Journal of Environmental Economics and Management **40,** 211–235 (2000)
doi:10.1006/jeem.1999.1120, available online at http://www.idealibrary.com on IDEAL®

Climate Change and Forest Sinks: Factors Affecting the Costs of Carbon Sequestration[1]

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Received September 11, 1998; revised May 4, 1999; published online August 10, 2000

The possibility of encouraging the growth of forests as a means of sequestering carbon dioxide has received considerable attention, partly because of evidence that this can be a relatively inexpensive means of combating climate change. But how sensitive are such estimates to specific conditions? We examine the sensitivity of carbon sequestration costs to changes in critical factors, including the nature of management and deforestation regimes, silvicultural species, relative prices, and discount rates. © 2000 Academic Press

1. INTRODUCTION

The Kyoto Protocol to the United Nations Framework Convention on Climate Change [37] establishes the principle that carbon sequestration can be used by participating nations to help meet their respective net emission reduction targets for carbon dioxide (CO_2) and other greenhouse gases.[3] Several studies have found that growing trees to sequester carbon could provide relatively low-cost net

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[1] Valuable comments on previous versions of this paper were provided by Lawrence Goulder, William Nordhaus, Andrew Plantinga, Kenneth Richards, Roger Sedjo, two anonymous referees, an associate editor, and participants in seminars at the Universities of California at Los Angeles and Santa Barbara, Maryland, Michigan, and Texas, Harvard, Stanford, and Yale Universities, Resources for the Future, and the National Bureau of Economic Research. The authors alone are responsible for any errors.

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[3] After fossil-fuel combustion, deforestation is the second largest source of carbon dioxide emissions to the atmosphere. 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 [10, 31]. There are three pathways along which carbon sequestration is of relevance for atmospheric concentrations of carbon dioxide: carbon storage in biological ecosystems, carbon storage in durable wood products, and substitution of biomass fuels for fossil fuels [24]. The analysis in this paper considers the first two pathways. For further discussion, see Parks et al. [18].

0095-0696/00 $35.00

emission reductions for a number of countries [3], including the United States [1, 4, 19, 20, 23, 33].[4]

When and if the United States chooses to ratify the Kyoto Protocol and/or subsequent international agreements, it will be necessary to decide whether carbon sequestration policies—such as those that promote forestation[5] and discourage deforestation—should be part of the domestic portfolio of compliance activities. The potential cost-effectiveness of carbon sequestration activities will presumably be a major criterion, and so it is important to ask what factors affect the costs of such programs. We examine the sensitivity of sequestration costs to changes in key factors, including the nature of the management regimes, silvicultural species, relative prices, and discount rates.

Our analytical model takes account of current silvicultural understanding of the intertemporal linkages between deforestation and carbon emissions, on the one hand, and between forestation and carbon sequestration, on the other. Furthermore, our analysis uses a methodology whereby econometric estimates of the costs of carbon sequestration are derived from observations of landowners' actual behavior when confronted with the opportunity costs of alternative land uses [33]. This is in contrast with "engineering" or "least cost" approaches used to estimate the costs of carbon sequestration, of which even the best are unlikely to capture important elements of landowner behavior, such as the effects of irreversible investment under uncertainty, non-pecuniary returns from land use, liquidity constraints, decision making inertia, and other costs and benefits of land use of which the analyst is unaware.[6]

In summary, we find, first, that the costs of carbon sequestration can be greater if trees are periodically harvested, rather than permanently established. Second, higher discount rates imply higher marginal costs and non-monotonic changes in the amount of carbon sequestered. Third, higher agricultural prices lead to higher marginal costs or reduced sequestration. Fourth, retarded deforestation can sequester carbon at substantially lower costs than increased forestation. These results depend in part on the time profile of sequestration and the amount of carbon

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[4] There is a range of estimates of the relevant marginal cost function. These various estimates are compared by Stavins [33], whose own estimates are significantly greater than the others for more ambitious sequestration programs.

[5] Distinctions are sometimes made in the forestry literature between "afforestation" and "reforestation," where the former refers to changes from non-forest to forest production on lands that have not been forested during the preceding 50 years or more, and the latter refers to changes to forest production on lands that have more recently been deforested [11]. In our analysis, there is no reason to make this distinction, and so we simply refer to any change *to* forest use as "forestation." This is in contrast to a change *from* forest use of land—"deforestation."

[6] The simplest of previous analyses derived single point estimates of average costs associated with particular sequestration levels [8, 13, 14, 27, 29], sometimes assuming that the opportunity costs of land are zero [7, 16, 38, 39]. "Engineering/costing models" have constructed marginal cost schedules by adopting land rental rates or purchase costs derived from surveys for representative types or locations of land, and then sorting these in ascending order of cost [15, 23]. Simulation models include a model of lost profits due to removing land from agricultural production [19], a mathematical programming model of the agricultural sector and the timber market [1, 2], a related model incorporating the effects of agricultural price support programs [4], and a dynamic simulation model of forestry [35]. An analysis by Plantinga [20] adopts land-use elasticities from an econometric study to estimate sequestration costs, an approach similar in some respects to the methodology used here. For surveys of the literature, see Richards and Stokes [24] and Sedjo et al. [28, 30].

released upon harvest, both of which may vary by species, geographic location, and management regime, and are subject to scientific uncertainty.

In Section 2 of the paper, we describe the analytical model; in Section 3, we carry out simulations for various scenarios and thereby examine the sensitivity of the marginal cost of carbon sequestration; and in Section 4, we offer some conclusions.

2. ANALYTICAL MODEL

We draw upon econometrically estimated parameters of a structural model of land use, layer upon it a model of the relationships that link changes in alternative land uses with changes in the time paths of CO_2 emission and sequestration, and examine the sensitivity of carbon sequestration costs to key underlying factors. Our analysis focuses on the empirically relevant land-use options of forest and farm.[7]

2.1. *A Structural, Empirical Model of Land Use*

In previous work with a different policy motivation, Stavins and Jaffe [34] developed a dynamic optimization model of a landowner's decision of whether to keep land in its status quo use or convert it to serve another purpose.[8] Landowners are assumed to observe current and past values of economic, hydrologic, and climatic factors relevant to decisions regarding the use of their lands for forestry or agricultural production and on this basis form expectations of future values of respective variables. Given this information, landowners attempt to maximize the expected long-term economic return to the set of productive activities that can be carried out on their land. They face ongoing decisions of whether to keep land in its current state—either forested or agricultural use—or to convert the land to the other state. Relevant factors a landowner would be expected to consider include: typical agricultural and forestry revenues for the area, the quality of a specific land parcel for agricultural production, agricultural costs of production, and the cost of converting land from a forested state to use as cropland. Thus, we anticipate that a risk-neutral landowner will seek to maximize the present discounted value of the stream of expected future returns.

