The Dynamic Competitiveness of U.S. Agricultural and Forest Carbon Sequestration

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Society is increasingly turning attention toward greenhouse gas emission control with for example the Kyoto Protocol has entered into force. Since many of the emissions come from energy use, high cost strategies might be required until new technological developments reduce fossil fuel dependency or increase energy utilization efficiency. On the other hand biologically based strategies may be used to offset energy related emissions. Agricultural soil and forestry are among the largest carbon reservoirs on the planet; therefore, agricultural and forest activities may help to reduce the costs of greenhouse gas emission mitigation. However, sequestration exhibits permanence related characteristics that may influence this role. We examine the dynamic role of carbon sequestration in the agricultural and forest sectors can play in mitigation. A 100-year mathematical programming model, depicting U.S. agricultural and forest sectoral activities including land transfers and greenhouse gas consequences is applied to simulate potential mitigation response. The results show that at low cost and in the near term agricultural soil and forest management are dominant sectoral responses. At higher prices and in the longer term biofuels and afforestation take over. Our results reveal that the agricultural and forest sector carbon sequestration may serve as an important bridge to the future helping to hold costs down until energy emissions related technology develops.

La société s'intéresse de plus en plus à la lutte contre les émissions de gaz à effet de serre (GES) depuis, par exemple, l'entrée en vigueur du Protocole de Kyoto. Comme la majorité des émissions sont attribuables à la production d'énergie, il faudra peut-être recourir à des stratégies coûteuses jusqu'à ce que de nouvelles percées technologiques permettent de diminuer la dépendance aux combustibles fossiles ou d'augmenter l'efficacité énergétique. Toutefois, des stratégies biologiques pourraient être employées pour contrebalancer les émissions attribuables à la production d'énergie. Les sols agricoles et les forêts figurent parmi les plus importants puits de carbone de la planète; par conséquent, les activités agricoles et forestières pourraient aider à diminuer les coûts liés à la réduction des émissions de GES. Toutefois, la séquestration présente des caractéristiques permanentes qui pourraient influencer ce rôle. Nous avons examiné le rôle dynamique de la séquestration du carbone dans les secteurs agricole et forestier en vue de diminuer les GES. Un modèle de programmation mathématique de 100 ans illustrant les activités agricoles et forestières aux États-Unis, y compris les conséquences du transfert de terres et des émissions de GES, a été utilisé pour simuler l'atténuation éventuelle. Les résultats ont montré, qu'à faible coût et qu'à court terme, la gestion des forêts et des sols agricoles constituaient les principales réactions de ces secteurs. À coût élevé et à long terme, les biocarburants et le boisement prennent la relève. Nos résultats ont révélé que la séquestration du carbone par les secteurs agricole et forestier peut contribuer à maintenir les coûts à de faibles niveaux jusqu'à la mise au point de technologies qui permettront de diminuer les émissions attribuables à la production d'énergie.

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INTRODUCTION

Global society is actively considering options to reduce greenhouse gas emissions (GHGE) as the IPCC asserts that anthropogenic GHGE are the dominant causal factor of climate change (Houghton et al 2001). However, emission reductions can be expensive. According to Konyar (2001), the United States would have to reduce GHG emissions by 45.2% to meet her Kyoto Protocol (KP) target given anticipated emission growth rates between 1990 and 2008–12. The majority of U.S. emissions come from energy use with about 40% coming from each of electricity generation and petroleum usage. A large emission reduction would thus require actions such as

- a large reduction in energy use, which could be both costly and economically disruptive,
- development of new technologies improving the emissions efficiency of fossil fuel usage, or
- actions reducing the dependence on fossil fuel sources by switching fuels.

The costs of such actions were a prominent argument used in justification of the U.S. decision to not sign the Kyoto Protocol. Nevertheless as manifest in the President's climate change initiative (Bush 2002) the United States has announced policies to limit GHGE.

Achievement of emission reductions through technological development or fuel switching takes time. Agriculture and forestry may be able to provide low-cost, near term GHGE reduction strategies, buying time for technological development (McCarl and Schneider 1999; Lal 2004). Specifically, known management manipulations may be employed to enhance sequestration by removing carbon from the atmosphere and storing it in trees or soils.

When considering agricultural and forest carbon sequestration, one needs to recognize that the capacity to sequester is limited and an ecological equilibrium will be approached effectively saturating the ecosystems ability to hold carbon. For example, West and Post (2002) in examining 67 long term tillage experiments consisting of 276 paired treatments find that "Carbon sequestration rates, with a change from [conventional tillage to no tillage] . . . , can be expected to peak in 5–10 yr . . . reaching a new equilibrium in 15–20 yrs." They also argue that under alterations in " . . . rotation complexity, . . . [soils] may reach a new equilibrium in approximately 40–60 yrs." Furthermore, while agricultural and forestry carbon sequestration activities can increase ecosystem carbon storage, such activities, if discontinued, result in the return of the sequestered carbon to the atmosphere and approach to the lower prepractice carbon equilibrium. Thus, the permanence of sequestered carbon and the need for possible maintenance of nonaccumulating stocks must be considered.

