The Costs of Carbon Sequestration: A Revealed-Preference Approach

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Increased concern by policy makers with the threat of global climate change has brought with it considerable attention to the possibility of encouraging the growth of forests as a means of sequestering carbon dioxide (National Academy of Sciences [NAS], 1992; James P. Bruce et al., 1996).[1] The Kyoto Protocol to the United Nations Framework Convention on Climate Change (1997), which establishes emission reduction targets for the United States and other industrialized nations, states that carbon sequestration can be used by participating nations to achieve their targets. Moreover, even before the Kyoto agreement, this approach had become an explicit element of both U.S. and international climate policies (U.S. Department of Energy, 1991; United Nations General Assembly, 1992; William J. Clinton and Albert Gore, 1993). This high level of interest has been due, in part, to: suggestions that sufficient lands are available to use the approach to mitigate a substantial share of annual carbon dioxide (CO_2) emissions (Greg Marland, 1988; Daniel A. Lashof and Dennis A. Tirpak, 1989; Mark C. Trexler, 1991); and claims that growing trees to sequester carbon is a relatively inexpensive means of combating climate change (Roger A. Sedjo and Allen M. Solomon, 1989; Daniel J. Dudek and Alice LeBlanc, 1990; NAS, 1992). In other words, the serious attention given by policy makers to carbon sequestration can partly be explained by (implicit) assertions about respective marginal cost functions.

I develop and demonstrate a method by which the costs of carbon sequestration can be estimated on the basis of evidence from landowners' behavior when confronted with the opportunity costs of alternative land uses. The simplest of previous economic analyses derived single point estimates of average costs associated with particular sequestration levels (Marland, 1988; Sedjo and Solomon, 1989; Dudek and LeBlanc, 1990; Edwin S. Rubin et al., 1992; Omar Masera et al., 1995). Often it has been assumed that land (opportunity) costs are zero (G. van Kooten et al., 1992; J. K. Winjum et al., 1992; New York State Energy Office, 1993; Robert K. Dixon et al., 1994). Another set of studies—essentially "engineering/costing models"—has constructed marginal cost schedules by using information on revenues and costs of production for alternative uses on representative types or locations of land, and then sorting these in ascending order of cost (Robert J. Moulton and Kenneth R. Richards, 1990; Richards et al., 1993). Simulation models include a model of the lost profits due to removing land from agricultural production (Peter J. Parks and Ian W. Hardie, 1995), a mathematical programming model of the agricultural sector and the timber market (Richard M. Adams et al., 1993), a related model incorporating the effects of agricultural price support programs (J. M. Callaway and Bruce McCarl, 1996), and a dynamic simulation model of forestry (Susan Swinehart, 1996). Lastly, an analysis by Andrew J. Plantinga (1995) adopts land-use elasticities from an econometric study to estimate sequestration costs. We draw on some of the best features of the previous studies, including the carbon levelization method of Moulton and Richards

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[1] After fossil-fuel combustion, deforestation is the second largest source of carbon dioxide emissions. Estimates of annual global emissions from deforestation range from 0.6 to 2.8 billion tons, compared with slightly less than 6.0 billion tons annually from fossil-fuel combustion, cement manufacturing, and natural gas flaring, combined (R. A. Houghton, 1991; T. M. Smith et al., 1993).

(1990) and Adams et al. (1993), and the intertemporal carbon yield curves of Richards et al. (1993).

Nearly all of the previous analyses are potentially limited by their inability to reflect the actual preferences of landowners, as revealed—for example—by landowners' decisions regarding the disposition of their lands in the face of relevant economic signals.[2] There are a number of reasons why landowners' actual behavior might not be well predicted by "engineering" or "least-cost" analyses: (1) land-use changes can involve irreversible investments in the face of uncertainty (Parks, 1995), and so option values may be important (Robert S. Pindyck, 1991); (2) there may be nonpecuniary returns to landowners from forest uses of land (Plantinga, 1995), as well as from agricultural uses; (3) liquidity constraints or simple "decision-making inertia" may mean that economic incentives will affect landowners only with some delay; and (4) there may be private, market benefits or costs of alternative land uses (or of changes from one use to another) of which an analyst is unaware.

I seek to address at least some of these problems by employing an econometric model to derive the costs of carbon sequestration. The paper is intended to be illustrative of how econometric analyses of land use, which already exist for a number of countries, can be used to develop better region-specific estimates of the marginal costs of carbon sequestration.[3] In Section I of the paper, I describe an econometric model of land use; in Section II, I develop a simulation model of carbon sequestration; in Section III, I derive our marginal cost results; in Section IV, I compare my results with other estimates of carbon sequestration costs and with estimates of the cost of abating carbon emissions through fuel switching and energy-efficiency enhancements; and in Section V, I offer some conclusions.

[2] Plantinga's (1995) analysis of southwestern Wisconsin is an exception; it is similar in some respects to my method, although the former model requires information on land characteristics (quality) *within* counties, whereas my approach is based upon an econometric model in which the unobserved heterogeneity of land is parameterized and thus estimated simultaneously with other structural parameters. Thus, the potential advantage of the present approach is simply that its data requirements are less, which could be important if a nationwide land-use analysis were carried out.

[3] Another possibility—in theory—would be to employ land sale price data, reflecting anticipated values of net returns to alternative uses. But useful price data are not available for sufficiently diverse geographic areas over time.

I. Econometric Model of Land Use

In previous work with a distinctly different policy motivation, a dynamic optimization model was developed of a landowner's decision of whether to keep his or her land in its status quo use or convert it to serve another purpose (Stavins, 1990; Stavins and Adam B. Jaffe, 1990). Landowners are assumed to observe current and past values of economic and other factors relevant to decisions regarding the use of their lands for forestry or agriculture,[4] and on this basis form expectations of future values of respective variables. Landowners are assumed to attempt to maximize the expected long-term economic return to their land. Thus, a risk-neutral landowner will seek to maximize the present discounted value of the stream of expected future returns:

$$(1) \quad \max_{\{g_{ijt}, v_{ijt}\}} \int_0^\infty [(A_{it}q_{ijt} - M_{it})(g_{ijt} - v_{ijt}) - C_{it}^{\alpha P_{it}} g_{ijt} + f_{it}S_{ijt} + W_{it}g_{ijt} - D_{it}v_{ijt}]e^{-r_i t}\, dt$$

$$(2) \quad \text{subject to:} \quad \dot{S}_{ijt} = v_{ijt} - g_{ijt}$$

$$(3) \quad 0 \leq g_{ijt} \leq \bar{g}_{ijt}$$

$$(4) \quad 0 \leq v_{ijt} \leq \bar{v}_{ijt}$$

where i indexes counties, j indexes individual land parcels, and t indexes time; uppercase letters are stocks or present values; and lowercase letters are flows. The variables are:

A_{it} = present value of typical expected agricultural revenues per acre in county i and time t;

[4] In both industrialized nations and in developing countries, nearly all deforestation is associated with conversion to agricultural use (C. J. Jepma et al., 1996). The previous work by Stavins and Jaffe (1990) focused on forested wetlands, but that quantitative analysis was of all forested areas.

q_{ijt} = index of feasibility of agricultural production (including effects of soil quality and moisture);
g_{ijt} = acres of land converted from forested to agricultural use (deforestation);
v_{ijt} = acres of cropland returned to a forested condition (forestation);
M_{it} = expected cost of agricultural production per acre, expressed as present value of future stream;
C_{it} = average cost of conversion per acre;
P_{it} = Palmer hydrological drought index (to allow precipitation and soil moisture to influence conversion costs);
f_{it} = expected annual net income from forestry per acre (annuity of stumpage value);
S_{ijt} = stock (acres) of forest;
r_t = real interest rate used by landowners for investment decisions, linked with their private pretax rate of return;
W_{it} = net revenue per acre from one-time forest harvest (prior to conversion to agricultural use);
D_{it} = expected present discounted value of loss of income (when converting to forest) due to gradual regrowth of forest (first harvest occurs in year $t + R$, where R is rotation length);
$\bar{g}_{ijt}$ = maximum feasible rate of deforestation; and
$\bar{v}_{ijt}$ = maximum feasible rate of forestation.

As is described in Stavins and Jaffe (1990), application of control theoretic methods yields a pair of necessary conditions for changes in land use. Forestation (conversion of agricultural cropland to forest) occurs if a parcel is cropland and:

$$(5) \qquad (F^*_{it} - A_{it} \cdot q_{ijt} + M_{it}) > 0$$

where F^*_{it}, delayed net forest revenue, equals $F_{it} - D_{it}$, and $F_{it} = f_{it}/r_t$. That is, a parcel of cropland should be converted to forestry use if the present value of expected net forest revenue exceeds the present value of expected net agricultural revenue. On the other hand, deforestation occurs if a parcel is forested and:

$$(6) \qquad (A_{it} \cdot q_{ijt} - M_{it} - C_{it}^{\alpha P_{it}} - FN_{it}) > 0$$

where FN_{it}, net forest revenue, equals $F_{it} - W_{it}$. That is, a forested parcel should be converted to cropland if the present value of expected net agricultural revenue exceeds the present value of expected net forest revenue plus the cost of conversion.

Inequalities (5) and (6) imply that all land in a county of given quality will be in the same use in the steady state but, in reality, counties are observed to be a mix of forest and farmland. Although this may partly reflect deviations from the steady state, it is due largely to the *heterogeneity* of land, particularly in regard to its quality (suitability) for agriculture. If conversion cost is allowed to be heterogeneous across land parcels (within counties) and flood-control projects affect conversion costs as well as agricultural feasibility (yields), then the conversion cost term in equation (1) is multiplied by q_{ijt}. Such unobserved heterogeneity can be parameterized within an econometrically estimatable model so that the *individual* necessary conditions for land-use changes [equations (5) and (6)] aggregate into a single-equation model, in which the parameters of the basic benefit-cost relationships and of the underlying, unobserved heterogeneity can be estimated simultaneously:

$$(7) \qquad FORCH_{it} = FORCH^a_{it} \cdot D^a_{it} - FORCH^c_{it} \cdot D^c_{it} + \lambda_i + \phi_{it}$$

$$(8) \qquad FORCH^a_{it} = \gamma_a \cdot \left[d_{it} \cdot \left[F\left[\frac{\log(q^y_{it}) - \mu(1 + \beta_2 E_{it})}{\sigma(1 + \beta_3 E_{it})} \right] \right] + (1 - d_{it}) - \left[\frac{S}{T} \right]_{i,t-1} \right]$$

$$(9) \qquad FORCH^c_{it} = \gamma_c \cdot \left[d_{it} \cdot \left[1 - F\left[\frac{\log(q^x_{it}) - \mu(1 + \beta_2 E_{it})}{\sigma(1 + \beta_3 E_{it})} \right] \right] + \left[\frac{S}{T} \right]_{i,t-1} - 1 \right]$$

(10) $$d_{it} = \left[\frac{1}{1 + e^{-(N_i + \beta_1 E_{it})}} \right]$$

(11) $$q^y_{it} = \left[\frac{F^*_{it} + M_{it}}{A_{it}} \right]$$

(12) $$q^x_{it} = \left[\frac{FN_{it} + M_{it}}{A_{it} - C_{it}^{\alpha P_{it}}} \right]$$

where all Greek letters are parameters that can be estimated econometrically; $FORCH_{it}$ is the change in forest land as a share of total county area; $FORCH^a_{it}$ is forestation (abandonment of cropland) as a share of total county area; $FORCH^c_{it}$ is deforestation (conversion of forest) as a share of total county area; D^a_{it} and D^c_{it} are dummy variables for forestation and deforestation, respectively; λ_i is a county-level fixed-effect parameter; ϕ_{it} is an independent (but not necessarily homoskedastic) error term; γ_a and γ_c are partial adjustment coefficients for forestation and deforestation; F signifies the cumulative, standard normal distribution function; q^y_{it} is the threshold value of (unobserved) land quality (suitability for agriculture) below which the incentive for forestation manifests itself; q^x_{it} is the threshold value of land quality above which the incentive for deforestation manifests itself; T_{it} is total county area; N_i is the share of a county that is naturally protected from periodic flooding; E_{it} is an index of the share of a county that has been artificially protected from flooding by federal programs (by time t); μ is the mean of the unobserved land-quality distribution; and σ is the standard deviation of that distribution.