We summarize the formal statement of the landowner's problem in the Appendix, where the application of control theoretic methods yields a pair of necessary conditions for changes in land use. The first necessary condition implies that 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. Stated formally, forestation (conversion of agricultural cropland to forest) occurs if a parcel is cropland and if

$$\left(F_{it} - D_{it} - A_{it} \cdot q_{ijt} + M_{it}\right) > 0, \tag{1}$$

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[7] In both industrialized nations and in developing countries, nearly all deforestation is associated with conversion to agricultural use [11].

[8] A detailed description of the dynamic optimization model and the derivation of the econometrically estimatable model is found in Stavins and Jaffe [34], while Stavins [32] provides an illustration of the use of the model for environmental simulation.

where i indexes counties, j indexes individual land parcels, and t indexes time; upper case letters are stocks or present values; lower case letters are flows; F is forest net revenue, equal to the expected present value of annual net income from forestry per acre (i.e., stumpage value); D is the expected present value of the income loss (when converting to forest) due to delay of first harvest for one rotation period; A is the expected present value of the future stream of typical agricultural revenues per acre; q is a parcel-specific index of feasibility of agricultural production, including effects of soil quality and soil moisture; and M is the expected cost of agricultural production per acre, expressed as the present value of an infinite future stream.

On the other hand, 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. That is, deforestation occurs if a parcel is forested and if

$$\left(A_{it} \cdot q_{ijt} - M_{it} - C_{it}^{\alpha P_{it}} - (F_{it} - W_{it})\right) > 0, \tag{2}$$

where C is the average cost of conversion per acre, P is the Palmer hydrological drought index, and W_{it} is the windfall of net revenue per acre from a one-time clear cut of forest (prior to conversion to agricultural use).

Inequalities (1) and (2) imply that all land in a county (of given quality) will be in the same use in the steady state. 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 regarding its suitability for agriculture. As shown in Stavins and Jaffe [34], such unobserved heterogeneity can be parameterized within an econometrically estimatable model so that the individual necessary conditions for land-use changes 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.

The complete model yields a set of econometrically estimatable equations, as shown in the Appendix. Using panel data for 36 counties, comprising approximately 13 million acres of land, in Arkansas, Louisiana, and Mississippi, during the period 1935−1984, the parameters of the complete model were estimated with nonlinear least squares procedures [34]. Table I provides descriptive statistics of the major variables used in the simulation analysis.

2.2. *A Dynamic Simulation Model of Future Land Use*

Our initial step in moving from an estimated model of historical land use to a model of carbon sequestration involves introducing relevant silvicultural elements into the necessary conditions previously derived. There are three principal silvicultural dimensions to be considered: symmetries and asymmetries between forestation and deforestation, alternative species for forestation, and alternative manage-

TABLE I

Descriptive Statistics[a]

Variable	Mean	Standard deviation	Minimum	Maximum
Gross agricultural revenue ($/acre/year)	259.04	44.58	184.77	376.03
Agricultural production cost ($/acre/year)	220.39	52.03	143.61	359.81
Forest revenue[b] ($/acre/year)				
Mixed stand	19.29	7.45	6.71	38.36
Pine stand	58.96	23.38	19.92	118.24
Tree-farm establishment cost ($/acre)	92.00	0.00	92.00	92.00
Conversion cost ($/acre)[c]	27.71	0.00	27.71	27.71
Carbon sequestration due to forestation[d] (tons/acre)				
Natural regrowth of mixed stand, periodically harvested	43.36	0.00	43.36	43.36
Natural regrowth of mixed stand, no harvest	50.59	0.00	50.59	50.59
Pine plantation, periodically harvested	41.05	0.00	41.05	41.05
Pine plantation, no harvest	49.99	0.00	49.99	49.99
Carbon emissions due to deforestation[e] (tons/acre)	51.83	0.00	51.83	51.83
Interest rate[f]	5%	0.00	5%	5%

[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] The historical analysis uses actual conversion costs, varying by year.

[d] Present-value equivalent of life-cycle sequestration.

[e] Present-value equivalent of life-cycle emissions.

[f] The historical analysis uses actual, real interest rates; simulations of future scenarios use the 5% real rate.

ment regimes. Two of the equations from the land use model need to be adjusted for this purpose,

$$q_{it}^{y} = \left[\frac{F_{it} - D_{it} + M_{it}}{A_{it}} \right] \tag{3}$$

$$q_{it}^{x} = \left[\frac{F_{it} - W_{it} + M_{it}}{A_{it} - C_{it}^{\alpha P_{it}}} \right], \tag{4}$$

where, for each county i at time t, q^{y} is the threshold value of land quality (i.e., suitability for agriculture) below which the incentive for forestation manifests itself, and q^{x} is the threshold value of land quality above which the incentive for deforestation manifests itself.

First, we note that Eqs. (3) and (4) already exhibit two significant asymmetries between forestation and deforestation. Forestation produces a supply of timber (and an associated forest-revenue stream) only with some delay, since the first harvest subsequent to establishment occurs at the completion of the first rotation, while deforestation involves an immediate, one-time revenue windfall from cutting of the stand, net of a loss of future revenues from continued forest production. Additionally, under actual management practices during the sample period of historical analysis, costs were associated with converting forestland to agricultural cropland, but no costs were involved with essentially abandoning cropland and allowing it to return to a forested state. For the simulations associated with carbon sequestration policies, however, we need to allow for the possibility of "tree farming," that is, intensive management of the forest, which brings with it significant costs of establishment.

Second, there is the choice of species. In the econometric analysis, only mixed stands[9] were considered to reflect historical reality, but in the carbon-sequestration context it is important to consider the possibility of both mixed stands and tree farms (plantations of pure pine). We develop revenue streams for both, based upon observed practice in the region.[10]

The third silvicultural dimension is the choice of management regime. The historical analysis assumed that all forests were periodically harvested for their timber. For purposes of carbon sequestration, however, we should consider not only such conventional management regimes, but also the possibility of establishing "permanent stands" that are never harvested. These three silvicultural considerations lead to the respecification of Eq. (3),

$$q_{its}^{y} = \left[\frac{F_{its} - D_{its} + M_{it} - K_{it}}{A_{it}} \right], \tag{5}$$

where subscript s indicates species and K is the cost associated with establishing a pine-based tree farm.[11] For the case of permanent (unharvested) stands, F and D are set equal to zero. Combining variable values associated with these silvicultural dimensions into logical sets yields four scenarios to be investigated: natural regrowth of a mixed stand, with and without periodic harvesting, and establishment of a pine plantation, with and without periodic harvesting.

