The Cost of Agricultural Carbon Savings

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Abstract

Economic impacts of agricultural carbon sequestration involve direct costs of sequestration management adoption as well as a variety of indirect costs and benefits. The nature and significance of these impacts are discussed. Spatial and temporal heterogeneity in agriculture is identified as an influential factor. Techniques to estimate the cost of agricultural carbon sequestration are briefly reviewed and compared. Mathematically programming is used to simulate carbon sequestration in the U.S. agricultural sector and to provide experimental evidence of the existence and magnitude of economic impacts.

Key words: agriculture, carbon sequestration, cost estimation, greenhouse gas mitigation policy, mathematical programming.

THE COST OF AGRICULTURAL CARBON SAVINGS

Introduction

Agricultural carbon sequestration has been suggested as a relatively low-cost option to reduce net greenhouse gas (GHG) concentrations in the atmosphere (McCarl and Schneider 2000). However, such a statement can easily be misperceived if used without further qualification. To begin with, the costs of agricultural carbon sequestration are not constant but vary substantially across space, time, and sequestration techniques. In general, the more carbon emission savings are targeted, the more it will cost. To efficiently capture the heterogeneity of costs, economists often use abatement cost curves. These curves show the cost of emission reductions (vertical axis) plotted against the associated emission reduction volume (horizontal axis). Abatement cost curves may display marginal, average, or total costs.

Generally, farmers do not voluntarily adopt carbon sequestration techniques but must be encouraged or forced to do so through governmental interference. Thus, a comprehensive cost assessment for carbon sequestration can be useful for finding out whether an agricultural carbon policy is worthwhile and what level of regulation would be required. For example, policymakers, who want to achieve a certain level of carbon emission reduction, could use an abatement cost curve for agricultural carbon reduction to determine the necessary tax or subsidy level.

The purpose of this paper is to discuss the nature of costs and benefits from agricultural carbon sequestration, highlight important characteristics, and summarize methodologies for estimation. For illustrative purposes, empirical estimates from a U.S. nationwide study will be presented.

Economic Impacts of Agricultural Carbon Sequestration

Carbon sequestration efforts are associated with a complex response of direct and indirect economic impacts. Each of these impacts can be beneficial or detrimental to various segments of society. Direct economic impacts are defined here as all primary economic effects that take place at the farm level. Indirect economic impacts include the effects of agricultural market changes and changes of untargeted environmental qualities. Furthermore, if agricultural carbon sequestration arises as the result of a policy, governmental institutions will incur economic impacts from the specific policies put in place.

Adjustment Costs

Reduced tillage, tree planting, production of biofuels, and other carbon emission mitigation efforts cause direct economic impacts at the farm level. First, the acquisition of new capital and skills to adopt a new management practice comes at a cost. While only temporary in nature, adjustment costs are generally higher the more farmers deviate from their traditional management. For example, farmers who change only their tillage systems but keep growing the same crops are likely to incur less adjustment cost than are farmers who switch to new crops or manage their lands in a completely new way.

Second, direct economic effects also result from increased or decreased factor expenditures that are permanently associated with carbon sequestration practices. Reduced tillage, for example, demands less machine power, fuel, and labor expenses relative to a deep tilling operation. The costs of planting, fertilizing, and other operations, however, may be higher or lower for reduced tillage depending on various characteristics of the chosen crop, location, and the alternative tillage management.

Opportunity Costs

Farm revenues change if carbon-sequestering farmers sell more or less of their original products and services or if they sell new products and services. With adoption of carbon sequestration practices, farmers often give up the opportunity to sell as much as they did before. The foregone revenue—also called opportunity cost—is especially high for afforestation, plantation of perennial energy crops, and conversion of cultivated cropland into grassland because farmers completely abandon their original crop products. Other carbon mitigation practices such as alternative tillage and fertilization practices are complementary to traditional production and result in less opportunity cost.

Opportunity costs also arise because major agricultural carbon mitigation strategies are competitive with one another. Farmers cannot implement conservative tillage on a wheat field and at the same time establish a permanent forest or plant a perennial energy crop to be used as feedstock in power plants. By choosing one mitigation strategy, they give up the opportunity to implement another. To appropriately capture the opportunity costs of carbon sequestration, the economic model should include simultaneously all major mitigation strategies as well as non-mitigating traditional agricultural production.

Stickiness

The overall effect of carbon sequestrating management alternatives is usually cost positive because otherwise the non-adopting farmer would loose profits. However, in some cases, soil and crop scientists have found alternative management to be cost saving; yet, farmers stick to traditional management. Increased real or perceived risk, cultural or individual stickiness to lifestyle related preferences, and lack of confidence in research results coupled with some scientists' tendency to overstate the benefits of new techniques might explain in part why farmers deviate from a strategy of maximizing expected net returns. For example, a field with no visible plant residues remaining after plowing has long been regarded as a mark of excellent farming skills in the traditional farming community. Stickiness adds additional cost to agricultural carbon sequestration. While these costs cannot be observed directly, they can be estimated econometrically.

Market Changes

If farmers adopted carbon sequestration strategies on a large scale, the sum of all direct effects would cause important secondary effects, which should be addressed by an appropriate economic analysis. First and foremost, agricultural markets would be affected. Production levels for traditional agricultural products are likely to decrease, in turn causing prices and per unit revenues to increase. If prices of agricultural commodities increase, consumers of these products incur losses. The net effect on farmers' welfare would depend on whether or not the increased per unit revenue outweighed the loss from selling less units overall. Welfare redistributions would be higher the more traditional agricultural production declined.

Market changes can also affect non-agricultural sectors of the economy through links on the input or the output side of agricultural production. For example, reduced fertilization may decrease overall fertilizer demand and affect the fertilizer-manufacturing sector. Increased supply of biofuels may lessen the demand of conventional fuels in the energy sector.

Environmental Co-effects

Actions to enhance soil carbon sequestration are likely to affect other agricultural externalities besides net emissions of GHGs. Initial studies and basic soil science suggest that many of the environmental co-effects are additional social benefits rather than additional costs. For example, reduced tillage also decreases soil erosion because plant residues offer more protection from wind and water forces and because intensive tillage destroys soil particle links. Higher soil carbon contents, which are based on reduced or zero tillage, increase the soil particle links not only indirectly by not destroying them but also directly by increasing the amount of clay-humus complexes.