Using panel data for 36 counties in Arkansas, Louisiana, and Mississippi, during the period 1935–1984, the parameters of the model embodied in equations (7) through (12) were estimated with nonlinear least-squares procedures (Stavins and Jaffe, 1990).[5]

II. Simulation Model of Carbon Sequestration

The initial step—conceptually—in moving from an estimated model of historical land use to a model of carbon sequestration involves introducing relevant silvicultural elements: (1) the possibility of "tree farming," that is, intensive management of forests, which brings with it significant costs of establishment; (2) alternative species, in particular, mixed stands and tree farms (pine plantations); and (3) alternative management regimes. Whereas the historical analysis assumed that all forests were periodically harvested, one might also consider the possibility of establishing "permanent stands" of biomass that are never harvested.

Next, simply as a means to generating a forest acreage supply function, consider a two-part policy that combines a subsidy on the flow of newly forested land with a tax on the flow of (new) deforestation. As a first approximation, the two price instruments can be set equal, although this is not necessarily efficient. We can treat the subsidy as an increment to forest revenues in the forestation part of the model [equation (8)] and treat the tax payment as an increment to conversion or production costs in the deforestation part of the model [equation (9)]. Letting Z_{it} represent the subsidy and tax, the threshold equations [(11) and (12)] for forestation and deforestation, respectively, become:

(13) $$q^y_{its} = \left[\frac{(F^*_{its} + Z_{it}) + M_{it} - K_{it}}{A_{it}} \right]$$

(14) $$q^x_{its} = \left[\frac{FN_{its} + (M_{it} + Z_{it})}{A_{it} - C_{it}^{\alpha P_{it}}} \right]$$

where

F^*_{its} = delayed net forest revenue ($F_{its} - D_{its}$), now subscripted by s to indicate species (mixed stand or pine), and set equal to zero for the case of permanent (unharvested) stands;

K_{it} = establishment costs associated with planting a pine-based tree farm.

[5] The time dimension of the panel had observations every five years; hence, the time series contained ten periods, and the entire panel contained 360 observations. Estimated parameters were all of the expected sign, and nearly all estimates were significant at the 90-, 95-, or 99-percent level. Both parameter and standard error estimates were robust with respect to modifications of the specification, and the dynamic goodness-of-fit, based upon Henri Theil's (1961) measure, was 0.675.

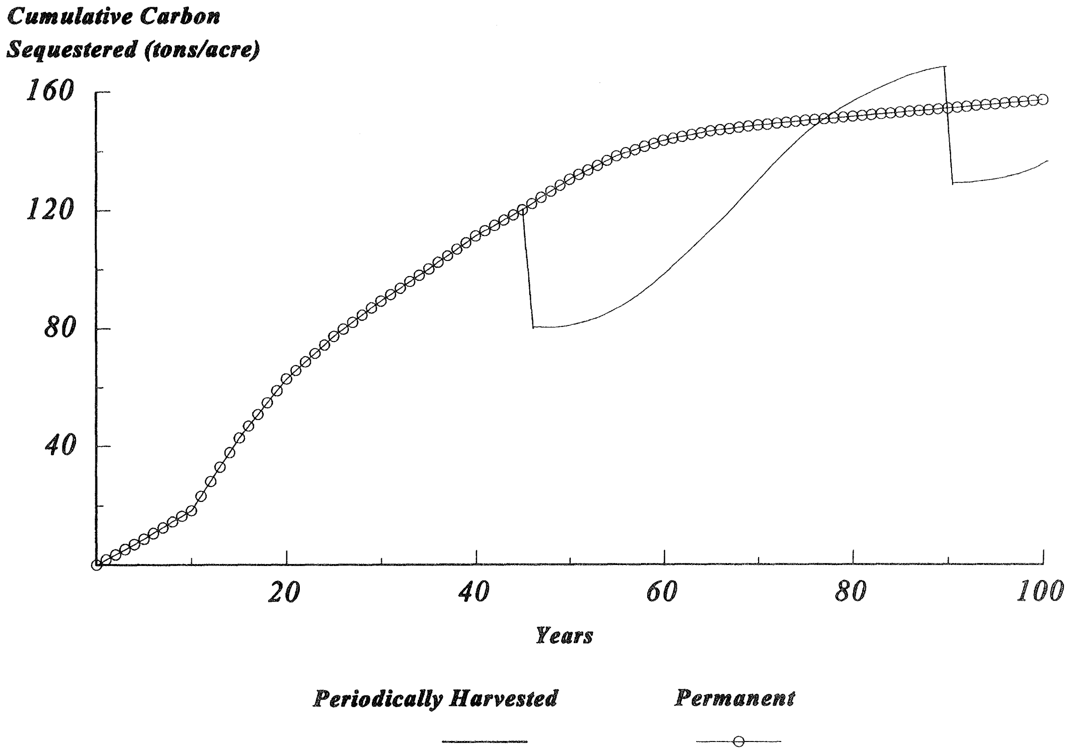

FIGURE 1. TIME PROFILE OF CARBON SEQUESTRATION
(Loblolly Pine in Delta States Region)
Sources: Based on data from Moulton and Richards (1990) and Richards (1994).

A dynamic simulation, based upon equations (7), (8), (9), (10), (13), and (14), in which the variable Z is set equal to zero, will generate a baseline quantity of forestation/deforestation over a given time period. By carrying out simulations for various values of Z over the same time period, and subtracting the results of each from the baseline results, we can trace out a forest acreage supply function, with marginal cost per acre (Z) arrayed in a schedule with total change in acreage over the time period, relative to the baseline.[6]

Now we need to link carbon sequestration (and emissions) with forestation (and deforestation). Figure 1 provides a representation of the time path of carbon sequestration and emission linked with a specific forest-management regime. In the example depicted in the figure, the time profile is of cumulative carbon sequestration associated with establishing a *new* loblolly pine plantation. Carbon sequestration occurs in four components of the forest: trees, understory vegetation, forest floor, and soil (Richard A. Birdsey, 1993).[7] When the plantation is man-

[6] A central assumption underlying the use of an econometric approach to simulating carbon sequestration costs is that estimated parameters remain valid with variable values employed in the counterfactual simulations; in particular, that landowners can be expected to react to carbon taxes or subsidies the same as they have reacted to *equivalent* changes in the relative revenues and costs associated with timber and agricultural crop production. A referee notes that—depending upon the forces behind the partial adjustment coefficients—those coefficients may be sensitive to the change.

