The Role of Agriculture in Climate Change: A Preliminary Evaluation of Emission Control Strategies[*]

Richard M. Adams, Ching-Cheng Chang, Bruce A. McCarl,
and John M. Callaway[**]

Introduction

Agricultural productivity is of obvious importance to human welfare. Climate is a major determinant of both the location and productivity of agricultural enterprises. It is thus not surprising that agriculture has been identified as an area of concern in the current public debate on the causes and effects of climatic change. Indeed, agriculture has been the central focus of several studies dealing with potential effects of climatic change [Decker et al.; Sonka and Lamb; Rosenzweig; Smith and Tirpak].

Most studies to date have evaluated the sensitivity of various dimensions of agricultural activity to climate change, including yields, input use and locational (geographic) patterns. The economic implications of such potential sensitivities have also been explored [Dudek, Adams et al.; Kane et al.]. The results of these economic evaluations, while preliminary, suggest that climate change is not a food security issue,

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[**] Richard M. Adams is Professor, Department of Agricultural and Resource Economics, Oregon State University; Ching-Cheng Chang and Bruce McCarl are Visiting Assistant Professor and Professor, respectively, Department of Agricultural Economics, Texas A&M University, College Station, TX 77843; John Callaway is Senior Economist, Battelle pacific Northwest Laboratory, Richland, Washington.

although substantial regional adjustments are likely.

On a worldwide scale, the agricultural sector is more than a receptor of possible climatic changes arising from anthropogenic trace gas emissions; it is also a source of trace gases, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The understanding of agriculture's contributions to trace gas emissions has increased considerably over the last decade. This has lead to a number of potential strategies to reduce such emissions. In addition, there is growing interest in the use of agricultural land as a potential sink for carbon through the establishment of forest plantations [Marland; Lashof and Tirpak; Moulton and Richards; Sedjo and Solomon; Dudek and Leblanc]. Several studies have suggested that tree plantations on marginal agricultural lands may be a relatively cost effective means of slowing the buildup of greenhouse gases. Such tree planting or "carbon-growing" activities have also recieved considerable political interest as an alternative to carbon taxes or "command and control" strategies.

Objectives

There are few economic evaluations of the costs to agricultural producers and consumers of strategies to reduce CH_4, CO_2 and N_2O emissions from agriculture. To the extent that reduction of these residuals implies changes in management, including reduced use of current inputs such as nitrogen fertilizer and certain types of feed rations for livestock, such strategies imply rising per unit costs, at least in the short run. While forest plantations on agricultural lands to sequester carbon have been the subject of economic analyses [Sedjo and Solomon; Dudek and Leblanc] most studies to date have not included the opportunity cost of converting large areas of agricultural lands to tree plantations. Large shifts in agricultural land use suggest reduced agricultural output and rising commodity prices. The associated welfare losses to consumers need to be considered.

The overall objective of the research reported here is to perform a preliminary economic evaluation of the social costs of selected strategies to reduce trace gas emissions from agriculture and to sequester carbon in tree plantations. These strategies are intended to reduce CH_4 emissions from livestock and rice production, reduce N_2O emissions from crop production and to increase through reforestation the amount of carbon sequestered in agricultural lands. In presenting this information we include 1) a review of the role of agriculture in trace gas emissions; 2) a discussion of strategies to reduce such emissions; 3) a quantification (in dollars per metric ton) of the costs of reducing agricultural trace gases using specific strategies and 4) an evaluation of the costs per metric ton of sequestering carbon in forest plantations on agricultural lands.

A number of caveats concerning this evaluation need to be noted. First, the empirical focus is limited to U.S. agriculture. The costs of similar strategies in the rest of the world are ignored. Second, the analysis is a comparative static evaluation of selected control strategies. The dynamic or long run adjustments to reduce emissions are likely to be different than those provided here. Thus, the results are preliminary and should be viewed more as sensitivity analyses, given the uncertainty in some key data, as noted subsequently. However, since the data used here are comparable to those in other studies, the results can be compared with existing cost estimates and suggest the importance of inclusion of some economic aspects not explicitly addressed elsewhere.

