economics

The cost of U.S. forest-based **carbon sequestration**

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Prepared for the Pew Center on Global Climate Change

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Contents

Foreword *Eileen Claussen, President, Pew Center on Global Climate Change*

Most analyses to date of options for mitigating the risk of global climate change have focused on reducing emissions of carbon dioxide and other greenhouse gases (GHGs). Much less attention has been given to the potential for storing (or "sequestering") significant amounts of carbon in forests and other ecosystems as an alternative means of offsetting the effect of future emissions on GHG concentrations in the atmosphere. The tendency to overlook sequestration opportunities can lead to incorrect and overly pessimistic conclusions about both the cost and feasibility of addressing global climate change in the decades ahead.

To remedy that gap, and to inform U.S. policymaking, the Pew Center asked economists Robert Stavins of Harvard University and Kenneth Richards of Indiana University to synthesize and expand upon available studies of forest-based carbon sequestration in the United States. They analyze the true opportunity costs of using land for sequestration, in contrast with other productive uses, and examine the multiple factors that drive the economics of storing carbon in forests over long periods of time. These factors include forest management practices for different tree species and geographical regions; the costs of land and competing prices for agricultural products; the ultimate disposition of forest materials, including the potential for fire damage as well as harvesting for use in different kinds of end products; the specific carbon management policy employed; and the effect of key analytical parameters, including in particular the discount rate applied to future costs and benefits. The authors then adjust the findings from major recent studies of forest sequestration to reflect consistent assumptions in each of these areas and use the normalized results to establish a likely range for the overall scope and likely costs of large-scale carbon sequestration in the United States.

Their conclusions are striking. Estimated costs for sequestering up to 500 million tons of carbon per year—an amount that would offset up to one-third of current annual U.S. carbon emissions—range from $30 to $90 per ton. On a per-ton basis, these costs are comparable to those estimated for other climate change mitigation options such as fuel switching or energy efficiency. A sequestration program on this scale would involve large expanses of land and significant upfront investment; as such, it would almost certainly require a phased approach over a number of years and careful attention to policy details to ensure efficient implementation. Nevertheless, the results of this study indicate that sequestration can play an important role in future mitigation efforts and must be included in comprehensive assessments of policy responses to the problem of global climate change.

The Pew Center and the authors are grateful to Ralph Alig, Ronald Sands, and Brent Sohngen for helpful comments on previous drafts of this report. A future Pew Center domestic policy report will focus on design aspects of a domestic mitigation program that includes sequestration. Insights from this report and from companion papers in the Pew Center's Economics series are being utilized to develop a state-of-the-art assessment of the costs to the United States of taking action to address climate change.

Executive Summary

When and if the United States decides on mandatory policies to address global climate change, it will be necessary to decide whether carbon sequestration should be part of the domestic portfolio of compliance activities. The potential costs of carbon sequestration policies will presumably be a major criterion, so it is important to assess the cost of supplying forest-based carbon sequestration in the United States. In this report we survey major studies, examine the factors that have affected their carbon sequestration cost estimates, and synthesize the results.

The Earth's atmosphere contains carbon dioxide (CO_2) and other greenhouse gases (GHGs) that act as a protective layer, causing the planet to be warmer than it would otherwise be. If the level of CO_2 rises, mean global temperatures are also expected to rise as increasing amounts of solar radiation are trapped inside the "greenhouse." The level of CO_2 in the atmosphere is determined by a continuous flow among the stores of carbon in the atmosphere, the ocean, the earth's biological systems, and its geological materials. As long as the amount of carbon flowing into the atmosphere (as CO_2) and out (in the form of plant material and dissolved carbon) are in balance, the level of carbon in the atmosphere remains constant.

Human activities—particularly the extraction and burning of fossil fuels and the depletion of forests—are causing the level of GHGs (primarily CO_2) in the atmosphere to rise. The primary sources of the slow but steady increase in atmospheric carbon are fossil fuel combustion, which contributes approximately 5.5 gigatons (billion metric tons) of carbon per year, and land-use changes, which account for another 1.1 gigatons. In contrast, the oceans absorb from the atmosphere approximately 2 more gigatons of carbon than they release, and the earth's ecosystems appear to be accumulating another 1.2 gigatons annually. In all, the atmosphere is annually absorbing approximately 3.4 gigatons of carbon more than it is releasing.

While the annual net increase in atmospheric carbon may not sound large compared with the total amount of carbon stored in the atmosphere—750 gigatons—it adds up over time. For example, if the current rate of carbon accumulation were to remain constant, there would be a net gain in atmospheric carbon of 25 percent over the next fifty years. In fact, the rate at which human activity contributes to increases in atmospheric carbon is accelerating. Emissions from land-use change have been growing at the global level, though not nearly as rapidly as emissions from fossil fuel combustion. In the United States, land-use change—which was a substantial source of carbon emissions in the 19th and early 20th centuries—became a sink (or absorber of carbon) by the second half of the 20th century. However, the rate of carbon absorption by terrestrial systems in the United States peaked around 1960 and has been falling since.

It may be possible to increase the rate at which ecosystems remove CO_2 from the atmosphere and store the carbon in plant material, decomposing detritus, and organic soil. In essence, forests and other highly productive ecosystems can become biological scrubbers by removing (sequestering) CO_2 from the atmosphere. Much of the current interest in carbon sequestration has been prompted by suggestions that sufficient lands are available to use sequestration for mitigating significant shares of annual CO_2 emissions, and related claims that this approach provides a relatively inexpensive means of addressing climate change. In other words, the fact that policy makers are giving serious attention to carbon sequestration can partly be explained by (implicit) assertions about its marginal cost, or (in economists' parlance) its supply function, relative to other mitigation options.

The economist's notion of cost, or more precisely, opportunity cost, is linked with—but distinct from—everyday usage of the word. Opportunity cost is an indication of what must be sacrificed to obtain something. In the environmental context, it is a measure of the value of whatever must be sacrificed to prevent or reduce the chances of a negative environmental impact. Opportunity cost typically does not coincide with monetary outlays—the accountant's measure of costs. This may be because out-of-pocket costs fail to capture all of the explicit and implicit costs that are incurred, or it may be because the prices of the resources required to produce an environmental improvement are themselves an inaccurate indication of the opportunity costs of those resources. Hence, the costs of a climate policy equal the social benefits that are foregone when scarce resources are employed to implement that policy, instead of putting those resources to their next best use.

The costs of carbon sequestration are typically expressed in terms of monetary amounts (dollars) per ton of carbon sequestered—that is, as the ratio of economic inputs to carbon mitigation outputs for a specific program. The denominator, carbon sequestered, is determined by forest management practices, tree species, geographic location and characteristics, and disposition of forest products involved in a hypothetical policy or program. The costs reflected in the numerator include the costs of land, planting, and management, as well as secondary costs or benefits such as non-climate environmental impacts or timber production. Well-developed analytical models include landowners' perceptions regarding all relevant opportunity costs, including costs for land, conversion, plantation establishment, and maintenance.

Among the key factors that affect estimates of the cost of forest carbon sequestration are: (1) the tree species involved, forestry practices utilized, and related rates of carbon uptake over time; (2) the opportunity cost of the land—that is, the value of the affected land for alternative uses; (3) the disposition of biomass through burning, harvesting, and forest product sinks; (4) anticipated changes in forest and agricultural product prices; (5) the analytical methods used to account for carbon flows over time; (6) the discount rate employed in the analysis; and (7) the policy instruments used to achieve a given carbon sequestration target.

Given the diverse set of factors that affect the cost and quantity of potential forest carbon sequestration in the United States, it should not be surprising that cost studies have produced a broad range of estimates. This report identifies eleven previous analyses that are good candidates for comparison and synthesis. Results from these studies were made mutually consistent, or normalized, by adjusting for constant-year dollars, identical discount rates, identical geographic scope, and reporting in equivalent annual costs. This normalization narrows the range of results considerably; for a program size of 300 million tons of annual carbon sequestration, nearly all estimated supply functions (or marginal costs) fall within the range of $25 - $75 per short ton of carbon ($7.50 - $22.50 per metric ton of CO_2-equivalent). This range increases somewhat—to $30 - $90 per ton of carbon—for programs sequestering 500 million tons annually. In addition, econometric methods were used to estimate the central tendency (or "best-fit") of the normalized marginal cost functions from the eleven studies compared here; this is presented as an additional result of the analysis and as a rough guide for policy makers of the projected availability of carbon sequestration at various costs.

Three major conclusions emerge from our survey and synthesis:

1) There is a broad range of possible forest-based carbon sequestration opportunities available at various magnitudes and associated costs.

This range depends upon underlying biological and economic assumptions, as well as the analytical methods employed. Several factors affect estimates of cost: forest species and practices; the value of land for alternative uses; the disposition of biomass, forest and agricultural product prices; methods used to account for carbon flows over time; the discount rate employed; and the policy instruments used.

2) A systematic comparison of sequestration supply estimates from national studies produces a range of $25 to $75 per ton for a program size of 300 million tons of annual carbon sequestration.

The range increases somewhat—to $30 - $90 per ton of carbon—for programs sequestering 500 million tons annually. This range is obtained from a synthesis of eleven national studies of U.S. sequestration opportunities in the forestry sector, where each study was adjusted for use of equivalent annual costs in constant-year dollars, together with identical discount rates and identical geographic scope. This approach allows for consistent comparisons across a variety of studies and narrows the range of estimated supply functions considerably.

3) When a transparent and accessible econometric technique is employed to estimate the central tendency (or "best-fit") of costs estimated in these eleven studies, the resulting supply function for forest-based carbon sequestration in the United States is approximately linear up to 500 million tons of carbon per year, at which point marginal costs reach approximately $70 per ton.

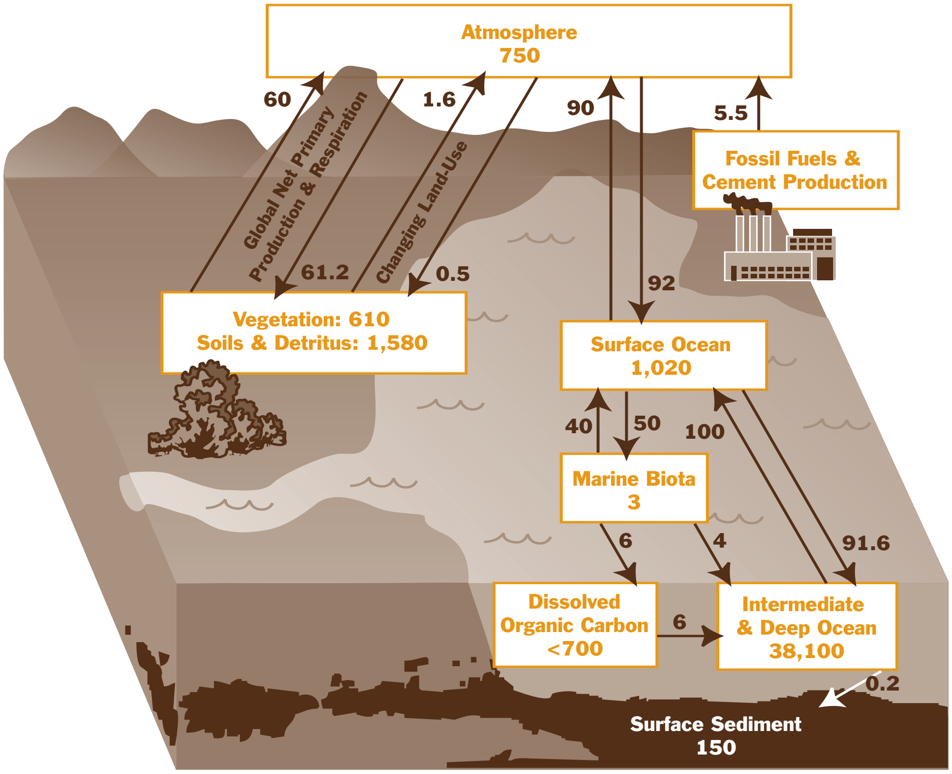
A 500-million-ton-per-year sequestration program would be very significant, offsetting approximately one-third of annual U.S. carbon emissions. At this level, the estimated costs of carbon sequestration are comparable to typical estimates of the costs of emissions abatement through fuel switching and energy efficiency improvements. This result indicates that sequestration opportunities ought to be included in the economic modeling of climate policies. It further suggests that if it is possible to design and implement a domestic carbon sequestration program, then such a program ought to be included in a cost-effective portfolio of compliance strategies when and if the United States enacts a mandatory domestic GHG reduction program.