[7] Although the shares vary greatly among forest types, reference points are: tree carbon contains about 80 percent of ecosystem carbon, soil carbon about 15 percent, forest litter 3 percent, and the understory 2 percent. Soil carbon is defined as all organic matter to a depth of one meter, excluding coarse tree roots larger than 2 millimeters in diameter (which are classified as part of "tree carbon"). The variation in these shares is significant; for some species, soil carbon accounts for nearly 50 percent of total forest carbon.

aged as a permanent stand, cumulative sequestration increases monotonically, with the magnitude of annual increments declining so that an equilibrium quantity of sequestration is essentially reached within a hundred years, as material decay comes into balance with natural growth.

The figure also shows the cumulative carbon sequestration path for a similar stand that is periodically harvested (with 45-year rotations). In this case, carbon accrues at the same rate as in a permanent stand until the first harvest, when a substantial amount of carbon is released as a result of harvesting, processing, and manufacturing of derivative products. Much of the carbon sequestered in wood products is also released to the atmosphere, although this occurs with considerable delay as wood products gradually decay.[8] As can be seen in the figure, in this scenario the forest is replanted, and the same process takes place again.

Although the carbon yield curve with harvesting in Figure 1 eventually moves above the yield curve for a "permanent" stand, this need not be the case. It depends upon the share of carbon that is initially sequestered in wood products and upon those products' decay rates (plus the decay rate of soil carbon). With zero decay rates, the peaks in the harvesting yield curve would increase monotonically, but with positive decay rates, the locus of the peaks approaches a steady-state quantity of sequestration, and that quantity can, in theory, lie above or below the level associated with the equilibrium level of the "permanent" yield curve.[9]

The intertemporal nature of net carbon sequestration raises a question: how can we associate a number—the marginal cost of carbon sequestration—with units of carbon that are sequestered in different years? This is important if we wish to compare the costs of carbon sequestration with the costs of conventional carbon abatement measures, such as fuel switching and energy-efficiency enhancements. Previous sequestration studies have used a variety of methods to calculate costs in terms of dollars per ton, the desired units for a cost-effectiveness comparison (Richards and Carrie Stokes, 1995). My approach is to divide the discounted present value of costs by the discounted present value of tons sequestered. This may be thought of as assuming that the marginal damages associated with additional units of atmospheric carbon are constant and that benefits (avoided damages) and costs are to be discounted at the same rate. Note that such an assumption of constant marginal benefits is approximately correct if marginal damages are essentially proportional to the rate of climate change, which many studies have asserted. I initially use a 5-percent real rate, supplemented by sensitivity analysis.

By developing the constituent intertemporal yield curves (and net revenue streams) for different species, location, and management conditions, a set of present-value equivalent carbon sequestration measures can be calculated. By way of example, I focus on periodically harvested pine, and assume that when and if deforestation occurs, on-site merchantable timber is sold.[10] In this case,

My calculations of releases from the understory, forest floor, soil, and nonmerchantable timber are based upon Moulton and Richards (1990) and Richards et al. (1993).

[8] The share of forest carbon that goes into merchantable wood varies considerably. A reference point is about 40 percent. Much of the remaining 60 percent is released at the time of harvest and in the process of manufacturing wood products (in both cases through combustion), the major exception being soil carbon, which exhibits a much slower decay rate (reasonably assumed to be zero in some cases). As Sedjo et al. (1994 p. 23) point out, examinations of the long-term effects of timber growth on carbon sequestration are "highly dependent upon the assumptions of the life cycle of the wood products." M. E. Harmon et al. (1990) found this to be the case in their scientific review. The two critical parameters are the assumed length of the life cycle of wood products, and the assumed share of timber biomass that goes into long-lived wood products. Drawing upon the work of Clark Row and Robert B. Phelps (1990), Row (1992), and D. P. Turner et al. (1993), I develop a time path of gradual decay of wood products over time, based upon an appropriately weighted average of pulpwood, sawlog, hardwood, and softwood estimates from Plantinga and Birdsey (1993). The final profile is such that one year following harvest, 83 percent of the carbon in wood products remains sequestered; this percentage falls to 76 percent after 10 years, and 25 percent after 100 years (and is assumed to be constant thereafter). At an interest rate of 5 percent, the present-value equivalent sequestration is approximately 75 percent, identical to that assumed by William D. Nordhaus (1991).

[9] A potential scenario that I do not consider is that harvested wood is used for fuel. If this were used to produce electricity or liquid fuels such as methanol, thereby substituting for fossil-fuel use, then the *net* impact on atmospheric CO_2 emissions of each unit of forestation would be significantly enhanced.

[10] For a comparison of sequestration costs under different management regimes and other conditions, see Richard G. Newell and Stavins, 1998. The growth curves that underlie

TABLE 1—DESCRIPTIVE STATISTICS[a]

Variable	Mean	Standard deviation
Gross agricultural revenue ($/acre/year)	259.04	44.58
Agricultural production cost ($/acre/year)	220.39	52.03
Forest revenue[b] ($/acre/year)		
Mixed stand (prior to deforestation)	19.29	7.45
Pine stand (subsequent to forestation)	58.96	23.38
Tree-farm establishment cost ($/acre)	92.00	0.00
Conversion cost ($/acre)	27.71	6.73
Fraction of county naturally protected from periodic flooding	0.614	0.264
Index of artificial flood protection	0.371	0.371
Palmer hydrological drought index	0.74	0.84
Carbon sequestration due to forestation[c] (tons/acre)		
Pine plantation periodically harvested	41.05	0.00
Carbon emissions due to deforestation, with sale of merchantable timber[d] (tons/acre)	51.83	0.00
Interest rate[e]	5 percent	0.00

[a] The sample is of 36 counties in Arkansas, Louisiana, and Mississippi, located within the Lower Mississippi Alluvial Plain. All monetary amounts are in 1990 dollars; means are unweighted county averages.
[b] Gross forest revenue minus harvesting costs; an annuity of stumpage values.
[c] Present-value equivalent of net life-cycle sequestration.
[d] Present-value equivalent of net life-cycle emissions.
[e] The historical analysis uses actual, real interest rates; simulations of future scenarios use the 5-percent real rate.

the present value of net carbon sequestration associated with forestation is 41.05 tons per acre, and the present value of carbon emissions associated with deforestation is 51.83 tons (Table 1).

