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)

---

[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*

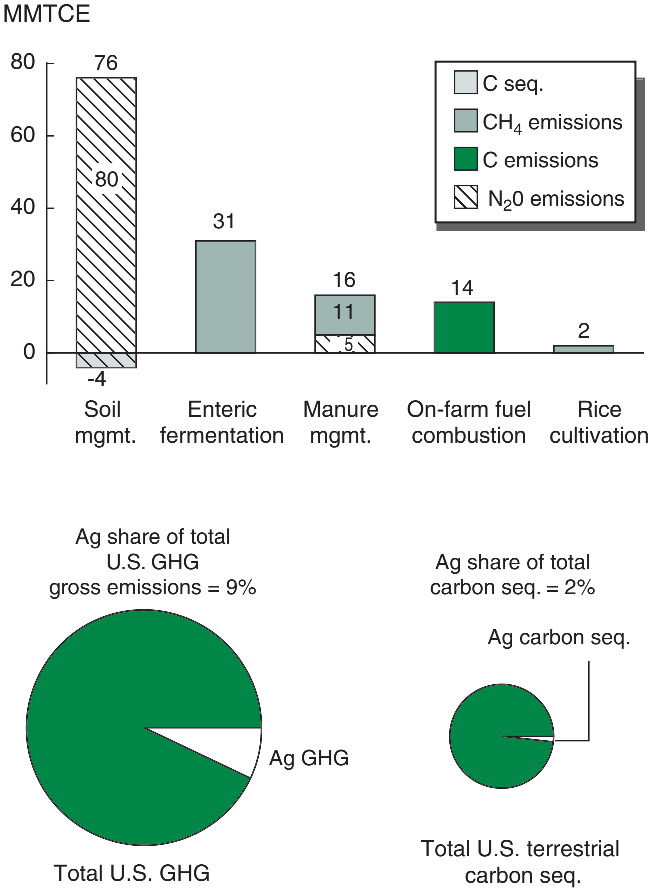
(fig. 2.2). These activities also rank relatively high in sequestration per acre—1, 2, and 5, respectively—among the cropland activities listed in table 2.2. Activities with lower carbon-storing potentials include changing crop rotations, expanding the use of winter cover crops, eliminating periods of 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

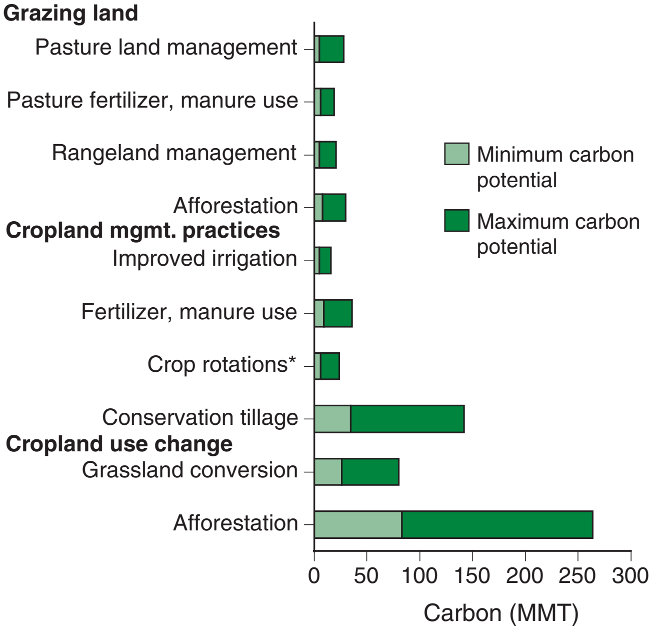
Agricultural emissions and carbon sequestration in 2001 by activity



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

---

[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-

---

[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.

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.

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

	Year					Net emissions
Activity	1	2	3	4	5	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.