Background

The contribution of agricultural sources to total trace gas emissions varies by the individual gas and location. For example, U.S. agriculture consumes about 3 percent of total U.S. fossil fuel for on-farm production activities. If storage, dehydration and other food and fiber processing activities are added, the use in agriculture is still less than 10 percent of total U.S. fossil fuel use. Thus, emissions of CO_2 from agricultural production are a relatively small share of the approximately 1 billion metric tons of carbon produced from fossil fuel combustion in the U.S. [Darmstadter and Edmonds]. However, CO_2 released by agricultural activity on a global scale is much higher, primarily due to the clearing of tropical forests for agriculture. Such tropical deforestation may account for 1.8 billion metric tons of carbon or up to 33 percent of total annual carbon emissions from all sources [Woodwell et al.; Houghton et al.].

For other trace gases, such as CH_4 and N_2O, agriculture's role in total U.S. emissions is higher. Worldwide, agriculture is believe to account for about 55 percent of total N_2O emissions, due primarily to deforestation and to the use of nitrogenous fertilizers such as anhydrous ammonia [Cates et al.]. Up to seven percent of total N applied as anhydrous ammonia may be lost as N_2O. Agriculture also plays a role in methane (CH_4) emissions, primarily from rice production and livestock. On a global scale approximately 60 percent of total methane is believe to be due to agriculture, with 30 percent from rice production and 15 percent from livestock [Gibbs et al.]. In addition, rice area and livestock numbers, while stable in the U.S., are increasing worldwide [Gibbs et al.].

Both CH_4 and N2O are much smaller constituents of the earth's atmosphere than is CO_2. For example, CH_4 concentrations are currently 1.7 ppm in the atmosphere and N_2O is 0.3 ppm in the atmosphere, whereas CO_2 is 350 ppm. However, each molecule of CH_4 and N_2O is more radiatively active than a molecule of CO_2 (N_2O is over 200 times more active than CO_2 as a "green house" gas).

Strategies to reduce CO_2 emissions from U.S. agriculture are generally similar to those for other sectors--increase fuel efficiency or seek alternative energy sources. Strategies to reduce methane include changes in feed rations (to lower CH_4 rations) in the short run and genetic and dietary improvements in the long run [Lashof and Tirpak; Gibbs et al.]. In the short run, use of some lower CH_4 feed rations implies higher finished livestock costs. Methane emissions from rice production are due to several factors. Nitrogen fertilization is believed to be a contributing factor, as CH_4 emissions from fertilized rice fields have been found to be 3 to 5 times higher than for unfertilized fields [Cicerone and Shetter], although data from other research has not confirmed the magnitude of this differential [Matthews et al.; Yagi and Minami]. Thus, one potential strategy is to reduce nitrogen fertilization of rice. Emissions of N_2O are directly related to nitrogen fertilizer applications and global deforestation. In the U.S., reduced use of nitrogen fertilizer, particularly those easily volatilized forms such as anhydrous ammonia, could reduce N_2O emissions.

In the short term, reduced use of nitrogen fertilizer and lower CH_4 feeding systems for livestock are expected to reduce yields and/or increase costs. Such effects, in turn, suggest higher food costs and, hence, losses to consumers. In the long run, improved breeding programs for livestock, better management of nitrogen in rice and other crop production, and improved crop breeding to reduce fertilizer dependence are needed to reduce emissions.

Procedure and Data

The preceding discussion highlights some simple strategies that could be used to both reduce agriculture's contribution to the worldwide increase in CH_4, N_2O and other trace gases and to help offset increasing CO_2 emissions. This section discusses the procedure used to quantify the social costs of some of these strategies and the data and assumptions that underlie this quantification effort.

The procedure used here involves imposing the yield and cost implications of each strategy on a spatial equilibrium model of U.S. agriculture. This model is discussed in detail in Chang and McCarl and has been used in a number of related evaluations of environmental issues, including the recent Adams et al. analysis of climate change effects on agriculture. The features of this model as they apply to the current effort are: 1) the model represents the range of crop and livestock activities found in the major agricultural regions of the U.S.; 2) the model allows for changes in yields, cost, input and other parameters of interest here; 3) the model captures the effects of changes in these parameters in terms of economic welfare measures (consumer's and producer's surpluses, in total and by commodity); and 4) the model includes arable cropland as well as pasture and rangelands in the land inventory, with 143 million hectares of cropland and 352 million hectares of pasture and rangeland. This land inventory is important to the tree planting or carbon sequestering analysis.