2.3. *Generating a Forest Supply Function*

Next, we introduce some policy-inspired modifications to develop a forest supply function. First, note that dynamic simulations of fitted values of the model, employing current/expected values of all variables (including prices), will generate

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[9] Mixed stands of appropriate shares of various species of hardwoods and softwoods, specific to each county and time period, were included in the data used for econometric estimation. The calculated revenue streams draw upon price data for both sawlogs and pulpwood in proportion to use, based upon 55-year rotations.

[10] The tree-farm revenue streams represent a mix of 80% loblolly pine and 20% slash pine, based upon practice in the area [5]. We use a rotation length of 45 years for loblolly and 30 years for slash pine, also reflecting standard practice [15].

[11] Forest establishment costs include the costs of planting (purchase of seedlings, site preparation, and transplanting), post-planting treatments, and care required to ensure establishment [15]. We adopt a value of $92/acre ($1990), based upon estimates by Richards et al. [23] for converted cropland in the Delta (three-state) region.

baseline predictions of future forestation and/or deforestation [32].[12] These results constitute our baseline for policy analysis. Second, we can simulate what land-use changes would be forthcoming with changed values of specific variables. In general, we can examine the consequences of public policies that affect the economic incentives faced by landowners. The difference in forestation/deforestation between the first (baseline) and the second (counterfactual) simulation is the predicted impact of a given policy.

In order to generate a representation of the forest supply function, several types of policies can be considered. A payment (subsidy) could be offered for every acre of (agricultural) land that is newly forested. But this would provide an incentive for landowners to cut down existing forests simply to replant in a later year in exchange for the government payment. On the other hand, a tax could be levied on each acre of land that is deforested. But such an approach would provide no added incentive for forestation of land that is not currently in that state. One solution is to think of 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 most efficient.

We simulate this policy by treating the subsidy as an increment to forest revenues in the forestation part of the model (Eq. (4)) and treating the tax payment as an increment to conversion or production costs in the deforestation part of the model (Eq. (5)). Letting Z represent the subsidy and tax, the threshold equations ((3) and (4)) for forestation and deforestation, respectively, become

$$q_{its}^{y} = \left[\frac{(F_{its} - D_{its} + Z_{it}) + M_{it} - K_{it}}{A_{it}} \right] \tag{6}$$

$$q_{its}^{x} = \left[\frac{F_{its} - W_{its} + (M_{it} + Z_{it})}{A_{it} - C_{it}^{\alpha P_{it}}} \right]. \tag{7}$$

Thus, a dynamic simulation based upon Eqs. (6) and (7) in conjunction with the other equations of the model (see the Appendix), 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 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.[13]

[12] Statistical tests, reported in Stavins and Jaffe [34], indicate a high degree of structural (and parametric) stability of the model over the 50-year time period of estimation. It is therefore possible to carry out future factual and counter-factual simulations. Extrapolations of historical trends would imply future increases in the relative price of timber to agricultural crops, but extrapolations of historical trends of relative yields would favor agriculture. Not knowing what the future will bring, the baseline simulations employ constant values of all variables, including real prices and yields. Nevertheless, the baseline simulations exhibit changes in land use over time, both because of the partial-adjustment nature of the model and because modifications of silvicultural practices are assumed for both baseline and policy simulations, as is explained later.

[13] This is a partial-equilibrium analysis of a 36-county region. If a national analysis were being carried out, it would be necessary to allow for price endogeneity, i.e., allow for land-use changes induced by changes in Z to affect agricultural and forest product prices. On this, see Stavins [33].

It might be argued that since the policy intervention we 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 may seem to be a valid criticism in the narrowest analytic sense, but it 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, because the costs of administering such policy interventions would be prohibitive. Looked at this way, such an instrument would likely be *more* costly per unit of carbon sequestered than would the deforestation tax/forestation subsidy policy considered here.[14]

2.4. *Computing the Marginal Cost of Carbon Sequestration*

For any parcel of land, there are several types of comparisons that could be made between the time-paths of carbon emissions/sequestration in a baseline and a policy simulation. First, we can consider a parcel that is continually in cropland in both simulations, in which case it exhibits zero net carbon sequestration/emission over the long run in both, and so the policy impact is also zero.[15] Second, a parcel may continually be in a forested state in both simulations, in which case it sequesters carbon in both simulations, but net sequestration due to the policy intervention is again zero. Third, a parcel may be in agricultural use in the baseline, but forestation takes place in the policy simulation in year t; here, net carbon sequestration due to the policy intervention will be the time-path of annual sequestration that commences in year t. Fourth, a parcel may be in a forested state in the baseline, but deforestation takes place in the policy simulation in year t; then the net carbon emissions due to the policy intervention will be the time-path of annual *emissions* that commence in year t, assuming durable wood products are produced from merchantable timber.

Carbon-Sequestration Time Profiles

The next step, conceptually, is to link specific time paths of carbon sequestration (and emissions) with forestation and deforestation. Scientific understanding of these linkages is evolving; we draw upon recent biological models and employ a set of temporal carbon yield curves based on Moulton and Richards [15] and Richards et al. [23].[16] Figure 1 provides a pictorial representation of one example of the time-path of carbon sequestration and emission linked with a specific forest management regime. In the example, the time profile of cumulative carbon

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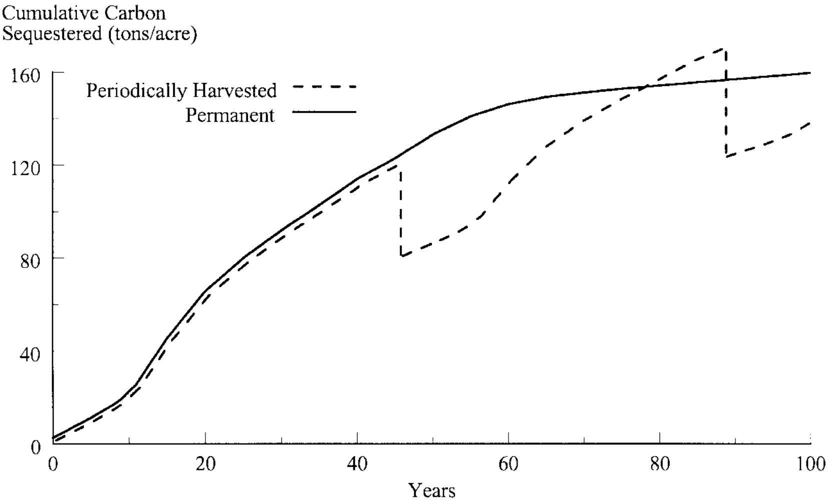
[14] This is not to suggest that a uniform tax/subsidy would be the first-best policy. A more efficient but still practical policy instrument might well involve a non-uniform tax/subsidy, set in accordance with regional and other factors.