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

---

[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]

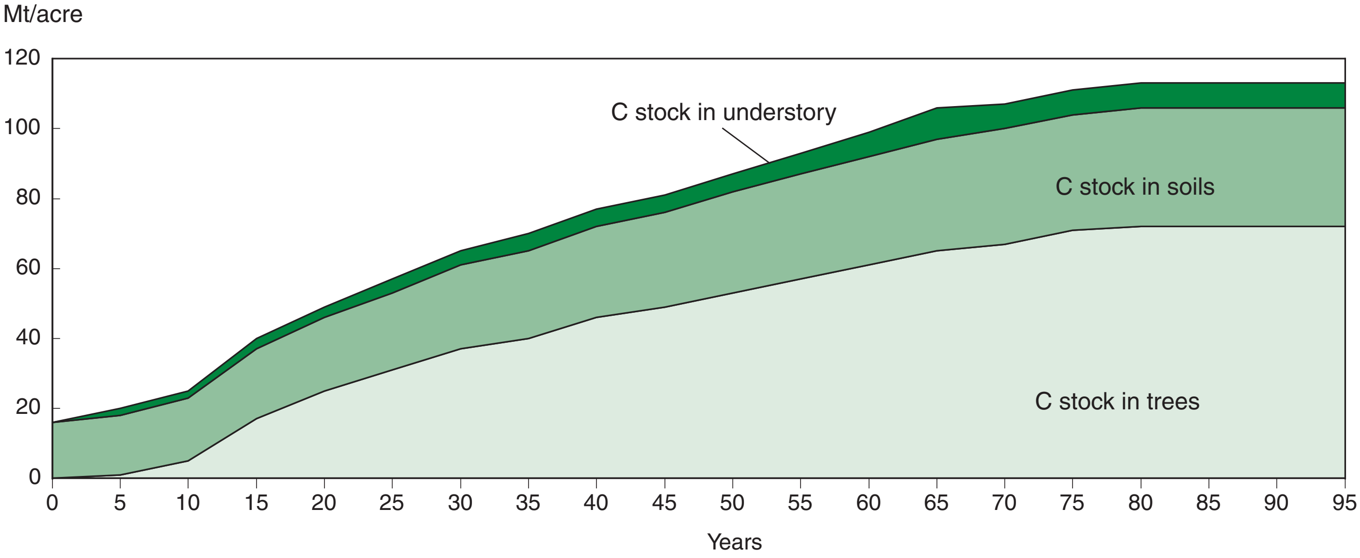
The C-stock equilibrium issue has two important implications for empirical analyses of the economic potential to sequester carbon in the farm sector. First, the finite periods of time in which terrestrial systems can accumulate additional carbon place a finite limit on the GHG-mitigation potential of 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.

---

[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:

$$a = rP \tag{1}$$

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

---

[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.

---

[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.

---

[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.

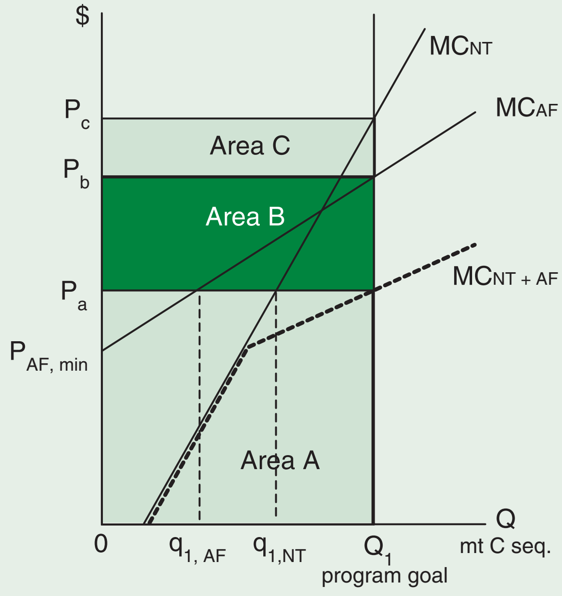
For voluntary programs, once a piece of land is enrolled in the program, rules could be established to prevent compensation for the repeated switching in the second case. Under gross sequestration, switching land from

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

---

[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.