I. Introduction

The Earth's atmosphere contains carbon dioxide (CO_2) and other greenhouse gases (GHGs) that act as a protective layer, causing the planet to be warmer than it would otherwise be. This heat retention is critical to maintaining habitable temperatures. If there were significantly less CO_2 in the atmosphere, global temperatures would drop below levels to which ecosystems and human societies have adapted. As CO_2 levels rise, mean global temperatures are also expected to rise as increasing amounts of solar radiation are trapped inside the "greenhouse." The concentration of CO_2 in the atmosphere is determined by a continuous flow among the stores of carbon in the atmosphere, the ocean, the earth's biological systems, and its geological materials (Figure 1). As long as the amount of carbon flowing

Figure 1

The Global Carbon Cycle (in GtC)



Source: www.met-office.gov.uk/research/hadleycentre/models/carbon_cycle/intro_global into the atmosphere (as CO_2) and out (in the form of plant material and dissolved carbon) are in balance, the level of carbon in the atmosphere remains constant.

Significant concern has arisen among scientists, politicians, and segments of the general public that human activity—particularly the extraction and burning of fossil fuels and the depletion of forests—is causing the level of GHGs (primarily CO_2) in the atmosphere to rise. Figure 1 illustrates that the primary sources of the slow but steady increase in atmospheric carbon that is now occurring are fossil fuel combustion, which contributes approximately 5.5 gigatons (billion metric tons) of carbon per year, and land use changes, which account for another 1.1 gigatons (although there is considerable uncertainty about this figure—see Table 1). In contrast, the oceans absorb from the atmosphere approximately 2 more gigatons of carbon than they release and the earth's ecosystems appear to be accumulating another 1.2 gigatons annually. In all, the atmosphere is annually absorbing approximately 3.4 gigatons of carbon more than it is releasing.

While the annual net increase in atmospheric carbon does not sound large compared with the total amount of carbon stored in the atmosphere—750 gigatons—it adds up over time. For example, if the current rate of atmospheric carbon accumulation were to remain constant, there would be a net gain in atmospheric carbon levels of 25 percent over fifty years. In fact, the rate at which human activity contributes to increases in atmospheric carbon is accelerating. Table 1 describes trends in world and

Table 1

World and U.S. Emissions from Fossil Fuels and Land-Use Change, Select Years (millions of metric tons of carbon per year)

	1850	1900	1950	1960	1970	1980	1990	2000
Fossil Fuel								
World	54	534	1612	2535	3998	5177	5969	6385
United States	5	181	692	797	1160	1263	1315	1529
Land-Use Change								
World	503	697	935	1302	1537	1608	2158	2081
United States	162	247	-91	-157	-149	-150	-110	-110

Source: All data derived from Oak Ridge National Lab, Carbon Dioxide Information Analysis Center.

Land-use change data from "Annual Net Flux of Carbon to the Atmosphere from Land-Use Change: 1850-2000" at http://cdiac.ornl.gov/ftp/trends/landuse/houghton/houghtondata.txt.

Fossil fuel emissions data from "Global CO_2 Emissions from Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751-2000" at http://cdiac.ornl.gov/ftp/ndp030/global00.ems, and "Global CO_2 Emissions from Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751-2000" at http://cdiac.ornl.gov/ftp/ndp030/nation00.ems.

U.S. carbon emissions from fossil fuel combustion and land-use change since 1850. There has been a steady increase in carbon emissions from fossil fuel use at both the national and global levels, with a much more rapid rise in the United States than in the rest of the world. Emissions from land use change have also been growing at the global level, though not nearly as rapidly as from fossil fuel combustion. In the United States, however, land-use change—which was a substantial source of carbon emissions in the 19th and early 20th centuries—became a sink by the second half of the 20th century. Equally telling, the rate of carbon absorption by terrestrial systems in the United States peaked around 1960 and has been falling since.

In 1992, over 180 countries joined in signing the United Nations Framework Convention on Climate Change, agreeing in principle to stabilize GHG levels in the atmosphere (United Nations, 1997). Since that time, attention has been given to ways to decrease—or at least decelerate—the flow of carbon from fossil fuels to the atmosphere. There has also been research on mechanisms to increase the rate at which oceans extract and store carbon from the atmosphere. Additionally, it may be possible to increase the rate at which ecosystems remove CO_2 from the atmosphere and store the carbon in plant material, decomposing detritus, and organic soil. In essence, forests and other highly productive ecosystems can become biological scrubbers by removing (sequestering) CO_2 from the atmosphere.

Since the late 1980s, much of the interest in carbon sequestration has been prompted by suggestions that sufficient lands are available to use sequestration for mitigating significant shares of annual CO_2 emissions (e.g., Marland, 1988; Lashof and Tirpak, 1989) and related claims that this approach provides a relatively inexpensive means of addressing climate change (Sedjo and Solomon, 1989; Dudek and LeBlanc, 1990). In other words, the fact that policy makers are giving serious attention to carbon sequestration can partly be explained by (implicit) assertions about its marginal cost, or (in economists' parlance) its supply function relative to other mitigation options.

When and if the United States chooses to implement a domestic GHG reduction program, it will be necessary to decide whether carbon sequestration policies—such as policies that promote forestation and discourage deforestation—should be part of the domestic portfolio of compliance activities. Because the costs of carbon sequestration options (relative to alternatives such as reducing emissions from fossil fuel use) will presumably be a major criterion for policy makers it is essential to understand how much carbon can be sequestered at various costs.[1]

To develop an understanding of the costs of carbon sequestration in the United States we surveyed a variety of studies, examining the factors that influenced their cost estimates and, to the degree possible, synthesizing their results. We begin in Section II of this report by developing the concept of opportunity cost—as understood by economists—in the context of policies to address the threat of global climate change. In Section III, we begin our review of major studies concerning the costs of forest-based carbon sequestration in the United States by examining the principle factors that are likely to affect cost estimates. These include biological factors (such as species, forestry practices, and carbon yield patterns), the opportunity cost of land, management practices, methods for the disposition of biomass, relevant prices, and the policy instruments used to achieve carbon sequestration.

In Section IV, we review previous studies with the aim of synthesizing their results to develop best estimates of the cost of supplying forest-based carbon sequestration in the United States. Specifically, we identify eleven previous analyses of carbon sequestration costs that are particularly good candidates for comparison and synthesis (the studies are listed, in chronological order by date of publication, in Table 2). To narrow the useful range of estimated costs and make them easier to compare, we normalize the estimates from these studies, expressing the results in a series of figures portraying national-level carbon sequestration supply functions. Finally, in the interests of making our results more transparent and accessible, we derive a curve that lies roughly in the center of this set of marginal cost functions and present this central tendency as an additional result of our analysis. In Section V of the report, we offer conclusions on the likely cost of forest-based carbon sequestration opportunities in the United States.

Table 2

Analyses of Carbon Sequestration Costs, Carbon Yield Formats, Accounting Methods, and Discount Rates

Study	Carbon Yield Format	Carbon Accounting Method	Discount Rate Employed: Benefits	Discount Rate Employed: Costs
Moulton and Richards (1990)	Average Carbon Flow	Levelized Cost	N/A	10%
Dudek and Leblanc (1990)	Average Carbon Flow	Levelized Cost	N/A	8.5%
New York State (1991)	Average Carbon Flow	Levelized Cost	N/A	10%
Adams et al. (1993)	Average Carbon Flow	Levelized Cost	N/A	10%
Richards, Moulton and Birdsey (1993)	Carbon Flow Curve	Discounting	5%	N/A
Parks and Hardie (1995)	Average Carbon Flow	Levelized Cost	N/A	4%
Alig et al.(1997)	Carbon Flow Curve	Discounting	N/A	4%
Richards (1997a)	Carbon Flow Curve	Discounting	0%, 2%, 5%, 8%	0%, 2%,5%, 8%
Stavins (1999)	Carbon Flow Curve	Discounting	5%	5%
Plantinga et al. (1999)	Carbon Flow Curve	Discounting	5%	5%
Lubowski, Plantinga and Stavins (2003)	Carbon Flow Curve	Discounting	5%	5%

II. Costs of Addressing the Threat of Global Climate Change

The economist's notion of cost or, more precisely, opportunity cost, is linked with—but distinct from—everyday usage of the word. Opportunity cost is an indication of what must be sacrificed to obtain something. In the environmental context, it is a measure of the value of whatever must be sacrificed to prevent or reduce the chances of a negative environmental impact. Opportunity costs typically do not coincide with monetary outlays, the accountant's measure of costs. This may be because out-of-pocket costs fail to capture all of the explicit and implicit costs that are incurred, or it may be because the prices of the resources required to produce an environmental improvement are themselves inaccurate indications of the opportunity costs of those resources. Hence, the cost of a climate policy equals the social benefits that are foregone when scarce resources are employed to implement that policy, instead of putting these resources to their next best use (Stavins, 2001). Costs and benefits are thus two sides of the same coin: environmental benefits are created by taking some policy action, while other benefits are thereby foregone. The cost of an environmental-protection measure may thus be defined as the gross decrease in social benefits (consumer and producer surpluses) caused by the measure together with any price and/or income changes that may result (Cropper and Oates, 1992).

Categories of environmental compliance costs range from the most obvious to the most subtle (Jaffe et al., 1995). First, many policy makers and much of the general public would identify the on-budget costs to government of administering (monitoring and enforcing) environmental laws and regulations as one cost of environmental regulation. This meets the economist's notion of (opportunity) cost, since administering environmental rules requires resources (labor and capital) that could otherwise be used elsewhere. But economic analysts would also include as costs the capital and operating expenditures associated with regulatory compliance. Indeed, these typically represent a substantial portion of the overall costs of regulation. Additional direct costs include legal and other transaction costs, the effects of refocused management attention, and the possibility of disrupted production.

Next are the beneficial effects—sometimes called "negative costs"—of environmental regulation, including the positive productivity impacts of a cleaner environment and the potential innovation-stimulating effects of regulation.[2] General equilibrium or multi-market effects associated with discouraged investment and retarded innovation constitute another important layer of costs, as do the transition costs of real-world economies responding over time to regulatory changes. For example, if a firm chooses to close a plant because of a new regulation (rather than installing expensive control equipment), this would be counted as zero cost in narrow compliance-cost estimates, but it is obviously a real cost. In essence, the general equilibrium costs of climate change policies (and the general equilibrium damages of climate change) reflect the degree to which consumers and producers can substitute new goods and services for what they buy and sell when relative prices change.[3]

Producing high-quality estimates of the costs of environmental protection requires careful analysis. Conceptually, four steps are involved. First, it is necessary to identify the policy instrument to be used. For example, is a conventional instrument (such as a technology standard) or a market-based instrument (such as an emissions charge) to be employed? This can be important because achieving the same environmental target (e.g., a given reduction in CO_2 emissions) may entail very different total costs depending on the policy instrument used. The second step is identifying the specific actions that sources will take to comply given the policy instrument being employed. Some of these actions may involve the adoption of a new piece of equipment, while others may involve a process change. Third, it is necessary to identify the true cost of each compliance action, which requires more than assessing required monetary outlays. Fourth, it is often useful to aggregate these costs across society and over the relevant time frame.

In the case of climate change policies, the cost of taking action includes: direct outlays for control measures (e.g., the incremental cost of using natural gas rather than more carbon-intensive coal for energy generation); costs to both producers and consumers as they adjust to the new constraints (e.g., accelerated depreciation of fixed capital); and the secondary or general equilibrium costs that arise in related markets as prices adjust. These general equilibrium effects can be important. The ultimate consequences of a given environmental policy depend on interactions between the new policy and existing regulations or tax policies. In particular, additional costs can arise from interactions between climate policies and pre-existing distortions in the economy, such as those due to taxes on labor (Goulder, 1995).

Estimates of climate change mitigation costs depend on several factors and how they are handled by the analysts who produce the estimates (Weyant, 2000). These factors include: (1) the baselines assumed for GHG emissions and carbon sequestration; (2) characteristics of the policy regimes being analyzed, including the degree of flexibility they allow; (3) how the analysis incorporates the potential for technological change; and (4) the degree to which producers and consumers can substitute goods as prices change.

The baselines utilized for climate policy cost analyses are very important. Indeed, a striking finding from a wide range of integrated assessment models (which layer economic models upon underlying scientific models of climate change) is that differences in net economic benefits (i.e., the difference between benefits and costs) attributable to plausible baseline assumptions are greater than the net economic benefits attributable to the climate policies themselves (Goulder, 2000). Typically, the baselines used in cost analyses are built upon various assumed time paths of future economic growth, encompassing overall rates of growth plus relevant sectoral changes. A particularly important factor in developing alternative baselines is the assumed rate and direction of technological change.

