A REVIEW OF FOREST CARBON SEQUESTRATION COST STUDIES: A DOZEN YEARS OF RESEARCH

KENNETH R. RICHARDS [1] and CARRIE STOKES [2]

[1] *School of Public and Environmental Affairs, Indiana University, 1315 E. Tenth Street, Bloomington, IN 47405-1701, U.S.A.*
E-mail: kenricha@indiana.edu
[2] *U.S. Agency for International Development, Washington, D.C., U.S.A.*

Abstract. Researchers have been analyzing the costs of carbon sequestration for approximately twelve years. The purpose of this paper is to critically review the carbon sequestration cost studies of the past dozen years that have evaluated the cost-effectiveness of the forestry option. Several conclusions emerge. While carbon sequestration cost studies all contain essentially the same components they are not comparable on their face due to the inconsistent use of terms, geographic scope, assumptions, program definitions, and methods. For example, there are at least three distinct definitions for a 'ton of carbon' that in turn lead to significantly different meanings for the metric 'dollars per ton of carbon'. This difference in carbon accounting further complicates comparison of studies. After adjusting for the variation among the studies, it appears that carbon sequestration may play a substantial role in a global greenhouse gas emissions abatement program. In the cost range of 10 to 150 dollars per ton of carbon it may be possible to sequester 250 to 500 million tons per year in the United States, and globally upwards of 2,000 million tons per year, for several decades. However, there are two unresolved issues that may seriously affect the contribution of carbon sequestration to a greenhouse gas mitigation program, and they will likely have counteracting effects. First, the secondary benefits of agricultural land conversion to forests may be as great as the costs. If that is the case, then the unit costs essentially disappear, making carbon sequestration a no-regrets strategy. In the other direction, if leakage is a serious issue at both the national and international levels, as suggested by some studies, then it may occur that governments will expend billions of dollars in subsidies or other forms of incentives, with little or no net gain in carbon, forests or secondary benefits. Preliminary results suggest that market interactions in carbon sequestration program analyses require considerably more attention. This is especially true for interactions between the forest and agricultural land markets and between the wood product sink and the timber markets.

1. Introduction

More than a decade ago Sedjo and Solomon (1989) published a paper speculating that it would be possible to substantially offset the world's emissions of carbon dioxide by expanding the world's forest areas.[1] Subsequent studies demonstrated that the carbon sequestration option was surprisingly cost-effective in the context of a greenhouse gas emissions stabilization plan. For example, Richards, Rosenthal et al. (1993) showed that including carbon sinks in a U.S. national policy to return emissions of carbon dioxide to 1990 levels would reduce costs by as much as 80 percent relative to a policy that addressed fossil fuel emissions only. The important

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potential role of carbon sinks has been recognized by the Kyoto Protocol to the Framework Convention on Climate Change, which includes carbon sequestration in the calculation of a country's net carbon emissions.

Could a policy to promote carbon sequestration in forests play a major role in the global effort to slow the accumulation of atmospheric carbon dioxide? Several studies over the past twelve years have analyzed the potential impact of forest carbon sink programs by estimating their cost-effectiveness and carbon sequestration capacity in a variety of settings. Table I provides a summary of the results of those analyses. The studies vary according to geographic scope. For example, Nordhaus (1991) and Sedjo and Solomon (1989) provided global analyses, Dixon et al. (1994) analyzed costs of sequestration on three continents, Alig et al. (1997), van Kooten et al. (1992), and Masera et al. (1995) considered sequestration costs in the United States, Canada, and Mexico, respectively, while Stavins (1999) and de Jong (2000) estimated costs of sequestration in the Delta States of the United States and Chiapas Mexico, respectively.

A brief examination of Table I suggests that there is tremendous potential to capture significant quantities of carbon for less than 50 dollars per metric ton (e.g., Callaway and McCarl, 1996; Adams et al., 1993). Similarly, Table I seems to indicate that carbon sequestration in developing countries may be more cost-effective than in industrialized countries (compare Wangwacharakul and Bowonwiwat (1995), Ravindranath and Somashekar (1995) and Xu (1995), with Newell and Stavins (1999), van Kooten et al. (2000) and Slangen and van Kooten (1996)).

Table I also shows, however, that even among studies that have focused on similar regions there are vastly different estimates of the costs of sequestration in forests. For example, Sedjo and Solomon (1989) suggested that a global sequestration program could capture 2,900 million tons of carbon per year at an average cost of 3.5 to 7.0 dollars per ton, while Nordhaus found less than ten percent of that potential, 280 million tons per year, and a cost that is more than an order of magnitude higher, 42 to 114 dollars per ton. Similarly, Adams et al. (1993) estimated that as much as 640 million tons of carbon could be captured each year at a marginal cost of 20 to 61 dollars per ton, while Stavins found that there might be 518 million tons per year available at a cost that ranges up to 136 dollars per ton.

As policy makers consider the role of carbon sink programs in national and global strategies to mitigate greenhouse gas emissions they will, undoubtedly, look to these and similar carbon sequestration cost studies to compare cost-effectiveness between carbon sink enhancement programs and carbon source reduction programs. They will also want to compare costs among various carbon sequestration strategies. However, the fact that analyses of apparently similar programs have led to such disparate results suggests that the consumer of these studies should practice caution in interpreting the results.

The purpose of this study is to critically review the carbon sequestration cost studies of the past dozen years that have evaluated the cost-effectiveness of the

Table I
Costs and potential quantities for carbon sequestration

Study	Region	Cost of carbon sequestration ($/ton) [a]			Potential carbon yield		
		Forest plantation	Forest management	Agroforestry	Forest plantation	Forest management	Agroforestry
Sedjo and Solomon (1989) [b]	Global	3.5–7	–	–	2,900 million tons/yr	–	–
Nordhaus (1991)	Global	42–114	–	–	280 million tons/yr	–	–
IPCC (2000)	Global	0.1–100	–	–	≤100,000 million tons		
Sohngen and Mendelsohn (2001) [c]	Global	10–188	10–188	–	1,280 million tons/yr	304 million tons/yr	–
Dixon, Schroeder and Winjum (1991)	Boreal	5–8	7	–	2,000 million tons	–	–
	Temperate	2–6	1–13	23	20,000 million tons	–	–
	Tropical	7	1–9	5	53,000 million tons	–	–
Houghton et al. (1993)	Latin America	–	–	–	2,300 million tons	13,200 million tons	49,100 million tons
	Africa	–	–	–	13,600 million tons	400 million tons	52,600 million tons
	Asia	–	–	–	1,900 million tons	15,000 million tons	18,700 million tons
Dixon et al. (1994) [d]	South America	–	–	4–41	–	–	4,550–26,6000 million tons
	Africa	–	–	4–69	–	–	21,000–30,800 million tons
	South Asia	–	–	2–66	–	–	9,100–17850 million tons
	North America	–	–	1–6	–	–	6,300–9,800 million tons
Sohngen, Mendelsohn, and Sedjo (1998)	North America/ Europe	–	–	–	7,820 million tons	–	–
	Subtropical	–	–	–	5,700 million tons	–	–
Moulton and Richards (1990)	United States	9–41	6–47	–	630 million tons/yr	110 million tons/yr	
Dudek and LeBlanc (1990)	United States	23.9–38.4	–	–	Not specified	–	–
Adams et al. (1993)	United States	20–61	–	–	640 million tons/yr	–	–
Richards, Moulton and Birdsey (1993)	United States	9–66	–	–	49,000 million tons	–	–
Parks and Hardie (1995)	United States	5–90	–	–	150 million tons/yr	–	–
Callaway and McCarl (1996)	United States	17–36	–	–	280 million tons/yr	–	–
Lewis, Turner and Winjum (1996)	United States	(16.1)	–	–	480 million tons	–	–
Alig et al. (1997)	United States	24–141	–	–	40 million tons/yr	–	–
Richards (1997a)	United States	10–150	–	–	450 million tons/yr	–	–
Adams et al. (1999) [e]	United States	15-21 [c]	–	–	43–73 million tons/yr [c]	–	–
New York State (1991)	New York State	14–54	12	–	0.8 million tons/yr	0.2 million tons/yr	–
Stavins (1999)	Delta States	0–66	–	–	7 million tons/yr	–	–
	United States	0–136	–	–	518 million tons/yr	–	–
Newell and Stavins (1999)	Delta States	0–664	–	–	13.8 million tons/yr	–	–
Plantinga et al. (1999)	Maine	0–250	–	–	2.5 million tons	–	–
	South Carolina	0–40	–	–	14 million tons	–	–
	Wisconsin	0–85	–	–	40 million tons	–	–

Table I
(Continued)

Study	Region	Cost of carbon sequestration ($/ton)[a]			Potential carbon yield		
		Forest plantation	Forest management	Agroforestry	Forest plantation	Forest management	Agroforestry
Plantinga and Mauldin (2000)	Maine	10.25–47.5	–	–	10.5 million tons	–	–
	South Carolina	4.94–22.76	–	–	47.7 million tons	–	–
	Wisconsin	9.05–38.13	–	–	193.1 million tons	–	–
van Kooten et al. (1992)	Canada	6–18	8–23	–	6 million tons/yr	13 million tons/yr	
van Kooten et al. (2000)	British Columbia & Alberta, Canada	0–50	–	–	1,000 million tons	–	–
Slangen and van Kooten (1996)	Netherlands	1810–6070	–	–	0.23–0.40 million tons/yr	–	–
Makundi and Okitingati (1995)	Tanzania	–	1.27–34.38	(3.40)–0.13	–	422 million tons	Not specified
Masera et al. (1995)	Mexico	5–11	0.3-3	–	1,400–2,000 million tons	1,500–2,300 million tons	–
De Jong, Tipper and Montoya-Gomez (2000)	Chiapas, Mexico	–	0–40	–	–	55 million tons	–
Ravindranath and Somashekhar (1995)[f]	India	0.13–1.06	0.09–1.22	0.95–2.78	3,700 million tons	2,600 million tons	2,400 million tons
Xu (1995)[g]	China	(12)–2	(2)–1	(13)–(1)	8,500 million tons	200 million tons	1,100 million tons
Wangwacharakul and Bowonwiwat (1995)	Thailand	(579)–0.92	0.9–12.5	(115)–(1.17)	Not specified	238 million tons	Not specified
Barson and Gifford (1990)	Australia	–	–	–	7 million tons/yr	–	–
Tasman Institute (1994)	New Zealand	–	–	–	5 million tons/yr	–	–
Sedjo (1999)	Patagonia, Argentina	20	–	–	Not specified	–	–
Kerr, Pfaff and Sanchez (2001)[h]	Costa Rica	–	10–30	–	–	0.128 million tons/yr	–

[a] The results of studies have been converted to metric tons and U.S. dollars to facilitate comparison. They have not been adjusted for inflation.
[b] Sedjo and Solomon (1989) do not provide a unit cost figure for carbon sequestration. The figures presented here are based on their gross cost and yield estimates treated over 40 years with a 5% discount rate on financial outlays.
[c] Sohngen and Mendelsohn (2001) provided cost estimates for a specific trajectory of carbon prices that rise over time. By the tenth decade of their scenario, when the carbon price has reached $188 per ton, there is 1.6 billion tons per year of additional carbon sequestration.
[d] These amounts of carbon are assumed to accumulate over a 50 year period.
[e] These figures include both afforestation and forest management practices.
[f] The interpretation of these figures is unclear. See discussion in text.
[g] Figures in parentheses indicate negative costs.
[h] The study reports annual carbon lease costs in the range of $0.50 to $1.50 per ton per year. Assuming a discount rate of 5%, this can be translated to a permanent storage cost of $10 to $30 per ton of sequestration.

forestry option. Several conclusions emerge. First, while full carbon sequestration cost studies all contain essentially the same components they are not comparable on their face due to the inconsistent use of terms, geographic scope, assumptions, and methods. For example there are three definitions for a 'ton of carbon' that in turn lead to significantly different meanings for the summary statistic 'dollars per ton of carbon'. Also, studies have not only used different ecosystem components and different data for carbon dioxide sequestration rates, but different formats for carbon yield, including average yield, cumulative lifetime yield, and yield curves. Moreover, there are three distinct methods for estimating the most important component of carbon sequestration costs – land opportunity costs – and some of those methods are more transparent than others. All of these differences complicate direct comparison of study results.

After adjusting for the variation among the studies, it seems that carbon sequestration could play a substantial role in a global greenhouse gas emissions abatement program. It appears that in the cost range of 10 to 150 dollars per ton of carbon[2] it may be possible to sequester 250 to 500 million tons per year in the United States, and globally upwards of 2,000 million tons per year or more. However, there are two unresolved issues that may seriously affect the contribution of carbon sequestration to a greenhouse gas mitigation program, and they will likely have counteracting effects. First, the secondary benefits of agricultural land conversion to forests may be as great as the costs. If that is the case, then the unit costs essentially disappear, making carbon sequestration a no-regrets strategy. In the other direction, if leakage is a serious issue at both the national and international levels, as suggested by some studies, then it may occur that governments will expend billions of dollars in subsidies or other forms of incentives, with no net gain in carbon, forests or secondary benefits.[3]

To circumscribe the type and scope of analyses included, this review is limited to studies that provide insight into the cost-effectiveness and potential of global, national or regional programs, policies or practices. It does not include studies of individual projects. The review starts by discussing the mechanics of cost-effectiveness studies (Section 2), interpreting the cost-effectiveness summary statistic 'dollars per ton of carbon', exploring the various measures of cost-effectiveness such as marginal, average and total costs, and considering the role of discount rates (Section 3). The discussion then turns to the sources of variation among studies with respect to the carbon yield data they employ (Section 4), their approaches to estimating land costs (Section 5), their treatment of other factors that contribute to the cost-effectiveness of the various carbon sequestration options (Section 6), and their approach to harvesting or otherwise disposing of the carbon (Section 7). Having considered the many sources of variation in cost-effectiveness analysis, the review compares and interprets the results of the studies in Table I (Section 8), discusses how future studies could be more useful to policy analysts and decision-makers (Section 9), and provides general conclusions (Section 10).

Table II

Forestry practices to increase carbon sequestration on forestland

1.	Afforestation of agricultural land
2.	Reforestation of harvested or burned timberland
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

2. Basics of Carbon Sequestration Cost-Effectiveness Studies

There are some unifying patterns among carbon sequestration cost studies. For example, all cost studies begin by identifying the geographic region to which they apply. Table I shows that studies have focused at many different geographic levels, including subnational, national, regional, and global levels.

