. Methane mitigation strategies do not interact with ethanol production as much as carbon sink strategies. Hence, the left shift of the emission reduction supply curve is higher if all carbon sink options are enabled. For carbon values of $70 per TCE and above, the biomass for power plant option leads to a strong decline of ethanol production.

The deviation of ethanol abatement curves obtained through individual or semi joint assessment from the joint abatement curve is a measure of the assessment bias. In Table 6-1, the percentage overstatement is listed from excluding other mitigation strategies when assessing ethanol emission offsets.

Non-joint assessment of GHGE mitigation strategies also lead to biased predictions of the total emission reduction potential in the agricultural sector (Figure 6-3). In particular, the sum of emission reductions from individually examined strategies is between 10 and 22 percent higher than the emission reduction obtained through a joint analysis of the same mitigation strategies. This result again confirms the existence of substantial interdependencies between agricultural mitigation strategies.

Table 6-1 Percentage Overstatement of Ethanol Mitigation From not Including All Other Mitigation Options

CE Value	Implementation Assumption of Other Mitigation Strategies		
(Dollars per TCE)	No Biomass	Ethanol + CH4	Ethanol Only
4	0.0	112.3	310.7
8	0.0	21.8	128.3
12	0.0	22.3	209.4
16	0.0	28.2	181.0
20	0.0	97.0	282.5
24	0.0	117.1	265.5
28	0.0	101.9	235.6
32	0.0	125.4	200.6
36	0.0	108.2	190.6
40	0.0	114.9	180.5
44	0.0	102.8	162.8
48	0.0	63.6	82.7
52	0.0	54.6	70.2
56	0.0	58.4	67.2
60	0.0	53.0	58.2
64	0.0	54.3	64.7
68	0.0	55.4	74.0
72	0.0	58.7	75.2
76	38.3	112.0	148.1
80	50.0	126.1	211.6
84	130.0	255.3	389.9
88	250.5	434.8	664.2
92	267.5	468.5	754.8
96	268.4	491.8	760.5
100	514.9	902.8	1347.2

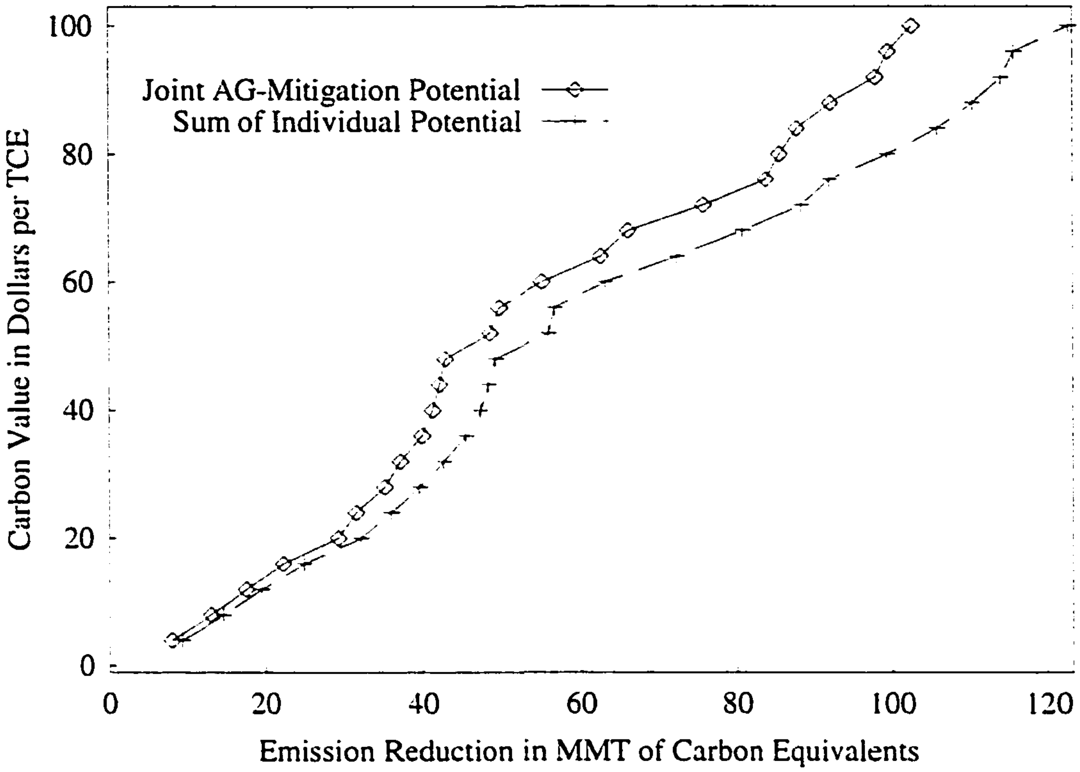

Figure 6-3 Total GHGE reduction potential obtained through joint mitigation analysis and through summation of individual strategies' potential

Limited availability of farmland was discussed to be the main reason for above described interdependencies (see section 3.1). Land use intensive mitigation strategies such as soil carbon sequestration, afforestation, and biofuel production lead to a competition for farmland that builds up as the value of carbon credits increases. The higher the aggregate demand for farmland, the higher will be the equilibrium prices. Empirical data on changes of land values are shown in Figure 6-4. The graphical display illustrates both the effects of the level of carbon prices and different assumptions about the simultaneous availability of mitigation strategies. Inclusion of carbon related mitigation strategies appear to increase of land values. Starting at $60 per TCE, the biomass power plant option raises land rental rates the most. In contrast, methane mitigation strategies tend to decrease land values. Methane emission reduction incentives lead to less extensive livestock production, hence, demand for pasture and feed crops decreases. Nitrous oxide mitigation appears to have only little effect on land rental rates.

6.2 Trade Between Greenhouse Gases

Global warming and associated environmental threats result from the combined presence of GHG in the atmosphere. Moreover, the value of CE emission reductions is the same regardless of which GHG has been reduced. In its current version, the Kyoto Protocol poses separate targets on emission reductions for each individual gas. While this policy design may be justifiable by reasons such as accountability and verifiability (see section 2.3.5), it may be criticized for imposing scientifically redundant restrictions.

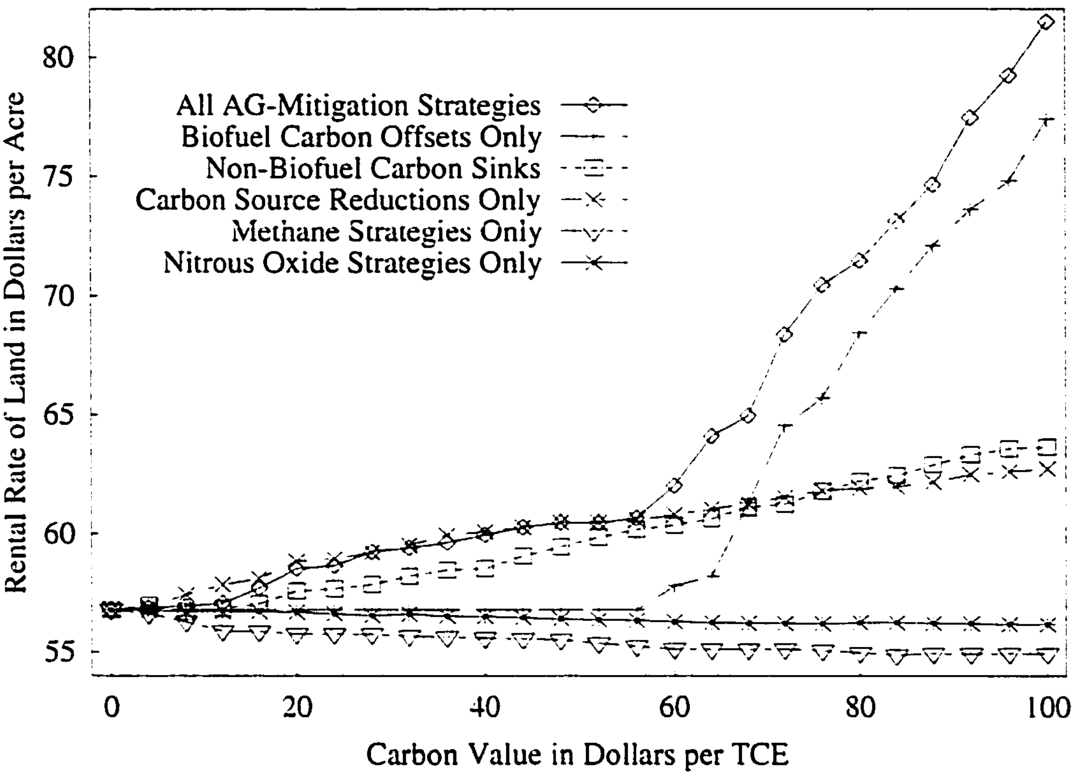

Figure 6-4 Land value changes under different assumptions about implementation of available mitigation strategies

A proposed alternative is to only limit CE emissions. Such a system would permit free exchange of emission reduction credits among different GHGs. In this section, the magnitude of dead weight losses from not allowing trade between CO_2, N_2O, and CH_4 emission reduction credits is examined.

Empirical data from individual versus joint GHGE reductions are displayed in Figure 6-5. The curve representing joint emission reductions was obtained by allowing for free trade of GHGE reductions. Trade is based on the global warming potential of each gas. Individual GHG abatement curves were computed by imposing carbon equivalent emission reduction incentives on individual gases only. The GWP-weighted sum of the individual GHGE reductions is also shown in Figure 6-5. Since individual abatement is more restrictive, the total mitigation potential at a given price is always lower. The difference between the no-trade and joint reduction abatement curves represents the dead weight loss from the trade ban between greenhouse gases (Figure 6-6).

6.3 Sensitivity Analysis

The empirical results in section 5 are in part based on uncertain assumptions and preliminary data. Some emission coefficients derived from simulation models had to be scaled considerably to match ASMGHG baseline emission predictions with baseline predictions from EPA or other institutions. Given doubtful coefficients, it is desirable to examine how sensitive main results are with respect to these coefficients.

