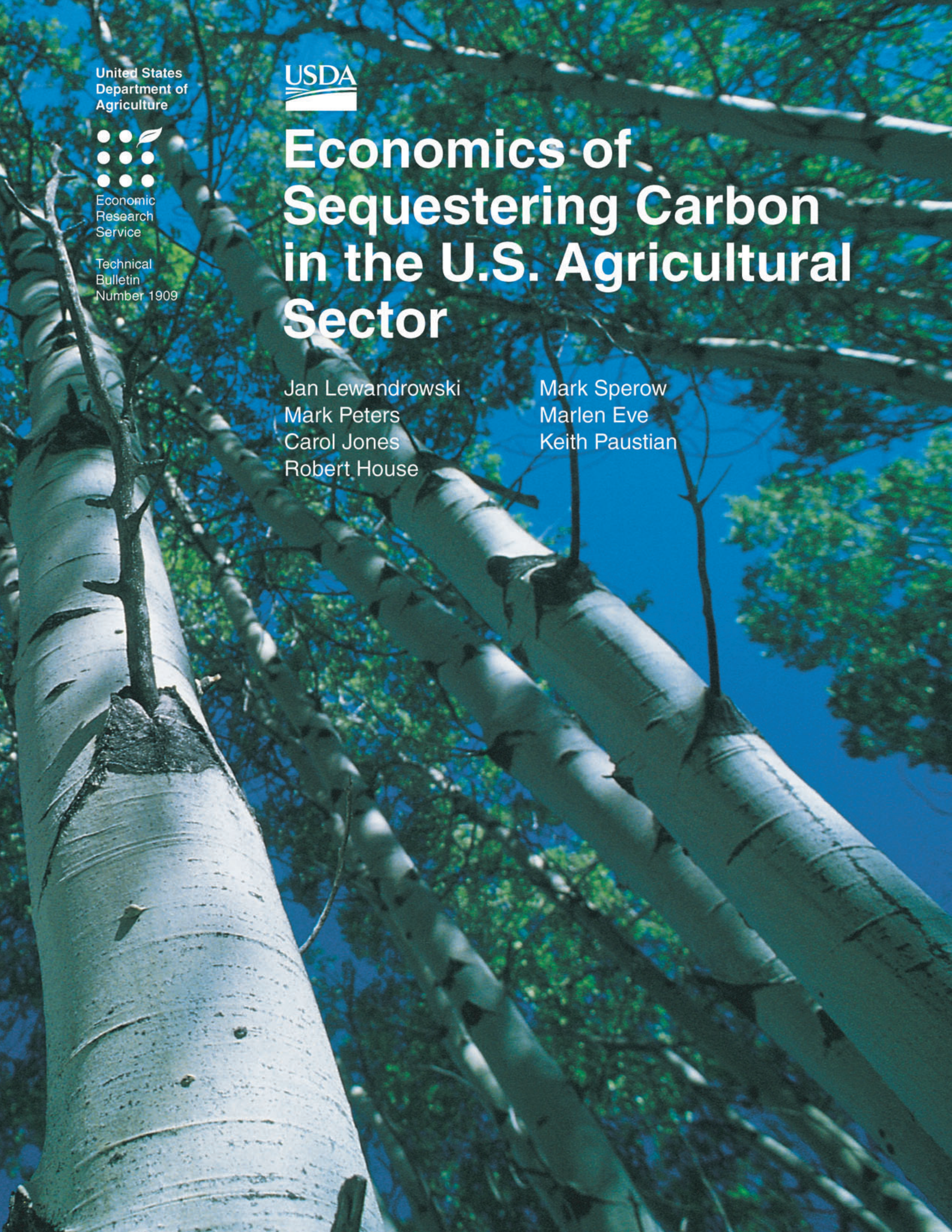

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Economics of Sequestering Carbon in the U.S. Agricultural Sector

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Abstract

Atmospheric concentrations of greenhouse gases can be reduced by withdrawing carbon from the atmosphere and sequestering it in soils and biomass. This report analyzes the performance of alternative incentive designs and payment levels if farmers were paid to adopt land uses and management practices that raise soil carbon levels. At payment levels below $10 per metric ton for permanently sequestered carbon, analysis suggests landowners would find it more cost effective to adopt changes in rotations and tillage practices. At higher payment levels, afforestation dominates sequestration activities, mostly through conversion of pastureland. Across payment levels, the economic potential to sequester carbon is much lower than the technical potential reported in soil science studies. The most cost-effective payment design adjusts payment levels to account both for the length of time farmers are willing to commit to sequestration activities and for net sequestration. A 50-percent cost-share for cropland conversion to forestry or grasslands would increase sequestration at low carbon payment levels but not at high payment levels.

Keywords: Carbon sequestration, greenhouse gas mitigation, afforestation, conservation tillage, no-till, incentive design, leakage, carbon stock, and permanence.

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Summary

Strategies that have been proposed to mitigate global climate change typically focus on reducing energy-related emissions of greenhouse gases (including carbon dioxide) into the atmosphere. But atmospheric concentrations of greenhouse gases also can be reduced by withdrawing carbon from the atmosphere and storing, or sequestering, it in soils and biomass. In examining the economics of sequestering carbon in the U.S. farm sector through changes in agricultural land use and management practices, this study focuses on two questions:

- How much of the estimated "technical" potential for carbon sequestration is economically feasible?
- How cost effective are alternative designs for incentive payments that might be used to encourage carbon-sequestering activities?

Model-based findings reflect the provision of financial incentives to landowners for sequestering carbon through changes in land use (converting cropland to forest or grassland) and cropland management practices (adopting conservation tillage or alternative crop rotations):

- **Agriculture can provide low-cost opportunities to sequester additional carbon in soils and biomass.** At a price of $10 per metric ton for permanently sequestered carbon, the ERS model estimates that from 0.4 to 10 MMT of carbon could be sequestered annually from adoption of the land-use changes or management practices analyzed; and at $125 per ton, from 72 to 160 MMT could be sequestered, enough to offset 4 to 8 percent of gross U.S. emissions of greenhouse gases in 2001.

- **The different sequestration activities studied become economically feasible at different carbon prices.** The model predicted that farmers would adopt cropland management (primarily conservation tillage) at the lowest carbon price, $10 per metric ton permanently sequestered carbon, and would convert land to forest as the price rose to $25 and beyond. The model predicted farmers in most regions would not convert cropland to grassland up through a $125 carbon price (in the absence of other incentives, such as Conservation Reserve Program payments), in part because conversion to afforestation was more profitable with its higher sequestration rate per acre. These estimates are comparable with estimates in earlier studies.

- **The estimated economic potential to sequester carbon is lower than previously estimated technical possibilities.** Soil scientists have estimated that increased adoption of conservation tillage on U.S. cropland has the technical potential to sequester as much as 107 million metric tons (MMT) additional carbon. The ERS model estimates *economic potential* by factoring into farmers' adoption decisions the tradeoff between the additional costs of sequestering practices, relative to the additional returns from the per ton carbon payments. We estimate that farmers could sequester up to an additional 28 MMT by adopting *conservation tillage* on additional lands at the top carbon price we studied, $125 per ton. For the *other activities* studied—afforestation and, particularly, for conversion to grassland—the estimated economic potential also was less than the literature estimates of technical potential.

- **Incremental sequestration from agricultural activities can continue for decades.** Conversion to conservation tillage could sequester additional soil carbon for 20-30 years, at which point a new equilibrium level of soil carbon would be attained. But carbon may be released relatively rapidly if farmers shift back to conventional tillage. Additional sequestration from afforestation may continue for many more decades, depending on region, species of trees, and harvest decisions.

These findings have implications for policy:

- **Payments for carbon sequestration may exceed their value if sequestration is not permanent.** To have the same greenhouse gas mitigation value as a unit of carbon emissions reduction, a unit of additional carbon sequestration must remain stored in soils or biomass permanently. If a program makes per ton payments equal to the value of permanent sequestration (“asset” payments), overpayments will occur if subsequent changes in land use or management practices release carbon back into the atmosphere—unless compensation is adjusted for the releases. “Rental” payment mechanisms, which pay farmers to store carbon for specific periods by maintaining carbon-sequestering practices, can help avoid this problem—particularly for contract renewals after the period when a new equilibrium level of soil carbon is reached and no more carbon is being added to the soil.

- **An incentive system that includes both payments for carbon sequestration and charges for carbon emissions may be much more cost effective than a system with payments only.** For example, at a carbon price of $125 per ton of permanently sequestered carbon, changes in tillage practices account for 7 MMT of additional sequestered carbon with a rental payment system that includes both payments and charges. Annual government expenditures for storage of this carbon during the 15-year contract period total $300 million. In contrast, when the incentives include only carbon payments, a price of $125 per ton results in half the sequestered carbon (3.5 MMT), while annual government expenditures increase tenfold to $1.5 billion.

- **Adding a cost-share subsidy does not appear to improve the cost effectiveness of incentive systems.** A 50-percent cost-share for cropland conversion to forestry or grasslands would increase sequestration at low carbon payment levels but not at high payment levels. The implications for cost per ton are minimal.

Economics of Sequestering Carbon in the U.S. Agricultural Sector

Jan Lewandrowski, Mark Peters, Carol Jones,
Robert House, Mark Sperow, Marlen Eve, and Keith Paustian

Chapter 1: Introduction

Increasing the quantity of carbon sequestered—or stored—in soils and biomass is an alternative to reducing emissions of carbon and other greenhouse gases (GHG) in an overall strategy to mitigate global climate change and its negative economic and environmental effects. In February 2002, the President directed the Secretary of Agriculture to develop recommendations for incentives designed to encourage owners of agricultural and forest lands to adopt production practices and land uses that extract carbon from the atmosphere and sequester it in terrestrial sinks. This report provides information useful for evaluating the economic implications of several frequently discussed designs for incentive programs that might be used to expand such land uses and production practices in the U.S. farm sector.

Recent studies indicate that U.S. agricultural soils are now being managed as a modest carbon sink—accounting for net sequestration of 4 million metric tons (MMT) of carbon annually (U.S. EPA, 2003).[1] It is generally believed that these soils could be managed to store significantly more carbon. Sperow et al. (2003) estimate that U.S. croplands could be managed to sequester an additional 60-70 MMT of carbon per year. Lal et al (1998) put this figure at 75-208 MMT. Follett et al. (2001) estimate that U.S. grazing lands could be managed to sequester an additional 29-110 MMT of carbon per year. These studies do not consider the option of sequestering carbon by shifting marginal croplands and grazing lands to forest. Hence, even in the absence of afforestation, the estimates in these studies suggest it may be technically possible to sequester an additional 89-318 MMT of carbon annually on U.S. croplands and grazing lands. Based on 2001 emissions, this level of carbon sequestration would offset between 5 and 17 percent of gross U.S. GHG emissions.[2]

From a policy standpoint, it is important to note that the carbon sequestration assessments of Sperow et al., Lal et al., and Follett et al. do not take into account the cost to store the additional carbon in agricultural soils. The marginal cost of sequestering additional units of carbon would be expected to rise as the quantity sequestered increases. Consequently, the cost of increasing the carbon content of all agricultural soils to the levels suggested by these studies could be very high. Further, it may be more cost effective to sequester carbon by changing the use of some lands now engaged in commodity production, for example, by shifting cropland or pasture to forest.

This study explores the economic potential of the U.S. farm sector to store additional carbon, and the resulting implications for land-use changes and the economic well-being of producers and consumers. To assess this potential, we adapt the U.S. Agricultural Sector Model (USMP) to include sequestration and emissions parameters associated with switching into and out of land uses and production practices that build carbon levels in soils and biomass. The cropland management and grassland conversion parameters are based on the Intergovernmental Panel on Climate Change (IPCC) GHG inventory procedures (1997). Forestry parameters are from U.S. Forest Service estimates (Birdsey, 1996). With this information as a base, we incorporate incentive payments for afforesting croplands and pasture, shifting cropland to permanent grasses, and increasing the use of production practices (particularly no-till) and rotations that raise soil-carbon levels. We run model simulations reflecting four alternative payment structures and six alternative payment levels for additional carbon sequestration from adoption of these activities.

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[1] For perspective, the U.S. Environmental Protection Agency (2003) estimates 2001 net sequestration in U.S. forests at 207 MMT of carbon.

[2] For 2001, the U.S. Environmental Protection Agency (2003) estimates gross U.S. emissions of greenhouse gases at 1,892 MMTCE, including carbon emissions of 1,580 MMT.

Chapter 2: Conceptual Issues

To provide context, we first review the GHG emissions profiles of the United States and the U.S. farm sector, and existing evidence on the technical potential of farm-sector activities to sequester carbon. We then discuss two key issues in establishing comparability between the GHG mitigation options of carbon sequestration and carbon emissions reduction—"permanence" and "C-stock equilibrium." The permanence issue refers to the potentially temporary GHG mitigation effect of carbon sequestration relative to GHG emissions reduction, and the C-stock equilibrium issue refers to the finite period of time that terrestrial systems can accumulate additional carbon under a new management system. Key issues in incentive design include defining the scope of the incentives and the scope of the GHG accounting, choosing the carbon measure (net or gross emissions) on which payments are based, and selecting the set of farmers eligible to receive incentive payments. The resolution of these design issues have important implications for the cost effectiveness of any incentives to store additional carbon in agricultural soils and biomass and the degree to which those incentives may encourage responses that result in offsetting carbon emissions.

U.S. Total Emissions and Agricultural Sector Emissions of Greenhouse Gases

The decades-long upward trend in GHG emissions for the United States as a whole and for the U.S. agricultural sector continued during the recent period 1990-2001 (table 2.1). Gross emissions for 2001 are estimated at 1,892 million metric tons carbon equivalent (MMTCE) (U.S. EPA, 2003), which implies an average annual increase of 1.1 percent during 1990-2001. Carbon dioxide (CO_2) emissions represent 82 percent of all U.S. GHG emissions in 2001. Although not evident in the table, about 98 percent of gross CO_2 emissions are attributed to the combustion of fossil fuels. The other major GHGs, methane (CH_4) and nitrous oxide (N_2O), represent 9 percent (CH_4) and 6 percent (N_2O) of total 2001 U.S. GHG emissions on a carbon-equivalent basis.[1, 2]

Agricultural sector emissions of carbon dioxide, methane, and nitrous oxide account for about 9 percent of all U.S. GHG emissions. However, the pattern of emissions in agriculture is quite different than in other sectors. Carbon dioxide emissions represent a small share of total agricultural GHG emissions, while the shares of nitrous oxide (60 percent) and methane (31 percent) are far more significant. In terms of agricultural activities, soil management emits the greatest amount of GHG, with an estimated 80 MMTCE of nitrous oxide emissions (primarily from applications of nitrogen fertilizers) (fig. 2.1). In contrast, soil management currently represents a "net sink" for carbon, sequestering 4 MMTCE in 2001. Thus, soil management emits a net total of 76 MMTCE. Livestock activities generate the next two highest emissions levels in agriculture, with enteric fermentation (i.e., digestion by ruminant livestock) emitting 31 MMTCE of methane and manure management emitting 11 MMTCE of methane and 5 MMTCE of nitrous oxide. Fuel combustion on farms, accounting for 14 MMTCE of carbon dioxide emissions, and rice production, accounting for 2 MMTCE of methane, are the next highest GHG-emitting activities.

Potential Activities for Mitigation of GHG Emissions in the U.S. Agricultural Sector

For cropland, the activities with the highest potential for storing carbon are afforestation, conversion of cropland to perennial grasses, and switching from conventional tillage to conservation tillage (particularly no-till)

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[1] GHGs vary in their contribution to global warming. To make cross-gas comparisons, the IPCC developed the concept of global warming potential (GWP) values. GWP values (on a mass basis) are expressed relative to CO_2 and for a 100-year time horizon. CO_2 is assigned a value of 1, CH_4 a value of 23, and N_2O a value of 296 (IPCC, 2001b).

[2] U.S. EPA (2003) presents emissions in teragrams of CO_2 equivalents (Tg CO_2 Eq). Since 1 Tg = 1 MMT, we can see that multiplying TgCO_2 Eq by 0.2727 yields MMTCE, million metric tons of carbon equivalent.

Table 2.1—Selected U.S. greenhouse gas (GHG) emissions

	1990	1995	2000	2001
	Million metric tons carbon equivalent			
Total U.S. emissions:				
Carbon	1,364.6	1,454.8	1,604.5	1,580.4
Methane	175.6	177.3	167.3	165.2
Nitrous oxide	108.4	117.5	117.2	115.8
HFCs, PFCs, and SF_6	25.7	27.1	33.0	30.3
Total U.S. gross emissions	1,674.4	1,776.8	1,922.0	1,891.7
Land-use change and forestry carbon sequestration*	-292.6	-290.2	-227.6	-228.6
Total U.S. GHG net emissions**	1,381.9	1,486.6	1,694.4	1,663.1
Agricultural sector emissions:				
Carbon:				
Fossil fuel combustion	12.6	15.5	13.7	13.7
Total - agricultural sources	12.6	15.5	13.7	13.7
Percent of U.S. total carbon emissions	2.1	2.2	2.1	2.1
Agricultural soils - sequestration*	-3.6	-4.1	-3.8	-4.1
Percent of U.S. total carbon sequestration	1.2	1.4	1.7	1.8
Methane:				
Enteric fermentation	32.2	33.5	31.6	31.3
Manure management	8.5	9.9	10.4	10.6
Rice cultivation	1.9	2.1	2.0	2.1
Crop residue burning	0.2	0.2	0.2	0.2
Total - agricultural sources	42.8	45.7	44.3	44.2
Percent of U.S. total methane	24.4	25.8	26.5	26.8
Nitrous oxide:				
Soil management	73.0	77.5	80.3	80.3
Manure management	4.4	4.5	4.9	4.9
Crop residue burning	0.1	0.1	0.1	0.1
Total - agricultural sources	77.6	82.2	85.4	85.4
Percent of U.S. total nitrous oxide	71.5	69.9	72.9	73.7
Total U.S. agriculture GHG net emissions**	133.05	143.44	143.47	143.39

* Carbon sequestered as a result of agricultural and forestry activities, involving both land-use change and land management. Negative values imply sequestration.

** Total carbon-equivalent emissions minus land-use change and forestry carbon sequestration, in million metric tons carbon equivalent.

Source: U.S. Environmental Protection Agency (2003). See *http://www.epa.gov/globalwarming/publications/emissions*

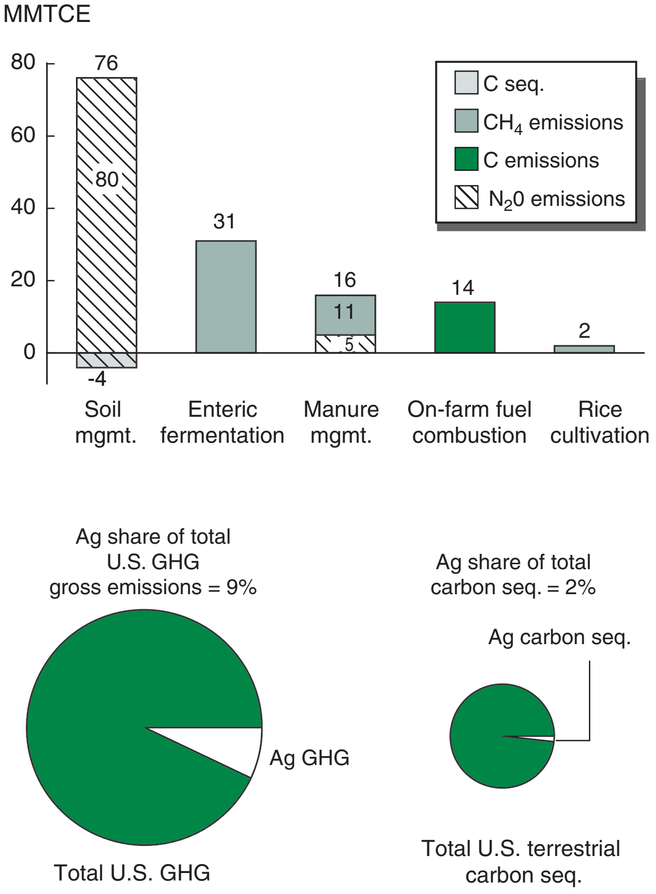
(fig. 2.2). These activities also rank relatively high in sequestration per acre—1, 2, and 5, respectively—among the cropland activities listed in table 2.2. Activities with lower carbon-storing potentials include changing crop rotations, expanding the use of winter cover crops, eliminating periods of summer fallow, changing fertilizer management, using more organic soil amendments (i.e., manure, sludge, and byproducts), improving irrigation methods, shifting land to conservation buffers, and restoring wetlands.

For grazing lands, afforestation ranks highest in both per acre carbon sequestration and total potential carbon sequestration. Generally, pasture-management activities have high per acre sequestration rates but low total carbon-storing potentials. This finding reflects the comparatively limited areas of pastureland in the United States on which these GHG-mitigating activities are, or could be, practiced. For example, Follett et al. (2001) estimate current levels of pasture management at 32 million acres using additional manure applications, 6 million acres planted with improved grass varieties, and 25 million acres using improved grazing practices. For each activity, potential expansion is estimated at 13 million acres. Conversely, rangeland management has a low per acre sequestration rate but a high total carbon-storing potential because the contiguous United States has about 260 million acres of rangeland.

Outside of agricultural soil management, the next greatest sources of farm-sector GHG emissions are

Figure 2.1

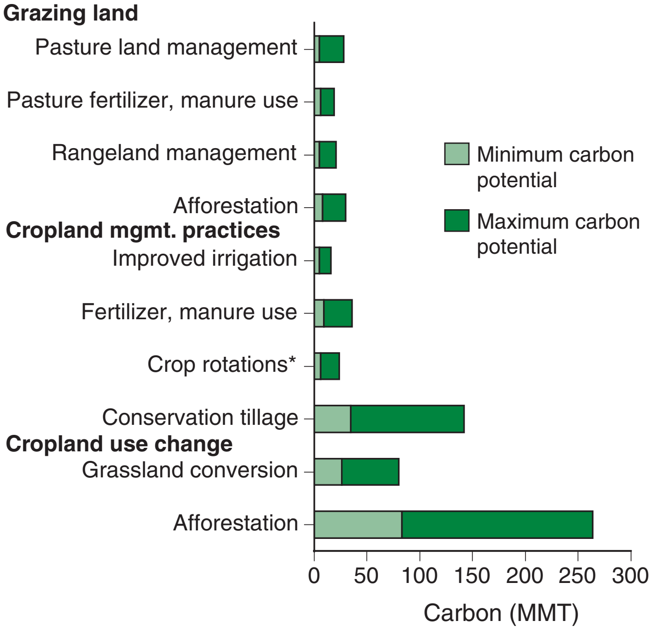
Agricultural emissions and carbon sequestration in 2001 by activity



Source: U.S. Environment Protection Agency (2003).
See website *http://www.epa.gov/globalwarming/publications/emissions*

Figure 2.2

Estimated potential carbon sequestration



* Includes winter cover crops and elimination of summer fallow.

Source: See table 2.2.

livestock enteric fermentation (methane) and manure management (methane and nitrous oxide). The technical and economic options for reducing emissions from these sources appear to be limited at this time. Substituting biofuels for fossil fuels on a continuous basis could reduce the rate of increase in atmospheric carbon over time. While every unit of fossil fuel consumed emits new stocks of carbon into the atmosphere, biofuel emissions are at least partially derived from recycling carbon already in the atmosphere via the production of biofuel crops.[3] Lal et al. (1998) estimate the average per acre reduction in net carbon emissions associated with biofuel crops at 1.42 metric tons (mt) for fuel substitution and 0.4 mt in additional soil carbon. They estimate a total GHG-mitigation potential of 39 MMT per year from shifting 10 million acres of idle cropland into biofuel crop production.

Comparing Reductions in Carbon Emissions With Increases in Carbon Sequestration

Conceptual discussions in the climate change literature often acknowledge that a unit of carbon emissions reduction and a unit of carbon sequestration may have very different contributions to net GHG mitigation over time. Studies cite two reasons for this variance in effect. First, to be equivalent with emissions reductions, carbon sequestration must be maintained for a period equal to the time emitted carbon remains in the atmosphere, which is referred to as “permanence.”[4]

Second, after undergoing a change from one management practice to another (e.g., from conventional

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[3] Bioenergy crops include corn (used to produce ethanol), soybeans (used to produce biodiesel), switch grass (used to generate electricity), and several fast-growing tree species (used to generate electricity). With the first three crop types, the carbon would be recycled in about a year. For tree species, the recycle time may be 5-10 years. Also, energy is an input in the production of ethanol and biodiesel. Carbon emissions related to this energy use would need to be accounted for in calculating the net GHG emissions reductions associated with increasing the use of these products.

[4] A 100-year time horizon is frequently employed, for example, in the IPCC calculation of global warming potential by EPA in its GHG inventory (U.S. EPA 2003, p. ES-9).

Table 2.2—Estimated potential annual carbon sequestration for selected changes in land use and production practices in U.S. agriculture

Land-use change or management practice	Estimated per acre sequestration	Total potential sequestration	Source	Included in this analysis
	Mt per acre	*MMT*	*Per acre/total potential*	
Cropland:				
Land-use changes:				
Afforestation of cropland[1, 2]	0.79 - 1.72	83 - 181	Birdsey (1996)/footnote 2	Yes
Croplands shifted to perennial grasses[1, 2]	0.25 - 0.51	26 - 54	Eve et al. (2000)/footnote 2	Yes
Conservation buffers[3]	0.13 - 0.25	1 - 2	Footnote 3/Lal et al. (1998)	No[4]
Restoration of wetlands[5]	0.10	5	Lal et al./see footnote 4	No
Production practice changes:				
Conservation tillage and residue management[6]	0.09 - 0.18	35 -107	Eve et al./Lal et al.	Yes
Improved crop rotations and winter cover crops	0.04 - 0.12	5 - 15	Lal et al.	Yes
Elimination of summer fallow	0.08	1 - 3	Lal et al.	Yes
Improved fertilizer management	0.02 - 0.06	6 - 18	Lal et al.	No
Use of organic manure and byproducts[7]	0.20 - 0.50	3 - 9	Follett et al. (2001)/Lal et al.	No
Improved irrigation management	0.04	5 - 11	Lal et al.	No
Grazing land:				
Afforestation of pasture	0.73 - 2.09	8 - 22	Birdsey/footnote 2	Yes
Rangeland management	0.05 - 0.15	5 - 16	Follett et al.	No
Pasture management:				
Improved use of fertilizers	0.10 - 0.20	2 - 4	Follett et al.	No
Use of organic manure	0.20 - 0.50	3 - 9	Follett et al.	No
Planting of improved species	0.10 - 0.30	1 - 3	Follett et al.	No
Grazing management	0.30 - 1.30	5 - 20	Follett et al.	No

[1] Estimated average annual carbon sequestration over first 15 years of growth.