Nutrient pollution of water bodies is likely to be lower under reduced tillage because of reduced erosion and higher nutrient holding capabilities. Because minimum tillage disturbs soil less, soil microorganism, fauna, and flora remain in a stronger equilibrium. Increased plant cover provides surface animals with more hiding grounds. Negative environmental side effects may result from increased use of chemicals, for example, herbicides, under minimum tillage systems. However, comprehensive, long-term assessments are still missing.

Changes in agricultural non-GHG externalities may have substantial economic impacts associated with it. Less polluted groundwater, for example, improves human and animal health and thus can lower medical bills. Assigning monetary values to environmental benefits or losses, however, is difficult and much complex work remains for social and natural scientists in the future.

Transaction Costs

Private carbon markets are unlikely to arise because these markets require private property rights. Assigning property rights to clean air, however, would be extremely costly. Nevertheless, pseudo carbon markets may be established through governmental regulations. The non-point-source nature of soil carbon sequestration may lead to management-based policies rather than to emissions-based policies. Management-based policies may not target emissions accurately and thus may raise the cost of carbon mitigation. Any workable agricultural carbon mitigation will also encounter costs of monitoring, enforcement, and verification. The non-point-source nature of soil carbon sequestration is likely to result in relatively high costs for these tasks. There are no empirical estimates on transaction cost for soil carbon sequestration. However, initial sequestration policies will establish demand for the development of low-cost monitoring and verification technologies such as remote carbon sensing. Thus, while transaction costs may be high for initial policies, technological development may decrease these costs in the future.

International Impacts

Carbon emissions constitute a global externality. The cumulative emissions from all countries are the major determinant for the degree of this externality. Thus, the domestic cost per unit of realized net emission reduction may increase if agricultural carbon sequestration implemented in a few countries increases agricultural carbon emissions in other countries. This leakage effect appears to be most likely for agricultural carbon mitigation strategies, which decrease domestic production of traditional agricultural products. Soil carbon sequestration achieved through different tillage management may not belong to this category because crop yield differences among different tillage practices seem insubstantial according to current research.[1] Conversion of traditional cropland to biofuel plantations or forests, however, completely removes existing agricultural products. Consequently, agricultural product imports may increase from countries that have not implemented agricultural carbon policies. Increased levels of agricultural production are likely to increase emissions. To specify the degree of correlation between production and emission, comprehensive studies must be undertaken for many countries.

Variability of Costs

Policymakers are often interested in national or global long-term assessments of the costs of agricultural carbon sequestration. Those assessments are further complicated because impacts differ widely across regions and change over time.

Spatial Variability

Spatial differences in mitigation costs are due to differences in local climate, soil type, and land management history. In some places, small management changes can achieve high net carbon savings while in other places even huge efforts may not sequester a lot of carbon. Regional differences may impact not only implementation cost but also opportunity cost of carbon sequestration. In very productive agricultural areas, the planting of trees may be very expensive because farmers forego significant revenue when moving land out of traditional agriculture. In marginal areas, these opportunity costs may be lower, and hence sequestration via forests or biofuel plantations may be cheaper.

Temporal Variability

Agricultural carbon mitigation options differ in their degree of sustainability over time. While biofuels could permanently offset fossil fuel related emissions, carbon absorption through sinks is only available for a limited time. The below-ground carbon sink of agricultural soils may increase for 20 to 50 years (Lal et al.) depending on the initial carbon level, soil and climate type, and the new management. Growing forests may sequester above-ground carbon for some decades longer. Eventually, carbon stored in soils or trees will reach a level of saturation.

The impermanence of carbon sinks imposes additional cost on related agricultural strategies. The costs arise not only from vanishing revenues in the future but also from the volatility of sequestered carbon in light of uncertain future land management. If landowners get paid for the amount of carbon sequestered annually, payments will cease after sinks have been filled. Without payments, farmers may abandon carbon-friendly management and revert to emission-intensive practices. The accumulated carbon may thus be released.

Cost Estimation Methods

Economists have used five general methods to estimate the costs of agricultural carbon sequestration: (*a*) farm-level budgeting, (*b*) econometrics, (*c*) optimal control (OC) theory, (*d*) mathematical programming (MP), or (*e*) computable general equilibrium (CGE) analysis. Below, these modeling approaches are briefly summarized.

Farm Budgeting

Budgeting (Francl, Nadler, and Bast) is the most simplistic approach, taking into account only the direct cost of mitigation incurred at the farm level. One major disadvantage of budgeting is the omission of substitution effects, that is, product and input substitution. Undoubtedly, carbon mitigation policies will promote emission-saving management through input and product substitution. Another disadvantage—closely related to the first one—is the fixation of all input and product prices except for explicit changes due to a tax or subsidy. For example, a carbon tax would be assumed to increase farmers' expenditure on all fossil fuel based inputs by the amount of implicitly contained carbon times the tax level. Despite enormous weaknesses, budgeting is still used occasionally because of its computational ease.

Econometrics

Econometric models (Antle et al.; Pautsch et al.; Plantinga, Mauldin, and Miller; Stavins; Parks and Hardie) use statistical methods to explain farmers' management decisions through various parameters considered exogenous. For example, an econometric model may explain the adoption of carbon-sequestering management through variables of soil characteristics (e.g., texture, depth, and initial carbon content), climate parameters (e.g., rainfall, temperature, and distribution), farmer's attributes (e.g., age and education), and through a profit variable. The estimated coefficients can then be used to predict the cost of additional carbon sequestration. The major advantage of econometric models is the potential computability of standard errors on all estimates. Standard errors provide valuable insights into the uncertainty of econometric estimates.

The econometric approach, however, has several drawbacks. First, it can be applied only to those strategies that are already in use by some farmers. Hence, it is difficult to examine brand new technologies. Second, the estimated coefficients of an econometric model are generally valid only within the observed data range. To predict the cost of large-scale adoption of environmentally friendly strategies, however, econometricians may have to extrapolate far beyond the observed data ranges. This extrapolation may involve adding a substantial carbon subsidy to the net profit variable for carbon-sequestering management and/or adding the same carbon tax on carbon-releasing management.

Third, macroeconomic feedback effects such as tax-subsidy–induced commodity price changes are often ignored. Fourth, econometric estimates are subject to misspecification errors. Omission of relevant variables, which might be difficult or impossible to observe, or simultaneous inclusion of highly correlated variables may significantly affect coefficient estimates. Because variable selection is, to a considerable degree, subject to the econometrician's expertise and data availability, the model specification that is finally chosen may be the one that best reflects reality.