[15] With constant relative prices in the baseline, the time-path of policy-induced changes in land use in the model is always such that individual counties are characterized by increases or decreases in forested acreage, *relative to the baseline*, but never both.

[16] Nordhaus [17] and Richards et al. [23] also use carbon yield curves, while many other sequestration cost studies have used point estimates of average flows.



Source: Based on data from Moulton and Richards (1990) and Richards (1994).

FIG. 1. Time profile of carbon sequestration (Loblolly pine in delta states region).

sequestration is for establishing a new loblolly pine plantation. Carbon sequestration occurs in four components of the forest: trees, understory vegetation, forest floor, and soil.[17] When a plantation is managed 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 100 years, as material decay comes into balance with natural growth.

The figure also shows the sequestration path for a stand that is periodically harvested. In this case, carbon accrues at the same rate as in a permanent stand until the first harvest, when carbon is released as a result of harvesting, processing, and manufacturing of derivative products.[18] Much of the carbon sequestered in wood products is also released to the atmosphere, although this occurs with

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[17] Although shares vary greatly among forest types, reference points are: tree carbon contains about 80% of ecosystem carbon, soil carbon about 15%, forest litter 3%, and the understory 2% [23]. Variation in these shares is significant; for some species, soil carbon accounts for nearly 50% of total forest carbon.

[18] Our calculations of releases from the understory, forest floor, soil, and non-merchantable timber are based upon Moulton and Richards [15] and Richards et al. [23]. The share of total forest carbon that actually ends up in merchantable wood varies considerably by species. A reasonable reference point is about 40%. Much of the remaining 60% is released at the time of harvest and in the manufacturing process (in both cases through combustion), the major exception being soil carbon, which exhibits much slower decay.

considerable delay as wood products decay.[19] In this scenario, the forest is replanted and the process begins again.[20]

Although the carbon yield curve with harvesting in Fig. 1 eventually moves above the yield curve for a "permanent" stand, this need not be 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, because eventually decay in the stock of carbon stored in existing wood products offsets the amount of new carbon sequestered through tree growth. That steady-state quantity can, in theory, lie above or below the level associated with the equilibrium level of the "permanent" yield curve.[21]

Discounting Carbon Costs and Benefits

Recognizing the intertemporal nature of net carbon sequestration raises a question: how can we associate a number—the marginal cost of carbon sequestration—with diverse units of carbon that are sequestered in different years over long time horizons? 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. These approaches have been classified as "flow summation," "mean carbon storage," and "levelization" [24].

The "flow summation" approach is the simplest: the present value of costs is divided by the total tons of carbon sequestered, regardless of when sequestration occurs. This summary statistic fails to take into account the time profile of sequestration, and second, the measure is very sensitive to the length of the time horizon selected for calculation (in the case of periodic-harvesting scenarios). Furthermore, assuming that not only costs but also benefits of sequestration are to be discounted over time, this approach implies that marginal benefits of sequestra-

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[19] As Sedjo et al. [30] 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" (p. 23). Harmon et al. [9] 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 Row [25], Row and Phelps [26], and Turner et al. [36], we 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 [21]. The final profile is such that one year following harvest, 83% of the carbon in wood products remains sequestered; this percentage falls to 76% after 10 years, and 25% after 100 years (and is assumed to be constant thereafter). At an interest rate of 5%, the present-value equivalent sequestration is approximately 75%, identical to that assumed by Nordhaus [17].

[20] Another potential scenario, which we do not consider, is that harvested wood is used for fuel. If this is to produce electricity or liquid fuels such as methanol, thereby substituting for fossil-fuel use, then there would be two additional effects to consider: (1) the net impact on atmospheric CO_2 emissions of each unit of forestation would be significantly enhanced, and (2) the demand for wood would be increased, which would matter in a general-equilibrium setting. On the other hand, the general-equilibrium effects of bringing a new source of wood to the market would also need to be considered.

[21] There has been a significant amount of debate within the scientific community about the relative superiority of these two regimes in terms of their carbon-sequestration potential. Harmon et al. [9] find that old growth forests are superior to periodic harvesting approaches in their ability to sequester carbon, but Kershaw et al. [12] demonstrate that this is dependent upon specific circumstances.

tion are increasing exponentially over time at the discount rate. A similar summary statistic is based upon "mean carbon storage." In this case, the present value of costs is divided by the numerical average of annual carbon storage. This statistic suffers from the same problems as the first.

The third alternative—"levelization"—seems most reasonable: the discounted present value of costs is divided by the discounted present value of tons sequestered. Alternatively (and equivalently), an annuity of present value costs is divided by an annuity of present value tons. This is the approach we use. It 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 damages are essentially proportional to the rate of climate change, which many studies have asserted.[22]

Specifically, we 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 sequestration/emissions associated with any baseline or policy simulation are calculated as

$$PV(SEQ) = \sum_{i=1}^{36} \left[\sum_{t=0}^{90} \left(FORCH_{it}^a \cdot D_{it}^a \cdot \Omega_t^S - FORCH_{it}^c \cdot D_{it}^c \cdot \Omega_t^E \right) \cdot (1+r)^{-t} \right], \tag{8}$$

where

$$\Omega_t^S = \sum_{h=t}^{90} CS_h \cdot (1+r)^{t-h} \tag{9}$$

$$\Omega_t^E = \sum_{h=t}^{90} CE_h \cdot (1+r)^{t-h}, \tag{10}$$

and where $FORCH^a$ and $FORCH^c$ are forestation and deforestation, respectively, as a share of total county area (see the Appendix for formulae), D^a and D^c are dummy variables for forestation and deforestation, respectively, and CS_h and CE_h are, respectively, annual incremental carbon sequestration and carbon emissions per acre under individual scenarios.

We develop the constituent carbon yield curves for various forest species, location, and management conditions, and initially use a 5% discount rate. The present-value equivalent carbon-sequestration measure associated with natural

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[22] If the marginal damages of carbon emissions were expected to change at some rate g over time, an appropriate modification of the levelization procedure could entail reducing the discount rate for carbon by the rate g. For monotonically increasing sequestration time profiles this modification would raise the present-value tons of carbon and lower the marginal cost of carbon sequestration if marginal damages were growing over time (i.e., $g > 0$); it would do the opposite if damages were expected to fall. For non-monotonic sequestration paths, such as those involving periodic harvesting, the effect depends on the specific shape of the path; $g > 0$ could in principle raise or lower present-value carbon. For the scenarios we investigate, such a modification—which is equivalent to lowering the discount rate (for $g > 0$)—also raises the present-value carbon for the harvesting scenarios, but not by as much as for the non-harvesting scenarios.

regrowth of a mixed stand is 43.36 tons if periodically harvested and 50.59 tons if permanent; for a pine plantation the values are 41.05 if periodically harvested and 49.99 tons if permanent.[23] Additionally, we calculate present-value carbon emission measures for deforestation with sale of merchantable timber (51.83 tons). These values are also reported in Tables I and IV. As described above, these values depend on the time profile of sequestration and the amount of carbon released upon harvest, both of which may vary by species, geographic location, and management regime, and are subject to scientific uncertainty. Silvicultural scenarios with more rapid carbon accumulation and less emissions upon harvest will exhibit higher carbon present values and thus lower costs of carbon sequestration per ton.