The cost of achieving any given climate protection target also depends critically upon the “physical scope” and flexibility of the policy action. Does the policy being analyzed affect CO_2 emissions only, for example, by encouraging fuel switching? Or does the policy also allow for other actions such as: promoting increased biological uptake of carbon through carbon sequestration (presumably through changes in land use); carbon management (that is, removal and storage of CO_2 in the deep ocean or in depleted oil and gas reservoirs); and/or geo-engineering (for example, increasing the earth’s reflectivity?) More broadly still, does the policy encompass adaptation measures, which may be less costly than “equivalent” mitigation efforts that work through emissions reduction, sequestration, carbon management, or geo-engineering? Finally, does the policy being assessed focus exclusively on CO_2 or does it target a larger set of GHGs? This is a crucial question, since broader targets enhance flexibility and can, in some cases, substantially reduce the costs of achieving a given climate goal (Reilly et al., 2003).

Just as the physical scope and flexibility of the policy response affects the costs of achieving a climate target, the policy instrument chosen will also have impacts on costs. Available policy instruments include conventional technology and uniform performance standards (so-called “command-and-control” approaches), as well as economic-incentive or market-based policy instruments, such as taxes and tradable permit systems (Fisher et al., 1996; Stavins 1997; Ellerman et al., 2003). As mentioned earlier, climate policy instruments can impose additional costs through their interaction with pre-existing distortionary taxes. This raises another issue for cost comparisons since some policy instruments generate revenues that can be used by governments to reduce pre-existing taxes, thereby lowering the overall cost of the policy below what it otherwise would be (Goulder, 1995).

The outcome of any cost comparison also depends upon the sophistication of the analytical models being used. Given the long-term nature of global climate change and related policies, dynamic (long-term) cost-effectiveness is an appropriate cost criterion. Accordingly, it can be important to allow for effects on the rate and direction of relevant (i.e., cost-reducing) technological change (Jaffe et al., 1999, 2003). In the give-and-take of policy debates, the abatement costs of proposed regulations have sometimes been over-estimated (Harrington et al., 2000; Hammitt, 2000). This may partly be due to the adversarial nature of the policy process, but it is also a natural consequence of employing short-term cost analyses that do not take into account the potential for future cost savings due to technological change, some of which may be endogenous to the regulatory regime. Most analyses of global climate policy have not allowed for endogenous technological improvements, but this has begun to change (Goulder and Mathai, 2000; Grübler et al., 2002).

III. Factors Affecting the Estimated Costs of Carbon Sequestration

The costs of carbon sequestration are typically expressed in terms of monetary amounts (dollars) per ton of carbon sequestered: that is, as the ratio of economic inputs to carbon sequestration outputs for a specific program.[5] The denominator, carbon sequestered, is determined by forest management practices, tree species, geographic location and characteristics, and disposition of forest products involved in a hypothetical policy or program. The numerator represents the summed cost of land, planting and management, and possibly secondary costs or benefits, such as non-climate environmental impacts or timber production. A well-developed model includes landowners' perceptions regarding all relevant opportunity costs, including costs for land, conversion, plantation establishment, and maintenance. Land costs include opportunity costs for alternative uses.

A. Biology: Species, Forestry Practices, and Carbon Yield Functions

A variety of practices affect the rate of carbon sequestration on agricultural and forest land in the United States (Table 3). Two of these practices—afforestation of agricultural land and reforestation of harvested or burned forest land—are characterized as "plantation" methods. Four other practices are essentially modifications of forest management practices on existing forest lands. These include modifications to emphasize carbon storage; adoption of low-impact harvesting methods to reduce carbon releases; lengthening of forest rotation cycles; and preservation of forest land from conversion to alternative uses (that is, preventing deforestation). Distinctions are sometimes made between "afforestation" and

Table 3

Forestry Practices that Increase Carbon Sequestration on Forestland

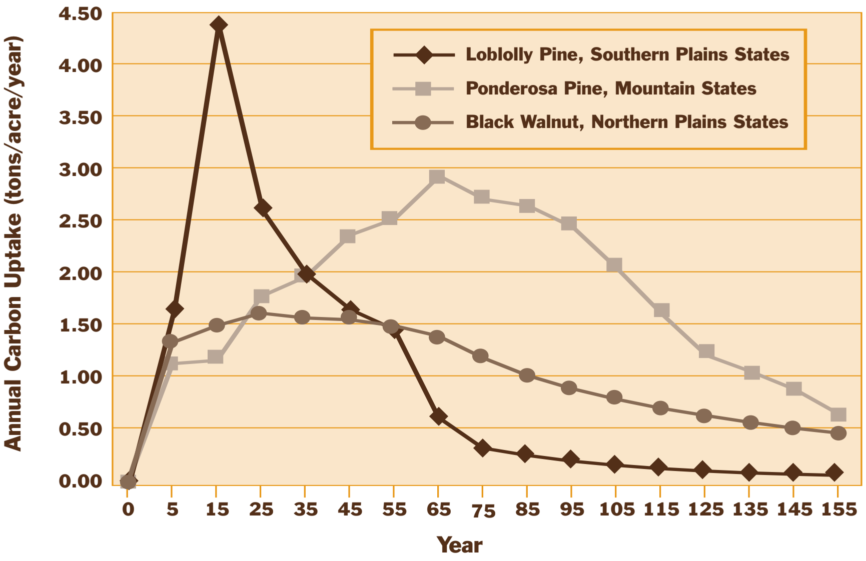
1. Afforestation of agricultural land
2. Reforestation of harvested or burned timberland storage
3. Modification of forestry management practices to emphasize carbon storage
4. Adoption of low impact harvesting methods to decrease carbon release
5. Lengthening forest rotation cycles
6. Preservation of forestland from conversion
7. Adoption of agroforestry practices
8. Establishment of short-rotation woody biomass plantations
9. Urban forestry practices

"reforestation," where the former refers to a change from non-forest to forest production on lands that have not been forested during the preceding 50 years or more and the latter refers to a change to forest production on lands that have more recently been deforested. In this report, we refer to any land-use change *to* forest use as "forestation." This is in contrast to a change *away* from forest use of land or "deforestation." Agroforestry is the practice of combining forestry production and agricultural production to derive synergistic benefits. For example, biomass grown on short-rotation plantations can displace fossil fuels in the provision of energy services and thereby decrease carbon emissions. Finally, urban forestry makes use of space in urban areas to increase carbon sequestration and reduce energy use for heating and air conditioning. Most economic analyses, including all of those reviewed and synthesized in this report, assess sequestration costs for forest plantations. However, a few studies also include cost analyses of modified forest management practices.

Rates of carbon sequestration on forest lands depend on the management practices adopted, the species of trees involved, and the geographic area covered. For any given land-use change—for example, conversion of cropland to forestland—sequestration rates will vary considerably depending on the region and species involved (Figure 2). As illustrated by the figure, conversion to loblolly pine in the Southern Plains states leads to rapid uptake of carbon, peaking at approximately 4.5 tons per acre per year in the second decade of growth and declining rapidly thereafter, with carbon uptake becoming insignificant after 70 years. In contrast, ponderosa pine plantations in the Mountain states region exhibit a gradually increasing rate of carbon

Figure 2

Carbon Sequestration Rates for Three Region/Species Combinations



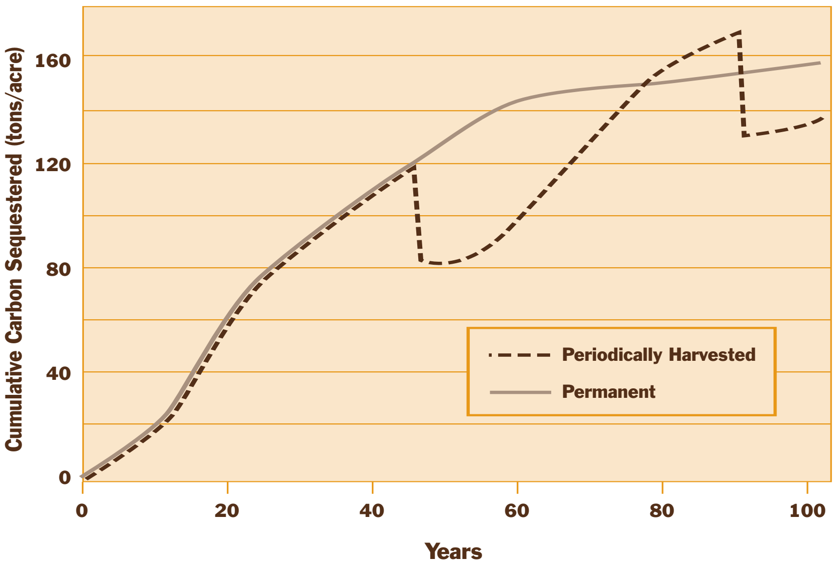
Source: Based on data from Richards, Moulton and Birdsey (1993).

sequestration over 70 years, peaking at about 3 tons per acre per year, and declining gradually over the succeeding century. Thus, the total quantity of carbon sequestered over the lifetime of a plantation may be greater in the case of ponderosa pine, but the sequestration occurs much later than with loblolly pine.

Although the sequestration trajectories depicted in Figure 2 differ in their timing and peak flow levels, they share a pattern of initially rising rates of carbon sequestration followed by gradually declining rates. Thus, in terms of cumulative carbon sequestered, carbon yield curves exhibit roughly "logistic" patterns (the smooth curve in Figure 3).[6] Studies of sequestration costs in the United States have generally reported carbon uptake in one of three formats: (1) *carbon flow curves* that provide a trajectory of (and therefore account for variation in) annual carbon uptake rates over time, as in Figures 2 and 3; (2) *average carbon flows* that express mean annual increments of carbon, averaged over the life of a forestry project or practice; and (3) *cumulative carbon capture*, which sums all carbon captured by a project or practice without regard to timing. Of the eleven studies we summarize (and list in Table 2), the earlier studies tended to employ carbon yield estimates in terms of average carbon flows, whereas the later studies employed carbon flow curves.

Figure 3

Cumulative Carbon Sequestration



Source: Stavins (1999), based on data from Moulton and Richards (1990) and Richards (1997a).

Note: Time profile is of loblolly pine in the Mississippi Delta states region of the United States.

Diverse components of the forest ecosystem store carbon, including tree trunks, branches, leaves, coarse and fine roots, soils, litter (forest floor detritus), and understory (low-growing trees and plants below the forest canopy). With one exception, all of the studies included in this analysis account for carbon storage in all of these components. The New York State study (1991) accounted only for carbon uptake in above and below-ground tree components and excluded uptake by soil, understory, and litter components. In general, excluding carbon uptake by any forest component that would be affected by the practice under analysis will increase the estimated per ton cost of sequestration. Among U.S. studies, the range of estimates for overall forest carbon sequestration potential is from 0.9 to 4.6 tons per acre per year.[7]

B. Opportunity Cost of Land

There is little doubt that the most important factor affecting the cost of forestry-based carbon sequestration in the United States is the cost of land. In a statistical analysis of carbon sequestration cost studies, Manley, van Kooten and Smolak (2003) found that average carbon sequestration cost estimates were greater by 2 to 3.5 times in studies that took the opportunity cost of land into account. As emphasized in Section II, the notion of opportunity cost is critical. In this context, accounting for the opportunity cost of affected land means capturing the net economic benefits that are foregone by diverting land from other uses so as to establish a carbon sink. Three general approaches have been used to estimate these costs: bottom-up engineering cost studies; optimization models that seek to account for behavioral responses in the forest and agricultural sectors; and econometric analyses of the revealed preferences of landowners concerning the use of their land for alternative purposes, including forestry and agriculture. Below we briefly describe these three approaches, noting their employment by the eleven studies that are included in our analysis.

Engineering Cost Studies. Most previous sequestration cost studies—including six of the eleven studies that are synthesized in this report—employ "bottom-up" or "engineering cost" methods. This means, essentially, that they construct marginal cost curves by using information on revenues and costs of production for alternative land uses assuming representative types or locations of land, and then sorting these data in ascending order of cost. In the earliest and, in some ways, simplest of these types of analyses (i.e., Moulton and Richards, 1990; Dudek and Leblanc, 1990; New York State, 1991), researchers first estimated available land area, forest carbon accumulation rates, and land and planting costs for hypothetical sequestration programs (Table 4). From these key inputs, they then estimated the total amount of carbon (or CO_2, in the case of Dudek and LeBlanc, 1990) that could be captured and the cost per ton of sequestration. In a variation on this theme, Parks and Hardie (1995) substituted estimates of foregone net revenues from agricultural production for observed sale and rental prices of agricultural land. Importantly, these studies did not consider behavioral responses by landowners or other economic agents.