The saturating behavior suggests that effectiveness, efficiency, and significance of agricultural and forestry carbon sequestration as a total society GHGE mitigation option is likely to vary dynamically. Previous studies examining carbon sequestration mitigation strategies in the agricultural and forest sectors have generally ignored the saturation and volatility characteristics embodied in ecosystem carbon pools or limited in analytical analysis (McCarl and Schneider 2000, 2001; Antle et al 2001; McCarl et al 2001; Noble and Scholes 2001; Schuman et al 2002). Consequently, previous analyses may overestimate the long run mitigation potential of agricultural and forestry sequestration programs.

Finally the effectiveness of GHG emission mitigation programs could be undermined if what is called "leakage" occurs (Murray et al 2004). Actions taken to enhance carbon sequestration or emission offsets can alter the market conditions (prices and productions) and therefore induce GHG emissions in nontarget activities. For example, forest carbon sequestration program that attract afforestation can (1) reduce total crop production acreage raising crop prices in turn encouraging more intensive crop management and possibly increasing GHGE on that land, (2) expand future timber supply causing deintensification of management on existing timber lands with reduced sequestration on those lands.

This study will attempt to examine the dynamic role of agricultural and forestry carbon sequestration activities in the portfolio of agricultural and forestry responses to GHGE reduction efforts when considering saturation, permanence, and leakage issues.

METHODOLOGY

To examine the dynamic role of agriculture and forest carbon sequestration we need an analytical framework that can depict the time path of offsets from carbon sequestration vis a vis other agricultural and forestry possibilities as they vary over time. To do this we will use a GHG version of the Forest and Agricultural Sector Optimization Model (FASOM; Adams et al 1999) as developed in Lee (2002) and hereafter called FASOMGHG. This model has the forest carbon accounting of the original FASOM model unified with a detailed representation of the possible mitigation strategies in the agricultural sector adapted from Schneider (2000) and McCarl and Schneider (2001).

FASOMGHG, as developed in Lee (2001), is an intertemporal, price-endogenous, spatial equilibrium model depicting land transfers between the agricultural and forest sectors in the United States. The model solution portrays a multiperiod equilibrium that arises from a modeling structure that maximizes the present value of aggregated producers' and consumers' surpluses across both sectors over 10 decades subject to resource constraints. We use a 100-year model as 100 years is long enough to complete the better part of two Pacific Northwest timber rotations (the longest rotation in the modeled area) but cut the explicit time period off at 100 years as we cannot afford to get much bigger and still solve in reasonable time. We also have a terminal condition that values ending standing inventory and thus does not really mean that the activities stop at year 100 but rather persist on forever in an annuity fashion from year 100 on as explained in Adams et al (1999) FASOMGHG depicts production of 48 primary agricultural, 54 secondary processed, agricultural commodities, and 8 forest products as well as GHG emission/sequestration/offset accounting in 11 geographical regions. It also includes 28 international trade regions. FASOMGHG assumes competitive behavior in forest, agricultural, and input markets. It simulates the markets response to given policy implementation. The results from FASOMGHG yield a simulation of prices, production, management, and consumption within these two sectors under the scenario depicted in the model data. A mathematical presentation of the model appears in the Appendix.

In terms of GHGE mitigation FASOMGHG depicts the GHGE mitigation alternatives summarized in Table A1. Namely, the model considers the level and potential alteration of nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2) emissions from agricultural crop and livestock plus forest management and forest establishment activities. In addition, the possibility of enhancing carbon sequestration through tillage change and avoided deforestation[1] is also depicted. Likewise, additional costs associated with mitigation activities are included. Furthermore, since FASOMGHG is built in a dynamic framework, saturation conditions for agricultural terrestrial pools are incorporated as explained below.

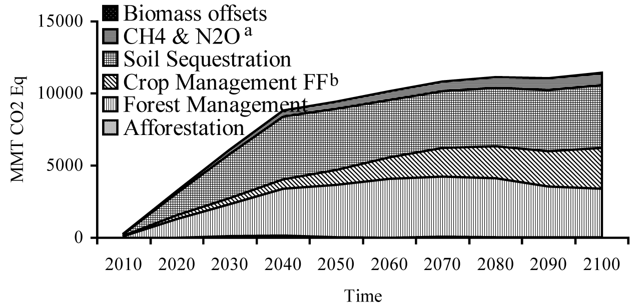
Incorporating Agricultural Soil Sequestration Saturation

Terrestrial carbon sinks are capable of accumulating carbon, but are limited by ecosystem capability in interaction with the management system. In particular, carbon only accumulates until a new equilibrium is reached under the management system. Moreover, the carbon accumulated in soils or trees exists in a potentially volatile form where increased soil or vegetation disturbance can release it. Thus, current GHGE reductions by sinks can result in potential future GHGE increases. FASOMGHG assumes when cropland tillage practice or land use (to pasture or grasslands) is altered, the carbon gain/loss stops after the first 30 years based on the previous tillage studies (West and Post 2002) and opinions of soil scientists (Parton 2001). The gains in carbon vary according to the previously used and newly adopted tillage practice. Carbon gains or losses in FASOMGHG are assumed linear over 30 years. Furthermore, the sequestering tillage practice may have to remain in use even after the soil carbon content reaches equilibrium, otherwise if tillage is intensified the carbon will be released. FASOMGHG does not require the cropland joining the sequestration program to maintain its tillage practice after saturation. Tillage practices can be reverted to more intensive choices with accompanying losses in sequestered carbon.