Since we derive marginal costs on an annual per acre basis using the tax/subsidy scheme, Z, we first convert present value tons of carbon to an equivalent annuity, $AV(SEQ)$, as

$$AV(SEQ) = \frac{PV(SEQ)}{PVFAC(r)}, \tag{11}$$

where $PVFAC$ is a present-value factor used to annualize the present value at rate r. We then divide the carbon-sequestration annuity by the total acreage of forestation, $TFORCH$, relative to the baseline in order to place it on a per acre basis. Lastly, we compute the marginal cost per ton of carbon sequestration MC for each scenario by dividing marginal cost per acre per year by the per acre carbon-sequestration annuity:

$$MC = \frac{Z}{\left(\dfrac{AV(SEQ)}{TFORCH}\right)}. \tag{12}$$

As discussed below, Table II illustrates this computation for a periodically harvested pine plantation.

3. THE COSTS OF CARBON SEQUESTRATION

The results of dynamic land-use simulations for the 90-year period from 1990 to 2080 constitute the fundamental inputs into the final carbon simulation model consisting of Eqs. (8), (9), and (10).[24] A 90-year period was used to allow at least

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[23] The yield curves provided in Fig. 1 are simply examples for one species, loblolly pine. The growth curves that underlie 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 [6]. We 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. The mixed-stand carbon paths are weighted averages from hardwood and pine constituents, assuming 55% hardwoods and 45% southern pine [5]. The assumed density of carbon in merchantable hardwoods is from Moulton and Richards [15] for Delta state hardwoods. In the case of softwoods (pines), density and assumed rotation length are for loblolly pine and slash pine [15], weighted as 80% and 20%, respectively, of total softwoods. Carbon-sequestration patterns and merchantable wood volumes for pine are based on Richards et al. [23] for cropland in the Delta region.

[24] In a prior step, the econometrically estimated parameters were used with newly available data for 1989 to simulate total forested acreage per county in 1989, the base year for the simulations.

TABLE II

Land Change and Carbon-Sequestration Costs and Quantities, Periodically Harvested Pine Plantation

Marginal cost per acre ($/acre/year) Z	Forestation relative to baseline (1,000's acres) $TFORCH$	Average cost per acre ($/acre/year)	Annualized carbon sequestration relative to baseline (1,000's tons/year) $AV(SEQ)$	Marginal cost of carbon sequestration ($/ton) $MC = Z/[AV(SEQ)/TFORCH]$	Average cost of carbon sequestration ($/ton)
0	0	0.00	0	0.00	0.00
10	518	10.00	784	6.61	6.61
20	1,057	15.10	1,600	13.21	9.97
30	1,615	20.25	2,445	19.82	13.38
40	2,192	25.45	3,319	26.42	16.81
50	2,787	30.69	4,219	33.03	20.27
60	3,398	35.96	5,145	39.63	23.76
70	3,893	41.27	5,895	46.24	27.26
80	4,224	46.60	6,395	52.84	30.78
90	4,455	51.95	6,745	59.45	34.31
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

Notes: Variable symbols are given at the bottom of certain headings to illustrate how figures were computed (see Section 2.3). Discount rate is 5%; baseline forestation is 52,000 acres; baseline carbon sequestration is 4.6 million tons.

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. Different time-paths of annual carbon increments, CS_h and CE_h, and different cost and revenue streams of forestation and deforestation are associated with each of the four scenarios to be examined.

As previously described, simulations are employed to trace out the supply curve of net carbon sequestration, in which the marginal costs of carbon sequestration, measured in dollars per ton, are arrayed in a schedule with net annualized[25] carbon sequestration (relative to the baseline). Table II provides the results for one scenario, a periodically harvested pine plantation, with the sale of merchantable timber when/if deforestation occurs. We focus initially on this scenario and provide detailed results for it, by way of example. 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 thousand

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[25] As explained above, 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 for a given discount rate.

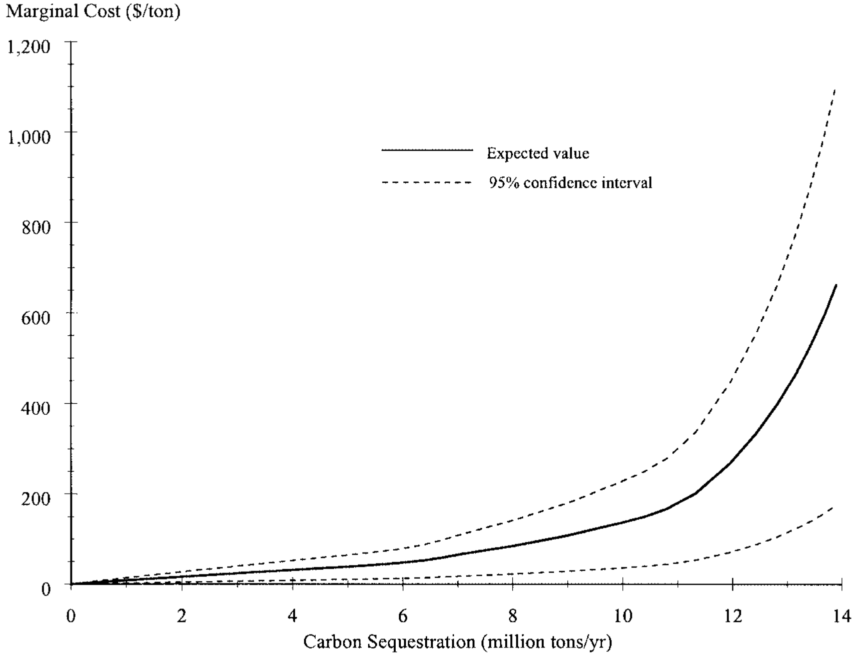

FIG. 2. Marginal cost of carbon sequestration (scenario #3—periodically harvested pine plantation).

acres (over the 90-year study period). Baseline net carbon sequestration is approximately 4.6 million tons annually. As can be seen in Table II and Fig. 2, the marginal costs of carbon sequestration increase approximately linearly 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 increasingly depart from a linear trend. Beyond about $200 per ton, they turn steeply upward. Indeed, the marginal cost function appears to be nearly asymptotic to a sequestration level of about 15 to 16 million tons annually (Figure 2).[26] This is not surprising. Such an implicit limit would be associated in the model with net forestation of about 10.5 million acres,

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[26] Although the assumption of exogenous prices becomes less tenable as land-use impacts become more severe, it is nevertheless true that the relevant agricultural prices (and to a lesser degree, stumpage values) are determined on national and international markets of which the study region represents only a trivial share. In any event, however, the reliability of the model's predictions decreases as we move further outside the range of the data on which the underlying econometric parameters were estimated.

