ASSESSING THE ECONOMICS OF CARBON SEQUESTRATION IN AGRICULTURE

Luther Tweeten, Brent Sohngen, and Jeff Hopkins*

*Respectively, Anderson Professor; Assistant Professor; and Graduate Research Associate. Department of Agricultural, Environmental, and Development Economics, The Ohio State University, Columbus. Paper presented at the conference on Assessment Methods for Soil Carbon Pools held November 2-4 at Columbus, Ohio

TABLE OF CONTENTS

1. INTRODUCTION

Most industrial countries have signed the United Nation's Framework Convention on Climate Change to reduce anthropogenic contributions to climate change. Towards that end, international negotiators proposed the Kyoto Protocol in December 1997 setting targets for emissions reductions for individual countries. For the United States, the Protocol calls for reduction in atmospheric carbon emissions by 7 percent from the 1990 level by years 2008-2012. This amounts to a challenging 25-30 percent reduction from "business-as-usual" trend levels (Bruce et al., p.4). This Protocol, though signed by the President not yet ratified by Congress, will continue to be a benchmark.

The Protocol permits a combination of carbon sinks and emission reductions to reach targets. As such, agriculture becomes a potential major sink. The global soil organic carbon pool, 1550 Pg (Pg = petagram = 10^{15}g), is twice the atmospheric pool and three times the biotic pool (Lal, 1997, p.86). Currently, most agricultural soils in the United States and Canada are nearly neutral with respect to emissions--they are neither major sources of carbon dioxide nor sinks of carbon (Bruce et al., p.1).

North American soils, accounting for about 22 percent of the carbon pool, have lost 5.5 Pg of carbon since land opened for agriculture but could regain some of that pool if economic and other incentives were favorable (Bruce et al., p.1). The objective of this paper is to examine the economics of expanding carbon sequestration in agricultural soils.

Alternative agricultural tillage, crop rotations, livestock waste disposal, and other practices influence the level of carbon in farm soils. The growing popularity of conservation tillage, including no-till, which adds to carbon in the soil has heightened the interest in the role agriculture might play in sequestering carbon to diminish greenhouse gases and global warming.

To ascertain the potential role of agriculture in sequestering carbon to alleviate global warming, several issues are addressed in this paper:

1. The economic benefits of carbon sequestration to society.

2. The cost of controlling the level of atmospheric carbon through sequestration in agricultural soils. In addition to cropping, alternatives considered include fossil fuel energy conservation and growing of trees to sequester carbon.

3. Complementarities to enhance economic feasibility of soil carbon sequestration. Examples include combining goals of soil conservation and water quality with carbon sequestration.

4. Public policies to increase carbon stocks in soils.

2. BENEFITS OF SEQUESTERING CARBON

Nordhaus and Yang (p.745) cautioned that "Estimates of the economic impacts or damages from climate change are sparse at this stage" partly because of complex systems determining climate. According to Nordhaus (1993, p.28), major greenhouse gases have an atmospheric residence time of over a century. Because of the great thermal inertia of the oceans, the climate has a lag of several decades behind the change in greenhouse gases (Nordhaus, p.28).

Nordhaus (p.43) calculated that global real economic output would fall 0.6 percent from 1989 levels by 2105 due to inefficiencies caused by policies to reduce greenhouse gas emissions by 20 percent. However, a more nearly optimal emissions policy could slightly increase global real economic output. As shown in Table 1, the optimal tax equal to the benefit per ton of atmospheric carbon reduction ranged from approximately \$6 in year 2000 to \$21 in year 2100 to address the presumed 3^0 Celsius "business as usual" warming expected in the 21st century in the absence of ameliorative public policy (Nordhaus, p.44; Nordhaus and Yang, p.745). Nordhaus (p.48) reported five previous studies which "…find conclusions that are roughly similar to those reported here."

Fankhauser and Pearce (1994) estimated that each ton of carbon emitted into the atmosphere causes some $20 in damages (Table 1). Worldwide economic benefits of reducing carbon dioxide summarized by Brown (p.28) ranged from zero to $300 per ton of carbon. That literature placed the most likely range of global benefits at $8 to $59 per ton of carbon according to Brown.

Based on the results of a systematic set of new studies, Mendelsohn and Neumann (1998) examined implications for the United States economy resulting from 1.5, 2.5, and 5.0 degrees Celsius increases in temperature and 0, 7, and 15 percent increases in precipitation over base levels by year 2060. Scenarios depict the impact of the sea level rising 33 to 66 centimeters by year 2100. Under eight of the nine scenarios presented by Mendelsohn and Neumann, U.S. gross domestic product (GDP) was projected to increase from global warming. However, the increases (and one decrease for 5^0 Celsius warming, no precipitation change) in GDP were so small they can be viewed as not statistically different from zero (Table 1). Some sectors such as coastal areas, energy, and water are worse off while agriculture and timber industries increase their real output due to carbon fertilization. The study did not examine adjustment costs or nonmarket impacts such as health effects.

Other U.S. analyses (see Schimmelpfenning) like that of Mendelsohn and Neumann report no major net impact on agricultural output, although costs could be sizable from regional dislocations and adjustments as warming shifts output north. Global analysis suggests a range of potential impacts, with developing countries near the equator experiencing the largest losses (for a review see Watson et al.; Reilly).

The estimates in Table 1 permit a first approximation of the benefits of carbon sequestration in soils. No-till on average sequesters 3 tons per hectare based on 27 studies primarily of the United States summarized by Paustian et al. Estimates of carbon gains ranged from –4 to +10 tons per hectare. If benefits of sequestered carbon currently are $6 per ton and each hectare of no-till cropland can sequester 3 tons, then the public can afford to pay $18 per ha once-for-all for perpetual sequestration, or $.90 annual rent per hectare in perpetuity (assuming a discount rate of 5 percent). If benefits of sequestered carbon are $20 per ton (year 2000 estimate in Table1) and each hectare of cropland can sequester 3 tons, then the public could afford to pay $60 once-for-all per ha for perpetual sequestration, or a rent of $3 per ha per year in perpetuity (assuming a discount rate of 5 percent). The $20 to $60 value of a hectare of farmland for the purpose of carbon sequestration is dwarfed by a typical value of farmland in all productive uses of $5,000 per ha in the Midwest.