FASOMGHG also depicts sequestration gains from land use change namely conversion of croplands to grasslands or forests and conversion of grasslands to forests. As cropland converts to grasslands the carbon content is assumed to change over a 30-year period.

Incorporating Forest Sequestration Saturation

FASOMGHG as explained in Adams et al (1996, 1999) and Alig et al (1998) simulates activity over a 100-year period in the forest and agricultural sectors. Forest carbon accounting is based on the procedures in the FORCARB model as developed by Birdsey (1992), and Birdsey and Heath (1995), and the HARVCARB model of Rowe (1992). Forest carbon is accounted in four basic pools: soil, ecosystem, standing trees, and products after harvest. Under afforestation actions soil carbon initially rises rapidly, but later levels off particularly after the first rotation. The ecosystem component (carbon in small vegetation, dropped leaves, woody detritus, etc.) follows a similar pattern. The standing tree parts is based on forest growth and yield tables from the Forest Service ATLAS model (Haynes et al 1994) coupled with FORCARB which exhibits rapid initial growth and then approach a near steady state forest as the stand matures. The product accounting uses the results of Rowe (1992) where products decay overtime due to characteristics or use discontinuation. Thus in all of these cases saturation occurs as stands age.



[a]Other mitigation strategies are associated with CO_2 emissions.
[b]Crop Management FF refers to the fosil fuel reduction from changing crop management.

Figure 1. Cumulative mitigation contributions from major strategies at a \$5 CO_2 equivalent price

RESULTS AND IMPLICATIONS

The basic focus of this paper involves an examination of the dynamic portfolio of GHGE offsets that arise from agriculture and forestry under different CO_2 equivalent (CE) prices. This price is applied to CO_2, CH_4, and N_2O emissions/offsets time their Global Warming Potential (GWP). Studies have estimated CE prices in association with the KP target ranging from less than \$10 to more than \$100 (Energy Information Administration 1998; Bernstein et al 1999; Metz et al 2001; Peters et al 2001; Sohngen and Mendelsohn 2002). However, the U.S. government at one point suggested a CE price ceiling below \$7 (or \$25 per ton of carbon; Congressional Budget Office 2001). Based on these data we chose to construct FASOMGHG simulations for prices ranging between \$0 and \$50 per ton of CO_2 equivalent, which are held constant over time. Offset estimates are computed on a total U.S. basis relative to responses under a business as usual (BAU)-zero carbon price scenario and are thus only those additionally stimulated by carbon prices plus account for all domestic leakage.

Dynamic GHG Emission Changes in Different CE Price Scenarios

Figures 1–3 present the accumulated GHGE mitigation credits from forest sequestration (by forest management and afforestation), crop management, agricultural soil sequestration, power plant feedstock biofuel offsets, and non-CO_2 strategies.

At low prices (below \$10 with \$5 portrayed in Figure 1) and in the near term, the carbon stock on agricultural soil grows rapidly initially and is the dominant strategy. However, the offset quantity later diminishes with saturation occurring in the effective carbon gains after 30 years. Carbon stocks in the forest grow over time, mainly by forest management, at low prices and non-CO_2 strategies continually grow throughout the whole time period. Biofuel is not a factor as it is too expensive to be part of a low carbon price mitigation plan.

When the prices are higher (\$10 and above per tonne), the forest carbon stock increases first then diminishes; the agricultural soil carbon stock is much less important in the big picture especially in the later decades; non-CO_2 mitigation and crop management credit grows over time but are not very large players. Power plant feedstock biofuel potential grows (ethanol is not used). When the price is \$15 per tonne, it keeps growing

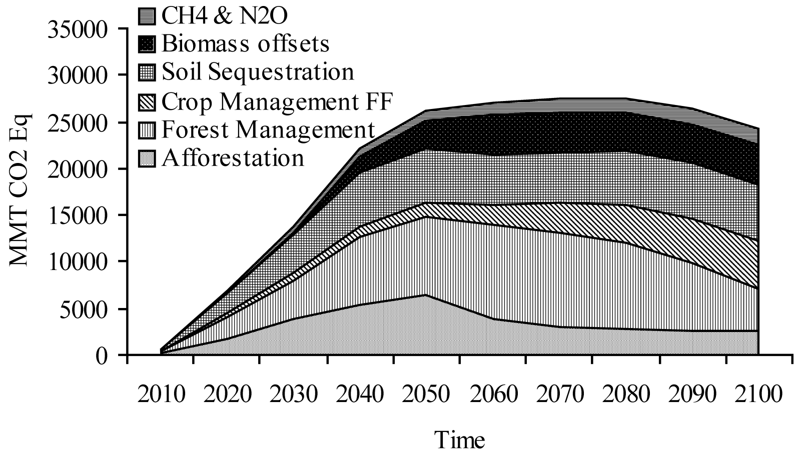


Figure 2. Cumulative mitigation contributions from major strategies at a $15 CO_2 equivalent price