Finally, I define the present values (in year t) of the time paths of carbon sequestration and carbon emissions associated with forestation or deforestation occurring in year t as Ω_t^S and Ω_t^E, respectively. Thus, the total, present-value equivalent net carbon changes associated with a baseline or policy simulation are calculated as:

$$(15)\quad PV(SEQ) = \sum_{i=1}^{36}\left[\sum_{t=0}^{90}(FORCH_{it}^a \cdot D_{it}^a \cdot \Omega_t^S - FORCH_{it}^c \cdot D_{it}^c \cdot \Omega_t^E)\cdot(1+r)^{-t}\right]$$

$$(16)\quad \Omega_t^S = \sum_{h=t}^{90} CS_h \cdot (1+r)^{t-h}$$

$$(17)\quad \Omega_t^E = \sum_{h=t}^{90} CE_h \cdot (1+r)^{t-h}$$

where CS_h and CE_h are, respectively, annual incremental carbon sequestration and carbon emissions per acre, and $FORCH_{it}$, is simulated with equations (7), (8), (9), (10), (13), and (14), above.[11]

III. The Costs of Carbon Sequestration

It might be argued that since the policy intervention I model is a tax/subsidy on land use, not on carbon emissions and sequestration, it does not lead to the true (minimum) carbon sequestration marginal cost function. This criticism is not valid in a realistic policy context. It would be virtually impossible to levy a tax on carbon emissions or a subsidy on sequestration,

respective yield curves are themselves a function, partly, of precipitation and temperature, both of which are presumably affected in the long run by atmospheric concentrations of CO_2 and induced climate change (Dixon et al., 1994). I ignore this endogeneity to climate change in estimating sequestration costs, as have all previous studies. Likewise, all studies have ignored potential economic endogeneity of relevant variables to climate change (Brent Sohngen and Robert Mendelsohn, 1995).

[11] A 90-year period was used to allow at least one rotation of each forest species. Given the consequences of discounting, the results are not fundamentally affected by the length of the period of analysis, once that period exceeds 50 years or so.

TABLE 2—SIMULATED LAND CHANGES AND CARBON SEQUESTRATION
Periodically Harvested Pine Plantation, Sale of Merchantable Timber at Deforestation
Baseline deforestation = +51,654 acres Baseline carbon sequestration = 4,578,202 tons

Marginal cost per acre ($/acre/yr)	Forestation relative to baseline (1,000s acres)	Average cost per acre ($/acre/yr)	Annual carbon sequestration relative to baseline (1,000s tons/yr)	Marginal cost of carbon sequestration ($/ton)	Average cost of carbon sequestration ($/ton)
0	0	0.00	0	0.00	0.00
100	4,653	57.32	7,045	66.05	37.86
200	6,579	105.63	9,961	135.97	69.77
300	7,484	129.15	11,332	202.03	85.31
400	7,897	142.25	11,957	268.05	93.96
500	8,212	155.98	12,434	334.11	103.03
600	8,470	169.22	12,825	400.18	111.77
700	8,689	182.74	13,156	466.22	120.71
800	8,874	195.72	13,437	532.20	129.28
900	9,038	208.21	13,685	598.31	137.53
1,000	9,178	219.53	13,897	664.35	145.01

because the costs of administering such policy interventions would be prohibitive. Looked at this way, it becomes clear that such an instrument would likely be *more* costly per unit of carbon sequestered than would the deforestation tax/forestation subsidy policy instrument.

A simulation of equations (15), (16), and (17) with the subsidy/tax, Z, set equal to zero [in equations (13) and (14)] generates a baseline quantity of carbon sequestration/emissions. By subtracting this quantity from the results of simulations employing positive values of Z, we trace out a supply curve of net carbon sequestration, in which the marginal costs of carbon sequestration, measured in dollars per ton, can be arrayed in a schedule with net annual[12] carbon sequestration.

Table 2 provides the results for a periodically harvested pine plantation, with the sale of merchantable timber when/if deforestation occurs. Such a scenario is most directly comparable with those examined in other studies. The relatively attractive forest revenues associated with this management regime result in a small amount of net forestation taking place in the baseline simulation, a gain of about 52,000 acres (over the 90-year study period). Baseline net carbon sequestration is approximately 4.6 million tons annually. Marginal costs of carbon sequestration increase gradually, until these costs are about $66 per ton, where annual sequestration relative to the baseline has reached about 7 million tons. This level of sequestration is associated with a land-use tax/subsidy of $100 per acre and net forestation, relative to baseline, of 4.7 million acres.

Beyond this point, marginal costs depart more rapidly from a linear trend. Beyond about $200 per ton, they turn steeply upward. Indeed, the marginal cost function is nearly asymptotic to a sequestration level of about 15 to 16 million tons annually. This is not surprising, since such an implicit limit would be associated with net forestation of about 10.5 million acres, for a total forested area of 13 million acres, just shy of the total area of the study region.[13]

IV. Placing the Sequestration Cost Estimates in Context

In this section, I first seek to compare the estimated sequestration marginal cost function

[12] Recall that both dollars of costs and tons of sequestration (and emission) are discounted. Hence, annual sequestration refers to an annuity that is equivalent to a respective present value (employing a discount rate of 5 percent).

[13] Because of the long time horizon employed, it is natural to ask how sensitive are the results to the assumed interest rate. As the discount rate decreases, marginal sequestration costs decrease monotonically because the present-value equivalent sequestration increases with decreased interest rates. Later in the paper, when I compare marginal cost results with those from other sequestration and abatement studies, I always normalize the results so that all, in effect, employ the same discount rate.