The initial 3 tons per ha might be built to over 10 tons per ha with time depending on soil, climate, production practices, and incentives (Lal et al. 1998, pp.60, 61). Benefits would rise accordingly, but still would be dwarfed by earnings (rent) of $250 per ha or more for producing crops in the Midwest. We note later that low values for carbon sequestration do not preclude economic feasibility when complementarities of soil organic matter with soil and water conservation and other benefits are recognized.

The conclusion from the above carbon studies is that analysts have not reached concensus on the benefits of carbon sequestration to avoid global warming--even if the latter is occurring. Although the benefits of sequestering carbon are unclear, the Kyoto protocol suggests that policy may move forward anyhow. It is therefore important to address the costs of controlling greenhouse gases. The costs of carbon sequestration in cropland soils must be balanced against the cost of alternatives such as fossil fuel conservation or carbon sequestration through afforestation.

3. COSTS OF SEQUESTERING CARBON

Carbon in the atmosphere is accumulating in part from utilizing fossil fuels to produce energy, fertilizer, and pesticides central to our food supply and standard of living. Massive reduction in carbon emissions called for by the Kyoto Protocol will reduce living standards and food supplies unless cutbacks are achieved in a cost-effective manner through a combination of carbon emissions reduction and sequestration.

This section mainly addresses carbon sequestration but recognizes that an overall strategy for reducing greenhouse gases also would feature measures to conserve energy and fossil fuel consumption through taxes, subsidies, regulation, research, and education. We focus on carbon because carbon dioxide is the most abundant greenhouse gas and because agriculture can sequester carbon.

Fossil fuels producing energy (while releasing carbon dioxide) are the lifeblood of industrial economies. Reduction of greenhouse gases by 50 percent mainly through greenhouse gas emission reduction would require major cutbacks in carbon dioxide and could cost about 1 percent of global output (Nordhaus, p.36). The average productivity of fossil fuels is so large that cutbacks have severe and pervasive ill effects as apparent in the energy crises of the 1970s. Marginal, carefully selected cutbacks can be made, however, with a gain to society as illustrated by the example of the Green Light energy saving initiative launched by the U.S. Environmental Protection Agency in January 1991 (Table 2). Green Light featured incentives for firms and agencies to adopt energy-efficient fluorescent bulbs, occupancy sensors, and a number of other measures to reduce lighting costs which account for one-fourth of energy use in the United States.

Decanio (p.11) estimated an internal rate of return of 45 percent for investment in Green Light based on a 3-year payback--near the average for 3,673 Green Light projects up to 1995.

Green Light is but one illustration of opportunities to reduce carbon dioxide emissions while raising real national income. Another option is a tax on fossil fuels. While potentially costly, fossil fuel taxes might have many benefits in addition to reducing carbon dioxide emissions: less traffic congestion, urban sprawl, smog, and scarcity from depleting energy reserves.

3.1 SEQUESTRATION WITH CROPS AND TREES

While achieving the goals outlined at Kyoto would require

ant. Some trees store more t

build large stores of soil organic matter. Net carbon storage is likely to occur only if land is converted from cultivated crop use to forest. Second, the ultimate fate of the wood products must be considered. Carbon is sequestered for long periods of time if the forest is never harvested. Even if the forest is harvested, however, sequestration can be long lived if slow-growing older trees are processed to lumber used in construction of houses that last for decades. Alternatively, sequestration is short lived if trees are burned for firewood, or processed into paper that is recycled into animal bedding later spread with manure on fields. Current estimates suggest that 35 percent of carbon removed from U.S. forests is stored immediately, 30 percent returns to the atmosphere through decay, and 35 percent is burned for energy (Heath et al., 1996).

One of the first estimates of the costs of planting trees investigated how much land would be needed to sequester all carbon emissions (Sedjo, 1989). With temperate forest plantations sequestering 6.24 tons per hectare per year, Sedjo estimates that some 465 million hectares of temperate zone forest plantations can sequester an additional 2.9 Pg of carbon emissions per year for 30-50 years. Assuming land rental costs are zero, Sedjo estimates that it would cost $3.50 per ton of carbon stored.

Adams et al. estimated the marginal cost of sequestering carbon by converting some U.S. agricultural land to tree plantations in regions with over 18 inches of rainfall per year (Table 2). Their (p.79) estimated incremental cost per ton of carbon sequestered ranged from $7.40 for 132 million tons of carbon (2.5 percent of U.S. annual carbon emissions and taking approximately 5 million hectares of agricultural land and assuming timber harvest) to $60.65 for 635 million tons of carbon sequestered (50 percent of total U.S. annual carbon emissions and taking 111 million hectares of agricultural land and assuming no timber harvest).

Using data from Conservation Reserve Program contracts, Parks and Hardie estimate a cost of $9 to $10 per ton of carbon sequestered on 8.9 million hectares of marginal agricultural land. Some $3.7 billion would be required to sequester these hectares. This study, however, did not address the indirect effects of purchasing land. Afforestation of extensive areas of cropland would raise food and land values--a factor accounting for the higher costs shown by Adams et al. compared to the estimates of Moulton and Richards who assumed constant land costs as tree plantation areas expand on croplands (Table 2).