[2] Moulton and Richards (1990) identify 105.5 million acres of cropland and 10.6 million acres of pasture where erosion exceeds the erosion tolerance rate. The total technical potential for afforestation assumes a complete conversion of these lands to trees. The total technical potential for grasses assumes a complete conversion of the 105.5 million acres of cropland to perennial grasses. The technical potential sequestration values are obtained by multiplying these acreages by the associated per acre sequestration rates.

[3] Conservation buffers are vegetated strips 5-50 meters in width used to reduce water pollution and erosion. The per acre values shown here are derived from the total values from Lal et al. (1998) and their assumption that 7.9 million acres of conservation buffers will be in place by 2020.

[4] Activities were omitted from the analysis when there was a lack of farm-level data on adoption cost. Without such data, it is not possible to assess the net returns associated with undertaking an activity relative to alternative production possibilities.

[5] Heimlich and Claassen (1998) estimate that there are 47.4 million acres of former wetlands and cropped wetlands that are suitable for restoration. The total potential sequestration is derived by multiplying the per acre sequestration from Lal et al. by 47.4 million acres.

[6] Per acre sequestration rates here assume conversion from conventional tillage to no-till.

[7] Per acre sequestration is Follett et al.'s (2001) estimate for application of manure on pasture.

Source: Listed in table.

tillage to conservation tillage), terrestrial systems tend to move to new equilibrium carbon levels over time. Terrestrial systems then accumulate additional carbon from activity changes for a finite period, until they reach a new “C-stock equilibrium.”[5] In empirical work, the treatment of permanence and C-stock equilibrium can greatly affect the economic analysis of carbon sequestration incentives. Many previous studies have simply treated carbon sequestration and emissions reductions as being equivalent—implicitly or explicitly assuming that any sequestration induced by incentives will be permanent.

Temporary Versus Permanent Terrestrial Sequestration

To illustrate the potential differences in GHG mitigation between emissions reduction and carbon sequestration, we use an example of a farm under one baseline emis-

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[5] In the literature, this concept has often been erroneously referred to as “saturation.” In soil science, saturation refers to an ultimate limit for the ability of soils to stabilize organic carbon irrespective of management change (Six et al., 2002). This true saturation level is likely several times greater than the total carbon found in most agricultural soils and is thus not a limiting condition for soil carbon sequestration in the near term.

sions scenario and two GHG mitigation scenarios—one assuming a decrease in farm fuel use (i.e., an emissions-reduction activity) and the other assuming a shift to no-till (i.e., a carbon-sequestering activity). For simplicity, we assume that each activity lasts 4 years and that all carbon stored as a result of shifting to no-till is released to the atmosphere when conventional tillage is resumed.[6] In the baseline scenario, the farm emits 10 mt of carbon annually (table 2.3). The first mitigation scenario assumes that the farmer accepts a payment to decrease fuel use. The decrease in fuel use reduces carbon emissions by 1 metric ton for each year the program is in effect. Furthermore, the reduction in the stock of atmospheric carbon achieved during the 4 years the program is in effect remains even after the program ends and both annual fuel use and related carbon emissions return to baseline levels (i.e., 10 mt per year). In this sense, activities that reduce emissions—even those with a finite duration—create "permanent" GHG-mitigation benefits.

Table 2.3—Hypothetical net carbon emissions from reducing farm fuel use or expanding no-till for a 4-year period

Activity	Year 1	2	3	4	5	Net emissions 5-yr total
			Metric tons			
Baseline emissions	10	10	10	10	10	50
Change from baseline emissions from mitigation activities						
Reduce fuel use	-1	-1	-1	-1	0	46
Expand no-till	-1	-1	-1	-1	+4	50

Source: Economic Research Service, USDA.

In the second mitigation scenario, the farmer accepts a payment to shift from conventional tillage to no-till for a period of 4 years. When the program stops, the farmer switches back to conventional tillage. In each year that the farmer uses no-till, 1 metric ton of carbon is sequestered in the soil. However, when the land is returned to conventional tillage at the start of year 5, the carbon added to the soil as a result of using no-till is released back to the atmosphere. So the stock of atmospheric carbon is temporarily lowered by the use of no-till but shifts back to the baseline accumulation path in year 5. Hence, the "temporary" GHG mitigation benefits gained from 4 years of sequestration activity are only a portion of the "permanent" benefits gained from the 4 years of emissions reduction.

Generally, for a unit of carbon sequestered in soil or biomass in year *t* to have the same climate change mitigation effect as a similar unit of emissions reduction in year *t* (and to be of equal mitigation value), the unit sequestered must remain in the soil or biomass for a period of about 100 years. In agricultural studies with one decision point, this means either assuming that sequestered carbon is stored permanently in sinks or designing the incentive as a "rental" payment, based on the duration of the rental commitment period. Carbon-sequestration studies typically specify payment structures that require participants to commit to sequestration activities for periods of at least 15-20 years. Such commitment periods, however, are substantially shorter than the time carbon remains in the atmosphere, leaving the temporary-permanent ton equivalency issue unresolved.

The scenarios in the example assume a modeling framework with a single decision point. In a framework that allows for multiple decision points through time, a third option is available: linking payments and charges to a long-term, real-time accounting system for sequestration and emissions. In this setup, farmers can receive payments when adopting activities that reduce net emissions and be charged when adopting activities that increase emissions. However, most empirical studies of the farm sector's potential to sequester carbon employ static modeling frameworks with one-time decision-making. In such cases, analysts need to state clearly whether they are assuming farmers continue or cease sequestration activities at the end of the commitment

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[6] This assumption is probably somewhat extreme for most real world situations but represents a reasonable simplification. Soil scientists generally agree that a large majority—but not all—of the carbon sequestered in U.S. soils as a result of converting conventionally tilled cropland to conservation tillage or grasses for a period of several years would be released to the atmosphere relatively quickly when conventional tillage resumes. Scientific studies that estimate such losses are scarce, but several studies on related topics support this view. In a study of soils in Lower Saxony, Germany, that had been managed with conservation tillage for 20 years, Stockfisch et al. (1999) found that all of the associated increase in soil organic matter was lost with a single application of conventional tillage. In a study of Wisconsin cropland that had been planted to grasses for several years, Lindstrom et al. (1998) found that the associated soil erosion benefits disappeared rapidly with resumption of conventional tillage. Finally, studies have demonstrated relatively large releases of CO_2, termed a CO_2 "burp," from soils in the period just after intensive tillage (Reicosky et al., 1997; and Reicosky, 1997).

period. More importantly, any payment for a unit of carbon sequestration needs to accurately reflect the net GHG mitigation achieved relative to an equivalent unit reduction in carbon emissions.

Carbon Stock Equilibration in Terrestrial Systems

Organic carbon is maintained in soils through a dynamic process. Plants convert carbon dioxide into tissue during photosynthesis; after a plant dies, a portion of the stored carbon is left behind in the soil by decomposing plant residue and a larger portion is emitted back into the atmosphere. Decomposition rates tend to be proportional to the amount of organic matter in the soil. Hence, over time and under relatively constant environmental and management conditions, rates of carbon additions and emissions tend to equilibrate and the amount of organic carbon in soils stabilizes at a constant, or steady-state, level (i.e., the C-stock equilibrium). If the relationship between additions and losses changes due to a change in soil management, the soil will gradually move to a new C-stock equilibrium. For example, if a shift from conventional tillage to reduced tillage increases the amount of crop residues returned to the soil and/or decreases the decomposition rate of organic matter, soil carbon will increase over time until a higher C-stock equilibrium is reached. Typically, the absolute gains in carbon per unit of time will diminish as the stock approaches the new equilibrium. Further increases after this point would require additional changes in management (e.g., switching to no-till).

Carbon stocks and potential rates of accumulation vary significantly across ecosystems with land use (e.g., forest, grassland, or cropland), management practices (e.g., tillage system, crop rotation, use of fallow and cover crops, nutrient applications, and irrigation management), geographic location, and local environmental factors (e.g., climate and soil characteristics). Due to past management practices, most agricultural soils have relatively depleted stocks of soil carbon, compared with native ecosystems, and thus can readily respond to improved management. Soil science studies generally find that agricultural ecosystems could be managed to accumulate additional soil carbon for periods of 15-60 years (U.S. EPA, 1991; Paustian et al., 1998; Dumanski et al., 1998; Bruce et al., 1998; and West and Post, 2002). For example, in summarizing more than 67 long-term agricultural experiments, West and Post find that it may take 23-30 years for soils to achieve a new C-stock equilibrium following a shift from conventional tillage to no-till, with the highest annual increments to soil carbon occurring between years 5 and 10. For shifts to crop rotations that enhance soil carbon (e.g., eliminating fallow periods or including hay in continuous rotation systems), soils may not approach a new equilibrium for 40-60 years.

In forest ecosystems, newly planted pine forests in the Southern United States tend to reach C-stock equilibrium after about 90 years, with maximum accumulation rates occurring between 15 and 25 years (Birdsey, 1996). New ponderosa pine and douglas fir forests in the West take more than 120 years to reach this equilibrium, with maximum accumulation rates occurring between 35 and 60 years. Figure 2.3 presents an average time profile of carbon sequestration for an acre of cropland in the Southeast after conversion to fully stocked southern pine under average management intensity. Carbon accumulation over the first 5 years is relatively modest (averaging 0.91 mt per year) but grows at an increasing rate over a period of 15 years. Between years 10 and 15, the average annual sequestration rate is three times higher than it is over the first 5 years. A lengthy period of positive but declining sequestration rates follows year 15. Assuming no timber harvests, the system reaches its C-stock equilibrium of 113.2 mt per acre after about 90 years. Of the carbon in the system, about 72.3 mt are contained in trees, 33.6 mt are contained in soil, and the balance is stored in understory vegetation and litter.[7]

The C-stock equilibrium issue has two important implications for empirical analyses of the economic potential to sequester carbon in the farm sector. First, the finite periods of time in which terrestrial systems can accumulate additional carbon place a finite limit on the GHG-mitigation potential of any carbon-sequestering activity at any given location. In contrast, an emissions-reduction activity will continue to reduce emissions relative to a pre-activity baseline every year the activity is maintained. Second, because annual carbon accumulation eventually will decline toward zero, incentive payments based on annual increments of carbon sequestration will eventually fall to zero. In empirical work then, it is important to be clear about the modeling assumptions regarding landowner responses when sequestration payments fall to zero.

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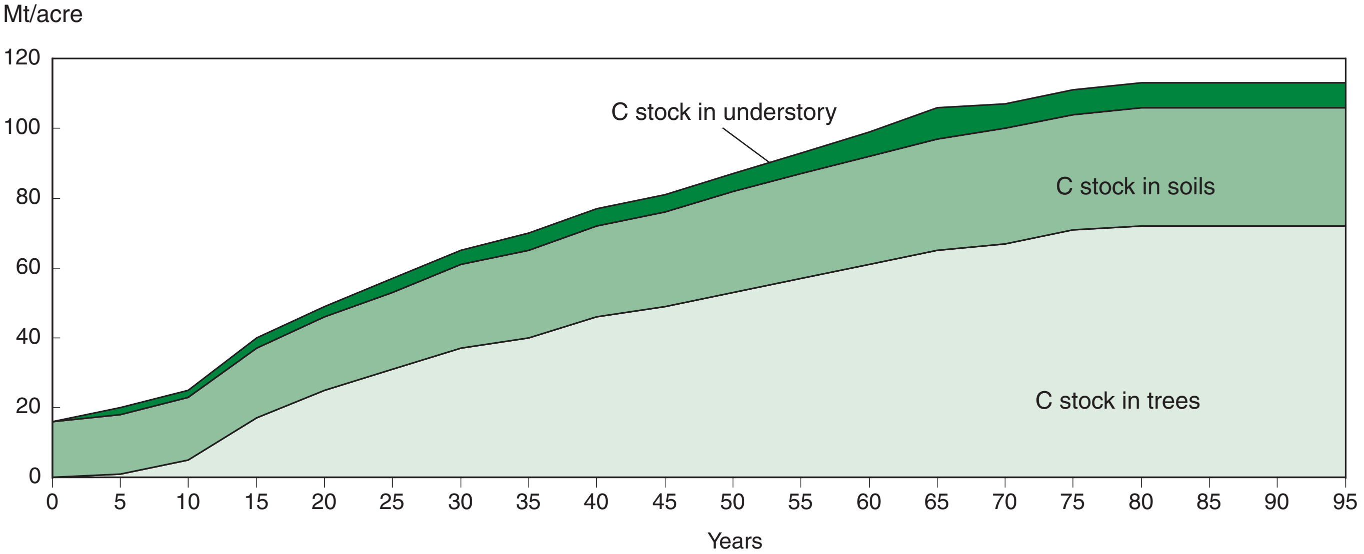
[7] If the trees are harvested, most of the carbon contained in removed biomass and logging residues, and some of the soil carbon, is returned to the atmosphere within a few years. The exception is the carbon stored in long-lived wood products (e.g., furniture and structures).

Figure 2.3

Accumulation of carbon stock and incremental change per acre of fully stocked southern pine timberland under average management after cropland conversion to forest



Source: Birdsey (1996).

Similarly, it is important to be clear about the assumptions regarding the actions landowners will take at the end of a commitment period, even if the new C-stock equilibrium has not been reached—because in the absence of a subsequent contract period, payments again fall to zero.

Defining Alternative Payment Structures To Address the Permanence Issue

Our discussions of permanence and C-stock equilibrium highlight the need to establish an equivalency between a unit of sequestered carbon and a unit of emissions reduction—both for conducting empirical analyses of carbon sequestration incentives and for designing carbon-sequestration policies. To that end, we develop a rental payment incentive and define a rental value for a commitment period. A series of rental contract payments for sequestering a ton of carbon through time will be equivalent, in present discounted value terms, with the asset price per ton of net emissions reduction or permanent carbon sequestration.

We employ a carbon accounting system based on metric tons of carbon stored per year, over defined (commitment) time periods. If adoption of a given sequestration activity results in an average annual addition to soil carbon during the contract period of s mt, the metric tons of carbon sequestered in the soil relative to baseline in years 1, 2, 3, and n are, respectively s, $2s$, $3s$, and ns.[8] For simplicity, we abstract from the longrun decay function of atmospheric carbon and assume an infinite time horizon for the atmospheric impacts of emissions (and so, too, of emissions reductions). If we make the simplifying assumption of a constant value (or payment level) for emissions reduction,[9] we can think of the rental payments for temporary sequestration in terms of the simple annuity formula. We denote the payment for 1 metric ton of sequestration for 1 year (paid in the year of sequestration) as a and define it as:

(1) $a = rP$

where P = payment for permanent reduction in carbon emissions of 1 mt, and

r = discount rate

In equation 1, the value of a metric ton of temporary sequestration for 1 year is the value of a metric ton of permanent emissions reduction, P, discounted by the factor r. With this payment structure, payments do not cease when land in a given use or production practice

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[8] We adopt an annual average framework because the IPCC sequestration parameters we employ for soil represent annual averages over a 20-year period, and the cost parameters have been annualized as well. This is a reasonable simplification because the decision is for the commitment period, not a year-by-year basis.

[9] This is not a necessary condition—the formula can be adjusted readily for a varying carbon price.

reaches C-stock equilibrium because the payments are for carbon *storage* above baseline levels, not for *new additions* to the carbon stock. Payments cease only when the carbon is released back into the atmosphere—for example, when a farmer stops using no-till and returns to conventional tillage. Analogously, if a metric ton of carbon is sequestered and held for 10 years, then the present discounted value (PDV) in year 1 would be:

$$(2) \qquad \int_{t=0}^{10} (rP)e^{-rt}dt$$

where the discount factor applied to permanent emissions reduction is $(1 - e^{-10r})$.

Next, consider the discount factor for a pattern of temporary carbon sequestration accumulated over a fixed commitment period of J years (where J is less than the time needed to reach C-stock equilibrium) relative to a matched time path of permanent emissions reductions. For simplicity, assume that the rate of carbon accumulation over the commitment period is 1 mt per year. Hence, for the commitment period, the time path of carbon sequestration is 1 mt in year 1, 2 mt in year 2, etc. In the last year of the program, the amount sequestered will be J mt. In contrast, emissions reductions of 1 metric ton per year will have an essentially permanent effect on the atmosphere. Hence, the ratio of the value of the temporary sequestration relative to the value of the permanent emissions reductions during the same time period is:

$$(3) \qquad \lambda_{\alpha} = \frac{P \int_{t=0}^{J} rt\, e^{-rt} dt}{P \int_{t=0}^{\infty} e^{-rt} dt}$$

Assuming that the value of permanent carbon emissions reductions is constant over time, the value of this ratio is affected by choices of years for length of sequestration commitment period and discount rate (table 2.4).[10]

In summary, alternative assumptions regarding the permanence and C-stock equilibrium issues motivate alternative payment structures for carbon sequestration. The asset price payment structure assumes the carbon will be sequestered permanently and so values a unit of carbon sequestration in year *t* equally with a similar unit of carbon emissions reduction in year *t*. With this structure, farmers receive payments based on the additional carbon sequestered in each year. On the other hand, the rental payment structure is based on the assumption that, at some point in the future, sequestered carbon may be released back into the atmosphere—thereby reducing its GHG-mitigation value relative to reductions in carbon emissions. The rental approach makes payments for total additional carbon based on that portion of the market value of permanent sequestration that occurs during the contract period. The rental approach will pay for the value of all sequestered carbon that actually occurs regardless of how long that carbon is stored in soils or biomass. The asset-price payment approach, on the other hand, could result in significant overpayments if the assumption of permanence is incorrect.

Table 2.4—Ratio (λ_a) of value for temporary sequestration to value for emissions reduction for selected discount rates and sequestration periods

	Carbon sequestration period (years)				
Discount rate	1	5	10	15	20
.05	.050	.145	.254	.354	.443
.10	.100	.280	.469	.620	.738

Source: Economic Research Service, USDA.

Design of an Incentive Program

An overarching policy design issue is evaluating the optimal path of GHG concentration level in the atmosphere over the next several centuries, balancing the costs and benefits of achieving different paths of atmospheric concentration levels of greenhouse gases through time. The analysis required to address this issue is both extraordinarily complex and subject to substantial unknowns.

In this report, we focus on two more narrow aspects of designing an incentive program. First, by evaluating the economic potential for different agricultural activities to sequester carbon, we can highlight the activities that will yield the greatest amount of sequestration at a given carbon incentive level. Further, our analysis is designed to contribute to an evaluation of the least-cost mix of terrestrial carbon sequestration and GHG emissions-reduction activities to achieve any desired level of GHG mitigation.

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[10] If the carbon price is expected to decrease (increase) over time, the ratio of the value of temporary sequestration to the value of permanent emissions reduction will rise (fall). That is, temporary sequestration today will be worth more (less) relative to permanent emissions reduction.

Second, we evaluate the cost effectiveness of alternative designs for incentives to promote carbon sequestration in agriculture. In this section, we consider the implications of three types of choices regarding the coverage of incentives for the cost effectiveness of achieving additional carbon net sequestration, relative to the baseline level. The first is the scope of the incentives, and of the associated accounting—in terms of geographical regions, economic sectors, mitigating activities, and GHGs covered. The second and third address what measure of carbon sequestration (net emissions reduction) the payments will cover. Will they be limited to net sequestration (gross sequestration net of any land-based emissions), or will they cover all gross sequestration? And will they be limited to additional carbon sequestration (beyond the pre-incentive program baseline), or will they compensate early adopters of carbon-sequestering practices too?

Defining the Scope of the Incentives and the Scope of Accounting

In analyzing any set of incentives to encourage farmers to adopt land uses and production practices that sequester carbon in soils and biomass, it is important to note two potential issues related to program scope. First, designs that limit activities covered by incentives may exclude more cost-effective options for achieving a given level of mitigation. As a result, the estimated costs of achieving a given level of carbon sequestration/GHG mitigation may be substantially higher than what is really possible.[11]

Second, if the incentives being analyzed induce actions that decrease carbon sequestration and/or increase GHG emissions in noncovered GHGs, activities, sectors, or regions, the estimated net sequestration/GHG mitigation attributed to the incentives may be overstated—perhaps significantly. The scope of GHG accounting, however, need not be limited to the scope of activities included in the incentives. If the scope of GHG accounting is broad enough to encompass—at least most of—the induced effects, the accounting will more accurately reflect the net sequestration/ GHG mitigation attributable to the incentives.

“Leakage” refers to decreasing carbon sequestration or increases in GHG emissions that are induced by price changes associated with market adjustments in response to carbon incentives. The term leakage is used because the increase in net emissions results from activities, gases, or sectors that are not covered by the program or entities in the covered sector that are not participating in the program.[12]

In the context of farm-sector incentives to increase the use of carbon-sequestering land uses and production practices, leakage can occur both within and outside the farm sector. For example, a program to afforest large areas of marginal cropland and pasture can cause leakage in the forest sector due to its impact on forest harvest and land-use decisions. Forestry is an alternative economic use for tens of millions of acres now in crop or livestock production.[13] Large-scale conversions of agricultural lands to forest could create expectations of higher timber supplies and lower timber prices in the future. A sufficient fall in the expected longrun returns to forestry could induce landowners to shift timber harvests (and associated carbon emissions) forward. Further, the lower expected returns could also induce forest owners to reduce forest management activities and lower future replanting rates, thereby lowering carbon sequestration rates per acre.[14] The higher net emissions (or leakage) in the forest sector would partially offset the sequestration gains in the agricultural sector covered by the incentives.

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[11] To illustrate, Reilly et al. (1999) estimate the cost of reducing U.S. GHG emissions by 650 MMTCE would be 60 percent lower if all GHGs are included relative to a carbon-only strategy.

[12] For completeness, we acknowledge that some activities induced by, but not included in, such a set of incentives may also sequester carbon or reduce GHG emissions. From an incentive design standpoint, such outcomes would be desirable since more GHG mitigation would be achieved than paid for. The GHG mitigation literature, however, suggests that leakage would be much more common than sequestration and/or GHG emissions reductions outside the incentive coverage. Given this consensus and the negative implications that leakage has for policy design—namely, getting less GHG mitigation than is paid for—we focus solely on leakage in this analysis.

[13] Parks and Hardie (1995) and Moulton and Richards (1990) both identify about 116 million acres of cropland and pasture in the contiguous 48 States suitable for growing hardwood or softwood trees. The Parks and Hardie estimate is derived from the 1987 National Resources Inventory data and a map of tree species ranges. The Moulton and Richards estimate reflects agricultural lands where erosion exceeds the erosion tolerance rate. Moulton and Richards also identify an additional 149.7 million acres of cropland and pasture that are suitable for conversion to forest but are not suited to sustained agricultural production (including wet soils).

[14] The degree to which forest sector responses to farm sector afforestation programs might offset carbon sequestered in agriculture is addressed in several studies reviewed in chapter 3 of this report.

Leakage within agriculture can be illustrated by the potential effect of farmers' responses to incentives to eliminate fallow periods from rotations. Farmers may increase soil carbon by eliminating fallow; however, if farmers keep the affected lands in production and apply additional fertilizer, the GHG-mitigation benefits of the carbon-sequestration activities would be at least partially offset by higher N_2O emissions. If GHG accounting is limited to carbon, the estimated changes in net GHG emissions may be misleading. The net effects of an incentive may not be accurately assessed unless accounting reflects all GHG emissions across all markets and activities that are directly and indirectly affected by the incentives.

What To Pay for—Gross Versus Net Sequestration?

The payment basis for carbon incentives has important implications for leakage. Conceptually, one option is to have symmetric incentives—positive payments for sequestration and negative payments for emissions from land use and land management activities. The system would provide payments for net sequestration across the covered sectors/activities—that is, for carbon sequestration, net of carbon emissions from changing land use and land management activities. A tradable permit system could provide symmetric incentives for sectors/activities and regions subject to emissions limits. For activities with emissions limits, emissions and sequestration would be tracked on a periodic basis. Yet, energy production is generally the primary activity considered for emissions limits in the economic literature on tradable permit systems for greenhouse gases; the transactions costs of imposing limits on agriculture are generally considered to be prohibitive.

Consequently, the literature generally discusses agricultural activities as a potential source of sequestration offsets against energy emissions in a tradable permit system, where the energy emissions are subject to an emissions limit (but the agricultural activities are not). In an offset system, symmetric incentives could be realized only for entities *that participate in the offset program*, and *only if* the offset program requires entitywide accounting for sequestration and emissions. Analogously, a voluntary subsidy program for carbon sequestration could provide symmetric incentives for entities that enroll in the program *only if* the program requires entity-wide accounting for sequestration and emissions, rather than accounting only on enrolled acres. In this context, adoption of carbon-emitting activities by entities elsewhere in the sector or the economy, which are not enrolled in the program, will not be subject to negative incentives. Such responses might occur, for example, when program-induced shifts of cropland to forestry reduce the supply of crops; as a result, crop prices will increase in order to ration the smaller supply. Farmers may respond to rising product prices by bringing currently idle land into production, which would generate additional carbon emissions without a negative incentive for such emissions. If the carbon accounting in a GHG emissions offset or subsidy program covered only the fields where sequestering activities are adopted, the accounting would likely overstate net sequestration and understate the marginal costs of sequestration from the payment system.

An alternative system would base payments on gross sequestration of carbon in soils or biomass as a direct result of adopting a covered activity, without any deduction for emissions from the participating entity. To illustrate how payments for gross sequestration could reduce the cost effectiveness of a given set of carbon-sequestration incentives, we consider a farmer with two 1,000-acre parcels—one managed with conventional tillage and the other with no-till. Under a gross-sequestration payment system, the farmer can receive payments for any land shifted from conventional tillage to no-till. The farmer could achieve eligibility for program payments under two courses of action that have very different implications for net incremental carbon sequestration. First, the farmer could expand the use of no-till to both parcels. In this case, the farmer will be managing an additional 1,000 acres of land with no-till relative to the pre-program baseline and will be generating additional net carbon sequestration on those acres.

Second, the farmer could simply switch tillage practices on the two parcels so that the one initially managed with conventional tillage is now managed with no-till, and vice versa. In this case, the farmer potentially could claim payments for half of the land in any period, but the additional carbon stored on the land shifted to no-till is largely offset by increased carbon tillage. In other words, no additional net carbon sequestration will occur in this case.