TABLE III

Costs of Carbon Sequestration for Alternative Silvicultural Scenarios for 5 Million Tons of Sequestration above Baseline

	Alternative silvicultural scenarios			
Species regime	Natural regrowth of mixed stand		Pine plantation	
Management regime Scenario	Periodic harvest #1	No harvest #2	Periodic harvest #3	No harvest #4
Baseline change in forestation (1,000 acres)	−259	−297	52	−69
Baseline carbon sequestration (1,000 tons)	4,005	3,931	4,578	4,368
Marginal cost per acre ($/acre/year)	55.80	49.20	58.40	49.10
Forestation relative to baseline (1,000 acres)	3,074	2,662	3,301	2,710
Average cost per acre ($/acre/year)	33.80	30.31	35.12	30.23
Forestation carbon sequestration (tons/acre)	43.36	50.59	41.05	49.99
Deforestation carbon emissions (tons/acre)	51.83	51.83	51.83	51.83
Annualized carbon sequestration (1,000 tons/year)	5,000	5,000	5,000	5,000
Marginal cost of carbon sequestration ($/ton)	34.33	26.30	38.57	26.61
Average cost of carbon sequestration ($/ton)	20.79	16.20	23.20	16.38

Note: Discount rate is 5%.

for a total forested area of 13 million acres, just shy of the total area of the 36 counties of the study region.[27]

3.1. *Alternative Silvicultural Scenarios*

Simulated costs of carbon sequestration are summarized in Table III for four scenarios. In scenario #1, all forestation is assumed to be through natural regrowth of mixed stands that are periodically harvested. The more modest forest revenues associated with this management regime (relative to the pine plantation) result in net deforestation taking place in the baseline simulation, a loss of about 260 thousand acres. The marginal cost of carbon sequestration is about $34 when 5 million tons are sequestered annually.

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[27] An advantage of our revealed-preference approach, compared with the usual engineering approaches, is that because the simulation model's parameters are econometrically estimated, those parameters have associated with them not only estimated values (coefficients), but also estimated standard errors. Hence, 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. Based upon these simulations, Fig. 2 provides not only a set of point estimates of the marginal cost function, but also the 95% confidence interval around that function. There is also uncertainty associated with a number of the variables employed in the analysis. Hence, the figure probably presents an under-estimate of the true error bounds.

If we modify the previous scenario to eliminate periodic harvesting (thus setting the forest revenue stream for *new* forests equal to zero), deforestation increases somewhat in the baseline (scenario #2, Table III).[28] The timber revenue stream in scenario #1 was forestalling some conversion of forest to agriculture; with the elimination of this revenue stream in scenario #2, deforestation increases. On its own, preventing periodic harvesting of timber would tend to increase the marginal costs of carbon sequestration, since the net opportunity costs associated with an agriculture/forestry change increase. Indeed, this modest loss of expected revenue (about 13%) does cause a modest decrease in the total amount of induced forestation that occurs relative to the case with harvesting (scenario #1). But the time-path of carbon sequestration without harvesting is sufficiently favorable to overcome this effect, so that the marginal costs of sequestration are actually *less* in the no-harvest cases than in those cases where periodic harvesting is permitted. For example, the marginal cost of carbon sequestration is now only $26 (compared with $34 in the presence of periodic harvesting) when 5 million tons are sequestered annually.

The picture changes somewhat when we allow for tree farms of pure pine to be established as the regime of forestation. Now the economic incentives that exist in the baseline actually cause little or no deforestation to occur. Potential annual revenues from forestry are significantly greater than in the case of mixed stands, but up-front plantation establishment costs partially mitigate this effect. Overall, a given land-use tax/subsidy brings about greater net forestation in the pure pine case, but this effect is overwhelmed by the differences in carbon-sequestration potential, and so the periodic pine scenario (#3) exhibits *greater* marginal sequestration costs than the periodic mixed-stand case (scenario #1). The difference in carbon sequestration is being driven by the fact that retarded deforestation is responsible for a considerable part of the net carbon sequestration (relative to baseline) for the mixed stands, but in the pine plantation case, we find that all of the carbon sequestration in scenario #3 is due to forestation (which in present-value equivalent terms provides substantially less carbon saved per acre). Scenario #4, the pine plantation without periodic harvesting, provides an intermediate case, which yields results quite similar to the related mixed-stand scenario (#2), because the absence of periodic harvesting eliminates one of the major economic differences and the carbon yield curves themselves are similar.

3.2. *Discount Rates*

Because of the long time horizons employed in the analysis, it is natural to ask about the sensitivity of the results to the assumed discount rate (5%). Changing the discount rate has two types of effects on the simulations. First, many of the economic variables take on new values. One example is the trade-off between foregone future forest revenues F and the immediate windfall of revenue from

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[28] Note that the alternative scenarios imply alternative parameter values for each pair of baseline and counter-factual simulations. What is critical for our marginal cost calculations is that any pair of baseline and counter-factual simulations employs identical assumptions (parameter values), with the exception, of course, of Z_{it}, the tax/subsidy that generates the counter-factuals and leads to our marginal cost estimates.

TABLE IV

Present-Value Equivalent Carbon Sequestration and Emissions with Alternative Discount Rates

Carbon sequestration and emissions	Alternative discount rates			
	2.5%	5.0%	7.5%	10.0%
Present-value equivalent carbon sequestration (tons per acre)				
Natural regrowth of mixed stand				
Periodic harvest (scenario #1)	61.90	43.36	30.63	22.72
No periodic harvest (scenario #2)	91.48	50.59	32.85	23.52
Pine plantation				
Periodic harvest (scenario #3)	54.66	41.05	30.76	23.75
No periodic harvest (scenario #4)	80.68	49.99	34.33	25.25
Present-value equivalent carbon emissions (tons per acre)				
Deforestation	54.28	51.83	50.99	50.55

carrying, W. Second, the present-value equivalent tons per acre of sequestration are affected by changing discount rates (Table IV).[29]

In Table V, we examine the impact of changing discount rates on three output variables: marginal sequestration costs, induced forestation, and induced carbon sequestration. The sensitivity analysis is carried out for two pine-plantation scenarios—periodically harvested (#3) and no periodic harvests (#4). First, we find that as the discount rate increases (from 2.5% to 10%), marginal sequestration costs increase monotonically, as expected. The simplest explanation of this effect is that the present-value equivalent sequestration decreases with increased interest rates. The magnitude of the impact is similar to that reported by [23], who found that raising the discount rate in their analysis from 3 to 7% nearly doubled marginal costs.

