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Economic Potential of Greenhouse Gas Emission Reductions: Comparative Role for Soil Sequestration in Agriculture and Forestry

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Abstract

We use the Agricultural Sector Model to analyze the economic potential of soil carbon sequestration as one of several agricultural greenhouse gas emission mitigation strategies, including afforestation. For low incentives on carbon emission savings, agricultural soil carbon sequestration is the most cost-efficient strategy. As incentive levels increase above $50 per ton of carbon equivalent, afforestation and biofuel production become the key strategies, while the role of soil carbon diminishes. If saturating sinks are discounted based on their net present value, the competitive economic equilibrium among agricultural mitigation strategies shifts away from soil carbon sequestration and afforestation and toward more biofuel production. Regardless of the discounting assumption and the carbon savings incentive level, the economic potential of soil carbon sequestration never attains its technical potential as estimated by soil scientists. The study also estimates the impacts of agricultural mitigation policies on welfare, prices, production, and input use in the traditional food and fiber sector and the effects of emission leakage from unregulated agricultural sources.

Key words: afforestation, Agricultural Sector Model, carbon sequestration dynamics, economic potential, emission leakage, greenhouse gas emission mitigation, sink saturation, technical potential, volatility.

ECONOMIC POTENTIAL OF GREENHOUSE GAS EMISSION REDUCTIONS: COMPARATIVE ROLE FOR SOIL SEQUESTRATION IN AGRICULTURE AND FORESTRY

Introduction

Many in society today are expressing concerns about the implications of the build-up in atmospheric concentrations of greenhouse gases. Alterations in agricultural and forestry (AF) land use and/or management provide a prospective way of mitigating net greenhouse gas (GHG) emissions. A number of AF practices are known to stimulate the absorption of atmospheric carbon or reduce GHG emissions at relatively modest cost with generally positive economic and environmental effects. Thus, an investigation of the comparative role for AF mitigation-based practices in terms of economic implications appears to be in order.

AF practices partially involve sequestration and merit special consideration from that viewpoint. Sequestration involves capture of GHGs biologically or through industrial processes (e.g., by separating GHGs from fuels). GHGs are then fixed biologically or through industrial injection into soils, aquifers, oceans, or geological formations. AF sequestration generally refers to the absorption of carbon dioxide from the atmosphere through photosynthetic processes by plants or trees and subsequent fixation into soils, plants, or trees. Thus, sequestration involves absorption of previously emitted gases and subsequent storage. Sequestration activities exhibit saturation where storage reservoirs fill up due to physical or biological capacity. They also generally store carbon in a potentially volatile state. For example, cutting down a forest or plowing up the soil for intensive farming quickly releases much of the sequestered carbon. Program costs involve development and operation costs, as well as maintenance costs to keep the carbon sequestered, possibly even after achieving saturation. Comparison of the relevant role of sequestration considering these characteristics is another research need.

Objective

This paper examines the relative contribution of AF activities in an emission reduction program, focusing in part on the relative desirability of sequestration in forests and agricultural soils. We consider the effects of competition for land and other resources between AF activities and traditional production. In addition, we provide analysis on the influence of saturation and volatility.

Approach

We take a two-pronged approach in this analysis. First, following McCarl and Schneider 2001, we use AF sector modeling to develop information on the marginal abatement cost curve, describing the volume of GHG emission offsets at different farmer-received carbon prices (i.e., market prices less brokerage fees and other transactions costs) and ignoring saturation and volatility. We conduct that analysis in the context of the total spectrum of U.S-based AF responses to a net greenhouse gas mitigation effort. In particular, we investigate the role of AF sequestration efforts in the total portfolio of potential agricultural responses at alternative carbon price levels. Table 1 identifies the strategies considered. Definitions of those strategies and the characteristics of the underlying model are summarized in the next section.

Second, following McCarl and Murray 2001, we use a dynamic net present value framework to investigate the question of how a firm having to buy emission credits for the foreseeable future might factor in sequestration saturation and volatility to the prices it would be willing to pay for sequestration offsets. In turn, we use the sector modeling methodology to investigate the implications for the role of soil carbon sequestration in a total AF mitigation effort.