All studies also identify at the outset forestry practices on which they focus. Table II provides a partial list of carbon sink-enhancing forestry practices. The first two practices, afforestation and reforestation, fall generally in the category of forest plantations. The next four practices are methods of modifying forest management on existing forest stands. Agroforestry is the practice of blending forestry production and agricultural production to derive synergistic benefits. This review will focus only on these three broad categories of forestry practices. Because of their unique characteristics, urban forestry and short rotation plantations for biomass energy will be left for separate review exercises.[4]

Having selected the geographic area and forestry practices for analysis, studies must also identify the scope of the hypothetical program within which the practices will be implemented. For example, Moulton and Richards (1990), Parks and Hardie (1995), and Alig et al. (1997) all examined tree planting on agricultural land in the United States. However, the tree studies assumed considerably different program designs and constraints. Moulton and Richards (1990) considered a program that would include up to 100 million hectares of land, while Parks and Hardie (1995) described a program that was limited to a present value of 3.7 billion dollars, and Alig et al. (1997) examined a program designed to sequester 40 million tons per year. If each of these analyses were designed to identify the costs of the least-cost afforestation options, *ceteris paribus*, they would all have similar costs over comparable annual carbon sequestration ranges. However, they are precluded from arriving at similar estimates of the potential amount of carbon sequestration by the differences in their assumed design constraints.

The final step in defining the boundaries of a cost-effectiveness study is to determine the baseline. The costs and effects of a carbon sequestration program must be evaluated relative to what would have happened in the absence of such a program. For example, in the relatively simple case of conversion of marginal agricultural land to forests, Moulton and Richards (1990) adopted a baseline in which the carbon content in the cropland and pastureland is static over time. This means that if carbon rises under a tree planting program, all increases are additional. In contrast, Sohngen et al. (1998) developed an elaborate baseline case for forest carbon inventories in four global regions projected over 140 years. In that baseline the sum of carbon uptake across the four regions is high the first 40 years and gradually falls to zero and below over the next century. They then posited four carbon management programs, the accomplishments of which were each measured relative to the baseline.[5]

Once carbon sequestration studies identify the geographic scope, subset of forestry practices, size of the hypothetical program, and the baseline to which costs and accomplishments will be compared in the analyses, they generally identify, for each distinct region/forestry practice combination, three key variables:

1. The suitable land area for that practice (e.g., hectares);
2. The treatment cost and land cost for the practice (e.g., in annualized costs as dollars per hectare per year) relative to the baseline; and
3. The annual carbon yield for that practice in that geographic location (e.g., tons of carbon per hectare per year) relative to the baseline.

Two critical results can be derived from these three pieces of data. The potential yield of carbon from a given practice, expressed in tons per year, can be derived by multiplying the first and third factors. The cost of carbon sequestration, expressed in dollars per ton, can be derived by dividing the second factor by the third. For a given land type i and a given practice j, the cost-effectiveness metric can be expressed as

$$\text{Unit cost} = C_{ij} = \frac{I_{ij}}{Y_{ij}}, \tag{1}$$

where C_{ij} is the dollars per ton of carbon sequestration; I_{ij}, is the net costs, in dollars per hectare, of inputs and outputs other than carbon;[6] and Y_{ij} is the net yield of carbon attributable to the new forestry treatment. I_{ij} is a function of land, labor, management, and initial treatment costs as well as harvesting expenses and revenues and external effects outside the treatment area. Y_{ij} varies according to the geographic location, the type of forestry practice, species involved, and whether harvesting is included in the forestry treatment.

The results of Equation (1) can then be combined across practices within a region to develop a supply function for carbon sequestration in that region.

The amount of suitable land area for a particular forestry practice within a geographic region is a function of the criteria that are applied. The criteria, in turn, are chosen on the basis of professional judgement and policy goals. For example, in a study of carbon sequestration costs in the United States, Moulton and Richards (1990) included all agricultural land that was economically or environmentally marginal; i.e., land that had poor soil quality or high erosion rates. Treatment costs are largely derived from past experience.

One of the perplexing aspects of interpreting carbon cost studies arises from the fact that while most studies express input costs, I_{ij}, in either present values or annual values, there is much more variation in how studies express the yield figure, Y_{ij}, in the denominator of Equation (1). The next section discusses three common approaches for calculating the cost-effectiveness of carbon sequestration projects. While the results of each are explained in terms of 'dollars per ton of carbon' they each express different concepts and can not meaningfully be compared directly (although, unfortunately, that has not prevented some analysts from trying).

3. Carbon Accounting Methods and the Discount Rate in Cost-Effectiveness Studies

One of the difficulties in comparing the results of sequestration cost studies is the lack of consistency with which they employ terms. Two of the most important concepts to clarify are those of 'dollars per ton of carbon sequestered' and 'cost curve'. Section 3.1 below discusses three fundamentally different summary statistics for 'cost per ton' that are often confused. Section 3.2 discusses the different types of cost curves and how they can lead to substantially different and often confusing results. Finally, Section 3.3 discusses the choice of discount rate and how it has affected the results of cost-effectiveness studies.

3.1. DEFINING A 'TON OF CARBON'

Carbon sequestration cost-effectiveness studies must estimate the expected accomplishments of hypothetical programs; i.e., how much carbon will be captured, when, and at what cost? Two steps are involved in this stage of the analysis: (a) assessing the physical effects of the project, whether on carbon flows or stocks; and (b) deriving a summary expression of those effects, Y_{ij} in Equation (1), that expresses those effects in a single number.

To illustrate the potential difficulty in capturing carbon effects in a single number, consider the case of forest plantations and the significant variation across different species and regions with respect to the timing of carbon uptake and storage. Figure 1 illustrates for example that while loblolly pine in the Southern Plains of the United States achieve their maximum uptake rates within two decades of establishment, black walnut forests in the Northern Plains do not achieve their

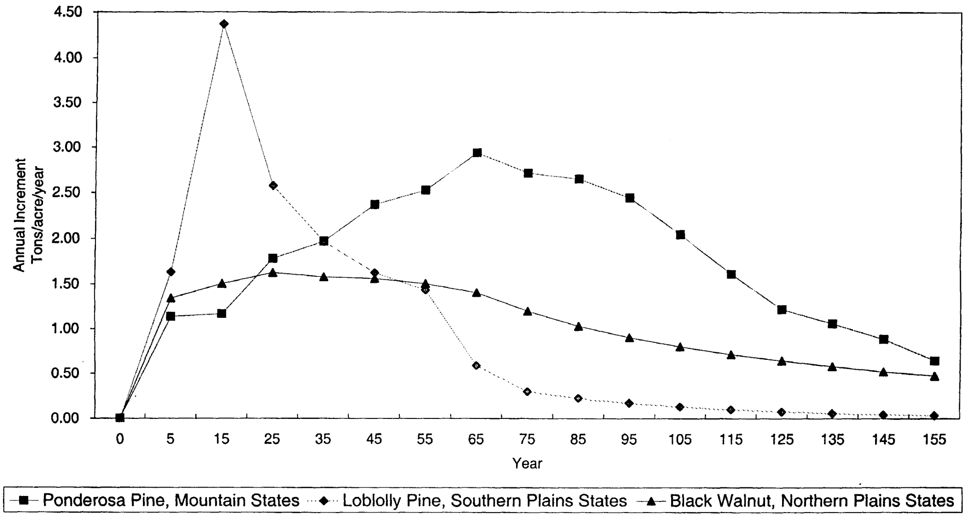

Figure 1. Carbon sequestration rates in the United States for three region/species combinations.

maximum carbon capture rate for as much as five decades after initial planting. Carbon sequestration cost studies must accommodate this dynamic variation in flows.

Analyses of carbon sequestration practices could simply identify flows of carbon over time, as in Figure 1, and stop at that. In fact, reporting the net present value of costs and the expected pattern and magnitude of carbon flows as a function of time may be the most accurate and detailed way to describe practices and their potential. However, that approach would not facilitate comparison among sequestration options or between sequestration options and other greenhouse gas mitigation options. In particular, policy-makers find it difficult to use this information to identify preferred technologies or carbon mitigation practices for greenhouse gas emissions abatement. At the other extreme, studies could supply carbon costs as a function of total carbon captured over a specified period of time without differentiating among forestry options with respect to when carbon uptake occurs within the time period. This latter approach, while simple, would not recognize the advantages that accrue from achieving earlier carbon capture.

Most studies have, in fact, adopted some type of summary statistic to describe the cost-effectiveness of the carbon sequestration practices they analyze. While the specific summary statistic has varied significantly across studies, almost all cost studies have labeled their statistic as ‘dollars per ton of carbon sequestered’. The imprecision in the use of this term has led to unfortunate confusion. Subsequent users and reviewers of these studies have generally compared the results, unaware that they may each be expressing vastly different concepts, all under the rubric of ‘dollars per ton’.

At least three different approaches for calculating dollars per ton of carbon sequestered can be identified in the literature; the 'flow summation' method, the 'average storage' method, and the 'levelization/discounting' method. Each method renders results that are considerably different than the other two. To illustrate the importance of the choice of summary statistic, the next section presents four examples of hypothetical sequestration projects. The subsequent sections then apply the three summary statistics to each of the four hypothetical practices to calculate 'dollars per ton of carbon sequestered'.

3.1.1. *Hypothetical Practices*

The following examples provide stylized illustrations of four different forestry management approaches to carbon sequestration: the 'carbon graveyard', 'delayed growth carbon graveyard', 'cycled carbon storage', and 'carbon preservation'. Assume in all cases that the net present value of all costs (land, establishment, maintenance and administration) is $1000. Sections 3.1.2 to 3.1.4 will demonstrate the differences among the three summary statistics listed above by analyzing each of these forestry management strategies.

1. *Carbon graveyard:* A new forest plantation is established to sequester carbon on converted cropland. The forest captures 2 tons of carbon per year for 50 years. Thereafter, the plantation captures no additional carbon and stands permanently without being harvested.
2. *Delayed growth carbon graveyard:* The forest plantation is established as above, but the species is slower growing initially. During the first 25 years it captures only 1 ton of carbon per year, and then increases to 3 tons per year for 25 years. Thereafter, the plantation captures no additional carbon and stands permanently without being harvested.
3. *Cycled carbon storage:* The forest plantation is established and grown as in Example 1, but in the fiftieth year it is harvested. All accumulated carbon is released to the atmosphere upon harvest, thus creating a source of emissions that partially or wholly offsets the initial carbon capture. The area is replanted and the process repeats itself.
4. *Forest preservation:* An existing forest is preserved, avoiding 100 tons of carbon emissions that would have taken place at time $t = 0$.

3.1.2. *Flow Summation Method*

The simplest approach to summarizing the cost-effectiveness of carbon sequestration projects is to divide the net present value of costs by the sum of the total tons of carbon captured, regardless of when the capture takes place. The formula for the flow summation cost-effectiveness calculation for land type i and forestry practice j is:

$$\text{Flow summation unit cost} = C_{ij}^{F} = \frac{\sum_{t=0}^{n} \frac{I_{ijt}}{(1+r)^t}}{\sum_{t=0}^{n} Y_{ijt}}, \tag{2}$$

where I_{ijt} is the cost in year t, n is the analysis time horizon, r is the social discount rate, and Y_{ijt} is the additional flow of carbon into ($Y_{ijt} > 0$) or out of ($Y_{ijt} < 0$) the sink in year t.

This approach treats early capture (release) of carbon equally with later capture (release) of carbon. Using this approach, the first, second and fourth examples each have a cost of 10 dollars per ton. The third example is more difficult to analyze. While the costs are clearly identified, the carbon flow is indeterminate. The cumulative tons sequestered is cyclical, rising to 100 tons just prior to harvest, but falling to zero immediately following harvest. This suggests that under this analytical approach there is no value to capturing carbon that is eventually released, no matter how long the storage period.

3.1.3. *Average Storage Method*

This approach involves dividing the present value of all implementation costs that occur over a specified period (e.g., Dixon, Schroeder and Winjum (1991) use 50 years) by the average carbon stored over one full management rotation. The denominator in the flow summation method is replaced by an expression, $\overline{S_{ij}}$, for the average carbon storage arising from practice j on land type i.

$$\text{Average storage} = \overline{S_{ij}} = \frac{\sum_{t=1}^{m} S_{ijt}}{m}, \tag{3}$$

where S_{ijt} is the additional carbon stock in year t, and m is the rotation length. Because stock at a point in time, t, is equal to the sum of the flows since the last harvest, the denominator is equivalent to

$$\overline{S_{ij}} = \frac{\sum_{t=1}^{m} S_{ijt}}{m} = \frac{\sum_{t=1}^{m}\left(S_{ij0} + \sum_{s=1}^{t} Y_{ijs}\right)}{m} = S_{ij0} + \frac{\sum_{t=1}^{m}\sum_{s=1}^{t} Y_{ijs}}{m}, \tag{4}$$

where S_{ij0} is the initial rise in stock of carbon attributable to treatment j on land type i. Generally, $S_{ij0} > 0$ only for forest preservation projects.

Thus the unit cost using the average storage method is

$$\text{Average storage unit cost} = C_{ij}^{A} = \frac{\displaystyle\sum_{t=0}^{n} \frac{I_{ijt}}{(1+r)^t}}{S_{ij0} + \dfrac{\displaystyle\sum_{t=1}^{m}\sum_{s=1}^{t} Y_{ijs}}{m}}. \tag{5}$$

The first two hypothetical practices from Section 3.1.1 are difficult to analyze using this approach since the rotation length is not defined. If a 50-year planning horizon is artificially imposed on the analysis, the average storage is 51 tons in the carbon graveyard example and 38.5 in the delayed growth carbon graveyard, for carbon costs of \$19.61 per ton and \$25.97 per ton, respectively. As the rotation length approaches infinity, the average storage asymptotically approaches 100 tons. This would yield a unit cost C_{ij}^{A}, of \$10 per ton. In the third example, where the rotation length is clearly 50 years the average storage is 49 tons, giving a carbon cost of \$20.41 per ton. In the fourth example, forest preservation, the denominator reduces to S_{ij0}, and the average storage unit cost would be \$10 per ton.

3.1.4. *Levelization/Discounting Method*

This method distinguishes among both costs and carbon capture according to when they occur. There are actually two approaches that yield identical results, although they may appear quite different.[7] The first, used in most bottom-up energy analyses and many carbon sequestration studies, is to annualize (levelize) the present value of costs over the period of carbon flows and to divide by the annual carbon capture rate. This levelization approach is convenient when the carbon uptake rate is treated as a constant over the period of analysis. This approach is more difficult to apply when carbon capture rates change over time, as illustrated in Figure 1.

The second approach, better adapted to irregular flows of carbon, is to apply the social discount rate to discount the value of each ton of carbon captured back to a summary statistic (hereafter referred to as present tons equivalent (PTE)) and divide that figure into the present value of costs. Implicit in this discounting approach is that the real value of the marginal damage caused by a one ton increment in atmospheric carbon is constant over time (Richards, 1997b; Stavins, 1999; van Kooten et al., 2000).[8] The discounting approach is calculated as

$$\text{Levelization/discounting unit cost} = C_{ij}^{D} = \frac{\displaystyle\sum_{t=0}^{n} \frac{I_{ijt}}{(1+r)^t}}{\displaystyle\sum_{t=0}^{n} \frac{Y_{ijt}}{(1+r)^t}}. \tag{6}$$

Note that when $r = 0$, i.e., the future value of carbon capture and social costs is not discounted relative to the present, this approach is equivalent to the flow summation method. In fact, if we distinguish between the discount rate in the numerator, r' applied to costs, and the denominator, r'' applied to sequestration benefits, and set $r'' = 0$, then Equation (6) reduces to the flow summation approach described in Equation (2).