For the purposes of these analyses, the model was expanded to include forest planting activities in each region, an issue which will be discussed in more detail subsequently. As with any programming based exercise of this type, the resulting solution generated for each analysis represents the minimum social cost of achieving the desired objective constraint within the context of the production possibilities included in the model.

To address the cost of reducing emissions of trace gases, strategies to reduce methane (from rice and livestock production) as well as nitrous oxide (from fertilizer applications) were evaluated. The first methane analysis simulates reductions in the use of nitrogen fertilizer in rice production (arbitrarily set at 50 and 100 percent). The yield implications of this reduced use of nitrogen in rice production were estimated using nitrogen response functions for rice [Hexem and Heady] which suggests 25- and 45-percent yield reductions, respectively. The changes in methane emissions associated with this reduction in rice fertilization are estimated to be 35 and 70 percent [Cicerone and Shetter]. The costs of reducing methane emissions from livestock are evaluated in two ways. In the first case, the use of certain high energy feed rations is assumed to be reduced 10 percent, resulting in a 5 percent reduction in meat and dairy product yields. In the second case, beef consumption is reduced via a simulated reduction in the demand for beef products.

A reduction in the use of nitrogen in crop production is assumed in the N_2O evaluations. Specifically, anhydrous ammonia is reduced 50 percent and other nitrogenous fertilizers are assumed to be reduced by 10 percent. The percent reduction in yields associated with this reduced use of nitrogen are derived from a series of nitrogen fertilizer response functions taken from the agronomic literature [Hexem and Heady; Andersen and Køie; Arnold et al.; Brinkman and Rho; Cochran et al.; Constable and Rochester; Eck; Køie and Morrill; Perry and Olson; Reneau et al.; Singh et al.; Sorenson and Penas]. Estimated reductions in yields, which range from 3 to 15 percent across crops and regions, are then used to adjust the yields in the sector model to evaluate the costs of these strategies.

The evaluation of a policy of converting agricultural lands to forest plantations for the purpose of growing carbon is the most complex of the evaluations performed here. Various assumptions concerning total tons of carbon sequestered, the extent of land available for such purposes, and the use of timber from such plantations will affect the social costs of such a policy. In this analysis, we use the cost, yield and carbon sequestering information from Moulton and Richards. Establishment costs are converted to annual costs by discounting at 10 percent for an assumed rotation of 50 years. We also adopt similar carbon fixation goals as Moulton and Richards. These cost and yield data are then used to develop the forest plantation activities for each of 10 regions in the economic model. In this analysis, the resulting stumpage was assumed to not be sold and thus not affect existing timber markets.

An important issue in evaluating agricultural land as a potential site for forest plantations is the inventory of lands capable of growing trees (without the need for major investments, such as irrigation) [USDA]. Several studies have noted the apparent large areas of "marginal" farmland in the U.S., such as the inventory of over 16 million hectares of lands currently enrolled in the Conservation Reserve Program

(CRP). These CRP and similar areas are frequently suggested as candidates for tree planting activities. However, more than 50 percent of CRP enrolled hectares are in the semi-arid west (with rainfall of less than 450 mm) where the dominant forms of natural vegetation are drought-tolerant grasses and shrubs, not trees. This suggests that any realistic tree planting program needs to emphasize more easterly regions of the U.S., which involves competition with higher valued crops at the margin. The importance of the land inventory assumption is explored in the subsequent analysis.

Results

This section presents quantitative estimates of the social costs of reducing trace gas emissions from U.S. agriculture, along with the costs of sequestering carbon through tree planting activities on agricultural land. These costs are in terms of *net* economic surplus changes associated with each policy option or strategy. Thus, in some cases, consumer losses are partially offset by gains to producers (associated with rising commodity prices). Further, these are aggregate effects; the regional implications will not be explored in detail. It should be stressed that all these estimates are preliminary, given the nature of the physical and natural science assumptions underlying each analysis.