Optimal Control

In an OC framework, the carbon mitigation problem is represented by a multitude of time dependent, differentiable functions. The dynamically optimal decision path and associated carbon costs are obtained by solving derived first-order conditions. Frequently, functional parameters are not explicitly specified. Nevertheless, general results can be derived through comparative dynamics. Such a method, while not revealing the magnitude of costs explicitly, shows how costs change as a function of various parameters. Because of its dynamic nature, OC is often used for forestry related problems. Empirical applications include regional or global forest models (Sohngen and Mendelsohn).

One disadvantage of OC is the need for explicit functions in order to solve the problem. Often the functional form chosen is not the one that best fits the underlying behavior but is one of analytical convenience.

Mathematical Programming

MP (Alig, Adams, and McCarl; De Cara and Jayet; Garmhausen; McCarl and Schneider 2001; House; Schmid) has been used to examine alternative agricultural management at the farm, regional, or sectoral level. The scope of MP models ranges from linear, static to non-linear, dynamic. The major advantage of MP lies in its ability to analyze not only policies on existing agricultural management strategies but also policies on new or proposed strategies for which sufficient historical data do not yet exist. Major macroeconomic feedback effects are accounted for in price-endogenous sectoral MP models (Alig, Adams, and McCarl; House; McCarl and Schneider 2001). Disadvantages of MP models include the tendency toward extreme, purely profit-based specialization. Often omitted in large MP models are so-called option values (Pindyck) arising from irreversible investments (Parks); non-pecuniary, risk related, unobservable, or otherwise unaccounted costs and benefits from alternative land management (Plantinga); and macro-economic impacts in excluded sectors and regions of the economy. In addition, MP models provide point estimates without a confidence interval.

Computable General Equilibrium Analysis

Computable general equilibrium models (Reilly et al.; Burniaux; Sands et al.) look at the whole world economy and are built top-down from the world level to country and sub-country levels. Similarly, goods and services, which are initially represented by a broad composite good, can be disaggregated into specific commodities. The level of accuracy often depends critically on how far down the model disaggregation occurs, both regionally and with respect to goods and services.

The major advantage of CGE models is that potentially all economic interactions are accounted for. However, most current models lack necessary data for fine-tuned disaggregation and hence do not provide much region-, crop-, or management-specific detail. This disadvantage is noteworthy, especially in the field of agriculture with its high degree of heterogeneity. As computers become more powerful and data become generally more available, the accuracy of these CGE models may increase significantly.

Model Linkage

Although the above-described methods and models may appear fairly unrelated, there are several important links. For example, the data established for simple budgeting may be useful in econometric and MP models. Econometrically estimated parameters of demand and supply curves are often an essential part of MP models. In addition, econometric estimates of non-profit related stickiness to traditional management can also be incorporated into MP models. Results from econometric or MP models in turn can be linked to CGE models.

Models may be linked in one direction or iteratively. Iterative model linkage can be very useful for connecting models of different scales, for example, for connecting a number of detailed econometric or MP models at the farm level with a global CGE model. The regional farm-level models would be solved first, supplying data for the CGE model. Subsequently, the CGE model would be solved, supplying updated values for exogenous parameters of the farm models. This procedure would be repeated until equilibrium is achieved.

The Cost of Carbon Mitigation in the U.S. Agricultural Sector

In this section, empirical cost estimates will be presented using the U.S. agricultural sector model with GHG features (ASMGHG) as documented in Schneider. This mathematical programming model portrays farmers' choices among a broad set of crop and livestock management options including tillage, fertilization, irrigation, manure treatment, and feeding alternatives. ASMGHG depicts production and consumption in 63 U.S. regions for 22 traditional and 3 biofuel crops, 29 animal products, and more than 60 processed agricultural products. It also depicts 8 crops being traded within 28 international regions. Information from U.S. Department of Agriculture (USDA) farm surveys is used to represent basic crop and livestock production technologies. Several economic (FASOM, Alig, Adams, and McCarl; GREET, Wang) and crop growth (EPIC, Williams et al.) simulation models from the agricultural, forestry, and energy sectors were used to establish data for alternative management practices. These data include cost changes from the base technology, as well as yield adjustments, emission coefficients, and other environmental effects.

GHG emissions and emission reductions are recorded for all major sources, sinks and offsets from agricultural activities for which data were available or could be generated. Generally, ASMGHG considers the following:

- direct carbon emissions from fossil fuel use (diesel, gasoline, natural gas, heating oil, LP gas) through tillage, planting, care operations, harvesting, grain drying, and irrigation water pumping
- direct carbon emissions from decomposition of soil organic matter (cultivation of forested lands or grasslands)
- indirect carbon emissions from fertilizer and pesticide manufacturing
- carbon savings from increases in soil organic matter (reduced tillage intensity and conversion of arable land to grassland) and from tree planting
- carbon offsets from biofuel production (ethanol,and power plant feedstock via production of switchgrass, poplar, and willow)
- nitrous oxide emissions from fertilizer usage and livestock manure
- methane emissions from enteric fermentation, livestock manure, and rice cultivation
- methane savings from improved livestock management

Carbon mitigation efforts were induced through a combined tax-subsidy policy placing hypothetical prices on agricultural carbon emissions and emission reductions. The magnitude of examined prices ranged from $0 to $500 per ton of carbon equivalent (TCE).[2] Under the simulated policy, farmers have to pay the price for their own GHG emissions but receive payments for carbon sequestration or offsets. Methane and nitrous oxide emissions were jointly regulated, with equivalency based on the one-hundred-year global warming potentials of the Intergovernmental Panel on Climate Change (IPCC).

Figure 1 shows the competitive equilibrium for major carbon mitigation strategies. The emission reduction impacts of all included agricultural strategies from all U.S. regions are grouped into three national abatement accounts: (*a*) soil carbon sequestration via traditional agricultural production (ASC), (*b*) carbon sequestration via afforestation (AF), and (*c*) fossil fuel carbon offsets via biofuel (BF) production. Note that these three abatement options are fully competitive with one another, implying that total acres used for ASC, AF, and BF cannot exceed total cropland in each region.