In the first example, the present value of costs, \$1000, can be annualized over a fifty year period at 5 percent, to derive a value of \$54.78 per year. Dividing by the annual carbon yield of 2 tons per year leads to a cost of \$27.39 per ton. Alternatively, discounting the number of tons of carbon at a 5% social discount rate yields 36.5 PTEs, and dividing into the present cost of \$1000 also gives \$27.39 per ton. The irregular carbon flow in the second example makes it more difficult to apply the levelization approach in that case, but the carbon discounting approach can easily be applied to derive a yield of 26.6 PTEs and a carbon cost of \$37.62 per ton. In the third example, the stream of flows is again irregular so the discounting approach is easier to apply than the levelization method. The continuous rotations yield approximately 30.4 PTEs for a cost of \$32.87 per ton. In the case of forest preservation, the present value of the costs is, by assumption, \$1000 and the present value of the carbon gain is 100 tons, leading to a cost of \$10 per ton.

Table III summarizes the cost figures for the three approaches applied to the four management examples. Note that the flow summation method and the average storage method yield the same result in the first two examples where the rotation period approaches infinity. This occurs despite the fact that carbon capture in the second example is substantially delayed relative to the first example. It is only by imposing an artificial time horizon for the analysis that the average storage method can be made to differentiate between the first and second examples. In contrast, the levelization/discounting approach differentiates between the two examples purely on the basis of when the flows occur. The flow summation method provides no results with respect to the third example, where continuous rotations occur. The result in that case is that the cost oscillates between 10 and infinity dollars per ton of carbon sequestered. For both the average storage and the levelization/discounting methods the costs rise slightly in the third case relative to the first case.[9] Notice that only in the case of forest preservation do the three summary statistics yield identical results.

Van Kooten et al. (1992) demonstrated the importance of the choice of summary statistic in their analysis of the cost-effectiveness of carbon sequestration in Canada. Their analysis of costs employed the flow summation method, but in an appendix they provided calculations using the levelization approach. The costs in the latter case rose by a factor of 5 to 10 relative to the former case. Table IV provides an overview of the approaches employed by the carbon sequestration cost studies reviewed here.

Table III

Carbon sequestration unit costs for four hypothetical practices, by method

Approach	Carbon graveyard	Delayed carbon graveyard	Cycled carbon storage	Forest preservation
Denominator (tons)				
Flow summation	100	100	Indeterminate	100
Average storage	100 [51] [a]	100 [38.5] [a]	49	100
Levelization/discounting (PTEs)	36.5	26.6	30.4	100
Costs (\$/ton)				
Flow summation, C_{ij}^F	10	10	Indeterminate	10
Average storage, C_{ij}^A	10 [19.61] [a]	10 [25.97] [a]	21.57	10
Levelization/discounting, C_{ij}^D	27.39	37.62	32.80	10

[a] Term in brackets is derived by imposing a 50-year rotation period.

3.2. PRESENTATION OF RESULTS IN COST CURVES

If the summary statistic, as discussed in Section 3.1, has been the leading source of confusion for those comparing cost studies, the use of total, average and marginal costs has run a close second. Moreover, there has been confusion over what the term ‘marginal’ refers to in the context of a carbon sequestration program.

3.2.1. *Total, Average, and Marginal Costs in Cost-Effectiveness*

Sedjo and Solomon (1989) estimated the annual costs and annual quantities of carbon involved in a hypothetical global carbon sequestration program. Their figures were based on average costs per hectare of land and average yield of carbon per hectare. From their analysis it is possible to develop a point estimate of average costs as

$$\overline{C} = \frac{\overline{I}}{\overline{Y}}, \tag{7}$$

where $\overline{C}$ is average cost (dollars per ton of carbon), $\overline{I}$ is average cost of inputs across all regions (dollars per hectare per year), and $\overline{Y}$ is average annual yield across regions (tons carbon per hectare per year). Moulton and Richards (1990) modified this approach to recognize the range of costs across potential applications, e.g., carbon sequestration in the Corn Belt would be more costly than in the Southeast United States. To address this issue they developed average cost estimates for 70 different types of applications, arranged them according to increasing costs, and graphed that array of costs against the quantity of carbon available in each of the 70 applications. Thus, they derived a curve that estimated the rising marginal costs of sequestration. Figure 2 shows the relation between these two approaches.

Table IV
Summary of studies' treatment of time, yield profile and costs

Study	Summary statistic	Yield format	Discount rate (%) applied to:		Measure of cost-effectiveness
			Cost	Carbon benefits	
Sedjo and Solomon (1989) [a]	Levelized cost	Average carbon flow	NA	5 (see note)	Average cost point
Nordhaus (1991)	Discounting	Carbon flow curve	8	NA	Average cost points
Sohngen and Mendelsohn (2001) [b]	Levelized cost	NA	NA	2.2	Marginal cost points
Dixon, Schroeder and Winjum (1991)	Average storage	Average storage	5	NA	Total and marginal cost curves
Houghton et al. (1993)		Cumulative carbon	NA	NA	NA
Dixon et al. (1994)	Average storage	Average storage	Not specified	NA	Average cost points
Sohngen, Mendelsohn, and Sedjo (1998)	NA	Carbon flow curve	NA	NA	NA
Moulton and Richards (1990)	Levelized cost	Average carbon flow	10	NA	Marginal cost curve
Dudek and LeBlanc (1990)	Levelized cost	Average carbon flow	8.5	NA	Average cost point
Adams et al. (1993)	Levelized cost	Average carbon flow	10	NA	Marginal cost curve
Richards, Moulton and Birdsey (1994)	Discounting	Carbon flow curve	NA	5 with sensitivity analysis for 3 to 7	Marginal cost curve
Parks and Hardie (1995)	Levelized cost	Average carbon flow	4	NA	Marginal cost curve
Callaway and McCarl (1996)	Levelized cost	Average carbon flow	10	NA	Marginal cost curve
Lewis, Turner and Winjum (1996)	Flow summation	Carbon flow curve	6.15	NA	Average cost point
Alig et al. (1997)	Discounting	Carbon flow curve	4	NA	Average cost point
Richards (1997a)	Discounting	Carbon flow curve	0, 2, 5 and 8		Marginal cost curve
Adams et al. (1999)	Discounting	Carbon flow curve	4	4	Marginal cost curve
New York State (1991)	Levelized cost	Average carbon flow	10	NA	Average cost point
Stavins (1999)	Discounting	Carbon flow curve	5	5	Average and marginal cost curves
Newell and Stavins	Discounting	Carbon flow curve	5	5	Average and marginal cost curves
Plantinga et al. (1999)	Discounting	Carbon flow curve	5	5	Marginal cost curve
Plantinga and Mauldin (2000)	Flow summation	Carbon flow curve	Not specified	NA	Average cost curves
van Kooten et al. (1992)	Flow summation	Average carbon flow	10	NA	Marginal cost curve
van Kooten et al. (2000)	Discounting/ flow summation	Average carbon flow	4	0,2,4	Average cost point
Slangen and van Kooten (1996)	Discounting	Average carbon flow	2, 4	2 and 4	Average cost point
Makundi and Okitingati (1995)	Flow summation	Conserved carbon	0, 3 and 10	NA	Average cost point
Masera et al. (1995)	Average storage	Average carbon flow/ average storage	10	NA	Average cost point
De Jong, Tipper and Montoya-Gomez (2000)	Average storage	Carbon flow curve	10 with 5 to 40 sensitivity analysis	NA	Marginal cost curve
Ravindranath and Somashekhar (1995) [d]	Flow summation	Cumulative carbon	12 to 17.5	NA	Average cost point
Xu (1995) [e]	Average storage	Average storage	Not specified	NA	Marginal cost curve
Wangwacharakul and Bowonwiwat (1995)	Flow summation/ average storage	Average carbon flow/ average storage	0, 3, and 10	NA	Marginal cost curve
Barson and Gifford (1990)	NA	Average carbon flow	NA	NA	NA
Tasman Institute (1994)	NA	Average carbon flow	NA	NA	NA
Sedjo (1999)	Discounting	Carbon flow curve	10	10	Average cost point
Kerr, Pfaff and Sanchez (2001)	Levelized cost	Conserved carbon	NA	NA	Average cost point

[a] Sedjo and Solomon did not provide a unit cost analysis. We used a five percent discount rate to derive the implicit unit cost reported in Table I of this review.
[b] Sohngen and Mendelsohn (2001) did not explicitly state the discount rate applied to carbon benefits. This figure was implicit in the shadow price on carbon they used in their analysis.

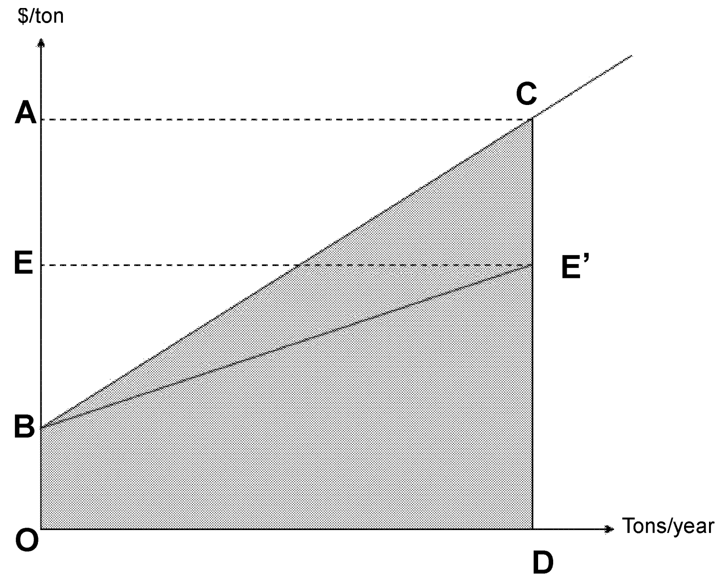

Figure 2. Total, average and marginal costs.

For a program of size D, the marginal cost of adding another ton of carbon to the program is A. The total cost of the program is the shaded area under the marginal cost curve, *OBCD*, which in the case of a linear marginal cost curve is $\frac{1}{2}D(A+B)$. The average cost is simply the total cost, $\frac{1}{2}D(A+B)$, divided by the total quantity, D, or $\frac{1}{2}(A+B)$, represented by point E on the graph. In fact, where the line BC represents the marginal cost of carbon sequestration as a function of program size, the average cost for any size program is represented by the line BE'. Note that for programs with rising marginal cost, the average cost will lie below the marginal costs for all program sizes. This principle is well illustrated by the results reported by Stavins (1999), where the marginal cost per ton of carbon ranges from zero to 664 dollars per ton of carbon, but the average cost for the same size programs ranges only from zero to 145 dollars per ton.

It is important to avoid confusing marginal and average costs when comparing the results of analyses. The last column of Table IV indicates that many of the studies have provided only point estimates of costs. Like Sedjo and Solomon (1989) they have identified a particular target or constraint, and have not examined the effect of varying the size of the hypothetical program. In this sense they are estimating an average cost for a specific program size, analogous to E in Figure 2. Others, like Adams et al. (1999), and Plantinga et al. (1999) have developed marginal cost curves. In contrast, Plantinga and Mauldin (2000) described results purely in terms of an average cost curve, suggesting that the results should not be compared directly with other studies that employ marginal cost curves. By describing results with both marginal and average cost curves, Stavins has provided the greatest clarity and most broadly comparable results.

3.2.2. *Tons of Carbon versus Program Size*

Most analyses express their marginal cost results in terms of the cost of adding one more ton of carbon, one time, to the global carbon sink. In this sense, the cost figure truly is ‘dollars per ton of carbon’. However, this marginal cost of adding one ton of carbon can be expressed either as a function of the total tons of carbon captured throughout the program life, i.e., the PTEs of the program, as Richards, Moulton and Birdsey (1993) did, or as a function of the amount of carbon captured annually (Moulton and Richards, 1990; Stavins, 1999). Moreover, some analyses have even expressed their results in terms of the marginal present cost of expanding a hypothetical program by one ton per year (e.g., Parks and Hardie, 1995), thus, the marginal cost figure expresses the cost of capturing an additional *n* tons of carbon, one in each of the *n* years of the program. These different approaches yield substantially different results and cannot be directly compared.

3.3. DISCOUNT RATE

Initial treatment costs are generally expressed as capital outlays, while the maintenance costs, if included, are expressed as annual costs. Land costs may be expressed as either annual costs (rent) or capital costs. The cost analysis is facilitated by summarizing these costs as either a net present value equivalent or an equivalent annual cost. The key factor for this operation is the discount rate applied to these costs. Table IV summarizes the discount rates used by various sequestration cost studies. The importance of the choice of discount rate depends critically upon the specific structure of the analysis. For example, Moulton and Richards (1990) defined the cost per ton of carbon as the quotient of land rent plus annualized establishment costs divided by annual carbon capture. Since establishment costs were such a small part of the total costs in that analysis, the difference between applying a 4% and 10% discount rate was minor. However, in Richards, Moulton and Birdsey (1993), which used land purchase costs and time-dependent carbon yield curves, raising the discount rate from 3 to 7% nearly doubled the unit cost of carbon sequestration. In general, because the cost of carbon sequestration programs tend to occur early and the carbon sequestration benefits are often substantially delayed, higher discount rates tend to produce higher unit costs of carbon sequestration (Newell and Stavins, 1999).

Newall and Stavins (1999) found that in the case of a subsidy for tree planting, fixed in terms of dollars per acre and paid entirely at the time of planting, as the discount rate rises the subsidy will become more effective because the present value of the subsidy is unaffected by the discount rate while the value of the foregone future revenue from the agricultural alternative declines. Another way of expressing this result is that at higher discount rates the value of future rents from agriculture declines and so does the value of the land itself. Therefore, the amount of land that can be secured at a given price rises. Newall and Stavins (1999) also demonstrated that where the value of carbon sequestration benefits are expressed in PTEs, a rising discount rate initially increases the amount of induced carbon sequestration when land values decline as described above. However, as discount rates rise further, the PTEs of a given flow of carbon decline rapidly and the amount of effective sequestration (PTEs) induced by a given subsidy declines.

4. Carbon Yields

The previous section discussed various summary statistics for describing the amount and unit costs of carbon sequestration provided by forestry practices. In this section the discussion turns to the data that studies have used as they have applied those methods. Section 4.1 discusses five different approaches to depicting carbon yields. Section 4.2 examines the ecosystem components of carbon sequestration and how various studies have addressed those components. Section 4.3 provides a summary and comparison of the sequestration rates or yield levels that the studies have employed.