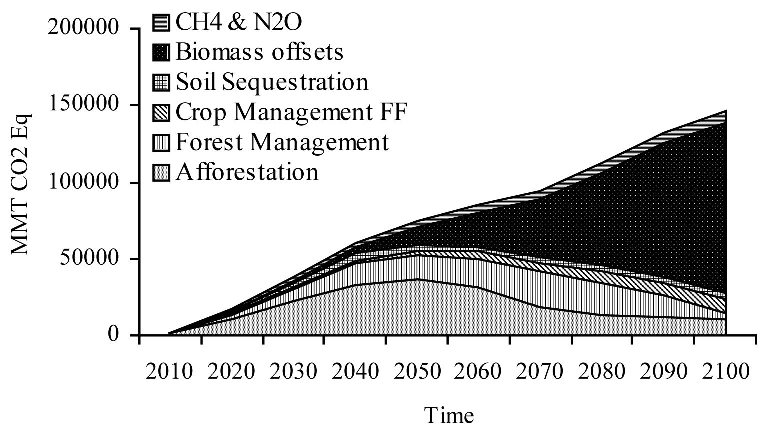


Figure 3. Cumulative mitigation contributions from major strategies at a $50 CO_2 equivalent price

for several decades then becomes stable. When the prices get higher, $50 per tonne for example, biofuel grows dramatically over time and becomes the dominant strategy in the later decades.

Across these and other runs several patterns emerge.

- Carbon sequestration, including agricultural soil and forest carbon sequestration, and power plant feedstock biofuel offsets are the high quantity mitigation strategies in the agricultural and forest sectors. The importance of these three strategies varies by price and time.
- At low prices and in early periods agricultural soil carbon is the dominant strategy. When prices get higher this is replaced by afforestation and powerplant feedstock biofuels as they have higher per acre carbon production rates.
- The sequestration activities tend to rise then stabilize largely due to saturation phenomena. Soils saturate faster than trees.

- The higher the price the more carbon stored in the forests in the early decades, but the intensified forest sequestration comes with a price in that CO_2 emissions from forests increase later. When the forest carbon sequestration program starts, reforestation or afforestation is encouraged and the harvest of existing timber is slowed down. However, the future harvest increases because of the increased mature forests by the increasing inventory of reforestation, afforestation, and previous postponed harvests. By 2050, the forest sector annually emits about 100 MMT of CO_2 compared to the BAU scenario when the price is \$15. Although the mitigation potential is smaller in the early decades when the price is low, e.g., \$10, the carbon capacity of forest is not saturated until 2070, and thus extends the time to sequester additional carbon.
- In the early stage of the mitigation program, when the prices are lower than \$15, the higher the price, the more agricultural sequestration occurs. Agricultural soil carbon sequestration annually mitigates 139 MMT of CO_2 at a \$5 price. Its mitigation potential peaks around \$15 with 194 MMT of CO_2 mitigation potential and becomes 177 MMT of CO_2 at a \$50 price in the first decade.
- Biofuels do not enter the mitigation portfolio until the price reaches certain level in the first decade. The higher the price, the more power plant feedstock biofuel production is encouraged. The potential of annual biofuel offsets is 1 MMT of CO_2 at \$5, increases to 6 MMT at \$15, and reaches 2188 MMT at \$50 by 2100.
- After the agricultural sequestration program has lasted for 30 years, the agricultural carbon pool begins to contribute to CO_2 emissions. About 9 MMT CO_2 are added to the air annually in the fourth decade when the price is \$5. When the price is \$15, the annual carbon increment is 20 MMT in the fourth decade and when the price goes up to \$50, the annual carbon increment increases to 45 MMT in the fourth decade.

Sensitivity Tests

This study incorporates the saturation and volatility characteristics of agricultural soil carbon sequestration. In a joint mitigation implementation program, FASOMGHG results generally show that after 30 years of sequestration programs, the net emissions increase from cropland compared with the base scenario. If we overlook the saturation characteristic in agricultural soil carbon sequestration, and assume that cropland can sustainably absorb or emit CO_2 once it is in some specific tillage management. FASOMGHG is modified to simulate such a change by using a 30-year average carbon intake or discharge of different tillage management for all future decades, thus assuming rates continue for 100 years.