Project Description: Sector Modeling

The basic approach used for comparing the relative desirability of alternative mitigation strategies involves estimation of the amount of GHG net emission reduction supplied in U.S. AF sectors and the choice of strategies under alternative carbon prices. The analytical framework employed had to be capable of looking at the induced adoption of the mitigation strategies listed in Table 1, as well as the complex interrelated nature of

TABLE 1. Mitigation strategies included in the analysis

Strategy	Basic Nature	Greenhouse Gas Effected CO_2	Greenhouse Gas Effected CH_4	Greenhouse Gas Effected N_2O
Afforestation / timberland management	Sequestration	X		
Biofuel production	Offset	X	X	X
Crop mix alteration	Emission, sequestration	X		X
Crop fertilization alteration	Emission, sequestration	X		X
Crop input alteration	Emission	X		X
Crop tillage alteration	Emission	X		X
Grassland conversion	Sequestration	X		
Irrigated/dry land conversion	Emission	X		X
Livestock management	Emission		X	
Livestock herd size alteration	Emission		X	X
Livestock production system substitution	Emission		X	X
Manure management	Emission		X	
Rice acreage	Emission		X	

activities in the AF sectors. For example, use of a mitigation strategy could alter corn production and corn prices, which in turn could impact exports, livestock diets, livestock herd size, and manure production, as well as land allocation to biofuels and forests. To capture these and other interactions, we use the Agriculture Sector Model (ASM) (McCarl et al. 2000b; Chang et al. 1992), a mathematical programming-based, price-endogenous model, modified by Schneider (2000) to include GHG emissions accounting, and hereafter called ASMGHG. It also is expanded to include data from a forestry sector model (Adams et al. 1996; Alig, Adams, and McCarl 1998). ASMGHG depicts production, consumption, and international trade in 63 U.S. regions of 22 traditional and 3 biofuel crops, 29 animal products, and more than 60 processed agricultural products. Environmental impacts include levels of greenhouse gas emission or absorption for carbon dioxide, methane, and nitrous oxide; surface, subsurface, and ground water pollution for nitrogen and phosphorous; and soil erosion. ASMGHG simulates the market and trade equilibrium in agricultural markets of the United States and 28 major foreign trading partners. Domestic and foreign supply and demand conditions are considered, as are regional production conditions and resource endowments. The market equilibrium reveals commodity and factor prices, levels of domestic production, export, and import quantities, GHG emissions management strategy adoption, resource usage, and environmental impact indicators. ASMGHG was then repeatedly solved for carbon prices ranging from $0 to $500 per ton of carbon equivalent. The 100-year global warming potentials of 1 for carbon dioxide, 21 for methane, and 310 for nitrous oxide were used to convert methane and nitrous oxide emissions to carbon dioxide equivalency. In turn, the estimates were multiplied by 12/44 to convert them from a carbon dioxide equivalent to a ton carbon equivalent.

Mitigation Strategy Overview

Agricultural practices are complex and heterogeneous. An understanding of the basic nature of the mitigation strategies and their underlying assumptions is important in order to compare the role of the agricultural and forestry sector in the whole portfolio of sequestration efforts. In what follows, we briefly summarize data and assumptions for all greenhouse gas emission mitigation strategies that are included in ASMGHG. Schneider (2000) provides a detailed technical description.

Afforestation and Timberland Management

Forest-based carbon sequestration can be stimulated by afforesting agricultural lands, increasing rotation length, or changing management intensity through improved silvicultural practices. The data for the forest sequestration increase were developed using the Forest and Agricultural Sector Optimization Model (FASOM) (Adams et al. 1996; Alig, Adams, and McCarl 1998). FASOM was solved repeatedly under alternative prices ranging from $0 to $400 per ton of carbon equivalents. For each FASOM solution, we computed and exported into ASMGHG the average annual sequestration rate over the first 30 years of the program (2000-2030) and the associated net land transfer from agriculture to forestry. The underlying data reflect regionally specific conversion of crop and pasture lands to and from forested land as well as rotation and management changes.

Biofuel Production

Offsets of GHG emissions from fossil fuel usage were examined by considering substitution of biofuels for fossil fuels. In particular, we incorporated poplar, switchgrass, and willow for fueling electrical power plants, and cornstarch for conversion into ethanol. Information on the production and conversion alternatives were drawn from a joint U.S. governmental department study of biofuels as elaborated on in McCarl et al. 2000a. The emission savings were computed in British thermal units, assuming biomass substitution for coal in power plants and ethanol substitution for gasoline. In estimating emissions offsets, the emissions accounting was the savings from not using traditional fossil fuels less the emissions from the energy involved in raising, hauling, and processing the biofuels.