4.1. CARBON FLOWS

Figure 1 provides a graphical depiction of the carbon flows for three different species of tree plantations in the United States. Although the patterns differ in their timing and level of peak flows, all three demonstrate the pattern of initially rising rates of carbon sequestration followed by gradually declining rates. As mentioned in the discussion above, studies have accounted for these differences either by ignoring the differences in timing of carbon capture (flow summation method), using an average of the amount of carbon stored over the life of the program (average storage method), or discounting the benefits of carbon that is captured later relative to that captured earlier (levelization/discounting method).

Studies generally report their assumptions or data regarding carbon uptake or conservation rates in one of five formats (Table IV, Column 3): (1) *carbon flow curves* that provide a trajectory of (and therefore account for variation in) annual carbon uptake rates over time, as in Figure 1, (2) *average carbon flows* that express mean annual increments of carbon, averaged over the life of a forestry practice, (3) *cumulative carbon capture*, which sums all carbon captured by a project or practice without regard to timing, (4) *average carbon stored* which measures the amount, on average, by which the forestry practice expands the inventory or stock of carbon in the carbon sink, and (5) *conserved carbon*, which is a measure of the amount of carbon emissions avoided by implementing a forestry practice or program.

Note that the units for the first two yield formats are in ‘tons per hectare per year’, while the units for the latter three formats are simply ‘tons per hectare’.

Note also that of the five, only the carbon flow curve involves an array of size n, where n is the number of years over which the program is analyzed.[10]

Although there is not a one-to-one correspondence between the yield format and the choice of accounting methods, the two are closely related. For example, the levelized cost method depends upon data in the average carbon flow format (Moulton and Richards, 1990; Dudek and LeBlanc, 1990; Adams et al., 1993; Parks and Hardie, 1995; Callaway and McCarl, 1996; New York State, 1991), while the discounting method is generally associated with carbon flow curves (Nordhaus, 1991; Richards, Moulton and Birdsey, 1993; Alig et al., 1997; Richards, 1997a; Adams et al., 1999; Stavins, 1999; Newall and Stavins, 1999; Plantinga, 1999; Sedjo, 2000).[11] Studies that employ the flow summation approach have used data in the form of carbon flow curves (Lewis, Turner and Winjum, 1996; Plantinga, 2000), average carbon flow (van Kooten et al., 1992, 2000; Wangwacharakul and Bowonwiwat, 1995), cumulative flow (Ravindranath and Somashekhar, 1995), and conserved carbon (Makundi and Okitingati, 1995). Finally, of course, the average storage method requires data expressed in terms of average carbon storage levels (Dixon, Schroeder and Winjum, 1991; Dixon et al., 1994; Masera et al., 1995; Xu, 1995; Wangwacharakul and Bowonwiwat, 1995).

4.2. ECOSYSTEM COMPONENTS

Several components of a forest ecosystem store carbon, including tree trunks, branches, leaves and coarse and fine roots, soils, litter, and understory. Studies have varied significantly with respect to how they address these various components. Some have included all components in their carbon accounting (e.g., Moulton and Richards, 1990; Adams et al., 1993; De Jong, 2000). Others have limited their analysis to above ground carbon only (Dixon et al., 1991; Kerr et al., 2001). Table V provides a summary of which carbon components are included in each of the studies reviewed. In general, including a carbon component that increases as a result of the practice under analysis will also increase the cost-effectiveness of the practice.

4.3. CARBON YIELD DATA

Most of the cost analysis studies provided some form of explicit estimate of the carbon yield potential of the forestry practice they analyzed (Table VI). At the global level Sedjo and Solomon (1989) estimated carbon yields of 6.24 tons per hectare per year while Nordhaus (1991) estimated a range of only 0.8 to 1.6 tons per hectare per year. Among United States studies the range for most studies is between two and 10 tons per hectare per year. At first glance, this would seem to be at odds with the figures employed by Plantinga et al. (1998) and Stavins (1999) who found potential for a total cumulative uptake of only 16 to 41 tons per hectare. Note however that these two studies provide their figures in PTEs as discussed above in Section 3. The actual accumulation of physical carbon over the life of the

Table V
Ecosystem components included in carbon sequestration studies

Study	Ecosystem carbon components included					Comment
	Above-ground tree	Below-ground tree	Soil	Understory	Litter [a]	
Sedjo and Solomon (1989)	X	X				
Nordhaus (1991)						Not specified
Sohngen and Mendelsohn (2001)	X	X	X	X	X	Above-ground biomass included
Dixon, Schroeder and Winjum (1991)	X	X				
Houghton et al. (1993)	X	X		X		Above- and below-ground biomass
Dixon et al. (1994)	X	X				Above- and below-ground tree [b]
Sohngen, Mendelsohn, and Sedjo (1998)	X	X	X	X	X	
Moulton and Richards (1990)	X	X	X	X	X	
Dudek and LeBlanc (1990)	X	X	X	X	X	
Adams et al. (1993)	X	X	X	X	X	
Richards, Moulton and Birdsey (1993)	X	X	X	X	X	
Parks and Hardie (1995)	X	X	X	X	X	
Callaway and McCarl (1996)	X	X	X	X	X	
Lewis, Turner and Winjum (1996)						Not specified
Alig et al. (1997)	X	X	X	X	X	
Richards (1997a)	X	X	X	X	X	
Adams et al. (1999)	X	X	X	X	X	
New York State (1991)	X	X				
Stavins (1999)	X	X	X	X	X	
Newell and Stavins (1999)	X	X	X	X	X	
Plantinga et al (1999)	X	X	X	X	X	
Plantinga and Mauldin (2000)	X	X	X	X	X	
van Kooten et al. (1992)	X					Tree bole only [b]
van Kooten et al. (2000)	X	X	X			
Slangen and van Kooten (1996)	X					
Makundi and Okitingati (1995)	X		X			
Masera et al. (1995)	X	X	X			
DeJong, Tipper and Montoya-Gomez (2000)	X	X	X	X	X	
Ravindranath and Somashekhar (1995)	X	X	X	X		
Xu (1995)	X	X			X	
Wangwacharakul and Bowonwiwat (1995)	X	X				
Barson and Gifford (1990)	X	X	X	X		
Tasman Institute (1994)	X	X	X	X	X	
Sedjo ((1999)	X	X				
Kerr, Pfaff and Sanchez (2001)	X			X		Above ground biomass

[a] Litter includes coarse woody debris.
[b] Implied in text, but not explicitly stated.

hypothetical program would be consistent with figures used in other studies. Van Kooten et al. (1992) used figures for Canada in the range of 0.6 to 0.8 tons per hectare per year, which is low compared to other studies. In analysis of a different application in Canada, Van Kooten et al. (2000) used figures in the range of 107 to 159 cumulative tons per hectare, which are closer to those used in other North American studies. Sedjo's cumulative carbon uptake figures for Argentina, 241 tons per hectare, are toward the high end of estimates of potential carbon storage capacity, but still within the range of estimates employed by Kerr et al. (2001) of

Table VI
Carbon sequestration rates

Study	Region	Yield format	Potential carbon yield		
			Forest plantation	Forest management	Agroforestry
Sedjo and Solomon (1989)	Global	Average carbon flow	6.24 tons/ha/yr	–	–
Nordhaus (1991) [a]	Global	Carbon flow curve	0.8–1.6 tons/ha/yr	–	–
Sohngen and Mendelsohn (2001)	Global	Not specified	Not specified	Not specified	–
Dixon, Schroeder	Boreal	Average storage	15–40 tons/ha	4–20 tons/ha	–
and Winjum (1991)	Temperate	Average storage	30–175 tons/ha	10–125 tons/ha	15–160 tons/ha
	Tropical	Average storage	25–125 tons/ha	20–200 tons/ha	50–150 tons/ha
Houghton et al. (1993)	Latin America	Cumulative carbon	30–61 tons/ha	5–26 tons/ha	67 tons/ha
	Africa	Cumulative carbon	29–78 tons/ha	5–30 tons/ha	59 tons/ha
	Asia	Cumulative carbon	34–67 tons/ha	5–44 tons/ha	69 tons/ha
Dixon et al. (1994)	South America	Average storage	–	–	39–195 tons/ha
	Africa	Average storage	–	–	29–53 tons/ha
	South Asia	Average storage	–	–	12–228 tons/ha
	North America	Average storage	–	–	90–198 tons/ha
Sohngen, Mendelsohn, and Sedjo (1998)	North America/ Europe	Carbon flow curve	Not specified	–	–
	Subtropical	Carbon flow curve	Not specified	–	–
Moulton and Richards (1990)	United States	Average carbon flow	2.0–10.9 tons/ha/yr	0.0–7.6 tons/ha/yr	–
Dudek and LeBlanc (1990)	United States	Average carbon flow	3.7–8.9 tons/ha/yr	–	–
Adams et al. (1993)	United States	Average carbon flow	2.0–10.9 tons/ha/yr	–	–
Richards, Moulton and Birdsey (1994) [b]	United States	Carbon flow curve	0.0–9.4 tons/ha/yr	–	–
Parks and Hardie (1995)	United States	Average carbon flow	3.3–5.1 tons/ha/yr	–	–
Callaway and McCarl (1996)	United States	Average carbon flow	Not specified	–	–
Lewis, Turner and Winjum (1996)	United States	Carbon flow curve	Not specified	–	–
Alig et al. (1997)	United States	Carbon flow curve	Not specified	–	–
Richards (1997) [b]	United States	Carbon flow curve	0.9–9.4 tons/ha/yr	–	–
Adams et al. (1999)	United States	Carbon flow curve	Not specified	–	–
New York State (1991)	New York State	Average carbon flow	2.1 tons/ha/yr	1.1 tons/ha/yr	–
Stavins (1999) [c]	Delta States	Carbon flow curve	41 tons/ha	–	–
	United States	Carbon flow curve		–	–
Newell and Stavins (1999) [c]	Delta States	Carbon flow curve	41 tons/ha	–	–
Plantinga (1999) [c]	Maine	Carbon flow curve	20–23 tons/ha	–	–
	South Carolina	Carbon flow curve	22–26 tons/ha	–	–
	Wisconsin	Carbon flow curve	15.6–16.4 tons/ha	–	–
Plantinga (2000)	Maine	Carbon flow curve	Not specified	–	–
	South Carolina	Carbon flow curve	Not specified	–	–
	Wisconsin	Carbon flow curve	Not specified	–	–
van Kooten et al. (1992)	Canada	Average carbon flow	0.6–0.8 tons/ha/yr	0.6–0.12 tons/ha/yr	–
van Kooten et al. (2000)	British Columbia & Alberta, Canada	Average carbon flow	107–159 tons/ha	–	–
Slangen and van Kooten (1996)	Netherlands	Average carbon flow	1.4–2.3 tons/ha/yr	–	–
Makundi and Okitingati (1995) [d]	Tanzania	Conserved carbon	–	61 tons/ha	–
Masera et al. (1995) [e]	Mexico	Average carbon flow/Average storage	25–150 tons/ha	–	–
De Jong, Tipper and Montoya-Gomez (2000)	Chiapas, Mexico	Carbon flow curve	Not specified	–	–
Ravindranath and Somashekhar (1995) [f]	India	Cumulative carbon	76–121 tons/ha	62–87 tons/ha	25 tons/ha
Xu (1995) [g]	China	Average storage	22–146 tons/ha	9–15 tons/ha	6–33 tons/ha
Wangwacharakul and	Thailand	Average carbon flow	–	134–510 tons/ha	–
Bowonwiwat (1995)		Average storage	2.21–18.75 tons/ha/yr	–	0.95–6.25 tons/ha/yr
Barson and Gifford (1990)	Australia	Average carbon flow	7.5 tons/ha/yr	–	–

Table VI

(Continued)

Study	Region	Yield format	Potential carbon yield		
			Forest plantation	Forest management	Agroforestry
Tasman Institute (1994)	New Zealand	Average carbon flow	7.7 tons/ha/yr	–	–
Sedjo (1999)	Patagonia, Argentina	Carbon flow curve	241 tons/ha	–	–
Kerr, Pfaff and Sanchez (2001)	Costa Rica	Conserved carbon	94–259 tons/ha	–	–

[a] Nordhaus (1991) developed logistic yield curves based on estimated carrying capacity, average flows, and time to maturity.
[b] The range represents the lowest yield year for the slowest growing species to the highest yield year for the fastest growing species.
[c] Plantinga et al. (1999), Stavins (1999) and Newell and Stavins (1999) did not provide the actual carbon flow profiles for each state, but instead expressed yield in present value of carbon flows, identical to the concept of PTE introduced in Section 3.1.4 above.
[d] Makundi and Okitingati (1995) used a flow summation method to calculate cost-effectiveness of forest conservation in Tanzania based on total 'conserved carbon' without differentiating when the carbon would have been released. The study provided carbon flow figures for forest plantation and agroforestry only in terms of net emissions, i.e., after adjusting for displaced carbon releases.
[e] Carbon yield for forest management was estimated as avoided emissions form deforestation.
[f] These figures appear to count total carbon standing at 50 years, but may use the average storage method since rotations are considered for some practices.
[g] In addition to components included in the average storage method, includes carbon stored in wood products.

the amount of carbon that would be conserved by preventing deforestation in Costa Rica.

An important observation is that the carbon yield figures that studies cite are not directly comparable. Some figures are expressed in annual uptake rates while others are in cumulative potential. Some express physical flows of carbon while others express values of carbon in PTEs. Also note that even where flows are directly comparable, there may be as much as a factor of five difference in assumed yields (Sedjo and Solomon, 1989; Nordhaus, 1991).

5. Three Approaches to Modeling Land Cost

The previous section addressed the methods and data that studies have employed to estimate the denominator, carbon yield, in Equation (1). This section considers the primary component of the numerator, land costs. In the next section we turn to other factors that influence total costs including establishment and maintenance costs.

Generally, the single most important factor in producing or conserving carbon sinks is land. Studies have employed a variety of methods to estimate the economic costs of diverting land from other uses so that they can produce forest carbon sinks.

Identifying the social costs associated with conversion of land to forestlands has proven to be a particularly difficult task. This section provides a review of three general categories of studies: bottom-up engineering cost studies, sectoral optimization studies that account for behavioral response in the forest and agricultural sectors; and econometric studies of the revealed preferences of agricultural land owners. The vast majority of the studies fall in the first category, bottom-up studies.

5.1. BOTTOM-UP ENGINEERING STUDIES

So called bottom-up studies exogenously determine the value of inputs to production and derive an estimate of costs. They include little or no consideration of behavioral responses of landowners or other economic actors. They do not generally account for how one market will adjust to changes in another. Bottom-up studies have the advantage of being relatively transparent and simple to interpret. At the same time the market adjustments that they miss may overwhelm the first order effects of carbon sequestration programs.