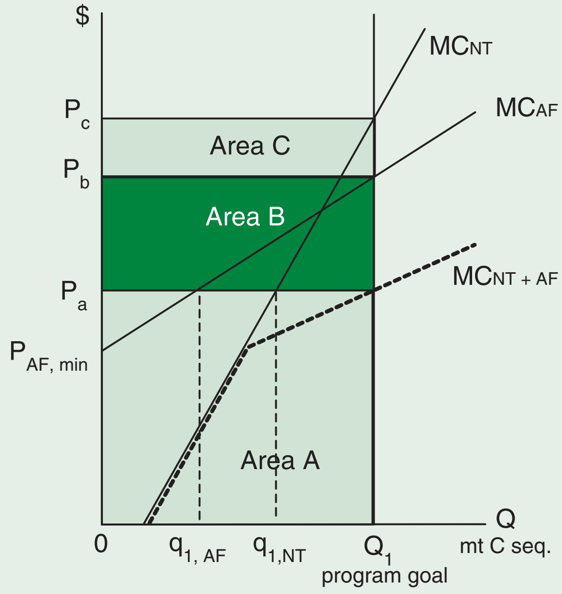
For voluntary programs, once a piece of land is enrolled in the program, rules could be established to prevent compensation for the repeated switching in the second case. Under gross sequestration, switching land from

Expanding the Scope of Sequestration Incentives

In general, increasing the scope of carbon-sequestration incentives will decrease both the marginal cost per unit of carbon sequestered and the total program cost of achieving a given level of sequestration. To make this point more concrete, we consider a stylized set of incentives to increase the quantity of carbon sequestered in agricultural soils and biomass. We focus on the greater efficiency of including multiple sequestration activities, but the logic generalizes to multiple geographic areas, economic sectors, and greenhouse gases.

The figure below shows hypothetical marginal cost (MC) curves for carbon sequestered by afforesting (AF) agricultural land or by expanding the use of no-till (NT). Also shown is the MC curve for carbon sequestered using both activities (AF+NT). As we have drawn the MC curve for no-till sequestration, any positive price for sequestered carbon will result in some additional use of no-till. In many areas of the United States, no-till, reduced tillage, and conventional tillage systems are practiced in close proximity—often on the same farm. In these areas, the expected returns to the different tillage systems are relatively close and it is reasonable that relatively small incentives would induce some expanded use of no-till.

Illustrative marginal cost curves for sequestering carbon through no-till and afforestation



Source: Economic Research Service, USDA.

Conversely, no afforestation occurs until the price of sequestered carbon exceeds $P_{AF,\ min}$. The conversion of pasture or cropland to forest requires a minimum of site preparation and tree establishment costs. Afforestation payments would have to cover these costs, as well as any income that might be lost by taking the land out of commodity production, before farmers would shift these lands into trees. Note also that the MC curve for expanding no-till rises faster than the MC curve for afforestation. As a result, the least-cost mix of sequestration activities will vary with the amount of carbon sequestration desired.

Consider the case where the program goal is to sequester Q_1 metric tons (mt) of carbon in the farm sector. As drawn, sequestering Q_1 metric tons of carbon can be accomplished by paying farmers only to adopt no-till, only to afforest agricultural land, or to undertake a combination of the two activities. If the program only pays for expanding no-till, the MC of sequestering Q_1 mt carbon will be P_c per mt and total payments will equal Areas (A+B+C). If the program only pays for afforestation, the MC of sequestering Q_1 mt carbon will be P_b and total payments will equal Areas (A+B). Hence, if only one activity is to be targeted, the more cost-effective option for sequestering Q_1 mt of carbon is to pay farmers to shift land into trees. Opening the program to both activities, however, lets low-cost suppliers of carbon from each activity respond to the incentives. As a result, Q_1 mt of carbon can be sequestered at a MC of P_a - with $q_{1,\ AF}$ mt sequestered by afforestation and $(Q_1 - q_{1,\ AF} = q_{1,\ NT})$ mt sequestered by expanding no-till. Total payments in this case are equal to Area (A).

Note, however, that a multiple-activity program does not necessarily mean that all targeted activities will occur. For example, if the carbon payment were less than $P_{AF\ min}$, afforestation will not be competitive and the only sequestration activity observed will be some additional use of no-till.

no-till to conventional tillage may be economically rational for other reasons. Consider, for example, the case where, in the baseline, no-till systems produce lower yields per acre than conventional tillage but the no-till cost advantage compensates for the revenue differential. As crop prices rise due to the offset program, for example due to converting cropland to forestry, the lost revenues from maintaining no-till will increase and at some point no-till may no longer be advantageous. Further, declining supplies and associated price increases would provide incentives for entry of idle land into crop production, resulting in additional carbon emissions.

Establishing accounting for net sequestration across the whole entity enrolled in a voluntary program, rather than simply for the enrolled acres, will tend to capture some of the price-induced increases in emissions. However, some farms will find no advantage to joining the program because their most profitable response will be to increase net emissions. (The structure of the incentive will influence the size of this group of farms.) Consequently, accounting for sectoral gains in net carbon sequestration based on entities participating in the offset program—rather than on all entities in the sectors eligible for offset—will tend to overstate the sequestration gains and understate the true costs incurred per ton of net carbon sequestered in the offset sectors.

Eligibility for Sequestration Payments— New Adopters Versus All Adopters (Including "Good Actors")

In terms of eligibility requirements, two payment options relating to the additionality of carbon sequestration dominate both policy discussions and published studies. The first option pays all farmers who practice the activities covered by the incentives regardless of how long they have been practicing the activities. Hence, if a payment were offered to encourage farmers to expand the use of—say, conservation tillage—all farmers managing with conservation tillage would be eligible for the payment. This option is referred to as the "good actor" approach because it is perceived as not penalizing farmers who undertook the desired activity before the compensation policy was available. The alternative "new adopters" option limits sequestration payments to farmers not engaged in the desired land uses and production practices at the time of the program baseline. As a result, payments only cover additional carbon sequestration relative to the pre-program baseline.

Supporters of the good-actor payment criterion argue that it avoids "moral hazard," in which farmers already engaged in desired practices revert to undesirable land uses and production practices to qualify for incentives. This rationale requires the assumption that it is not possible to avoid this situation by observing and penalizing such behavior.[15] Those in favor of the new-adopter criterion argue that it does not pay farmers for having made changes in land uses or production practices that they previously concluded were economically rational; instead, it limits payments to farmers who require an additional incentive to economically rationalize the adoption of the desired uses and practices.

From an incentive design perspective, the new-adopters criterion will generally be less costly—perhaps significantly so—than the good-actor criterion, particularly if the moral hazard issue can be resolved. For example, the United States has approximately 450 million acres of privately owned cropland and 352 million acres of privately owned grassland (i.e., pasture or range) (Vesterby and Krupa, 2001). In a program providing incentives to shift economically marginal cropland to permanent grasses under the new-adopter criterion, owners of any of the 450 million acres of cropland that shift into grasses would be eligible for the incentive payments. Under the good-actor criterion, not only would owners of these acres be eligible to receive payments but so, too, would owners of at least some of the 352 million acres of privately owned pasture and range that remained in those uses. The same issue could arise with providing farmers incentives to afforest cropland and pasture, or incentives to shift from conventional to conservation tillage. At present, about 420 million acres of privately owned forest land and over 100 million acres of cropland in the United States are managed with some form of conservation tillage (Vesterby and Krupa, 2001; USDA, ERS, 1998).

Conceptual Framework for the ERS Analysis

Due to limitations in the data available for our analysis, we were forced to limit the scope of our

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[15] "Moral hazard" refers to situations where an incentive or policy actually encourages behavior detrimental to the objectives of the incentive or policy. The classic example is insurance, which once obtained, reduces people's incentive to act in ways that decrease the probability of incurring a loss—and in the extreme, may encourage people to act fraudulently to collect on the insurance.

analysis along several dimensions. The scope of our analysis covers the major carbon-sequestering activities in the agricultural sector. Among the three major agricultural GHGs, we limit our analysis to carbon. Our analysis simulates payments offered to producers to adopt specific carbon-sequestering land uses and production practices: shifting cropland or grazing land (i.e., pasture or range) to forest, shifting cropland to perennial grasses, switching from conventional to conservation tillage (particularly no-till), shifting to carbon-sequestering crop rotations, expanding the use of winter cover crops, and eliminating periods of summer fallow. The cropland and grazing land activities included in our analysis represent about 80 percent of the technical carbon-sequestration potential for all management activities listed in table 2.2. The primary reason for omitting activities from our analysis is a lack of data on the farm-level costs of adoption. Without data on adoption costs, we cannot assess the net returns associated with undertaking a given activity relative to alternative production possibilities and, therefore, cannot assess the likelihood of adoption of certain activities. Our GHG accounting is also limited to carbon in the agricultural sector. Consequently, our analysis does not track leakage related to GHG emissions in response to the program in other economic sectors (notably forestry) or to other GHG gases (notably methane and nitrous oxide) in agriculture. We account for farm-sector carbon leakage by comparing performance of incentives based on net sequestration, relative to those based on gross sequestration.

Decisionmaking in the model regarding production activities (input mix, output choice, production technology, and crop rotation) is done at the region level, not at the individual farm level. Consequently, net sequestration payments are made on a sectorwide basis, not on the basis of voluntary farm participants; as a result, there is full symmetry in the treatment of land-based carbon emitted or sequestered as a result of the program. We examine the impact of different treatments of the permanence issue by designing a rental carbon payment system to complement a carbon asset-price payment system.

Chapter 3: Literature Review

Recent studies have estimated the potential farm-sector impacts of strategies to increase the quantity of carbon sequestered in agricultural soils and biomass. Findings in these studies suggest farm-sector sequestration activities that might be economically feasible at different prices. A review of the accounting and modeling procedures employed in the studies reveals how researchers have addressed permanence, C-stock equilibrium, and leakage, and, where possible, highlights the economic implications of alternative treatments (app. 1).

The general approach in past studies has been to construct a hypothetical situation in which farmers are paid to change land uses and/or production practices to store additional carbon in soils and biomass. Most of the analyses focus on a single carbon-sequestering activity. Parks and Hardie (1995), Alig et al. (1997), Stavins (1999), and Plantinga et al. (1999) assess the sequestration potential of afforesting marginal agricultural lands. Antle et al. (2001) look separately at shifting cropland to grasses and reducing summer fallow. Pautsch et al. (2001) focus on expanding the use of no-till systems. McCarl and Schneider (2001) and McCarl et al. (2003) present more comprehensive assessments in which carbon sequestration is part of agriculture's larger potential to mitigate GHG emissions. In these studies, farmers can adjust land uses, crop choices, and management practices in ways that increase carbon sequestration, decrease GHG emissions (i.e., CO_2, CH_4, and N_2O), or increase production of biofuel crops.

Discussion of Past Studies

In a 1995 study, Parks and Hardie simulate a strategy to afforest marginal agricultural lands patterned on USDA's Conservation Reserve Program (CRP). The strategy assumes farmers enroll lands in year 1 for a period of 10 years, receive a 50-percent cost-share payment to plant trees, and receive an annual payment to offset lost agricultural revenue. Region-specific carbon-sequestration values for lands converted to forests are developed by disaggregating 116.1 million acres of private nonprime farmland deemed suitable for forest into 433 regions, which are then linked to a map of forest types. Sequestration is defined narrowly to include only carbon stored in trees. Agricultural and forest rents reflect the discounted returns to lands in each use in each region. Thus, the decision to move land from agriculture to forest is based on a comparison of the longrun returns in each use.

The study is limited in its treatments of permanence, C-stock equilibrium, and leakage. It is assumed that 10 years after agricultural lands are planted to trees, timber production becomes the profit-maximizing land use. At that point, farmers will maintain the forests without additional Government payments. By assumption, the study sidesteps the permanence issue. Additionally, because the carbon accounting terminates at 10 years—which is shorter than the optimal rotation period in most regions—the study fails to address the issue of permanence raised by potential harvests. The 10-year timeframe of the analysis also sidesteps the C-stock equilibrium issue—since it takes decades for a newly planted forest to reach a carbon equilibrium state. Finally, because the model does not include any carbon-emitting activities that might occur in the farm or forest sectors in response to the afforestation incentives, the analysis does not consider the potential for agricultural- or forest-sector carbon leakage.

Parks and Hardy present results for four scenarios assuming an afforestation program funded at $456.2 million annually. The first two scenarios target both cropland and pasture under the enrollment criteria of minimizing the cost per ton of carbon sequestered and minimizing the cost per acre enrolled (based on a fixed per acre payment). The last two scenarios consider the same enrollment criteria but limit enrollment eligibility to cropland. The most cost-effective strategy bases payments directly on carbon sequestered and has the broadest land eligibility criterion. For the two scenarios that target both cropland and pasture, afforestation is 0.9 million acres less and carbon sequestration is 3.3 MMT more under the criterion of minimizing costs per ton sequestered than under the criterion of minimizing costs per acre (app. 1). More generally, for the strategy that targets carbon directly, the supply curve for sequestered carbon rises gradually from a level of 18.1 MMT and a marginal cost of $85 per mt to a sequestration level of 90.7 MMT and a marginal cost of $465 per MT.[1] For levels of sequestration above 90.7 MMT, the supply curve turns up sharply, suggesting an upper limit to the amount of carbon that can be economically removed from the atmosphere by afforesting agricultural lands.[2] When afforestation incentives are limited to cropland, enrollment and sequestration levels drop by over 55 percent, indicating that most afforestation would occur on lands now in pasture.

Alig et al. also analyze CRP-type incentives that would pay farmers to shift marginal agricultural lands to forest. Their framework—the Forest and Agricultural Sector Optimization Model (FASOM)—is an intertemporal market and spatial equilibrium model in which agriculture and forestry compete for the use of land. FASOM's forestry sector consists of nine geographic regions and various categories reflecting differences in product class, land ownership, forest type, site productivity, and management intensity. The model's agricultural component is a version of McCarl and Schneider's Agricultural Sector Model (ASM). Model simulations run for 90 years, but policy impacts are only reported for 50 years. Producers maximize the return to land by shifting land between agriculture and forestry and by changing forest management intensity (endogenous forest management decisions include harvest age, management intensity, and forest type).

FASOM runs on a decadal time step, allowing land to shift between agriculture and forestry every 10 years as the relative returns to these uses change over time. It addresses the permanence and leakage issues in that decisions on afforestation, deforestation, and forest management are endogenous to the model and the associated activities are tracked over time. Hence, the model accounts for changes in the net levels of carbon sequestration that occur over the years in each simulation. Conceptually, the C-stock equilibrium issue is reflected in the model's timber growth functions, although in the simulations, forests are typically harvested before this equilibrium is reached. In this study, sequestration incentives are based on gross rather than net sequestration—meaning landowners are rewarded for adopting practices that sequester carbon but are not penalized for adopting practices that emit carbon.

Among the model's simulations, the scenario with a fixed carbon flux target of 1.6 gigatons per decade has a relatively large economic impact. Over the 90-year simulation, the present value of losses for U.S. forest and agricultural consumers are $7.5 billion and $76.4 billion, respectively, while the present value of gains for U.S. forest and agricultural producers are $6.6 billion and $39.6 billion, respectively. During the first 50 years of the simulation, many owners of private forestland shift to earlier timber harvests, and some of this land moves into agricultural production. Overall, 59 million acres shift between the two sectors—with a net increase in forest area of 19 million acres. Alig et al. conclude that afforesting agricultural lands could be an effective component of a national GHG-mitigation strategy, but that the net carbon sequestration achieved will be much overstated if the program does not account for emissions from related forest-sector responses.

Plantinga et al. and Stavins also focus solely on the afforestation of agricultural lands. These studies develop econometric land-use models based on behavioral data. The methodologies lack an explicit link between afforestation of agricultural lands and related responses in forest product markets but do capture the impacts of various difficult-to-measure factors (e.g., becoming familiar with forestry) that make decisions to shift agricultural land into forest more "sticky" than if based strictly on maximizing expected profits. As in Alig et al., land moves between agriculture and forestry over time, and so these studies track changes in net carbon sequestration as land shifts between the two sectors—that is, they account for permanence and leakage. Stavins bases incentives on the *net* carbon sequestration from land-use decisions, while Plantinga et al. base incentives on *gross* sequestration. Again, C-stock equilibrium could be addressed in the model's timber growth functions, but forests are generally harvested before equilibrium is reached.

Plantinga et al. estimate separate models for Maine, Wisconsin, and South Carolina using data from various years between 1971 and 1996. The dependent variables are the share of county land in agriculture relative to the share in forest, and the share of county land in other uses relative to the share in forest. Independent variables include agricultural rents per acre (stated as the present discounted value of all net

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[1] The figures $85 and $465 are obtained by setting T=20 tons (i.e., 18.1 mt) and T=100 (i.e. 90.7 mt), respectively, in the MC equation in Parks and Hardie (p. 130) and dividing the results by 0.8051 (to convert to 1997 dollars).

[2] We do not mean to imply here that any particular level of sequestration is economical. Only that the shape of the MC curve implies an upper limit to quantity of carbon that would be economical to sequester.

returns from agricultural uses over the simulation period), forest rents per acre (stated as the present discounted value of timber revenues), population, and land quality. Afforestation incentives are again patterned on the CRP and offer landowners annual payments to convert agricultural lands to trees for a period of 10 years starting at the beginning of each decade. Simulations start in 2000 and run for 60 years. Although not included in the simulation, program costs are adjusted to reflect a one-time tree establishment payment.

Results are presented for four scenarios reflecting different assumptions about population growth, timber harvest, and payment structure. Across scenarios and regions, results indicate that the marginal cost of carbon sequestration increases almost linearly with the level of sequestration. Marginal costs are generally lowest when population is held constant, sequestration payments are uniform across States, and harvesting is not allowed on enrolled lands. For this scenario and a payment of $45.09 per mt carbon, the States would have total sequestration of 1.36 MMT (Maine), 12.89 MMT (South Carolina), and 27.22 MMT (Wisconsin) (with future sequestration discounted at 5 percent).[3] At the same payment level but allowing for timber harvests, the discounted sequestration levels decrease to 1.04 MMT (Maine), 11.53 MMT (South Carolina), and 22.69 MMT (Wisconsin).

Stavins models the shares of county land in forest and in agriculture as functions of agricultural rents, farm production costs, existing forest area, conversion costs, and net returns to forestry. The model is estimated with panel data for 36 parishes/counties in Louisiana, Arkansas, and Mississippi covering the period 1935-1984. Model simulations run for 90 years, and the sequestration incentives include a payment for afforestation and a charge for deforestation.

For the three Delta States, Stavins finds that the marginal cost of sequestering carbon rises gradually to a sequestration level of about 6.35 MMT per year. At this level, the marginal cost of sequestration is about $79.86 per mt, net afforestation is 4.6 million acres, and the carbon payment/charge is about $109.81 per acre. Marginal costs rise steeply for sequestration levels above 6.35 MMT annually, becoming nearly asymptotic at about 14.52 MMT per year. Stavins concludes that sequestration would be competitive with abatement at lower levels of net emissions reduction.

Shifting from afforestation, Antle et al. and Pautsch et al. assess the economic feasibility of paying farmers to sequester carbon in agricultural soils by eliminating fallow periods from crop rotations, expanding grasslands, and increasing the use of no-till systems. The methodologies differ from the afforestation studies in two key respects. First, the geographic scopes are smaller—Pautsch et al. is limited to Iowa and Antle et al. focus on a subregion of Montana. Second, the crop production models used in these works are estimated with field-level data, which precludes these frameworks from comparing sequestration opportunities across regions. Still, the use of field-level data allows site-specific factors—or spatial heterogeneity—to be considered in the design and evaluation of incentives to encourage farmers to adopt the desired land uses and production practices.

Neither Antle et al. nor Pautsch et al. explicitly addresses C-stock equilibrium, leakage, or permanence. The studies omit the C-stock equilibrium issue because the timeframes of the scenarios are less than the period needed for most of the affected lands to reach new carbon equilibrium levels. Leakage is omitted because all land-management changes reflect changes to carbon-sequestering uses or practices. Regarding permanence, both studies implicitly assume that farmers continue the new land uses or production practices when the payments end.

Antle et al. assess the potential costs of paying farmers in Montana's dryland grain region to sequester carbon by switching from crop-fallow to continuous cropping rotations and by shifting cropland into permanent grass. The study analyzes each activity separately. In the scenarios, farmers commit to maintaining the new land use or production practice for a period of 20 years. Antle et al. develop econometric production models for wheat, barley, and permanent grass in both continuous crop and crop-fallow rotations using 1995 data for 425 farms and 1,200 fields. These models are then incorporated into a producer-decision framework that allocates land among the different rotations in response to payments to switch additional land to continuous cropping or permanent grasses. The study estimates changes in soil carbon by running the land-

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[3] These dollar and sequestration values were obtained from the graphs in Plantinga et al. (pp. 820-21). We convert the results—presented in 1995 dollars and short tons—to 1997 dollars and metric tons.

use changes obtained in the model simulations through the Century crop-ecosystem model.

Three findings in Antle et al. are especially noteworthy. First, eliminating fallow periods appears to be a cost-effective method of carbon sequestration while expanding grasslands does not—at least in eastern Montana. Over a 20-year simulation, sequestering about 7 MMT of carbon by expanding grasslands requires an annual rental payment of $51.77 per acre and costs the Government $3.15 billion (not discounted). By contrast, sequestering the same amount of carbon by increasing continuous cropping requires an annual payment of $4.14 per acre and costs the Government $206.34 million (again, not discounted).

Second, a comprehensive GHG-mitigation strategy can include activities that sequester relatively small amounts of carbon but at a very low cost. At the highest payment level, switching from crop-fallow rotations to continuous cropping sequesters less than 19 MMT of carbon over the 20-year simulation. While this amount represents only a fraction of the sequestration potential of afforestation, two-thirds, or about 12 MMT, could be captured for an annual payment of $8 per acre.

Finally, for a given activity, the cost of sequestering carbon can vary significantly within a region due to site-specific biophysical and economic characteristics. Across locations in the study area, the marginal cost of sequestering carbon ranges from $51.15 to $511.51 per mt in the permanent grassland simulation and from $12.28 to $143.22 per mt in the continuous cropping simulation. While it is difficult to account for differences among fields and farms in national agricultural sector models, policymakers should note the potential for cost savings if sequestration incentives are designed with flexibility to take advantage of heterogeneity among locations in each region.

Pautsch et al. examine the cost of paying farmers in Iowa to expand use of no-till systems under alternative payment and program eligibility structures. Payment schemes include a uniform per acre payment and a variable per acre payment based on the amount of carbon sequestered. Program eligibility options include paying all users of no-till systems and limiting payments to new adopters.

Using field-level soil and weather data, county-level crop yield data, and State-level price and cost data, Pautsch et al. develop an econometric model in which the probability of adopting no-till is a function of net returns to conventional tillage, local soil characteristics, and regional temperature and precipitation variables. Production possibilities include 14 rotations consisting of mixes of corn, soybeans, wheat, sorghum, and hay. As in Antle et al., the changes in area under no-till are fed into a biophysical model to estimate changes in soil carbon.

Two findings in Pautsch et al. highlight the importance of payment structure and eligibility criteria in determining the costs associated with incentives to increase the quantity of carbon stored in agricultural soils. First, the average cost per metric ton of carbon sequestered is lower when per acre payments to adopt no-till are based on carbon sequestered rather than set at a fixed level. Parks and Hardie also support this finding, but to a lesser degree; in Pautsch et al., the average cost per unit sequestered is about four times lower under the price-discriminating structure than under the fixed payment structure. Second, cost savings are considerable when eligibility is limited to new adopters. In this analysis, paying all farmers who typically use no-till doubles the average cost per unit of carbon sequestered relative to paying only new adopters.

McCarl and Schneider expand the focus beyond a single carbon-sequestering activity, developing a comprehensive GHG-mitigation strategy that pays farmers to change land uses, crop mixes, crop-management practices, and livestock-management practices in ways that increase carbon sequestration, decrease GHG emissions (i.e., CO_2, CH_4, or N_20), or increase biofuel crop production. Their ASMGHG model—a market and spatial equilibrium mathematical programming framework—depicts production and consumption in 63 U.S. regions for 22 traditional crop commodities, 3 biofuel crops, 29 livestock commodities, and more than 60 processed agricultural products. In responding to relative changes in input prices, farmers can adjust tillage, fertilization, irrigation, manure treatment, and feed mixes. The study uses the biophysical Environmental Policy Integrated Climate (EPIC) model to calculate changes in carbon sequestration associated with changes in crop management activities. Thirty-year simulations of FASOM (see Alig et al., 1999) provide data on land shifting from agriculture to forestry and the associated quantities of carbon sequestered. Changes in emissions associated with livestock management are based on EPA data.

McCarl and Schneider simulate ASMGHG with carbon valued at $0.0 (i.e., the baseline), $9.60,

$48.10, $96.20, and $480.80 per MT.[4] These values are treated as a subsidy when farmers switch to activities that reduce GHG emissions and a charge when farmers change to activities that increase emissions. By design, the framework pays farmers only for the net GHG mitigation that results from their response to the full set of incentives. Additionally, the link between the agricultural and forestry sectors allows ASMGHG to reflect the forest sector's response to the afforestation of agricultural lands—at least in the long run. Hence, the framework explicitly accounts for carbon leakage through forest-sector activities. While McCarl and Schneider do not explicitly address the permanence and C-stock equilibrium issues, they adapt the framework to address these issues in McCarl et al. (2003).

For carbon valued at $9.60, $48.10, $96.20, and $480.80 per MT, net carbon sequestration is, 51.80, 146.40, 238.50, and 395.50 MMT, respectively, while net GHG mitigation is equivalent to 53.90, 154.10, 255.70, and 425.90 MMT of carbon, respectively. McCarl and Schneider conclude that paying farmers to sequester carbon, reduce GHG emissions, and increase biofuel crop production would positively affect farmers and negatively affect U.S. consumers. For carbon valued at $9.60, $48.10, $96.20, and $480.80 per MT, farm welfare increases $ 0.40, $4.30, $13.40, and $76.90 billion, respectively, while U.S. consumer welfare decreases $0.40, $5.20, $18.50, and $104.60 billion, respectively. More generally, at low carbon prices soil carbon sequestration, afforestation, and CH_4 / N_2O emissions reduction dominate GHG-mitigation activities. At high carbon prices, the dominant mitigation activities are afforestation and biofuel production. Regardless of the value assigned to carbon, CH_4 and N_2O emissions reduction activities make a relatively small contribution to GHG mitigation.

More recently, Jones et al. (2002) and McCarl et al. (2003) identified approaches for treating permanence and C-stock equilibrium in static models that do not implicitly assume sequestration is permanent.[5] As described in chapter 2 of this report, this approach employs a series of annual payments based on a pay-as-you-store principle. In essence, a discount—based on the length of the contract period for carbon sequestration and the choice of discount rate—is applied to the value of a unit of emissions reduction to determine the value of a unit of carbon sequestration during the contract period. Our analysis also employs this approach to valuing sequestered carbon.