Modified FASOMGHG results show the agricultural soil is a sink during the total modeling period and a dominant strategy (Figure 4). In addition, the agricultural soil carbon sequestration potential in the first three decades is substantially higher than in the "with saturation" case. For example, at a \$15 CE price, FASOMGHG projects agricultural soil sequestration potential under the "without saturation" scenario is about five times more than in the "saturation" case for the first decade. In terms of strategies when one does not consider agricultural soil carbon saturation then agricultural soil strategies are found to be more important than forest carbon sequestration in the early decades and later displaces some of the biofuel reliance at higher prices. Moreover, this strategy maintains

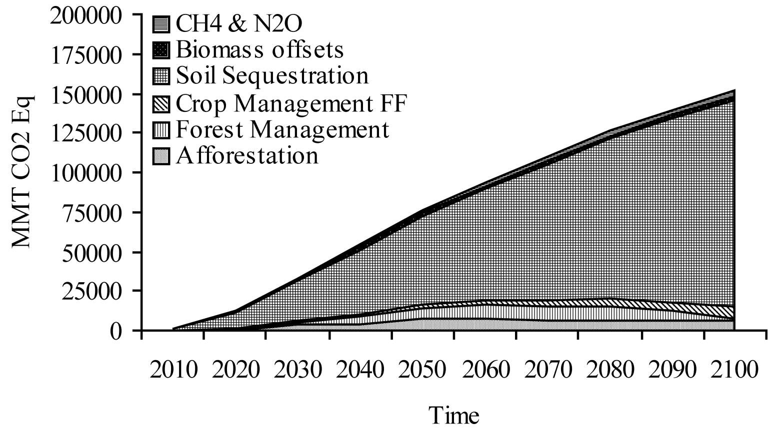


Figure 4. Cumulative mitigation contributions from major strategies at a \$15 CO_2 equivalent price under a "nonsaturation" of agricultural soils assumption

a dominant role through the whole modeling period in the mitigation portfolio. Clearly neglecting sequestration approach to equilibrium or saturation overestimates the cropland sequestration potential and the aggregate mitigation potential of the total agricultural and forest sector.

FASOMGHG considers resource competitiveness between mitigation strategies and this generates a gap between the potential of strategies evaluated one at a time versus when they are evaluated simultaneously.

The debate over the KP has resulted in a set of rules that allow some activities but disallow others and also rely particularly under the Clean Development Mechanism (CDM) on projects with limited eligibility. Such programs raise the specter of leakage where gains from some activities are offset by induced additional emissions or lessened sequestration in other categories. Using the approach explained in Murray et al (2004) we examine the magnitude of such leakage by considering what happens when only certain activities are eligible and look at the gains due to the eligible items relative to the total effect across all the GHGE accounts. Our results show that the leakage rates depend on chosen strategy. For example, when CE price is around \$15, using agricultural soil carbon sequestration alone resulted in a 4% leakage rate—the amount offsetting increased net emissions in other agricultural and forestry GHGE accounts were relative to the soil sequestration gains. Similarly, afforestation gains were offset by 19%. Overall, agricultural soil carbon sequestration has a lower leakage rate because cropland enrolled in soil carbon sequestration allows conventional production activities while afforestation prohibit agricultural production and therefore has higher demand pressure on remaining cropland and existing forest land management.

CONCLUSIONS

This study analyzes the optimal dynamic portfolio of GHGE mitigation strategies in the agricultural and forest sectors. Focus is placed on the role of agricultural and forest carbon sequestration activities in a dynamic portfolio of agricultural and forestry responses to GHGE reduction efforts with consideration of ecosystem and management system related saturation.

Our results show that the agricultural and forest sectors offer substantial potential to mitigate GHGE, offsetting about 3–15% of U.S. projected GHGE, assuming between 8,000 and 10,200 MMT of CO_2 equivalent, by 2010 for a CO_2 equivalent price ranging from \$5 to \$50. The optimal mitigation portfolio to achieve such offsets changes dynamically depending on price and time. Carbon sequestration is the primary mitigation strategy implemented in the early decades but then saturate and even turn into sources after 40–60 years. Agricultural soil carbon sequestration is the most efficient approach at low carbon prices (\$10 below) and forest carbon sequestration is more desirable at prices at \$10 and above. On the other hand, power plant feedstock biofuel activities become more important in the longer run or at higher prices. Our sensitivity analysis shows ignoring in the fact that soil carbon sequestration reaches a new equilibrium effectively saturating for a practice in turn causes one to overstate the importance of agricultural carbon sequestration program. Furthermore, we show that when pursuing only selected mitigation strategies afforestation will stimulate substantial leakage (about 20%) while agricultural carbon sequestration generates about 5%.

The findings of this study support the argument that agricultural and forest carbon sequestration provides more time to find long-run solutions such as new technologies to halt the increasing ambient greenhouse gas concentration as discussed in Marland et al (2001). It also shows that power plant feedstock biofuels is likely to be an important long run strategy at higher CO_2 equivalent prices.

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NOTE

[1] By decreasing or postponing harvest, deforestation can be used as a mitigation strategy.

REFERENCES

Adams, D. M., R. J. Alig, J. M. Callaway, B. A. McCarl and S. M. Winnett. 1996. The Forest and Agricultural Sector Optimization Model (FASOM): Model structure and policy applications. United States Department of Agriculture Forest Service Research Paper PNW-495, Pacific Northwest Research Station, Portland, OR.

Adams, D. M., R. J. Alig, B. A. McCarl, J. M. Callaway and S. M. Winnett. 1999. Minimum cost strategies for sequestering carbon in forests. *Land Economics* 75 (3): 360–74.

Alig, R. J., D. M. Adams and B. A. McCarl. 1998. Impacts of incorporating land exchanges between forestry and agriculture in sector models. *Journal of Agricultural and Applied Economics* 30 (2): 389–401.