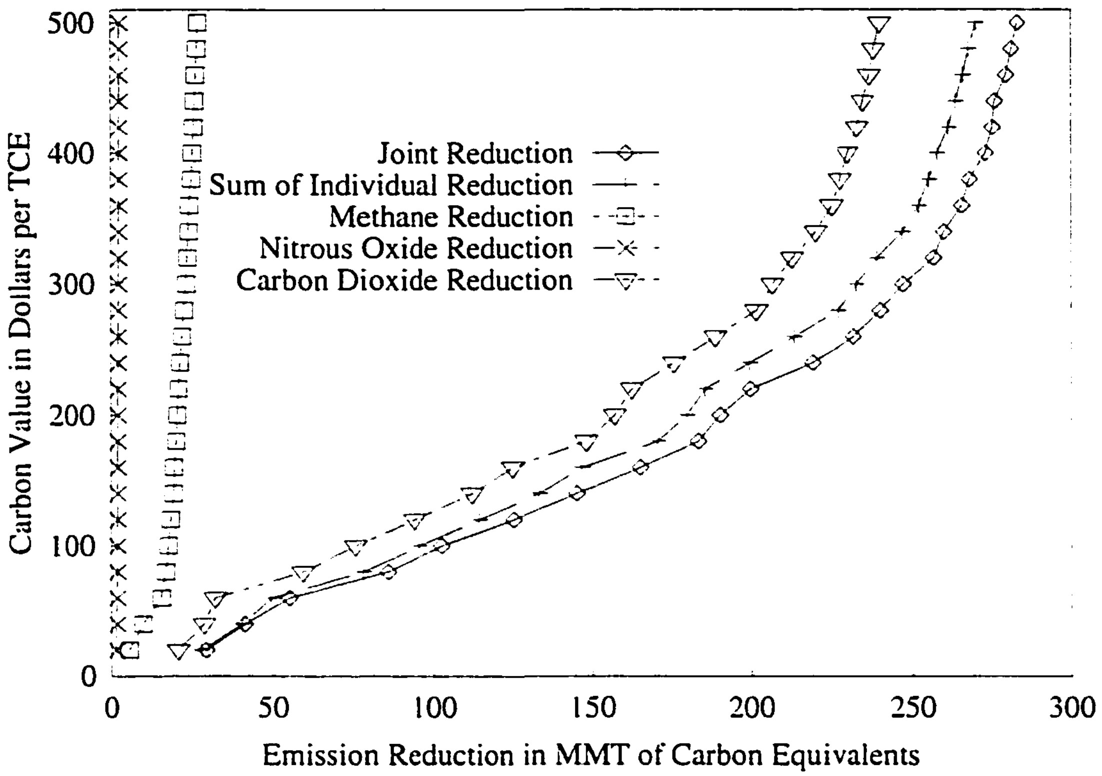

Figure 6-5 Efficiency gain of joint emission reduction versus individual GHGE reduction

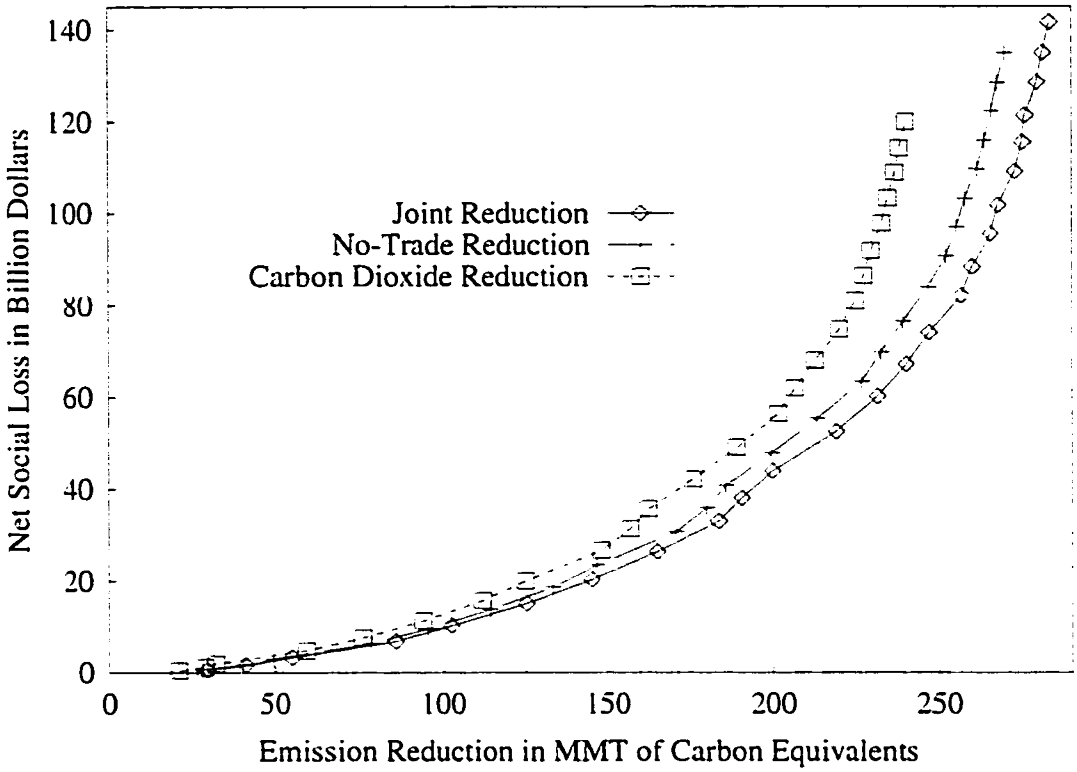

Figure 6-6 Social costs of GHGE mitigation under different assumptions about GHG involvement and substitutability

In the following two sections, a sensitivity analysis is performed on the impact of both soil organic matter and nitrous oxide emission coefficients on overall mitigation results.

6.3.1 Soil Organic Matter Coefficients

Soil organic matter coefficients (SOMC) were varied over a range from 10 to 1000 percent relative to the values used in ASMGHG. The effects of these modifications are shown in Figure 6-7 and Figure 6-8. Two characteristics are worthwhile noting. First, different absolute magnitudes of SOMC alter the general shape of emission reduction supply curves only for low carbon incentives below $20 per TCE. At higher carbon prices, the emission reduction supply curve moves fairly parallel to the right or to the left depending on the direction of SOMC adjustments (Figure 6-7).

The relatively parallel shifts above $20 per TCE indicate the low-cost nature of SOM related emission reductions. Under all SOMC scenarios, net emission reductions from SOM changes reach a peak at carbon values between $60 and $100 per TCE. The most dramatic carbon net emission reductions occur for carbon incentives below $20 per TCE (Figure 6-8) regardless of how much SOMC are scaled. Above $20 per TCE, emission reductions from SOM changes increase only little. Second, the magnitude of the supply curve shift depends on the direction of SOMC adjustments. Smaller values of SOMC result in fairly small shifts of the aggregate emission reduction supply curve. If SOM emission savings are smaller, other mitigation strategies will be used more intensely. These other strategies compensate for smaller SOM emission reductions and therefore buffer the effect on total emission reductions.

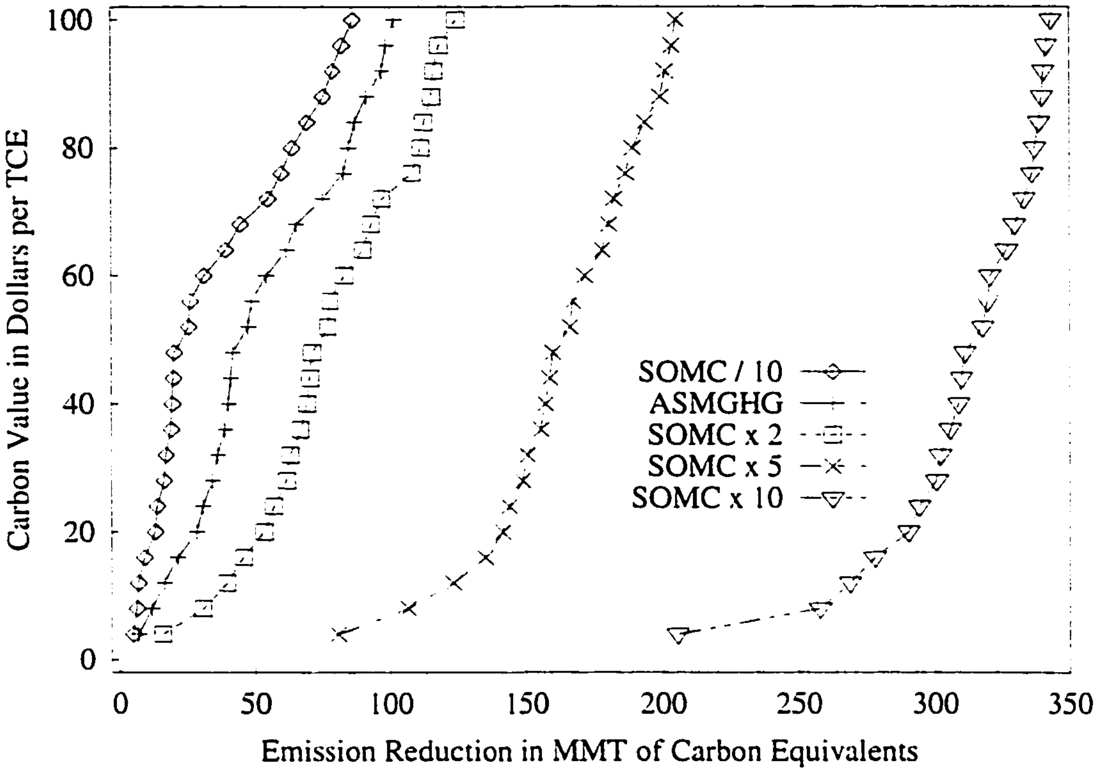

Figure 6-7 Total GHGE reductions in the agricultural sector for different levels of soil organic matter coefficients (SOMC)

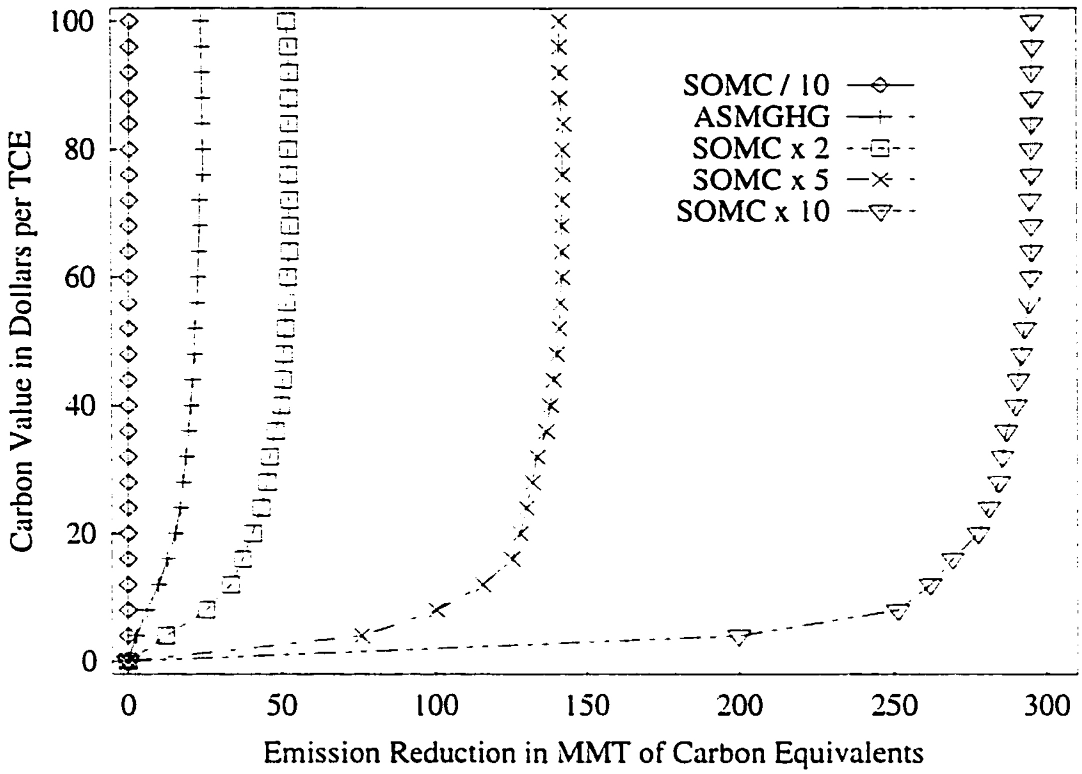

Figure 6-8 Soil carbon emission reductions for different SOMC levels and different carbon values

However, if SOMC are proportionally increased, then shifts of the aggregate supply function can be large (Figure 6-7). As SOM emission savings increase, soil carbon sequestration will eventually become the most competitive mitigation option. Thus, the level of SOMC adjustments relates more directly to the level of emission reductions.