TABLE 3—COMPARISON WITH RESULTS FROM OTHER STUDIES

Study	Total quantity		Average cost		Marginal cost	
	Land (million acres)	Carbon (million tons/yr)	Land ($/acre/yr)	Carbon ($/ton)	Land ($/acre/yr)	Carbon ($/ton)
This study[a]						
United States normalization	342	518	106	70	≤200	≤136
Delta states	5	7	58	38	≤100	≤66
Moulton and Richards (1990)						
United States[b]	269	690	—	27	≤81	≤37
Delta states cropland	25	67	50	22	—	—
Richards et al. (1993)						
United States[c]	244	416	—	—	—	≤41
Delta states cropland[d]	11	29	42	18	≤52	≤22
Adams et al. (1993)[e]	274	700	—	—	—	≤27
Nordhaus (1991)[f]	248	44	81	64	—	—
Parks and Hardie (1995)[g]	9	22	49	21	—	≤24
Rubin et al. (1992)[h]	71	73	—	23	—	—
Dudek and LeBlanc (1990)[i]	14	—	—	38	—	—
Plantinga (1995)[j]	0.65	1.5	—	—	—	6–13
Callaway and McCarl (1996)[k]	187	280	—	—	—	≤25

[a] Pine plantation, periodically harvested, at a 5-percent discount rate.
[b] Permanent stands on cropland and pastureland only, i.e., not forestland.
[c] Figure for total U.S. carbon sequestration is an annuity calculated at 5 percent over 160 years.
[d] These figures were used, but not reported, in Richards et al. (1993). Reference is to a permanent pine stand, based on data provided in a personal communication from Richards (1994). Carbon costs and tonnages were annualized over 160 years at a 5-percent discount rate.
[e] Nationwide results for a scenario with harvesting and sale of timber (Table 1 p. 79 and Table 4 p. 83), recalculated at a 5-percent discount rate.
[f] Permanent forestation of "marginal U.S. land" (Table 8 p. 60). For this and other studies, I have converted to acres at a rate of one hectare = 2.477 acres and to short tons at a rate of one metric ton = 1.102 short tons.
[g] Figures are for U.S. cropland-only scenario (Table 1 p. 127). Marginal costs were computed from marginal cost formula for Figure 4 (p. 131) using 22 million tons per year and annualized using a 4-percent discount rate over 10 years.
[h] Nationwide results converted from original study (Table 3 p. 261) at a rate of 3.67 tons of carbon dioxide (CO_2) equals one ton of carbon, and into short tons from metric tons.
[i] An average permanent stand of U.S. tree species, from Table 3 p. 36; CO_2 converted to carbon.
[j] Figures are for a 14-county region of Wisconsin for the scenario assuming a least-cost program at a 4-percent discount rate and a constant annual sequestration rate of 2.25 tons of carbon per acre (Table II). Hectares converted to acres.
[k] Calculations use a 5-percent discount rate, employ carbon yield functions from Birdsey (1993), and do not allow for farm programs.

with estimates of sequestration costs from previous studies using different methods. Then, I compare the sequestration cost estimates with estimates of the costs of abating carbon emissions through fuel switching and energy-efficiency enhancements.

First, to compare my results with those of other sequestration studies, I need to normalize the results to some common set of standards (Table 3). Since the other studies of carbon sequestration costs (and carbon abatement costs) are for the United States as a whole, one thing I need to do is normalize my results for the United States. In doing so, it is important to recognize that the marginal costs of sequestration in the Delta states are not necessarily representative of nationwide sequestration costs.[14] In effect, I rescale the horizontal dimension of the estimated supply function to represent the change from the study area to the relevant U.S. land base,[15] and I normalize the results from

[14] It is likely that the difference is not very great. During the relevant time period, farm real estate prices in Arkansas, Louisiana, and Mississippi have tended to be within about 15 to 20 percent of the U.S. average.

[15] The scaling factor is equal to the ratio of total farm acreage in the continental United States (551 million acres in Richards et al., 1993) to total farm acreage in my 36 study counties (10.6 million acres). It is agricultural acreage alone

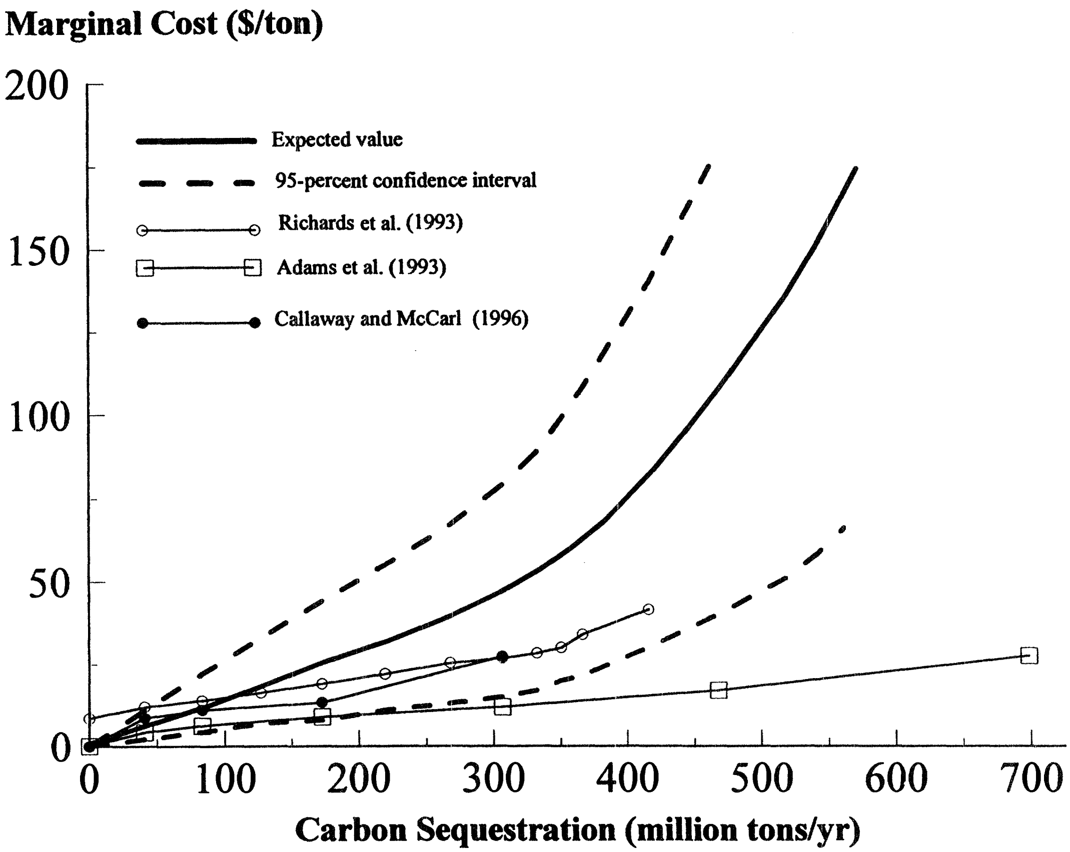

FIGURE 2. ALTERNATIVE ESTIMATES OF MARGINAL COST OF U.S. CARBON SEQUESTRATION

other studies by converting those results to appropriately discounted units.