Antle, J. M., S. M. Capalbo, S. Mooney, E. T. Elliott and K. H. Paustian. 2001. Economic analysis of agricultural soil carbon sequestration: An integrated assessment approach. *Journal of Agricultural and Resource Economics* 26 (2): 344–67.

Bernstein, P. M., W. D. Montgomert and T. F. Rutherford. 1999. Global impacts of the Kyoto agreement: Results from the MS-MRT Model. *Resource and Energy Economics* 21: 375–413.

Birdsey, R. 1992. *Prospective Changes in Forest Carbon Storage from Increasing Forest Area and Timber Growth*. Washington, DC: United States Department of Agriculture Forest Service Publication.

Birdsey, R. A. and L. S. Heath. 1995. Carbon changes in U.S. forests. In *Climate Change and the Productivity of America's Forests*, edited by L. A. Joyce. U. S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station General Technical Report, Ft. Collins, CO, pp. 56–70.

Bush, G. W. 2002. Clear Skies & Global Climate Change Initiatives. Available at http://www.whitehouse.gov/news/releases/2002/02/20020214-5.html (February 14, 2002).

Congressional Budget Office. 2001. *An Evaluation of Cap-and-Trade Programs for Reducing U.S. Carbon Emissions*. Washington, DC: Congress of the United States.

Energy Information Administration. 1998. *Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity*. Washinhton, DC: United States Department of Energy.

Haynes, R., R. Alig and E. Moore. 1994. *Alternative Simulations of Forestry Scenarios Involving Carbon Sequestration Options: Investigation of Impacts on Regional and National Timber Markets*. Portland, OR: United States Department of Agriculture Forest Service, PNW Station.

Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell and C. A. Johnson. 2001. *Climate Change 2001: The Scientific Basis*. Cambridge, England: Cambridge University Press.

Konyar, K. 2001. Assessing the role of US agriculture in reducing greenhouse gas emissions and generating additional environmental benefits. *Ecological Economics* 38: 85–103.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science* 304: 1623.

Lee, H. 2002. The dynamic role for carbon sequestration by the U.S. agricultural and forest sectors in greenhouse gas emission mitigation. Ph.D. thesis, Department of Agricultural Economics, Texas A&M University.

McCarl, B. A., B. C. Murray and U. A. Schneider. 2001. Jointly estimating carbon sequestration supply from forests and agriculture. Paper Prepared for Presentation at the Western Agricultural Economics Association Annual Meeting, San Francisco, July 5–8, 2001.

McCarl, B. A. and U. A. Schneider. 1999. Curbing greenhouse gases: Agriculture's role. *Choices* (first quarter): 9–12.

McCarl, B. A. and U. A. Schneider. 2000. Agriculture's role in a greenhouse gas emission mitigation world: An economic perspective. *Review of Agricultural Economics* 22 (spring/summer): 134–59.

McCarl, B. A. and U. A. Schneider. 2001. The cost of greenhouse gas mitigation in U.S. agriculture and forestry. *Science* 294 (21): 2481–82.

Marland, G., B. A. McCarl and U. A. Schneider. 2001. Soil carbon: Policy and economics. *Climatic Change* 51: 101–17.

Metz, B., O. Davidson, R. Swart and J. Pan. 2001. *Climate Change 2001: Mitigation*. Cambridge, England: Cambridge University Press.

Murray, B. C., B. A. McCarl and H-C. Lee. 2004. Estimating leakage from forest carbon sequestration programs. *Land Economics* 80 (1): 109–24.

Noble, I. and R. J. Scholes. 2001. Sinks and the Kyoto protocol. *Climate Policy* 1 (1): 5–25.

Parton, W. J. 2001. Natural Resource Ecology Laboratory and Professor of Rangeland and Ecosystem Science, Colorado State University, Fort Collins, CO, Private communication.

Peters, M., R. House, J. Lewandrowski and H. McDowell. 2001. Economic impacts of carbon charges on U.S. agriculture. *Climatic Change* 50 (4): 445–73.

Rowe, C. 1992. Carbon sequestration impacts of forestry: Using experience of conservation programs. Paper Presented at Symposium on Forest Sector, Trade, and Environmental Impact Models: Theory and Applications. Sponsored by CINTRAFOR, University of Washington, Seattle, WA.
Schneider, U. A. 2000. Agricultural sector analysis on greenhouse gas emission mitigation in the U.S. Ph.D. dissertation, Department of Agricultural Economics, Texas A&M University.
Schuman, G. E., H. H. Janzen and J. E. Herrick. 2002. Soil carbon dynamics and potential carbon sequestration by rangelands. *Environmental Pollution* 116: 391–96.
Sohngen, B. and R. Mendelsohn. 2002. Optimal forest carbon sequestration. Working Paper, Ohio State University.
West, T. O. and W. M. Post. 2002. Soil organic carbon sequestration rates as influenced by tillage and crop rotation: A global data analysis. *Soil Science Society of America Journal* 66: 1930–46.