6.3.2 Nitrous Oxide Emission Coefficients

Nitrous oxide emission coefficients from denitrification involve large uncertainties. For this study, all denitrification values were derived from EPIC simulations (see section 4.3.6). Unfortunately, absolute levels of EPIC coefficients on denitrification did not correspond to assumptions used in previous analyses. To be consistent with those analyses and to be conservative, all EPIC denitrification coefficients were adjusted proportionally and only relative differences were preserved (see section 4.3.6). The impacts of such adjustment on GHGE mitigation are shown in Figure 6-9 and in Figure 6-10.

Comparison between emission reduction supply curves from using ASMGHG coefficients versus using original EPIC coefficients reveals large differences (Figure 6-9). When applying ASMGHG coefficients, nitrous oxide emission reductions contribute only little to total agricultural GHGE reductions. However, when using the original EPIC values, nitrous oxide emission reductions exceed by far reductions from all other agricultural mitigation options.

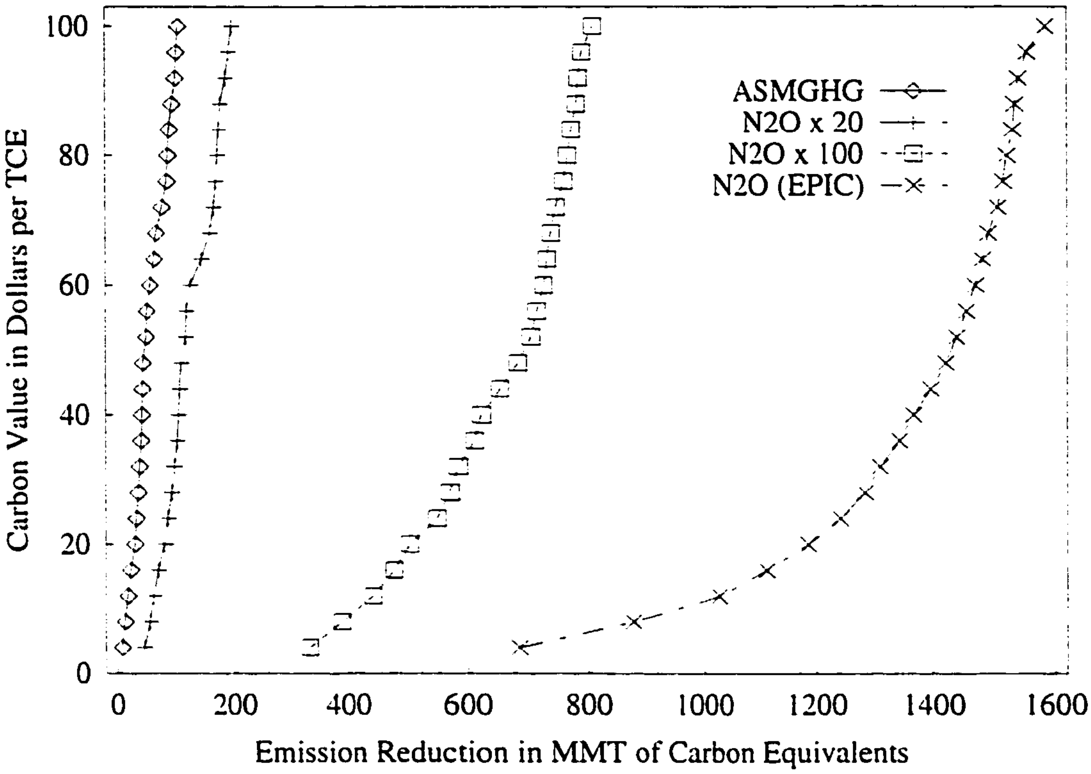

Figure 6-9 Total GHGE reductions in the agricultural sector for different adjustments of N_2O emission coefficients and different carbon values

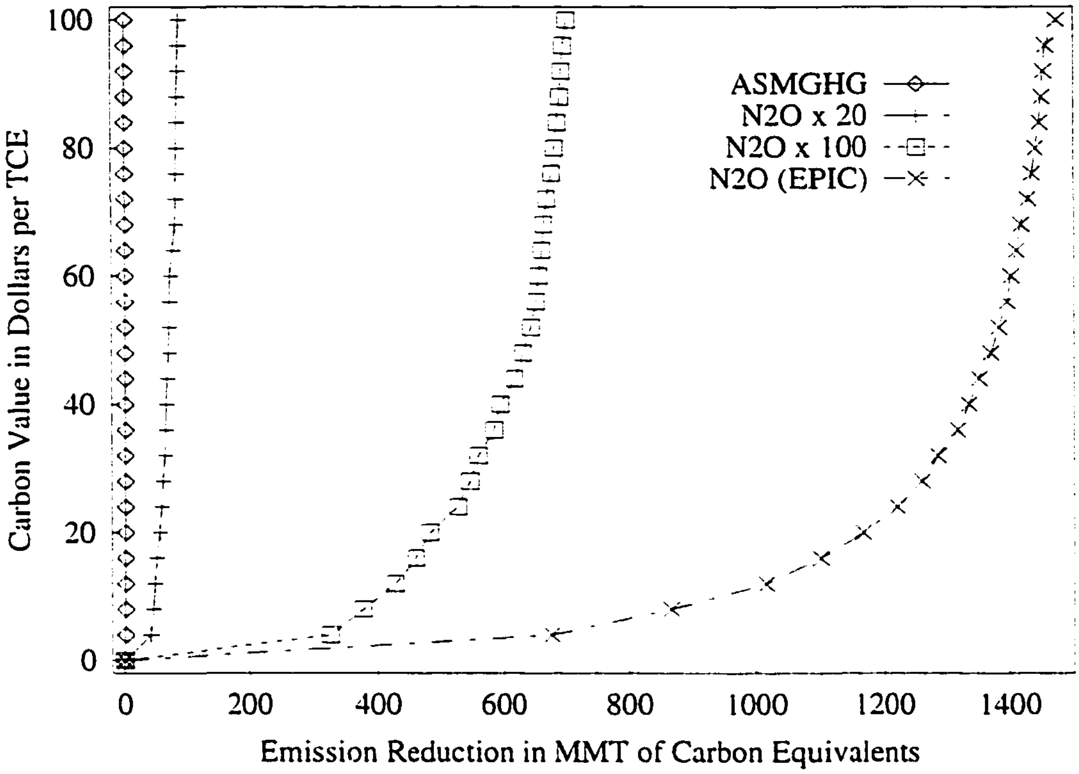

Figure 6-10 Nitrous oxide emissions reductions for different adjustments of N_2O emission coefficients and different carbon values

While the emission reduction supply curves from reduced denitrification appear more elastic for higher coefficient values (Figure 6-10), most reductions occur for carbon values between $0 and $20. The high sensitivity of total CE emission reductions to the magnitude of nitrous oxide emission coefficients is in part caused by the high GWP of 310 relative to carbon dioxide.

6.4 Efficiency Losses and Transaction Costs From Upstream Policies

Direct measurement and regulation of emissions from agricultural management is often impractical. In section 2.3, it was argued that emission policies implemented upstream might provide a feasible alternative to expensive downstream approaches. ASMGHG can be used to estimate efficiency losses, and hence, partial transaction costs of upstream emission regulations. This will be demonstrated here for two alternative types of a soil carbon sequestration policy. The first policy is a downstream emission based policy as used in section 5. Soil carbon emission incentives are linked to true emission reductions. All transaction costs are ignored.

The second policy corresponds to an upstream mitigation policy. Soil carbon sequestration is encouraged through incentives placed on low tillage intensity. For each of the three different tillage systems, farmers will receive or pay a system specific amount of money. To keep efficiency losses at a low level, incentives for each tillage system were calculated proportional to the sequestration potential of each system. In section 4.3.5.2.1, soil carbon was assumed to increase by 1,000 MMT of carbon equivalents for zero tillage, by 600 MMT for conservation tillage, and to decrease by 282

MMT for conventional tillage. Thus, each incentive dollar for zero tillage was joined by a 60-cent per acre incentive on conservation tillage, and a 28.2-cent per acre disincentive on conventional tillage (Table 6-2).

Observed differences between upstream and downstream implementations of soil carbon policies are summarized in Figure 6-11. The efficiency loss at each level of emission reduction equals the horizontal distance between the two curves. Given program costs of, for example, two million dollars, the upstream policy achieves only about 85 percent of the emission reduction realized by a downstream policy. The vertical distance at each level of emission reduction represents the cost of upstream inefficiencies. In addition to costs of monitoring and enforcement, this inefficiency cost item pertains to transaction costs of an upstream soil carbon policy. In the policy example used here, these partial transaction costs amount to about 50 percent of the program costs[13] incurred by the downstream policy.

6.5 External Effects of Specific Mitigation Policies on Unregulated Emission Sources

Agricultural mitigation policies can become expensive if many detailed management decisions of agricultural enterprises have to be reported, monitored, and enforced. However, cost savings may be possible because several mitigation strategies appear to be linked. If, for example, a fossil fuel tax creates considerable incentives for farmers to switch from intensive tillage to conservation or zero tillage, then costs of implementing a tillage subsidy may be redundant.