Crop Fertilization Alteration

Nitrous oxide emissions are a by-product of nitrogen fertilization. In turn, nitrogen fertilization also influences carbon sequestration rates. We examined altered fertilization practices using data on crop yield response and resultant carbon sequestration rates. These data were developed via a crop simulation model, as described in a following crop tillage section. We used the Intergovernmental Panel on Climate Change (IPCC) good practice inventory guidelines to estimate nitrous oxide emissions per unit of fertilizer applied. These formulas released about 1.25 percent of applied nitrogen as nitrous oxide.

Crop Input Alteration

A number of the inputs used in crop production are fossil fuel-based or embody substantial GHG emissions in their manufacture. Carbon content estimates, including upstream manufacturing carbon emissions, were incorporated in the analysis for diesel, gasoline, natural gas, electricity, and fertilizers, using the IPCC good practice guidelines. Thus, changes in practices such as crop mix, crop management, and livestock numbers alter input use and resultant emissions patterns.

Crop Mix Alteration

Not all crops emit equally because of differences in fertilizer applied, tillage practices, chemical inputs, harvest requirements, irrigation intensities, and post-harvest processing, among other factors. In this study, we included both direct emissions from these activities and indirect emissions from the involved inputs. As a result, carbon dioxide, nitrous oxide, and methane emissions are affected by crop mix choices.

Crop Tillage Alteration

Energy intensity and soil carbon content are sensitive to choice of tillage method. The analysis considered implications of using conventional tillage, minimum tillage, and no tillage. Emission estimates for soil carbon increments were derived from a simulation study with 63 regions, 10 crops, and 5 soil types using the EPIC crop growth simulator (Williams et al. 1989). The carbon sequestration rates pertaining to tillage changes were the average results for the first 30 years of the program (2000-2030), adjusted to be consistent to an annual 75 million metric tons (MMT) from treating all U.S. croplands for sequestration, as developed in Lal et al. 1998 (which actually developed a range from 75 to 200+ MMT). Estimates were also developed on emissions from fossil fuels used to carry out the alternative tillage systems, and an altered mix of chemical inputs were applied based on production budgets from the U.S. Department of Agriculture (USDA), Natural Resource Conservation Service.

Grassland Conversion

Reversion of cropland back to grassland is another mitigation strategy that is considered. Such a reversion generally increases soil carbon and in addition affects nitrous oxide emissions by displacing fertilizer used in crop production.

Irrigated and Dry Land Conversion

Alterations in the allocation of land between irrigated and dry land usage affects soil carbon, nitrous oxide emissions, and fossil fuel use needed for water delivery and other crop production and requirements.

Livestock Management

Methane emissions per unit of product produced may be influenced by giving growth hormones to animals or by increasing the use of grain relative to forage in feeding. Growth hormone–based alternatives were incorporated based on Environmental Protection Agency (EPA) data (EPA 1998). Feed substitution was also embodied in the choice of livestock production system, as discussed in that section.

Livestock Herd Size Alteration

Livestock produce methane and nitrous oxide as a function of the total size of the livestock herd through manure and ruminant enteric fermentation. Thus, a simple mitigation alternative is to cut the size of the total herd.

Livestock Production System Substitution

Mitigation may be pursued by substituting livestock production systems for one another. In the case of beef cattle, slaughter animals can be produced using either stocker or feedlot operations. The relative GHG emission rate varies across these alternatives; for example, feedlot production has lower per unit emissions.

Manure Management

Manure is a source of methane and nitrous oxide. The manure handling system can influence emissions. For example, methane emissions are greater when more water is involved in the system, but methane recovery systems also can be employed. For this analysis, we incorporated data on methane emissions from liquid manure handling alternatives by region and by livestock type based on EPA data (EPA 1998).

Rice Acreage

Decomposition of plant material in flooded rice fields leads to methane emissions. While alternative management systems may affect the amount of methane released, no consistent data were currently available. Thus, the only rice-related mitigation alternative examined here involves reductions in acreage.

Results: Sector Modeling

Scientific evidence and the number of inquiries regarding AF GHG mitigation are growing rapidly. The data underlying this study, while the best available to us as at this time, will soon be obsolete. Consequently, we will not concentrate on specific empirical results. Instead, we will highlight a set of general findings that we believe are highly relevant to consideration of the appropriate role for AF sequestration and, to the extent possible, that rise above the flaws in the underlying data.