Methane Reduction

Worldwide, agricultural activities are estimated to contribute about 50 percent of total methane emissions. In the U.S., the two agricultural sources are rice production and livestock. As evaluated here, methane reductions are achieved by reducing nitrogen applications to rice in the U.S. (by 50 and 100 percent) and by adopting low

CH_4 rations for livestock (cattle, including beef and dairy, and sheep). In the latter case the use of low CH_4 feed systems is treated in two ways; a shift in supply to reflect a decrease in total livestock meat production and a shift (reduction) in livestock demand to reflect reduced consumption, analogous to a tax on finished meat products. These methane results are reported in Table 1.

Table 1. Costs Per Ton of Methane and Nitrous Oxide Emission Reductions

Strategy	Changes in Economic Surplus ($ million)	Cost Per 1000 kg ($)
Methane		
Reduced rice fertilization by		
50%	-268	590
100%	-724	663
Low CH_4 rations		
5% yield reduction (supply shift)	-1,282	1166
5% demand shift for fed beef (tax)	-4,590	4180
Nitrous Oxide		
Reduced anhydrous ammonia/nitrogen applications	-643	4708

As is evident from the table, the average costs of methane emission reductions range from approximately $500 to more than $4,000 per metric ton of methane, depending on the strategy (the reductions for rice are 0.5 and 1.1 million metric tons of CH_4 for the 50 and 100 percent nitrogen reduction, respectively, and 1.1 million metric tons for the low CH_4 feed ration policies). For rice, the costs are due to reduced yields associated with reduced nitrogen applications. These reductions in nitrogen increase total area in rice production. For livestock, the costs are due to either (assumed) changes in per unit product yields for all livestock or reduced consumption of fed beef. Costs are borne primarily by consumers; producers in some cases gain due to rising prices associated with reduced supply. Whether these social costs are "large" depends on the benefits per 1000 kg associated with reductions of these gases. However, the U.S. is a relatively small contributor to total world methane emissions, given that the U.S. share of world rice and livestock production is approximately 1 and 8 percent, respectively.

N_2O Reductions

Agricultural nitrous oxide emissions come from two sources: deforestation and nitrogenous fertilizers. The U.S. accounts for about 10 percent of global nitrogenous fertilizer consumption. The U.S. also has a higher proportion of anhydrous ammonia in the mix of nitrogenous fertilizers than the rest of the world. Since anhydrous ammonia releases more N_2O than other forms of nitrogenous fertilizers (up to 7 percent of the total nitrogen is lost as N_2O), the U.S. contribution to worldwide N_2O emissions (from fertilizers) is probably somewhat higher than 10 percent. In this analysis, it is assumed that the U.S. can reduce its total annual N_2O emissions by 50 percent (to 136 thousand metric tons) by reducing the use of anhydrous ammonia by 50 percent and reducing all other nitrogenous fertilizer use by 10%. The net costs of this strategy, as presented in Table 1, are approximately \$650 million or approximately \$4,700 per 1000 kg of N_2O. These costs, as modeled here, are borne entirely by consumers; in the aggregate, producers again through increased commodity prices. Again, whether these costs are "large" depends on the benefits associated with the reduced N_2O emissions.

There are obvious sources of error in both the CH_4 and N_2O cost estimates of emission reductions. For example, relatively small adjustments in some inputs (i.e., 10 percent reduction in total N applications) are assumed here to result in major reductions in emissions, suggesting that these costs estimates may be understated. Given the lack of good data on methane and N_2O emissions under alternative management systems for actual field conditions, it is difficult to know whether the extent of emission reductions reported here could be achieved. Conversely, the substitution of other inputs or technologies (which are not explicitly modeled here) in response to control strategies could reduce social costs presented here.

Forest Plantations

As noted earlier, several studies have focused on the technical feasibility of large-scale forest plantations as a means of slowing atmospheric CO_2 increases. The use of marginal agricultural land to "grow carbon" has appeal for several reasons. These include the assorted benefits of reduced erosion, reduced use of agricultural chemicals, increased wildlife habitat, and, perhaps, aesthetic values arising from forested landscapes. Tree plantations also would appear to be a less politically painful alternative to other potential strategies, such as carbon taxes.