At each hypothetical carbon price level, two implicit conditions must be met in order for a strategy to become adopted. First, the net cost in $/TCE of implementing the strategy must be below the imposed carbon price. Second, the net cost of implementing

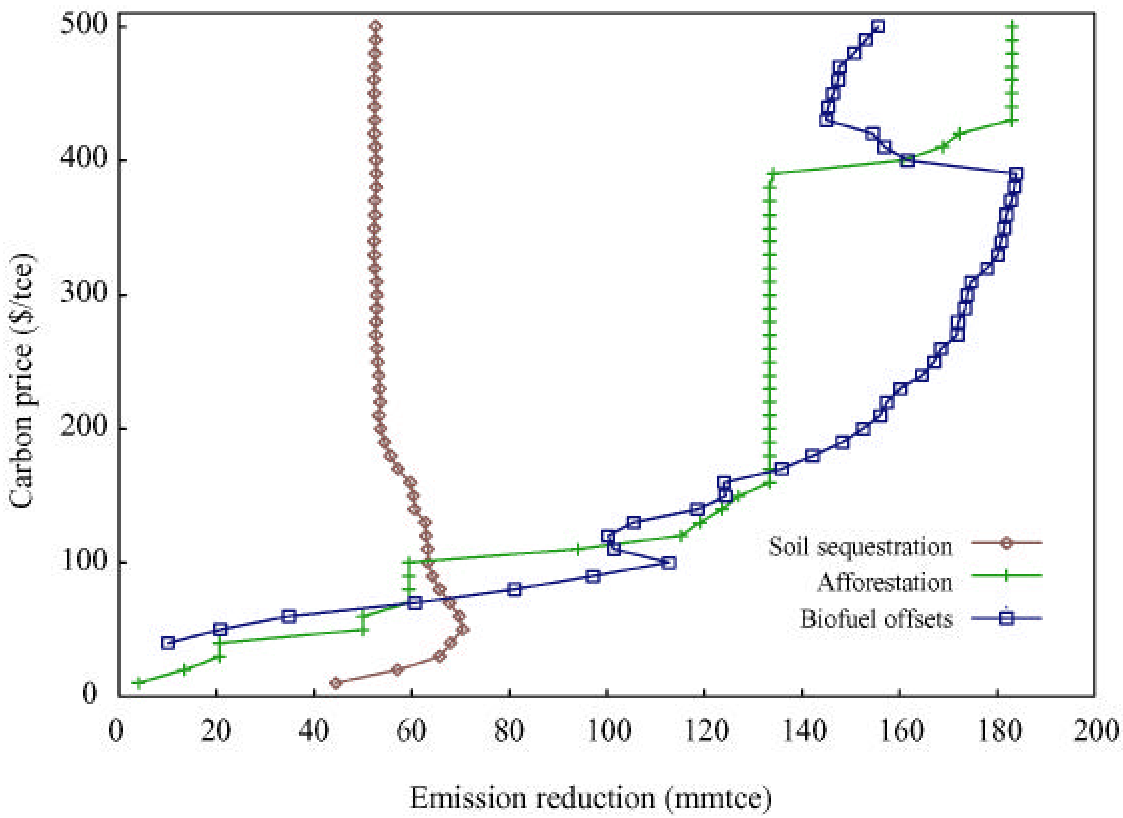

FIGURE 1. Competitive equilibriums of major agricultural carbon mitigation strategies in the U.S. agricultural and forestry sector

this strategy must also be below the net cost of any competing strategy.[3] The paths of the abatement curves imply that ASC is a low-cost strategy, dominating AF and BF for carbon prices below $50/TCE. At higher price levels, substantial amounts of cropland are allocated to AF and BF. These two strategies have higher mitigation potentials but come at higher implementation costs. The increase in BF and AF reduces the amount of cropland used for ASC. Hence, the ASC abatement curve bends backwards at high carbon prices.

To illustrate the concept of competitive economic abatement potential, two additional commonly used measures of abatement potential are contrasted with the ASC strategy in Figure 2. The technical potential of soil carbon sequestration is the maximum amount of carbon that can be stored regardless of cost.[4] The single strategy economic potential, while taking into account cost, represents a situation in which ASC is the only mitigation option available to farmers. Two conclusions can be drawn. First,