Conclusions

Differences in scope (including geographic region, sector, activity, and GHG coverage), methodology, and underlying assumptions make it difficult to directly compare the results of previous studies of the economic potential to sequester carbon in agriculture. Recognizing these limitations, however, the literature does provide some insights regarding carbon-sequestering land uses and production practices that may be competitive at different carbon prices and the levels of carbon that might be sequestered at those prices. Additionally, the studies reveal how researchers have addressed permanence, C-stock equilibrium, and leakage.

Taken collectively, the studies reviewed here suggest that the farm sector's economic potential to sequester additional carbon is significantly less than amounts deemed technically possible in soil science-based assessments. For example, for the United States as a whole, the studies cited in table 2.2 estimate the technical potential for sequestering carbon at 35-107 MMT per year for expanding conservation tillage and 6-18 MMT per year for eliminating summer fallow and changing rotations. In contrast, for expanding no-till in Iowa, Pautsch et al. estimate the cost of sequestering 1 MMT of carbon at about $200 per MT. On the national scale, McCarl and Schneider estimate the maximum economic potential of about 70 MMT per year for all farm-sector soil management activities at a carbon price of $500 per MT.

The most noteworthy divergence between soil science and economic assessments concerns conversions of cropland to permanent grasses. From a national perspective, Eve et al. (2000) estimate the technical potential of converting cropland to grassland at between 26 and 54 MMT of carbon per year. In contrast, economic assessments by Antle et al. and McCarl and Schneider find that sequestering carbon via this land use change would not be competitive with other carbon-sequestering activities.

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[4] Money values in McCarl and Schneider are in 2000 dollars. We have converted their values to 1997 dollars. To obtain the values reported in McCarl and Schneider, multiply the values reported here by 1.04.

[5] The Jones et al. citation refers to a presentation at the Forestry and Agriculture Greenhouse Gas Modeling Forum in Shepherdstown, WV (October 9-11, 2002). This presentation and the paper by McCarl et al. are not included in appendix 1 because of similarities to, respectively, the present analysis and McCarl and Schneider.

The published studies indicate that the most cost-effective mix of carbon-sequestering activities will depend on the level of carbon payment offered—or equivalently, the target quantity of total sequestration to be achieved by the program. Across studies, changes in production practices—such as expanding no-till and shifting to carbon sequestering rotations—dominate farm sector responses at very low payment levels. Afforestation becomes the dominant sequestration activity at a carbon payment between $20 and $100 per MT, depending on the specific features of the context modeled. McCarl and Schneider, the one study that considers multiple GHGs, finds that CH_4 and N_2O emissions reduction activities become feasible as carbon payments approach $50 per MT. Above payments of $100 per mt, additional emissions reductions from these activities become very limited at any price. McCarl and Schneider also find that production of biofuel crops starts to become economically attractive at a payment of about $50 per mt and joins afforestation as a dominant GHG-mitigation activity at payments above $75 per mt.

The treatment of permanence, C-stock equilibrium, and leakage in previous studies is noteworthy for several reasons. First, the finite time period for annual increments to the carbon stock in agricultural soils is generally sidestepped, without comment. In the predominant static frameworks, the sequestration programs generally end before affected soils or forests reach their new carbon equilibrium levels. The longrun dynamic models employed for forestry explicitly address the issue because they typically incorporate a carbon-stock accumulation function by age of timber.

Treatment of permanence varies in previous studies. Studies that employ dynamic frameworks generally track changes in net carbon storage over time; however, some of the forestry modeling has not employed negative charges for emissions from terrestrial storage. In dynamic models, permanence can be incorporated in sequestration incentives by paying landowners when they switch to land uses or production practices that sequester carbon and charging them when they switch to uses and practices that emit carbon. In static models, permanence can be accounted for by using the rental price for a specified commitment period, derived from the full asset value employed for permanent sequestration. In our analysis, which employs a static model, we follow this approach to account for the temporary nature of carbon sequestration in the design of sequestration incentives.

The literature also varies in the treatment of leakage. By design, models that are limited to a single land use or production practice cannot account for leakage related to changes in other land uses or production practices. Similarly, single-sector models cannot account for leakage related to changes in land uses or production practices in other economic sectors. Past farm sector studies (Parks and Hardie, Antle et al., and Pautsch et al.) have generally focused on a single carbon-sequestration activity, and the carbon accounting has not included activities outside of the incentive program to check for leakage. With such limited coverage of activities, the potential for leakage from other activities in agriculture or forestry is great. In contrast, the forestry literature, which uses dynamic longrun models in which agriculture and forestry are linked via competition for land (Alig et al., Stavins, and Plantinga et al.), has examine the issue. These studies generally find that forest sector responses to farm sector carbon sequestration incentives can be an important source of leakage—particularly at higher carbon payment levels.

Our framework is limited to the agricultural sector, but it does account for the net effect on sequestered carbon after farmers have adjusted for land-use changes among crop, grass, or forest land and for a variety of crop land-management practices. It does not, however, capture forest-sector leakage, so we acknowledge the potential for upward bias in our sequestration results relative to a full accounting of the agriculture and forestry sectors. With respect to past studies, we note that the magnitude of forest-sector leakage is critically linked to assumptions previous researchers have employed regarding the longrun (50-100 years) time paths of income growth, population growth, technological change, price expectations, and consumer preferences. Different assumptions about the longrun time paths of these variables can have very different implications for the longrun demand for land in the two sectors and thus very different implications concerning potential leakage.

Finally, researchers to date have formulated hypothetical incentives—often based on those in USDA's CRP—which are then incorporated into economic models and simulated for various exogenously specified carbon payments. The result is to trace out scenario-specific supply curves for sequestered carbon. Our analysis will also trace out a farm-sector supply curve for sequestered carbon.

Chapter 4: Empirical Framework

The empirical framework for this study, the U.S. Agricultural Sector Model (USMP), is a spatial and market equilibrium model built to assess a wide range of economic, environmental, and policy issues of interest to U.S. agriculture. USMP simulates farm-sector impacts resulting from changes in commodity market conditions, agricultural technologies, and Government policies related to commodity production, resource use, environmental quality, and trade. Because adjustment paths are not modeled, USMP simulation results are properly interpreted as a comparison between an initial baseline and a new medium-run equilibrium state.[1]

USMP can be used to carry out analysis relative to any base year between 1988 and 2010 inclusive. Simulations begin by calibrating the model's acreage, tillage practice shares, domestic production, domestic consumption, imports and exports, input and output prices, and corresponding spatial information to the desired historical year or to approximate conditions in a USDA baseline year.[2] In response to changes in farm policy or market conditions, the model endogenously determines new equilibrium levels of its variables after all output and input markets have fully adjusted. Agriculture's response to price changes involves all producers adjusting their input use, output choices, and production levels such that the marginal value of product produced per unit of input equals the marginal input cost for all inputs and the net returns to the last units of production are equal across all commodities.

Reported farm-sector impacts include changes in regional commodity production, national commodity prices, national commodity consumption, use of production inputs, farm income, agricultural producer and consumer surplus, participation in Government commodity programs, Government program expenditures, and environmental indicators.[3] The model is linked with regularly updated USDA production practices surveys (USDA, ERS, 1992; and USDA, NASS, 1996), the USDA multiyear baseline, and geographic information system databases, such as the National Resources Inventory (NRI) (USDA, NRCS, 1994).

USMP depicts the U.S. farm sector in considerable geographic, commodity market, and production-enterprise detail (fig. 4.1, table 4.1). The model disaggregates the 48 contiguous States into 45 regions defined by the intersection of the 10 USDA farm-production regions and 26 land-resource regions. Crops include corn, sorghum, oats, barley, wheat, rice, cotton, soybeans, hay, and silage. Collectively, these 10 crops account for about 75 percent of the value of U.S. agricultural production (USDA, OCE, 1999).[4] USMP also includes 16 primary livestock commodities (the most important being dairy, swine, beef cattle, and poultry) and over two dozen processed and retail products (including dairy, pork, fed beef, nonfed beef, poultry, soy meal, soy oil, and livestock feed). With respect to enterprise management, USMP has nearly 1,000 production activities reflecting alternative choices of input mixes, output choices, production technologies (e.g., choice of tillage system), and crop rotations. The model also includes 70 production activities that process primary farm commodities into intermediate and final demand products.

USMP's objective function is to maximize the sum of consumer and producer surplus across all commodity markets. The input markets for cropland, pasture land, family labor, hired labor, and irrigation water are modeled at the regional level with upward-sloping supply curves—that is, input supplies increase (decrease) when their prices increase (decrease). Twenty-three other farm-input markets—including fuels, fertilizers, pesticide, seed, machinery, and custom operations—are modeled at the national level. In national input markets, supply functions are perfectly elastic—implying input supplies can change without affecting input prices.[5]

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[1] The elasticities that determine supply and input use changes in USMP are medium-run elasticities.

[2] The USDA Long-Term Agricultural Baseline provides annual projections for various market variables related to U.S. agriculture through the 2010. Detailed information about the baseline can be obtained at USDA, OCE (2001), and at *http://usda.mannlib.cornell.edu/data-sets/baseline*

[3] USMP is modeled in the General Algebraic Modeling System (GAMS) as a nonlinear programming problem with solutions obtained using the MINOS nonlinear optimizer solver. The model consists of some 2,000 equations and 5,400 variables.

[4] Due to limited production data, fruits, vegetables, and sugar are not included in USMP. These crops are the only major commodity groups not included in the model.

[5] Conceptually it would be straightforward to model these input markets with upward-sloping supply curves, but there is generally limited empirical work on which to base the choice of supply elasticity.

Figure 4.1

USMP model regions

Farm Production Regions

NT - Northeast
LA - Lake States
CB - Corn Belt
NP - Northern Plains
AP - Appalachia
SE - Southeast
DL - Delta States
SP - Southern Plains
MN - Mountain
PA - Pacific

Land Resource Regions

A - NW Forest, Forage, and Spec. Crops
B - NW Wheat and Range
C - Cal. Subtrop. Fruit, Truck, and Spec. Crops
D - Western Range and Irrigated
E - Rocky Mountain Range and Forest
F - N. Great Plains Spring Wheat
G - W. Great Plains Range and Irrigated
H - W. Great Plains Winter Wheat and Range
I - SW. Plateaus and Plains Range and Cotton
J - SW. Prairies Cotton and Forage

K - N. Lake States Forest and Range
L - Lake States Fruit, Truck, and Dairy
M - Central Feed Grains and Livestock
N - East and Central Farming and Forest
O - Mississippi Delta Cotton and Feed Grains
P - S. Atl. & Gulf Slope Cash Crops, Forest, Lvst.
R - Northeast Forage and Forest
S - North Atlantic Slope Diversified Farming
T - Atlantic & Gulf Coast Lowland Forest and Crop
U - Fla. Subtropical Fruit, Truck Crop, Range

The model disaggregates the 48 contiguous States into 45 regions defined by the intersection of the 10 USDA farm-production regions and 26 land-resource regions. USMP model region nomenclature is the concatenation of abbreviations for farm production and land resource region, e.g., CBM is Corn Belt M, LAM is Lake States M.

USMP production units reflect representative farm enterprises for the relevant geographic areas (e.g., a State or region). Hence, production activities in each USMP region are composites of the different production techniques that are actually practiced in the particular geographic area. Production activities are generally represented by fixed-coefficient production functions. In the case of crop enterprises, fertilizer inputs per acre (and their corresponding yields) are variable coefficients. For livestock operations, the mixes of feed input and the feed rations vary with changes in feed grain and livestock prices (subject to various physical requirements of the different livestock). For crop commodities, production activities are differentiated by tillage practice, multiyear crop rotation, dryland or irrigated system, participation in Government farm programs, and other characteristics.

Final product markets are modeled at the national level. On the demand side, USMP distinguishes between the demands for domestic consumption, export, commercial stocks, and Government stocks. Government farm programs in USMP include production flexibility contract payments, target prices, acreage reduction, acreage flexibility, acreage diversion, conservation reserve, and Commodity Credit Corporation (CCC) loan programs.[6] Participation in

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[6] Historically, not all of these programs are in effect in any given year.

Table 4.1—USMP commodity coverage

Farm-produced crops	Farm-produced livestock	Processed products
Barley	Whole farm milk	Eggs
Corn	Cull dairy cows for slaughter	Broilers
Cotton	Cull dairy cows for veal	Turkeys
Hay	Feeder pigs	Evaporated milk
Oats	Cull sows for slaughter	Fluid milk
Rice	Slaughter hogs	Manufactured milk
Silage	Beef feeder calves	Nonfat dry milk
Sorghum	Beef feeder yearlings	Butter
Soybeans	Cull beef calves for slaughter	American cheese
Wheat	Cull beef cows for slaughter	Other cheese
	Cull bulls for slaughter	Ice cream
	Fed beef for slaughter	Ethanol
	Fed beef for commercial feedlots	Soybean meal
	Nonfed beef for slaughter	Soybean oil
	Other livestock	Other oilseed meal
	Items not otherwise specified	Animal protein
		High-protein beanmeal feed
		Fed beef
		Nonfed beef
		Veal
		Pork
		Corn oil
		Gluten meal
		Gluten feed
		Distillers dried grains
		Livestock feed mixes

Source: Economic Research Service, USDA.

farm programs is voluntary and is determined endogenously in response to market forces affecting the costs and returns associated with commodity production, participation costs, and program benefits.

Carbon Sequestration Rates

Changes in soil-carbon levels that result from changes in land uses or production practices are determined by a variety of relatively local factors—including climatic conditions, soil characteristics, historical land-use patterns, and current management practices (Lal et al., 1998). Data derived from field experiments are not available in sufficient detail to account for all of these factors across the full range of U.S. agricultural soils. Therefore, this study uses a less precise but more broadly applicable approach based on the IPCC methodology for estimating the effects of changes in land uses and/or production practices on the quantity of carbon stored in agricultural soils (IPCC, 1997).

Cropland Management and Land-Use Change to Grassland

The IPCC methodology was developed for use in national assessments as a first-order approach to estimating changes in soil-carbon levels. It uses simple assumptions about the effects of land use and management changes on soil-carbon stocks. The framework is based on a 20-year inventory period and the top 30 cm of the soil profile. The IPCC methodology also provides guidelines and default values for estimating initial soil-carbon stocks for land in different uses as well as changes in soil carbon levels related to changes in land uses or production practices that occur over the inventory period. Because experimentally derived parameters are not available for much of the United States, we applied the default-factor values provided in the IPCC documentation, which take into account differences in climate, soil, disturbance history, tillage intensity, productivity, and residue management. Estimates of average annual sequestration rates are obtained by subtracting soil carbon stocks at the start of the inventory period from soil carbon stocks at the end of the inventory period and dividing the results by 20.

Climate regions in the IPCC inventory are delineated based on average annual temperature, precipitation, and potential evapotranspiration. Of the eight IPCC climatic regions, six are represented in the contiguous United States (i.e., cold temperate moist, cold temperate dry, warm temperate moist, warm temperate dry, subtropical moist, and subtropical dry) (Eve et al., 2001). Soil categories in the IPCC inventory are groups of taxonomic soil orders based on a soil's ability to store and stabilize organic carbon. The default IPCC guidelines contain five categories of mineral soils and one category of organic soils (IPCC, 1997).

To establish a set of initial soil-carbon levels for lands in different uses, we first derive a composite native soil for each of the 10 farm production regions. Each of these soils is a weighted average of all of the agricultural soils represented in the 1997 National Resources Inventory (NRI) data points within that region (USDA, NRCS, 2000).[7] Next, based on the six representative IPCC soil groupings, IPCC assigns each composite native soil a native soil (i.e., undisturbed) carbon stock. The IPCC

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[7] The NRI data describe soil conditions and track land-use changes at over 800,000 locations across the United States. While aggregating these sites to the Farm Production Region level obscures significant variations among soils in each region, it does at least capture more aggregate differences in productivity and climatic conditions.

base factors (i.e., default parameters that account for the effect of the historical land use on soil-carbon stocks) are then used to determine initial carbon levels for soils that have been under long-term cultivation and in long-term grasslands.

The IPCC methodology assigns native soils a base factor of 1.0 and soils under long-term cultivation a base factor of 0.7 (0.6 for wetland soils). That is, the methodology assumes that long-term cultivation decreases native soil-carbon levels by about 30 percent. Continuous hay or pasture is not explicitly reflected in the IPCC framework. We assume that lands in hay or pasture will accumulate soil carbon but will not return to their native soil-carbon levels without improved management. Hence, the methodology assigns a base factor of 0.9 (i.e., 10 percent less carbon than in native soils)—which is the average of the base factor values for soils under long-term cultivation and improved pasture. Improved pasture—that is, pasture being managed for increased biomass production through fertilizer use, irrigation, or species selection—is included in the IPCC with a default base factor of 1.1 (i.e., 10 percent more carbon than soils under native conditions).

In addition to assigning base factors, the IPCC methodology assigns tillage factors and input factors. tillage factors are used to estimate the longrun impacts of tillage management on soil carbon. The default tillage factor for conventional tillage is 1.0 (i.e., no longrun change in soil carbon over the inventory period). Changing from conventional tillage to no-till is assumed to increase soil carbon by 10 percent over the 20-year inventory period (a tillage factor of 1.1). Reduced tillage (more than 30 percent residue remaining at planting, but less than no-till) also increases soil carbon but to a lesser degree than no-till. For temperate climate zones, the IPCC tillage factor for reduced till is 1.05. In subtropical climates, the tillage factor values are somewhat lower.

Input factors are used to measure longrun effects of residue management on soil carbon. Input factor values reflect the level of biomass input to the soil. A crop/fallow rotation is considered low input because residue is only being produced every second year (input factor of 0.9). Continuous annual cropping is considered medium input, with an input factor of 1.0. Increasing soil residue by adding a winter cover crop or putting hay into a crop rotation is considered high input (input factor of 1.1). To estimate changes in soil carbon on lands that shift from crop production to grasses, we use the base factor for continuous pasture (i.e., we assume these lands will return to 90 percent of their native soil-carbon levels over a 20-year period).

Given the set of initial soil-carbon conditions for lands in different uses in each farm production region, we apply the IPCC's default tillage and input factors to develop a "from-to" table showing changes in annual soil-carbon levels associated with shifting "from" any possible rotation-tillage system in USMP "to" another possible rotation-tillage system (table 4.2). The "from" management systems are assumed to have been in place long enough for soil-carbon levels to be in a steady state and the "to" management systems are assumed to have been adopted for long-term use. If land use or production practice does not change during the inventory period, the IPCC framework assumes no change in soil carbon. If land use or production practice does change, change in the opposite direction results in an equal and opposite impact on soil-carbon stocks. Because of the relatively large quantities of potentially affected land, the values most relevant to this analysis are the values for shifting cropland into permanent grasses and changing from continuous cropping with conventional tillage to continuous cropping with no-till.

Land-Use Change to Forest

For each USMP region, we develop estimates of carbon sequestered by afforesting agricultural lands from data in Birdsey (1996). Birdsey disaggregates the 48 contiguous States into eight forest regions and reports per acre carbon accumulation in forests for selected tree species in each region.[8] Carbon accumulation values are reported in 5-year intervals from year 0 (conversion from pasture or cropland to forest) to year 120 and reflect fully stocked timberland under average management conditions. Carbon values are presented for trees, soils, understory, litter, and total ecosystem.

For this analysis, we assigned to each USMP region the tree species associated with the most geographically similar region in the Birdsey study. For regions

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[8] Birdsey focuses on commercially valuable species. Specifically, southern pine in the Southeast and South Central regions, white/red pine and fir/spruce in the Northeast and Lake State regions, white/red pine and oak/hickory in the Central States, ponderosa pine in the northern and southern Rocky Mountain regions, and douglas fir and ponderosa pine in the Pacific Coast.

with multiple tree species, we selected the species with the highest value for accumulated ecosystem carbon over the first 15 years of forest growth (i.e., the duration of our commitment period). We then took this accumulated carbon value and divided it by 15 to obtain an average annual rate of carbon sequestration (table 4.2, fig. 4.2). Hence, our values for carbon sequestered on lands shifted from cropland or pasture to forest reflect average per acre annual sequestration in trees, soils, understory, and litter over the first 15 years of growth.

Economic Incentives for Carbon Sequestration: Basic Features for Each Activity

In calculating the net returns to the activities covered by our carbon sequestration incentives (see box on structure of incentives) we employ a 15-year contract period for adoption of carbon-sequestrating land uses and production practices. This timeframe follows previous studies and is consistent with the historical tendency to limit farmer commitment periods in USDA conservation programs.[9] We assume farmers will participate when the net economic returns to shifting land into the carbon-sequestering land uses or production practices for 15 years exceed the net economic returns of allocating land to the next most profitable use for 15 years.[10] Reflecting the medium-run nature of USMP simulations, this calculation reflects any price increases (or decreases) induced by farm-sector adjustments to the incentives.

Land-Use Change to Forest

The net value of the afforestation option will be the sum of the sequestration payments plus the present discounted value of the standing timber at the end of 15 years minus the costs of establishing trees. To simplify the modeling exercise, we annualize these benefits and costs, which allows us to capture their collective net effect on producer decisions with a single number.

Our analysis does not offer the afforestation incentive in the Southern Plains, Northern Plains, or the Mountain regions because natural conditions do not favor forest growth throughout much of these regions. Establishing forests in these regions would require relatively costly human interventions (e.g., fire-suppression activities), compared with regions in which we offer the afforestation incentive. Nor does our analysis offer incentives to convert lands currently enrolled in CRP. CRP objectives include reducing soil erosion, improving water quality, and enhancing wildlife habitat—not all of which are necessarily compatible with increasing carbon sequestration. Including CRP lands in our analysis would conflate the costs and benefits associated with carbon sequestration with those associated with the other environmental goods and services provided by CRP (particularly in cases where there are tradeoffs). Consequently, we focus our carbon sequestration incentives on land currently in crop or livestock production.

We derived expected per acre timber quantities, prices per 1,000 cubic feet, and per acre values of timber at the end of the contract period by region and prior land use from various sources (table 4.3, figs. 4.3a-b). The timber quantities on converted pasture and converted cropland are from Birdsey (1996). Expected timber prices in each region reflect average prices for timber harvested from Federal forests between fiscal years 1996-1997 and 1999-2000 (inclusive).[11] The per acre timber values are the products of the timber quantities and their associated prices.

Current estimates of forest-establishment costs are not generally available for most regions of the country but

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[9] Conservation programs in the Farm Security and Rural Investment Act of 2002 (i.e., the 2002 Farm Act) that contain longrun land retirements include the Conservation Reserve Program (CRP) and the Wetlands Reserve Program (WRP). The CRP is by far the larger program with over 33.6 million acres enrolled as of August 2001 (USDA, FSA, 2001). CRP contracts run for 10 years. WRP enrollment is presently about 1 million acres. WRP easements run for 30 years or perpetuity. Additionally, except in the Pacific region, all of the forest types used in this analysis reach their maximum annual carbon accumulation rate between 15 and 20 years. Differences in the 15- and 20-year rates, however, are typically less than 0.25 mt per acre per year. Given these marginal differences and the demonstrated preference for shorter land-retirement programs, we selected 15 years as the length of our contract period.

[10] To be more precise, USMP does not operate strictly on the basis of profit maximization. It also includes a set of parameters that reflect the "stickiness" of decisionmaking regarding choices of rotations and tillage systems, in response to changes in costs and returns. That is, these parameters dampen what otherwise might be large-scale shifts in input use and/or commodity production in the model when costs or returns change by very small amounts but certain economic thresholds are crossed.

[11] These prices are available on the U.S. Forest Service website: *http://www.fs.fed.us/land/fm/s_h/s_hindex.htm*

Table 4.2—Selected carbon-sequestration rates by USMP region, for changes in land use or production practice

Region	From cropland to forest	From pasture to forest	From CAC* to grassland	From conventional till to conservation till	Forest species planted (for afforestation)
	Metric tons per acre per year				
Appalachia/ N	1.724	1.028	0.383	0.134	Southern pine
Appalachia/ P, S, and T	1.573	0.938	0.383	0.134	Southern pine
Corn Belt/ L, M, N, O	0.938	0.847	0.491	0.170	White/red pine
Corn Belt/ R	1.210	1.119	0.491	0.170	White/red pine
Delta States	1.724	1.028	0.506	0.178	Southern pine
Lake States	1.331	1.240	0.425	0.150	White/red pine
Mountain States**			0.249	0.085	--
Northeast	1.210	1.119	0.384	0.134	White/red pine
Northern Plains**			0.378	0.134	--
Pacific States/A and D	0.817	0.877	0.312	0.109	Douglas fir
Pacific States/B, C, and E	0.786	0.726	0.312	0.109	Ponderosa pine
Southeast	1.573	0.938	0.329	0.113	Southern pine
Southern Plains**			0.394	0.138	--

Note: See figure 4.1 for USMP regions.

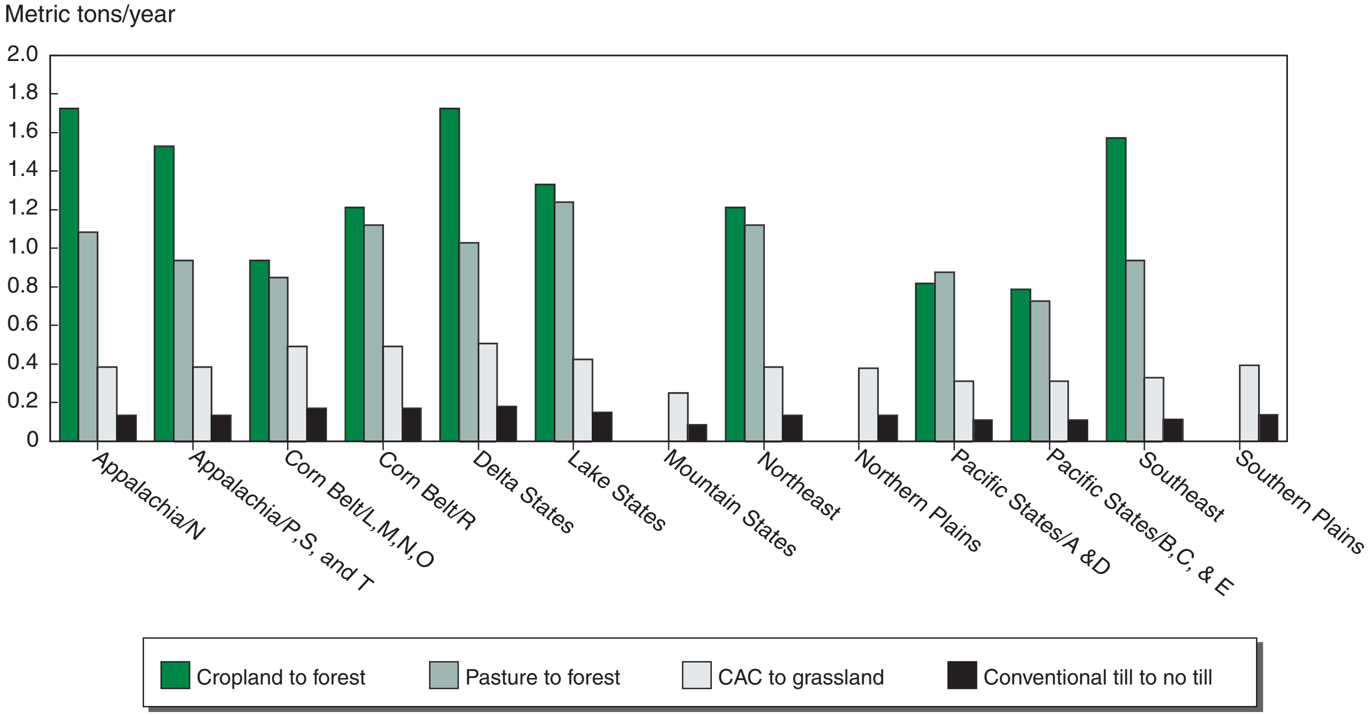
* Continuous annual cropping (CAC) reflects use of conventional tillage and moldboard plow. Depending on the region, CAC includes some combination of soybeans, corn, sorghum, silage, oats, wheat, barley, peas, barley, and rice. Sequestration values are generally lower for rotations with cotton or fallow periods and higher for rotations with hay.