Table 6-2 Tillage System Specific Tax Levels of Hypothetical Soil Carbon Policy in Dollars per Acre

Policy Level	Conventional Tillage	Conservation Tillage	Zero Tillage
4	0.56	-1.20	-2.00
8	1.13	-2.40	-4.00
12	1.69	-3.60	-6.00
16	2.26	-4.80	-8.00
20	2.82	-6.00	-10.00
24	3.38	-7.20	-12.00
28	3.95	-8.40	-14.00
32	4.51	-9.60	-16.00
36	5.08	-10.80	-18.00
40	5.64	-12.00	-20.00
44	6.20	-13.20	-22.00
48	6.77	-14.40	-24.00
52	7.33	-15.60	-26.00
56	7.90	-16.80	-28.00
60	8.46	-18.00	-30.00
64	9.02	-19.20	-32.00
68	9.59	-20.40	-34.00
72	10.15	-21.60	-36.00
76	10.72	-22.80	-38.00
80	11.28	-24.00	-40.00
84	11.84	-25.20	-42.00
88	12.41	-26.40	-44.00
92	12.97	-27.60	-46.00
96	13.54	-28.80	-48.00
100	14.10	-30.00	-50.00

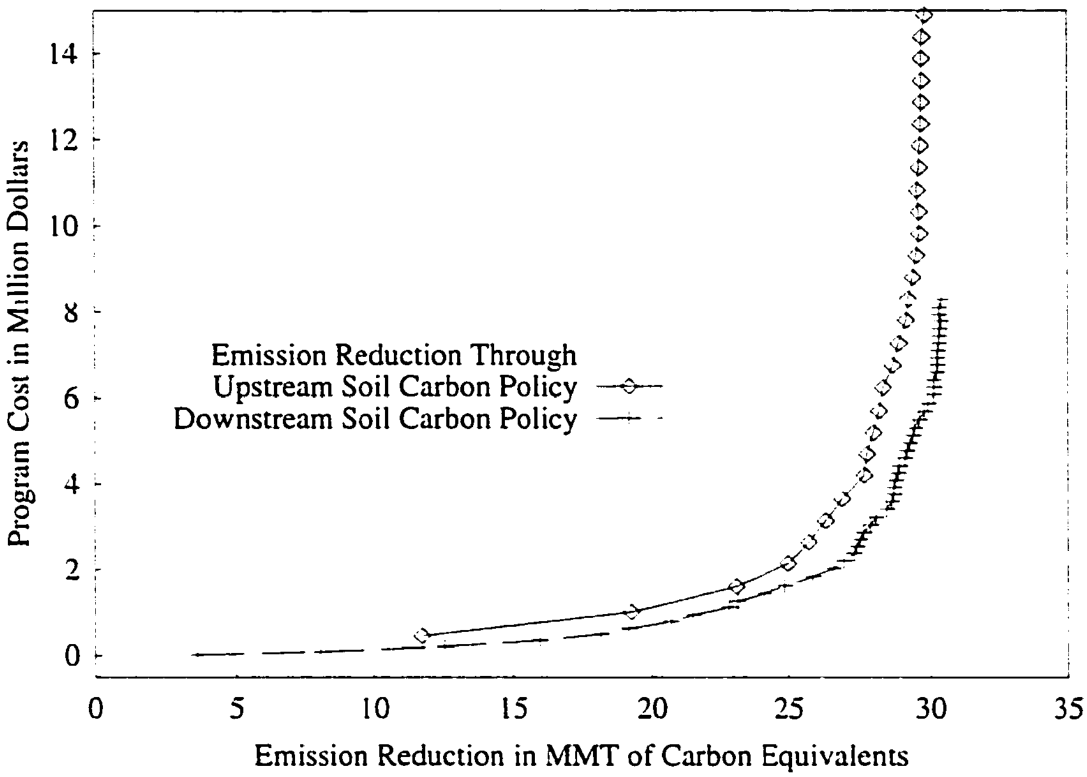

Figure 6-11 Carbon sequestration efficiency for different types of policy implementation

The dual emissions accounting in ASMGHG (see section 4.3.8.1) makes it possible to examine external effects of specific mitigation policies on unregulated emission sources and sinks. To demonstrate this aspect, the hypothetical soil carbon policy described in section 6.4 (upstream emission tax) was used again. For 25 different levels of incentives (zero and conservation tillage) and disincentives (conventional tillage), emission reductions were recorded from all GHGE sources and sinks, which are contained in ASMGHG.

In Figure 6-12, the recorded net GHGE reductions are graphed for four different degrees of emission aggregation at each policy level. SOM carbon reductions represent intentional or gross emission savings due to changes in the soil organic matter content. Unintentional emission changes from the applied soil carbon policy were aggregated into two categories, non-SOM carbon reductions and non-carbon reductions. The first category relates to the combined emission savings from all carbon emission sources and sinks except for the soil carbon sink. Similarly, non-carbon reductions denote the sum of all changes from methane and nitrous oxide emission sources and sinks contained in ASMGHG. Net GHGE reductions correspond to the total effects on agricultural emissions and were computed by adding together above three emission components.

Inspection of Figure 6-12 reveals that policy induced SOM carbon savings contribute most to overall GHGE reductions. However, other emission and sink accounts change as well. Substantial complimentary emission reductions up to 19 percent of SOM carbon changes result from untargeted, non-SOM carbon sources and sinks (Table 6-3). Nitrous oxide and methane emission accounts vary relatively little.

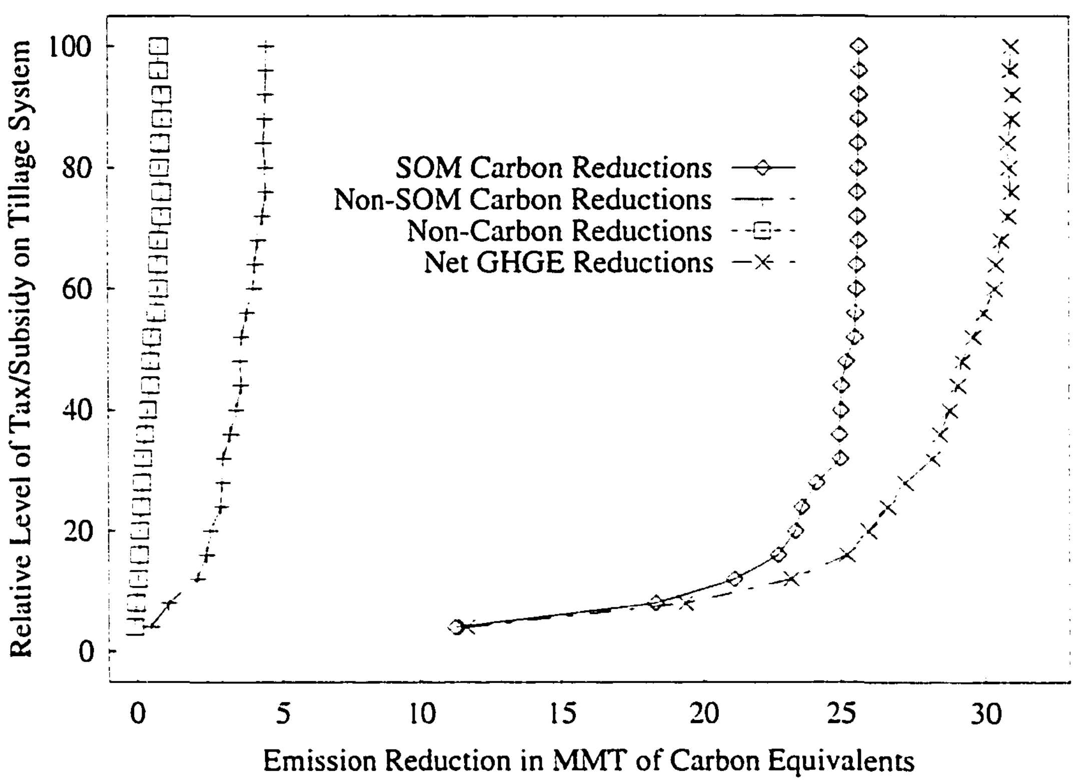

Figure 6-12 Effects of hypothetical soil carbon policy on regulated (SOM carbon) and unregulated GHGE sources and sinks

Table 6-3 Relative Contribution of Unregulated Emission Sources and Sinks to GHGE Reduction Under Hypothetical Soil Carbon Policy

Policy Level	Net Emission Reductions in MMTCE (in Percent of SOM Carbon Savings)						
	SOM Carbon	Non-SOM Carbon		Non-Carbon		Net GHGE	
4	11.25	0.44	(3.9)	-0.09	(-0.8)	11.66	(103.6)
8	18.30	1.04	(5.7)	-0.03	(-0.2)	19.34	(105.7)
12	21.12	2.03	(9.6)	0.04	(0.2)	23.22	(109.9)
16	22.75	2.35	(10.3)	0.09	(0.4)	25.21	(110.8)
20	23.37	2.51	(10.7)	0.09	(0.4)	25.97	(111.1)
24	23.60	2.92	(12.4)	0.15	(0.6)	26.63	(112.8)
28	24.13	2.96	(12.3)	0.18	(0.8)	27.24	(112.9)
32	24.99	3.01	(12.0)	0.22	(0.9)	28.17	(112.7)
36	24.96	3.30	(13.2)	0.29	(1.2)	28.45	(114.0)
40	25.01	3.56	(14.2)	0.39	(1.6)	28.78	(115.1)
44	25.03	3.79	(15.1)	0.48	(1.9)	29.07	(116.1)
48	25.20	3.75	(14.9)	0.49	(1.9)	29.21	(115.9)
52	25.51	3.83	(15.0)	0.53	(2.1)	29.60	(116.1)
56	25.53	4.12	(16.1)	0.68	(2.7)	29.97	(117.4)
60	25.56	4.41	(17.3)	0.76	(3.0)	30.33	(118.7)
64	25.57	4.45	(17.4)	0.75	(2.9)	30.38	(118.8)
68	25.64	4.55	(17.8)	0.77	(3.0)	30.57	(119.2)
72	25.61	4.79	(18.7)	0.88	(3.4)	30.81	(120.3)
76	25.61	4.89	(19.1)	0.89	(3.5)	30.93	(120.8)
80	25.63	4.78	(18.6)	0.80	(3.1)	30.83	(120.3)
84	25.62	4.73	(18.5)	0.82	(3.2)	30.78	(120.2)
88	25.64	4.80	(18.7)	0.90	(3.5)	30.93	(120.6)
92	25.66	4.80	(18.7)	0.89	(3.5)	30.96	(120.7)
96	25.67	4.71	(18.4)	0.78	(3.0)	30.88	(120.3)
100	25.67	4.74	(18.4)	0.79	(3.1)	30.91	(120.4)

7 SUMMARY AND CONCLUSIONS

This dissertation analyzes the economic potential of agriculture to participate in greenhouse gas emission mitigation efforts. Special focus is placed on the assessment methodology. While previous studies often ignore interactions among simultaneously available mitigation strategies and between mitigation strategies and conventional agricultural practices, this study tries to more fully capture likely interdependencies. The study required development of a model (ASMGHG), which simultaneous included available agricultural mitigation strategies.