A recent study by Stavins (1998) examined how carbon sequestration policies would affect land markets and land use in a 36 county region of the southern U.S. He found that 7-8 million tons could be sequestered each year for less than $66 per ton. Alig et al. (1997, p.S108) used a U.S. timber and agriculture model to predict that for each hectare of agricultural land converted to forest plantations, an offsetting hectare of forestland somewhere else would be converted back to agriculture.

Sohngen et al. took a global perspective to note that forest expansion would lower global timber prices, thus discouraging economic timber plantations elsewhere. Fewer trees planted elsewhere would offset some of the intended benefits of sequestration. On the other hand, lower timber prices diminish incentives to harvest the boreal forest of the North and rainforests of the tropics, thus protecting wildlife and biological diversity while sequestering substantial carbon.

Richards and Stokes, in a comprehensive review of literature in 1995, provide a wide range of estimates--from $1 to $187 per ton of carbon sequestered. In general, costs were lower for small efforts and expanded as more carbon was sequestered.

Notably absent from the Richards-Stokes review was estimates of sequestration costs on cropland used for crops. Bruce Babcock of Iowa State University (private correspondence) provides preliminary estimates of carbon sequestration with conservation tillage on cropland in a 12-state Midwest region (Table 2). In 1998, this region accounted for one fourth of U.S. crop production. Several conclusions follow:

- Approximately 11 million metric tons of carbon are sequestered at private expense and at no direct cost to the public because it is complementary with other economic crop production practices.
- The marginal incentive required for adding another ton of carbon cumulatively per year increases from near zero dollars to $200 per ton at 19 million metric tons of soil carbon in the 12-state region.
- Marginal private costs for sequestration rise sharply above 19 million tons and reach $400 for adding another ton of carbon cumulatively when soil carbon stocks reach 22 million metric tons.

- Per hectare payments required to induce conservation tillage range from zero dollars up to 40 percent of crop area, rise at a nearly linear increasing rate from zero to $86 per hectare up to 95 percent participation, and become very high for further participation. These numbers may be compared with the average annual cost of $120 per hectare for the Conservation Reserve Program of general land retirement. The conclusion is that carbon sequestration is economically most feasible within the range where its complementarities with best management crop production practices are strongest.

3.2 SEQUESTRATION BY RESTORING DEGRADED SOILS

We now turn to estimates of costs and benefits of sequestering carbon on degraded lands currently or historically used for agriculture. Based on estimates by Oldeman et al. that nearly 2 billion ha of soil are degraded worldwide, Lal (1997, p. 99) calculated that soil restoration by growing trees and vigorous cover crops "…could lead to carbon sequestration at the rate of 3 Pg per year….", a rate near the annual increase in carbon in the atmosphere (Lal et al., 1995). Lal (1997, p.99) cautioned that "…this rate of increase in humus content may be difficult to achieve in arid and semi-arid tropics, and if so only for a limited period of time."

Dregne and Chou (1992, p. 276) classified 216 million ha or 47 percent of global rainfed cropland as degraded (moderate to very severe desertification), 43 million ha or 30 percent of irrigated land as degraded, and 3,333 million ha or 73 percent of rangeland as degraded. The worldwide total, 3,592 million ha, exceeds estimates by Oldeman et al. but includes arid and semi-arid tropical rangeland with limited capacity to sequester carbon.

Progress in restoring degraded soils will depend on economic incentives. In this context, it is notable that Dregne and Chou (p. 272) classified 276 million ha or 85 percent of U.S. rangeland as moderately or more severely desertified. Low rainfall precludes sizable economic buildup of soil organic carbon in much of this rangeland. Restoration of many degraded lands can be profitable according to calculation by Dregne and Chou shown in Table 3. The benefit-cost ratio for rehabilitating land ranges from 3.5 for rangeland to 1.9 for rainfed cropland, and averages 2.6 over all land uses.

Several considerations suggest viewing the favorable benefit-cost ratios in Table 3 with caution. Many assumptions underlying the estimates are not stated but the benefit-cost ratios may more nearly depict what is judged to be socially beneficial rather than privately profitable.

Although following practices that avoid degradation is cheaper than reclaiming degraded land, allowing soils to degrade may be cheaper for producers than paying the costs of conservation. This is because annual loss of productivity is judged by farmers and ranchers to be too small to justify conservation measures. Practices that degrade land continue also because "downstream" costs of desertification are not charged to operators or owners of eroding soil. The lack of rehabilitation of degraded land suggests that rehabilitation is not *privately* profitable. Thus, rehabilitation of degraded lands will not be as rapid as implied by the favorable benefit-cost ratios in Table 3.

Because of "downstream" costs and high private discount rates, social benefits of soil, water, and air improvements exceed private benefits. Hence, public monetary inducements for land conservation and rehabilitation could be effective and economically justified in poor countries using revenues from industrial countries purchasing carbon emission permits.

4. COMPLEMENTARITIES ENHANCING ECONOMIC FEASIBILITY OF CARBON SEQUESTRATION

A conclusion from the foregoing analysis is that raising crops and trees for carbon sequestration becomes economic only through complementarity of cropland with other private and social benefits derived from soil, water, and air quality conservation. Carbon sequestration is best viewed as one component of a package of environmental benefits economists classify as *externalities*--benefits or costs that accrue to society but not to the parties engaged in market transactions. Potential externalities complementary to carbon sequestration include conservation of soil nutrients, fossil fuels, water quality, wildlife habitat, and biodiversity. The magnitudes of these externalities remain points of controversy.

Sanders, Southgate, and Lee (1995, p.14) cite four studies indicating that U.S. on-farm costs of soil erosion range from $500 million to $1.2 billion per year. This contrasts with off-site externality damage costs of $2.2 billion (Clark et al., 1985) to $7 billion (Ribaudo et al., 1989). Off-site costs include sediment with associated nitrogen,
contamination of water.