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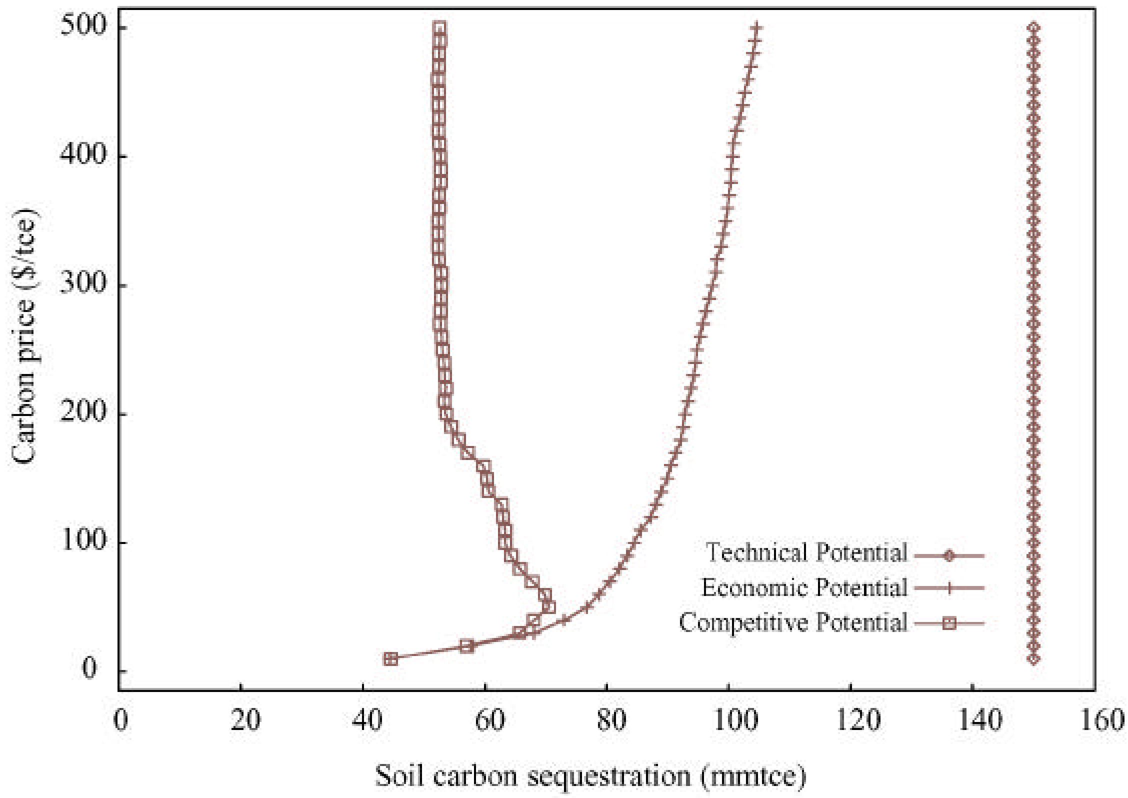
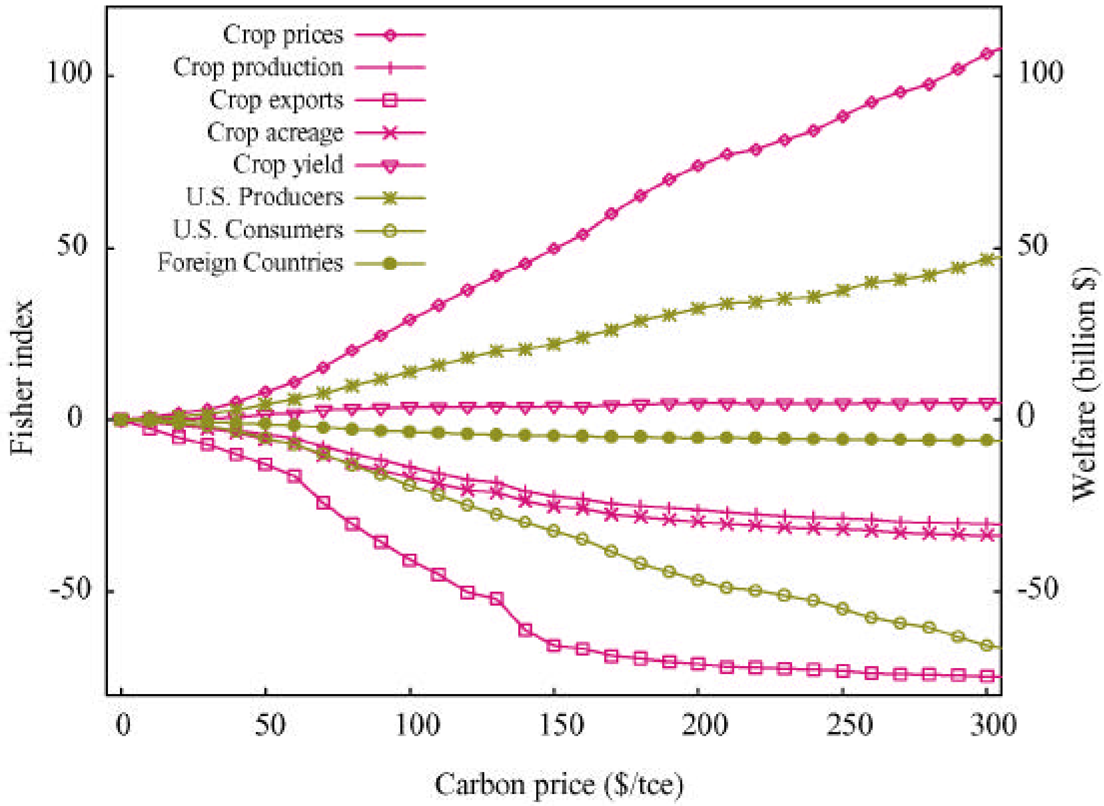


Soil carbon accounting includes changes on traditional cropland and pasture but does not include soil carbon changes from diversion of agricultural crop or pasture land to forestry or biofuel plantations.

FIGURE 2. Marginal emission reduction supply curve of agricultural soil carbon sequestration on U.S. croplands

the economic potentials do not match the technical potential even for carbon prices as high as $500/TCE. Second, the competitive potential of ASC is substantially lower than the single strategy economic potential for carbon prices above $50/TCE. At these prices, more cropland is diverted from traditional agricultural production to forests and biofuel plantations.

Economic impacts of U.S. carbon sequestration on agricultural markets are summarized in Figure 3. First, mitigation efforts are competitive with food and fiber production. High carbon prices lead to large amounts of afforestation and biofuel generation, causing traditional agricultural crop acreage to decline. Consequently, traditional crop production falls while crop prices rise. Second, the costs of using



Welfare effects are in billion dollars (right vertical axis). Crop production effects are absolute deviations of the Fisher index from baseline (left vertical axis).

FIGURE 3. Agricultural market effects from agricultural carbon mitigation efforts in the U.S. agricultural sector

emission-abating practices are not shared equally among agricultural market segments. Agricultural producers in the United States would gain welfare because higher operational costs are more than offset by higher revenues because of increased prices. U.S. consumers' welfare, on the other hand, decreases substantially. Slight losses in overall welfare would also occur in foreign countries.

Figure 4 shows the impacts of carbon mitigation on a few selected environmental parameters. As carbon prices increase, nitrogen water pollution, erosion, and phosphorous pollution decrease. However, at higher prices, environmental co-benefits on traditional cropland largely stabilize. The financial benefits to society from changed levels of these environmental properties remain to be valued.

If carbon credits from sinks are discounted, afforestation and soil sequestration become more expensive and the competitive equilibrium will shift towards greater