Table 4

Land Costs in Bottom-Up Engineering Cost Studies

		Land Costs	
Study	**Region**	**Forest Plantation**	**Forest Management**
Moulton and Richards (1990)	United States	$360-$8,400/ha	$120-$1,440/ha
Dudek and LeBlanc (1990)	United States	$100/ha/year	—
New York State (1991)	New York	$0-$1,200/ha	$0
Richards, Moulton and Birdsey (1993)	United States	$275-$5,135/ha	—
Parks and Hardie (1995)*	United States	$40-$650/ha/year	—
Richards (1997a)	United States	$116-$6,174/ha	—

*Land costs were expressed as annual rental payments to landowners within a subsidy program.

In two other studies, the engineering approach was modified to include an anticipated increase in agricultural land prices as the hypothetical carbon sequestration program expands and crop and pastureland are removed from agricultural production. This was done by drawing upon previous (exogenous) estimates of the price elasticity of demand for agricultural land (Richards, Moulton and Birdsey, 1993; Richards, 1997a). Likewise, Adams et al. (1993) employed a model of consumer surplus loss from increases in food prices caused by the reduced availability of agricultural land. Like the demand elasticity approach, this has the effect of elevating the opportunity cost of land as increasing quantities of land are shifted from agriculture to carbon sequestration.

Sectoral Optimization Models. It is possible that a carbon sequestration program would increase the price of agricultural land and cause landowners to convert unregulated forest lands to agricultural uses. If such "leakage" were significant, then some or all of the climate benefits of a carbon sequestration program could be offset. An analysis by Alig et al. (1997) attempted to address this issue through the application of a two-sector simulation model. In this multi-period model, the forest and agricultural sectors are linked and the welfare of producers and consumers in the two sectors is maximized. The prices of goods and the effects of changes in production and consumption are predicted by the model as a function of this welfare maximization process. Finally, the model estimates where and how much conversion of land between forest and agricultural uses would be induced by a carbon sequestration program. The opportunity costs of land are calculated as one component of the optimization process.

Econometric Studies. A very different approach to estimating carbon sequestration costs in general, and the opportunity cost of land in particular, is the revealed-preference approach, which involves analyzing actual land-use changes to estimate relationships between land use choices and relative prices in the forest and agricultural sectors (Stavins, 1999; Plantinga et al., 1999; Lubowski et al., 2003). This is done by examining the relationship between observable historic events (e.g., changes in timber and agricultural product prices) and landowner responses (in terms of conversion of land into and out of forest), and statistically estimating a response function. Using that response function it is then possible to model the effect of a similar hypothetical economic stimulus—for example, government subsidies for carbon sequestration—and estimate how landowners would respond.

In taking this approach, researchers have sought to allow for a variety of factors that might affect the costs of carbon sequestration. In theory, there are a number of reasons why landowners' actual behavior regarding the disposition of their lands might not be well predicted by "engineering" or "least-cost" analyses (Stavins, 1999). Such reasons might include the fact that: (1) land-use changes can involve irreversible investments in the face of uncertainty (Parks and Hardie, 1995) and landowners may want to retain options for future land use directions (Pindyck, 1991); (2) there may be nonpecuniary returns (e.g., esthetics and recreation) to landowners from forest uses of land (Plantinga, 1997), as well as from agricultural uses; (3) liquidity constraints or simple "decision-making inertia" may mean that economic incentives affect landowners only with some delay; and (4) there may be private, market benefits or costs associated with alternative land uses (or with changes from one use to another) of which the analyst is unaware.

The econometric cost analyses seek to address at least some of these problems. With the econometric approach, it is not necessary to understand the details of landowners' decision processes. Rather, a well-designed econometric model relies on observed data to reveal the total opportunity cost of converting land to forestry from alternative uses. This cost will include the effects of explicit or implicit agricultural subsidies, which are generally capitalized into land values. In such cases, actual carbon sequestration costs to landowners may be estimated accurately, but social costs will be over-estimated because the social benefits of reducing agricultural subsidies are not accounted for. It should be noted, however, that estimates of the costs of alternative climate policies, such as those that seek to reduce emissions from fossil fuel combustion, also include the effects of a considerable number of government subsidies.

C. Forest Management: Initial Treatment and Maintenance Costs

Initial treatment and maintenance costs contribute to the overall costs of a carbon sequestration program. The U.S. Forest Service maintains extensive records on the costs of domestic afforestation and reforestation, so there are data available on historic costs for the establishment of new forest stands (Moulton and Richards, 1990). A limitation of existing studies is that they have not considered how quickly afforestation or reforestation programs were implemented. This is problematic because it is likely that forcing a rapid increase in planting rates will affect marginal costs as timber, labor, and other prices adjust. Also, the inherent failure rate in the establishment of new forests has generally not been considered, though one study (Moulton and Richards, 1990) provided for a 15 percent failure rate, leading to higher total planting costs. Following establishment of a forestry project, there are ongoing maintenance costs, including those associated with fertilization, thinning, security, and other activities that are essential to assure that expected carbon sequestration yields are realized. None of the studies included in this analysis explicitly included annual maintenance costs in their calculations. Nor did any of these studies explicitly include the costs of fire and pest protection (or the risks of carbon loss that these threats pose).

D. Disposition of Biomass: Burning, Harvesting, and Forest Product Sinks

Carbon flows into forests can be halted or even reversed by harvest, conversion to alternative uses, or fire. Some studies have assumed that land planted with trees is permanently withdrawn from use, including harvest for wood products, so that there is no future release of carbon. This has been characterized as the "carbon graveyard" approach (Richards, Moulton and Birdsey, 1993). Other studies have implicitly assumed either that the forest will not be harvested at all or that it will be harvested so far in the discounted future as not to be a concern (Moulton and Richards, 1990; Parks and Hardie, 1995). Finally, a few studies have explicitly assessed the costs of carbon sequestration both with and without harvesting (Adams et al., 1993; Stavins, 1999; Plantinga et al., 1999).

The disposition of biomass—whether it is converted into wood products or biofuel, or left standing permanently—can have significant effects on carbon flows (see Figure 3, p.11), as well as on financial flows linked with timber harvest. Studies that include the effects of harvest on carbon flows but do not incorporate the resulting financial benefits will almost certainly overstate the costs of carbon sequestration. Conversely, studies that consider financial returns from the harvest of forest products but do not adjust carbon flows to reflect increased releases of carbon back to the atmosphere will systematically understate the costs of carbon sequestration. At the extreme, some carbon sequestration practices might pay for themselves in the form of forestry products, in which case the carbon benefits would be a costless bonus (often referred to as “no regrets” mitigation options). For example, it has been suggested that such negative costs may be associated with some potential carbon sequestration practices in China (Xu, 1995).

A number of studies have posited that including timber harvests in a carbon sequestration program would substantially reduce marginal costs. For example, Adams et al. (1993) found that the estimated marginal cost of sequestering 35 million tons of carbon per year declined from $13.90 per ton to $8.13 per ton when harvest was allowed.[8] These savings accrued through an increase in consumer surplus from lower-priced wood products together with farm producer surplus from increased revenue on carbon sequestration plantations, but were partially offset by losses to forest sector producers caused by lower timber prices. The analysis treated all sequestered carbon as remaining sequestered after harvest in long-lived wood products.

In a series of econometric analyses and related simulation models, Stavins (1999), Plantinga et al. (1999), and Newell and Stavins (2000) address the effects of harvest on carbon sequestration. Stavins (1999) estimates that approximately 40 percent of forest carbon goes into wood products at the time of harvest and that a significant portion of the remaining carbon remains in soils. According to this analysis, the carbon in wood products decays gradually, releasing approximately 75 percent of its stock within 100 years. Building on these findings, a later study by Newell and Stavins (2000) demonstrated that allowing harvest can actually increase the cost of forest-based carbon sequestration, even though the cost per acre declines. The reason for this result is that unlike Adams et al. (1993), Newell and Stavins (2000) account for both the decline in the amount of carbon sequestered (per acre) when harvesting is permitted *and* for resulting changes in the timing of net carbon flows. Plantinga et al. (1999) and Plantinga and Maudlin (2000) use a related analytical approach and find a similar effect.

While these studies addressed the impacts of harvesting—both in terms of the total quantity of carbon sequestered and in terms of program costs—their findings reflect a partial equilibrium result and do not include effects on timber prices or wood product supply. As we discuss in Section III.E, a more comprehensive analysis requires general equilibrium models that tie together models of agriculture and forest land supply and demand, forest product supply and demand, forest plantation carbon uptake, and wood product carbon flows.

E. Relevant Prices

Pricing assumptions will have a large effect on the costs of carbon sequestration. In this section, we examine three sets of pricing questions: first, the likely effects of changes in forest product and agricultural product prices; second, the impact of different methods of carbon accounting; and third, the effects of alternative discount rates.

Impacts of Changes in Forest and Agricultural Product Prices. At first blush, it would seem that since forest products are complements to forestry-based carbon sequestration, an anticipated increase in future forest product prices (relative to agricultural product prices) would have the unambiguous effect of reducing the opportunity cost of land and thereby reducing the marginal cost of carbon sequestration. Things are not quite this simple, however, because an increase in forest product prices can cause more frequent harvesting, which in turn can increase sequestration costs. As noted by Stavins (1999), ascertaining the net impact of higher forest product prices is an empirical question and depends ultimately upon the discount rate employed by landowners (see below).

Likewise, since agricultural products are substitutes for forestry-based carbon sequestration, we would anticipate that an increase in expected future agricultural product prices (again, relative to forest product prices) would increase the opportunity cost of land and thereby drive up the costs of carbon sequestration. In a sensitivity analysis of the model developed by Stavins (1999), Newell and Stavins (2000) examine the consequences of changing agricultural product prices in both baseline and policy simulations, taking note of the impacts on land-use changes (net forestation) and carbon sequestration

Table 5

Impact of Agricultural Prices on Cost of Supplying Carbon Sequestration

Carbon Sequestration and Forestation Costs and Quantities (Delta States)*	Departures from Base Case Agricultural Product Prices -30%	-20%	-10%	Base Case	+10%	+20%	+30%
Baseline Forestation/Deforestation (1000 acres)	5,968	3,317	1,430	52	-977	-1,758	-2,362
Marginal Cost of Carbon Sequestration ($/ton) (Sequestration = 5 million tons/yr)	21.93	26.88	32.44	37.91	38.87	39.60	40.94
Carbon Sequestration Relative to Baseline (1000 tons/year) (Subsidy/tax = $50/acre)	7,656	6,212	5,094	4,219	3,914	3,669	3,183

Source: Newell and Stavins (2000)

*From Table V in Newell and Stavins (2000). Calculations are for the Mississippi Delta states only, and are for a periodically harvested pine plantation, employing a 5 percent discount rate throughout.

(Table 5). Not surprisingly, increasing agricultural prices produce baseline simulations with more deforestation. Newell and Stavins then examine the impacts of such price changes on carbon sequestration relative to the baseline at a given level of policy intervention (such as a land-use subsidy/tax of $50 per acre). Again, not surprisingly, induced sequestration decreases continuously as the background agricultural product price level increases. The change, however, is by no means linear. Assuming low agricultural prices (30 percent below the base case) increases induced sequestration by 80 percent, whereas in the high price case (which assumes prices 30 percent above the base case) induced sequestration declines by only 25 percent.

The same non-linear impact is observed with respect to the marginal costs of sequestration (Table 5). Marginal sequestration costs increase continuously as agricultural prices rise. This is as expected, since the opportunity cost of the land increases. But the change is far from linear: decreases in agricultural prices have a much greater impact than do increases. This happens because higher agricultural product prices cause a substantial amount of deforestation in the baseline. In this high-price context, the effect of a given tax or subsidy to promote carbon sequestration is not only to increase forestation, but also to retard deforestation. Limiting deforestation is particularly important as deforestation releases more carbon (51.8 tons per acre according to Newell and Stavins [2000]) than forestation sequesters (41.0 tons per acre), in terms of “present-value equivalents,” i.e. discounted quantities. Thus, the increased “carbon efficiency” of a given policy intervention in the context of high levels of background deforestation reduces the marginal costs of sequestration below what they otherwise would be with high agricultural prices.

Carbon Accounting Methods. The fact that the amount of carbon in a forest changes over time raises a question: how can we associate a single number—the marginal cost of carbon sequestration—with the changing amounts of carbon that are sequestered from year to year over long time horizons? Sequestration studies have used a variety of methods to calculate costs in terms of dollars per ton, the desired units for a cost-effectiveness comparison. The terms used to distinguish these methods are "flow summation", "mean carbon storage", "levelization," and "discounting" (Richards, 1997b; Richards and Stokes, 2004).