The complementary among yields, nutrients, and organic matter carbon is illustrated by Table 4. Soil organic matter (SOM) loss is both a cause and effect of erosion. As the SOM declined by 39 percent on Corwin soils, SOM that averaged 3.03 percent on slightly eroded Corwin soils fell to 1.86 percent on severely eroded soils. Sound conservation management practices that raise SOM from that found in severely eroded soil to that found in moderately eroded soil would raise SOM by 0.31 percentage points (19 percent). Carbon is sequestered in that SOM.

Severe erosion as opposed to slight erosion reduced corn yields on Corwin soils in Indiana by 9 percent, Miami soils 18 percent, and Morley soils 14 percent. Soybean yields fell proportionately more. Phosphorus fell 29 to 38 percent and plant available water fell 49 to 70 percent due to severe erosion on these Indiana soils. Thus, more commercial fertilizer would be required to maintain yield after erosion on the Indiana soils. Only relative clay content improved as larger size mineral particles eroded more rapidly than clay.

4.1 MARGINAL CROPLAND AND CARBON SEQUESTRATION

Because of the large and inelastic demand for global food, trees will not compete with crops for prime farmland. Trees can compete with crops for more marginal land, however. Shakya and Hitzhusen (1997, p. 24) compared net present value per hectare for Southcentral Ohio land in the Conservation Reserve Program (CRP) used for (1) cropland, (2) white pine tree plantation, and (3) continued in CRP. The analysis contrasted incentives for the landowner considering (1) only private costs and returns and (2) social costs and returns. Social costs included environmental effects such as soil erosion and water quality. Ignoring the unique and special case of a contract to supply pulpwood to a local paper company, the highest *private* return was from cropping the land. The highest *social* return was from growing white pine. Using a social discount rate of 4 percent and considering environmental impacts, the white pine plantation offered a net present social return of $1376 per hectare compared to a *negative* net present social return of $2134 for cropping the land.

The value of carbon sequestration was not considered, but if wood were "sequestered" as lumber in houses for many decades the social return would be $60 (4 percent) higher based on estimates from the previous section. The conclusion is that full accounting for externalities would call for conversion of many additional hectares of marginal, environmentally sensitive cropland in the eastern United States to timber plantations. Many of those hectares are currently in the 14 million hectare Conservation Reserve Program.

The complementarity between carbon sequestration and cropping practices is especially apparent from a recent study of North America as a carbon sink. The study (Fan et al., p.442) found that the continent takes up 1.7 Pg of carbon annually, a large portion indeed of the 1.0 to 2.2 Pg global terrestrial annual uptake of carbon. The authors listed "…regrowth on abandoned farmland and previously logged forest" as one source of the sink. Marginal land has become unprofitable for crops because science and technology have raised productivity, lowering crop prices. These sink numbers, three fifths of the net carbon added each year to the atmosphere, are tentative. But they reveal how agricultural science and technology investments having a high economic payoff in greater crop and livestock productivity alone have a potentially higher payoff after accounting for cropland released from food production to grow trees and preserve wildlife.

4.2 CONSERVATION AND CARBON SEQUESTRATION

Much of the interest in carbon sequestration in agriculture stems from major opportunities to build soil organic matter through conservation tillage. Adoption of conservation tillage was encouraged by advances in planting equipment and chemical weed control coupled with enhanced knowledge of benefits of conservation tillage for soil conservation and water quality. Other contributing factors included conservation education and the 1985 and 1996 farm programs requiring conservation compliance in order to receive direct payments from the government.

Producers appear to have exploited most opportunities for profitable conservation tillage in the United States--conservation tillage area was plateauing in the country by the mid-1990s (Table 5). Conservation tillage was practiced on 36 percent of cropland planted in 1996, up only 1 percentage point since 1993 and near the mid-1980s level. No-till, one form of conservation tillage, disturbs the soil least, preserves the most surface crop residue, and sequesters the most carbon. It increased from 5 percent to 15 percent of all "tillage" from 1989 to 1996. Considering only conventional tillage, the share classified as "reduced tillage" (15-30 percent residue) remained at one-fourth of all cropland while the share with less than 15 percent residue fell from 49 percent in 1989 to 38 percent in 1996.

Much of the decline in low residue conventional tillage is accounted for by less use of moldboard plows. In the 1950s nearly all U.S. corn was tilled with a moldboard plow. By 1995, only 8 percent of all U.S. corn and indeed of all crops on average was tilled with a moldboard plow (U.S. Department of Agriculture, p.162). Although moldboard plow tillage is not dominant for any major U.S. crop, conventional tillage with less than 30 percent residue remains the practice of choice on 98 percent of cotton acres, about three-fourths of wheat acres, and over two-thirds of southern soybean acreage (U.S. Department of Agriculture, July 1997, p.162). Thus, the potential is great for further conservation tillage--given sufficient inducements.

Farmers tend to adopt conservation tillage if it is privately profitable. The numerous studies of the profitability of conservation tillage reveal that in some circumstances net returns per hectare for conservation tillage are higher and in other circumstances are lower than returns for conservation tillage--depending on soil type, drainage, rainfall, crop, and other factors (Doster et al.; Klemme 1983; Hopkins et al.; Stephen et al.). Yield is frequently less in the short run with conservation than with conventional tillage. But production costs tend to be less for conservation tillage, hence it is often more profitable than conventional tillage even when conventional tillage yields are higher.

Results of a recent comprehensive study by Day et al. are shown in Table 6. Net returns for corn on all soil productivity classes are higher for conservation mulch tillage (at least 30 percent residue) than for any of the other three tillage methods considered. Conventional moldboard plow tillage was least profitable on low and medium productivity soils and nearly tied with no-till for least profitability on high productivity soils. In addition to soil conservation, advantages of conservation tillage include less power and labor requirements and less overall production costs. Disadvantages of conservation tillage include learning and time required to bring yield and profitability to conventional tillage levels, poor stands or late germination (causing yield loss) because of a cool and wet seedbed on tight soils shaded by mulch during cool and wet springs, and potential herbicide contamination of water. According to Day et al. (p.2), economic returns tend to vary more with conservation than with conventional tillage.