The results of this process are provided in Figure 2, where our results are compared with those of Adams et al. (1993), Richards et al. (1993), and Callaway and McCarl (1996). All of these marginal cost functions lie within the 95-percent confidence interval,[16] at least up to 300 million tons/year in the case of Adams et al. (1993), but all are less steep than my central tendency and lie well below it for most of their ranges. Other studies have not reported, indeed not calculated, confidence intervals around their results, and so it is especially difficult to make comparisons. Overall, the general impression is that my marginal cost estimates are at least as great and may well be greater than others previously reported. Such differences may arise because several of the factors previously identified as affecting land-use decisions—including nonpecuniary returns to land and decision-making inertia—would tend to lead "engineering" or "least-cost" analyses to underestimate sequestration costs.

that is relevant for the normalization because in the scenario considered there is no deforestation in the baseline (and hence all carbon sequestration is coming from planting trees on formerly agricultural land).

[16] An advantage of the econometric approach is that we can provide a richer description of the marginal cost function through the use of stochastic (Monte Carlo) simulations, drawing upon the relevant variance-covariance matrix from the econometric estimation, but because there is also uncertainty associated with several variables employed in the analysis, the confidence bounds in the figure may underestimate the true error bounds.

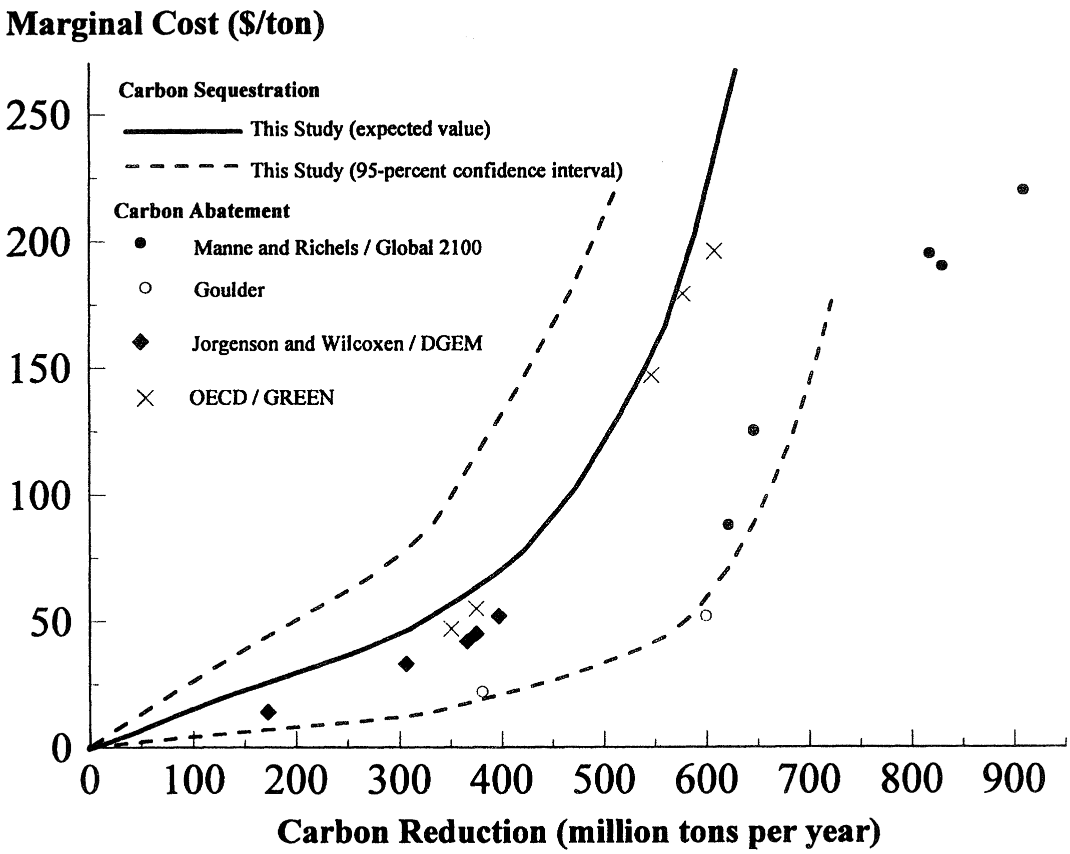

FIGURE 3. ESTIMATES OF MARGINAL COSTS OF U.S. CARBON ABATEMENT AND SEQUESTRATION

Sources: Carbon abatement marginal cost estimates are annuities calculated from time paths of 100-year predicted baseline carbon emissions and predicted carbon emissions under alternative policy scenarios presented in Energy Modeling Forum (1995). See text of present study for detailed explanation.

Next, I turn to estimates of the costs of carbon emissions abatement. I use results from Working Group 12 of the Energy Modeling Forum (EMF) (1995), which examined carbon abatement costs for the United States. The EMF results are presented as time paths of predicted carbon emissions under baseline and policy scenarios over 100-year time frames, and include estimates of the time paths of carbon taxes necessary under each of the policy scenarios.[17]

To construct comparable marginal cost estimates, I first calculate the present discounted value of carbon abatement and the present discounted values of carbon taxes for each time path of taxes and emission reductions from baseline; from this set of numbers, I calculate an equivalent annuity (at the 5-percent discount rate). Each of the time paths for alternative policy scenarios then constitutes a single point on a marginal cost function associated with a given model. These results are plotted along with the estimated carbon sequestration marginal cost function in Figure 3.

The central tendency of marginal seques-

[17] The policy scenarios are: 20-percent reduction from 1990 emission levels by 2010; a 50-percent reduction in annual emissions by 2050; emission stabilization by 2000; 2-percent per year emissions reductions; and a phased-in carbon tax.

tration costs lies everywhere above the estimated marginal abatement costs, although the difference is small at low levels of carbon reduction.[18] As we move beyond 400 million tons per year (30 percent of current U.S. emissions, and 12 percent of estimated emissions in 2050), the two central tendencies depart more dramatically, as the marginal cost function for sequestration begins to approach an implicit vertical asymptote, due to limited availability of land.[19] Still, most of the abatement cost estimates lie within the confidence interval for sequestration costs. Hence, we cannot conclude rigorously that sequestration costs are systematically greater than abatement costs, particularly given the fact that the EMF abatement cost estimates do not have associated confidence intervals.