The earliest bottom-up engineering studies simply employed observed prices from agricultural land rental (Moulton and Richards, 1990; New York State, 1991) or purchase (Sedjo and Solomon, 1989; Richards, Moulton and Birdsey, 1993) markets. Parks and Hardie (1995) and de Jong et al. (2000) estimated lost economic rent incurred by removing land from agricultural production. Van Kooten et al. (2000) combine these approaches, using lost net returns on forage land, and market prices for leases on pasture land. In a study limited to land costs only (i.e., it does not address carbon costs directly) Suchavek, Shaikh and van Kooten (2001) used a variation of the contingent valuation method to model Canadian grain belt farmers' willingness to accept payment to convert agricultural land to forest. Based on survey results, the research showed that the average farmer required $U.S. 132 per hectare to convert to trees, while the owner of marginal land required $U.S. 84 per hectare.

To account for increasing marginal costs of land as a hypothetical carbon sequestration program expands, some studies have included an exogenously determined elasticity of demand for agricultural land (Richards, Moulton and Birdsey, 1993; Richards, 1997a) or elasticity of supply of forestland (Sohngen and Mendelsohn, 2001). Adams et al. (1993) used a model of consumer surplus loss from increases in food prices due to constriction of agricultural land availability. Like the demand elasticity approach, this consumer welfare measure has the effect of elevating the opportunity cost of land as increasing quantities are shifted from agriculture to carbon sequestration.

As difficult as estimation of land costs is in the United States, it is more difficult in countries that do not have well established land markets. In some cases, land tenure laws do not allow permanent transfer of land. Even where land markets do function, the lack of data about market activities renders land cost estimates speculative at best. Further complicating the analysis, in some countries governments own much of the land that is suitable for afforestation or reforestation.

Because of the difficulty in determining the appropriate figures, some studies simply have not included land costs as an element of the cost analysis (e.g., Dixon, Schroeder and Winjum, 1991). Others have apparently assumed that the use of land is costless because it is either public land (New York State, 1991) or because the wood products will eventually pay for the land (van Kooten et al., 1992; Xu, 1995). As might be expected, those that have included land costs have arrived at a wide

Table VII
Land costs in bottom-up engineering cost studies

Study	Region	Land costs		
		Forest plantation	Forest management	Agroforestry
Sedjo and Solomon (1989) [a]	Global	0–400 U.S.$/ha	–	–
Nordhaus (1991)	Global	20–200 U.S.$/ha	–	–
Dixon, Schroeder and Winjum	Boreal	0	0	0
(1991)	Temperate	0	0	0
	Tropical	0	0	0
Dixon et al. (1994)	South America	–	–	0
	Africa	–	–	0
	South Asia	–	–	0
	North America	–	–	0
Moulton and Richards (1990)	United States	360–8400 U.S.$/ha	120–1440 U.S.$/ha	–
Dudek and LeBlanc (1990)		100 U.S.$/ha/yr	–	–
Richards, Moulton and Birdsey (1993)	United States	275–5135 U.S.$/ha	–	–
Parks and Hardie (1995) [b]	United States	40–650 U.S.$/ha/yr	–	–
Lewis, Turner and Winjum (1996)	United States	67–276 U.S.$/ha	–	–
Richards (1997a)	United States	116–6174 $/ha	–	–
New York State (1991)	New York State	0–1200 U.S.$/ha	0	–
van Kooten et al. (1992)	Canada	0	0	–
van Kooten et al. (2000)	Brit. Col. and Alberta, Canada	6–208 U.S.$/ha	–	–
Slangen and van Kooten (1996)	Netherlands	1068 U.S.$/ha/yr	–	–
Makundi and Okitingati (1995)	Tanzania	–	0	—
Masera et al. (1995)	Mexico	0	0	–
De Jong et al. (2000)	Chiapas, Mexico	–	0–358 U.S.$/ha	–
Ravindranath and Somashekhar (1995) [c]	India	16 U.S.$/ha	16 U.S.$/ha	0
Xu (1995) [d]	China	0	0	0
Wangwacharakul and Bowonwiwat (1995)	Thailand	44 U.S.$/ha/yr	44–88 U.S.$/ha/yr	Not specified
Sedjo (1999)	Patagonia, Argentina	50–150 U.S.$/ha	–	–

[a] Sedjo and Solomon estimated that land costs in the tropics would be negligible, while those in temperate areas would be $400 per hectare.
[b] The land costs were expressed as annual rental payments to landowners within a subsidy program.
[c] These figures are referred to as land rent but are included in the total investment costs, which appear to be initial costs only. It is not clear whether these figures represent a one time cost or an annual rent. d.It is not clear whether land costs are included in investment costs (see Table IX).

range of estimates for that variable. Table VII provides a summary of the land cost data employed in the various studies.

5.2. SECTORAL MODELS

Each of the studies described above treated land conversion as a unidirectional activity; that is, once land has been converted to forests it can not be converted back to agricultural land. It is entirely possible, however, that a sequestration program will raise prices in agricultural land markets, thereby leading landowners to convert unregulated forestlands to agricultural land. If this ‘leakage’ is significant, then some or all of the accomplishments of a carbon sequestration program may be offset. Studies by Alig et al. (1997) and Adams et al. (1999) have attempted to address this issue using the Forestry and Agricultural Sector Model (FASOM).[12]

The FASOM model is a multi-period, price endogenous, spatial equilibrium model that links the forest and agricultural sectors in the United States. The model maximizes the welfare of producers and consumers in the two sectors over a 50-year period subject to policy constraints. Because landowner decisions are endogenous within the optimization model, it can portray those land conversions between forest and agriculture that are induced by a sequestration program.

Alig et al. (1997) examined five scenarios: (1) a *BASE* case that portrays activities in the two sectors as business-as-usual, (2) a *fixed afforestation* case in which there is an initial, government-induced, conversion of 4.9 million hectares of pastureland to forest stands, but no government intervention thereafter, (3) a *constant flux* case in which the net uptake of carbon in U.S. forests is 1.61 gigatons per decade (161 million metric tons per year averaged over the decade), (4) a *fixed increment* case in which the net uptake of carbon in U.S. forests relative to the BASE case is 0.4 gigatons per decade (40 million metric tons per year averaged over the decade), and (5) a *growing flux* case in which the net uptake of carbon in U.S. forests grows by 0.2 gigatons per decade (20 million metric tons per year) relative to the initial level in the base case. In essence, the fixed afforestation case portrays an input-based program, while the latter three cases depict output-based programs. Table VIII summarizes the study's findings. Perhaps the most important result concerns the fixed afforestation case, where 4.9 million hectares are converted out of pastureland into forestland, with no further restrictions on landowner decisions. While the study estimated positive flows relative to the BASE case during the first three decades of the program, the increases are at least partially offset during the fourth and fifth decade following the conversion. Because the agricultural sector responds to the loss of pastureland by converting some forestland back to agricultural use, there is actually less flow into the carbon sink for later decades in the fixed afforestation case than for the base case. Consequently, on net there is relatively little actual carbon sequestration, and the cost is relatively high, 81 dollars per ton. The costs associated with the three output-based programs vary significantly. The most cost-effective of the three is the fixed increment program that constrains carbon flows to a constant 400 million metric tons per decade above the BASE case. Because the other two programs require substantial, and artificially induced, shifts from one-year to the next relative to the BASE case, their unit costs are significantly higher, even at lower levels of sequestration.[13]

Sohngen et al. (1998) developed a global forest sector model that they used to examine regional market adjustments to various carbon sequestration policies. Although that study did not provide cost-effectiveness estimates, it did highlight some of the secondary effects that will determine the efficacy of carbon sequestration programs. First, they demonstrated that even in the absence of a carbon sink program, the timber market and rising industrial wood prices will lead to the establishment of new plantations. Rising timber prices will also induce more intensive management of forests and therefore more carbon storage. As the quantity of timber supplied to the market increases, so too will the quantity of carbon stored in wood products.

The analysis by Sohngen et al. (1998) also considered strategies for further increasing carbon storage relative to their base or 'no-policy' case. They examined three major tree planting programs[14] and a timber conservation approach that

Table VIII
Summary of FASOM modeling results (Alig et al., 1997)

	Fixed afforestation	Constant flux	Fixed-increment	Growing flux
Decadal flows relative to BASe case (millions of metric tons per decade)				
1991–2000	60	630	400	0
2001–2010	50	0	400	0
2011–2020	20	140	400	0
2021–2030	–40	510	400	480
2031–2040	–150	930	400	1100
Total 1991 to 2040	–60	2210	2000	1580
Net present tons equivalent (millions of tons) [a]	48	847	859	306
Equivalent annual flow (millions of tons per year)	2.2	39.4	40	14
Welfare cost ($billions NPV) [a]	3.9	50.8	20.7	43.4
Average cost of carbon ($/metric ton) [a]	81	60	24	141

[a] Derived from Alig et al. (1997) based on the levelization discounting method described in Section 3.1.4 above.

sets aside certain European and North American forests from harvest. The study provided several interesting results. First, programs to establish new forests for harvest in Europe and North America will lead to a significant drop in establishment of plantations in the tropics, but also a decrease in harvesting of forests in remote northern regions. Second, a set-aside or forest conservation program in North America and Europe will actually reduce global carbon storage because timber prices rise and sales decline, leading to a smaller wood product sink. Higher timber prices also place additional pressure to harvest more remote forests, thereby decreasing that natural sink. Third, one of the greatest advantages of establishing plantations in the tropics is that they grow quickly, reduce timber prices relative to the base case sooner, and move carbon into forest sinks earlier. The study by Sohngen et al. (1998) demonstrated that land cost accounting needs to consider both interactions with other markets, especially other regional forestland markets and wood product markets, and the dynamic effects that differences in regional growth rates might have on those markets.

In a subsequent study, Sohngen and Mendelsohn (2001) combined the global forest sector model with an energy-economy model to investigate the role and costs of carbon sequestration in the presence of an international tax on net carbon emissions. By employing the forest sector model using wood product supply and demand curves they were able to circumvent the problem of directly estimating land costs in much the same manner as the FASOM model (Alig et al. 1997).

5.3. ECONOMETRIC STUDIES

Recent studies by Stavins (1999), Newell and Stavins (1999), and Plantinga et al. (1998), Plantinga and Mauldin (2000), and Kerr, Pfaff, and Sanchez (2001) have provided an alternative approach to modeling the potential costs of land for carbon sequestration in the United States. The FASOM model, discussed previously in Section 5.2, used econometric specification of consumer demand to measure the costs associated with withdrawing land from agricultural production. It assumed that landowners would maximize profit subject to forest, agriculture and carbon prices. In contrast, these recent econometric studies analyzed how landowners have historically allocated land use between agriculture and forests in response to differences in prices. Thus econometric studies work with a revealed-preference approach based on actual practices rather than assumed profit maximizing.

To model historic land use conversion as a function of market prices, Stavins (1999) drew on land cover and price data gathered for 36 counties in Arkansas, Louisiana, and Mississippi during the years 1935–1984. From this data he derived the price differentials that would induce land conversions within that geographic area. Based on data for land conversion costs and biological growth rates he developed carbon sequestration cost curves for two planting scenarios (natural regeneration and pine plantations) and two harvesting scenarios (periodically harvested and permanent-never harvested). Plantinga et al. (1999) derived econometric estimates of the cost of carbon sequestration in the states of Maine, South Carolina and Wisconsin. In contrast to Stavins (1999), who used panel data to estimate landowner responses to forestry and agriculture prices, Plantinga et al. used cross-sectional, county-level data. Plantinga et al. (1999) also allowed for the possibility that as population rises, the expanding demand for nonagricultural land uses (e.g., urban, public lands, and wetlands) will raise the cost of diverting land into forests. Although Plantinga et al. (1999) did not provide direct estimates, the average costs[15] of conversion of Wisconsin agricultural land would be 480 to 1440 dollars per hectare.

Following similar econometric methods to those used by Stavins (1999), Kerr, Pfaff and Sanchez (2001) developed an econometric model to estimate the difference between the economic yields of cleared versus forested land in Costa Rica as a means of gauging the cost of conserving potentially deforested land in that country. Using this information they calculated a land-use baseline that provides a prediction of the deforestation that will occur in the absence of an international program. They then estimated the change in deforestation levels that would occur for different carbon prices. Although their data is preliminary and they only project their estimates over two years, the study suggested that the econometric method can be usefully employed in developing countries and in cases of forest management.

6. Other Factors in Carbon Sequestration Cost Studies

While the carbon accounting and land cost modeling issues discussed in Sections 3 and 5 account for most of the variation among studies, there are other factors that also contribute to differences among cost-effectiveness estimates. These factors include the initial cost of forestry practices, the maintenance costs of forestry practices, the secondary environmental effects, and the administrative costs. This section briefly addresses each of these factors.

6.1. COST OF INITIAL TREATMENT

For some practices, in some regions of the world, data on the costs of initial treatments has been adequate. For example, the United States Forest Service has extensive records on the costs of domestic afforestation and reforestation (e.g., Moulton and Richards, 1990). But estimation of initial treatment costs, even for common practices such as tree planting, is not always simple. In many regions of the world, data on costs are simply not available. Also, the rate at which the afforestation or reforestation takes place is likely to affect marginal costs as forestry supplies and skilled labor capacity are consumed. This ‘rate of implementation’ effect is seldom considered in studies. Finally, there is an inherent failure rate in the establishment of new forests. While Moulton and Richards (1990) included provisions for a 15 percent failure rate resulting in additional replanting costs, this issue has generally not been explicitly addressed.

For many of the other beneficial activities listed in Table II, such as forest preservation, agroforestry, and modification of forestry management practices, the costs are likely to be even more difficult to assess. These forestry practices are less standardized than tree planting, so costs are apt to be site-specific. Table IX provides a summary of the figures that studies have used for initial treatment costs.

6.2. MAINTENANCE COSTS

Once a forestry project is established there are continuing annual costs that should be considered. These costs cover fertilization, thinning, security, and other activities that are essential to assure that the expected carbon yields are realized. Many studies do not include these costs. Of the studies listed in Table I, only Nordhaus (1991), Dixon, Schroeder, and Winjum (1991), Dixon et al. (1994), and Xu (1994) explicitly included annual maintenance costs in their calculations. None of the studies explicitly included the costs of fire and pest protection or the risks of carbon loss that these threats pose.