Recent innovations include fall strip tillage leaving considerable mulch along with a lightly cultivated band of cleared soil. This strip provides a warm seedbed for early spring germination. Other adaptations also will expand conservation tillage, but economic incentives currently seem inadequate to reach the goal of up to 75 percent adoption in the United States projected by Lal (1997, p. 81).

Conservation tillage may provide even less opportunity to raise soil organic carbon (SOC) in the tropics. Conservation tillage leads to high SOC near the surface compared to conventional tillage (Lal, 1997, p. 95). Surface SOC is especially vulnerable to volatilization from high heat and humidity. Conversion to conservation tillage also may have little effect on SOC for soils with coarse texture in arid climates that have been cultivated for many years (Lal, 1997, p. 95).

The stalling of conservation tillage in the United States at just over one-third of cropland indicates that "business as usual" may not bring satisfactory progress toward soil conservation, improved water quality, or carbon sequestration. A multifaceted approach discussed in the next section could speed progress towards environmental goals, recognizing complementarity in reaching targets, including low cost food.

5. POLICY OPTIONS

Carbon sequestration can be profitable on cropland as a joint product with crop production through practices such as conservation tillage, cover crops, legume forages, grass waterways, filter strips, recycled wastes, and the like. These practices largely pay for themselves even in the absence of carbon sequestration. Recycling of degraded lands also offers promise as noted earlier.

Data presented in the previous sections indicate that carbon sequestration in tree plantations as a complement to production of lumber and other forest products is feasible at relatively low costs. However, costs of carbon sequestration rise as area expands. Although a hectare of forest may sequester more carbon than a hectare of crops, tree plantations cannot be markedly expanded on cropland or grazing land in temperate zones without generating high costs to society from rising prices for food. The greatest opportunities for expanding carbon sequestration at low cost is on tree plantations in the subtropics (Sohngen et al.) and in the temperate zone on land marginal for crops but where rainfall is adequate.

Free market incentives alone may not reach socially desirable carbon sequestration levels in soils because not all value to society enters the accounts of market participants. If global warming is occurring and creating costs worth avoiding, several public policies potentially can help to alleviate the situation. We address global cooperation, a market in carbon, and U.S. farm policy initiatives.

5.1 INTERNATIONAL COOPERATIVE AGREEMENT

Because air is common property, any one individual, firm, or nation bears only a small share of the cost of the carbon each adds to the atmosphere. Because private costs that motivate decisions fall far short of social costs, too much carbon dioxide accumulates in the atmosphere. The result is the so called “tragedy of the commons”. Everyone desires to be a freerider--not taking action but waiting to reap the benefits of carbon control by others. One solution among countries is an international cooperative agreement to limit carbon emissions or to sequester carbon as in the Kyoto Protocol. This Protocol does not provide a mandate to guide actions of individual firms and agencies, however.

5.2 TRADING CARBON EMISSION AND SEQUESTRATION PERMITS IN THE MARKET

In theory, a system of property rights can align private marginal costs of releasing carbon dioxide into the atmosphere with social marginal cost. And a system of taxes, subsidies, regulations, education, and other tools can bring marginal social costs for controlling carbon emissions in line with marginal social costs of carbon sequestration--and all in line with marginal social benefits of using fossil fuels to provide energy. Assuming controversies over the need to sequester carbon are settled and global accord is reached for reducing atmospheric carbon, the task remains to find a system that achieves target carbon levels cost effectively.

Lessons from past successes creating a market in SO_2 emissions from power plants for cost-effective environmental protection might be applied to a carbon market extended to farms and forests. One procedure is to auction carbon emission rights to the highest bidders. The public sector would receive the receipts from the initial auction. An alternative procedure would begin by establishing *historic* carbon emission and sequestration levels for each firm or agent. Emitters then would be assigned carbon emission reduction quotas based on the target reduction below historic levels.

Regardless of how the issue of initial carbon permit allocations is decided, once established a private market for carbon would allow trading in permits to promote efficiency--those with higher benefits from adding atmospheric carbon and high cost of cutting back would purchase permits from entities with low benefits from adding atmospheric carbon or low costs of sequestering carbon. The credits purchased by firms allowing them to exceed allowances would be exactly offset by credits sold below allowances by other carbon credit market participants.

The market in carbon would create some inequities. Farmers who have diligently built soil organic carbon over the years would have little scope to collect receipts for carbon credits. Another problem with this system of carbon permits is inability of most farmers to sell carbon permits in sufficient volume to hold down administrative, verification, and monitoring costs. Farmers desiring to sell carbon sequestration credits might form cooperative pools to reduce such transaction costs. Officials could spot check farmer compliance periodically. Compliance might most efficiently be measured by use of best practices rather than soil carbon. Also to reduce administrative costs, only farmers who wish to enter the sequestration market would need to have their historic base established.

For sequestors, the sale of a carbon credit would constitute a lien on property to sequester that carbon in perpetuity. A farm buyer would be committed to maintain the contract level of sequestered carbon or return to the carbon market to buy back credits to sequester carbon.

5.3 TAXES AND SUBSIDIES

Historically, the public has used the “carrot” of payments to farmers rather than the “stick” of regulation to serve the environment. Strong political pressure may continue production flexibility contract transition payments as “green” payments after the 1996 farm bill expires in year 2002. Such green payments could be for conservation compliance extended to practices that encourage carbon sequestration as well as other environmental goals such as conservation tillage, cover crops, grass waterways, and filter strips that benefit society as well as farmers.