Agricultural and Forestry Emissions Offsets

Figure 1 shows the amount of carbon offsets gained at carbon prices ranging from $0 to $100 by broad category of strategy. Note in those results that up to 326 MMT carbon equivalents can be offset by AF means (Table 2). Low-cost strategies involve foremost soil carbon sequestration and, to some extent, afforestation, fertilization, and manure management. To place these costs in perspective, one should note Weyant and Hill's (1999) report of a multimodel study of nonagricultural Kyoto compliance costs sponsored by the Energy Modeling Forum. As shown in the Forum's set of studies, abatement costs vary because of different assumptions on emissions trading and different baseline emissions scenarios across models. For the case of the United States with carbon emissions trading among Annex I regions, primarily with the developed industrial countries along with eastern Europe and the former Soviet Union, abatement costs were generally in the range of $50 to $100 per metric ton of carbon but went as high as $227. See MacCracken et al. 1999 for an example of the range of abatement costs that can be derived within one model. Marginal abatement costs are much higher without international trade in carbon emissions rights.

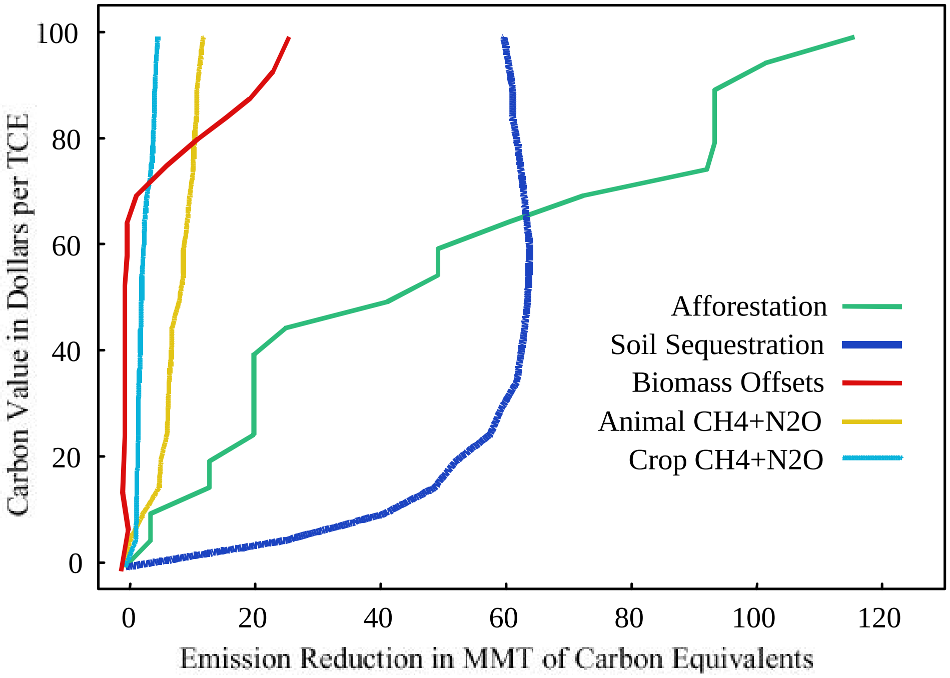

FIGURE 1. Agricultural mitigation potential at $0 to $100 per ton carbon equivalent prices

TABLE 2. Results at selected carbon price scenarios

Category Subcategory	Unit	Carbon Equivalent Price in $/Metric Ton C 10	20	50	100	200	500
Strategy							
Soil carbon	1000 TCE	52,771	63,148	60,341	51,060	44,967	44,163
Afforestation	1000 TCE	13,445	20,619	116,361	183,191	192,893	192,947
Biomass	1000 TCE	0	0	26,154	61,020	105,045	113,456
Fossil fuel ag-inputs	1000 TCE	4,285	6,696	10,156	12,433	14,971	15,807
Livestock related	1000 TCE	5,674	7,390	12,462	13,989	16,547	19,443
Crop noncarbon	1000 TCE	1,959	2,427	5,304	9,081	12,239	13,003
GHG emission mitigation							
C	MMT C	71.26	91.81	216.14	309.3	356.7	364.61
CH_4	MMT CH_4	0.78	1.02	1.89	2.39	3.07	3.50
N_2O	MMT N_2O	0.04	0.05	0.09	0.14	0.18	0.20
CE	MMT CE	79.11	101.98	235.31	334.11	389.09	400.94
Market effects							
Production	Fisher Index	99.81	98.74	91.20	77.77	67.73	65.37
Prices	Fisher Index	100.65	102.41	118.81	155.93	222.07	261.01
Ag-sector welfare	Billion $	-0.45	-0.90	-5.65	-15.33	-29.79	-35.05
Net exports	Fisher Index	99.17	96.11	74.26	35.33	25.58	22.81
Other externalities							
Nitrogen pollution	% Change	2.10	3.63	-6.26	-21.47	-34.65	-37.40
Phosphorous pollution	% Change	-43.35	-49.02	-52.93	-53.61	-58.15	-60.54
Erosion	% Change	-35.04	-41.28	-49.70	-55.62	-61.23	-63.27