The "flow summation" approach, sometimes referred to as the "stock change method," is the simplest: total costs (in present value terms) are divided by total tons of carbon sequestered, regardless of when sequestration occurs. This summary statistic fails to take into account the time profile of sequestration; as a measure it is very sensitive to the time horizon selected for calculation (particularly in the case of periodic-harvesting scenarios). Furthermore, assuming that not only the costs but also the benefits of sequestration are to be discounted over time, this approach implies that the marginal benefits of sequestration are increasing exponentially over time at the discount rate. A similar summary statistic, which suffers from the same problems as the flow summation approach, is based upon "mean carbon storage." In this case, the present value of costs is divided by the numerical average of annual carbon storage.

The "levelized cost" and "discounting" methods are mathematically identical, though the latter tends to be more adaptable to uneven flows of carbon over time. With the levelized cost approach, the annuity of the present value of costs is divided by annual carbon flows. This yields units of $/year in the numerator and tons/year in the denominator, which simplify to $/ton. The "discounting" approach is more adaptable to uneven carbon flows because the discounted present value of costs is divided by the discounted present value of tons sequestered. Alternatively (and equivalently), an annuity of present value costs is divided by an annuity of present value tons. This alternative may be thought of as assuming that the marginal damages associated with additional units of atmospheric carbon are constant and that benefits (avoided damages) and costs are to be discounted at the same rate.[9]

One of the major differences between the flow summation (stock-change) method and the levelized/discounting approach is that the former implies that there is no value to temporary storage. So, for example, under the flow summation method a ton of carbon captured today and released in 100 years would have no value. In contrast, under the discounting approach, a ton of carbon stored for 100 years would be nearly as valuable as a ton of carbon sequestered permanently.

In general, the earlier among the eleven studies synthesized in this report used the levelized cost approach for carbon accounting, whereas the more recent studies have employed the discounting approach (see Table 2, p.4).

Effects of Discount Rates. Because of the long time horizons relevant for analyzing the costs of carbon sequestration—typically spanning 100 years or more (see Figure 2, p.10)—it is important to consider the sensitivity of results to assumed discount rates. Conceptually, changing the discount rate can have three different types of effects on cost estimates. First, depending upon the nature of the analysis, many economic variables may take on different values. One example is the economic trade-off between foregone future forest revenues and the immediate windfall that would result from harvesting a forest now. As the discount rate increases, immediate harvesting becomes more attractive. Second, and closely related to the example above, the rotation period may be responsive to changes in the discount rate. The extent of the response will depend on the range of discount rates analyzed and the sensitivity of stumpage values (i.e., values of standing timber) to changes in rotation period. The effect can, in principle, be substantial. Finally, the discount rate affects the present-value of future carbon flows in terms of equivalent tons sequestered per acre (Table 6).

The impact of changing discount rates is particularly interesting in the context of three output variables: marginal sequestration costs, induced forestation, and induced carbon sequestration. Newell

Table 6

Effects of Discount Rate on Estimated Carbon Sequestration Rates

	Alternative Discount Rates			
Carbon Sequestration and Emissions	2.5%	5.0%	7.5%	10.0%
Natural Regrowth of Mixed Stand				
Periodic Harvest	61.90	43.36	30.63	22.72
No Periodic Harvest	91.48	50.59	32.85	23.52
Pine Plantation				
Periodic Harvest	54.66	41.05	30.76	23.75
No Periodic Harvest	80.68	49.99	34.33	25.25
Natural Regrowth of Mixed Stand				
Deforestation	54.28	51.83	50.99	50.55

Source: Newell and Stavins (2000), Table IV. Results are for Mississippi Delta states only.

Note: All values are present-value equivalent carbon sequestration (tons per acre).

and Stavins (2000) report the results of a sensitivity analysis carried out for two scenarios involving pine plantations—one in which the plantation is periodically harvested and one in which there are no periodic harvests (Table 7). First, they found that as the discount rate increased (from 2.5 percent to 10 percent), marginal sequestration costs increased steadily, as expected. The simplest explanation for this effect is that the present value of sequestration decreases with higher discount rates. The magnitude of the impact is similar to that reported by Richards et al. (1993), who found that raising the discount rate in their analysis from 3 to 7 percent nearly doubled marginal costs.

Table 7

Effects of Discount Rate on Cost and Quantity of Carbon Sequestration

	Alternative Discount Rates			
Carbon Sequestration and Forestation Costs and Quantities	2.5%	5.0%	7.5%	10.0%
Marginal Cost of Sequestration				
($/ton, sequestration = 5 million tons/yr)				
Periodic Harvest	33	39	58	92
No Periodic Harvest	18	27	46	81
Forestation Relative to Baseline				
(1000 acres, subsidy/tax = $50/acre)				
Periodic Harvest	1,467	2,787	4,368	6,131
No Periodic Harvest	1,453	2,763	4,336	6,092
Sequestration Relative to Baseline				
(1000 acres, subsidy/tax = $50/acre)				
Periodic Harvest	3,271	4,219	4,301	3,928
No Periodic Harvest	4,460	5,099	4,832	4,242

Source: Newell and Stavins (2000), Table V, for pine plantation. Results are for Mississippi Delta states only.

Next, Newell and Stavins found that as the discount rate increased, the forestation induced by a given subsidy/tax ($50/acre, in their example) also increases (Table 7). This too would be anticipated, since the up-front subsidy/tax becomes more important relative to discounted future revenue flows with the increased discount rate. Finally (and most interestingly), as the discount rate increased, the impact on induced carbon sequestration was not always in the same direction: at lower discount rates, an increase in the discount rate increased the amount of induced sequestration. But at higher interest rates, further increases had the opposite effect—decreasing carbon sequestration (Table 7). Two factors account for this result: land-use changes and the per-acre present-value equivalent of carbon sequestration over the life of the project. At first, the land-use effect is dominant, so as discount rates rise and the present subsidy gains value relative to foregone future agricultural returns there is more induced forestation and hence more sequestration. But eventually, as discount rates rise to higher levels, the effect of smaller present values of carbon sequestration becomes dominant. At this point the present value of carbon sequestered begins to decrease with higher discount rates. The effect is particularly dramatic in the case of no periodic harvesting, since the fall in present-value carbon equivalents is greatest in that case.

In this study we have applied a 5 percent discount rate in normalizing the results from different studies. This choice is largely pragmatic—a 5 percent discount rate was employed by many of the studies analyzed. It also represents a social discount rate that has been commonly employed in the analysis of public projects and policies.

F. Policy Instruments Used to Achieve Carbon Sequestration

Policy makers could attempt to produce or induce increases in forest carbon sequestration in a variety of ways. The government could provide subsidies (in the form of payments, tax credits, or cost sharing) to private landowners for adopting practices that are known to increase carbon stocks; alternatively the government could tax undesirable land-use changes or practices, establish a tradable carbon-rights system, or otherwise regulate activities on private lands. In addition, the government could expand its own forest plantations on public lands (Richards, Sampson and Brown, 2004).

The design of a carbon sequestration program will have significant effects on the costs of sequestration. Alternative program designs will differ in the degree to which landowner practices align with government intentions and will incur very different direct and indirect costs related to implementation and administration.

In aligning the interests of private parties with those of government, it is generally most cost-effective to provide outcome-based incentives. In this context, that means rewarding actual increases in carbon sequestration rather than, for example, practices that might be more or less correlated with increased sequestration. By rewarding outcomes, government maximizes the incentive for individuals to innovate and select practices that match local conditions. Conversely, policies that depart from directly rewarding carbon sequestration are likely to create inefficiencies and will therefore be less cost-effective. For example, a policy that provided payments simply for planting trees on agricultural land would not differentiate among high-productivity and low-productivity lands or among farmers who are more or less skilled.

The cost of a carbon sequestration program is also affected by implementation costs which can include costs related to marketing the program and educating the public, establishing the conditions for payments (for example, negotiating contracts, processing claims for subsidies, or assessing tax liabilities), and monitoring the compliance and performance of landowners with respect to carbon sequestration practices or quantities. Good program design can significantly affect these direct implementation costs. In general, performance measures based on inputs to carbon sequestration (for example, the quantity of land or type of practice) are relatively easy to monitor, whereas it can be problematic for the government to estimate and monitor the amount of carbon sequestered relative to an assumed reference case. Thus, there may be a significant trade-off between keeping implementation costs low and pursuing a theoretically more cost-effective, outcome-based program design (Richards et al., 2004).

The studies described below assume a variety of implementation mechanisms, including the government renting (Moulton and Richards, 1990) or buying (Richards et al., 1993; Richards, 1997a) land and planting tree stands, and using taxes and subsidies to discourage forest clearing and promote forestation (Stavins, 1999; Lubowski et al., 2003). None of the studies attempted to differentiate among hypothetical implementation approaches in terms of their effects on the costs of sequestration.

The discussion below assumes a program design that effectively taxes the release of carbon from land-use changes while providing a subsidy for carbon capture. In all cases, program costs are an estimate of the additional social costs for the sequestration program relative to the reference case without a program (i.e., the status quo). Moreover, though the discussion is couched in terms that reflect a tax and subsidy regime, it would be equally valid to substitute a marketable allowance and offset program with auctioned or grandfathered allowances, or even a program in which the government undertakes forest planting and maintenance activities directly.

IV. Empirical Analysis of the Costs of Carbon Sequestration

Given the number of factors that affect the cost and quantity of potential forest carbon sequestration, it should not be surprising that cost studies to date have produced a broad range of estimates. In this part of the report, we review eleven such studies with the aim of synthesizing their results to develop a best estimate of the cost of supplying forest-based carbon sequestration in the United States. Summary statistics for these eleven studies, including geographic coverage and the quantity and costs of sequestered carbon—both as originally reported and normalized for comparative purposes—are provided in Table 8.

A handful of previous analyses have surveyed carbon sequestration cost studies. For example, Sedjo et al. (1995) undertook a general overview of the carbon sequestration cost literature available to that date, and Richards and Stokes (2004) explored differences in both the methodology and data used in various studies. Neither of those works, however, attempted to synthesize the results of past studies to

Table 8

Carbon Sequestration **Cost Studies** Included in Normalization

Authors	Scope	Potential Quantity Reported (short tons C/year)	Range of Costs Reported ($/short ton C)	Potential Normalized Quantity (short tons C/year)	Range of Normalized Costs ($/short ton C)
Moulton and Richards (1990)	National	809 x 10^6	5-43	809 x 10^6	5-57
Dudek and Leblanc (1990)	National	NA[a]	23.9-38.4	37.9 x 10^6	60
New York State (1991)	New York	1.2 x 10^6	14-54	75 x 10^6	8-53
Adams et al. (1993)	National	700 x 10^6	18-55	700 x 10^6	24-71
Richards, Moulton and Birdsey (1993)	National	NA[b]	8-60	448 x 10^6	11-81
Parks and Hardie (1995)	National	120 x 10^6	4-82	120 x 10^6	2-37
Alig et al. (1997)	National	44 x 10^6	22	44 x 10^6	27
Richards (1997a)	National	495 x 10^6	9-125	495 x 10^6	10-143
Stavins (1999)	Delta States	13.9 x 10^6	0-664	722 x 10^6	0-816
Plantinga, Maudlin and Miller (1999)	Maine, South Carolina, and Wisconsin	NA[c]	0-250	77 x 10^6	0-263
Lubowski, Plantinga, and Stavins (2003)	National	1700 x 10^6	7-275	1700 x 10^6	7-275

[a] The total quantity was not reported.

[b] Potential yield was reported as the cumulative amount of carbon over 160 years.

[c] Quantities were reported in "present ton equivalents" rather than tons per year.

narrow the range of available cost estimates. A further step was taken by Manley et al. (2003), who provided a meta-analysis (statistical examination) of carbon sequestration cost studies from around the world in an effort to assess the relative importance of various factors in affecting cost estimates. Because of the very broad range of studies included, however, that analysis provides relatively little empirical insight into the costs of carbon sequestration in the United States.

A consequence of the fact that previous studies have employed diverse methods for estimating carbon sequestration costs is that it becomes difficult to directly compare their results. For example, in their assessment of cost studies, Sedjo et al. (1995) examined reasons for the much higher cost estimates derived by Parks and Hardie (1995) relative to the estimates of Adams et al. (1993) and Moulton and Richards (1990). However, the Sedjo study did not recognize that Parks and Hardie used a definition of "dollars per ton" that was fundamentally different from that used in any other study. In fact, the cost metric used by Parks and Hardie would have been better labeled "dollars per ton per year." Similarly, the Intergovernmental Panel on Climate Change (2001) cited several cost studies in providing a range of cost estimates, thereby implicitly comparing a group of analyses with very different underlying methods and assumptions.