Previous discussion by economists has focused on eventually targeting transition or green payments to control soil erosion and water quality (see Tweeten and Zulauf). A far wider base of political support for programs could emerge if the payments, totaling $4 billion in year 2002, were targeted in future years to carbon sequestration as well. Nearly every farmer can sequester carbon but not all face soil erosion or water quality problems. In short, helping to correct the negative externalities of greenhouse gas accumulation, soil erosion, and water pollution by using funds with low opportunity cost (otherwise they might go to farmers for doing nothing) would likely have much political appeal.

6. SUMMARY AND CONCLUSIONS

Carbon sequestration in soils is less likely to be another cash "crop" than a farm income supplement. Some benefits of carbon sequestration through soil organic matter improve soil tilth, nutrient release, and moisture holding capacity. Because such benefits add economic returns to farmers, producers can be expected to make decisions that provide such benefits.

Other benefits of soil organic matter are not well allocated by markets because they are public rather than private goods—benefits accrue to society rather than to farm market participants. Traditionally the public interest in organic matter in soils has focused on soil conservation and water quality—externalities that can entail costs to "downstream" entities not part of on-farm costs and returns which determine a farmer's decisions. Growing concerns about global warming add another public interest in private decision making—build-up of organic matter that sequesters carbon to reduce greenhouse gas accumulation and possible attendant global warming.

Alternative agricultural tillage, crop rotations, livestock waste disposal, and other practices influence the degree of organic matter in farm soils. The growing popularity of conservation tillage, including no-till, which adds to carbon in the soil has heightened the interest in the role agriculture might play in sequestering carbon and thereby diminishing greenhouse effects.

To ascertain the potential role of agriculture in sequestering carbon to alleviate global warming, several questions were addressed:

1. What is the value to society of sequestering carbon?

2. What is the cost to agricultural producers of sequestering carbon?

3. How does the cost of carbon sequestration in agricultural soils compare with alternative means of carbon sequestration and fossil fuel energy conservation. An example of the former is growing of trees; an example of the latter is a shift from fossil fuels to wind, solar, or nuclear power.

4. What are the limits of *economically feasible* carbon sequestration in agriculture? Is it a potential major or minor player in an effort to reduce greenhouse gases?

5. What public policies might most effectively increase carbon sequestration in agriculture?

The current incremental value of carbon sequestration cannot be estimated with precision but some only estimate the value to be about $5 per ton. The value may rise in the future (see Table 1). The cost to agriculture of sequestering carbon is low or negative (it pays) for up to perhaps 40 million tons, is modest for the next 40 million tons, and becomes high for over 80 million tons (see Table 2). Other means such as afforestation and fossil fuel energy conservation can efficiently reduce atmospheric carbon. However, soil carbon sequestration can compete with other approaches to reduce greenhouse gases over some ranges (see Table 2).

Question 4 above cannot be answered with much confidence. Appropriate public policy decisions regarding global warming are not possible without better measures of the marginal social costs and benefits of soil carbon sequestration. Estimates of costs (and benefits) of carbon sequestration on cropland are primitive, an empirical vacuum waiting to be filled. Proper modeling to find answers could use a mathematical programming model, parametrically raising the price of carbon per hectare from low to high levels while observing the increase in carbon sequestration on representative resource situations (typical farms) across the nation. Such analyses would need to account for complementarities of soil organic mater (SOM) with crop yields, water quality, and soil erosion over time--considering on- and off-site costs and benefits. Analysis needs to consider the time sequence of SOM buildup under alternative fertilization, tillage, rotation, and other cropping practices. The total discounted cost of commercial fertilizer would be estimated over time recognizing that more fertilizer may be applied in early years to build SOM, and less applied in later years as SOM conserves soil and nutrients while appropriately releasing them for plant growth. Such measures of incremental social costs of soil carbon sequestration then can be compared with improved measures of incremental social costs of global warming to formulate proper carbon emission control and sequestration levels.

Turning now to question 5 above, three public policy initiatives were proposed to address soil carbon sequestration. One was the need for collaborative international arrangements to avoid the “tragedy of the commons.” The second was to establish a carbon emission and sequestration permit market to minimize costs of meeting established greenhouse gas targets. The third was to target production flexibility contract payments--if they are continued--to “green” payments for soil conservation, water quality, and carbon sequestration.

7. REFERENCES

Adams, R., Adams, D., Calloway, J., Chang, C., and McCarl, B., Sequestering carbon on agricultural land: social cost and impacts on timber markets, *Contemporary Social Issues* 12, 76, 1993.

Alig, R., Adams, D., McCarl, B., Callaway, J., and Winnett, S., Assessing effects of mitigation strategies for global climate change with an international model of the U.S. forest and agricultural sectors, *Economics of Carbon Sequestration in Forestry*, Sedjo, R., Sampson, R., and Wisniewski, J., Eds., Lewis Publishers, Boca Raton, FL, 1997, S97-S111.

Babcock, B. Unpublished worksheets on carbon sequestration through conservation tillage in 12 Midwest states, Center for Agricultural and Rural Development, Iowa State University, Ames 1998.

Brown, S., Global warming policy: some economic implications, *Economic Review*, Dallas, TX: Federal Reserve Bank, Fourth Quarter 1998, 26-35.

Bruce, J., Frome, M., Haites, E., Janzen, H., Lal, R. and Paustian, K., Carbon Sequestration in Soils. Paper from Soil and Water Conservation Society, Carbon Sequestration in Soils Workshop, Calgary Alberta, May 1998.

Clark, E., Haverkamp, J., and Chapman, W., *Eroding Soils: The Off-Farm Impact,* Conservation Foundation, Washington, D.C., 1985.

Day, J., Sandretto, C., McBride, W., and Breneman, V., Conservation Tillage in U.S. Corn Production: an Economic Appraisal, Paper presented at the annual meeting of the American Agricultural Economics Association, Salt Lake City Utah, August, 1998, Economic Research Service, U.S. Department of Agriculture, Washington, D.C., 1998.