An Agricultural and Forestry Portfolio Solution

Today there are many different GHG emission-mitigating agricultural strategies under consideration, and often individual strategies are advocated. Our results show that a portfolio solution appears to be appropriate. Figure 2 shows the total response of mitigation over the total range of carbon prices. The results show a role for strategies based on biofuels, forests, agricultural soils, methane, and nitrous oxide. The figure also shows that different strategies take on different degrees of relative importance depending on price level. While soil carbon sequestration peaks at around $50 per ton, biofuel offsets are not competitive for prices below $60 per ton. Reliance on individual strategies appears to increase costs. For example, reliance solely on agricultural soil carbon

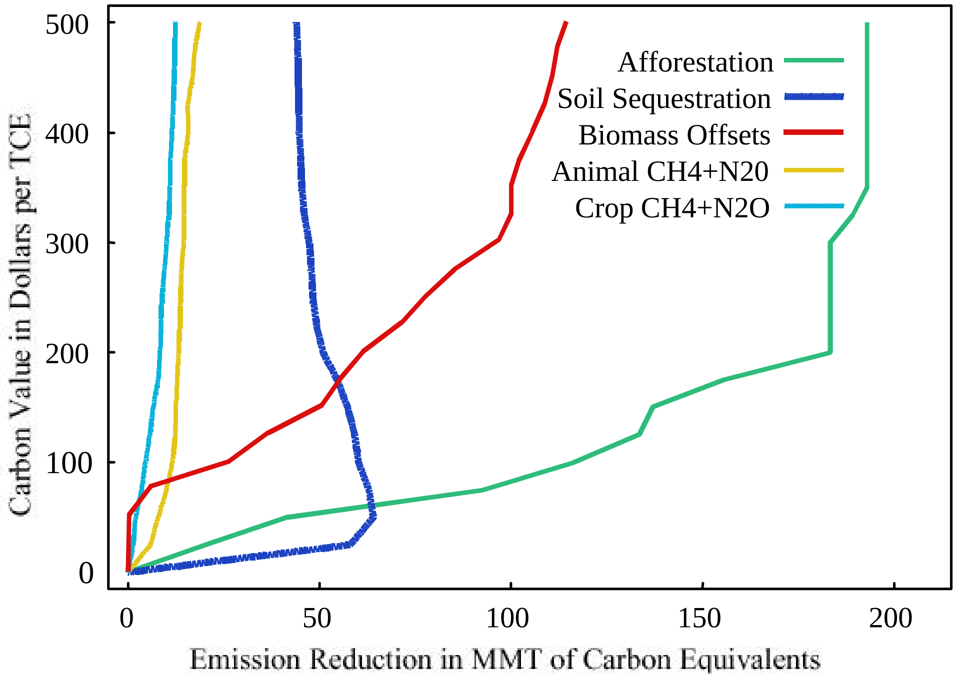

FIGURE 2. Agricultural mitigation potential at $0 to $500 per ton carbon equivalent prices

(economic potential line of Figure 3) means it would cost $30 to achieve 60 MMT while consideration of the total portfolio leads to a cost below $15 per ton (Table 2).

Technical, Economic, and Competitive Economic Potential

Many of the estimates for the potential of selected strategies ignore cost and resource competition. Lal et al., for example, compute a total agricultural soil carbon (ASC) potential but do not specify the cost of achieving such a potential level of sequestration. Figure 3 displays ASC technical, economic, and competitive economic potential. The total technical potential in this case is 75 MMT annually, but under reliance only on ASC this does not occur even for prices as high as $500 per ton. At lower prices, substantially less carbon is sequestered. Furthermore, when ASC strategies are considered simultaneously with other strategies, the carbon price ($500 per ton) stimulates, at most, 64 MMT or 87 percent of maximum potential, while sequestration falls to 50 MMT (67 percent) at $200 because other strategies are more efficient at that payment level.