** Our analysis does not offer afforestation incentives in these regions.

Sources: IPCC inventory method for cropland and grassland carbon levels (IPCC, 1997); Birdsey (1996) for forest carbon levels. See text for detailed explanation.

Figure 4.2

Selected carbon sequestration rates by USMP region, for changes in land use or production practice



Note: See figure 4.1 for USMP regions.

CAC = continuous annual cropping.

Sources: IPCC inventory method for cropland and grassland carbon levels (IPCC, 1997); Birdsey (1996) for forest carbon levels.

See text for detailed explanation.

Table 4.3—Estimated quantities and values of timber per acre at end of 15-year carbon sequestration program, by farm-production region

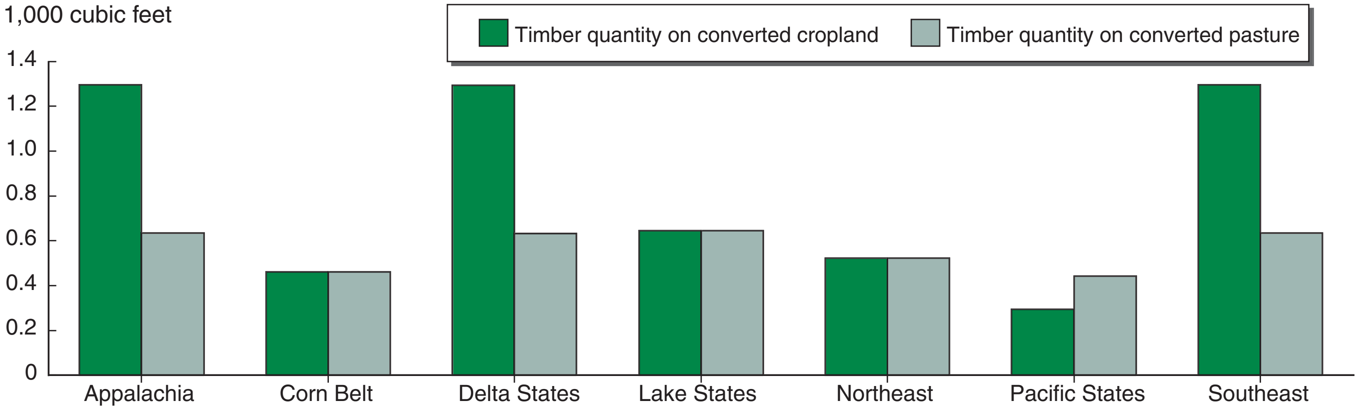
		From cropland		From pastureland	
Region	Price	Timber quantity	Timber value	Timber quantity	Timber value
	$/1,000 cu. ft.	1,000 cubic feet	Dollars	1,000 cubic feet	Dollars
Appalachia	790.18	1.295	1,023.28	0.634	500.97
Corn Belt	485.24	.461	223.70	.461	223.70
Delta	790.18	1.293	1021.70	.632	499.39
Lake States	485.24	.644	312.99	.644	312.49
Northeast	485.24	.522	253.30	.522	253.30
Pacific	696.92	.295	205.59	.443	308.74
Southeast	790.18	1.295	1023.28	.634	500.97

Note: Quantities and dollar values are per acre.

Sources: Timber quantity source is Birdsey (1996). Timber prices source is *http://www/fs.fed.us/land/fm/s_h/s_hindex.htm*.
Prices reflect average prices for timber harvested from Federal forests between fiscal years 1996-1997 and 1999-2000 (inclusive).

Figure 4.3a

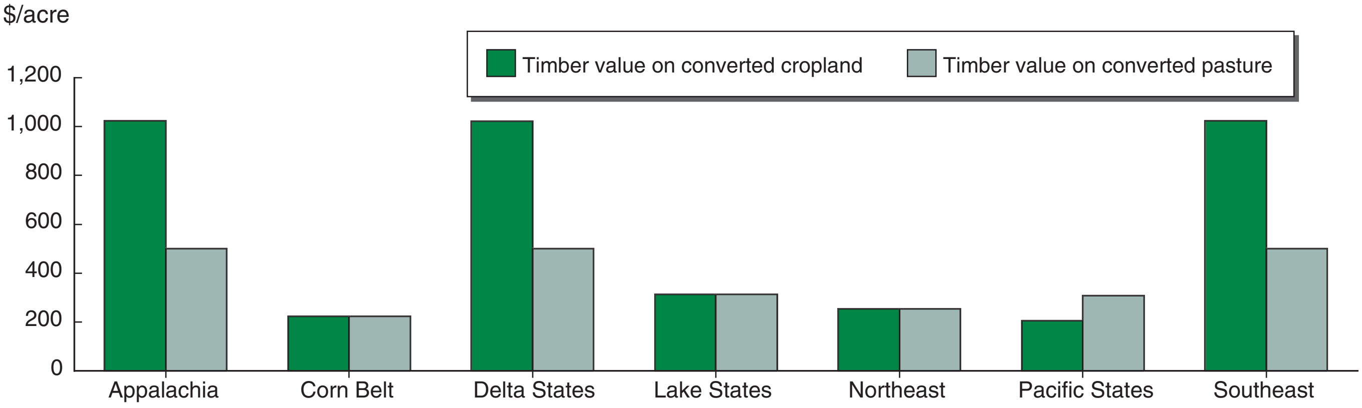
Estimated quantities of timber per acre at end of 15-year carbon sequestration program, by farm-production region



Source: Birdsey (1996).

Figure 4.3b

Estimated values of timber per acre at end of 15-year carbon sequestration program, by farm-production region



Prices reflect average prices for timber harvested from Federal forests between fiscal years 1996-1997 and 1999-2000 (inclusive).
Source: *http://www/fs.fed.us/land/fm/s_h/s_hindex.htm*

Structure of Carbon Sequestration Incentives in USMP Simulations

Generic features

- Farmers commit to adopt carbon-sequestering land uses and production practices for 15 years. Commitment period begins in 2010.
- Sequestration payments are only offered for bringing new lands into forests, grasses, or carbon-sequestering production practices. Hence, forest land that stays in forest, grassland that stays in grass, and cropland that is in, and remains in, no-till count for zero additional sequestration.

Afforestation

- Establishment costs—annualized over 15 years.
- Value of standing timber at the end of 15 years.
- Payment for carbon sequestered.
- Ineligible lands: Southern Plains, Northern Plains, or Mountain regions (throughout much of these regions, natural conditions do not favor forest growth).
- No double enrollment in CRP.

Land-use change to grassland

- Establishment costs—annualized over 15 years (estimates based on CRP data).
- No value from sale of co-products (not used by livestock for forage).
- Payment for carbon sequestered.
- Eligible land: all cropland in all regions.
- No double enrollment in CRP.

Changing production practices (i.e., adopting conservation tillage on carbon-sequestering rotations)

- Costs of production by rotation and by tillage system.
- Revenue from sale of crops (reflecting potential yield/acre effects).
- Payment for carbon sequestered.
- Eligible land: all land in all regions where conservation tillage or carbon-sequestering rotations are currently practiced.

are published biannually for the South. The total cost of seedlings, prescribed burning, and hand planting in the Southeast in 1998 averaged about $93.29 per acre (DuBois et al., 1999). To estimate regional forest-establishment costs, we used State-level data on the value and quantity of timber harvested from National Forests in 1998 (USDA, FS, 1999) to derive a share of harvest-weighted timber price for each farm production region and then also for the Southeast as defined by the Forest Service. To generate estimates of forest establishment cost differentials for each region, we divided the farm production region prices by the Forest Service Southeast region price; these ratios were multiplied by the Southeast cost estimate of $93.29 to obtain an estimated forest-establishment cost in each farm production region.

Land-Use Change to Grasslands

The net value of the grassland-conversion option will be the sum of the annualized sequestration payments net of the sum of annualized grassland establishment costs. In our simulation scenarios, we assume no revenue from the sale of co-products, such as forage or hunting opportunities, for lands converted to permanent grass.[12] All cropland is considered eligible for conversion to grasses. Pasture land, which has the same carbon-sequestration rates as grassland in our carbon-sequestration methodology, is not eligible for conversion. Again, our analysis does not allow incentives to convert grasslands enrolled in the CRP. Estimates of grassland-establishment costs are based on CRP data. Estimates of the carbon-sequestration rates that provide the basis for the incentive payments are based on the IPCC inventory methodology.

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[12] This assumption is consistent with the CRP, which limits (and until 2002 generally prohibited) grazing or haying on enrolled lands. Allowing lands covered by this incentive to be grazed or hayed would make this incentive more attractive to landowners. It would also, however, require that we specify how these lands are managed—since management practices would affect the net sequestration achieved. Given the example of the CRP, and the finding in Antle et al. (2001) and McCarl and Schneider (2001) (see chapter 3 in this report) that this land-use change would not be competitive with other carbon-sequestration activities, we simplify our analysis and omit co-products on croplands converted to grasses.

Cropland Management

For each cropland-management activity that receives a sequestration payment, the net value of the option to the farmer will be the expected net revenue from the sale of crops (reflecting any changes in yields or acreage) plus the annualized payment for net carbon sequestration minus the baseline net revenue of production. For each activity, eligible lands include all lands in regions where that activity is currently practiced. Again, estimates of the carbon-sequestration rates that provide the basis for the incentive payments are based on the IPCC inventory methodology.

Model Baseline and Simulation Scenarios

Our carbon-sequestration incentives are assumed to begin in 2010. To establish the baseline scenario, we calibrate USMP to approximate the supply, demand, production, acreage, tillage, Government program, input cost, and other conditions projected in the USDA baseline for 2010.[13] Simulation results should be interpreted as reflecting differences relative to 2010, when there are no new incentive programs targeting carbon sequestration. To trace out the marginal cost curve for sequestered carbon, we run each scenario with six alternative payment levels—these payments are based on the assumption that the value of a metric ton of carbon emissions reduction is $10, $25, $50, $75, $100, and $125.[14] Each year during the contract period, participants are paid for the additional metric tons of carbon they sequester that year.

With USMP calibrated to reflect the agricultural-sector conditions projected in the USDA baseline for 2010, we simulate four alternative incentive scenarios (see box on simulation scenarios). In scenario 1, our reference scenario, carbon payments are for carbon rental, compensating for storage during the commitment period only. The incentive program covers a 15-year contract period. At the 5-percent discount rate employed in the analysis, 15 years of storage is equivalent to 0.354 times the “full” asset value for carbon-emissions reduction (see table 2.5). Hence, for carbon emissions reductions valued at $10, $25, $50, $75, $100, and $125 per metric ton, payments to farmers for 15 years of storage are $3.54, $8.85, $17.70, $26.55, $35.40, and $44.25, respectively, per mt of carbon sequestration. (For permanent storage, the present discounted value of the total payments farmers will receive under the rental payment format will equal the full asset value of permanent carbon sequestration paid at the time the carbon was put in storage.) For purposes of clarity, in comparing the results of different scenarios, we will refer to the six payment levels in terms of the full asset value of emissions reductions or permanent carbon sequestration—that is, $10, $25, $50, $75, $100, and $125 per metric ton.

Summary of Simulation Scenarios

Scenario 1: *Reference scenario.*

Rental payment for net sequestration during contract period only, with no cost-share supplement.

Scenario 2: *A common approach to permanence in the early literature.*

Asset-value payment (assuming permanent sequestration) for net sequestration, no cost-share supplement.

Scenario 3: *A standard feature of USDA conservation subsidy programs.*

Rental payment for net sequestration, *with cost-share supplement.*

Scenario 4: *Exploring the potential for emissions “leakage” within cropland management.*

Rental payment *for gross sequestration*, no cost-share supplement.

Another key feature of scenario 1 is that payments reflect *net* carbon sequestration. In other words, the farm sector is credited for changes in land uses and/or practices that sequester carbon and is debited for related changes in land uses and production practices that increase carbon emissions. Scenario 1 serves as a reference scenario because of its incentive structure: It accounts for the permanence issue (it pays only for the

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[13] Calibration of USMP to the USDA baseline projections for 2010 is not exact. The differences between prices and quantities in USMP’s 2010 baseline and the USDA’s 2010 estimates for most commodities are less than 1 percent. The major exceptions to this are for beef, pork, and dairy where USMP price and quantity values more closely approximate the USDA’s estimates for 2005.

[14] In our analysis, carbon payment levels are set exogenously and provided to USMP as given. The range of payments analyzed was chosen to be consistent with the payment levels considered in previous studies.

value of sequestration occurring during the commitment period), it accounts for farm-sector leakage (it pays only for net sequestration), and it is consistent with the C-stock equilibrium issue (again, it pays only for the value of sequestration occurring during the commitment period).

Scenario 2 employs an incentive structure similar to structures employed in many previous studies (app. 1). Specifically, rather than receiving rental payments covering storage during the contract period only, farmers receive full payments for permanent storage. As in scenario 1, farmers receive payments when the carbon is added to the soils or biomass, and farmers are paid only for net sequestration.

The payment structure in scenario 2 implicitly assumes that any sequestering activity that receives a payment is permanent. Still nothing prevents farmers from reverting to carbon-emitting land uses and production practices when their contracts expire. In this case, society would receive less carbon sequestration—and emissions offsets—than it paid for. Specifically, society would pay for permanent carbon storage but receive a sequestration stream in which the carbon sequestered in year 1 is stored for 15 years, the carbon sequestered in year 2 is stored for 14 years, and so forth until year 15, when the incremental carbon sequestered is stored only for 1 year.

On the other hand, the sequestration outcomes of the rental program are independent of the assumption about permanence. If sequestration is maintained permanently, farmers will ultimately receive the same present discounted value of sequestration payments. A comparison of the costs between scenarios 1 and 2 provides insights on the cost effectiveness of implementing carbon sequestration incentives based on the assumption of permanence, if that assumption turns out to be faulty.[15]

Scenario 3 reverts to the rental payment structure but adds a 50-percent cost-share payment to help landowners offset the startup costs of the desired land-use changes—that is, afforesting cropland or pasture and converting cropland to grasses.[16] We include this scenario because USDA conservation programs often include cost-share assistance to help farmers establish conservation practices. For example, the CRP allows for a 50-percent cost-share payment to help landowners cover tree-establishment costs in afforestation agreements, in addition to the annual land rental payment. Hence, scenario 3 will provide insights on the cost effectiveness of adding a cost-share payment to the annual per ton carbon payment for different levels of carbon payments. To simplify the modeling, we annualize the value of the cost-share payment for the afforestation activity and add it to the yearly per ton payment and the annualized end-of-program timber value. Payments are again based on net sequestration.

Scenario 4 drops the cost-share provision and keeps the rental payment structure but offers payments for *gross* sequestration rather than *net* sequestration. In other words, the per ton carbon payments credit farmers for changes in land uses and/or practices that sequester carbon but do not penalize them for related changes in land uses and production practices that increase carbon emissions. With this scenario, we can explore the potential for farm-sector carbon leakage related to activities that farmers undertake in response to, but which are not included in, the sequestration incentive set. These activities include switching lands under conventional tillage to no-till while simultaneously switching to conventional tillage on land currently under no-till, or shifting lands into trees or grasses while simultaneously bringing idle land into production.

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[15] The differential costs of using this payment system when the true assumption is one of permanence most likely will be reflected in a different time path of transaction costs because payments will be made throughout the full storage period, rather than simply in the years in which carbon is accumulating. The result is likely to be higher total transaction costs.

[16] Historically, USDA has not provided farmers with cost-share payments for changes in production practices. Hence, our analysis does not consider cost-share payments for changes in tillage practices or rotations.

Empirical results were obtained from running USMP under the four farm-sector incentive scenarios for carbon sequestration described in chapter 4 of this report. Tables 5.1-5.4 detail selected results for the four simulation scenarios that capture alternative designs for carbon-sequestration incentives. Results of the simulation scenarios represent changes relative to the 2010 baseline, that is, they reflect impacts beyond those that would occur in a 2010 world with no new carbon sequestration incentives.

Scenario 1: Rental Payment for Net Sequestration, No Cost-Share—*Reference Policy Scenario*

Table 5.1, scenario 1 suggests that U.S. agriculture has significant economic potential to store additional carbon—although the amounts sequestered are well below the levels estimated to be technically possible in soil science studies (see table 2.2). For permanent sequestration valued at $10, $25, $50, $75, $100, and $125 per mt, farmers receive rental payments of $3.54, $8.85, $17.70, $26.55, $35.40, and $44.25 per mt of carbon sequestered during the 15-year contract period. [Remember, if they were to sequester the carbon permanently, the present discounted value of their receipts would be the full asset value for permanent sequestration per ton.] At these carbon prices, the farm sector is estimated to sequester 0.4, 6.3, 30.3, 42.8, 54.3 and 72.0 MMT of carbon per year. At the lowest carbon price, neither of the land-use change options appears to be economically attractive: all net sequestration (i.e., 0.4 MMT) results from the expanded use of conservation tillage (fig. 5.1). At all higher payment levels, however, afforestation accounts for 86-94 percent of total sequestration.

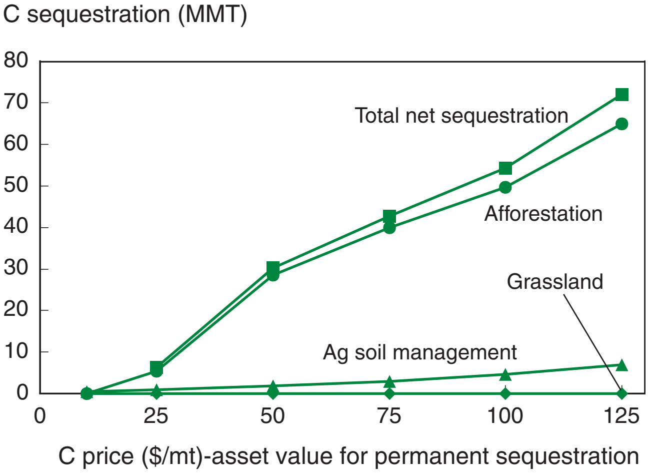
The dominance of afforestation reflects the significantly higher per acre carbon payments relative to those for other activities—due to the significantly higher per acre sequestration rates associated with shifting land into trees (see table 4.2 and fig. 4.2). Between 68 and 77 percent of the carbon from afforestation comes from conversion of pasture, with the share from cropland generally increasing as the payment level rises. Pasture is generally less productive than cropland, so this pattern is consistent with farmers afforesting more marginal lands first. No payment level in this scenario is sufficient to induce farmers to sequester carbon by converting cropland to permanent grasses.[1]

As the asset value for permanent sequestration increases from $10 to $125 per mt, annual carbon sequestration from expanding conservation tillage increases from 0.4 to 7.5 MMT. Some of the carbon sequestered through additional use of conservation tillage, however, is offset by other cropland management decisions that increase carbon emissions. These other activities include shifting land from conservation tillage to conventional tillage, switching to rotations with higher emissions, and bringing idle land into crop production.[2] Net emissions from these activities, reflected in the category "other changes in cropland

Figure 5.1

Annual net carbon sequestration

Scenario 1: Rental payments on net sequestration



Source: Economic Research Service, USDA.

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[1] It is important to note, however, that the simulations only incorporate incentives for land-use *change* to grassland—we do not take into account any continuing sequestration that may occur due to past land-use change, until a new C-stock equilibrium is reached. Nor do we capture the sequestration potential for improved *management* of range or pasture because we lack cost data for the associated activities.

[2] To track flows in and out of conservation tillage, we report the sequestration impacts of changes into conservation tillage in the "changes to conservation tillage" category, and the impacts of changes out of conservation tillage in the "other changes in cropland management" category, along with the net impacts on carbon sequestration of rotation changes.

Table 5.1—Average annual change in total carbon sequestered by practice/land-use change, for alternative policy scenarios and carbon-payment levels

	Price per metric ton of permanent carbon sequestration*					
Activity	$10	$25	$50	$75	$100	$125
			Million metric tons			
Scenario 1: Rental payment on net sequestration, with no cost-share:						
Afforestation	0.0	5.4	28.5	39.9	49.7	65.0
From cropland	0.0	1.7	6.7	10.6	13.3	18.5
From pasture	0.0	3.7	21.8	29.3	36.4	46.4
Additional grasses	0.0	0.0	0.0	0.0	0.0	0.0
Changes to conservation tillage**	0.4	1.0	2.0	3.2	5.0	7.5
Other changes in cropland management	0.0	-0.1	-0.2	-0.3	-0.4	-0.5
Total	0.4	6.3	30.3	42.8	54.3	72.0
Scenario 2: Asset payment on net sequestration, with no cost-share:						
Afforestation	8.5	38.4	72.4	103.1	125.2	133.1
From cropland	2.6	10.2	20.2	26.6	33.1	40.1
From pasture	6.0	28.2	52.2	76.6	92.1	93.1
Additional grasses	0.0	0.0	0.0	0.0	0.0	0.0
Changes to conservation tillage**	1.1	2.9	8.5	14.0	20.0	27.6
Other changes in cropland management	-0.1	-0.2	-0.5	-1.0	-1.0	-0.7
Total	9.5	41.1	80.4	116.1	144.2	160.0
Scenario 3: Rental payment on net sequestration, with cost-share:						
Afforestation	2.8	16.6	34.3	41.1	54.9	68.4
From cropland	0.1	3.2	7.7	10.9	14.4	18.8
From pasture	2.7	13.4	26.6	30.2	40.5	49.6
Additional grasses	0.0	0.0	0.0	0.0	0.0	0.0
Changes to conservation tillage**	1.0	1.4	2.1	2.8	3.5	4.3
Other changes in cropland management	-0.1	-0.1	-0.2	-0.2	-0.2	-0.4
Total	3.7	17.9	36.2	43.7	58.2	72.3
Scenario 4: Rental payment on gross sequestration, with no cost-share:						
Afforestation	0.0	5.4	28.5	39.6	47.4	61.1
From cropland	0.0	1.7	6.7	10.6	13.3	18.5
From pasture	0.0	3.7	21.7	29.0	34.1	42.6
Additional grasses	0.0	0.0	0.0	0.0	0.0	0.0
Changes to conservation tillage**	31.8	32.1	32.5	32.9	34.1	34.4
Other changes in cropland management	-31.7	-31.6	-31.6	-31.5	-31.3	-30.9
Total	0.1	5.9	29.4	41.0	50.3	64.6

* Corresponding payments to farmers during the 15-year contract period are $3.54, $8.85, $17.70, $26.55, $35.40, and $44.25 per mt in rental payment scenarios 1, 3, and 4 and $10, $25, $50, $75, $100, and $125 per mt in asset payment scenario 2.

** These rows report gross sequestration from changes to conservation tillage. Emission increases from changes out of conservation tillage are in “other changes in cropland management.”

Source: Economic Research Service, USDA.

management,” increase from 0.0 to 0.5 MMT over the range of carbon values analyzed.

Table 5.2 reports the effects of land-use and land-management changes associated with the carbon-sequestration quantities reported in table 5.1. For cropland management, at asset carbon prices of $10, $25, $50, $75, $100, and $125 per mt with scenario 1, farmers shift, respectively, 2.1, 5.2, 10.5, 15.9, 20.3, and 27.9 million acres from conventional tillage to conservation tillage. The net effect of these cropland-management decisions on carbon sequestration, however, is partially offset by the reverse shift of some cropland—between 0.3 and 7.3 million acres—from conservation tillage to conventional tillage. (We discuss the shift from conservation tillage to conventional tillage in more detail for scenario 4).

The ability of very modest carbon payments to induce additional use of conservation tillage reflects the sizable set of producers who base decisions to use one system over another on marginal economic considerations. In many areas, conservation and conventional tillage systems exist side by side. In these cases, it is

Table 5.2—Acres changing land use or tillage practice as a result of contract, by policy scenario and carbon-payment level

	Price per metric ton of permanent carbon sequestration*						
Activity	Base	$10	$25	$50	$75	$100	$125
	Total acres (mil.)	*Change in acres (mil.)*					
Scenario 1: Rental payment on net sequestration, with no cost-share:							
Change to forest land:							
From cropland	0	0.0	1.1	4.4	6.9	8.7	12.7
From pasture	0	0.0	4.1	24.2	32.3	40.4	51.9
Total change to forest	0	0.0	5.2	28.6	39.2	49.1	64.6
Total change to grassland	0	0.0	0.0	0.0	0.0	0.0	0.0
Cropland - tillage changes:							
From conventional to conservation tillage	0	2.1	5.2	10.5	15.9	20.3	27.9
From conservation to conventional tillage	0	0.3	0.9	1.7	2.9	3.9	7.3
Net change to conservation tillage		1.8	4.3	8.8	13.0	16.4	20.6
Scenario 2: Asset payment on net sequestration, with no cost-share:							
Change to forest land:							
From cropland	0	1.7	6.6	13.8	18.1	22.5	27.4
From pasture	0	6.7	31.2	58.6	87.5	105.4	106.1
Total change to forest	0	8.4	37.8	72.4	105.6	127.9	133.5
Total change to grasslands	0	0.0	0.0	0.0	0.0	0.0	0.1
Cropland - tillage changes:							
From conventional to conservation tillage	0	5.8	14.6	29.9	42.6	54.3	66.9
From conservation to conventional tillage	0	0.8	2.4	6.9	8.4	12.0	14.2
Net change to conservation tillage		5.0	12.2	23.0	34.2	42.3	52.7
Scenario 3: Rental payment on net sequestration, with cost-share:							
Change to forest land:							
From cropland	0	0.1	2.1	5.0	7.1	9.7	12.9
From pasture	0	2.9	14.9	29.5	33.3	45.7	56.3
Total change to forest	0	3.0	17.0	34.5	40.4	55.4	69.2
Total change to grassland	0	0.0	0.0	0.0	0.0	0.0	0.0
Cropland - tillage changes:							
From conventional to conservation tillage	0	3.2	4.9	9.1	13.4	16.8	21.0
From conservation to conventional tillage	0	1.7	1.3	2.0	2.9	2.6	3.3
Net change to conservation tillage		1.5	3.6	7.1	10.5	14.2	17.7
Scenario 4: Rental payment on gross sequestration, with no cost-share:							
Change to forest land:							
From cropland	0	0.0	1.1	4.4	6.9	8.7	12.7
From pasture	0	0.0	4.1	24.1	31.9	38.1	48.1
Total change to forest	0	0.0	5.2	28.5	38.8	46.8	60.8
Total change to grassland	0	0.0	0.0	0.0	0.0	0.0	0.0
Cropland - tillage changes:							
From conventional to conservation tillage	0	76.8	80.3	79.1	81.5	81.3	82.7
From conservation to conventional tillage	0	76.1	78.1	74.8	74.2	73.1	72.6
Net change to conservation tillage		0.7	2.2	4.3	7.3	8.2	10.1

* Corresponding payments to farmers are $3.54, $8.85, $17.70, $26.55, $35.40, and $44.25 per mt in scenarios 1, 3, and 4 and $10, $25, $50, $75, $100, and $125 per mt in scenario 2.