Decanio, S., The Energy Paradox: Bureaucratic and Organizational Barriers to Profitable Energy-Saving Investments, Working Paper in Economics No. 19-95, Santa Barbara: Department of Economics, University of California, 1995.

Doster, D., Griffith, D., Mannering, J., and Parsons, S., Economic returns from alternative corn and soybean tillage systems in Indiana, *Journal of Soil and Water Conservation,* 38, 504, 1983.

Dregne, H. and Chou, N., Global desertification dimensions and costs, in *Degradation and Restoration of Arid Lands,* Dregne, H. E., ed., International Center for Arid and Semi-Arid Land Studies, Texas Tech University, Lubbock, 1992, 249-281.

Fan, S., Gloor, M., Mahlman, J., Pacala, S., Sarmiento, J., Takahashi, T., and Tans, P., A large terrestrial carbon sink in North America implied by atmospheric and oceanic carbon dioxide data and models, *Science*, 282, 442, October 16, 1998.

Fankhauser, S. and Pearce, D., The Social costs of greenhouse gas emissions, *Economics of Climate Change,* Organization for Economic Cooperation and Development, Paris, 1994.

Heath, L., Birdsey, R., Row, C., and Plantinga, A., Carbon Pools and Fluxes in U.S. Forest Products, NATO ASI Series, I(40), 271-278, 1996.

Hoen, H. and Solberg, B., Potential and economic efficiency of carbon sequestration in forest biomass through silvicultural management, *Forest Science*, 40(3), 429, 1994.

Hopkins, J., Schnitkey, G. and Tweeten, L., Impacts of nitrogen control policies on crop and livestock farms at two Ohio farm sites, *Review of Agricultural Economics,* 18, 311, September 1996.

Klemme, R., A stochastic dominance comparison of reduced tillage systems in corn and soybean production under risk, *American Journal of Agricultural Economics*, 67, 550, August 1985.

Lal, R., Residue management, conservation tillage, and soil restoration for mitigating greenhouse effect by CO_2-enrichment, *Soil and Tillage Research* 43, 81, 1997.

Lal, R., Kimble, J., Levine, E., and Whitman, C., World soils and greenhouse effect: an overview, in *Soils and Global Change*, Lal, R., Kimble, J., Levine, E., and Stewart, B., Eds., CRC/Lewis Publishers, Boca Raton, FL, 1995, 1-8.

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

Mendelsohn, R., and Neumann, J., *The Market Impact of Climate Change on the U.S. Economy*, Cambridge U. Press, 1998.

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

Nordhaus, W., Rolling the "Dice": An Optimal Transition Path for Controlling Greenhouse Gases, Cowles Foundation Paper No. 836, Cowles Foundation for Research and Economics, Yale University, New Haven, CT, 1993.

Nordhaus, W. and Yang, Z., A regional dynamic general-equilibrium model of alternative climate-change strategies, *American Economic Review*, 6, 741, September 1996.

Oldeman, R., Hakkeling, R., and Sombroeck, W., World Map of the Status of Human-Induced Soil Degradation: An Explanatory Note, Wageningen, International Soil Reference and Information Center, United Nations Environmental Program, The Netherlands, Nairobi, Kenya, 1990.

Parks, P. and Hardie, I., Least-cost forest carbon reserves: cost-effective subsidies to convert marginal agricultural land to forests, *Land Economics*, 71(1), 122, 1995.

Paustian, K., Andren, O., Janzen, H., Lal, R., Smith, P., Tian, G., Tiessen, H., van Noordwijk, M., and Woomer, P., Agricultural soil as a C sink to offset CO_2 emissions, *Soil Use and Management*, 13, 230, 1997.

Reilly, J., Agriculture in a Changing Climate: Impacts and Adaptation, *Climate Change 1995--Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analysis,* Watson, R., Zinyowern, M., and Moss, R. Eds., *Cambridge*: Cambridge U. Press, Cambridge, Chap. 13, 1996.

Ribaudo, M., Colacicco, D., Barbarika, A., and Young, C., The economic efficiency of voluntary soil conservation programs, *Journal of Soil Conservation*, 44, 40, 1989.

Richards, K. and Stokes, C., National, Regional, and Global Carbon Sequestration Cost Studies: A Review and Critique, Draft Paper, Indiana University, 1995.

Sanders, J., Southgate, D., and Lee, J., The economics of soil degradation: technological change and policy alternatives, Technical Monograph Number 22, USAID Soil Management Support Service, Washington, 1995.

Schimmelpfenning, D., Global climate change: could U.S. agriculture adapt? *Agricultural Outlook,* Economic Research Service, USDA, Washington, D.C., January-February 1997, 28.

Sedjo, R., Forests, a tool to moderate global warming?, *Environment*, 13(1), 14, 1989.

Shakya, B. and Hitzhusen, F., A benefit-cost analysis of the conservation reserve program in Ohio: are trees part of a sustainable future in the Midwest?, *Journal of Regional Analysis and Policy*, 27, 13, 1997.

Sohngen, B., Mendelsohn, R. and Sedjo, R., The Effectiveness of Forest Carbon Sequestration Strategies with System-Wide Adjustments, Paper presented at 1998 Annual Meeting of American Agricultural Economics Association, Salt Lake City, Utah, July 21, 1998, Department of Agricultural, Environmental, and Development Economics, Ohio State University, Columbus, 1998.

Stavins, R., The costs of carbon sequestration: a revealed-preference approach, *American Economic Review*, forthcoming, 1998.

Stephen, J., Henderson, W., and Stonehouse, D., Effects of soil tillage and time of planting on corn yields and farm profits in southern Ontario, *Canadian Journal of Agricultural Economics*, 36, 127, October 1987.