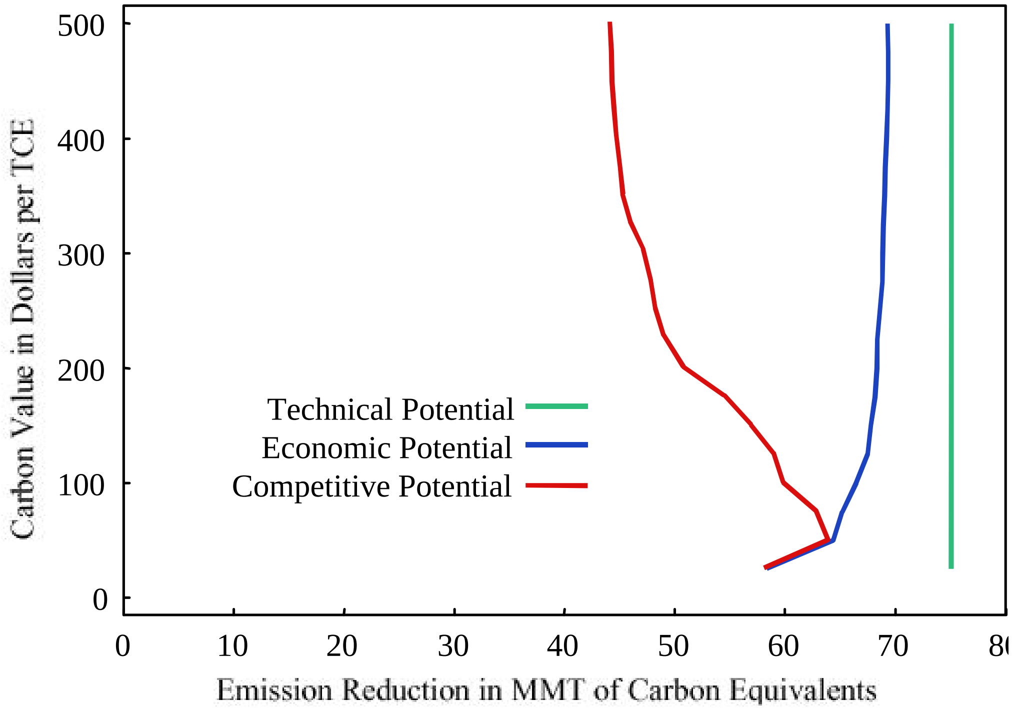

FIGURE 3. Technical, sole source economic, and competitive economic potential of agricultural soil carbon sequestration on U.S. croplands

Strategy Leakages

Figure 4 shows the relationship between the increase in forest-based offsets and emissions in the rest of the AF sector. The results indicate that for a case of afforestation accounting only, the anticipated gains in forestry are in some cases augmented and in other cases offset by emissions in the rest of the AF sectors. This more complex relationship occurs because land moving out of agriculture and into forests places pressure on the remaining cropland, intensifying production in terms of irrigation, tillage, and fertilization. Thus, we find more emission-intensive technologies on fewer acres of agricultural cropland. Leakage also occurs in forestry, where the underlying FASOM results show up to a 50 percent offset, largely from traditional forestland moving into agriculture or from reduced management intensity (McCarl 1998 shows such results).

Mitigation-Based Offsets Competitive with Food and Fiber Production

Achieving net GHG emission offsets requires that AF operations change. Many of the strategies divert land or inputs away from crop or possibly timber production. On the