To narrow the useful range of estimated forest sequestration costs in the United States, we normalize the estimates from previous studies to increase their comparability. Specifically, we convert past estimates to common units of marginal cost (in 1997 dollars) by adjusting for program size (measured in tons of carbon sequestered per year), applying a consistent discount rate of 5 percent to both costs and sequestered carbon, and assuming a standardized geographic scope covering the 48 contiguous states.

A. Major Studies of U.S. Forest-Based Carbon Sequestration Costs

As noted previously, we identified eleven previous analyses of carbon sequestration costs in the United States as good candidates for comparison and synthesis (Table 8). Many more studies can be found in the literature, but most do not lend themselves to achieving our central purpose: providing practical insight into the likely costs of a large-scale forest carbon sequestration program in the United States. For example, we include only those studies that estimated sequestration costs associated with modified management of existing forests or conversion of agricultural land to forests or agroforestry in the United States. Three of the studies reviewed here—New York State (1991), Stavins (1999), and Plantinga et al. (1999)—covered only sub-regions of the United States. We normalize results from these regional studies by making an upward adjustment using the ratio of similar land in the United States to land in the study area.

Our review and synthesis does not include studies that develop global or regional estimates of carbon sequestration costs (Sedjo and Solomon, 1989; Nordhaus, 1991; Kauppi, 2001; Sohngen and Mendelsohn, 2001), or studies that provide estimates for other countries, such as Canada (van Kooten et al., 1992, 2000), the Netherlands (Slangen and van Kooten, 1996), Tanzania (Makundi and Okitingati, 1995), Mexico (Masera et al., 1995; De Jong et al., 2000), India (Ravindranath and Somashekhar, 1995), China (Xu, 1995), Thailand (Wangwacharakul and Bowonwiwat, 1995), Argentina (Sedjo, 1999), and Costa Rica (Kerr et al., 2003).

The vast majority of carbon sequestration cost studies conducted to date—including the first eight of the eleven studies reported in Table 8—employ "bottom-up" or "engineering cost" methods, as described above in Section III.B. The last three studies in Table 8 used revealed-preference approaches, applying an econometric analysis of actual land-use changes to estimate relationships between land-use choices and relative prices in the forest and agricultural sectors, and simulating econometrically-based sequestration cost functions.

B. Synthesis of Cost Estimates

As the standard for normalizing results across the eleven sets of cost estimates reviewed here, we employ the most recent study in our sample: the econometric/simulation analysis by Lubowski, Plantinga and Stavins (2003). Any of the other studies could have been used for this purpose without changing the fundamental conclusions of our analysis—it was simply convenient and reasonable to use the most current study as the standard for normalization because of its recent vintage.

First, all costs were converted to 1997 dollars using the Consumer Price Index.[10] Second, in cases where sequestration quantities were estimated in terms other than tons per year, these estimates were converted to equivalent annual carbon flows over 100-year time horizons. For example, Richards et al. (1993) estimated costs as a function of total cumulative tons of carbon sequestered over a 160-year period, while Parks and Hardie (1995) estimated costs on the basis of only 10 years of sequestration. The figures from both studies were first converted to "present ton equivalents" (that is, the amount of carbon sequestered in the present that would be equivalent to the reported flow, assuming constant marginal benefits of sequestration). Then, the present ton equivalent estimates were converted to equivalent annual cost over a 100-year time horizon. Because of discounting, equivalent annual cost (EAC) is not simply equal to the present value divided by the number of years in the time horizon, but rather has the following relation to present value cost (PVC), where r is the discount rate and T is the time horizon:

$$\text{EAC} = \text{PVC} * \left[\frac{r}{1-(1+r)^{-T}}\right]$$

Note that for an infinite planning horizon, EAC = (PVC)r. Likewise, the results from Plantinga et al. (1999), which were reported in present value ton equivalents, were annualized over a 100-year period.

Third, where possible, estimates were adjusted by applying a consistent 5 percent discount rate to both costs and benefits. For example, Moulton and Richards (1990) apply a 10 percent discount rate, while Dudek and LeBlanc (1990) apply an 8.5 percent rate—for this analysis, results from both studies were recalculated using a 5 percent rate. In a few cases, it was not possible to adjust the discount rate with the information provided. Specifically, results from Adams et al. 1993, Parks and Hardie 1995, and Alig et al. 1997 were not recalculated for a 5 percent discount rate. This is not as large a problem as it might seem. Cost estimates in the latter two analyses were originally derived with a discount rate of 4 percent, and so adjusting the discount rate would not have had much effect in any case.

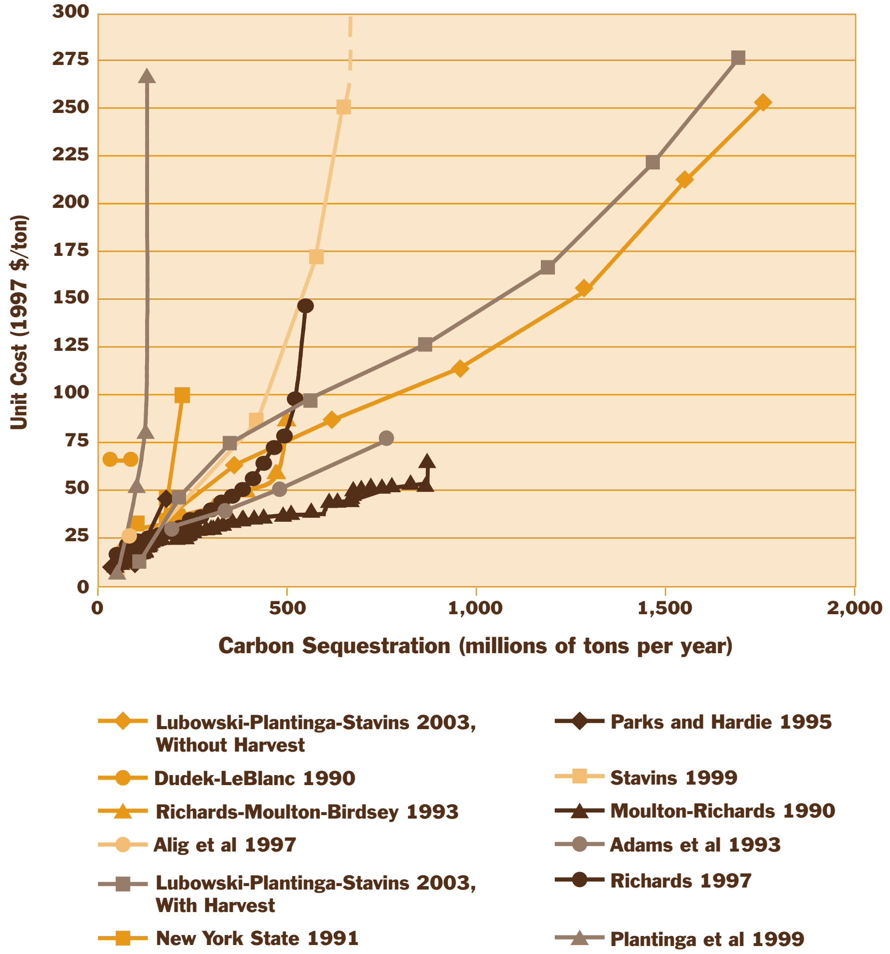
Fourth, the results of three studies that were geographically limited to a particular U.S. region were extrapolated to the national level. For example, the New York State (1991) study was limited to a total of 1.5 million acres, comprised of 500,000 acres each of public land, private land, and existing forest. Using scaling factors developed from data in Moulton and Richards (1990),[11] the potential land area (and hence quantity of carbon) in the New York State (1991) study was scaled up to the national level. Similarly, for the Stavins (1999) study of 36 counties in the Mississippi Delta States (Arkansas, Louisiana, and Mississippi), a scaling factor (of 52.0) was used for the ratio of national farm acreage to farm acreage in the Delta states. For the Plantinga et al. (1999) study, estimated cost curves for three states—Maine, South Carolina, and Wisconsin—were horizontally summed into a single aggregate cost curve. This aggregate cost curve was then scaled up to the national level using the ratio of national cropland acreage to cropland acreage in the three states (a factor of 27.18).[12] Implicit in these extrapolations is the simplifying assumption that relevant characteristics of the respective regions are typical of the entire nation. Clearly, this is not the case, and so we later remove these three studies from one of our normalizations.

The initial set of normalized results from all eleven studies is presented in Figure 4. As anticipated, the process of normalization leads to a significant narrowing of the range of costs reported in these studies, compared with the original results reported in Table 8. In fact, the normalized results from these diverse studies are in most cases quite comparable. The exception, of course, is where regional results were extrapolated to the entire country. Given that the assumptions required for this extrapolation are problematic, our final synthesis of estimated marginal costs for forest-based carbon sequestration in the United States relies exclusively upon the eight studies from Table 8 that are national in scope. The results are portrayed in Figure 5.

It requires a degree of judgment to characterize the dispersion of results as being "narrow" or "broad," but we observe that the dispersion reported in Figure 5 is no greater than that typically associated with cost estimates for carbon abatement through fuel switching and energy efficiency improvements.[13] The range of marginal cost estimates is particularly narrow up to 300 million tons of carbon sequestered per year, with nearly all estimates falling in the range of $25 to $75 per ton of carbon ($7.50 to

Figure 4

Normalized Marginal Cost of Carbon Sequestration, All Studies

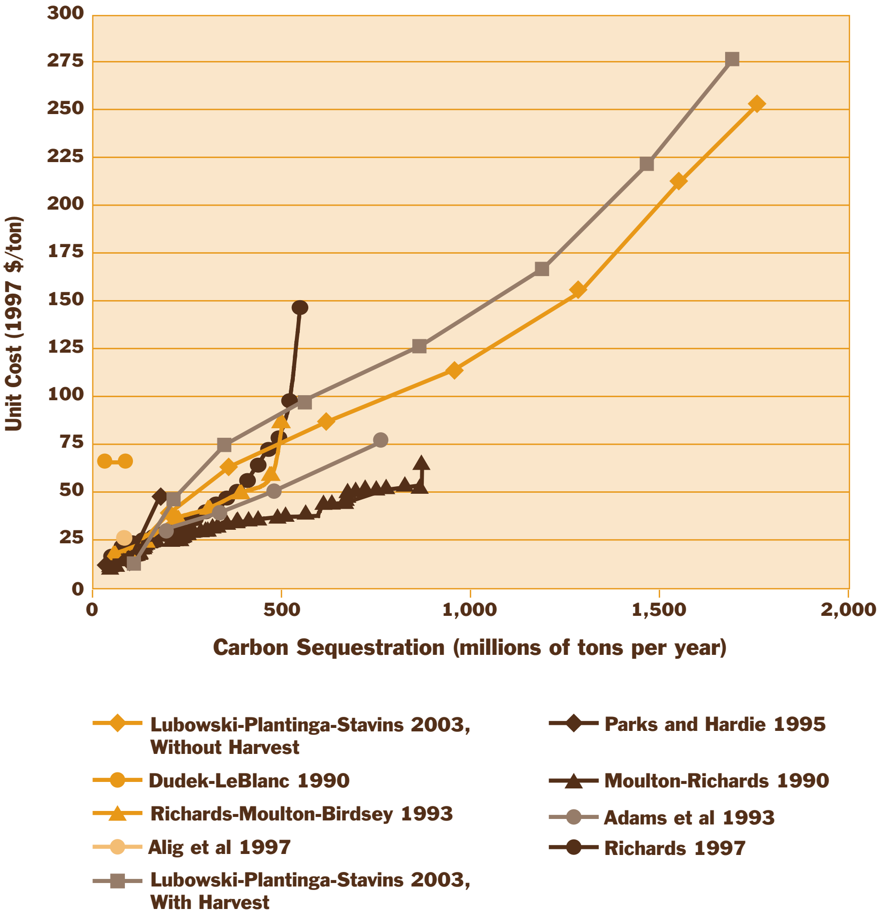


\$22.50 per metric ton of CO_2-equivalent). Beyond this, the normalized results suggest that it may be possible to sequester considerably more than 300 million tons of carbon per year—perhaps as much as 500 million to one billion tons per year. The range of cost estimates is greater—but not much greater—for these more ambitious sequestration goals. At 600 million tons per year, estimates of marginal cost per ton of carbon include \$27 (Moulton and Richards, 1990), \$62 (Adams et al., 1993), \$85 (Lubowski et al., 2003, without harvesting), and \$102 (Lubowski et al., 2003, with harvesting).