The social costs of such tree planting and growing operations include the establishment and management costs, plus the opportunity costs of tying up potentially large areas of agricultural land for extensive periods. While the U.S. has substantial areas of marginal agricultural or pastureland available for such purposes, the climatic and edaphic characteristics of some regions are not well suited to tree plantations. Thus, successful tree-growing activities need to be confined to a subset of the available agricultural land inventory in the U.S. Obviously, the more carbon that is to be sequestered, the greater the impacts will be in those regions that are suited for tree growing.

In the analysis reported here, the sensitivity of the economic cost estimates is tested under several assumptions concerning 1) the carbon-fixing goals (total metric tons) and 2) areas of pastureland vs cropland utilized. In addition, carbon growing activities are restricted to regions with adequate rainfall to grow trees. As discussed in the Procedure Section, these sensitivities are explored via changes in a sector model of the U.S. agricultural sector. The changes include addition of regional tree-growing activities in regions with sufficient rainfall and the specification of carbon-fixing goals. The total carbon-fixing goals are 140, 280, 420, and 700 million short tons (or 127, 255, 382, 636 million metric tons equivalent) of carbon per year. They represent approximately 10, 20, 30, and 50 percent of total annual carbon emissions from the U.S. These carbon-fixing goals are similar to levels analyzed in Moulton and Richards. The higher level (700 million short tons) corresponds to levels found in Sedjo and Solomon.

The results of these evaluations are reported in Table 2. The results present estimates for the four carbon goals under several assumptions with respect to location of carbon-fixing activities and the use of pastureland versus cropland within each region. Analysis 1 allows carbon to be grown in most regions of the U.S. (the exceptions are arid portions of the Southern Plains, Southwest, and parts of the Northern Plains, where rainfall is less than 450 mm per year). The analysis also allows unrestricted use of the pastureland inventory for such purposes. As is evident from the table, the marginal costs (averaged across all regions) per 1000 kg increase as the carbon-fixing goals are increased, from a low of $16.30 per 1000 kg for 140 million short tons to approximately $62.00 per 1000 kg for a goal of 700 million short tons (about half of total U.S. carbon emissions). The rising costs per 1000 kg reflect the rising opportunity costs of agricultural land as more land and land of higher quality is diverted from crop activities to tree planting activities. This diversion increases consumers' losses due to rising commodity prices.

For perspectives, the range of estimates from this analysis can be compared with other recent studies. However, caution is needed in such a comparison due to differences in assumptions concerning annual or cumulative carbon fixation, discount rates and whether the analyses report average or marginal costs. For example, the marginal costs per 1000 kg reported here are slightly to moderately higher than the marginal cost estimates in Moulton and Richards. Specifically, Moulton and Richards report costs of $12.00, $15.70, and $18.00 per short ton as "least cost" estimates to sequester 140, 280, and 420 million short tons of carbon. The current estimates also appear similar to the average costs reported by Dudek and Leblanc (of 3.50 to 11.00 per short ton) for sequestering approximately 140 million short tons of CO_2 (or 38 million short tons of carbon). However, the costs here are considerably higher than

Sedjo and Solomon's average cost range of $12.00 to $19.00 per short ton to achieve a larger carbon sequestration (2.9 billion short tons). The somewhat higher costs generated via the spatial optimization used here reflect the costs to consumers of foregone agricultural production and the elimination of selected arid areas from the land inventory (as well as the differences between marginal and average costs).

Analysis 2 from Table 2 is similar to Analysis 1 except that a restriction is imposed on the proportion of pastureland converted to trees. Specifically, pastureland is limited to 50 percent of total tree production (in Analysis 1 it is approximately 60 percent). The purpose of this analysis is to test the effect of the land inventory and productivity assumptions as such estimates (some "pastureland" in the inventory is of low productivity). As the numbers in Table 2 suggest, use of slightly more cropland to achieve the various carbon goals translates into slightly higher costs for the modest goals (e.g., 140 million short tons of carbon) but results in dramatically higher costs at more extreme goals (700 million short tons), due to increasing pressure on the cropland-resource base.