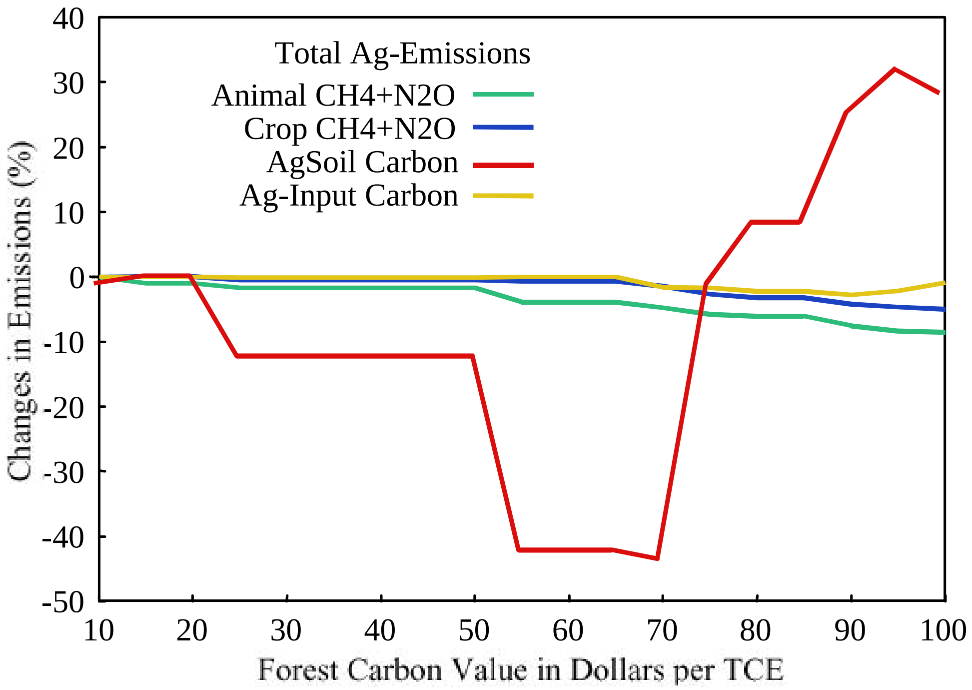

FIGURE 4. Gross and net mitigation of sole reliance on forestry-related strategies

agricultural side, Table 2 shows that crop prices generally rise the more mitigation is undertaken while production falls.

Exports also are strongly affected. On the forestry side, afforestation can cause price declines if the rotation of harvested stands lengthens. At higher carbon prices, increasing land competition among strategies leads to increased afforestation and biofuel usages of croplands but reduced agricultural soil sequestration.

Mitigation Strategies and the Environment

Many of the proposed agricultural mitigation actions (tillage intensity reduction, manure management, land retirement, etc.) have long been discussed as strategies that simultaneously improve environmental quality. Consequently, one may expect benefits, such as erosion control and runoff, to be created simultaneously with emissions abatement. Table 2 shows changes in a few selected environmental parameters as carbon equivalent prices increase. For the most part, these results confirm declining rates of nitrogen and phosphorous runoff as well as reduced erosion. However, reliance on biofuels causes the environmental co-benefits largely to stabilize at prices around $200 per ton.

Project Description: Saturation and Volatility

Yet another question regarding sequestration involves the way a decisionmaker might view AF sequestration relative to, say, an emissions reduction, given the opportunity to buy one or the other. To investigate this question, we use net present value analysis to find the break-even carbon price a decisionmaker would be willing to pay for nominally equal cost and carbon potential sequestration and emission offset opportunities. In so doing, we follow the work of McCarl and Murray (2001).

The basic procedure involves the evaluation of the price for carbon that renders the net present value of a stream of carbon equivalent offsets equal to program costs. Specifically, we solve the following equation for the break-even carbon price p:

$$\sum_{t=0}^{T} (1+r)^{-t} p\ E_t = \sum_{t=0}^{T} (1+r)^{-t} C_t ,$$

where r is the discount rate and is assumed to be 4 percent, T the number of years in the planning horizon and is assumed to be 100, p is a constant real price of emission offsets, E_t is the emissions offset in year t, and C_t is the cost of the emissions offset program in year t. Then, by comparing prices for different possibilities, we can determine the effect of saturation and volatility.

Results: Saturation and Volatility

For illustrative purposes, we consider three hypothetical cases that allow comparison of relative carbon prices by opportunity. McCarl and Murray (2001) consider many more.

Case A: Emissions Offset. Suppose an emission offset can be obtained which annually offsets one unit of carbon for the full 100 years at a cost of one monetary unit (e.g., one dollar) per year. The break-even price for this is one unit ($1 per unit of carbon).