Empirical results confirm the existence of substantial interactions, which are manifest by price and production responses to mitigation incentives throughout the traditional agricultural sector. Results also indicate that agriculture's contribution to greenhouse gas emission reduction may be substantial, but not sufficient to fulfill the requirements of the Kyoto Protocol. Even under extreme economic incentives, the annual emission reduction potential does not exceed 300 MMT of carbon equivalents if considering carbon dioxide emissions only, or 400 MMT if emission reductions were summed across all greenhouse gases. Under the current version of the Kyoto Protocol, carbon dioxide emissions alone would require a reduction volume of approximately 700 MMT by the year 2010 (U.S. EPA).

The joint presence of mitigation strategies in ASMGHG made it possible to identify preferred emission reduction strategies at each incentive level. For carbon prices above $80 dollars per TCE, biofuel production via switch grass and willow becomes the dominating strategy. The annual emission reduction contribution for incentives between $80 and $400 per TCE ranges from 50 to 200 MMT of carbon equivalents, respectively. However, for carbon prices below $60 per TCE, the ASMGHG equilibrium yields no biofuel production at all. This observation confirms the currently unimportant commercial production of woody crops or switch grass for electrical power generation. Biofuel production saves about 1.5 metric tons of carbon equivalent per acre and year. Thus, a $60 per TCE incentive corresponds to a price subsidy for biomass crops between 50 and 100 percent of the current market price.

Low carbon prices between $0 and $60 per TCE lead to a more complex mixture of actively used mitigation strategies. For example, an incentive level of $25 per TCE leads to less fertilization, tillage, and irrigation intensity, increased afforestation, and improved liquid manure management, and reduces overall emissions by about 50 MMT of carbon equivalents. Soil organic matter buildup contributes about one third or 17 MMT. Note that at $25 per TCE the average costs of emission reductions only amount to about $5 per TCE.

The above cost summary does not incorporate all costs and benefits associated with agricultural participation in greenhouse gas mitigation. Not monetarized in this analysis were transaction costs of mitigation policies, costs or benefits from reduced levels of other agricultural externalities, and costs or benefits of changed income distribution in the agricultural sector. Monitoring and enforcement may not be cheap given the non-point source nature of agricultural greenhouse gas emissions. However, policies targeting emission reductions at the upstream level may reduce transaction costs.

Efficiency losses from upstream regulations were shown for soil carbon sequestration policies.

Agricultural externalities examined besides greenhouse gas emissions included soil erosion, nitrogen and phosphorous pollution. At an incentive level of $50 per TCE, all three externalities were reduced by 25 to 40 percent per acre of cropland. Beyond incentive levels of $50 per TCE, changes in external effects were limited. Thus, when making an overall decision about the worthiness of agricultural mitigation options, policy makers should also account for, or at least be aware of, these additional effects.

Many agriculturists oppose the Kyoto Protocol and related efforts to introduce new environmental policies, arguing that farmers would be subjected to substantial economic losses. The findings in this dissertation do not justify this perspective. On the contrary, farmers are likely to experience higher earnings specifically in the intermediate run after adoption of mitigation technologies and market adjustment.

Throughout the 20th century, U.S. agricultural food production has increased faster than demand for agricultural products. With inelastic demand encountered for many agricultural products, this disproportionate growth led to a decline in agricultural prices and farmers' net income. The empirical results of this dissertation suggest that this negative trend from farmers' point of view could be alleviated through mitigation efforts. Positive net income effects result from both higher food prices and additional revenue opportunities in the mitigation arena.

The findings in this dissertation provide support for a new breed of combined environmental and farm policies. Traditionally, a large amount of governmental money was allocated to reduce soil erosion (CRP program) and stabilize agricultural prices at "fair" levels (farm program). The expenses incurred through those individual programs may be dispensable through a new combined policy. For example, a "smart" mitigation program could encourage farmers to grow switch grass or woody crops on cropland. If the economic incentives of such a program would be higher for land with higher erodibility, then cropping on highly erodible land would be reduced, GHGE would be offset, and farmers' net income would increase due to market effects described above.

In interpreting the empirical results of this study, a few words need to be said about existing limitations. Sources of errors relate to data inaccuracies, model structural assumptions, and aggregation approximation errors.

A warning has to be given with respect to the data of included mitigation options. As outlined in section 4, many data were obtained from simulation models, in particular from EPIC. These data reflect the evolving nature of those models. Absolute levels of simulated parameters did not always concur with literature estimates when aggregated. Adjustments were made, which generally preserved the relative difference between different management options but scaled the absolute level of data.

A particular objective was to include all major agricultural mitigation options. Difficulties arose for mitigation options which were known qualitatively, but for which no quantitative data were available. The decision to include a particular mitigation option depended on the justifiability of assumptions that were needed to overcome missing data.

Another shortcoming of the presented analysis is the lack of temporal dynamics. All included mitigation strategies were assumed to have constant mitigative effects over time. While this assumption may be justifiable for methane, nitrous oxide, and carbon dioxide source emission reduction strategies, and for carbon sink strategies in the intermediate run, it does not hold for carbon sink strategies in the long run. In the long run, i.e. 50 to 200 years, tree and soil carbon sequestration will cease. Thus, further analysis is needed.

NOTES

1 This chapter is drawn from a publication authored by McCarl and Schneider (2000). The article is entitled "U.S. Agriculture's Role in a Greenhouse Gas Emission Mitigation World: An Economic Perspective" and is published in Volume 22, Number 1 of the Spring/Summer 2000 issue of the *Review of Agricultural Economics*. For the copyright statement, see Appendix A.

2 Enteric fermentation relates to methane emissions through microbial fermentation in digestive systems of ruminant animals.

3 N_2O emissions in 1990: 0.4 million metric tons, current emissions: 0.5 million metric tons (U.S. EPA).

4 Note that the U.S. agricultural sector is currently experiencing a reduction in commodity programs and environmental incentive programs. Under the 1996 Farm Act, the Conservation Reserve Program (CRP) will spend twenty-two percent less than CRP historically and as of yet it will expire in 2002.

5 A weighted U.S. average of 210 pounds CO_2 per million BTU generated is used based on the CO_2 content of coal (U.S. DOE, 1998a) and biomass is assumed to displace 95 percent of that level of emissions.

6 Note that the tax levels examined in all studies reviewed here are substantially greater than any anticipated carbon tax. Current policy discussions seem to indicate a carbon tax much more in the neighborhood of $10 per ton carbon.

7 Annex B countries comprise the developed countries including countries which are undergoing the transition to a market economy. The countries listed in Annex B are almost identical to the countries listed in Annex I to the UNFCCC with the exception of Croatia, Liechtenstein, Monaco, and Slovenia (included only in Annex B), and Turkey (included only in Annex I). The listing in Annex B to the Kyoto Protocol imposes specific emission reduction quantities on each contained country while the listing in Annex I or II of the convention only indicates the general agreement of contained countries to various emission control measures as qualified in the convention.

8 Agriculture is assumed to face an elastic demand curve for GHGE reductions. This assumption is used for convenience only. A downward-sloped demand curve for emission reductions does not alter the qualitative results of the analysis.

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

[10] 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.

[11] 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.

[12] The emission reduction supply curves in Figure 6-1 do not show mitigation potentials beyond $100 per TCE. However, results were recorded for carbon prices up to $500 per TCE.

[13] Program costs include only governmental costs. They should not be confused with the total economic costs incurred by producers, consumers, and the government.

REFERENCES

Adams, D.M., R.J. Alig, B.A. McCarl, J.M. Callaway, and S.M. Winnett. "Minimum Cost Strategies for Sequestering Carbon in Forests." *Land Econ.* 75(August 1999):360-74.

Adams, D.M., R.M. Adams, J.M. Callaway, C. Chang, and B.A. McCarl. "Sequestering Carbon on Agricultural Land: A Preliminary Analysis of Social Costs and Impacts on Timber Markets." *Contemp. Policy Issues* (Winter 1993):76-87.

Adams, R.M., C.C. Chang, B.A. McCarl, and J.M. Callaway. "The Role of Agriculture in Climate Change: A Preliminary Evaluation of Emission Control Strategies." *Economics Issues in Global Climate Change: Agriculture, Forestry, and Natural Resources.* J.M. Reilly and M. Anderson, eds., pp. 273-87. Boulder, CO: Westview Press, 1992.

Adams, R.M., S.A. Hamilton, and B.A. McCarl. "The Benefits of Air Pollution Control: The Case of Ozone and U.S. Agriculture." *Amer. J. Agr. Econ.* 68(1986):886-94.

Allison, F.E. "Organic Matter and Soil Conservation." *Soil Organic Matter and Its Role in Crop Production*, 637 pp. Amsterdam: Elsevier, 1973.

Antle, J.M, S.M. Capalbo, J.B. Johnson, and D. Miljkovic. "The Kyoto Protocol: Economic Effects of Energy Prices on Northern Plains Dryland Grain Production." *Agr. and Res. Econ. Rev.* 28(April 1999):96-105.

Arrhenius, S. "On the Influence of Carbonic Acid in the Air Upon the Temperature of the Ground". *Philosophical Magazine* 41(1896):237-76.

Babcock, B.A., and G.R. Pautsch. "Relative Efficiency of Sequestering Carbon in Agricultural Soils Through Second Best Instruments." Paper presented at the Third Toulouse Conference on Environment and Resource Economics - Environment, Energy Uses and Climate Change, Toulouse, France, 14-16 June 1999.

Barnola, J.M., D. Raynaud, Y. S. Korotkevich, and C. Lorius. "Vostok Ice Core Provides 160,000-year Record of Atmospheric CO_2." *Nature* 329(1987):408-14.

Battye, W., A.S. Werner, and G. Hallberg. "Evaluation of Available Control Measures, Potential Emission Reductions, and Costs of Control for Anthropogenic Agricultural Emissions of Nitrous Oxide." Paper presented at Workshop on Atmospheric Nitrogen Compounds II: Emissions, Transport, Transformation, Deposition and Assessment, Chapel Hill, NC, 7-9 June 1999.

Baumes, H. "A Partial Equilibrium Sector Model of U.S. Agriculture Open to Trade: A Domestic Agricultural and Agricultural Trade Policy Analysis." PhD dissertation, Purdue University, 1978.