Next, we find that as the discount rate increases, the forestation caused by a given ($50/acre) subsidy/tax increases. This is also as anticipated, since the up-front subsidy/tax becomes more important, relative to discounted future flows of net revenue, with the increased discount rate. Finally, and most interesting, as the discount rate increases, the impact on induced carbon sequestration is not monotonic: at first increasing interest rates increase induced sequestration, but then they have the opposite effect, decreasing carbon sequestration. The explanation is that there are two factors at work here: land-use changes and the present-value equivalent of carbon sequestration per acre. At first, the land-use effect is dominant, and so with higher interest rates, we find more induced forestation and so more sequestration, but then the effect of smaller present values of carbon sequestration per acre becomes dominant, and so carbon sequestration begins to decrease with higher discount rates. The effect is particularly dramatic in scenario

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[29] The rotation period may also be responsive to changes in the discount rate. The extent of the response will depend on the range of discount rates analyzed and the sensitivity of stumpage values to changes in rotation period. While the effect can, in principle, be substantial, it is not for the species and range of discount rates we analyze, and the ultimate effect on annualized carbon yields and sequestration costs is very small.

TABLE V

Discount Rate Sensitivity of the Cost and Quantity of Carbon Sequestration, Pine Plantation

Carbon sequestration and forestation costs and quantities	Alternative discount rates			
	2.5%	5.0%	7.5%	10.0%
Marginal cost of sequestration ($/ton)				
(Sequestration = 5 million tons/year)				
Periodic harvest (scenario #3)	33	39	58	92
No periodic harvest (scenario #4)	18	27	46	81
Forestation relative to baseline (1,000 acres)				
(Subsidy/tax = $50/acre)				
Periodic harvest (scenario #3)	1,467	2,787	4,368	6,131
No periodic harvest (scenario #4)	1,453	2,763	4,336	6.092
Carbon sequestration relative to baseline				
(1,000 tons/year) (subsidy/tax = $50/acre)				
Periodic harvest (scenario #3)	3,271	4,219	4,302	3,928
No periodic harvest (scenario #4)	4,460	5,099	4,832	4,242

#4, where there is no periodic harvesting, since the fall in present-value carbon equivalents is greatest in that case.

3.3. *The Economic Environment*

It is of particular interest to ask what would happen to the estimated quantities of carbon sequestration and marginal costs if there were significant changes in the economic environment. The baseline simulation with recent price data reflects the reality currently being experienced in the study area—minimal, although not trivial, deforestation. In contrast to this, other parts of the United States—such as New England and the Middle Atlantic states—began to experience positive net rates of forestation as early as the middle of the 19th century. Such background patterns of land-use changes are potentially important. By modifying the assumed level of agricultural product prices in the analysis, we can produce baseline simulations with significant amounts of forestation or deforestation occurring (in the absence of policy intervention), and then investigate the consequences of policy interventions in these new dynamic contexts. We focus here on sensitivity analysis for the periodically harvested pine plantation scenario.

Thus, we change agricultural product prices (in both the baseline and policy simulations) and observe what happens to net forestation and sequestration. As can be seen in Table VI, increasing agricultural prices produces baseline simulations with significant deforestation. What are the impacts of such price changes on carbon sequestration *relative to baseline* at a given level of policy intervention, such as a land-use subsidy/tax of $50 per acre? Not surprisingly, we find that induced sequestration decreases monotonically as the background agricultural product price level increases. The change, however, is by no means linear. The context of low agricultural prices (30% below the base case) increases induced sequestration by 80%, whereas the high price context (30% above the base case) decreases induced sequestration by only 25%.

TABLE VI
Sensitivity of Results to Agricultural Prices,
Periodically Harvested Pine Plantation

Carbon sequestration and forestation costs and quantities	Departures from base case agricultural product prices						
	−30%	−20%	−10%	Base case	+10%	+20%	+30%
Baseline forestation/deforestation (1,000 acres)	5,968	3,317	1,430	52	−977	−1,758	−2,362
Marginal cost of carbon sequestration ($/ton) (Sequestration = 5 million tons/yr)	21.93	26.88	32.44	37.91	38.87	39.60	40.94
Carbon sequestration relative to baseline (1,000 tons/year) (subsidy/tax = $50/acre)	7,656	6,212	5,094	4,219	3,914	3,669	3,183

Note: Discount rate is 5%.

The same non-linear impact is seen when we observe the effect of agricultural price changes on the marginal costs of sequestration, again in Table VI. Marginal sequestration costs increase monotonically as we increase the background context of agricultural prices. This is as expected, since the opportunity cost of the land increases. Once again, the change is far from linear; decreases in agricultural prices have a much greater impact than do increases. This happens because higher agricultural product prices result in a substantial amount of deforestation in the baseline. As a result, the effect of a given tax/subsidy—in the context of high agricultural prices—is not only to increase forestation, but also to *retard deforestation*. And the carbon consequences of a unit of retarded deforestation (51.83 tons per acre from Table II) are significantly greater than those associated with a unit of forestation (41.05 tons per acre from Table II), in terms of present-value equivalents. The increased "carbon efficiency" of the policy intervention in the context of a high level of background deforestation thus reduces the marginal costs of sequestration below what they otherwise would be in the context of high agricultural prices.

4. CONCLUSIONS

When and if the United States chooses to ratify the Kyoto Protocol or subsequent international agreements, it will be necessary to decide whether carbon sequestration policies should be part of the domestic portfolio of U.S. compliance activities. For this reason, we have examined the sensitivity of sequestration costs to changes in key factors, including the nature of the management and deforestation regimes, silvicultural species, relative prices, and discount rates.

What conclusions can be drawn from these quantitative results? First, there is the somewhat surprising finding that marginal sequestration costs can be greater for cases with periodic harvesting of timber. Despite the fact that opportunity costs for landowners are less, the more favorable sequestration pattern provided by permanent stands can counteract and overwhelm this effect.[30]

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[30] A consistent set of assumptions is employed in the baseline and policy simulations underlying each scenario. This means that comparisons across scenarios typically involve different amounts of deforestation (or forestation) in respective baselines.

Second, changing the discount rate has two types of effects: many of the economic variables take on new values, and the present-value equivalent tons per acre of sequestration are affected. As the discount rate increases, the *marginal costs* of sequestration increase monotonically, because the present-value equivalent sequestration decreases. But as the discount rate increases, the impact on the *quantity* of induced carbon sequestration is not monotonic, because two factors work in opposite directions: forestation increases, but the present-value equivalent of carbon sequestration per acre decreases.