Finally, we turn to a key question for policy makers: is it possible to derive from the available studies a single estimate of likely costs for forest-based carbon sequestration in the United States? Given the different methods used by different investigators and given the substantial uncertainties associated with each of their estimates, a single summary function would be misleading if it were taken as synthesizing all that is known from the component analyses. Instead, in the interests of making our results more transparent and accessible, we calculate a simple “central tendency” of the component marginal cost functions and present this central tendency as an additional result of our analysis.

Figure 5

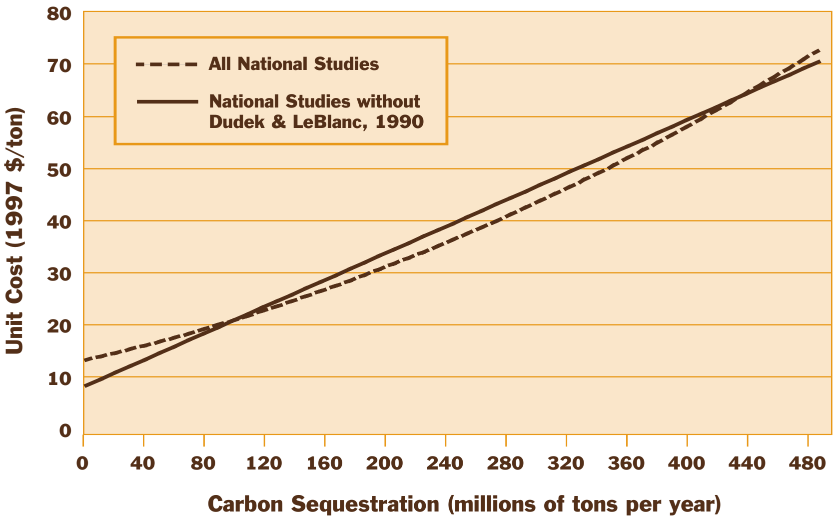
Normalized Marginal Cost of Carbon Sequestration, National Studies



Specifically, we have taken the nine national-level marginal cost functions from Figure 5 and identified points along each curve at sequestration intervals of 10 million tons (the y-axis in Figure 5) within the ranges for which each of the respective cost functions were originally developed. Restricting our attention to an overall range from zero to 500 million tons of annual carbon sequestration,[14] this exercise resulted in 296 data points. Simple econometric estimation techniques were then used to identify the best fitting curve through these points—our measure of central tendency. As can be seen in Figure 6, the result indicates a fairly linear relationship between unit cost and amount of carbon sequestered within the range considered (i.e., up to 500 million tons per year). (As is apparent from Figure 5, the relationship may be considerably less linear at higher levels of sequestration.) Nevertheless, a quadratic function provided the best fit to these data; it is illustrated by the dashed line in Figure 6 which represents the estimated central tendency of results from all the cost studies surveyed here.

Figure 6

Central Tendency of Normal Marginalized Cost of Carbon Sequestration



The study by Dudek and LeBlanc (1990) is one of the oldest and simplest of the national carbon sequestration studies we have included in this analysis and was limited in its original scope. Moreover, an examination of Figure 5 suggests that the Dudek and LeBlanc results have a considerable effect on our estimate of central tendency for low levels of sequestration. To eliminate any bias that might thereby be introduced, particularly at low levels of sequestration, we performed the same econometric estimation without the five data points from Dudek and LeBlanc. The solid line in Figure 6, also quadratic but even closer to linear, illustrates the result of this recalculation and represents our estimate, based on the central tendency of cost data from more recent studies, of the cost of supplying forest-based carbon sequestration in the United States.

V. Conclusions

When and if the United States chooses to implement a domestic GHG reduction program and/or joins in any international efforts to mitigate climate change, it will be necessary to decide whether carbon sequestration policies should be part of the domestic portfolio of compliance activities. The potential opportunities and associated costs of carbon sequestration will presumably be a major criterion in determining its role and so it is important to assess the cost of supplying forest-based carbon sequestration in the United States. Failure to include carbon sequestration as a mitigation option in economic models will lead to over-estimation of the cost of reducing net GHG emissions. However, including carbon sequestration in a naïve manner could produce misleading results as well.

In this report, we have surveyed major previous studies of sequestration, examining the factors that have affected their cost estimates and synthesizing their results. The assumptions that stand out as being particularly important in previous cost estimates include those concerning biological factors such as species, forestry practices, and carbon yield patterns; the opportunity cost of land; management practices; methods of disposition of biomass; relevant prices; and policy instruments used to achieve carbon sequestration.

We identified eleven previous analyses of carbon sequestration costs in the United States as particularly good candidates for comparison and synthesis and normalized their findings to narrow the useful range of estimated costs and allow for consistent comparisons. The normalization included adjustments for constant year dollars, use of identical discount rates, adjustments to scale for identical (national) geographic scope, and consistent reporting in equivalent annual costs. As anticipated, normalizing results across studies led to a significant narrowing of the range of estimated marginal cost functions (Figure 4). This range was subsequently narrowed further by excluding regional studies, since we judged the extrapolation from regional results to national estimates to be problematic. After excluding the three regional studies, our analysis shows that at 300 million tons of annual carbon sequestration nearly all supply functions fall within a marginal cost range of $25 - $75 per short ton of carbon

($7.50 - $22.50 per metric ton of CO_2-equivalent). Not surprisingly, the range increases somewhat—to $30 - $90 per ton—for programs sequestering 500 million tons annually (Figure 5).

To make our results more transparent and accessible, we also used econometric techniques to estimate the central tendency of these marginal cost functions; the resulting "best fit" cost curve is presented as an additional output of our analysis. Graphically (Figure 6), it approximates a straight line up to 500 million tons of annual sequestration at which point each additional ton of carbon sequestration costs a bit more than $70 per ton.

Three conclusions emerge from our analysis: (1) there is a broad range of possible forest-based carbon sequestration supply functions whose shape and magnitude depend on what is assumed about underlying biological and economic factors, as well as on the analytical methods used to estimate costs and supply; (2) by limiting the set of supply functions to those that come from national studies and that lend themselves to quantitative normalization, the results from previous analyses can be rendered more comparable and the range of estimated supply functions can be narrowed considerably; and (3) when a transparent and accessible approach is employed to estimate econometrically the central tendency of the individual studies making up this range of results, the resulting marginal cost function indicates that the cost of supplying forest-based carbon sequestration in the United States is nearly, though not exactly, linear up to 500 million tons per year, where marginal costs reach a bit more than $70 per ton.

The results presented in this report represent a synthesis of the best existing cost studies, not the final word on the topic. Future research could benefit from further attention to important issues of programmatic leakage (or countervailing forces) that might diminish the positive impacts of a program and thus raise the social cost of sequestration, the impermanence or reversibility of forest carbon sequestration, the broader impacts of a forest carbon sequestration program on the agriculture and forestry sectors and on public finance and tax systems, and the potential secondary costs and benefits of a carbon sequestration program with respect to, for example, natural resources such as water quality and wildlife habitat. Moreover, additional exploration is needed of the interaction between different policy mechanisms to promote sequestration (whether offset trading, agricultural subsidies for specific practices, command-and-control, or direct government production) and the ultimate opportunity costs of sequestration. In general, there may be a tradeoff between the power of incentives directly linked to desired outcomes (in this case the quantity of carbon sequestered) and the costs of implementing and monitoring a program. The optimal program design for promoting sequestration, and how that design affects the issues delineated above, merits more attention.

It is important to understand the magnitude of the hypothetical programs under consideration in this study. The amount of agricultural land involved is huge—approximately 27 million acres for a program achieving 50 million tons of sequestration per year and 148 million acres for a program achieving 300 million tons of sequestration per year. Total annual costs, based on the cost estimates developed here, would be approximately $840 million and $7.2 billion, respectively, for 50 and 300 million ton programs. Because much of this cost would occur upfront, the total social cost in present value terms may be thought of as similar to incurring a one-time cost of $17 billion to $143 billion. Needless to say, this would be a large amount for the U.S. or any other economy to absorb—financially, physically, and administratively—and so a program of this size would probably need to be implemented gradually over many years.

The estimate of carbon sequestration potential discussed in this report (i.e., up to 500 million tons per year) would require a very significant sequestration program, equivalent to about one-third of annual U.S. carbon emissions. Given that available sequestration cost estimates (at these quantity levels) are not very far above typical cost estimates for emissions abatement through fuel switching and energy efficiency improvements, it follows that a domestic carbon sequestration program (assuming such a program can be designed and implemented) ought to be included in a cost-effective portfolio of compliance strategies if and when the United States chooses to implement a domestic GHG reduction program.

References

Adams, R., D. Adams, J. Callaway, C. Chang, and B. McCarl. 1993. “Sequestering Carbon on Agricultural Land: Social Cost and Impacts on Timber Markets.” *Contemporary Policy Issues* XI(1): 76-87.

Alig, R., D. Adams, B. McCarl, J.M. Callaway, and S. Winnett. 1997. “Assessing Effects of Mitigation Strategies for Global Climate Change with an Intertemporal Model of the U.S. Forest and Agriculture Sectors.” *Environmental and Resource Economics* 9: 259-274.

Cropper, M.L., and W.E. Oates. 1992. “Environmental Economics: A Survey.” *Journal of Economic Literature* 30: 675-740.

De Jong, B., R. Tipper, and G. Montoya-Gomez. 2000. “An Economic Analysis of the Potential for Carbon Sequestration by Forests: Evidence from Southern Mexico.” *Ecological Economics* 33(2000): 313-327.

Dudek, D. and A. LeBlanc. 1990. “Offsetting New CO_2 Emissions: A Rational First Greenhouse Policy Step.” *Contemporary Policy Issues* 8: 29-42.

Ellerman, A., P. Joskow, D. Harrison. 2003. *Emissions Trading in the U.S.: Experience, Lessons and Considerations for Greenhouse Gases.* Pew Center on Global Climate Change, Arlington, VA.

Energy Modeling Forum. 1995. *Reducing Global Carbon Emissions: Cost and Policy Options.* Stanford University, CA.

Fisher, B., S. Barrett, P. Bohm, M. Kuroda, J. Mubazi, A. Shah, and R. Stavins. 1996. “Policy Instruments to Combat Climate Change.” In *Climate Change 1995: Economic and Social Dimensions of Climate Change*, eds. J.P. Bruce, H. Lee, and E.F. Haites, pp. 397-439, Cambridge University Press.

Goulder, L.H. 1995. “Effects of Carbon Taxes in an Economy with Prior Tax Distortions: An Intertemporal General Equilibrium Analysis.” *Journal of Environmental Economics and Management* 29: 271-297.

Goulder, L.H. 2000. “Central Themes and Research Results in Global Climate Change Policy.” Paper prepared for the Intergovernmental Panel on Climate Change, Working Group III, Third Assessment Report. Mimeo, Stanford, CA.

Goulder, L.H. and K. Mathai. 2000. “Optimal CO_2 Abatement in the Presence of Induced Technological Change.” *Journal of Environmental Economics and Management* 39(1): 1-38.

Grübler, A., N. Nakicenovic, and W.D. Nordhaus, eds. 2002. *Technological Change and the Environment.* Washington, DC. RFF Press.

Hammitt, J. 2000. “Are the Costs of Proposed Environmental Regulations Overestimated? Evidence from the CFC Phase-out.” *Environmental and Resource Economics* 16: 281-301.

Harrington, W., R. Morgenstern, and P. Nelson. 2000. “On the Accuracy of Regulatory Cost Estimates.” *Journal of Policy Analysis and Management* 19(2): 297-332.

Intergovernmental Panel on Climate Change. 2001. *Climate Change 2001: Mitigation - Contribution of Working Group III to the Third Assessment Report of the IPCC.* Cambridge, England. Cambridge University Press.

Jaffe, A.B., R.G. Newell, and R.N. Stavins. 1999. “Energy-Efficient Technologies and Climate Change Policies: Issues and Evidence.” *Climate Issue Brief No. 19.* Washington, DC. Resources for the Future.

Jaffe, A.B., R.G. Newell, and R.N. Stavins. 2003. "Technological Change and the Environment." In *Handbook of Environmental Economics*, Volume I, eds. K.G. Mäler and J. Vincent, Chapter 11, pp. 461-516. Amsterdam. Elsevier Science.

Jaffe, A.B., S.R. Peterson, P.R. Portney, and R.N. Stavins. 1995. "Environmental Regulation and the Competitiveness of U.S. Manufacturing: What Does the Evidence Tell Us?" *Journal of Economic Literature* 33: 132-163.

Jorgenson, D.W., R.J. Goettle, P.J. Wilcoxen, and M.S. Ho. 2000. *The Role of Substitution in Understanding the Costs of Climate Change Policy.* Pew Center on Global Climate Change, Arlington, VA.