Table IX
Initial treatment costs of forestry practices

Study	Region	Initial treatment costs (U.S.$/ha)		
		Forest plantation	Forest management	Agroforestry
Sedjo and Solomon (1989)	Global	400	–	–
Nordhaus (1991)	Global	400–450	–	–
Sohngen and Mendelsohn (2001)	Global	Not specified	Not specified	–
Dixon, Schroeder and Winjum (1991)	Boreal	125–450	50–250	–
	Temperate	25–800	0–1600	1000
	Tropical	250–320	50–500	250–750
Dixon et al. (1994)	South America	–	–	500–3500
	Africa	–	–	500–3500
	South Asia	–	–	500–3500
	North America	–	–	500–3500
Moulton and Richard (1990)	United States	140–520	–	–
Dudek and LeBlanc (1990)	United States	420	–	–
Adams et al. (1993)	United States	140–520	–	–
Richards, Moulton and Birdsey (1993)	United States	190–690	–	–
Parks and Hardie (1995) [a]	United States	370	–	–
Calloway and McCarl (1996)	United States	144–480	–	–
Richards (1997a)	United States	190–690	–	–
Adams et al. (1999)	United States	Not specified	–	–
New York State (1991)	New York State	660	288	–
Stavins (1999)	Delta States	28	–	–
Plantinga et al. (1999)	Maine, South Carolina, and Wisconsin	Not specified	–	–
Plantinga and Mauldin (2000)	Maine, South Carolina, and Wisconsin	Not specified [b]	–	–
Newall and Stavins (2000)	Delta States	28	–	–
van Kooten et al. (1992)	Canada	300–500	650–1000	–
van Kooten et al (2000)	British Columbia and Alberta, Canada	1270	–	–
Slangen and van Kooten (1996) [c]	Netherlands	1575–2495	–	–
Makundi and Okitingati (1995) [d]	Tanzania	–	3.2–7.3	30–43
Masera et al. (1995) [e]	Mexico	387–700	Not specified	–
De Jong, Tipper and Montoya-Gomez (2000)	Chiapas, Mexico	–	212–286	–
Ravindranath and Somashekhar (1995)	India	367–550	77–205	39
Xu (1995)	China	46–828	11–31	14–240
Wangwacharakul and Bowonwiwat (1995) [f]	Thailand	247–705	540–1940	118–367
Sedjo (1999)	Patagonia, Argentina	1000	–	–
Kerr, Pffaf and Sanchez (2001) [g]	Costa Rica	–	Not specified	–

[a] Parks and Hardie (1995) categorized treatment according to hardwood and softwood treatments. The figure listed here is for hardwood treatment. The costs for softwood are cited but not listed.
[b] Cites Moulton and Richards (1990) as source of establishment cost data.
[c] Slangen and van Kooten (1996) provided both planting costs and management costs. The figure reported in this table is for the net present value of the sum of costs over the 15–40 year rotation period, derived with a 4% discount rate.
[d] The figure for forest plantation and agroforestry treatment costs included only initial (first year) treatment costs.
[e] Although there are costs associated with forest management in Masera et al. (1995), it is not clear how to interpret the figures.
[f] The figure for forest management is an annual figure, not the present value of total costs of the practice.
[g] Kerr, Pfaff, and Sanchez (2001) address only the case of preventing deforestation so there is no initial treatment cost.

6.3. SECONDARY ENVIRONMENTAL EFFECTS

Activities that increase carbon sequestration will also generally have secondary environmental costs and benefits. Some of the studies reviewed here have acknowledged these effects (e.g., van Kooten et al., 1992; Dixon et al., 1994), but none have provided a full assessment of these benefits (or costs) and incorporated them in the analysis. Recent work by Plantinga and Wu (2001) suggest that the secondary effects of converting land from agricultural production to forest may be substantial. That study examined the costs and effects of a hypothetical subsidy program designed to induce landowners to convert as much as 25 percent of the agricultural land in Wisconsin to forests. Using environmental production functions, the study examined the benefits associated with reductions in sediment, nitrogen and atrazine runoff when agricultural land is converted to forest. The rough estimates suggest that a program designed to achieve carbon sequestration rates of 4.1 million tons of carbon per year would cost approximately $101 million per year. Interestingly, the secondary benefits from soil erosion reduction ($42 million per year), hunting improvements ($30 million per year), and non-consumption uses ($31 to $109 million per year) could more than offset the entire cost of the program. In contrast, Matthews, O'Connor and Plantinga (2001) demonstrated that conversion of farmland to forestland in Maine, South Carolina, and Wisconsin could have a negative effect on bird populations in those states.

Carbon sequestration projects could also cause an increase in carbon emissions if the forestry practices require significant fossil fuel use. None of the studies addressed the incremental fossil fuel use and carbon emissions that might be associated with the forestry practices.

6.4. ADMINISTRATION COSTS

Site-specific financial expenditures are only one element of the costs associated with a large carbon sequestration endeavor. The administration costs associated with establishing forestry programs can be significant. Even in well-developed market economies, the costs of program administration can rise to as much as 15 percent of the total costs of land rental, establishment and maintenance (Richards, Moulton and Birdsey, 1993). The function of markets is to reduce the transaction costs associated with individual economic exchanges. Consequently, it is reasonable to expect that where land and labor markets are not as well developed, the relative costs of administration and information-gathering might rise to a much higher level, even surpassing the financial outlays. However, estimation of these administration costs in the absence of extensive experience presents problems. Consequently, most studies have not accounted for these costs in their analysis (Xu (1995) is a notable exception).

7. The End-Game: Harvesting and the Forest Product Sink

Carbon flows into forests can also be reversed by harvest. Studies have varied with respect to how they have addressed these factors. The group of studies that employ the average storage method assumed that all carbon is released upon harvest, but that the forestry practices are repeated in continuous rotations (Dixon, Schroeder, and Winjum, 1991; Dixon et al., 1994). Hence, the concept of carbon release is built into the analysis. Another group of studies assumed that the land planted to trees will be permanently withdrawn from other uses, including harvest for wood products, so that there is no release of carbon – a kind of carbon graveyard approach (e.g., Nordhaus, 1991; Richards, Moulton and Birdsey, 1993). This assumption must be reflected in the treatment of land costs since decreasing the amount of agricultural land will lead to higher land prices. Some studies have analyzed carbon sequestration costs for both cases, i.e., with and without harvesting (e.g., Adams et al., 1993; Stavins, 1998; Plantinga et al., 1999). Finally, some studies simply did not address the release of carbon upon harvest, implicitly assuming that either the forest area will not be harvested, or that harvest will occur so far in the (discounted) future as not to be a concern (e.g., Moulton and Richards, 1990; van Kooten et al., 1992). For example, Parks and Hardie (1995) acknowledged the possibility of eventual harvest, but did not treat the impacts on either the carbon flows or the net costs.

As the hypothetical examples summarized in Table III illustrate, harvesting can have a significant negative impact on the carbon benefits of a program. Further, that impact depends very much on the choice of summary statistics. At the same time, the economic benefits of timber harvest can be significant. Studies that do not quantify either of these effects will overstate both the costs of projects and the carbon benefits. Studies that include the effects of harvest on carbon flows but do not incorporate the economic benefits of harvest will almost certainly overstate the unit costs of carbon sequestration. At the extreme, some forestry practices may pay for themselves in the form of forestry products and the carbon benefits are a costless bonus (often referred to as 'no regrets' mitigation options). For example, Xu (1995) suggested that there may be negative costs associated with some carbon sequestration practices in China. Conversely, those studies that only consider the benefits of forestry products but do not adjust the carbon flows to reflect increased releases of carbon back to the atmosphere will understate the costs of carbon sequestration.

Adams et al. (1993) suggested that including timber harvest in a carbon sequestration program could substantially reduce unit costs. For example, in that analysis the marginal cost of sequestering 32 million metric tons of carbon per year declined from $15.35 per ton in the case when harvest was not included to $8.95 per ton when harvest was allowed. The savings accrued through improvements in consumer surplus (from lower wood product prices) and farm producer surplus (from added revenue on carbon sequestration plantations), but were partially offset by losses to forest sector producers caused by lower timber prices. Adams et al. (1993) seem to have based their analysis of harvesting on the assumption that all carbon sequestered in a plantation remains sequestered even after harvest. Hence they did not detect a decline in the quantity of carbon that could be captured, although they did suggest that the effective carbon sequestration level might be less than one half of the ostensible carbon capture or carbon goal if losses associated with harvest were included.

Stavins (1999), Plantinga et al. (1999), and Newall and Stavins (2000) partially addressed the effects of harvest on carbon sequestration. Stavins (1999) estimated that approximately 40 percent of forest carbon goes into wood products at the time of harvest and a significant portion of the carbon remained in soils. That portion of carbon in wood products decays gradually, releasing approximately 75 percent of carbon within 100 years. Building on this analysis of the physical flows of carbon following harvesting, Newall and Stavins (2000) demonstrated that allowing harvest actually increases the cost of carbon sequestration, even though the cost per acre of carbon sink decreases. The reason for this result is that unlike Adams et al. (1993), Newall and Stavins (2000) accounted for both the decline in the amount of carbon captured (per acre) when harvesting is permitted and the change in timing of the capture that does occur. For example, to achieve five million short tons (4.545 million metric tons) of carbon sequestration per year they estimate the forestland area would need to rise from 2.7 million acres (1.09 million hectares) to 3.3 million acres (1.33 million hectares) if harvesting is allowed.[16]

While these latter studies addressed the change in quantity of onsite carbon accumulation in carbon sequestration programs and the change in costs that are associated with allowing harvesting in a carbon sequestration program, they did not consider the secondary effects of the new timber and wood product supply on the size of the wood product carbon sink. Rather, they assumed the wood product sink would increase by the same amount as the carbon contained in the harvested wood products. In fact, it is likely that some portion of the existing suppliers of wood products would discontinue production. To the extent that the wood product carbon sink expands, it would have to occur in response to a decline in prices of wood products themselves. Accurately modeling the effect of harvesting will require general equilibrium models that tie together agriculture and forest land supply and demand models, forest product supply and demand models, forest plantation carbon yield models, and wood product carbon flow models.

8. Comparing the Studies

Table I summarizes estimates of the unit costs and the potential yield of carbon sequestration reported by the various studies reviewed here. In this section we compare the cost and carbon yield estimates of the various studies. The table separates the studies into four general categories, including global cost estimates, sub-global regional estimates, national or sub-national estimates for the United States, and other national or sub-national estimates.

8.1. COST ESTIMATES

Sedjo and Solomon (1989) did not provide unit cost calculations of carbon sequestration (although for purposes of comparison in this review article, cost estimates have been derived using a levelized cost method), while Nordhaus applies a discounting method. The IPCC (2000) report did not provide original estimates but rather summarized the results of other studies. The two original studies of global cost estimates differ significantly. Nordhaus' (1991) estimate of the unit costs of global carbon sequestration through afforestation is much higher than Sedjo and Solomon (1989) – 42 to 114 dollars per ton – and higher than many of its contemporary studies for the United States. This is a bit surprising, given the fact that Nordhaus' land and treatment cost figures are similar to those used by other studies (Tables VII and IX). The difference in results is almost entirely attributable to how the study treated carbon yields. First, Nordhaus (1991) used average carbon yield factors derived from the review of greenhouse gas policy options conducted by Lashof and Tirpak (1989). These figures are for carbon yields on average commercial timber land and probably substantially underestimate yields expected from conversions of marginal agricultural land to forestry plantations (see Table VI for a comparison with other studies). Second, the analysis limited the total cumulative carbon to between 30 and 50 tons per hectare, and assumed that this amount occurs over a forty-year period following plantation establishment. These figures are certainly at the low end of the expected carrying capacity of forest plantations, particularly for those established on converted agricultural land, which tends to be of better quality than average forestland. Finally, to portray the timing of carbon capture, Nordhaus applied a logistic growth curve that has the effect of delaying carbon uptake relative to approaches that use an average carbon flow or average carbon storage estimate. Combined with a levelization approach to costs, this delay in carbon uptake contributes to an increased unit cost of carbon capture.

At the other extreme, Sedjo and Solomon (1989) provided land and treatment cost figures that led to a cost of carbon sequestration in the geographic temperate zone of 7 dollars per ton on a cost levelization basis. Moreover, because they assumed there was no opportunity cost for land in the tropics, their unit-cost estimate for the tropics was only one half of the estimate in the temperate zone. This relatively low cost estimate is due to their optimistic assumption regarding carbon yield, which is based upon growth rates in the Pacific Northwest and Southeast regions of the United States. Applying these rates to a global analysis is probably unrealistic, but it does suggest that in some regions of the world carbon sequestration could be relatively inexpensive.

The cost estimates from Sohngen and Mendelsohn (2001) lie between these two extremes. For sequestration rates of 280 million tons per year Nordhaus found the average costs are $114 per ton. Sohngen and Mendelsohn (2001) found that a similar rate of sequestration would occur when the price of carbon was between 15 and 20 dollars per ton. The interesting result here is that the lower cost estimate occurs despite the fact that Sohngen and Mendelsohn at least partially controlled for leakage.

The second group of studies considered the carbon sequestration potential of major ecological regions of the world (Dixon, Schroeder, and Winjum, 1991; Dixon et al., 1994).[17] These two studies provided cost estimates based on the average storage method of carbon accounting. The results suggest that the costs of carbon sequestration may be relatively low for all three types of practices – forest plantations, forest management and agroforestry. Even adjusting for the fact that these costs were developed with the average storage method, the costs presented here suggest lower estimates than those derived in the United States studies. It is interesting to note that Dixon, Schroeder and Winjum (1991) find relatively little difference among the boreal, temperate and tropical regions with respect to the carbon sequestration costs associated with forest plantations and forest management, which range from 2 to 8 dollars per ton and 1 to 13 dollars per ton, respectively. In contrast, the carbon sequestration costs associated with agroforestry are considerably higher in the temperate region, 23 dollars per ton, than in the tropics where the costs are 5 dollars per ton. In the second study, however, that relation seems to be reversed, where the cost for agroforestry in the tropical areas is 2 to 69 dollars per ton and the cost in North America is 1 to 6 dollars per ton (Dixon et al., 1994). The reason for this switch is apparently due to the fact that the relative costs of initial treatment in the temperate zone were lower in the second study and the average storage capacity of land was higher.

The third group of studies concentrates on the potential for the United States or one of its subregions to sequester carbon (Moulton and Richards, 1990; Dudek and LeBlanc, 1990; Adams et al., 1993; Richards, Moulton and Birdsey, 1993; Parks and Hardie, 1995; Callaway and McCarl, 1996; Alig et al., 1997; Richards, 1997a; Adams et al., 1999; New York State, 1990; Stavins, 1999; Newell and Stavins, 2000; Plantinga et al., 1999; Plantinga and Mauldin, 2000). With only two exceptions, the studies in this group used the cost levelization/discounting approach. The first exception is Lewis, Turner and Winjum (1996) who employed a variation of the flow summation method and arrived at an extremely low (in fact, negative cost) estimate. The other, Plantinga and Mauldin (2000), used flow summation to derive average (rather than marginal) cost curves. Note that the range of cost figures reported in that study were less than one half of those reported in the earlier Plantinga et al. (1999) analysis, which provided marginal cost figures derived with the discounting method of carbon accounting.[18]

The United States studies can also be differentiated according to the methods they employed to estimate land cost. Among the bottom-up engineering studies there is a fairly narrow range of estimates, suggesting that substantial amounts of carbon could be sequestered for less than 50 dollars per ton. Parks and Hardie (1995) present a different picture. They suggest a similar lower range on costs but a very rapid increase that approaches 90 dollars per ton of carbon.[19] More importantly, they move into the higher cost range at a much lower level of carbon sequestration than other studies do. This difference can be attributed in part to the fact that Parks and Hardie (1995) recognize much less land availability than other studies (e.g., Adams et al., 1993; Richards, Moulton and Birdsey, 1993). This means that they move into more expensive land very quickly. Also, their annual land costs are estimated at 40 to 650 dollars per hectare per year and their discount rate is 4 percent. This suggests a capitalized land cost over the 10-year rental contracts of 320 to 5300 dollars per hectare. For comparison, this is a higher range than was used for the outright purchase of land used in Richards, Moulton and Birdsey (1993) or Richards (1997a). Also, Parks and Hardie (1995) use lower carbon yield estimates. Finally, and perhaps most importantly, their costs are annualized over only a 10-year contract period. While this may be appropriate for their analysis of a specific hypothetical government, it almost certainly overstates the costs of carbon sequestration in a broader context since carbon capture continues for several decades into the future, even after the end of government land rental payments. If instead they had annualized their initial costs over a period that more closely corresponded to the productive period of a forest stand, say 30 years or more, the estimated cost of sequestration would have been less than half of their reported costs.