Source: Economic Research Service, USDA.

expected that the returns to the different tillage systems would be fairly similar and that relatively small carbon payments would be sufficient that some farmers currently using conventional tillage would maximize profits by shifting to conservation tillage.

Across the payment levels analyzed, afforestation of cropland and pasture increases from 0.0 to 64.6 million acres. At payment levels of $100 per mt and below, the Delta States, the Southeast, and Appalachia account for the large share of acres shifting to forest (between 82 and 100 percent) (app. 2). At $100 per mt, some afforestation occurs in all regions in which it is considered feasible, including the Pacific.

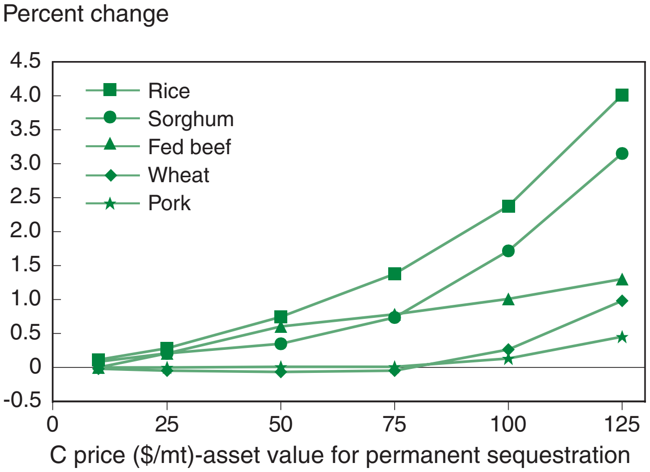
Across the carbon-payment range analyzed, U.S. timberland acreage—now estimated at 503.7 million acres (Vesterby and Krupa, 2001)—increases from 0 to 13 percent. Within USMP, we cannot currently identify at what point substantial program-induced price and output effects would occur through carbon-sequestration activities in forestry markets. At least for the higher carbon-payment levels, not accounting for potential carbon leakage in the forestry sector probably results in an overestimate of net sequestration.

With respect to commodity markets, the carbon-sequestration incentives simulated in scenario 1 typically result in lower output and higher prices (fig. 5.2, table 5.3). This pattern is consistent with the observed shifts of land out of crop and livestock production and into trees. Commodity market impacts, however, are quite modest for carbon payments up to $75 per mt—production declines are all less than 1.7 percent and price increases are all less than 1.4 percent. At a payment of $100 per mt, some price and production impacts start to become more substantial. The price of rice increases 2.4 percent, production of rice drops 2.5 percent, and production of sorghum drops 2.9 percent. At a payment level of $125 per mt, four of the nine commodities in table 5.3 have price increases between 2.4 and 4.1 percent and three have production declines between 2.9 and 5.6 percent. Among the commodity markets, the most affected are the major feed grains (corn and sorghum), rice (for crops), and fed beef (for livestock). The effects on the markets for wheat, soybeans, pork, and milk are relatively small.

Figure 5.2

Commodity price changes

Scenario 1: Rental payments on net sequestration



Source: Economic Research Service, USDA.

Table 5.4 reports the impacts on agricultural-sector welfare and Government spending under alternative policy scenarios. Aggregate producer welfare impacts are shown as changes in net farm income and domestic producer surplus. In USMP, net farm income nets out variable costs while producer surplus nets out both variable and fixed costs. For payment levels of $50 per mt and below, increases in net farm income in scenario 1 are less than 2.0 percent. As payments increase from $75 to $125 per mt, net farm income increases from 3.3 to 7.6 percent.

For full carbon payments of $10, $25, $50, $75, $100, and $125 per mt, Government payments to farmers total $1.3 million, $55.7 million, $537.1 million, $1,137.1 million, $1,924.4 million, and $3,181 million, respectively. For context, annual outlays during 1989-2000 for USDA's CRP varied between $1.40 billion and $1.73 billion, including rental payments, cost-share assistance, and technical assistance for the 29.2 to 35.1 million enrolled acres during the period (USDA, FSA, 2001).

The higher commodity prices and lower production levels associated with carbon payments to producers hurt U.S. consumers of agricultural products. This impact is measured by changes in domestic consumer surplus, which is the difference between the amount that consumers would be willing to spend and the amount they actually have to spend for a specific quantity of a good. Reductions in consumer surplus indicate a decline in consumer welfare. Across the payment levels, however, declines in domestic consumer surplus are relatively modest—between 0.0 and 0.2 percent (or never more than $1.9 billion).

Table 5.3—Estimated commodity market impacts, by policy scenario and carbon-payment level

	Price per metric ton of permanent carbon sequestration*						
Activity	$0	$10	$25	$50	$75	$100	$125
	Baseline (units noted)	*Percent change from baseline*					
Scenario 1: Rental payment on net sequestration, with no cost-share:							
Commodity production:							
Corn	11.234 bil. bu	0.0	0.0	- 0.1	-0.1	-0.3	-0.5
Sorghum	0.670 bil. bu	-0.1	-0.3	-1.0	-1.6	-2.9	-5.6
Wheat	2.545 bil. bu	0.0	0.0	0.1	0.0	-0.3	-1.0
Rice	0.194 bil. cwt	-0.1	-0.3	-0.8	-1.4	-2.5	-4.2
Soybeans	3.245 bil. bu	0.0	0.0	0.1	0.0	-0.7	-1.5
Cotton	17.50 mil. bales	-0.1	-0.2	-0.5	-0.9	-1.6	-2.9
Fed beef	152.20 mil. cwt	0.0	-0.2	-0.3	-0.4	-0.5	-0.6
Pork	189.80 mil. cwt	0.0	0.0	0.0	0.0	0.0	0.0
Milk	1,794.00 mil. cwt	0.0	0.0	0.0	0.0	0.0	-0.1
Commodity prices:							
Corn	$2.60 bu	0.02	0.04	0.00	0.07	1.02	2.67
Sorghum	$2.35 bu	0.09	0.21	0.35	0.74	1.72	3.15
Wheat	$3.70 bu	-0.02	-0.04	-0.06	-0.04	0.27	0.98
Rice	$7.71 cwt	0.12	0.29	0.75	1.38	2.38	4.01
Soybeans	$6.30 bu	-0.01	0.01	0.20	0.34	1.04	1.87
Cotton	$312.00 bale	0.07	0.17	0.40	0.71	1.33	2.35
Fed beef	$334.04 cwt	0.00	0.21	0.61	0.79	1.01	1.30
Pork	$262.93 cwt	0.00	0.01	0.02	0.04	0.15	0.34
Milk	$14.30 cwt	0.00	-0.02	-0.07	-0.50	0.80	0.29
Scenario 2: Asset payment on net sequestration, with no cost-share:							
Commodity production:							
Corn	11.234 bil. bu	0.0	-0.1	-0.7	-1.7	-3.0	-4.1
Sorghum	0.670 bil. bu	-0.4	-1.5	-6.6	-10.1	-14.4	-17.4
Wheat	2.545 bil. bu	0.0	0.0	-1.3	-3.9	-8.4	-12.1
Rice	0.194 bil. cwt	-0.3	-1.4	-5.3	-8.3	-11.6	-16.0
Soybeans	3.245 bil. bu	0.0	0.0	-1.9	-4.2	-7.9	-11.2
Cotton	17.50 mil. bales	-0.2	-0.8	-3.3	-5.7	-9.5	-16.1
Fed beef	152.20 mil. cwt	-0.4	-0.4	-0.7	-1.1	-1.5	-1.9
Pork	189.80 mil. cwt	0.0	0.0	-0.1	-0.1	-0.2	-0.3
Milk	1,794.00 mil. cwt	0.0	0.0	-0.2	-0.4	-0.7	-0.9
Commodity prices:							
Corn	$2.60 bu	0.04	0.06	3.53	7.79	13.35	17.15
Sorghum	$2.35 bu	0.22	0.68	3.68	7.77	13.47	17.29
Wheat	$3.70 bu	-0.04	-0.04	1.27	3.82	8.16	11.73
Rice	$7.71 cwt	0.32	1.30	5.07	7.94	11.06	15.23
Soybeans	$6.30 bu	0.03	0.32	2.29	4.49	8.18	11.31
Cotton	$312.00 bale	0.19	0.67	2.71	4.68	7.76	13.14
Fed beef	$334.04 cwt	0.35	0.77	1.46	2.23	3.11	3.76
Pork	$262.93 cwt	0.01	0.03	0.44	0.91	1.58	2.05
Milk	$14.30 cwt	-0.02	-0.06	0.41	0.97	1.64	2.10

See notes at end of table.

Continued--

Table 5.3—Estimated commodity market impacts, by policy scenario and carbon-payment level—Continued

	Price per metric ton of permanent carbon sequestration*						
Activity	$0	$10	$25	$50	$75	$100	$125
	Baseline (units noted)	*Percent change from baseline*					
Scenario 3: Rental payment on net sequestration, with cost-share:							
Commodity production:							
Corn	11.234 bil. bu	0.0	0.0	-0.1	0.0	-0.2	-0.4
Sorghum	0.670 bil. bu	-0.1	-0.3	-0.8	-1.2	-1.7	-2.8
Wheat	2.545 bil. bu	0.0	0.0	0.0	-0.1	-0.2	-0.6
Rice	0.194 bil. cwt	0.0	0.0	-0.1	-0.3	-1.0	-1.3
Soybeans	3.245 bil. bu	0.0	0.1	0.2	0.1	-0.3	-0.9
Cotton	17.50 mil. bales	0.0	-0.1	-0.2	-0.4	-0.9	-1.2
Fed beef	152.20 mil. cwt	0.0	-0.2	-2.0	-0.4	-0.5	-0.6
Pork	189.80 mil. cwt	0.0	0.0	0.0	0.0	0.0	0.0
Milk	1,794.00 mil. cwt	0.0	0.0	0.0	0.0	0.0	0.0
Commodity prices:							
Corn	$2.60 bu	-0.03	-0.12	-0.25	-0.28	0.12	1.19
Sorghum	$2.35 bu	0.05	0.06	0.21	0.55	1.16	1.64
Wheat	$3.70 bu	0.00	-0.01	0.01	0.08	0.22	0.58
Rice	$7.71 cwt	0.01	0.04	0.08	0.32	1.00	1.20
Soybeans	$6.30 bu	0.00	0.06	0.14	0.18	0.65	1.27
Cotton	$312.00 bale	0.03	0.07	0.15	0.32	0.70	0.98
Fed beef	$334.04 cwt	0.06	0.35	1.78	0.81	1.01	1.25
Pork	$262.93 cwt	0.00	0.00	0.00	0.00	0.06	0.18
Milk	$14.30 cwt	-0.01	-0.05	-0.09	-0.06	0.04	0.20
Scenario 4: Rental payment on gross sequestration, with no cost-share:							
Commodity production:							
Corn	11.234 bil. bu	0.0	0.0	-0.1	-0.1	-0.1	-0.2
Sorghum	0.670 bil. bu	-0.1	-0.2	-0.8	-1.1	-1.5	-2.1
Wheat	2.545 bil. bu	0.0	-0.1	-0.2	-0.3	-0.4	-0.7
Rice	0.194 bil. cwt	-0.1	-0.3	-0.5	-0.8	-1.1	-2.0
Soybeans	3.245 bil. bu	0.0	0.0	0.1	0.2	0 .1	-0.3
Cotton	17.50 mil. bales	0.0	0.0	0.0	0.0	-0.1	-0.4
Fed beef	152.20 mil. cwt	0.0	0.0	-0.3	-0.4	-0.5	-0.5
Pork	189.80 mil. cwt	0.0	0.0	0.0	0.0	0.0	0.0
Milk	1,794.00 mil. cwt	0.0	0.0	0.0	0.0	0.0	0.0
Commodity prices:							
Corn	$2.60 bu	0.01	0.00	-0.08	-0.05	0.08	0.68
Sorghum	$2.35 bu	0.05	0.11	0.11	0.21	0.51	0.90
Wheat	$3.70 bu	0.04	0.09	0.17	0.27	0.41	0.68
Rice	$7.71 cwt	0.10	0.26	0.52	0.77	1.06	1.87
Soybeans	$6.30 bu	-0.02	-0.01	0.12	0.17	0.23	0.70
Cotton	$312.00 bale	0.00	0.00	0.00	0.00	0.06	0.32
Fed beef	$334.04 cwt	0.00	0.09	0.60	0.78	0.92	1.10
Pork	$262.93 cwt	0.00	0.00	0.01	0.02	0.03	0.11
Milk	$14.30 cwt	0.00	-0.02	-0.07	-0.06	-0.02	0.09

bu = bushel. cwt = hundredweight.

* Corresponding payments to farmers are $3.54, $8.85, $17.70, $26.55, $35.40, and $44.25 per mt in scenarios 1, 3, and 4 and $10, $25, $50, $75, $100, and $125 per mt in scenario 2.

Source: Economic Research Service, USDA.

Table 5.4—Estimated changes in annual farm income and agricultural sector welfare, by policy scenario and carbon-payment level

	Price per metric ton of permanent carbon sequestration*						
Activity	$0	$10	$25	$50	$75	$100	$125
	Baseline (units noted)	*Percent change from baseline*					
Scenario 1: Rental payment on net sequestration, with no cost-share:							
Net farm income:	$76.937 bil.	0.0	0.2	1.9	3.3	4.9	7.6
Value of crop production	$80.027 bil.	0.0	0.0	0.1	0.1	0.3	0.6
Variable crop production costs	$44.695 bil.	0.1	0.2	0.3	0.4	-0.1	-1.0
Value of livestock production	$110.667 bil.	0.0	0.0	0.4	0.5	0.8	1.2
Variable livestock production costs	$74.064 bil.	0.0	0.0	-0.2	-0.3	0.1	0.6
Payments to farmers for:							
New rotations and tillage systems (in mil. $)	$0.0	1.3	8.0	32.1	77.2	164.0	306.9
Planting trees/grasses (in mil. $)	$0.0	0.0	47.7	505.0	1,059.9	1,760.4	2,874.1
Surplus measures:							
Domestic consumer surplus	$832,469.8 mil.	0.00	-0.01	-0.05	-0.07	-0.13	-0.22
Domestic producer surplus	$53,371.2 mil.	0.00	0.10	1.00	1.94	4.14	7.45
Foreign consumer surplus	$25,759.1 mil.	-0.01	-0.06	-0.28	-0.45	-1.21	-2.40
Foreign producer surplus	$954.3 mil.	0.00	0.15	1.03	1.34	1.73	2.30
Scenario 2: Asset payment on net sequestration, with no cost-share:							
Net farm income:	$76.937 bil.	0.4	3.0	9.2	17.7	27.9	37.3
Value of crop production	$ 80.027 bil.	0.1	0.1	0.8	1.5	2.2	2.2
Variable crop production costs	$44.695 bil.	0.2	0.4	-1.4	-3.4	-6.8	-10.1
Value of livestock production	$110.667 bil.	0.1	0.5	1.4	2.3	3.5	4.3
Variable livestock production costs	$74.064 bil.	-0.1	-0.2	0.9	2.2	3.9	5.1
Payments to farmers for:							
New rotations and tillage systems (in mil. $)	$0.0	9.8	67.5	399.8	977.0	1,912.5	3,357.6
Planting trees/grasses (in mil. $)	$0.0	85.5	960.3	3,619.0	7,735.6	12,519.4	16,645.2
Surplus measures:							
Domestic consumer surplus	$832,469.8 mil.	-0.01	-0.07	-0.26	-0.50	-0.81	-1.05
Domestic producer surplus	$53,371.2 mil.	0.17	1.78	9.41	19.89	34.42	48.00
Foreign consumer surplus	$25,759.1 mil.	-0.08	-0.43	-2.98	-6.06	-10.42	-13.96
Foreign producer surplus	$954.3 mil.	0.24	1.31	2.66	4.28	5.91	7.19
Scenario 3: Rental payment on net sequestration, with cost-share:							
Net farm income:	$76.937 bil.	0.1	0.9	2.5	3.4	5.1	7.4
Value of crop production	$80.027 bil.	0.0	0.0	0.0	0.0	0.0	0.2
Variable crop production costs	$44.695 bil.	0.1	0.1	0.3	0.4	0.1	-0.5
Value of livestock production	$110.667 bil.	0.0	0.2	0.5	0.5	0.1	1.1
Variable livestock production costs	$74.064 bil.	0.0	-0.1	-0.3	-0.4	0.0	0.3
Payments to farmers for:							
New rotations and tillage systems (in mil. $)	$0.0	3.0	11.1	33.4	69.8	115.6	171.4
Planting trees/grasses (in mil. $) **	$0.0	9.9	147.1	607.9	1,091.4	1,945.1	3,026.0
Surplus measures:							
Domestic consumer surplus	$832,469.8 mil.	0.00	-0.02	-0.05	-0.06	-0.10	-0.16
Domestic producer surplus	$53,371.2 mil.	0.04	0.41	1.22	2.01	3.74	6.34
Foreign consumer surplus	$25,759.1 mil.	-0.01	-0.08	-0.19	-0.25	-0.69	-1.41
Foreign producer surplus	$954.3 mil.	0.10	0.58	1.24	1.39	1.77	2.27

See notes at end of table.

Continued--

Table 5.4—Estimated changes in annual farm income and agricultural sector welfare, by policy scenario and carbon-payment level—Continued

	Price per metric ton of permanent carbon sequestration*						
Activity	$0	$10	$25	$50	$75	$100	$125
	Baseline (units noted)	*Percent change from baseline*					
Scenario 4: Rental payment on gross sequestration, with no cost-share:							
Net farm income:	$76.937 bil.	0.1	0.6	2.7	4.4	5.9	8.1
Value of crop production	$80.027 bil.	0.0	0.0	0.1	0.1	0.1	0.3
Variable crop production costs	$44.695 bil.	0.0	0.1	0.1	0.2	0.2	-0.1
Value of livestock production	$110.667 bil.	0.0	0.0	0.4	0.5	0.7	0.9
Variable livestock production costs	$74.064 bil.	0.0	0.0	-0.2	-0.3	-0.2	0.1
Payments to farmers for:							
New rotations and tillage systems (in mil. $)	$0.0	112.8	284.2	575.6	873.6	1,207.5	1,523.9
Planting trees/grasses (in mil. $)	$0.0	0.0	47.7	503.7	1,050.8	1,678.2	2,703.8
Surplus measures:							
Domestic consumer surplus	$832,469.8 mil.	0.00	-0.01	-0.05	-0.06	-0.08	-0.12
Domestic producer surplus	$53,371.2 mil.	0.18	0.58	1.92	3.25	4.79	7.24
Foreign consumer surplus	$25,759.1 mil.	0.00	-0.04	-0.22	-0.32	-0.45	-0.96
Foreign producer surplus	$954.3 mil.	0.00	0.15	1.04	1.35	1.61	2.04

* Corresponding payments to farmers are $3.54, $8.85, $17.70, $26.55, $35.40, and $44.25 per mt in scenarios 1, 3, and 4 and $10, $25, $50, $75, $100, and $125 per mt in scenario 2.

** Includes cost-share payments.

Source: Economic Research Service, USDA.

Since the United States is a major importer and exporter of agricultural products, changes in U.S. commodity prices and production would also affect foreign producers and consumers. These impacts are measured in USMP as changes in foreign producer surplus and foreign consumer surplus. Following the pattern of domestic impacts, foreign consumers are negatively affected by the carbon payments while foreign producers benefit. Across payment levels, reductions in foreign consumer surplus range from 0.01 to 2.4 percent. In relative terms, the negative impacts of the carbon payments are significantly higher for foreign consumers than for U.S. consumers. Conversely, foreign producers receive no carbon payments so their gains are relatively small, compared with gains of domestic producers.

Scenario 2: *Asset Payment (Assuming Permanent Sequestration)* for Net Sequestration, No Cost-Share—*Traditional Approach to Permanence*

Scenario 2 most closely represents the traditional static approach to modeling incentive payments to encourage farmers to adopt carbon-sequestering land uses and/or production practices, developed in the early economic literature on farm sequestration (see Parks and Hardie, 1995: Antle et al., 2001; and Pautsch et al., 2001). The payment structure implicitly assumes that a unit of carbon sequestered in a given year will be permanently removed from the atmosphere. From this perspective, a unit of carbon sequestration has the same GHG-mitigation value as a similar unit of carbon emissions reduction. Hence, in scenario 2, farmers receive payments equal to the full asset value of permanent carbon sequestration rather than the 15-year rental payments they received in scenario 1.

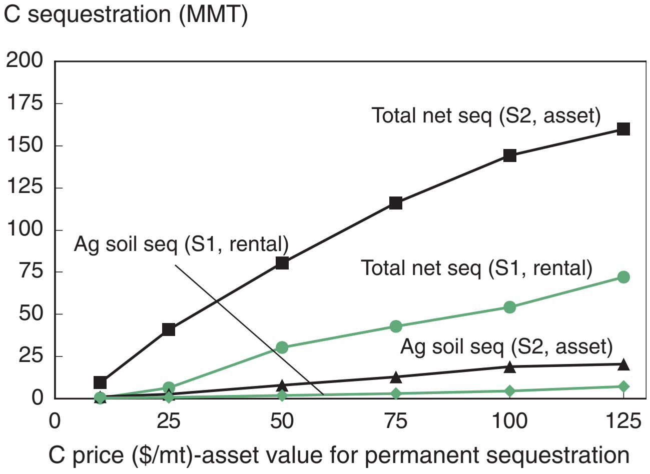
Because payments to farmers per mt of carbon sequestered in scenario 2 are 2.8 times the amount received in scenario 1 (i.e., 1 / 0.354 = 2.8), the anticipated effect of using the “full” (i.e., emissions reduction) values will be to increase the levels of sequestration activities and of economic impacts for the various payment levels relative to the levels observed for scenario 1. Inspection of tables 5.1-5.4 and figure 5.3 reveals this to be the case. As we would expect, the empirical results for the $25 per mt simulation of scenario 2 (which represents a carbon asset value of $71) are very similar in direction and magnitude to results for the $75 per mt simulation of scenario 1.

Annual net carbon sequestration in scenario 2 ranges from 9.5 MMT for a payment level of $10 per mt to 160.0 MMT per year for a payment of $125 per mt,

Figure 5.3

Annual net carbon sequestration

Asset (S2) versus rental (S1) net sequestration payments



Source: Economic Research Service, USDA.

compared with a range of 0.4 to 72.0 MMT per year for scenario 1 (table 5.1). The increases in carbon sequestration relative to scenario 1 are the result of farmers responding to the higher payment levels by making more changes in land uses and production practices.

Unlike scenario 1, afforestation dominates sequestration activities in scenario 2 at all payment levels—although there is a general decrease in the share of sequestration accounted for by afforestation in scenario 2 as the payment level increases. Relative to scenario 1, afforestation accounts for a larger share of total carbon sequestration for payments of $10 and $25 per mt and a smaller share of the total sequestration for payments of $50 per mt and above. Turning to land-use change, land afforested increases from 8.4 million acres at a payment of $10 per mt to 133.5 million acres at a payment of $125 per mt. As in scenario 1, afforestation is dominated by land shifting out of pasture; however, the share of afforested lands related to pasture conversions is somewhat smaller in scenario 2—at least when permanent sequestration is valued at $25 per mt or more (70-74 percent in scenario 2 versus 78-85 percent in scenario 1).

Regional patterns of afforestation differ significantly between scenarios 1 and 2 (app. 2). While the Delta States, Appalachia, and the Southeast still provide virtually all of the afforested acres at payment levels of $10 and $25 per mt, at $50 per mt, the quantity of additional pasture available for conversion to trees in these regions starts to become more limited. At payment levels of $50 per mt and above, the Pacific region becomes the largest supplier of afforested acres, and, producers in the Lake States and the Corn Belt become much more active—that is, relative to scenario 1—with afforestation.

With respect to cropland management, carbon payments of $10, $25, $50, $75, $100, and $125 per mt induce farmers to shift, respectively, 5.8, 14.6, 29.9, 42.6, 54.3, and 66.9 million acres from conventional tillage to conservation tillage systems (table 5.2). Across payment levels, these amounts are about 2.5 times the acres that make this shift relative to the associated discount payment levels in scenario 1. The carbon sequestration on lands moving from conventional to conservation tillage, however, is offset somewhat by emissions from land moving in the opposite direction. Shifts from conservation to conventional tillage systems increase from 0.8 million acres for a payment of $10 per mt to 14.2 million acres for a payment of $125 per mt. When carbon emissions from these land management changes are added to the net emissions related to changes in rotations, net carbon sequestration from cropland management is 1.0, 2.7, 8.0, 13.0, 19.0, and 26.9 MMT for payment levels of $10, $25, $50, $75, $100, and $125 per MT, respectively. Cropland management assumes a larger share of total sequestration activity as the carbon payment increases, rising from about 10 percent of total net sequestration at $10 per mt to about 17 percent of total net sequestration at a payment of $125.