On the other hand, there are two reasons why it is likely that the figure underestimates the difference between the sequestration and abatement cost functions. First, since the EMF scenarios do not represent cost-effective time paths of achieving a given present value of abatement at minimum cost, the true carbon abatement marginal cost function is better thought of as constituting the lower envelope of these points. Second, the partial-equilibrium nature of my underlying econometric estimates means that the true marginal cost function for sequestration likely lies above the estimated function, because endogenous agricultural prices and endogenous forest product prices would both lead to greater sequestration cost estimates.[20]

In the long term, carbon sequestration costs are likely to increase further, relative to carbon abatement costs, because of three factors: (1) there is a limited land base on which sequestration can operate, in contrast with a much less limited emissions base—due to economic growth—on which abatement operates; (2) the available land base for forestry may decrease due to population pressures, driving up the opportunity cost of land; and (3) the magnitude of improvements in the silvicultural domain (growing more biomass more quickly per acre) and the forest product domain (less decay of wood products, for example) will probably be less than the magnitude of technological improvements in the case of abatement, including increased efficiency of energy generation and use, and decreased reliance on fossil fuels.

Subject to the various caveats expressed above, this comparison between carbon sequestration and abatement costs suggests that sequestration ought to be *part* of our overall portfolio of greenhouse strategies in the short term, providing a significant fraction of overall carbon reductions, although less than from conventional abatement activities (such as through carbon taxes on fossil fuels or tradeable carbon rights). In the long term, however, the relative cost of carbon sequestration in the United States is likely to be such that it should provide a smaller and smaller share of overall reductions.

V. Conclusions

My purpose was to develop and demonstrate a method by which the marginal costs of carbon sequestration can be estimated for various regions of the world by drawing upon (existing) regional econometric analyses of the factors

[18] Forestation and retarded deforestation provide a set of secondary environmental benefits, and it has been argued that these should be taken into account in a cost-effectiveness comparison with energy-efficiency enhancements (Sedjo et al., 1994). However, the same would need to be done for calculating the costs of energy efficiency (which may, for example, bring about reduced emissions of sulfur dioxide).

[19] These U.S. comparisons cannot simply be extrapolated to other nations. It can be noted, however, that at the global level, Nordhaus (1991) has combined results from a number of studies, and provided a schedule of marginal costs associated with percentage reductions in worldwide greenhouse gas emissions. As in my analysis for the United States, Nordhaus finds an increasing departure between the global marginal cost functions for carbon abatement and carbon sequestration. The sequestration marginal cost function rapidly becomes nearly vertical, while marginal abatement costs increase more gradually.

[20] In a general-equilibrium context, a given conversion tax/forestation subsidy decreases agricultural production, thereby increases agricultural product prices, and thus increases carbon sequestration costs (since the opportunity cost of the land is increased). Likewise, a conversion tax/forestation subsidy increases forest production, thereby decreases timber prices, and thus increases carbon sequestration costs (since the private benefits of forestry relative to agriculture decrease). Thus, taking account of the potential endogeneity of agricultural and forest product prices may lead to greater sequestration cost estimates.

affecting land use. Since my empirical application was intended mainly to be illustrative, what conclusions—if any—can be drawn from the quantitative results?

First, focusing exclusively on the regional analysis, I found that the marginal costs of carbon sequestration are by no means trivial, and that the heterogeneity of land brings sharply increasing marginal costs of sequestration as higher quality agricultural lands are converted to forested use. Therefore, studies that provide only single point estimates of average costs or even linear estimates of marginal costs may be very misleading.

Moving beyond the regional cost estimates, what can be made of my illustrative comparison with national cost estimates of sequestration and abatement costs from other studies? First, subject to the necessary caveats regarding the results of any extrapolation, my sequestration cost function is significantly less linear than ones previously estimated with engineering/optimization methods. This becomes potentially important if one is interested in relatively high levels of annual sequestration, i.e., greater than 300 or 400 million tons. Second, subject to the same caveats, my implied sequestration costs for the United States as a whole are not very different from carbon abatement costs for relatively low levels of carbon reduction, but marginal sequestration costs appear to turn upward more rapidly than abatement costs. Further, I identified a set of reasons why the estimate of the difference between sequestration and abatement cost is probably a lower bound, and I identified another set of factors that suggest that this difference will likely increase over time.

Finally, I can reflect briefly on the analytical method that has been employed. The model can be improved along a number of dimensions. Primary among these is endogenizing some variables currently treated as exogenous: agricultural and forestry product prices; the mix of cultivated crops and forest species; and management regimes.[21] A general-equilibrium approach should be possible, both at the econometric stage and in simulations. This would not simply be desirable, but necessary, if the general approach developed here were to be applied directly to estimate the carbon sequestration marginal cost function for the United States as a whole.

Opportunities abound for the application of land-use econometrics to estimating sequestration costs.[22] The major advantage of this approach is that simulations of marginal costs build directly upon revealed-preference patterns of how landowners have actually responded to the economic incentives they continually face regarding the alternative uses of their lands. Linking such regional econometric models of land use with dynamic simulation models of carbon sequestration can provide better estimates of the true costs of carbon sequestration, and thereby add significantly to our understanding of the costs of addressing the threat of global climate change.

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[21] For example, it would be desirable to allow for the economic endogeneity of the forest rotation length. In this regard, a very different approach to thinking about the carbon supply function is found in a paper by G. Cornelis van Kooten et al. (1995). They examine the sensitivity of the socially optimal rotation length to alternative values of carbon (dollars per ton), and thus develop a supply curve of carbon *per acre.* As timber prices increase, the optimal rotation length decreases; and as carbon value increases, the (socially) optimal rotation length increases.

[22] There is a growing literature of econometric analyses of forestation and deforestation (Theodore Panayotou and Somthawin Sungsuwan, 1989; Douglas Southgate et al., 1991; Eustáquio J. Reis and Rolando M. Guzmán, 1992; Parks and Randall A. Kramer, 1995; Alexander S. P. Pfaff, 1997). The increasing availability of digital land-use data derived from satellite images means that econometric analysis of the type described in this paper can now be carried out at relatively moderate cost for large geographic areas.

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