Benson, V. National Resource Conservation Service, U.S. Department of Agriculture Crop Enterprise Budgets, Personal Communication, February 1999.

Bolin, B. "The Kyoto Negotiations on Climate Change: A Science Perspective." *Science* 279(January 1998):330-1.

Bruce, J.P., H. Lee, and E.F. Haites. "The Social Costs of Climate Change: Greenhouse Damage and the Benefits of Control." Chapter 6 in *Climate Change 1995: Economic and Social Dimensions of Climate Change*, pp. 178-224. Cambridge: Cambridge University Press, 1996.

Burton, R.O., and M.A. Martin. "Restrictions on Herbicide Use: An Analysis of Economic Impacts on U.S. Agriculture." *N. Cent. J. Agr. Econ.* 9(1987):181-94.

Burtraw, D., K. Palmer, and A. Paul. *The Opportunity for Short-Run Carbon Mitigation in the Electricity Sector*. Unpublished, Resources for the Future, Washington DC, January 1999.

Canada. "Methodological Issues, Inventories and Uncertainties." United Nations Framework Convention on Climate Change, Subsidiary Body for Scientific and Technological Advice. Additional submissions by parties to the Ninth Session at Buenos Aires, 2-13 November 1998, Item 4 of the provisional agenda. Other Matters, Approaches to resolving methodological issues related to national communications from Annex I Parties, pp. 3-9 [Online]. Available at http://www.unfccc.de/resource/docs/1998/sbsta/misc06a01.pdf, 1998.

Chang, C.C., B.A. McCarl, J.W. Mjelde, and J.W. Richardson. "Sectoral Implications of Farm Program Modifications." *Amer. J. of Agr. Econ.* 74(1992):38-49.

Changsheng, L., V. Narayanan, and R.C. Harriss. "Model Estimates of Nitrous Oxide Emissions From Agricultural Lands in the United States." *Global Biogeochemical Cycles* 10(June 1996):297-306.

Cole, C.V., C. Cerri, K. Minami, A. Mosier, N. Rosenberg, D. Sauerbeck, J. Dumanski, J. Duxbury, J. Freney, R. Gupta, O. Heinemeyer, T. Kolchugina, J. Lee, K. Paustian, D. Powlson, N. Sampson, H. Tiessen, M. van Noordwijk, and Q. Zhao. "Agricultural Options for the Mitigation of Greenhouse Gas Emissions." Chapter 23 in *Climate Change 1995: Impacts, Adaptation, and Mitigation of Climate Change: Scientific-Technical Analyses.* Prepared by IPCC Working Group II, 726-71. Cambridge: Cambridge University Press, 1996.

Collins, K., USDA. "Analysis of Consequences of Fuel Taxes." Paper presented at Workshop on Climate Change and Agriculture, Washington DC, Spring 1998.

Council of Economic Advisors (CEA). "The Kyoto Protocol and the President's Policies to Address Climate Change: Administration Economic Analysis" [Online]. Available at http://www.whitehouse.gov/WH/New/html/augnew98.html#Kyoto, July 1998.

Crandall, R. W. "The Political Economy of Clean Air: Practical Constraints on White House Review." In Environmental Policy Under Reagan's Executive Order: The Role of Benefit-Cost Analysis, V. Smith, ed, Resources for the Future, Washington DC, 1984.

Diewert, W.E. "Exact and Superlative Index Numbers." *Essays in Index Number Theory*, Volume I. W.E. Diewert and A.O. Nakamura, eds., Amsterdam: Elsevier Science Publishers, 1993.

Doningan, A.S., Jr., T.O. Barnwell, R.B. Jackson, A.S. Patwardhan, K.B. Weinreich, A.L. Rowell, R.V. Chinnaswamy, and C.V. Cole. *Assessment of Alternative Management Practices and Policies Affecting Soil Carbon in Agroecosystems of the Central United States*. Publication No. EPA/600/R-94/067. Athens, GA: U.S.-EPA, 1994.

Dudek, D.J., and A. Leblanc. "Offsetting New CO_2 Emissions: A Rational First Greenhouse Policy Step." *Contemp. Policy Issues* 8(1990):29-42.

Epplin, F.M., and G.A. Al-Sakkaf. "Risk-Efficient Tillage Systems and Program Participation Strategies for Land Subject to Conservation Compliance." *Rev. of Agr. Econ.* 17(1995):311-21.

Fischer, C., S. Kerr, and M. Toman. "Using Emissions Trading to Regulate U.S. Greenhouse Gas Emissions: An Overview of Policy Design and Implementation Issues." *Nat. Tax J.* 51(September 1998):453-64.

Flach, K.W., T.O. Barnwell, Jr., and P. Crosson. "Impacts of Agriculture on Atmospheric Carbon Dioxide." Chapter 1 in *Soil Organic Matter in Temperate Agro-Ecosystems: Long Term Experiments in North America.* E.A. Paul, E.T. Elliott, K. Paustian, and C.V. Cole, eds., pp. 3-13. Boca Raton, FL: CRC Press, 1997.

Francl, T. "American Farm Bureau Position on Kyoto Protocol." Paper presented at Workshop on Climate Change and Agriculture, Washington DC, Spring 1998.

Francl, T., R. Nadler, and J. Bast. "The Kyoto Protocol and U.S. Agriculture." Heartland Policy Study No. 87 [Online]. Available at www.heartland.org/studies/gwag-study.htm, 30 October 1998.

Gerbens, S. *Cost-effectiveness of Methane Emission Reduction From Enteric Fermentation of Cattle and Buffalo.* Unpublished, Department of Agricultural, Environmental, and Systems Technology, Subdepartment of Environmental Technology, Agricultural University Wageningen, The Netherlands, January 1999a.

Gerbens, S. *Cost-effective Methane and Nitrous Oxide Emission Reduction Technologies for Animal Waste.* Unpublished, Department of Agricultural, Environmental, and Systems Technology, Subdepartment of Environmental Technology, Agricultural University Wageningen, The Netherlands, January 1999b.

Gibbs, M.J., ed. *Costs of Reducing Methane Emissions in the United States.* Preliminary Report, ICF Incorporated, for the Methane and Utilities Branch, Atmospheric Pollution Prevention Division, Office of Air and Radiation, U.S. Environmental Protection Agency, Washington DC, 31 July 1998.

Graham, R.L., E. Lichtenberg, V.O. Roningen, H. Shapouri, and M.E. Walsh. "The Economics of Biomass Production in the United States." *Proceedings of the Second Biomass Conference of the Americas: Energy, Environment, Agriculture, and Industry*, Golden, CO: National Renewable Energy Laboratory, August 1995.

Granli, T. and O.C. Bøckman. "Nitrous Oxide From Agriculture." *Norwegian Journal of Agricultural Sciences* 12(1994):7-128.

Harnisch, J. Personal communication, Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, Cambridge, MA, 18 January 1999.

Hayhoe, K.A.S. "A Modeling Study of the Role of Methane in Global Climate Change." MS thesis, University of Illinois at Urbana-Champaign, 1997.

Hendrix, P.F. "Long-Term Patterns of Plant Production and Soil Carbon Dynamics in a Georgia Piedmont Agroecosystem." Chapter 17 in *Soil Organic Matter in Temperate Agroecosystems: Long-Term Experiments in North America*, E.A. Paul, E.T. Elliott, K. Paustian, and C.V. Cole, eds., pp. 235-45. Boca Raton, FL: CRC Press, 1997.

Houghton, J.T., G.J. Jenkins, and J.J. Ephramus, eds., *1990: Climate Change: The IPCC Scientific Assessment*. Cambridge: Cambridge University Press, 1991.

Houghton, R.A. "Tropical Deforestation and Atmospheric Carbon Dioxide." *Climatic Change* 19(1991):99-118.

Isermann, K. "Agriculture's Share in the Emission of Trace Gases Affecting the Climate and Some Cause-Oriented Proposals for Sufficiently Reducing This Share." *Environ. Pollut.* 83(1994):95-111.

Jaffe, Adam B. and Robert N. Stavins. "Dynamic Incentives of Environmental Regulation: The Effects of Alternative Policy Instruments on Technology Diffusion." *J. of Environ. Econ. and Manage.* 29(1995):43-63.

Jerko, C. "The Economic Potential of Producing Energy From Agricultural Biomass." MS thesis, Texas A&M University, 1996.

Johnson, K.A., H. H. Westberg, B. K. Lamb, R. L. Kincaid and D. Yonge. "Application of Strategies to Mitigate Methane Emissions From Ruminant Livestock." Annual Conference Proceedings, Ruminant Livestock Efficiency Program Atmospheric Pollution Prevention Division, U.S. Environmental Protection Agency, Washington DC, November 3-5, 1998.

Jouzel, J., C. Lorius, J.R. Petit, C. Genthon, N.I. Barkov, V.M. Kotlyakov, and V.M. Petrov. "Vostok Ice Core: A Continuous Isotope Temperature Record Over the Last Climatic Cycle (160,000 years)." *Nature* 329(1987):403-8.

Kaestle, C., D. Williams, and M. Gibbs. "An Environmental Study of Bovine Somatotropin Use in the U.S. - Impacts on Methane Emissions." Paper prepared for Tom Wirth, Ruminant Livestock Methane Program, Atmospheric Pollution Prevention Division, U.S. Environmental Protection Agency, Washington DC, August 1996.

Kane, S.M., and J.M. Reilly. *Economics of Ethanol Production in the United States*. U.S. Department of Agriculture, Economic Research Service, Agr. Econ. Rep. 607, Washington DC, March 1989.

Kern, J.S. "Spatial Patterns of Soil Organic Carbon in the Contiguous United States." *Soil Sci. Soc. of Amer. J.* 58(1994):439-55.

Klemme, R.M. "A Stochastic Dominance Comparison of Reduced Tillage Systems in Corn and Soybean Production Under Risk." *Amer. J. Agr. Econ.* 67(August 1985):550-7.

Kline D., T. Hargrove, and C. Vanderlan. *The Treatment of Biomass Fuels in Carbon Emissions Trading Systems*. Prepared for the Center for Clean Air Policy's Greenhouse Gas Emissions Trading Braintrust [Online]. Available at http://www.ccap.org/m-pub-d.htm#AIRLIEPUB. Washington DC, March 1998.

Kutsch, W.L., and L. Kappen. "Aspects of Carbon and Nitrogen Cycling in Soils of the Bornhöved Lake District II: Modeling the Influence of Temperature Increase on Soil Respiration and Organic Carbon Content in Arable Soils Under Different Managements." *Biogeochemistry* 39(November 1997):207-24.

Lal, R., J.M. Kimble, R.F. Follett, and C.V. Cole. *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect*, pp. 128, Chelsea, MI: Sleeping Bear Press Inc., 1998.