Analysis 3 further investigates the effects of changes in the land inventory assumption on estimated carbon-fixing costs. In this case, the Southern Plains (Texas and Oklahoma) are removed from the potential land inventory for such tree planting. While primarily a sensitivity exercise, there is some reason to suspect that climate change will adversely affect the ability of this region to produce trees in the future. Specifically, forecasts from two general circulation models (Goddard Institute of Space Studies or GISS and Princeton's Geophysical Fluids Dynamics Laboratory or GFDL) indicate that the Southern Plains will experience a hotter and drier climate under a doubled CO_2 environment (or the equivalent amount of climate forcing from all trace gases). If the production of trees in the Southern Plains is eliminated from the model solution, then the costs per 1000 kg of carbon increase by 40 to almost 100 percent. The rise in costs across each carbon goal is due to increased diversion of land in regions of higher agricultural productivity.

The results of all analyses suggest that a modest program of carbon sequestering can be achieved without major impacts on agricultural areas and commodity production. For example, 140 million short tons of carbon can be sequestered by diverting approximately 20 million hectares from agricultural to tree plantations. However, the results also suggest that costs per 1000 kg are likely to rise rapidly as more ambitious goals are attempted, due to increased land diversions from traditional agricultural activities. At 700 million short tons, over 109 million hectares are diverted from agriculture. As the costs per 1000 kg rise, the use of tree plantations as a "greenhouse" strategy becomes less appealing. Indeed, purchase of tropical forests as carbon sinks appears to be less costly as an "offset" strategy than continued conversion of U.S. cropland and pastureland.

Table 2. Marginal Costs per Ton and Agricultural Acreage to Sequester Carbon via Tree Plantations

Evaluation	Total Carbon Sequestered (short tons)							
	140		280		420		700	
	$/1000 kg	Acreage (million hectare)	$/1000 kg	Acreage (million hectare)	$/1000 kg	Acreage (million hectare)	$/1000 kg	Acreage (million hectare)
Analysis 1[a]	16.30	22.18	23.30	43.85	30.25	65.70	61.90	112.00

Analysis 2[b]	17.50	21.49	26.40	42.04	34.65	63.41	118.70	109.52
Analysis 3[c]	22.30	19.38	41.10	41.11	66.55	62.21	218.35	108.38

[a] Analysis 1: Restricts tree planting activities to regions where rainfall exceeds 450 mm per year.

[b] Analysis 2: Same as Analysis 1 but also restricts pastureland to not exceed 50 percent of total acreage in tree plantations.

[c] Analysis 3: Same as Analysis 1 but removes Sourthern Plains from solution.

Conclusions

The economic consequences of reducing trace gas emissions from agriculture as estimated here are subject to considerable uncertainty but indicate potentially high social costs to agricultural constituents. Most of these costs are borne by consumers due to rising commodity prices. Strategies to reduce inputs, such as reducing nitrogenous fertilizers also have some other undesirable side effects, including pressure to increase land use for affected commodities. This would conflict with any policy of converting agricultural lands to forest plantations.

The costs of sequestering carbon through tree plantations vary with the carbon-fixing goals and the land inventory available for such conversion. Average costs per 1000 kg rise as more land is diverted from agriculture, suggesting that modest levels of carbon sequestration may be feasible. However, these analyses indicate that tree plantations are only one component of an overall strategy to control trace gas buildups; other solutions are needed.

These analyses suggest the importance of specific biological and physical data in performing economic assessments. The analyses of changes in input use are conditional on the accuracy of a broad set of biophysical relationships, such as fertilizer response functions and trace gas emission rates. The evaluation of costs of land conversion to tree plantations reflects the importance of the land inventory assumptions, including differences in land productivity within and across regions. In view of these data uncertainties, the results reported here are best viewed as sensitivity analyses. The estimates can, however, provide some general perspective on whether the costs of these agricultural strategies are "large or small" relative to non-agricultural options for reducing trace gas emissions

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