APPENDIX

Table A.1. Mitigation strategies in FASOMGHG

		Greenhouse gas emission effect		
Mitigation strategy	Data source/reference	CO_2	CH_4	N_2O
Existing forest stand	FASOM	–[a]		
Reforestation	FASOM	–		
Deforestation	FASOM	+		
Afforestation/timberland	FASOM	–		
Biofuel production	POLYSIS analysis, GREET model, EPIC model	–	–	+
Crop mix alteration	EPIC model	+/–	+/–	+/–
Rice acreage reduction	EPA		–	
Crop fertilizer rate reduction	EPIC model, IMPLAN software	+/–		–
Other crop input alteration	USDA data	+/–		
Crop tillage alteration	EPIC model	+/–		+/–
Grassland conversion	EPIC model	–		
Irrigated/dry land conversion	Ag-census	+/–		+/–
Livestock management	EPA data, IPCC		+/–	
Livestock herd size alteration	EPA data, IPCC		+/–	+/–
Livestock production system substitution	EPA data, IPCC		+/–	+/–
Liquid manure management	EPA data, IPCC		–	

[a]A negative sign refers to a GHG emission offset and a positive sign refers to a GHG emission increase.
Source: Adams et al (1996) and McCarl and Schneider (2001).

Simplified Mathematical Presentation of FASOMGHG

(1) Objective function of FASOMGHG

$$\begin{aligned}
\text{Max } W = \sum_t (1+d)^{-t} \Bigg\{ \Bigg[& \sum_i \int F\varphi_i(FQ_{i,t})\, dFQ_{i,t} \\
& + \sum_{i,r} FE\varphi_{i,r}(FEX_{i,r,t})\, dFEX_{i,r,t} \\
& - \sum_{i,r} FI\varphi_{i,r}(FIM_{i,r,t})\, dFIM_{i,r,t} \\
& + FT \sum_r (FS_{r,t} - FS_{r,t-1}) \Bigg] \\
& + N \Bigg[\sum_i \int A\varphi_i(AQ_{i,t})\, dAQ_{i,t} - \sum_r \sum_j AC_{r,j,t} AX_{r,j,t} \\
& + \sum_{i,c} E\varphi_{i,c} \left(\sum_{c'} AEX_{i,c,c',t} \right) d \left(\sum_{c'} AEX_{i,c,c',t} \right) \\
& - \sum_{i,c} I\varphi_{i,c} \left(\sum_{c'} AIM_{i,c,c',t} \right) d \left(\sum_{c'} AIM_{i,c,c',t} \right) \\
& - \sum_{r,n} M_{r,n,t} \times MC_n + \sum_{s,g} T_g \times (TS_{s,g,t} - TE_{s,g,t}) \Bigg] \Bigg\} \\
+ (1+d)^{-T} \frac{TI}{(1+d)^{10} - 1}
\end{aligned}$$

(2) Existing forest inventory

$$\sum_{ot} EX_{ot,a,r,c,m} \leq IEX_{a,r,c,m} \quad \forall\, a, r, c, m$$

(3) Forest land balance

$$\begin{aligned}
& -\sum_{a,m} EX_{t,a,c,r,m} + \sum_{ot,w,m|(ot=t)} N_{w,ot,r,c,m,t} - \sum_{w,m,ot|(w+ot-1=t)} N_{w,ot,r,c,m,t} \\
& + \sum_l (TA_{c,l,r,t} - FA_{c,l,r,t}) = -LO_{c,r,t} \quad \forall\, t, c, r
\end{aligned}$$

(4) Transferable forest land limitation

$$\sum_{l,ot|(ot\leq t)} (TA_{c,l,r,ot} - FA_{c,l,r,ot}) \leq FL_{c,r} \quad \forall\, t, c, r$$

(5) Forest product balance

$$-\sum_{a,r,c,m} OY_{t,a,r,c,m,i} \times EX_{t,a,r,c,m} - \sum_{w,ot,r,c,\,m|(w+ot-l=t)} NY_{w,r,c,m,i} \times N_{w,ot,r,c,m,t,i} + FQ_{i,t} \leq 0 \quad \forall\, t, i$$

(6) Forest carbon stock accounting

$$\sum_{ot,a,c,m} OC_{ot,a,r,c,m,t} \times EX_{ot,a,r,c,m} + \sum_{ot,w,c,m} NC_{t,ot,w,r,c,m} \times N_{w,ot,r,c,m,t} = FS_{r,t} \quad \forall\, t, r$$

(7) Agricultural land balance

$$\sum_{tl} CP_{t,r,l,tl} - \sum_{c,ot|(ot\leq t)} (FA_{c,l,r,ot} - TA_{c,l,r,ot}) \leq LA_{r,l} \quad \forall\, t, r, l$$

(8) Transferable agricultural land limitation

$$\sum_{l,ot|(ot\leq t)} (FA_{c,l,r,ot} - TA_{c,l,r,ot}) \leq AL_{r,c} \quad \forall t, r, c$$

(9) Agricultural resource constraints

$$\sum_{j} (A_{r,j,k,t} \times AX_{r,j,t}) - R_{r,k,t} \leq 0 \quad \forall\, t, r, k$$