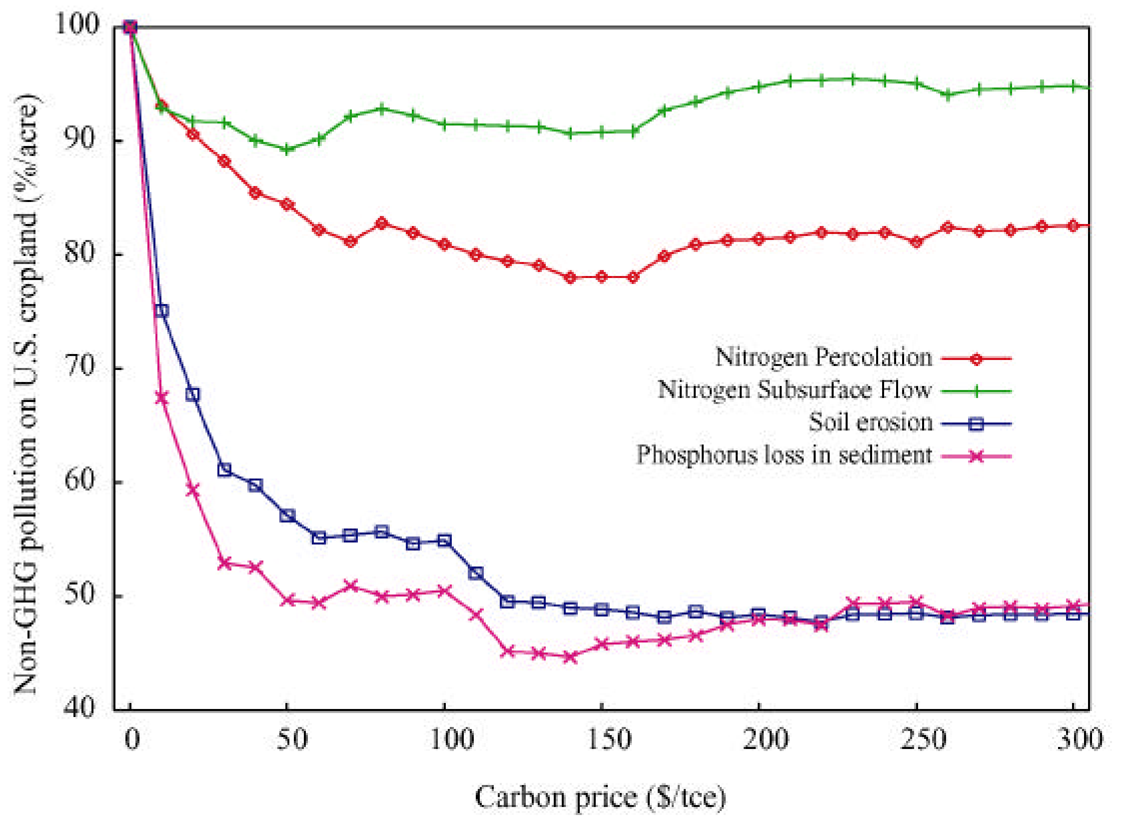
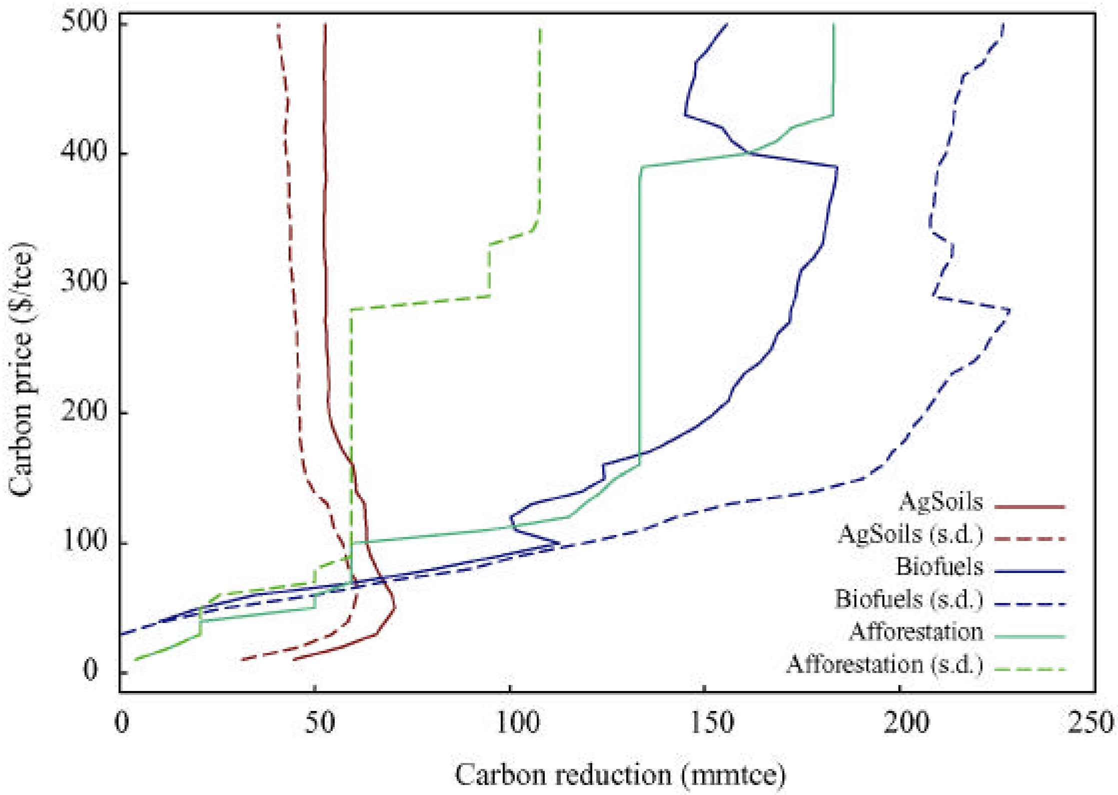


FIGURE 4. Environmental co-effects of agricultural carbon mitigation efforts in the United States

adoption of sustainable mitigation options. To simulate the economic impacts numerically, two sets of scenarios were simulated with ASMGHG. The first set of scenarios imposes equal credits to all carbon emission reductions. The second scenario discounts credits for soil carbon by 50 percent and credits for tree biomass carbon by 25 percent. These adjustments are representative of the permanence discount factors as estimated by McCarl, Murray, and Schneider.

With discounting in place, agricultural soil and forestry shares decline but the share of undiscounted biofuel carbon rises (Figure 5). In particular, the agricultural soil sequestration maximum falls by about 10 percent while abatement through forestry adjusts down by almost one-third. The strong decline in afforestation occurs because undiscounted biofuel production represents a closely competing strategy. Small relative price changes can switch the delicate balance between afforestation and biofuel production a great deal. Soil carbon sequestration, on the other hand, remains