Case B: Saturating Agricultural Soil Carbon. Consider an agricultural soil carbon case that sequesters an average amount of one carbon unit per year but then saturates after 20 years consistent with the findings in West et al. If payments stop after 20 years, the carbon-preserving practice ceases, releasing (volatilizing) the carbon into the atmosphere over the next 3 years. Given these characteristics we find a break-even price of 2.64 units. Alternatively, if the practice is subsidized for the remaining 80 years, this price amounts to 1.80. This implies that the saturating/volatile soil carbon is worth between 36 percent and 55 percent of the emissions offset.

Case C: Forest Carbon. Carbon in forests will saturate after trees reach maturity in about 80 years. The sequestered carbon is volatile because the trees may be harvested, releasing soil and standing tree carbon, but also placing carbon into products that provide longer-term storage or fuel offsets. A forest reserve that sequesters a unit for 80 years costing one monetary unit has a break-even price of 1.02 or just a 2 percent discount. A 20-year harvest pattern for pulpwood stands with fuel credits counted leads to prices in the range of 65-70 percent of emissions while a 50-year saw timber stand comes out at 85-87 percent. Other cases in McCarl and Murray (2001) are as low as 51 percent.

For illustrative purposes, we then reran the sector-modeling framework but multiplied the price applied to carbon from tillage changes on agricultural soils by 0.50 and that from forests by 0.75. In turn, the total portfolio of options (Figure 5) chosen shifted, with agricultural soil and forestry shares declining. The agricultural soil maximum fell by about 55 percent while the forestry share adjusted down by 48 percent.

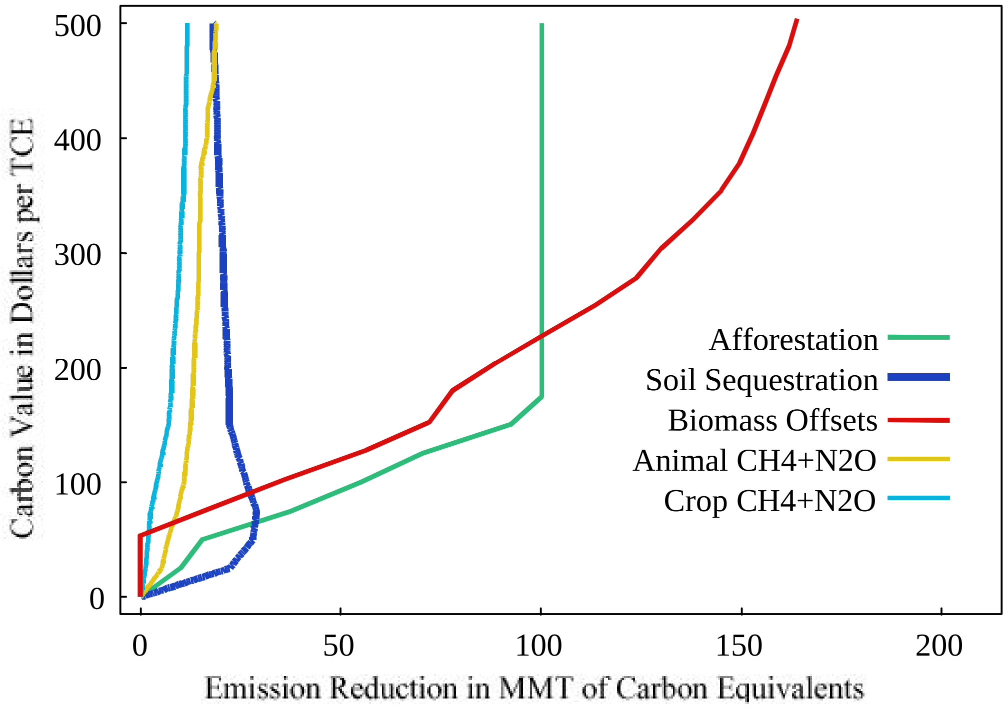

FIGURE 5. Agricultural mitigation potential at $0 to $500 per ton carbon equivalent prices when saturation and volatility are accounted for by price discounts

Application

Agricultural and forest carbon sequestration are important components of a possible total societal response to a greenhouse gas emission reduction initiative. Our analysis shows that determination of their appropriate role depends upon the carbon price. At low prices, agricultural soil sequestration appears highly competitive, but saturation and volatility will likely lead to price discounts. Forest-based sequestration and biomass offsets gain in importance at higher carbon prices.

Future Activities

We plan to accomplish more work along these lines to bolster the data underlying the sector model and to further investigate the role of sequestration in a situation where carbon prices change over time.

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