As in scenario 1, conversion of cropland to grassland is not economically attractive across the range of carbon payments analyzed. However, the “full” carbon payment of $125 per mt in scenario 2 appears to be a threshold price for conversions of cropland to permanent grasses. At that payment level, 100,000 acres of cropland in the Southern Plains shift to grasses, resulting in about 0.032 MMT of carbon sequestration. In understanding the limited appeal of grasslands, it is important to note that while the per ton carbon payments significantly increase the incentives to convert cropland to grasses, the opportunity costs of removing cropland from production also significantly increase due to the crop price increases. While the actual carbon payments to farmers are much higher in scenario 2 relative to scenario 1, the increases in commodity prices are much higher as well—because larger quantities of land are being afforested leading to greater decreases in commodity production.

These results strongly reinforce the scenario 1 finding that, while technically feasible, conversion of cropland to grassland does not appear to be an economically feasible option to sequester carbon in the farm sector. This finding is consistent with studies by Antle et al. and McCarl and Schneider.

In scenario 2, commodity market impacts are still quite modest for carbon payments of $10 and $25 per mt—all production declines are less than 1.5 percent and all price increases are less than 1.3 percent (table 5.3). At $50 per mt, commodity market impacts start to become more pronounced. Of the nine commodities shown in table 5.3, three have price increases larger than 3 percent and three have production declines greater than 3 percent. For carbon payments of $100 per mt and above, double-digit decreases in production and increases in prices are common. The commodity markets most affected by the sequestration incentives are corn, sorghum, rice, and cotton. Conversely, the markets for wheat, pork, and milk are relatively unaffected.

The farm sector income and welfare impacts associated with scenario 2 are also magnified versions of their counterpart impacts in scenario 1 (table 5.4). Table 5.4 highlights how costly it could be to design a set of carbon sequestration incentives based on an assumption of permanent carbon storage but without actually incorporating any features to ensure permanent storage. For payment levels of $10, $25, $50, $75, $100, and $125 per mt, annual program costs are $100 million, $1.03 billion, $4.02 billion, $8.17 billion, $14.43 billion, and $20.00 billion, respectively. These amounts are 73.3, 18.5, 7.5, 7.6, 7.5, and 6.3 times higher than the associated payment levels in scenario 1. In addition to the higher program costs, there are also additional costs to consumers of U.S. agricultural commodities associated with the higher commodity prices. Focusing on U.S. consumers, the decreases in consumer surplus for payments of $10, $25, $50, $75, $100, and $125 per mt are, respectively, $83.3 million, $583 million, $2.2 billion, $4.2 billion, $6.7 billion, and $8.7 billion. For the associated payments, these represent increased costs to U.S. consumers of about $83 million, $500 million, $1.6 billion, $3.6 billion, 5.6 billion, and 6.9 billion relative to scenario 1.

Alternatively, we can reinterpret the actual payments in scenario 2 within a rental payment framework (as per scenario 1) or we can reinterpret the actual payments in scenario 1 in a "full" payment framework (as per scenario 2). Viewed this way, the sequestration results of the two scenarios can be combined to form a single supply schedule for carbon—with the two alternative interpretations.

Reinterpreting actual payment levels in scenario 2 of $10, $25, $50, $75, $100, and $125 as rental payments, we calculate the associated full prices by multiplying each by 2.8 (1/.354), yielding full prices of $28, $70, $140, $210, $280, and $350 per mt. The axes for the combined supply function in figure 5.4 are labeled from the rental payments perspective. We could alternatively interpret the graph within a full payments perspective by dividing all the prices on the horizontal axis by 2.8.

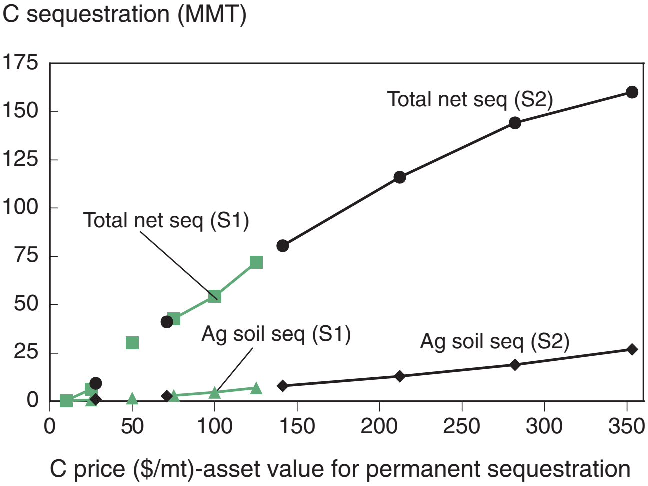
Scenario 3: Rental Payment for Net Sequestration, *With Cost-Share Supplement—Standard Conservation Program Feature*

Scenario 3 employs the reference scenario rental payments structure but augments the incentive package in scenario 1 to include a cost-share subsidy to partially offset the upfront costs of establishing trees on cropland or pasture or establishing permanent grasses on cropland. Assistance is set at 50 percent of the cost of establishing trees and grasses.[3]

Figure 5.4

Annual net carbon sequestration

Actual payments in S1 and S2 interpreted as rental payments



Source: Economic Research Service, USDA.

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[3] USDA's largest conservation program, the CRP, includes a 50-percent cost-share payment for planting trees, establishing grasses, and other approved vegetative practices (USDA, FSA, 2001).

As discussed in chapter 4, cost sharing the establishment of desired land uses and management practices is a common component of USDA conservation programs, including CRP, WRP, and WHIP.

Not surprisingly, the addition of the cost-share subsidy results in more carbon sequestration, more afforestation, and higher levels of total payments to producers in scenario 3 than in scenario 1. The differences in the quantities of carbon sequestered and land afforested, however, are only pronounced at lower payment levels. For example, annual net carbon sequestration in scenario 3 is 3.7, 17.9, 36.2, 43.7, 58.2, and 72.3 MMT for carbon payments of $10, $25, $50, $75, $100, and $125 per mt, respectively (table 5.1). These values are 9.3, 2.8, 1.2, 1.0, 1.1, 1.0 times the associated sequestration values in scenario 1. A similar pattern is evident in the results for afforestation. This pattern is not surprising, since the cost-share is a fixed-dollar amount per acre; consequently, the cost-share increases the total payments available to a much greater extent at low carbon prices. As in scenario 1, afforestation is concentrated in the Southeast, the Delta States, and Appalachia, with the Pacific becoming a source of afforested acres at carbon-payment levels of $100 per mt and above (app. 2).

The major economic impact associated with adding cost-share assistance to scenario 1 is a significant increase in the cost of the sequestration program. Relative to scenario 1, cost-share assistance increases net carbon sequestration 3.3, 11.6, 5.9, 0.9, 3.9, and 0.3 MMT for payment levels of $10, $25, $50, $75, $100, and $125 per mt, respectively (table 5.1). The associated increases in total payments to farmers, however, are $11.6 million, $102.5 million, $104.2 million, $24.1 million, $136.3 million, and $16.4 million. Also worth noting is that the effect of cost-share assistance on net farm income essentially disappears at carbon payments above $75 per mt. For payments of $10, $25, $50, $75, $100, and $125 per mt, net farm income increases, respectively, 0.0, 0.2, 1.9, 3.3, 4.9, and 7.6 percent in scenario 1, and, 0.1, 0.9, 2.5, 3.4, 5.1, and 7.4 percent in scenario 3 (table 5.4).

Scenario 4: Rental Payment *for Gross Sequestration,* No Cost-Share—*Exploring the Leakage Issue*

Scenario 4 differs from scenario 1 in that the incentive payments are based on gross, rather than net, increases in carbon sequestration. That is, scenario 4 pays the farm sector when land is shifted into a carbon-sequestering land use or production practice but does not debit these payments for any related land-based emissions due to shifting cropland out of conservation tillage, switching to rotations that release additional carbon, or bringing idle land into crop production. A comparison of the impacts of scenarios 1 and 4 suggests the consequences of ignoring the potential for feedback effects on market prices, which, in turn, can lead to farm-sector choices that result in emissions from the covered activities. Again, we note that our model is limited to the agricultural sector, so potential leakage due to related activities in the forest sector is not included in the GHG accounting.

For carbon values of $10, $25, $50, $75, $100, and $125 per mt, net carbon sequestration in scenario 4 is 0.1, 5.9, 29.4, 41.0, 50.3, and 64.6 MMT, respectively (table 5.1). Across payment levels, these values range between 0.3 and 7.4 MMT less than annual net sequestration values reported for scenario 1. The similarity in the net sequestration values is due to similarities in afforested acres, which typically account for more than 90 percent of all sequestration in both scenarios. Relative to scenario 1, acres of cropland moving into trees in scenario 4 are nearly identical for all payment levels, though acres of pasture moving to trees shows modest decreases at payment levels of $100 per mt and above (table 5.2). Since afforestation decisions in our simulations cannot be offset by related decisions to harvest other forests, forest-related land-use change is strictly a carbon-sequestering activity in our accounting. It is not surprising then that afforestation decisions are largely unaffected by the change in incentives between scenarios 1 and 4. Hence, we focus here on the results relating to changes in cropland management. Within that set of activities in scenario 4, net carbon sequestration falls by about 50 percent across the range of carbon payments.

For carbon payments of $10, $25, $50, $75, $100, and $125 per mt, total payments to farmers for changes in tillage systems and rotations are, respectively, $112.8 million, $284.2 million, $575.6 million, $873.6 million, $1,207.5 million, and $1,523.9 million in scenario 4. These amounts range from 10.8 to 87.0 times the total payments values in scenario 1. Land-management changes help explain the smaller quantities of net sequestration and higher program costs in scenario 4. For carbon payments of $10, $25, $50, $75, $100, and $125 per mt, farmers in scenario 4 shift, respectively, 76.8, 80.3, 79.1, 81.5, 81.3, and 82.7 million acres from conventional to conservation tillage systems. These land-management decisions are a direct response to the carbon-sequestration incentives. At the same time, however, farmers also shift 76.1, 78.1, 74.8, 74.2, 73.1, and 72.6 million acres out of conservation into conventional tillage systems. Unlike scenario 1, scenario 4 does not adjust the payments farmers receive for any land-based emissions that result from scenario-driven shifts of land to uses or production practices with higher carbon emissions. Hence, there is no penalty for moving land from conservation to conventional tillage, whereas there is an opportunity cost associated with leaving many lands in conservation tillage.

At this point, we need to ask whether the large shifts out of conservation tillage suggested by scenario 4 are likely to occur. Based on profit calculations, the shifts both to and from conservation tillage make sense as responses to both carbon incentive and crop price effects, as we outline in the paragraph that follows. However, this component of the model may not incorporate sufficient "stickiness" in the choice of tillage at a particular site, so we may be overpredicting the gross shifts from conventional to conservation and from conservation to conventional. The model does incorporate stickiness in the net changes among tillage options. Consequently, the "excessive" responsiveness would not affect the estimates of net sequestration but would affect the estimates of program cost (which are based on gross sequestration).

The relative profitability of conventional tillage versus conservation tillage depends on a variety of site-specific factors that affect yields and cost differentials. These factors include soil temperature and moisture conditions at planting time (conventional tillage allows soils to warm up and/or dry out quicker), length of growing season (crops with longer growing seasons need to be planted earlier and so in many areas rotations include 2 or 3 years of conservation tillage and one of conventional tillage), and farmer experience with conservation tillage (these systems tend to be management intensive and require sufficient time to learn).

In USMP, crop yields by rotation, tillage system, and region are derived from the biophysical Environmental Policy Integrated Climate (EPIC) model. The yields represent 7-year averages after the crop-rotation tillage-system region combination has been established for at least 5 years. For many region-rotation combinations, these yields are higher with conservation tillage systems, but on average yields tend to be lower. In the crop budgets used in the model, the direction of the cost differential also varies but tends to favor conservation tillage. For systems in which conservation tillage has lower costs but lower yields, crop price will affect the likelihood of revenue loss exceeding the cost gain: as crop prices rise conventional tillage tends to become more profitable. Thus, increasing carbon prices (from 0) will encourage shifts toward conservation tillage. And increasing crop prices due to shifts of cropland to forest lands will provide incentives to shift from conservation tillage to conventional tillage on lands where the cost advantage of conservation is outweighed by the revenue disadvantage as crop prices rise.

Commodity market impacts in scenario 4 tend to be somewhat muted versions of their counterparts in scenario 1 (table 5.3). Without a penalty for land-based emissions, it is profitable for farmers to bring some idle lands into commodity production. As a result, the decline in total cropland is not as large as in scenario 1, and the decreases in commodity production and increases in commodity prices are also more moderate.

Finally, scenarios 1 and 4 are similar with respect to changes in net farm income and agricultural sector welfare relative to the baseline. In scenario 4, the larger increases in program payments for changes in tillage systems are offset by smaller increases in net revenues from crop and livestock production (due to smaller decreases in quantities produced and smaller increases in prices) and marginally smaller payments for afforestation. Hence, the main consequences of ignoring the leakage issue in the design of a farm sector carbon-sequestration program will be that, at a given carbon price, the quantity of net carbon sequestration will be lower and the program cost will be higher. Both effects increase the per ton cost of net carbon sequestration.

Directions for Future Research

The changes in land uses and production practices considered in this analysis are likely candidates for incentives to increase the quantity of carbon stored in agricultural soils and biomass. However, to address the questions of the economic potential for overall GHG mitigation in the agricultural sector, it would be informative to extend the analysis in several directions.

First, it would be useful to expand the scope of the incentive payments to include a broader set of mitigation activities, particularly rangeland and pasture land management, as well as a broader set of GHGs, particularly methane and nitrous oxide.

Second, it would be useful to link a framework such as ours with a forest sector model to account for potential carbon leakage related to forest-sector responses to afforestation decisions on agricultural lands. As noted in chapter 3, agriculture and forestry often compete for the services of land resources. Several studies have looked at this competition and concluded that the shifting of millions of acres of cropland and pasture into trees would change timber harvest patterns in ways that would increase carbon emissions (see app. 1). These studies indicate that ignoring this leakage altogether could result in crediting agricultural afforestation programs with significantly more sequestration than actually occurs.

Finally, any assessment of the relative cost-effectiveness of different incentives to change agricultural land uses and production practices to mitigate GHG emissions needs to reflect the associated institutional costs associated with measuring, monitoring, and crediting the carbon sequestered for the different policy approaches. The carbon sequestration activities analyzed here—and those not analyzed (see table 2.2)—pose a wide variety of challenges with respect to carbon accounting and contract compliance over time. Hence, the costs associated with implementing and administering these activities within a Government carbon-sequestration program are likely to vary significantly. To date, however, all economic studies that have assessed potential to sequester carbon in the farm sector—including our study and those summarized in chapter 3—have assumed a costless institutional process.

Chapter 6: Summary of Findings and Implications for Policy

Strategies that have been proposed to mitigate global climate change typically focus on reducing energy-related emissions of greenhouse gases (including carbon dioxide) into the atmosphere. But atmospheric concentrations of greenhouse gases (GHG) can also be reduced by withdrawing carbon from the atmosphere and storing—or sequestering—it in soils and biomass. In examining the economics of sequestering additional carbon in the U.S. farm sector through changes in agricultural land use and management practices, this study focused on two questions:

- How much of the estimated "technical potential" for carbon sequestration is economically feasible?
- How cost effective are alternative incentive structures that might be used to encourage carbon sequestering activities?

To address these questions, we adapted ERS's U.S. Agricultural Sector Model to include financial incentives to agricultural producers for additional carbon sequestered as a result of changes in land use (e.g., converting cropland to grassland or forest) or cropland management practices (e.g., using conservation tillage or alternative crop rotations). We analyzed how land use and management practices change as financial incentives vary in four policy-relevant dimensions:

- **Asset or rental basis—**Comparing "asset" payments that implicitly assume carbon is permanently sequestered with "rental" payments for carbon storage over a specified period of time,
- **Level—**Comparing payments ranging from $10 to $125 per ton of carbon permanently sequestered,
- **Symmetric or one-sided—**Comparing a scenario in which producers are paid for carbon sequestered with a scenario in which producers are paid for carbon sequestered and charged for carbon emitted, and
- **Type—**Comparing scenarios in which carbon payments are augmented with a cost-share subsidy for converting cropland or pasture to forest or converting cropland to grassland.

In brief, we find that the asset or rental basis and the level of incentive payments are critical in determining how much carbon is sequestered, how it is sequestered, how long it is sequestered, where it is sequestered, and at what cost it is sequestered. But even at the highest level of incentive payments considered, less than two-thirds of the technical potential for carbon sequestration is economically feasible. Further, incentive systems in which producers are paid for carbon sequestered and charged for carbon emitted are much more cost effective than systems without charges for emissions. However, adding a cost-share subsidy for changes in land use does not substantially improve cost effectiveness relative to a system based on payments per ton of carbon sequestered.

Asset or Rental Basis of Incentive Payments

The effect of changes in land use or land-management practices on atmospheric concentrations of GHGs depends on the length of time for which carbon is sequestered. Cropland converted from conventional tillage to conservation tillage is estimated to sequester additional carbon for a period of 20-30 years until a new carbon equilibrium is reached. The additional carbon will remain stored in the soil or biomass as long as the land remains in conservation tillage, but most of it will be quickly released into the atmosphere if the land goes back into conventional tillage. Similarly, cropland converted to forest will sequester additional carbon for 20-70 years, depending on timber growth rates and harvest decisions, but most of the additional carbon may be released if/when the timber is harvested.

A unit of carbon sequestration in soil or biomass is equivalent to a unit of GHG emissions reduction if (and only if) the carbon remains sequestered permanently. This requires maintaining the carbon-sequestering activity permanently—either with a one-time permanent commitment or with a series of contracts extending through time.

Early research on the economics of carbon sequestration assumed that agricultural producers who received incentives to switch to carbon-sequestering land uses or management practices would maintain those practices permanently after the new carbon equilibrium was reached (and the incentive payments ceased). If producers switched out of the sequestering activities after payments ceased, however, the additional carbon would be released. Traditional research on agricultural carbon sequestration, which was based on this assumption, would then overestimate the amount of additional carbon sequestered, and incentive programs based on this assumption would overpay producers for the amount of additional carbon actually sequestered.

More recent research considers a system in which producers receive proportionally smaller "rental" payments to store additional carbon for a finite contract period. Payments cease at the end of the contract period, on the assumption that the sequestering activity then will be discontinued (and the additional carbon released). If producers continue the sequestering activity after the contract ends, however, the additional carbon remains stored in the soil or biomass. Research based on this assumption would then underestimate the amount of additional carbon sequestered, and incentive programs based on this assumption would underpay producers for the amount of additional carbon actually sequestered. If rental contracts are renewed indefinitely, payments will equal those provided under the "asset payment" system. Unlike with the asset payment system, however, permanent sequestration will be assured under a series of indefinitely renewed rental contracts.

The difficulty in choosing between the two assumptions/payment systems is that we do not know how many producers would actually continue carbon-sequestering activities after incentive payments cease. Continuation would depend on a combination of farm, producer, and market conditions. We analyze both systems to estimate a range of possible outcomes.

Lastly, adoption of agricultural activities that sequester carbon will add to the stock of carbon in soil or biomass for decades, but only until a new carbon equilibrium is reached. Permanent maintenance of the sequestering activities will store the added carbon permanently. But even permanent terrestrial sequestration can only serve as a "bridge" until new (low- or no-carbon) energy technologies are developed and adopted. Carbon sequestration in soil and biomass cannot offset increasing emissions of GHGs indefinitely.

Level of Incentive Payments

The amount of carbon that can feasibly be sequestered through changes in agricultural land use or management practices depends not only on the asset or rental basis of incentive payments but also on the level of incentive payments. We evaluated a range of incentive levels corresponding to payments of $10 to $125 per ton of permanent carbon sequestration.

We used two alternative payment systems to estimate how much carbon would be sequestered under 15-year contracts for a range of incentive levels. Under the asset payment system, producers receive the full $10 to $125 per ton over the 15-year contract period (on the assumption that they will continue the sequestering activities after the contract ends and the additional carbon will be permanently sequestered). Under the rental payment system, producers receive a share of the value of permanent sequestration in exchange for 15 years of storage of additional carbon (on the assumption that to discontinue the sequestering activities after the contract ends, they will require additional payments). At a 5-percent discount rate, the corresponding rental payments amount to $4 to $44 per ton of carbon over the contract period.

In the absence of incentive payments, about 4 MMT of additional carbon are currently sequestered in agricultural soils in the United States each year. With incentive payments corresponding to $10 per ton of permanent carbon sequestration, results suggest that producers would change land-use and land-management practices to the extent that an additional 0.4 MMT would be sequestered under the rental payment system per year and an additional 10 MMT would be sequestered under the asset payment system. Within this range, the actual amount of additional sequestration would depend on the extent to which producers continue carbon-sequestering activities after incentive payments cease. Similarly, results suggest that additional sequestration would range from 72 to 160 MMT with incentive payments corresponding to $125 per ton of permanent carbon sequestration. Permanent sequestration at these levels would offset 4 to 8 percent of gross U.S. GHG emissions in 2001.

Total program payments during the contract period range from $95 million to $2 billion per year under the asset payment system, for net increases in carbon sequestration ranging from 10 to 160 MMT per year. If producers discontinue carbon-sequestering land uses and management practices after the 15-year contract period ends, the program will have generated carbon sequestration worth only one-third of its payments—because most of the carbon will be released when the activities are terminated, and we estimate that 15 years of carbon storage has only one third the emissions-mitigating value of permanent carbon sequestration. At the $125-payment level, the overpayment would be approximately $1.3 billion. By contrast, the rental payment system pays only for the time carbon remains sequestered. If producers discontinue carbon-sequestering activities after contracts end, no overpayment will have been made. Likewise, if producers continue to renew their contracts and maintain their carbon-sequestering activities, the rental system will incur the same total cost as the asset payment system but will have ensured permanent sequestration.

The level of incentive payments also affects the type and geographic distribution of changes in land use and management practices because different sequestering activities become economically feasible at different incentive levels. At low levels of incentive payments (corresponding to less than $25 per ton of permanent carbon under the rental payment system), we estimate that increased use of conservation tillage would be the dominant source of additional sequestration. This effect reflects the fact that returns from conservation tillage systems are already close to returns from conventional tillage systems in many areas. At higher incentive payment levels, afforestation becomes the dominant source of additional carbon sequestration in agriculture. Land is drawn first from pasture. As incentives increase, an increasing share of afforested land is drawn from cropland (which is generally more productive than pasture). Only at incentive levels of $125 per ton with the asset payment system is a small amount of cropland converted to grassland (assuming no additional incentive, such as Conservation Reserve Program payments). This pattern of adoption is consistent with earlier economic studies using a variety of models and data sources (e.g., Antle et al., 2001, and McCarl and Schneider, 2001).

Regionally, most of the increase in conservation tillage occurs in the Great Plains, Corn Belt, and Lake States. Most afforestation occurs in the Southeast, the Delta States, and Appalachia. The small amount of cropland conversion to grassland (about 100,000 acres) occurs in the Southern Plains.

Incentive levels are thus critical in determining how much carbon will be sequestered, how it will be sequestered, and where it will be sequestered. Even at the highest incentive levels we analyzed, the economic potential to sequester additional carbon in agricultural soils and biomass is much less than the technical potential as indicated by soil science and forestry studies. Estimated economic potentials are lower than estimated technical potentials because our analysis incorporates the costs and returns associated with different activities and models the choices that farmers might make under different incentive systems. We assume that producers will adopt carbon-sequestering land uses and management practices that are technically feasible only if they are also economically feasible.

For conservation tillage, soil science studies (Lal et al., 1998, and Eve et al., 2000) estimate a technical annual carbon sequestration potential of 35-107 MMT. By contrast, at incentive levels corresponding to $125 per ton of additional carbon permanently sequestered, we estimate that only about one-fourth (7-27 MMT) of this technical potential would be economically feasible. For afforestation, estimates derived from Birdsey (1996) suggest a technical potential of 91-203 MMT; we estimate that only about two-thirds of this potential (65-133 MMT) would be economically feasible at incentives corresponding to $125 per ton of carbon permanently sequestered. Technical and economic potentials diverge the most for land use change from cropland to permanent grasses: Eve et al. (2000) estimate a technical potential of 26-54 MMT, whereas we estimate that virtually none of this would be economically feasible even at the highest incentive levels considered.

Symmetry of Incentive Payments

Our reference scenario incorporates both “carrots” (in the form of incentive payments to producers for additional carbon sequestered through changes in land use and management practices) and “sticks” (in the form of payments by producers for carbon emissions from changes in activities). For comparison, we analyzed a scenario using carrots alone.

Conservation tillage is the only activity that can be reversed in our model, so the choice of tillage practice is the only choice we analyze that could generate carbon emissions. In the carrots-only scenario, net carbon sequestration through conservation tillage is lower and program costs significantly higher across all payment levels. At incentive levels corresponding to $125 per ton of carbon permanently sequestered, a carrots-only system would sequester an additional 3.5 MMT at a cost of $1.5 billion. By contrast, at equivalent incentive levels, a system with both carrots and sticks would sequester an additional 7 MMT at a cost of $300 million—twice as much carbon at one-tenth the average cost per ton.

Type of Incentive Payments

In another set of simulations, we included a 50-percent cost-share subsidy for converting cropland to forest or grassland, in addition to the incentive payments per ton of carbon sequestered. Adding a cost-share subsidy does not appear to improve substantially the cost effectiveness of the incentive system. The cost-share subsidy would increase sequestration at low carbon-payment levels but not at high payment levels, and the incremental cost for the incremental sequestration does not appear to be lower than for the simple system. Furthermore, since the cost-share applies only to land-use change activities, it distorts the mix of carbon sequestration activities away from changes in cropland management.

Limitations in the Present Analysis Leave Questions

Our findings are consistent with the hypothesis that carbon sequestration in agricultural soils and biomass is a low-cost technology for reducing the atmospheric concentration of greenhouse gases. These GHG mitigation activities can serve as a bridge from the present to a time when new (low- or no-carbon) energy technologies are developed and adopted, or, alternatively, when technologies for the capture, separation, and storage of energy-related carbon emissions in other sinks become cost effective. If future research on GHG implications of land-management activities in the agricultural sector shows, for example, that nitrous oxide emissions could increase with carbon sequestration in some activities, our results would overstate the net reduction in total GHG emissions. Also, given that afforestation appears to have the greatest potential for additional sequestration, better understanding of market linkages between agriculture and forestry over an extended period is extremely important. McCarl et al. (2003) suggest that the long-term dynamics are complicated due to the feedback effects of substantially increasing the supply of timber and, consequently, dampening timber prices.

Finally, our analysis does not incorporate the institutional costs associated with measuring, monitoring, and crediting the carbon sequestered for the different policy approaches. Though the costs are likely to vary significantly depending on the features of the program and the range of activities covered, at this point we know very little about the cost structures. Full consideration of transaction costs would likely show, in most cases, that our present estimates of cost effectiveness are higher than what would be experienced in real-world situations.