Using the FASOM sectoral model, Alig et al. (1997) found that even their lowest cost scenario, the fixed-increment case, suggests a substantially higher cost than estimated in the bottom-up engineering models. In that study the *average cost* of accomplishing 40 million tons of sequestration per year over 50 years is 24 dollars per ton. From Richards (1997), the *marginal cost* of carbon sequestration at 100 million tons per year for 100 years is only about 20 dollars per ton. While the difference may be due to differences between the two models with respect to implicit land costs or carbon yields, it may also stem from the fact the fixed-increment case is not a cost-minimizing strategy. Rather, as in the study by Parks and Hardie (1995) the study by Alig et al. (1997) imposed an artificial constraint that requires that forests take up an additional 400 tons per decade, in each and every decade, relative to the BASE case. In contrast, the sequestration levels described in Richards (1997a) were based on annualized figures, i.e., there was no actual constraint that required certain amounts of carbon in particular years or decades. It will require further analysis with the FASOM model to reveal whether the constraints imposed by the fixed-increment case artificially raised the costs of carbon sequestration.

Stavins (1999) estimated the marginal costs of carbon sequestration for the Delta States to be in the range of zero to 60 dollars per ton for a program of up to seven million tons per year.[20] The study then extrapolated to the United States by scaling up with the ratio of total U.S. farmland acreage to the Delta State acreage covered by the study. The result was a curve that showed marginal costs of up to 136 dollars per ton for a program designed to capture 518 million tons per year. The three states treated in Stavins (1999) were the same states included in the Delta States region in Moulton and Richards (1990), Richards, Moulton and Birdsey (1993) and Richards (1997a). His conversion costs and carbon yield curves were drawn from Richards, Moulton and Birdsey (1993). The similarity of the studies on so many important dimensions permitted Richards (1997a) to compare the effects of the way that land costs are modeled in bottom-up engineering studies with the econometric approach. Where the bottom-up engineering approach of Richards (1997a) used current land prices adjusted for the effect of inelastic demand (with a highly uncertain estimate of price elasticity of agricultural land drawn from the

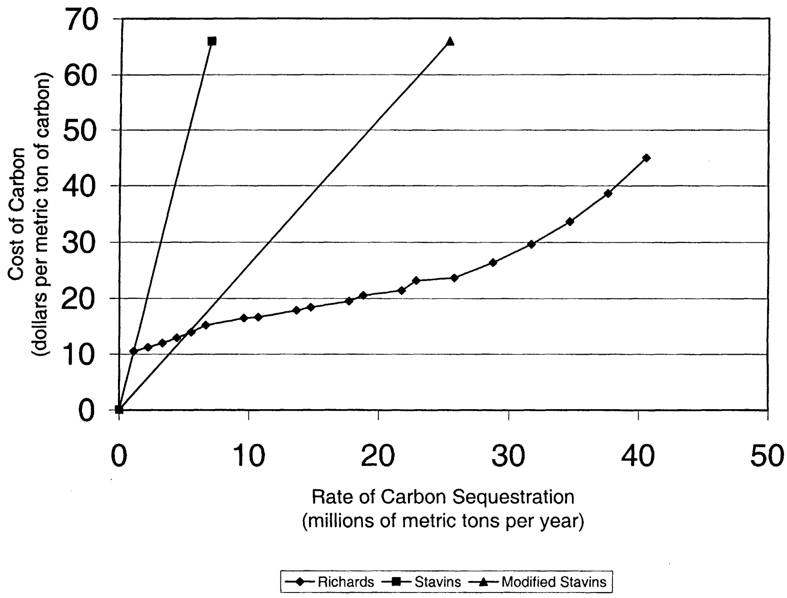

Figure 3. Carbon sequestration costs for the delta states comparison of Stavins (1999) with Richards (1997).

agricultural economics literature), Stavins used an econometrically derived land supply function.

It is possible to compare the econometric approach demonstrated by Stavins (1999) and Plantinga (1999) directly with the bottom-up approach employed by Richards (1997a). For example, Figure 3 shows the lower region of the cost curve that the Stavins (1999) study estimated for the Delta States, i.e., roughly linear between the origin and a marginal cost of 66 dollars per ton at a level of 7.0 million tons per year. Because Stavins considered only a subset of the farmland in the Delta States (10.6 million acres) it is necessary to first scale up the cost curve to account for the total farmland area in the three-state region (38.4 million acres (USDA, 1995)). This is described as the Modified Stavins curve in Figure 3. Compared to the figures used to construct the Richards (1997a) cost curve, Stavins' econometric approach yields a substantially higher estimate of costs.

Similarly, Figures 4a–c show a comparison between Plantinga et al. (1998) and Richards (1997a) for Maine, South Carolina, and Wisconsin. Note that once again the econometric study estimated much steeper cost curves than the engineering bottom-up approach. In part, the generally higher costs derived in Plantinga et al. are due to lower estimates of carbon yield in forestry plantations. Where Richards (1997a) estimated that the carbon yields in Maine, South Carolina, and Wisconsin would be 34 to 39, 32 to 42, and 40 to 46 PTEs per acre, respectively, Plantinga et al. used figures of 23, 26, and 16.4 respectively. Given that both studies used a 5 percent discount rate for carbon benefits and employed data for research by

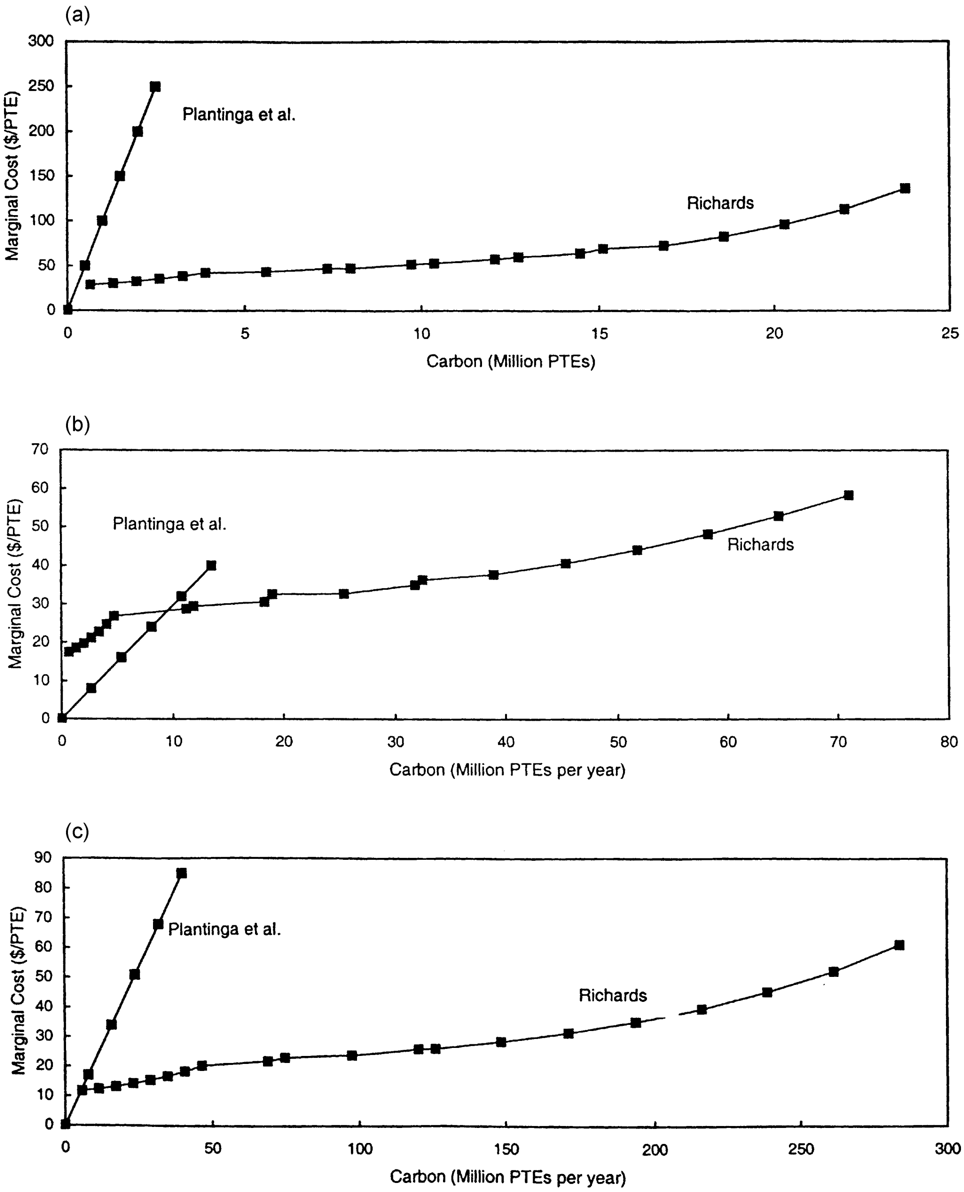

Figure 4. Carbon sequestration for (a) Maine, (b) South Carolina, and (c) Wisconsin. Comparison of Plantinga et al. (1999) with Richards (1997).

Birdsey (1992, 1996), it is likely that the differences in yield are due to the choice of species and methods of calculating present ton equivalent units of carbon. Differences in PTE yields used by the studies, however, cannot account for all of the difference in cost estimates. Plantinga et al. (1999) pointed out that the primary reason for the differences is almost certainly due to the fact that Plantinga et al. (1999) calculated a much higher land cost that Richards. Stavins suggested that the difference in land costs could be due to the fact that engineering studies do not recognize the ‘nonpecuniary returns to land and decision making inertia’, i.e., landowners can be slow to change their practices and money is not the only thing that motivates them.

The fourth group of studies examines the potential for carbon sequestration in individual countries (van Kooten et al., 1992; Masera et al., 1995; Ravindranath and Somashekhar, 1995; Xu, 1995; Wangwacharakul and Bowonwiwat, 1995; Slangen and van Kooten, 1996; Sedjo, 1999; van Kooten et al., 2000; de Jong et al., 2000; Kerr et al., 2001). There are two striking patterns among these studies. First, the cost estimates for the developing countries are substantially lower than for the industrialized countries. Second, with the exception of Kerr et al. (2001) all of the studies of developing countries use the average storage method or the flow summation method of carbon accounting. Since these methods lead to lower cost estimates that the levelized/discounting method, it suggest that the lower cost estimates for developing countries may be due as much to differences in accounting methods as to differences in underlying cost and yield factors.

The studies of individual developing countries also provide an interesting contrast among themselves. While Masera et al. (1995) estimate that carbon sequestration on forest plantations in Mexico would cost 5 to 11 dollars per ton, Xu (1995), Makundi and Okitingati (1995) and Wangwacharakul and Bowonwiwat (1995) estimate that there are opportunities for negative-cost carbon sequestration in China, Tanzania, and Thailand respectively. For example, Xu’s estimate stems from the assumptions that revenues from the sale of forestry products would more than offset costs, and that China has a largely unmet demand for timber. The interpretation of cost figures for Ravindranath and Somashekhar (1995) is unclear. While they apparently use a flow summation approach in their cost calculations, they discuss the application of discounting, at zero and one percent, to the carbon flow.

The presentation of levelized costs in van Kooten et al. (1992) also provides higher estimates of carbon costs than either Adams et al. (1993) or Richards, Moulton and Birdsey (1993). This might be surprising in light of the fact that van Kooten et al. (1992) do not include land costs in their estimates. The difference can be attributed in part to higher initial establishment costs and low growth rates expected in the Canadian forests. Their carbon capture rates are also low because they apparently only consider the carbon in the tree bole (trunk) and not the whole ecosystem carbon.

8.2. POTENTIAL AMOUNT OF SEQUESTRATION

While there is considerable variation in the predictions of the cost of carbon sequestration, the studies show an even wider range of estimates of the amount of potential carbon sequestration (Table I). At one extreme Sedjo and Solomon (1989) have estimated that if 465 million hectares of land could be converted to forest, 2.9 billion tons of carbon per year could be removed from the atmosphere in forest plantations. At the other extreme, Nordhaus (1991) suggests that an average of only 280 million tons per year could be captured over a period of 75 years, even in the presence of a global effort. The difference between these two estimates is almost entirely due to the estimates of carbon yields, since their assumptions on land availability are very similar. At the same time, Dixon et al. (1994) estimate that globally 1100–2200 million tons can be captured annually using expanded agroforestry practices alone.

Opportunities in the most northern latitudes appear somewhat limited. Dixon, Schroeder and Winjum (1991) suggest that summing across all practices, only 2 billion tons can be accumulated in the boreal regions. Over the study's 50-year period, this averages to 40 million tons per year. This estimate, which covers all boreal regions in the world, should be contrasted to the estimate by van Kooten et al. (1992) that forestry opportunities in Western Canada alone may provide as much as 13 million tons of carbon capture per year.

In the temperate regions there appear to be significant opportunities. Moulton and Richards (1990) suggest that in the United States an aggressive tree planting program could yield as much as 630 million metric tons per year for 40. Dixon, Schroeder and Winjum (1991) are not as optimistic. Their study suggests that across all forestry practices a total of 20 billion tons of carbon could be accumulated in the entire temperate zone. Over their fifty year analysis period this averages to 400 million tons per year. Since the estimate of land area availability in Dixon, Schroeder and Winjum (1991) is much higher than in Moulton and Richards (1990), the difference in the estimates must be attributed to the fact that the latter study uses much higher estimates of potential carbon accumulation per hectare.

The outlook in the tropics is even better than that in the temperate region. Dixon, Schroeder and Winjum (1991) suggests that a cumulative total of 53 billion tons of carbon could be captured across all forestry practices. Houghton et al. (1993) provide an even more optimistic estimate of the potential in the tropics, 167 billion tons of carbon accumulation, though they provide no cost figures.