(10) Production balance constraints

$$AQ_{i,t} - \sum_{r}\sum_{j} (B_{r,i,j} \times AX_{r,j,t}) + \sum_{c,r} AIM_{i,c,r,t} - \sum_{c,r} AEX_{i,c,r,t} \leq 0 \quad \forall\, t, i$$

(11) Agricultural commodity export balance

$$\sum_{c'} AIM_{i,c,c',t} - S_{c,i,t} \leq 0 \quad \forall\, t, c, i$$

(12) Agricultural commodity import balance

$$-\sum_{c'} AEX_{i,c',c,t} + D_{i,c,t} \leq 0 \quad \forall\, t, c, i$$

(13) Agricultural emission account

$$\sum_{r,j} (E_{r,j,s,g,t} \times X_{r,j,t}) = TE_{s,g,t} \quad \forall\, s, g, t$$

(14) Agricultural emission offset account

$$\sum_{r,j} (S_{r,j,s,g,t} \times X_{r,j,t}) = TS_{s,g,t} \quad \forall\, s, g, t$$

where

W = objective,
d = discount rate,
$F\varphi_i(^*)$ = inverse demand function for timber product i,
$FQ_{i,t}$ = forest product i demand at time t,
$FE\varphi_{i,r}(^*)$ = inverse forest export demand function for timber product i, in region r,
$FEX_{i,r,t}$ = forest product i export from region r at time t,
$FI\varphi_{i,r}(^*)$ = inverse forest import supply function for timber product i, in region r,
$FIM_{i,r,t}$ = forest product i import to region r at time t,
FT = price of per unit forest carbon sequestration,
$FS_{r,t}$ = forest carbon stock in region r at time t,
N = factor to convert annual agricultural value to decadal basis,
$A\varphi_i(^*)$ = inverse demand function for agricultural product i,
$AQ_{i,t}$ = agricultural product i produced at time t,
$AC_{r,j,t}$ = cost of agricultural production activity j in region r and time t,
$AX_{r,j,t}$ = agricultural production activity j in region r at time t,
$E\varphi_{i,r}(^*)$ = inverse agricultural export demand function for product i, in region r,
$AEX_{i,c,c',t}$ = agricultural product i export from country c to country c' at time t,
$I\varphi_{i,r}(^*)$ = inverse agricultural import supply function for product i, in region r,
$AIM_{i,c,c',t}$ = agricultural product i import from country c to c' at time t,
MC_n = cost of manure management for animal n,
T_g = price of per unit emission/offset for different strategy gas g,
T = last explicit time period,
TI = terminal value,
$EX_{ot,a,r,c,m}$ = existing forest stand at the beginning of modeling period with cohort age a, region r, land class c, management m, and harvested at time ot,
$IEX_{a,r,c,m}$ = initial forest inventory at the beginning of the modeling period at age a, region r, land class c, and management m,
$N_{w,ot,r,c,m,t}$ = new timber stand at time t planted in time ot, region r, land class c, management m, harvested w decades after planted,
$TA_{c,l,r,t}$ = land convert to agricultural use in land class c, land type l, region r, and time t,
$FA_{c,l,r,t}$ = land converted from agriculture in land class c, land type l, region r, and time t,
$LO_{c,r,t}$ = land converted to urban in land class c, region r, and time t,
$FL_{c,r}$ = available land converted to agricultural use in region r and land class c,
$OY_{t,a,r,c,m,i}$ = product i yield of existing forest stand harvested at time t in region r, land class c, management m, when cohort age a at the beginning of the modeling period,
$NY_{w,r,c,m,i}$ = product i yield of new forest stand w decade after planted in region r, land class c, and management m,
$OC_{ot,a,r,c,m,t}$ = carbon yield of per acre land in existing forest stand at time ot when cohort age a at the beginning of the modeling period and harvested w decades afterward, in region r, land class c, and management m,

$NC_{t,ot,w,r,c,m}$ = carbon yield of per acre land in newly planted forest stand at time t period, when planted at time ot, harvested w decades later, in region r, land class c, and management m,
$FS_{r,t}$ = forest carbon stock in region r and at time t,
$LA_{r,l}$ = available agricultural land in region r, land type l,
$AL_{r,c}$ = limit on land moved from agriculture in region r and land class c,
$A_{r,j,k,t}$ = per acre factor k used in production activity j in region r at time t,
$R_{r,k,t}$ = resource k available in region r at time t,
$B_{r,i,j}$ = per acre yield of commodity i using production activity j in region r,
$S_{c,i,t}$ = country c excess supply of commodity i at time t,
$D_{i,c,t}$ = country c excess demand of commodity i at time t,
$E_{r,j,s,g,t}$ = per acre GHG g emission from source s in region r, activity j, and time t,
$X_{r,j,t}$ = average in production activity j in region r and time t,
$TE_{s,g,t}$ = total emission of GHG g from source s at time t,
$S_{r,j,s,t}$ = per acre GHG g emission offset from source s in region r, activity j, and time t,
$TS_{s,g,t}$ = total emission reduction of GHG g from source s at time t.