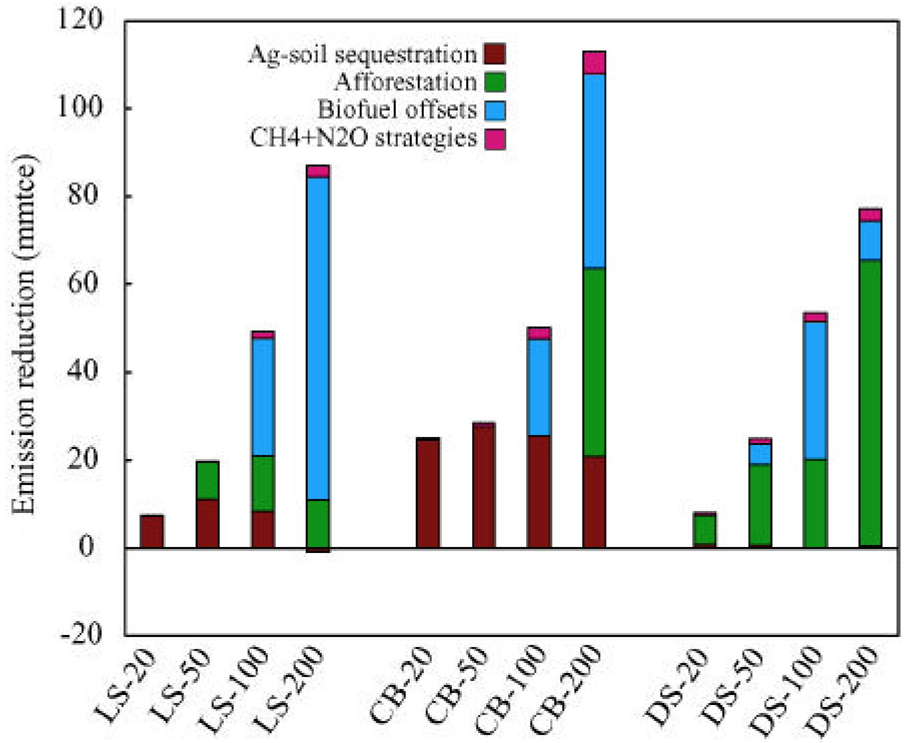
Solid lines represent the competitive strategy equilibrium under no discounting. Dashed lines represent the competitive abatement strategy equilibrium when sinks are discounted. Discounts are 50 percent for agricultural soil carbon, 25 percent for carbon sequestered from afforested lands, and 0 percent for carbon offsets from biofuel production.

FIGURE 5. Effects of sink discounting on the costs of major agricultural carbon mitigation strategies

the dominant low-cost strategy even after credits were discounted by as much as 50 percent.

Agricultural production is heterogeneous and so are the costs of carbon emission mitigation. Therefore, the composition of the optimal strategy portfolio varies regionally as illustrated for a few selected regions in Figure 6. Soil-based strategies are more cost-efficient in the Corn Belt (high opportunity cost), while biofuels dominate in the Great Lakes region, and afforestation dominates in the Mississippi Delta.

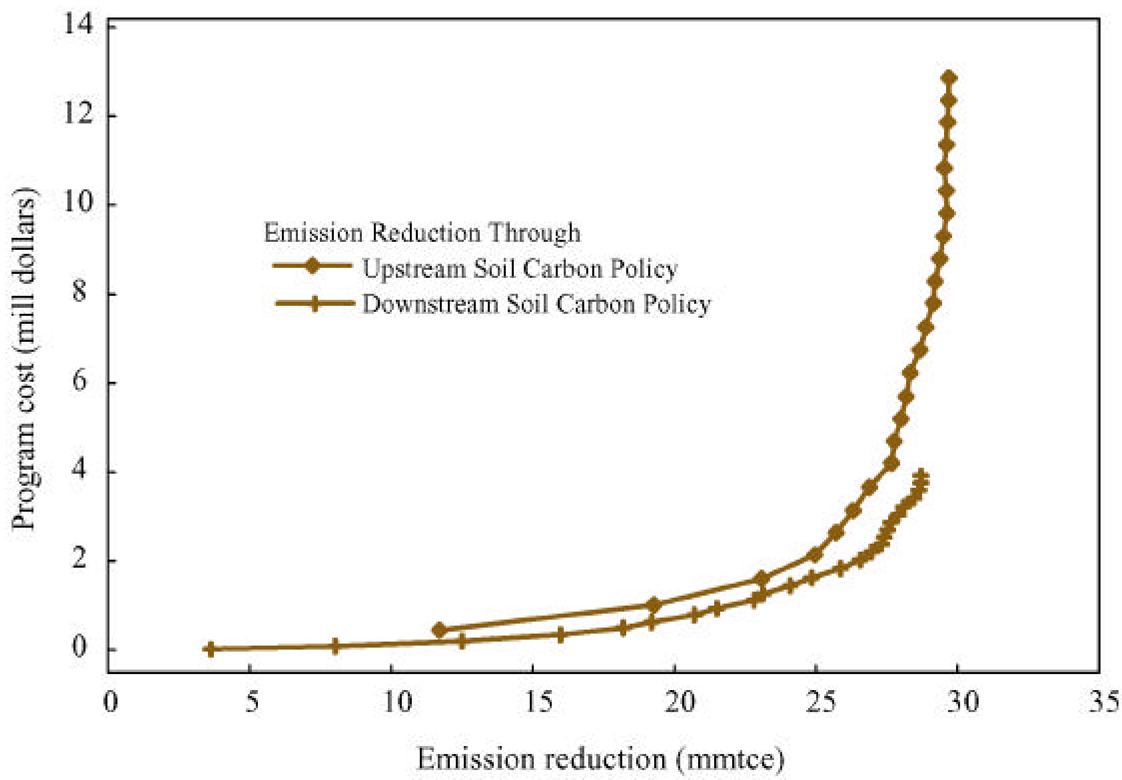
Direct measurement and regulation of emissions from agricultural sources is most likely impractical, at least until further technological advances are achieved in remote sensing. Management-based policies might provide a feasible alternative for the



Regions with high agricultural productivity (Corn Belt) incur high opportunity cost on crop production diverting strategies such as afforestation or biofuel plantations.

FIGURE 6. Regional differences in optimal strategy adoption as result of cost heterogeneity

intermediate future. However, because management is not 100 percent correlated to emissions, inefficiencies will occur, which will increase the overall cost of carbon mitigation. This effect is illustrated in Figure 7 for two alternative hypothetical soil carbon sequestration policies. The first policy is based on true emissions. The second policy is based on tillage management, where economics incentives and disincentives are imposed on different tillage systems.[5] For both policies, the costs of monitoring, verification, and enforcement were ignored because data on these transaction costs are currently not available. The cost of inefficiencies from a management-based policy at each level of emission reduction equals the vertical distance between the two abatement functions. Given program costs of, for example, $2 million, the tillage-based policy achieves only about 85 percent of the emission reduction realized by an emission-based policy.