Tweeten, L. and Zulauf, C., Public policy for agriculture after commodity programs, *Review of Agricultural Economics* 19(Fall/Winter 1997), 263.

U.S. Department of Agriculture, Agricultural Resources and Environmental Indicators, 1996-1997, Agricultural Handbook No. *712,* ERS, USDA, Washington, D.C., July 1997.

Watson, R., Zinyowera, M., and Moss, R., Eds., *The Regional Impacts of Climate Change: An Assessment of Vulnerability*, A special report of IPCC WORKING GROUP II, Cambridge, UK: Cambridge University Press, 1998.

Weesies, G., Livingston, S., Hosteter, W. and Schertz, D., Effects of soil erosion on crop yield in Indiana: results of a 10-year study, *Journal of Soil and Water Conservation* (November-December 1994), 598.

8. TABLES

Table 1. Economic benefit per ton of less carbon emissions or of more carbon sequestration

Analysts	*Benefit from carbon reduction*	*Comments*
Fankhauser and Pierce 1994	$20/ton (Global)	Simplified model; covered range of carbon levels
Nordhaus 1993; Nordhaus and Yang 1996	$6/ton in year 2000 to $21/ton in 2100 (Global)	Measured by tax justified to bring marginal cost in line with marginal benefit in efficient solution
Brown 1998	8 to $59 (Global)	Summary from eight studies. Actual range was from zero to $300. Numbers to left most likely range.
Mendelsohn and Neumann 1998	Zero (U.S.)	Gains to farming, timber, and recreation industries; loss to coastal, energy, and water sectors

Table 2. Summary of costs for reducing carbon emissions or sequestering carbon

Analysts	*Ecosystem*	*Cost/ton carbon*	*Comments*
Lower emissions			
Decanio 1995	U.S. businesses	Negative	45% internal rate of return on costs from measures to increase energy lighting efficiency.
Carbon sequestration: forest ecosystems and tree plantations			
Moulton and Richards 1990	U.S. forest plantations on marginal agricultural land	$8.50 to $38.29	Overall cost $700 million to $19.5 billion/yr.
Adams et al. 1993	U.S., conversion of agricultural land to tree plantations	$7.40 to $60.75	Assumes timber harvest with lower cost for 32 million metric tons, and higher cost for 635 million metric tons without timber harvest.
Parks and Hardie 1995	U.S. marginal agricultural land	$9 to $10	8.9 million hectares costing $3.7 billion to sequester 4.7 tons/ha/yr.
Sedjo 1989	Temperate zone forests	$3.50	465 million hectares required to offset 2.9 Pg carbon accumulation per year @ 6.24 tons of carbon/hectare could drive down lumber prices.
Hoen and Solberg 1994	Norwegian forests	$79	Examined different management strategies.
Stavins 1995	37 U.S. counties in the South	less than $66	Marginal cost nearly linear to 9 million ton carbon storage/yr.
Sohngen et al. 1998	Global, emphasizing subtropical forest plantation strategy	not available	Tree plantation in subtropical region most promising.

Analysts	*Ecosystem*	*Cost/ton carbon*	*Comments*
Richards and Stokes 1995	Review of studies over wide range of ecosystems	$1 to $187	Cost depends on region, growing factors, and other conditions.
Carbon sequestration: Cropland			
Bruce Babcock 1998 (preliminary)	12-state U.S. Midwest region, all major crops	$0 to 11 million tons, $200 at 19 million tons, $400 at 22 million tons	One-fourth of U.S. crop production, conservation tillage only. Marginal cost of 1 ton of cumulative carbon buildup per year.

Table 3. Income foregone over 20-year period and rehabilitation cost on desertified land that would produce positive cost-benefit ratio when rehabilitated.

Land use	*Area to be rehabilitated*	*Benefit: added income if land is rehabilitated*	*Cost of rehabilitation*	*Benefit-cost ratio*
	(million ha)	…………..… (million $) …….....…		(B/C)
Irrigated land	43.1 (100%)	215,500	86,200	2.5
Rainfed cropland	150.9 (70%)	114,684	60,360	1.9
Rangeland	1,666.8 (50%)	233,352	66,672	3.5
	1,860.8 (52%)	563,536	213,232	2.6

Source: Dregne and Chou (1992, p. 279).

Table 4. Soil properties and yields by soil: results of a 10 year study in Indiana

Soil series	*Crop yield*		*Phosphorus*	*Plant available water*	*Clay content*	*Organic matter*
	Corn	*Soybeans*				
	(Percentage change, severe versus slight erosion)					
Corwin	- 9	-20	-34	-49	+11	-39
Miami	-18	-17	-29	-70	+44	-20
Morley	-14	-24	-38	-51	+53	-16

Source: Weesies et al. p.598

Table 5. U.S. crop production tillage practices

Item	1989	1993	1996
	(Percent of total)		
Total cropland planted			
Conventional tillage (<30% residue)	74.4	65.1	64.2
Reduced tillage (15-30% residue)	25.3	26.3	25.8
Conv. tillage (<15% residue)	49.1	38.8	38.4
Conservation tillage (>30% residue)	25.6	34.9	35.8

Source: U.S. Department of Agriculture, July 1997, p. 158.

Table 6. Corn net returns over variable costs, by tillage system and soil productivity class, ten states, 1996[a]

	Soil Productivity Class[b]		
Tillage System	Low	Medium	High
	$Net return/ha.	$Net return/ha.	$Net return/ha.
Conventional w/o plow	433	524	607
Conventional with plow	315	418	539
Conservation: Mulch	470	558	619
Conservation: No-till	416	555	534

Source: Day et al., Table 2.

[a] States are: IA, IL, IN, MI, MN, MO, NE, OH, SD, and WI.

[b] Productivity classes are based on soil-crop sufficiency conditions for bulk density, water holding capacity, permeability, clay content, pH, soil depth, and soil profile.