Malik, A.S., B.A. Larson, and Marc Ribaudo. "Economic Incentives for Agricultural Nonpoint Source Pollution Control." *Water Resour. Bull.* 30(June 1994):471-80.

Mann, M.K., and P.L. Spath. "Life Cycle Assessment of a Biomass Gasification Combined-Cycle Power System. National Renewable Energy Laboratory, TP-430-23076. Golden, CO, 1997.

Manne, A.S., and R.G. Richels. "Global CO_2 Emissions Reductions - The Impacts of Rising Energy Costs." *The Energy J.* 22(1990):51-74.

Marland, G., and B. Schlamadinger. "Forests for Carbon Sequestration or Fossil Fuel Substitution: A Sensitivity Analysis." *Biomass and Bioenergy* 13(1997):389-97.

Marland, G., B.A. McCarl, and U.A. Schneider. "Soil Carbon: Policy and Economics." *Carbon Sequestration in Soils: Science, Monitoring, and Beyond.* Proceedings of the St. Michaels Workshop. N.J. Rosenberg, R.C. Izaurralde, and E.L. Malone, eds., pp. 151-78 , St. Michaels, MD, December 3-5, 1998.

McCarl, B.A. "Carbon Sequestration via Tree Planting on Agricultural Lands: An Economic Study of Costs and Policy Design Alternatives." Paper presented at the Energy Modeling Forum, Snowmass, CO, 3-11 August 1998.

McCarl, B.A., D.M. Adams, and R.J. Alig. "Analysis of Biomass Fueled Electrical Powerplants: Implications in the Agricultural & Forestry Sectors." *Ann. of Operations Res.* 94(2000):37-55.

McCarl, B.A., C.C. Chang, J.D. Atwood, and W.I. Nayda. "Documentation of ASM: The U.S. Agricultural Sector Model." Unpublished Report, Texas A&M University, 1993.

McCarl, B.A., M. Gowen, and T. Yeats. *An Impact Assessment of Climate Change Mitigation Policies and Carbon Permit Prices on the U.S. Agricultural Sector.* Report for Climate Change Policies and Programs Division, U.S. Environmental Protection Agency, Washington DC, 1997.

McCarl, B.A., and U. Schneider. "Curbing Greenhouse Gases: Agriculture's Role." *Choices* (First Quarter 1999):9-12.

McCarl, B.A., and U. Schneider. "U.S. Agriculture's Role in a Greenhouse Gas Mitigation World: An Economic Perspective." *Rev. of Agr. Econ. 22*(Spring/ Summer 2000):134-59.

McCarl, B. A. and T. H. Spreen, "Price Endogenous Mathematical Programming as a Tool for Sector Analysis." *Amer. J. Agr. Econ.* 62(1980):87-102.

Mikesell, C.L., J.R. Williams, and J.H. Long. "Evaluation of Net Return From Alternative Tillage Systems for Grain Sorghum and Soybean Rotations." *N. C. J. Agr. Econ.* 10(July 1988):255-71.

Mosier, A.R., W.J. Parton, D.W. Valentine, D.S. Ojima, D.S. Schimel, and O. Heinemeyer. "CH4 and N2O Fluxes in the Colorado Shortgrass Steppe. 2. Long-Term Impact of Land Use Change." *Global Biogeochemical Cycles* 11(1997):29-42.

Moulton, R.J., and K.B. Richards. "Costs of Sequestering Carbon Through Tree Planting and Forest Management in the U.S. " USDA Forest Service, General Technical Report WO-58, Washington DC, 1990.

Newell, R.G., and R.N. Stavins. "Climate Change and Forest Sinks: Factors Affecting the Costs of Carbon Sequestration." Working paper R98-14, John F. Kennedy School of Government, Harvard University, September 1998.

Norton, G.A. *Resource Economics*. 164 pp., London: Edward Arnold, 1984.

Parks, P., and I. Hardie. "Least-Cost Forest Carbon Reserves: Cost-Effective Subsidies to Convert Marginal Agricultural Land to Forests." *Land Econ.* 71(1995):122-36.

Parton, W.J., D.S. Ojima, C.V. Cole and D.S. Schimel. "A General Model for Soil Organic Matter Dynamics: Sensitivity to Litter Chemistry, Texture and Management." *Quantitative Modeling of Soil Forming Processes*. SSSA Spec. Pub. 39, pp. 147-67, Madison WI, 1994.

Plantinga, A.J., T. Mauldin, and D.J. Miller. "An Econometric Analysis of the Costs of Sequestering Carbon in Forests." *Amer. J. Agr. Econ.* 81(November 1999):812-24.

Post, W.M., R.C. Izaurralde, L.K. Mann, and N. Bliss. "Monitoring and Verification of Soil Organic Carbon Sequestration." Paper presented at Workshop on Carbon Sequestration in Soils: Science, Monitoring and Beyond, St. Michaels MD, December 3-5, 1998.

Reeburgh, W.S., S.C. Whalen, and M.J. Alperin. "The Role of Methylotrophy in the Global Methane Budget." *Microbial Growth on C-1 Compounds*. J.C. Murrell and D.P. Kelly, eds., pp. 1-14., Andover UK: Intercept, 1993.

Sandor, R.L., and J.R. Skees. "Creating a Market for Carbon Emissions - Opportunities for U.S. Farmers." *Choices* (First Quarter 1999):13-17.

Sedjo, R.A. "Forests, a Tool to Moderate Global Warming?" *Environment* 13(1989):1,14.

Sedjo, R.A., and A.M. Solomon. "Climate and Forests." *Greenhouse Warming: Abatement and Adaption*. N.J. Rosenberg, W.E. Easterling, P.R. Crosson, and J. Darmstadter, eds., pp. 105-20. Washington DC: Resources for the Future, 1989.

Spath, P.L, and M.K. Mann. "Life Cycle Assessment of Coal-Fired Power Production." Golden, CO: National Renewable Energy Laboratory TP-570-25119, 1999.

Sprugel, D.G. "Natural Disturbance and Ecosystem Energetics." *The Ecology of Natural Disturbance and Patch Dynamics*. S.T.A. Pickett and P.S. White, eds., pp. 335-52. New York: Academic Press, 1985.

Stavins, R.N. "The Costs of Carbon Sequestration: A Revealed-Preference Approach." *Amer. Econ. Rev.* 89(September 1999):994-1009.

Taff, S.J., and N. Senjem. "Increasing Regulators' Confidence in Point-Nonpoint Pollutant Trading Schemes." *Water Resour. Bull.* 32(December 1996):1187-93.

Tietenberg, T., M. Grubb, A. Michaelowa, B. Swift, Z.X. Zhang, and F.T. Joshua. "Greenhouse Gas Emissions Trading. Defining the Principles, Modalities, Rules and Guidelines for Verification, Reporting & Accountability." United Nations Conference on Trade and Development, August 1988.

Trachtenberg, E. and C. Ogg. "Potential for Reducing Nitrogen Pollution Through Improved Agronomic Practice." *Water Resour. Bull.* 30(December 1994):1109-18.

Tweeten, L., B. Sohngen, and J. Hopkins. "Assessing the Economics of Carbon Sequestration in Agriculture." Paper presented at the Conference on Assessment Methods for Soil Carbon Pools, Columbus, OH, November 2-4, 1998.

Tyner, W., M. Abdallah, C. Bottum, O. Doering, B.A. McCarl, W.L. Miller, B. Liljedahl, R. Peart, C. Richey, S. Barber, and V. Lechtenberg. "The Potential of Producing Energy From Agriculture." Purdue School of Agriculture, Department of Agricultural Economics, Final Report to Office of Technology Assessment, U.S. Congress, 1979.

United Nations, Framework Convention on Climate Change. *Kyoto Protocol.* Climate Change Secretariat (UNFCCC). [Online]. Available at http://www.unfccc.de/resource/convkp.html, March 1998.

U.S. Department of Agriculture, Economic Research Service, Natural Resources and Environment Division. Agricultural Resources and Environmental Indicators, 1996-97. Agricultural Handbook No. 712. [Online]. Available at http://www.ers.usda.gov/epubs/pdf/ah712/.

U.S. Department of Agriculture, Office of The Chief Economist, Global Change Program Office. "Economic Analysis of U.S. Agriculture and the Kyoto Protocol." [Online]. Available at http://www.usda.gov/oce/gcpo/Kyoto.pdf, May 1999a.

U.S. Department of Agriculture, Soil Conservation Service. *Summary Report 1997 National Resources Inventory*. Stat. Bull. No. 790. Washington DC, 1999b.

U.S. Department of Commerce, Census of Agriculture, Report AC92-RS-1. *Farm and Ranch Irrigation Survey*, Washington DC, 1994.

U.S. Department of Energy, Energy Information Administration. *Annual Energy Review 1997*. [Online]. Available at http://www.eia.doe.gov/emeu/aer/, June 1998a.

U.S. Department of Energy, Energy Information Administration. *Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity*. SR/OIAF/98-03, Washington DC, October 1998b.

U.S. Department of State. *The Kyoto Protocol on Climate Change*. Fact Sheet released by the Bureau of Oceans and International Environmental and Scientific Affairs. [Online]. Available at www.state.gov/www/global/oes/fs_kyoto_climate_ 980115.html, Washington DC, 15 January 1998.

U.S. Environmental Protection Agency (U.S. EPA). *Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-1996*. EPA-236-R-98-006, Washington DC, March 1998.

U.S. Forest Service, Department of Agriculture. *Land Areas of the National Forest System*. Washington DC, September 1999.

Van Kooten, G.C., E. Krcmar-Nozic, B. Stennes, and R. van Gorkom. "Economics of Fossil Fuel Substitution and Wood Product Sinks When Trees Are Planted to Sequester Carbon on Agricultural Lands in Western Canada." *Can. J. Forest Res.* 29(December 1999):1669-1678.

Walsh, M.E., D. de la Torre Ugarte, S. Slinsky, R.L. Graham, H. Shapouri, and D. Ray. "Economic Analysis of Energy Crop Production in the U.S. - Location, Quantities, Price and Impacts on the Traditional Agricultural Crops." *Bioenergy 98: Expanding Bioenergy Partnerships* 2(1998):1302-10.

Wang, W., C. Saricks, and D. Santini. "Effects of Fuel Ethanol Use on Fuel-Cycle Energy and Greenhouse Gas Emissions." Center for Transportation Research, Argonne National Laboratory, ANL/ESD-38, January 1999.

Watson, R.T., L.G. Meira Filho, E. Sanhueza, and A. Janetos. "Greenhouse Gases: Sources and Sinks." *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, J.T. Houghton, B.A. Collander, and S.K. Varney, eds., pp. 25-46. Cambridge: Cambridge University Press, 1992.