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Appendix 1: Methods, Assumptions, and Key Results of Selected Carbon Sequestration Studies

Parks and Hardie (1995)

Empirical framework: Optimization model that differentiates U.S. farm lands by expected net returns to agriculture, expected net returns to forestry, and potential to sequester carbon in trees. Develops supply curves for carbon sequestration on U.S. agricultural lands by exhausting a fixed budget to subsidize land-use change to forest under various sequestration program designs.

Geographic scope:	116.1 million acres of privately owned U.S. cropland and pasture classified as non-prime farmland and suited to forest. Land is disaggregated into 433 regions with each region linked to a forest type and thus a potential to sequester carbon.
Baseline time period:	A composite year reflecting the period 1985-90.
Land base:	Private agricultural land classified as not irrigated and not prime farmland.
Activities analyzed:	Shifting marginal cropland and pasture to forest.
Incentives analyzed:	Derives carbon prices by exhausting fixed sequestration budget.

Program design and incentive structure:

- Afforestation program modeled after CRP. All land enrolled in year 1 for 10 years, after which the program ends. Program provides 50 percent of tree-establishment costs paid in year 1 and annual rental payments equal to forgone agricultural rents.
- Pays for carbon in trees only.
- Scenarios analyzed:

  S1: eligible land—cropland and pasture/objective—minimize cost per acre,
  S2: eligible land—cropland and pasture/objective—minimize cost per ton of carbon,
  S3 and S4—objectives similar to S1 and S2 but limited to cropland.

Assumptions, modeling issues, and special features:

- Land allocated to the use with the highest expected net return.
- Treatment of time—static. Model features a one-time decision to afforest lands without considering the implications of potential future harvest.
- Permanence—not explicitly considered. After 10 years, forestry is assumed to be the land use with the highest expected return (so annual payments are not needed to keep land in trees).
- C-stock equilibrium (CSE)—not explicitly considered. Afforestation program ends before CSE occurs.

Key results:

- For a program with a present value of $4.60 billion and targeting both cropland and pasture:

  S1: Over 10-year program period, enrollment is 23.1 million acres, carbon sequestration is 40.8 MMT per year, average discounted costs = $112.54 per mt.
  S2: Over 10-year program period, enrollment is 22.2 million acres, carbon sequestration is 44.1 MMT per year, average discounted costs = $104.20 per mt.

- For scenario S2, the marginal cost (MC) of sequestration rises slowly from 0 to 100 mt per year then increases sharply.
- Enrollment and sequestration levels decrease more than 50 percent and costs more than double when only cropland is targeted.

Alig et al. (1999)

Empirical framework: Optimization model linking U.S. agriculture and forestry sectors through competition for privately owned land. Agriculture modeled using ASM (see McCarl and Schneider). Forestry sector has nine geographic regions, six product classes, two private land ownership classes, four forest types reflecting species composition, three site productivity classes, four management intensity classes, and six classes reflecting land's ability to shift between sectors. Model is simulated in 10-year time steps, with ASM solved statically at each step.

Geographic coverage: Contiguous 48 States.

Baseline period: U.S. agricultural and forest sectors initially calibrated to 1990 conditions. Model is then simulated in 10-year time steps through 2079, with no afforestation incentives to set the baseline. Policy results are tracked through 2039.

Land base: All agricultural and forest land in the contiguous 48 U.S. States.

Activities analyzed: Shifting land between agriculture and forestry.

Incentives analyzed: Sets payments to afforest agricultural lands at levels needed to achieve exogenously specified afforestation levels.

Program design and incentive structure:

- Programs start in 1990 and runs through 2079.
- Carbon-sequestration program modeled as subsidy for afforestation.
- Pays for incremental ecosystem carbon (carbon in trees, woody debris, understory, floor, and soil). Trees can be harvested with no deforestation penalty.
- Scenarios:
  S1: Force 12.1 million acres of agricultural land to shift to forest in decade 1 (1990-99).
  S2: Constant carbon flux of 1.61 gigatons per decade.
  S3: Flux set 0.4 gigatons above baseline in each decade.
  S4: Flux starts at baseline level and increases 0.2 gigatons above baseline in each succeeding decade.

Assumptions, modeling issues, and special features:

- Land allocated to the use with the highest expected net return.
- Afforestation and forest management decisions affect sequestered carbon levels.
- Framework accounts for interactions between the agricultural and forestry sectors.
- Management of public forests specified exogenously and held fixed.
- Existing farm programs assumed to end after 1 decade.
- Treatment of time: Dynamic, using 10-year time steps and 4-percent discount rate.
- Permanence: Reflected in carbon accounting but not in pricing of sequestration incentives.
- CSE: Forests generally harvested before CSE occurs.

Key results:

- Policies to afforest agricultural lands will generate offsetting deforestation activities in the forest sector. Over time, many lands will move back and forth between agriculture and forestry.
- Across the three carbon flux scenarios (S2-S4)
  Net transfers of land from agriculture to forest, relative to the baseline, range between 8.4 million acres and 21.4 million acres over the period 1990-2039.
  Over the 90-year simulation, in terms of the net present value:
    Society welfare decreases between \$22.7 billion and \$55.8 billion,
    Domestic agricultural producers gain between \$13.5 billion and \$44.3 billion,
    Domestic agricultural consumers lose between \$34.4 billion and \$83.9 billion,
    Domestic forest producers and consumers gain and lose depending on the scenario.

Stavins (1999)

Empirical framework: Econometric model describing the shares of county land in forest and in agriculture. Explanatory variables include agricultural rents, farm production costs, existing forest area, tree-establishment costs, conversion to cropland costs, and net returns for a one-time forest harvest. Simulates afforestation programs by exogenously increasing forest rents and deforestation costs. Uses changes in forest area and age to estimate changes in carbon sequestered. Estimates regional marginal cost curve for sequestered carbon by subtracting baseline sequestration from sequestration at different levels of an afforestation subsidy/deforestation tax.

Geographic scope:	Delta States (Louisiana, Arkansas, and Mississippi).
Baseline period:	Model estimated with panel data for 36 counties/parishes covering period 1935-84. Baseline scenario derived by simulating the model over 90-year period with the afforestation payment/deforestation tax set equal to zero.
Land base:	Agricultural and forest land
Activities analyzed:	Shifting agricultural land into forest.
Incentives analyzed:	Exogenously specifies a range of afforestation payments/deforestation penalties.

Program design and incentive structure

- Carbon-sequestration program modeled as subsidy for afforestation and a tax for deforestation.
- Pays for ecosystem carbon (carbon in trees, woody debris, understory, floor, and soil).
- Model simulations run for 90 years.

Assumptions, modeling issues, and special features:

- Landowners maximize the expected longrun return to land.
- Framework accounts for factors that may make landowners require a premium to shift land to forest.
- Sequestered carbon given in present value terms to account for the time profile of sequestration.
- Treatment of time: Dynamic using annual time step and 5-percent discount rate.
- Permanence: Explicitly accounted for—agents paid when they afforest and penalized when they deforest.
- CSE: Not an issue. Trees can be harvested at any time (and generally are harvested before reaching CSE).

Key results:

- For Delta States, MC of sequestering carbon rises gradually and linearly to 6.4 million mt per year. At that level: MC = $79.86 per mt, net afforestation is 4.6 million acres, carbon tax/subsidy = $109.87 per acre.
- Above 6.4 million mt, MC of carbon sequestration increases steeply becoming nearly asymptotic at about 14.5 million mt.
- For low levels of net GHG emission reduction, sequestration costs are similar to abatement cost.

Plantinga et al. (1999)

Empirical framework: Econometric land-use model describing the shares of county land in forest, agriculture, and other uses. Key explanatory variables include agricultural and forest rents, population density, and two measures of land quality. Simulates afforestation programs by exogenously increasing forest rents. Uses changes in forest area to estimate changes in carbon sequestered.

Geographic scope:	Models estimated for Maine (ME), South Carolina (SC), and Wisconsin (WI).
Baseline time period:	Data cover period 1971-96. Baseline scenario derived by simulating the model over 60-year period with afforestation payments set equal to zero.
Land base:	Private agricultural and forest land in ME, SC, and southern two-thirds of WI.
Activities analyzed:	Shifting agricultural land into forest.
Incentives analyzed:	Exogenously specifies a range of afforestation payments.

Program design and incentive structure:

- Afforestation program modeled after CRP.
- Starts in 2000 and runs for 60 years in 10-year steps.
- Landowners decide to enroll, leave program, or reenroll at the start of each decade.
- Provides annual fixed payment and one-time tree establishment costs paid in year of enrollment. No penalty for deforestation.
- In each State, enrollment capped at 25 percent of its agricultural land.
- Scenarios analyzed:
  S1—Constant 1995 population, uniform payments, harvests allowed.
  S2—Constant 1995 population, uniform payments, harvests not allowed.
  S3—Increasing population, variable payments, harvests not allowed.
  S4—Increasing population, uniform payments, harvests allowed.

Assumptions, modeling issues, and special features:

- Landowners maximize the expected longrun return to land.
- Framework accounts for factors that may make landowners require a premium to shift land to forest.
- Without afforestation, net sequestration on agricultural lands is zero.
- Land in urban/other uses held fixed implying only agricultural land shifts to forest.
- Sequestered carbon given in present value terms to account for the time profile of sequestration.
- Treatment of time: Dynamic in 10-year time steps and 5-percent discount rate.
- Permanence: Not accounted for—agents are paid to afforest but are not penalized for deforesting.
- CSE: Not an issue. Forests in ME, SC, and WI do not reach CSE in 60 years.

Key results:

- Across scenarios, the MC of carbon sequestration rises (almost) linearly from the origin. At 25 percent enrollment cap, the MC of sequestration varies:
  From $107.10 to $135.28 per mt in ME (sequestration = 3.176 million mt),
  From $50.73 to $101.46 per mt in SC (sequestration = 14.518 million mt),
  From $84.55 to $107.10 per mt in WI (sequestration = 54.444 million mt).
- S1 is almost always least-cost scenario.
- Lake States and Midwest are the most cost-effective areas to afforest; the Northeast is the least cost effective.

Antle et al. (2001)

Empirical framework: Field-level econometric production models for winter wheat, spring wheat, and barley in continuous cropping and crop-fallow rotations and permanent grass. Incorporates these models into a simulation model that sets farmer decisions on land allocation and input use in response to exogenous policy shocks. A crop ecosystem model (Century) then determines the net effect on soil carbon.

Geographic scope: Eastern Montana's dryland grain-producing region.

Baseline time period: Data are from mid-1990s. Baseline scenario derived by simulating the model over 20-year period with sequestration payments set equal to zero.

Land base: Privately owned cropland and pasture.

Activities analyzed: Switching cropland to permanent grasses.
Switch from crop-fallow rotations or permanent grass to continuous cropping.

Incentives Analyzed: $2.07 to 20.71 per acre to adopt continuous cropping.
$5.18 to $51.77 per acre to shift land to permanent grasses.

Program design and incentive structure:

- Provide payments to farmers to adopt continuous cropping and shift land to permanent grass (activities are analyzed separately).
- Payments for shifting land to grasses are in addition to CRP payments.
- Simulations begin today and run for 20 years.
- Scenarios analyzed (and discussed):
  PG: switch land to permanent grasses—all cropland and pasture is eligible,
  CC: shift to continuous cropping—only lands in crop fallow rotations and grasses are eligible.

Assumptions, modeling issues, and special features:

- Landowners maximize the expected returns to each field.
- Use of site-level data (i.e., field and farm) accounts for the spatial heterogeneity in biophysical and economic characteristics across farms.
- Permanence: Not accounted for.
- CSE: Not accounted for. Program ends before reaching CSE.
- Treatment of time: Static.

Key results:

- Spatial heterogeneity with respect to biophysical and economic characteristics is an important consideration in the design of farm policies to sequester carbon. Across locations in the study area, the MC of sequestering carbon ranges from $51.15 to $511.51 per mt in the PG scenario and from $12.28 to $143.22 per mt in the CC scenario. In the CC scenario, the average cost of sequestering carbon was less than $51.15 per mt in all regions.
- From the taxpayer viewpoint, a policy to promote CC is relatively more efficient at sequestering soil carbon than a PG policy. Over 20 years, the PG policy that pays farmers $51.77 per acre per year sequesters 7 MMT of carbon at an undiscounted Government cost of $3.15 billion. Over 20 years, the CC policy pays farmers $4.14 per acre per year to sequester 7.61 MMT at a Government cost of $206.34 million.
- Over the range of payments considered, soil carbon sequestration ranges from 2.37 to 6.76 MMT under the PG scenario and from 7.61 to 18.25 MMT under the CC policy.
- For CC policy, payments above $20.71 per acre do not significantly increase carbon sequestration because over 90 percent of land in crop-fallow rotations has been converted to CC.

Pautsch et al. (2001)

Empirical framework: Estimates an econometric model where the probability of adopting no-till is a function of net returns to conventional tillage, local soil characteristics, and regional temperature and precipitation variables. Production possibilities include 14 rotations consisting of mixes of corn, soybeans, wheat, sorghum, and hay. Econometric model is linked with a biophysical model so that changes in tillage practices can be paired with changes in soil carbon.

Geographic scope:	Iowa.
Baseline time period:	Model reflects a "typical" year during the 1990s.
Land base:	All cropland.
Activities analyzed:	Adopting conservation tillage (CC)—assumed to be no-till.
Incentives analyzed:	Specifies various levels of carbon sequestration and computes the average costs per ton needed to achieve those levels.

Program design and incentive structure:

- Provide payments to farmers to adopt conservation tillage (assumed to be no-till).
- Scenarios considered:
  S1: new CC adopters only with uniform per acre payment.
  S2: all CC adopters with uniform per acre payment.
  S3: new CC adopters with price discriminating per acre payment based on carbon-sequestration potential.
  S4: all CC adopters with price discriminating per acre payment based on carbon-sequestration potential.

Assumptions, modeling issues, and special features:

- Landowners maximize the expected returns to land.
- Use of site-level data (i.e., field and farm) accounts for the spatial heterogeneity in biophysical and economic characteristics across farms.
- Framework addresses the issue of designing programs to pay all adopters of conservation tillage versus only paying those who adopt as a result of the incentives.
- Treatment of time: Static—looks at an average year of an unspecified multiyear program.
- Permanence: Not accounted for.
- CSE: Not accounted for. Implicitly assumes carbon will accumulate as long as the program runs.

Key results:

- At a sequestration level of 1 MMT per year, the average cost per mt sequestered is about $294 in S1, $1,089 in S2, $207 in S3, and $686 in S4.
    Regardless of payment design, the average cost per mt sequestered falls when only new adopters are targeted.
    Regardless of who is targeted, the average cost per mt sequestered falls with a price-discriminating payment.

McCarl and Schneider (2001)

Empirical framework: The ASMGHG model—a market and spatial equilibrium mathematical programming model. Model depicts production and consumption in 63 U.S. regions for 22 traditional crop commodities, 3 biofuel crops, 29 livestock commodities, and more than 60 processed agricultural products. Trade is modeled for 28 international regions. In responding to relative changes in input prices, farmers can adjust tillage, fertilization, irrigation, manure treatment, and feed mixes. Changes in carbon sequestration associated with changes in crop-management activities are calculated using the biophysical model EPIC (Environmental Policy Integrated Climate model). Land shifting from agriculture to forestry and the associated carbon sequestration are obtained from 30-year simulations of FASOM (see Alig et al., 1999). Changes in emissions associated with livestock management based on EPA data.

Geographic scope:	Contiguous 48 States.
Baseline time period:	ASMGHG run with carbon valued at $0.00 per mt.
Land base:	All agricultural land (cropland and pasture).
Activities analyzed:	Afforestation and forest management, biofuel production, crop mix changes, changes in tillage practices, reductions in fertilizer use, reductions in rice acres, grassland conversions, changes in irrigation practices, changes in livestock management, and changes in manure management.
Incentives analyzed:	Exogenously specifies range of carbon prices.

Program design and incentive structure:

- Farmers paid for changes in land use and production practices that sequester carbon, increase biofuel production, or reduce GHG emissions. Farmers taxed for changes in land use or production practices that increase GHG emissions.
- Scenarios considered: ASMGHG simulated with carbon valued at $9.60, $48.10, $96.20, and $480.80 per mt (or $10, $50, $100, and $500 per mt in 2000 dollars).

Assumptions, modeling issues, and special features:

- Land allocated to the use with the highest expected net return.
- Simulations reflect points of market equilibrium. Simulations do not account for adjustment paths.
- Treatment of time: Static—economic agents and markets adjust fully and instantly to incentives for sequestering carbon, reducing CH_4 and N_2O emissions, and producing biofuels.
- Permanence: Not explicitly accounted for. Payments for carbon sequestration activities implicitly assume carbon is stored permanently.
- CSE: Not explicitly accounted for.
- Leakage: Explicitly accounted for (see empirical framework above and Alig et al, 1999).

Key results:

- For carbon valued at $9.60, $48.10, $96.20, and $480.80 per mt:
  Carbon sequestration is 51.80, 146.40, 238.50, and 395.50 MMT of carbon, respectively.
  Total mitigation is 53.90, 154.10, 255.70, and 425.90 MMTCE, respectively.
  Gross farm welfare increases $0.4 billion, $4.3 billion, $13.4 billion, and $76.9 billion, respectively.
  U.S. consumer welfare decreases $0.4 billion, $5.2 billion, $18.5 billion, and $104.6 billion, respectively.
- At low carbon prices, soil carbon sequestration, afforestation, and CH_4/N_2O emissions reductions activities dominate a national GHG-mitigation strategy.
- At high carbon prices, afforestation and biofuel production dominate a national GHG-mitigation strategy.
- The total contribution of CH_4 and N_2O emissions reductions activities is relatively small.

Parks and Hardie use acres, short tons, and 1987 dollars; Alig et al. use hectares, metric tons, and 1990 dollars; Stavins uses acres, short tons, and 1990 dollars; Plantinga et al. use acres, short tons, and 1995 dollars; Antle et al. use hectares, metric tons, and 1995 dollars; Pautsch et al. use acres, metric tons, and 1992 dollars; and McCarl and Schneider use acres, metric tons, and 2000 dollars. All reported monetary values have been converted to 1997 dollars, all area measures have been converted to acres, and all GHG emission reduction/carbon sequestration quantities have been converted to metric tons of carbon.

Appendix 2: Afforestation of cropland and pasture by region, policy scenario, and carbon-payment level

Land afforested	North-east	Lake States	Corn Belt	Appa-lachia	South-east	Delta States	Mountain & Great Plains	Pacific	Total U.S.
					Million acres				
Scenario 1 (Rental carbon payment, net sequestration, no cost-share):									
C Price=$10:									
From cropland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
From pasture	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total afforested	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C Price=$25:									
From cropland	0.0	0.0	0.0	0.4	0.3	0.4	0.0	0.0	1.1
From pasture	0.0	0.0	0.0	0.0	1.9	2.2	0.0	0.0	4.1
Total afforested	0.0	0.0	0.0	0.4	2.2	2.6	0.0	0.0	5.2
C Price=$50:									
From cropland	0.0	0.0	0.0	2.1	1.1	1.2	0.0	0.0	4.4
From pasture	0.0	0.3	0.0	5.9	10.0	8.0	0.0	0.0	24.2
Total afforested	0.0	0.3	0.0	8.0	11.1	9.2	0.0	0.0	28.6
C Price=$75:									
From cropland	0.0	0.0	0.0	3.5	1.8	1.6	0.0	0.0	6.9
From pasture	0.0	0.8	0.8	10.6	12.4	7.7	0.0	0.0	32.3
Total afforested	0.0	0.8	0.8	14.1	14.2	9.3	0.0	0.0	39.2
C Price=$100									
From cropland	0.0	0.1	0.0	3.9	2.6	2.1	0.0	0.0	8.7
From pasture	0.1	2.4	1.1	10.8	13.6	7.5	0.0	4.8	40.4
Total afforested	0.1	2.5	1.1	14.7	16.2	9.6	0.0	4.8	49.1
C Price=$125:									
From cropland	0.3	2.1	0.0	4.3	3.3	2.6	0.0	0.0	12.7
From pasture	1.2	4.1	1.4	11.0	13.6	7.4	0.0	13.2	51.9
Total afforested	1.5	6.2	1.4	15.4	16.9	10.0	0.0	12.2	64.6
Scenario 2 (Asset carbon payment, net sequestration, no cost-share):									
C Price=$10:									
From cropland	0.0	0.0	0.0	0.6	0.4	0.6	0.0	0.0	1.7
From pasture	0.0	0.0	0.0	0.0	3.0	3.7	0.0	0.0	6.7
Total afforested	0.0	0.0	0.0	0.6	3.4	4.3	0.0	0.0	8.4
C Price=$25:									
From cropland	0.0	0.0	0.0	3.4	1.7	1.6	0.0	0.0	6.6
From pasture	0.0	0.7	0.0	10.7	12.1	7.8	0.0	0.0	31.2
Total afforested	0.0	0.7	0.0	14.1	13.8	9.4	0.0	0.0	37.8
C Price=$50:									
From cropland	0.3	2.1	0.0	4.6	3.8	2.9	0.0	0.0	13.8
From pasture	1.6	4.8	1.5	11.1	13.6	7.4	0.0	18.7	58.6
Total afforested	1.9	6.9	1.5	15.7	17.4	10.3	0.0	18.7	72.4
C Price=$75:									
From cropland	0.4	2.3	0.0	5.9	5.2	4.3	0.0	0.0	18.1
From pasture	2.6	7.5	3.2	11.1	13.6	6.6	0.0	42.9	87.5
Total afforested	3.0	9.8	3.2	17.0	18.8	10.9	0.0	42.9	105.6

Continued--

Appendix 2: Afforestation of cropland and pasture by region, policy scenario, and carbon-payment level—Continued

Land afforested	North-east	Lake States	Corn Belt	Appa-lachia	South-east	Delta States	Mountain & Great Plains	Pacific	Total U.S.
					Million acres				
Scenario 2 (Full carbon payment, net sequestration, no cost-share):--continued									
C Price=$100:									
From cropland	0.6	3.0	0.0	7.1	5.8	5.9	0.0	0.0	22.5
From pasture	4.7	7.5	7.5	11.2	13.6	6.1	0.0	54.8	105.4
Total afforested	5.3	10.5	7.5	18.3	19.4	12.0	0.0	54.8	127.9
C Price=$125:									
From cropland	1.2	3.7	0.0	8.4	6.1	8.0	0.0	0.0	27.4
From pasture	4.7	7.5	11.3	11.0	13.6	3.1	0.0	54.8	106.1
Total afforested	5.9	11.2	11.3	19.4	19.7	11.1	0.0	54.8	133.5
Scenario 3 (Rental carbon payment, net sequestration, with cost-share):									
C Price=$10:									
From cropland	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1
From pasture	0.0	0.0	0.0	0.0	0.0	2.8	0.0	0.0	2.9
Total afforested	0.0	0.0	0.0	0.0	0.1	2.8	0.0	0.0	3.0
C Price=$25:									
From cropland	0.0	0.0	0.0	0.9	0.5	0.7	0.0	0.0	2.1
From pasture	0.0	0.0	0.0	1.4	5.1	8.4	0.0	0.0	14.9
Total afforested	0.0	0.0	0.0	2.3	5.6	9.1	0.0	0.0	17.0
C Price=$50:									
From cropland	0.0	0.0	0.0	2.6	1.3	1.2	0.0	0.0	5.0
From pasture	0.0	0.3	0.0	9.9	11.3	7.9	0.0	0.0	29.5
Total afforested	0.0	0.3	0.0	12.5	12.6	9.1	0.0	0.0	34.5
C Price=$75:									
From cropland	0.0	0.0	0.0	3.5	2.0	1.6	0.0	0.0	7.1
From pasture	0.1	0.9	1.0	10.6	13.2	7.5	0.0	0.0	33.3
Total afforested	0.1	0.9	1.0	14.1	15.2	9.1	0.0	0.0	40.4
C Price=$100:									
From cropland	0.3	0.6	0.0	3.9	2.8	2.1	0.0	0.0	9.7
From pasture	0.5	1.8	1.2	10.6	13.6	7.4	0.0	10.6	45.7
Total afforested	0.8	2.4	1.2	14.5	16.4	9.5	0.0	10.6	55.4
C Price=$125:									
From cropland	0.3	2.1	0.0	4.3	3.5	2.6	0.0	0.0	12.8
From pasture	1.3	3.1	1.4	10.8	13.6	7.1	0.0	18.9	56.3
Total afforested	1.6	5.2	1.4	15.1	17.1	9.7	0.0	18.9	69.2
Scenario 4 (Rental carbon payment, gross sequestration, no cost-share):									
C Price=$10:									
From cropland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
From pasture	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total afforested	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C Price=$25:									
From cropland	0.0	0.0	0.0	0.4	0.3	0.4	0.0	0.0	1.1
From pasture	0.0	0.0	0.0	0.0	1.9	2.2	0.0	0.0	4.1
Total afforested	0.0	0.0	0.0	0.4	2.2	2.6	0.0	0.0	5.2

Continued--

Appendix 2: Afforestation of cropland and pasture by region, policy scenario, and carbon-payment level—Continued

Land afforested	North-east	Lake States	Corn Belt	Appa-lachia	South-east	Delta States	Mountain & Great Plains	Pacific	Total U.S.
					Million acres				
Scenario 4 (Rental carbon payment, gross sequestration, no cost-share):--continued									
C Price=$50:									
From cropland	0.0	0.0	0.0	2.1	1.1	1.2	0.0	0.0	4.4
From pasture	0.0	0.3	0.0	5.9	10.0	7.9	0.0	0.0	24.1
Total afforested	0.0	0.3	0.0	8.0	11.1	9.1	0.0	0.0	28.5
C Price=$75:									
From cropland	0.0	0.0	0.0	3.5	1.8	1.6	0.0	0.0	6.9
From pasture	0.0	0.8	0.7	10.6	12.4	7.4	0.0	0.0	31.9
Total afforested	0.0	0.8	0.7	14.1	14.2	9.0	0.0	0.0	38.8
C Price=$100:									
From cropland	0.0	0.1	0.0	3.9	2.6	2.1	0.0	0.0	8.7
From pasture	0.1	1.4	1.1	10.2	13.6	7.0	0.0	4.8	38.1
Total afforested	0.1	1.5	1.1	14.1	16.2	9.1	0.0	4.8	46.8
C Price=$125:									
From cropland	0.3	2.1	0.0	4.3	3.3	2.6	0.0	0.0	12.7
From pasture	0.4	2.6	1.4	10.1	13.6	6.8	0.0	13.2	48.1
Total afforested	0.7	4.7	1.4	14.4	16.9	9.4	0.0	13.2	60.8

Source: Economic Research Service, USDA.