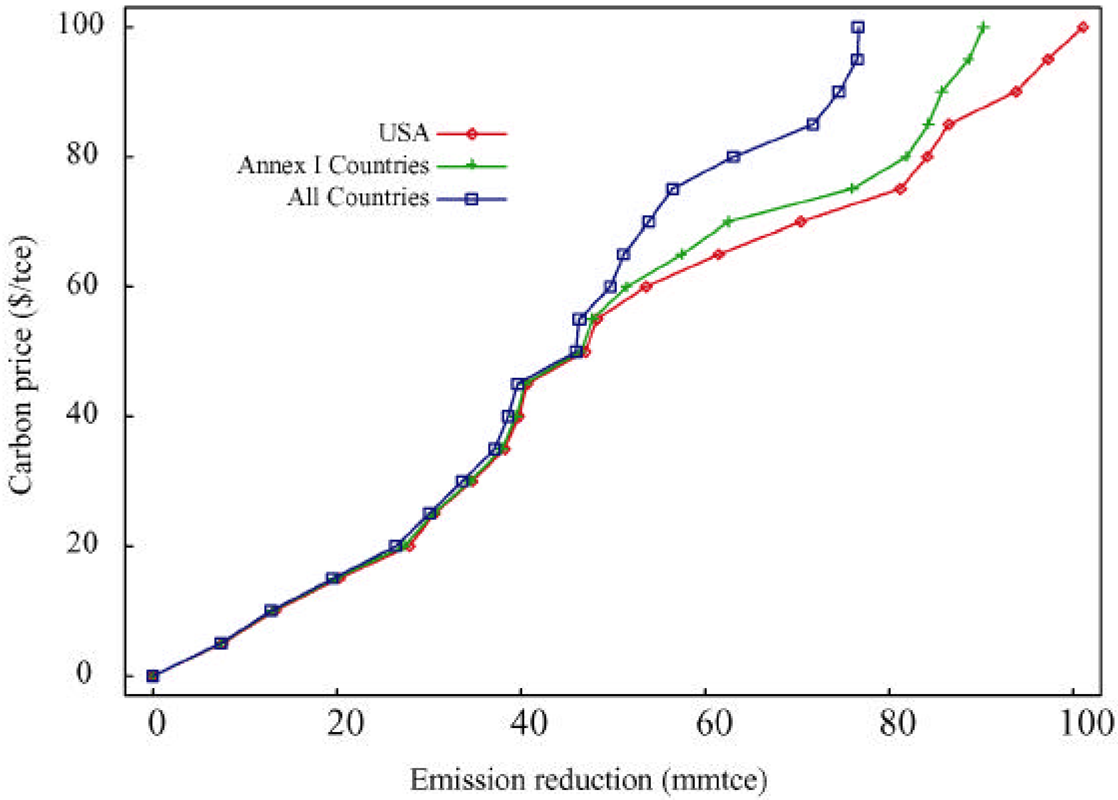


Practical "upstream" policies based on tillage management incur efficiency losses relative to theoretical "downstream" policies based on true soil carbon emissions. Costs of monitoring, verification, and enforcement are not included for both policies.

FIGURE 7. Program cost from soil carbon policies

International emission leakage is a serious concern when agricultural carbon mitigation policies are implemented in only some parts of the world. Figure 8 illustrates this problem using three alternative assumptions on international implementation of a hypothetical agricultural carbon policy. In the first scenario, the United States is the only implementer of this policy. In a second scenario, the policy is implemented in the United States and in all countries that are listed in the Annex I of the Kyoto Protocol. Finally, the third scenario portrays a worldwide implementation. The abatement functions for each scenario represent total carbon equivalent emission reductions from the U.S. agricultural sector.

For low carbon prices, scenario differences are negligible. At higher prices, however, the paths of the three abatement cost curves diverge. While a unilateral policy in the United States appears to be cheapest, worldwide implementation seems to be cost increasing. Care must be taken in interpreting these differences. The abatement curves in



USA = Implementation in U.S. only, Annex I Countries = Implementation in all countries that are listed in Annex I of the Kyoto Protocol, All Countries = Implementation in all countries.

FIGURE 8. U.S. agricultural sector emission reductions for alternative assumptions about international implementation of agricultural mitigation policies

Figure 8 show only U.S. agricultural emission reductions. Thus, potential emission changes in foreign countries are omitted. Because agricultural production in non-implementing countries increases while falling in implementing countries, agricultural emissions in non-implementing countries are likely to increase. Assuming worldwide implementation results in almost no leakage, the deviation of the partial implementation abatement curves can be interpreted as a rough indicator of leakage. Equivalently, the vertical deviation from the global implementation curves is a rough indicator for the social cost of emission leakage. A detailed description of model assumptions and results for these scenarios is available in Schneider et al.

Endnotes

1. Several scientists estimate yield losses from reduced or zero tillage because of increased weed damage. Other scientists point out positive yield effects from reduced tillage because higher organic matter contents improve the chemical and physical soil properties and result in better nutrient and water availability.

2. The magnitude of the imposed carbon prices is best illustrated using commodity gasoline. Given net carbon emissions of about 0.6 kg carbon per liter of combusted, fossil fuel based gasoline, a tax of $100 per metric ton of carbon would translate into a gasoline tax of $0.06 per liter.

3. For example, suppose a governmental tax-subsidy enforces a carbon price of $20/TCE. Suppose further the net costs and associated carbon emission reductions are $10/TCE and 0.8 TCE for ASC, $15/TCE and 1.2 TCE for AF, and $40/TCE and 2 TCE for BF. In this case, BF production would be too expensive to be implemented at $20/TCE. The profits of the other two mitigation strategies would equal ($20/TCE-$10/TCE)*0.8TCE =$8AF (ASC) and ($20/TCE-$15/TCE)*1.2TCE =$6 (AF). Thus, even though AF would be profitable at a carbon price of $20/TCE, it would not be adopted because its profits would be smaller than those from ASC. However, if the carbon price were at $50/TCE, profits for ASC, AF, and BF would equal $32, $42, and $40, respectively, making AF the preferred strategy. Using simple algebra, one can easily show that the optimal strategy in this simple example would be ASC for carbon price levels between $10/TCE and $25/TCE, AF for price levels between $25/TCE and $77.5, and BF for all carbon price levels above $77.5.

4. The technical potential of agricultural carbon sequestration is usually defined as the difference between the current carbon content and the native, pre-cultivation (pre-human) carbon level. However the native carbon level is not necessarily the highest possible level. For example, if costs did not matter, farmers could plant trees and deposit the harvested wood deep underground, where aerobic decomposition is limited. This technique would imitate to some extent the natural generation of fossil fuels, and sequestration would hardly encounter limits.

5. To keep efficiency losses low, incentives/disincentives for use of each tillage system were calculated proportional to the sequestration/emission potential of each system.

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