Kauppi, P. 2001. "Technological and Economic Potential of Options to Enhance, Maintain, and Manage Biological Carbon Reservoirs and Geo-engineering." Chapter 4 in *Climate Change 2001: Mitigation*, eds. B. Metz, O. Davidson, R. Swart, and J. Pan. Cambridge University Press, Port Chester, NY.

Kerr, S., S. Liu, A.S.P. Pfaff, and R.F. Hughes. 2003. "Carbon Dynamics and Land-Use Choices: Building a Regional-Scale Multidisciplinary Model." *Journal of Environmental Management* 69(1): 25-37.

Lashof, D. and D. Tirpak. 1989. *Policy Options for Stabilizing Global Climate; Report to Congress.* Volume II. United States Environmental Protection Agency, Washington, DC.

Lubowski, R.N., A.J. Plantinga, and R.N. Stavins. 2003. *Land Use Change and Carbon Sinks: Econometric Estimation of the Carbon Sequestration Supply Function.* Working Paper. John F. Kennedy School of Government, Harvard University, Cambridge, MA.

Makundi, W. and A Okitingati. 1995. "Carbon Flows and Economic Evaluation of Mitigation Options in Tanzania's Forest Sector." *Biomass and Bioenergy*, 8(5): 381-393.

Manley, J., G.C. van Kooten, and T. Smolak. 2003. *How Costly are Carbon Offsets? A Meta-Analysis of Carbon Forest Sinks.* Working Paper, University of California, Berkeley.

Marland, G. 1988. *The Prospects of Solving the CO_2 Problem through Global Reforestation.* Report DOE/NBB-0082 U.S. Department of Energy, Washington, DC.

Masera, O., M. Bellon, G. Segura. 1995. "Forest Management Options for Sequestering Carbon in Mexico" *Biomass and Bioenergy*, 8(5): 357-368.

Metz, B., O. Davidson, R. Swart, and J. Pan. 2001. *Climate Change 2001: Mitigation.* Cambridge University Press, Port Chester NY.

Moulton, R., and K. Richards. 1990. *Costs of Sequestering Carbon Through Tree Planting and Forest Management in the United States.* General Technical Report WO-58, U.S. Department of Agriculture, Washington, DC.

New York State. 1991. *Analysis of Carbon Reduction in New York State.* Report of the New York State Energy Office, in consultation with NYS Department of Environmental Conservation and NYS Department of Public Service. NYS Energy Office, New York.

Newell, R.G. and R.N. Stavins. 2000. "Climate Change and Forest Sinks: Factors Affecting the Costs of Carbon Sequestration." *Journal of Environmental Economics and Management*, 40(3): 211-235.

Nordhaus, W. 1991. "The Cost of Slowing Climate Change: A Survey." *The Energy Journal* 12(1): 37-65.

Palmer, K., W.E. Oates, and P.R. Portney. 1995. "Tightening Environmental Standards: The Benefit-Cost or the No-Cost Paradigm?" *Journal of Economic Perspectives* 9(4): 119-132.

Parks, P. 1995. "Explaining 'Irrational' Land Use: Risk Aversion and Marginal Agricultural Land." *Journal of Environmental Economics and Management* 28(1): 34-47.

Parks, P., and I. Hardie. 1995. "Least-Cost Forest Carbon Reserves: Cost-Effective Subsidies to Convert Marginal Agricultural Land to Forests." *Land Economics* 71(1): 122-136.

Pindyck, R.S. 1991. "Irreversibility, Uncertainty, and Investment." *Journal of Economic Literature* 29(3): 1110-1152.

Plantinga, A. 1997. "The Costs of Carbon Sequestration in Forests: A Positive Analysis." In *Economics of Carbon Sequestration in Forestry*, R.A. Sedjo, N. Sampson, and J. Wisniewski, eds., pp. 269-277. New York: CRC Press.

Plantinga, A. and T. Mauldin. 2000. *A Method for Estimating the Cost of CO_2 Mitigation through Afforestation*. Draft paper. Oregon State University.

Plantinga, A., T. Mauldin, and D. Miller. 1999. "An Econometric Analysis of the Costs of Sequestering Carbon in Forests. *American Journal of Agricultural Economics* 81(4): 812-24.

Porter, M.E. and C. van der Linde. 1995. "Toward a New Conception of the Environment-Competitiveness Relationship." *Journal of Economic Perspectives* 9(4): 97-118.

Ravindranath, N. and B. Somashekhar. 1995. "Potential and Economics of Forestry Options for Carbon Sequestration in India," *Biomass and Bioenergy* 8(5): 323-336.

Reilly, J., H. Jacoby, and R. Prinn. 2003 *Multi-Gas Contributors to Global Climate Change: Climate Impacts and Mitigation Costs of Non-CO_2 Gases*, Pew Center on Global Climate Change, Arlington VA.

Richards, K.R. 1997a. *Estimating Costs of Carbon Sequestration for a United States Greenhouse Gas Policy*. Charles River Associates, Boston, MA.

Richards, K.R. 1997b. "The Time Value of Carbon in Bottom-up Studies." *Critical Reviews in Environmental Science and Technology* 27: S279-S292.

Richards, K.R., R. Moulton and R. Birdsey (1993); "Costs of Creating Carbon Sinks in the U.S.," *Energy Conservation and Management*, 34(9-11): 905-912.

Richards, K.R., and C. Stokes. 2004. "A Review of Forest Carbon Sequestration Cost Studies: A Dozen Years of Research." *Climatic Change*, 63(1-2): 1-48.

Richards, K.R., R.N. Sampson, and S. Brown. 2005. *Agricultural and Forest Lands: Carbon Strategies for the United States*. Forthcoming report for the Pew Center on Global Climate Change, Arlington VA.

Sedjo, R. 1999. *Potential for Carbon Forest Plantations in Marginal Timber Forests: The Case of Patagonia, Argentina.* Discussion Paper 99-27, Resources for the Future, Washington, DC.

Sedjo, R., and A. Solomon. 1989. "Greenhouse Warming: Abatement and Adaptation." In *RFF Proceedings*, eds. P. Crosson, J. Darmstadter, W. Easterling, and N. Rosenberg. July 1989, pp. 110-119.

Sedjo, R., N. Sampson, and J. Wisniewski, eds. 1997. *Economics of Carbon Sequestration in Forestry*. New York, CRC Press.

Sedjo, R., J. Wisniewski, A. Sample, and J. Kinsman. 1995. “The Economics of Managing Carbon via Forestry: Assessment of Existing Studies.” *Environmental and Resource Economics* 6: 139-165.

Slangen, L., and G.C. van Kooten. 1996. *Economics of Carbon Sequestration in Forests on Agricultural Land in the Netherlands*. Draft paper. University of Victoria, British Columbia.

Sohngen, B., and R. Mendelsohn. 2001. *Optimal Forest Carbon Sequestration*. Draft paper. The Ohio State University.

Stavins, R.N. 1997. “Policy Instruments for Climate Change: How Can National Governments Address a Global Problem?” *The University of Chicago Legal Forum*, pp. 293-329.

Stavins, R.N. 1999. “The Costs of Carbon Sequestration: A Revealed-Preference Approach.” *American Economic Review*, 89: 994-1009.

Stavins, R.N. 2001. “Economic Analysis of Global Climate Change Policy: A Primer.” In *Climate Change: Science, Strategies, and Solutions*, eds. E. Claussen, V.A. Cochran, and D.P. Davis. Boston, MA Brill Publishing.

Stavins, R.N. 2003. “Experience with Market-Based Environmental Policy Instruments.” In *Handbook of Environmental Economics*, Volume I, eds. K.G. Mäler and J. Vincent, Chapter 9, pp. 355-435. Amsterdam, Elsevier Science.

United Nations. 1997. “United Nations Framework Convention on Climate Change.” A/AC.237/18 (Part II)/Add.I and A/AC.237/18 (Part II/Add.1/Corr.1), New York.

U.S. Council of Economic Advisers. 2001. *Economic Report of the President*. Washington, DC., U.S. Government Printing Office.

U.S. Department of Agriculture. 1995. *Farms and Land in Farms: Final Estimates 1988-1992*. Statistical Bulletin Number 895, National Agricultural Statistics Service, Agricultural Statistics Board.

van Kooten, G., B. Stennes, E. Krcmar-Nozic, and R. van Gorkom. 2000. “Economics of Afforestation for Carbon Sequestration in western Canada.” *The Forestry Chronicle* 76(1): 165-172.

van Kooten, G., L. Arthur and W. Wilson. 1992. “Potential to Sequester Carbon in Canadian Forests: Some Economic Considerations.” *Canadian Public Policy* XVIII(2): 127-138.

Wangwacharakul, V. and R. Bowonwiwat. 1995. “Economic Evaluation of CO_2 Response Options in the Forestry Sector: The Case of Thailand.” *Biomass and Bioenergy*, 8(5): 293-308.

Weyant, J. 2000. *An Introduction to the Economics of Climate Change Policy*. Pew Center on Global Climate Change, Arlington, VA.

Xu, D. 1995. “The Potential for Reducing Atmospheric Carbon by Large-Scale Afforestation in China and Related Cost/Benefit Analysis.” *Biomass and Bioenergy*, 8(5): 337-344.

Endnotes

1. An equally important issue—how to implement a carbon sequestration program—is only addressed tangentially in this paper. For a fuller treatment of program design considerations, see Richards, Sampson and Brown (2005).

2. The notion that environmental regulation can foster economic growth is a controversial one among economists. For a debate on this proposition, see Porter and van der Linde (1995); and Palmer et al. (1995).

3. For an analysis of the importance of such substitution in the assessment of climate change policies, see Jorgenson et al. (2000).

4. For a comprehensive review of experiences with market-based instruments for environmental protection, see Stavins (2003).

5. For a broader assessment of economic dimensions of forest carbon sequestration, see Sedjo et al. (1997).

6. In Section III.D, we discuss the effects of harvesting on rates of carbon sequestration, the results of which are also exhibited in Figure 2.

7. This may seem to be at odds with estimates employed by Plantinga et al. (1999) and Stavins (1999), who employed estimated *cumulative* uptakes of 7.3 to 17.8 tons per acre. But those two studies provide their estimates in "present ton equivalents," meaning that tons of carbon accruing later in time are discounted.

8. The sequestration cost figures reported here are in dollars per short ton of carbon unless otherwise reported. To convert these costs to dollars per metric ton of carbon, multiply the reported costs by a factor of 1.1. To convert the figures to carbon dioxide equivalents (CO_2-e) multiply the reported costs by 0.272.

9. Such an assumption of constant marginal benefits is approximately correct if damages are essentially proportional to the rate of climate change, which many studies have asserted. If the marginal damages of carbon emissions were expected to change at some rate g over time, an appropriate modification could entail reducing the discount rate for carbon by the rate g. For monotonically increasing sequestration time profiles this modification would raise the present value of tons of carbon and lower the marginal cost of carbon sequestration if marginal damages were growing over time (i.e., $g>0$); it would do the opposite if damages were expected to fall. For non-monotonic sequestration paths, such as those involving periodic harvesting, the effect depends on the specific shape of the path; $g>0$ could in principle raise or lower the present value of carbon.

10. Created from Table B60, All Items (CPI-U), U.S. Council of Economic Advisers (2001).

11. From Moulton and Richards (1990), New York State has 1.715 million dry cropland acres suitable for planting out of the U.S. total of 117.3 million acres, that is, 1.46 percent of suitable cropland is located in New York State. Assume that the ratio is the same for wet cropland and pastureland. For forest management, New York State has 2.0 million acres suitable for treatment out of a total of 79.0 million acres, or 2.53 percent. The factors for scaling up the New York State (1991) study are simply the reciprocals of these percentages. This leaves the question of public lands. For this normalization exercise, we applied the same ratio to public lands as to private lands.

12. Data are from Table 4, of the 1992, U.S. Department of Agriculture Economics and Statistics System, available at http://jan.mannlib.cornell.edu/data-sets/land/89003/.

13. See, for example, Energy Modeling Forum (1995); and Metz et al. (2001).

14. We restrict ourselves to the range up to 500 million tons per year, because only three of the original studies extended beyond that point and because it strains credulity to examine a U.S. carbon sequestration program beyond that point, which is itself equivalent to 30 percent of U.S. total annual CO_2 emissions.

notes

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This report analyzes the important role of forest-based sequestration for cost-effective mitigation of global climate change. The Pew Center on Global Climate Change was established by the Pew Charitable Trusts to bring a new cooperative approach and critical scientific, economic and technical experience to the global change debate. We intend to inform this debate through wide-ranging analyses that will add new facts and perspectives in four areas: policy (domestic and international), economics, environment, and solutions.

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