Two other studies that provide estimates of carbon sequestration potential without analyzing costs suggest that Australia and New Zealand could capture carbon at a rate of 7 million tons per year and 5 million tons per year, respectively, for 25 to 30 years (Barson and Gifford, 1990; Tasman Institute, 1994). For Mexico, India, and China it is estimated that approximately 3.5 billion tons, 8.7 billion tons, 9.8 billion tons, respectively, could be accumulated (Masera et al., 1995; Ravindranath and Somashekhar, 1995; Xu, 1995).

9. Discussion

Carbon sequestration cost analysis has developed substantially over the past dozen years. The first cost study, Sedjo and Solomon (1989), was essentially a 'back-of-the envelope' calculation based on globally aggregated estimates of land costs and carbon yields. The first cost-effectiveness study, Moulton and Richards (1990) was mostly a 'bean-counting' analysis that had limited economic content. However, in those studies lay the seed for future development. Both of the studies raised the issue of whether forests in a carbon sequestration program would be harvested and how that decision would affect the carbon sequestration costs. Foreshadowing the problems of leakage and rising land costs, Moulton and Richards (1990) advised that 'further research should consider nonmarginal changes in costs associated with very large-scale reforestation in a general equilibrium context'.

As more studies have emerged, the techniques have become more sophisticated, particularly in the area of land costs. The point estimates of land costs in Moulton and Richards (1990) evolved to reflect increasing marginal costs through elasticity figures in Richards et al. (1993) and Richards (1997). Adams et al. (1993) and Parks and Hardie (1995) introduced an implicit cost for land, measured as loss of consumer surplus or foregone agricultural returns. Stavins (1999) and Plantinga et al. (1999) introduced econometric methods based on historic landowner responses to timber market price signals.

While early studies simply raised the issue of harvesting (Sedjo and Solomon, 1989; Moulton and Richards, 1990) and timber disposal (Nordhaus, 1991), recent studies have begun rudimentary efforts to address the issue. For example, Stavins (1999) included calculations of additional carbon stored in wood products. However, that analysis was strictly partial equilibrium and did not consider whether there would be a 'crowding out' effect such that there was little or no net increase in the size of the wood product carbon sink. A recent study by Sohngen and Mendelsohn (2001) addressed the issue by including a wood product sector, though it is difficult to tell exactly how that market was modeled.

Early studies did little to address the issue of leakage (see Note 3). A form of leakage that is particularly important stems from the fact that as agricultural land is converted to forestland for carbon sequestration, there will be a corresponding pressure to convert unprotected, unsubsidized forestland into agricultural land. Alig et al. (1997) demonstrated that this countervailing pressure is serious enough that the accomplishments of a national carbon sequestration program could be largely dissipated over several decades as existing forestland is converted in response to rising agricultural land prices. Stavins (1999) addressed this issue in his model by allowing land conversion to occur in both directions, depending upon the relative rates of return between the two uses. Sohngen, Mendelsohn and Sedjo (1998) also demonstrated that the problem has a transboundary aspect. Because the timber market is global is scope, forest protection and expansion programs in one part of the world can be counterbalanced by market responses in other regions.

The accounting and reporting methods for carbon sequestration cost studies have also developed over time. Where Moulton and Richards (1990) employed a levelized cost approach, Richards et al. (1993) developed the discounting approach to accommodate an uneven flow of carbon over time. Stavins (1999) introduced the concept of converting present ton equivalents into a carbon annuity for purposes of comparing studies.

One of the difficulties of interpreting and comparing carbon sequestration cost studies is that there is no uniform format or methods for analysis. As research progresses, studies will be more comparable with each other and with non-forest mitigation options if they adopt a few common practices. First, the Stavins method of discounting and annualizing carbon flows provides the greatest comparability among studies. Further, studies that include a sensitivity analysis with a discount rate of zero will implicitly include the flow summation method of accounting.

Second, presenting results in both marginal and average cost curves will increase comparability and reduce confusion. Third, to the extent possible, studies should avoid artificial program constraints. The study by Parks and Hardie (1995) developed high estimates of carbon costs in part because they constrained the analysis to only ten years. When Alig et al. (1997) analyzed a program that forced particular patterns of carbon flow without allowing fungibility among the years, they raised the unit costs of carbon. Fourth, studies will be more transparent if they are explicit about the data and methods they use. In many cases it has been impossible to verify the results of studies. Finally, the results of studies will be more easily interpreted if, where possible, they disaggregate their cost components, particularly reporting on the explicit or implicit cost (shadow price) of land.

10. Conclusions

This review of carbon sequestration cost studies and related papers leads to several conclusions. First, full carbon sequestration cost studies all contain essentially the same components: a description of the new forestry practices that will lead to higher sequestration rates, a description of the land area over which the forestry practice will hypothetically be applied, the change in carbon uptake rate associated with the forestry practice, and the costs of the land, materials, and labor required to implement the new forestry practice. However, carbon sequestration cost studies are not comparable on their face due to the inconsistent use of terms, geographic scope, assumptions, and methods.

Second, there are at least three distinctly different definitions for a ‘ton of carbon’ that in turn lead to significantly different meanings for the summary statistic ‘dollars per ton of carbon’. This difference in carbon accounting further complicates comparison of studies.

Third, studies have not only used different ecosystem components and yield levels for carbon, but different yield formats, including average yield, cumulative lifetime yield, and yield curves. These differences further complicate direct comparison of study results.

Fourth, there are three distinct approaches for comparing the most important component of carbon sequestration costs – land opportunity cost. These include bottom-up engineering analysis based on observed land sale or lease prices, sectoral models that estimate lost social surplus as land is shifted out of agricultural production, and econometric models that model historic land owner response to relative timber and agricultural prices.

After adjusting for the variation among the studies, it seems that carbon sequestration may play a substantial role in a global greenhouse gas emissions abatement program. It appears that in the cost range of 10 to 150 dollars per ton of carbon[21] it may be possible to sequester 250 to 500 million tons per year in the United States, and upwards of 2,000 million tons per year globally. In the United States, the more optimistic estimates would suggest that as much as 40 percent of 1990 U.S. emissions could be reduced through forest programs with marginal costs of less than 60 dollars per ton. More recent, conservative estimates indicate that these costs may be doubled (Stavins, 1999). It is important to note, however, that when compared to source control of fossil fuel emissions, even the estimates of Stavins (1999) for the Unites States and Sohngen and Mendelsohn (2001) for the world suggest that one third to one half of a sizable carbon reduction program could be cost effectively accomplished through carbon sequestration.

However, all estimates are subject to considerable uncertainty. Preliminary results suggest that market interactions in carbon sequestration program analyses require considerably more attention. This is especially true for interactions between the forest and agricultural land markets and between the wood product sink and the timber markets. As a consequence it is possible that there may be substantial secondary losses associated with a large scale carbon sequestration program. Under some implementation scenarios, governments may spend billions of dollars and achieve no net increase in long term carbon sequestration. None of the studies have adequately addressed implementation issues that may prove to be the greatest determinants of the cost-effectiveness of the carbon sequestration option.

The uncertainty, however, lies on both sides of the cost estimates. Studies have generally not addressed the secondary effects of afforestation. Preliminary results suggest that the secondary benefits may be significant, making carbon sequestration a 'no-regrets' mitigation option.

In sum, this review of carbon sequestration cost studies suggests that there remains much work to be done in the area of carbon sequestration costs analysis. In particular, studies that capture the interaction of carbon sequestration programs with other environmental goals and with the energy, agriculture and forestry sectors would be particularly helpful.

Acknowledgements and Disclaimer

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Appendix: Proof of Equivalency of Levelization and Discounting Methods of Carbon Accounting

This appendix provides a proof of the equivalency of the 'discounting' and the 'levelizing' approach to the cost effectiveness calculation.

Consider two expressions from financial analysis/engineering economics. The single payment compound amount, $(1+i)^n$, expresses the future value of a present payment, where i is the interest rate and n is the year in the future. The single payment present worth factor, $1/(1+i)^n$, is the present worth of a future payment in year n.

A general result for the equivalency of the levelization and discounting approach can be derived as follows. Consider a general carbon reduction problem where X expresses the initial capital outlay at time $t = 0$, and Y_j is the capture of carbon in year j, with j ranging from 1 to n. The discounting approach to deriving the unit cost yields:

$$\text{Unit cost}\left(\frac{\$}{\text{PTE}}\right) = \frac{X}{\displaystyle\sum_{j=1}^{n} \frac{Y_j}{(1+i)^j}} \,. \tag{A.1}$$

Now consider the levelizing approach. The initial cost, X, must be allocated among the years in such a way that the NPV of the sum of the allocations is equal to X. That is

$$\sum_{j=1}^{n} \frac{X_j}{(1+i)^j} = X \,, \tag{A.2}$$

where X_j is the nominal amount allocated to year j. The basic condition for deriving the unit cost with this method requires that the unit costs be equivalent in each year.

$$\frac{X_1}{Y_1} = \frac{X_2}{Y_2} = \cdots = \frac{X_n}{Y_n} \,. \tag{A.3}$$

Expression (A.3) provides $n-1$ equations, and (A.2) provides one more, thus allowing solution for the n unknowns X_1 to X_n. Solve expression (A.3) for X_2 to X_n in terms of X_1.

$$\begin{aligned} X_2 &= \frac{X_1 Y_2}{Y_1} \\ &\vdots \\ X_n &= \frac{X_1 Y_n}{Y_1}\,. \end{aligned} \tag{A.4}$$

Substitute the expressions in (A.4) into Equation (A.2), and multiply both sides by Y_1.

$$\frac{X_1 Y_1}{(1+i)^1} + \frac{X_1 Y_2}{(1+i)^2} + \cdots + \frac{X_1 Y_n}{(1+i)^n} = X Y_1\,. \tag{A.5}$$

Separate the X_1 on the left hand side,

$$X_1 \left(\sum_{j=1}^{n} \frac{Y_j}{(1+i)^j} \right) = X Y_1\,. \tag{A.6}$$

The solution for X_1 follows immediately since X and all Y_j are given. More importantly,

$$\frac{X_1}{Y_1} = \frac{X}{\displaystyle\sum_{j=1}^{n} \frac{Y_j}{(1+i)^j}}\,. \tag{A.7}$$

The right hand side of (A.7) is equivalent to the expression of unit costs in Equation (A.1), which was derived using the discounting approach. The left hand side of (A.7) is one of the n expressions of unit costs in the levelization approach. This proves that the two approaches yield identical results.

Notes

[1] Earlier studies raised the question of whether expanded forests could help offset rising carbon dioxide levels in the atmosphere (Cooper, 1983; Brown et al., 1986; Woodwell, 1988; and Marland, 1988), but Sedjo and Solomon (1989) provided the first estimate of the cost of a large-scale carbon sequestration program. For a nearly identical analysis see Sedjo (1989).

[2] These would be annualized present tons equivalent (PTEs). See Section 3.1 for a discussion of the various definitions of a ton of carbon. The term 'ton' refers to a metric ton unless otherwise stated.

[3] 'Leakage' occurs when the effects of a program or project lead to a countervailing response beyond the boundary of the program or project. For example, if forestland is preserved in one region

the unchanged demand for agricultural land and forest products could lead to increased forest clearing and conversion in another region. Thus the effects of the preservation may be partially or entirely undone by the leakage.

[4] Both biomass crops and urban forestry present special challenges for cost analyses because they involve interactions with the energy sector through fossil fuel replacement and demand reduction, respectively.

[5] Because the baseline represents levels of carbon and sequestration costs in the absence of carbon management programs, it is implicit that the shadow price or imputed costs of any carbon storage are zero. The analysis by Lewis et al. (1996) demonstrated the difficulty that arises in the absence of a well-defined baseline. They examined four policy scenarios for carbon management in the United States, but one of the scenarios is the base projection in the absence of carbon policy intervention. Nonetheless, based on their assumed value of forestland and timber stock inventories, management costs, and annual net growth of timber, they calculated that the cost of carbon sequestration in existing forests was 400 dollars per ton. This implies that even in the absence of any incentives or explicit programs to encourage carbon sequestration, the nation is incurring substantial costs to sequester carbon.

[6] The cost of inputs is generally, although not always, expressed as either the net present value of all inputs or the amortized (annual) value of inputs.

[7] The proof of the equivalency of these two approaches is provided in the technical appendix. See also, Richards (1997b) for a discussion of the time-value of carbon benefits in cost analyses.

[8] Similarly, in a cost-effectiveness calculation, by treating carbon capture as if its value is independent of when it occurs, the analyst is implicitly assuming that the marginal value of damage is rising at the social discount rate.

[9] One referee correctly pointed out that the flow summation and the average storage methods yield the same result for cases that do not involve harvesting. The authors are grateful for this observation.

[10] In the case of carbon conservation practices (e.g., deforestation prevention) it is possible to report figures in terms of 'tons per hectare per year' when the analysis recognizes that carbon loss in the baseline (reference case) would not have all occurred at the same time. The data in this case would be an array of values representing the difference between baseline levels of annual flows (release) of carbon and the annual flows (or lack of flows) with the program or practice in place.

[11] Note that Slangen and van Kooten (1996) used the discount method to analyze a case based on average carbon flow data. They could have used the levelized cost approach to achieve identical results.

[12] Adams et al. (1993) was a precursor to the FASOM model, as was Callaway and McCarl (1996). Alig et al. (1998) also described and employed the FASOM model.

[13] In a subsequent study, Adams et al. (1999) employed the FASOM model to examine several scenarios similar to those in Alig et al (1997). The results of this latter study essentially followed the findings of the earlier analysis.

[14] The three strategies were (1) establishing plantations in Europe and North America without harvest of those plantations, (2) establishing plantations in Europe and North America with harvest when the trees have matured, and (3) establishing plantations in subtropical regions with harvest when the trees have matured.

[15] Plantinga and Mauldin (2000) developed a similar econometric analysis that provided results in terms of average (rather than marginal) cost curves.

[16] Plantinga et al. (1999) and Plantinga and Maudlin (2000) use a similar approach and find a similar effect.

[17] Neither Houghton et al. (1993) or Sohngen, Mendelsohn and Sedjo (1998) provided cost estimates.

[18] The flow summation method will generally produce lower estimates than the levelized/discounting method (see Section 3.1). The average cost curve will lie below the marginal cost curve (see Section 3.2).

[19] Parks and Hardie (1995) report their estimated marginal costs in two formats. The first set, which they refer to as dollars per ton, falls in the range of 37 to 735 dollars per metric ton. This figure would be more accurately labeled dollars per ton per year since it refers to the present cost of establishing a flow of carbon over many years. Their second set of figures, which they refer to as the 'annual equivalents' of the dollar per ton, fall in the range of 5 to 90 dollars per metric ton. This range is derived by annualizing the establishment and land costs to a figure for dollars per year, and dividing by the annual capture of carbon in tons per year, to yield a true dollars per ton figure. This anomaly in accounting has led to considerable confusion when comparing the results of this study to the figures derived in other studies.

[20] Newall and Stavins (2000) reported the same result.

[21] Expressed in terms of annualized present tons equivalent (PTEs) (c.f. Section 3.1).

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