Williams, J.R., C.A. Jones, J.R. Kiniry, and D.A. Spaniel. "The EPIC Crop Growth Model." *Transactions of the American Society of Agricultural Engineers.* 32(1989):497-511.

Williams, J.R., R.V. Llewelyn, and G.A. Barnaby. "Risk Analysis of Tillage Alternatives With Government Programs." *Amer. J. Agr. Econ.* 72(February 1990):172-81.

Winjum, J.K., R.K. Dixon, and P.E. Schroeder. "Estimating the Global Potential of Forest and Agroforest Management Practices to Sequester Carbon." *Water, Air, and Soil Pollut.* 64(1992):213-27.

NOMENCLATURE

GHG(s)	Greenhouse Gas(es)
GHGE(s)	Greenhouse Gas Emission(s)
MMT	Million Metric Tons
CE	Carbon Equivalent
TCE	Tons of Carbon Equivalent
MMTCE	Million Metric Tons of Carbon Equivalent
CH_4	Methane
N_2O	Nitrous Oxide
CO_2	Carbon Dioxide
GWP	Global Warming Potential
SOM	Soil Organic Matter
SOMC	Soil Organic Matter Coefficients

APPENDIX A

COPYRIGHT STATEMENT

Review of Agricultural Economics

May 17, 2000

Uwe Schneider
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Department of Agricultural Economics
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Dear Uwe:

I am responding to your letter of May 12, 2000, requesting information regarding your paper "U.S. Agriculture's Role in a Greenhouse Gas Emission Mitigation World: An Economic Perspective" which will be published in Volume 22, Number 1, Spring/Summer 2000 issue of the *Review of Agricultural Economics.* There should be no problem with use of the material in your dissertation or with the future publication of excerpts.

I hope that this has sufficiently answered your question. Please do not hesitate to contact me if I can be of any further assistance.

Sincerely,

Gail L. Cramer, Editor
RAE

GLC/sp
enclosures

APPENDIX B

EPIC PARAMETERS FOR CORN PRODUCTION IN IOWA

Management[a]	Y-Adj[b]	N-Adj[c]	C-Adj[d]	DN[e]	Wa-Er[f]	Wi-Er[g]	N-Ex[h]	P-Ex[I]
D N1 L V	1.042	1.04	-1,663	1,689	81.4	65.5	135.8	1.23
D N1 L C	1.039	1.03	1,955	1,668	50.9	43.5	136.0	0.38
D N1 L Z	1.039	1.02	3,670	1,628	28.1	31.2	135.2	0.54
D N1 M V	1.106	1.08	-2,518	1,410	225.5	71.0	147.2	1.02
D N1 M C	1.015	1.01	2,959	1,413	136.7	47.1	154.9	0.41
D N1 M Z	1.016	1.01	5,556	1,392	77.6	34.0	152.7	0.57
D N1 S V	0.739	0.77	-2,232	703	984.2	81.8	210.0	10.70
D N1 S C	0.861	0.90	1,987	710	617.5	53.8	211.2	3.75
D N1 S Z	0.860	0.91	5,691	705	357.7	37.9	208.5	4.40
D N1 W V	1.084	1.10	-951	2,086	12.9	46.4	132.1	0.32
D N1 W C	0.987	1.00	855	1,993	10.7	30.8	101.3	0.19
D N1 W Z	0.987	1.00	2,415	1,958	6.0	21.6	101.0	0.37
D N2 L V	0.904	0.77	-1,663	1,048	82.6	58.3	84.7	0.54
D N2 L C	0.910	0.79	1,955	1,036	51.7	38.7	84.7	0.28
D N2 L Z	0.910	0.79	3,670	1,011	28.5	27.8	84.1	0.36
D N2 M V	0.974	0.87	-2,518	820	230.0	64.8	84.1	0.39
D N2 M C	0.886	0.80	2,959	822	139.4	43.0	88.6	0.33
D N2 M Z	0.887	0.79	5,556	810	79.1	31.0	87.1	0.41
D N2 S V	0.638	0.58	-2,232	400	1,004.6	73.8	115.0	9.81
D N2 S C	0.744	0.67	1,987	405	630.3	48.5	114.8	3.56
D N2 S Z	0.742	0.67	5,691	402	365.1	34.2	113.3	3.98
D N2 W V	0.960	0.90	-951	1,391	12.8	41.2	92.5	0.11
D N2 W C	0.874	0.82	855	1,329	10.7	27.4	70.7	0.10
D N2 W Z	0.874	0.81	2,415	1,305	6.0	19.2	70.4	0.17
D N3 L V	0.707	0.53	-1,663	849	98.2	63.5	71.6	0.39
D N3 L C	0.710	0.55	1,955	839	61.4	42.2	71.7	0.23
D N3 L Z	0.710	0.55	3,670	818	33.9	30.3	71.2	0.25
D N3 M V	0.754	0.63	-2,518	626	287.6	72.1	65.6	0.30
D N3 M C	0.685	0.58	2,959	627	174.3	47.9	69.3	0.27

Management[a]				Y-Adj[b]	N-Adj[c]	C-Adj[d]	DN[e]	Wa-Er[f]	Wi-Er[g]	N-Ex[h]	P-Ex[i]
D	N3	M	Z	0.685	0.57	5,556	618	98.9	34.5	68.1	0.29
D	N3	S	V	0.504	0.39	-2,232	294	1,250.0	83.4	82.7	7.90
D	N3	S	C	0.578	0.47	1,987	297	784.3	54.8	82.8	3.19
D	N3	S	Z	0.578	0.47	5,691	295	454.2	38.6	81.6	3.46
D	N3	W	V	0.759	0.64	-951	1,168	14.7	44.0	83.0	0.09
D	N3	W	C	0.690	0.59	855	1,116	12.2	29.2	63.2	0.08
D	N3	W	Z	0.691	0.58	2,415	1,096	6.8	20.4	62.9	0.10
I	N1	L	V	1.035	1.02	-1,597	2,141	75.7	62.3	170.8	0.80
I	N1	L	C	1.013	0.99	1,878	2,115	47.3	41.4	173.1	0.40
I	N1	L	Z	1.013	0.99	3,525	2,064	26.2	29.7	172.3	0.57
I	N1	M	V	1.032	1.03	-2,438	1,890	217.7	67.4	189.3	0.85
I	N1	M	C	1.010	1.02	2,865	1,894	131.9	44.7	199.3	0.43
I	N1	M	Z	1.010	1.02	5,380	1,866	74.9	32.2	196.5	0.60
I	N1	S	V	0.872	0.92	-2,193	880	849.1	74.6	265.9	8.44
I	N1	S	C	0.970	1.02	1,952	889	532.7	49.0	267.2	3.36
I	N1	S	Z	0.969	1.02	5,591	882	308.6	34.5	263.6	4.02
I	N1	W	V	0.884	0.94	-899	2,776	12.7	47.3	173.2	0.40
I	N1	W	C	0.866	0.92	809	2,652	10.6	31.4	133.0	0.24
I	N1	W	Z	0.866	0.92	2,284	2,605	5.9	22.0	132.7	0.42
I	N2	L	V	0.896	0.78	-1,597	1,329	76.9	55.5	106.9	0.33
I	N2	L	C	0.877	0.76	1,878	1,313	48.0	36.8	108.1	0.30
I	N2	L	Z	0.877	0.76	3,525	1,281	26.5	26.4	107.3	0.36
I	N2	M	V	0.895	0.84	-2,438	1,100	222.0	61.5	108.1	0.37
I	N2	M	C	0.875	0.82	2,865	1,102	134.6	40.8	113.8	0.35
I	N2	M	Z	0.875	0.81	5,380	1,086	76.3	29.4	112.0	0.41
I	N2	S	V	0.770	0.74	-2,193	501	866.7	67.3	145.6	5.19
I	N2	S	C	0.847	0.80	1,952	506	543.8	44.3	145.6	3.05
I	N2	S	Z	0.846	0.80	5,591	503	314.9	31.2	143.5	3.45
I	N2	W	V	0.761	0.71	-899	1,851	12.6	42.0	121.3	0.15

Management[a]			Y-Adj[b]	N-Adj[c]	C-Adj[d]	DN[e]	Wa-Er[f]	Wi-Er[g]	N-Ex[h]	P-Ex[i]
I N2	W	C	0.744	0.70	809	1,768	10.5	27.9	92.8	0.13
I N2	W	Z	0.745	0.69	2,284	1,737	5.9	19.5	92.4	0.19
I N3	L	V	0.673	0.49	-1,597	1,076	91.3	60.4	90.6	0.27
I N3	L	C	0.658	0.47	1,878	1,063	57.1	40.1	91.5	0.25
I N3	L	Z	0.658	0.47	3,525	1,037	31.6	28.8	90.9	0.27
I N3	M	V	0.675	0.56	-2,438	839	277.6	68.5	84.2	0.31
I N3	M	C	0.660	0.55	2,865	841	168.2	45.5	88.8	0.28
I N3	M	Z	0.660	0.55	5,380	828	95.5	32.8	87.2	0.31
I N3	S	V	0.606	0.52	-2,193	367	1,078.4	76.0	105.1	4.57
I N3	S	C	0.647	0.54	1,952	371	676.6	50.0	105.2	2.66
I N3	S	Z	0.647	0.54	5,591	369	391.9	35.2	103.6	2.81
I N3	W	V	0.553	0.43	-899	1,554	14.4	44.8	108.6	0.11
I N3	W	C	0.542	0.42	809	1,485	12.0	29.7	82.7	0.09
I N3	W	Z	0.542	0.42	2,284	1,459	6.7	20.8	82.3	0.11

[a] I-irrigation, D-dry land, N1/N2/N3-5%/15%/30% nitrogen stress, L-low erodible land, M-medium erodible land, S-severe erodible land, W-W3-8 land, V-conventional tillage, C-conservation tillage, Z-zero tillage.

[b] Relative yield adjustment factor.

[c] Relative nitrogen fertilizer adjustment factor.

[d] Soil carbon change from average current level to new tillage equilibrium in Kg CE/acre.

[e] Denitrification rate in kg nitrogen/acre.

[f] Water erosion in kg soil/acre.

[g] Wind erosion in kg soil/acre.

[h] Nitrogen losses through erosion, leaching, surface, and subsurface flow in Kg nitrogen per acre

[i] Phosphorous losses through erosion, leaching, surface, and subsurface flow in Kg phosphorous per acre

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McCarl, B.A., and U. Schneider. "Curbing Greenhouse Gases: Agriculture's Role." *Choices*, First Quarter 1999:9-12.

McCarl, B.A., and U. Schneider. "U.S. Agriculture's Role in a Greenhouse Gas Emission Mitigation World: An Economic Perspective". *Rev. Agr. Econ.* 22(Spring/Summer 2000):134-56.