Third, background patterns of land-use changes are potentially important, a reality that we investigated by varying the baseline level of agricultural product prices. We found that induced sequestration decreases monotonically and non-linearly as the background agricultural product price level increases. Likewise, marginal sequestration costs increase monotonically and non-linearly as agricultural prices increase because the opportunity cost of the land increases.

Fourth and finally, there is the striking asymmetry between the marginal costs of carbon sequestration through forestation and those through retarded deforestation. This provides another argument for focusing carbon-sequestration efforts in areas of relatively high rates of deforestation, such as in tropical forests. In addition to the fact that these areas are more efficient engines of carbon storage than temperate forests and in addition to the lower opportunity costs of land that we would ordinarily anticipate to be associated with such areas, there is the additional reality that in an intertemporal economic context, retarded deforestation provides carbon conservation at much lower marginal costs than does forestation of the same area.[31] Of course this would have to be considered alongside other conditions present in any particular context, such as institutional concerns pertaining to administrative feasibility and the strength of property rights.

For many countries, carbon sequestration through forestation or retarded deforestation may be a cost-effective approach to contributing to reduced global atmospheric concentrations of CO_2. This seems most likely to be true for developing nations, although even for highly industrialized countries such as the United States, carbon sequestration through land-use changes could arguably be part of a cost-effective portfolio of short-term strategies [33]. Whether and to what degree "forestry instruments" belong in individual nations' global climate policy portfolios will depend upon geographic, institutional, and economic characteristics of countries and key local characteristics of forestry and land-use practices [22]. The investigation reported in this paper represents one step along the way to such comprehensive analysis.

APPENDIX: THE DYNAMIC OPTIMIZATION PROBLEM

A risk-neutral landowner will seek to maximize the present discounted value of the stream of expected future returns,

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

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[31] Additionally, many would argue that the non-climate change benefits of retarding tropical deforestation typically exceed those of increased forestation in temperate zones, because of the preservation of biological diversity in these exceptionally rich ecologies.

$$\text{subject to:}\quad \begin{aligned} &\dot{S}_{ijt} = v_{ijt} - g_{ijt}\\ &0 \le g_{ijt} \le \bar{g}_{ijt}\\ &0 \le v_{ijt} \le \bar{v}_{ijt}, \end{aligned}$$

where I indexes counties, j indexes individual land parcels, and t indexes time; upper case letters are stocks or present values and lower case letters are flows.[32] The variables are:

A_{it}	discounted present value of the future stream of typical expected agricultural revenues per acre in county I and time t;
q_{ijt}	parcel-specific index of feasibility of agricultural production, including effects of soil quality and soil 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 the discounted present value of an infinite future stream;
C_{it}	average cost of conversion per acre;
P_{it}	the Palmer hydrological drought index and α is a parameter to be estimated, 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;
W_{it}	windfall of net revenue per acre from clear cut of forest, prior to conversion to agriculture;
D_{it}	expected present discounted value of loss of income (when converting to forest) due to gradual regrowth of forest (first harvest of forest does not occur until the year $t + R$, where R is the exogenously determined rotation length);
$\bar{g}_{ijt}$	maximum feasible rate of deforestation, defined such that $\int_t^{t+\Delta} \left[\bar{g}_{ij\tau}\right] d\tau = S_{ijt}$ for arbitrarily small interval, Δ, over which $\bar{g}_{ij\tau}$ is constant; and
$\bar{v}_{ijt}$	maximum feasible rate of forestation, defined such that $\int_t^{t+\Delta} \left[\bar{v}_{ij\tau}\right] d\tau = T_{ijt} - S_{ijt}$ for arbitrarily small interval, Δ, over which $\bar{v}_{ij\tau}$ is constant.

The application of control theoretic methods yields a pair of necessary conditions for changes in land use [34]. Forestation (conversion of agricultural cropland to forest) occurs if a parcel is cropland and if

$$\left(F_{it} - D_{it} - A_{it} \cdot q_{ijt} + M_{it}\right) > 0, \tag{A1}$$

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[32] This specification implies that all prices and costs are exogenously determined in broader national or international markets, a reasonable assumption in the present application.

where F is forest net revenue, equal to f_{it}/r_t. On the other hand, deforestation occurs if a parcel is forested and if

$$\left(A_{it}\cdot q_{ijt} - M_{it} - C_{it}^{\alpha P_{it}} - (F_{it} - W_{it})\right) > 0. \tag{A2}$$

These inequalities imply that all land in a county will be in the same use in the steady state. In reality, counties are observed to be a mix of forest and farmland, due largely to the *heterogeneity* of land. If conversion costs are 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 the first equation in the Appendix (i.e., the objective function) is multiplied by q_{ijt}. As shown in [34], such unobserved heterogeneity can be parameterized within an econometrically estimatable model so that the *individual* necessary conditions for land-use changes 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. The complete model yields the following set of econometrically estimatable equations:

$$FORCH_{it} = FORCH_{it}^{a}\cdot D_{it}^{a} - FORCH_{it}^{c}\cdot D_{it}^{c} + \lambda_i + \phi_{it}$$

$$FORCH_{it}^{a} = \gamma_a\cdot\left[d_{it}\cdot\left[F\left[\frac{\log(q_{it}^{y}) - \mu(1+\beta_2 E_{it})}{\sigma(1+\beta_3 E_{it})}\right]\right] + (1-d_{it}) - \left[\frac{S}{T}\right]_{i,t-1}\right]$$

$$FORCH_{it}^{c} = \gamma_c\cdot\left[d_{it}\cdot\left[1 - F\left[\frac{\log(q_{it}^{x}) - \mu(1+\beta_2 E_{it})}{\sigma(1+\beta_3 E_{it})}\right]\right] + \left[\frac{S}{T}\right]_{i,t-1} - 1\right]$$

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

$$q_{it}^{y} = \left[\frac{F_{it} - D_{it} + M_{it}}{A_{it}}\right] \tag{A3}$$

$$q_{it}^{x} = \left[\frac{F_{it} - W_{it} + M_{it}}{A_{it} - C_{it}^{\alpha P_{it}}}\right], \tag{A4}$$

where all Greek letters are parameters that can be estimated econometrically;[33]

FORCH	change in forest land as a share of total county area;
$FORCH^{a}$	forestation (abandonment of cropland) as a share of total county area;
$FORCH^{c}$	deforestation (conversion of forest) as a share of total county area;
D^{a} and D^{c}	dummy variables for forestation and deforestation, respectively;
ϕ	an independent (but not necessarily homoscedastic) error term;

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[33] The econometrically estimatable coefficients have the following interpretations: λ_i is a county-level fixed-effect parameter; γ_a and γ_c are partial adjustment coefficients for forestation and deforestation; μ is the mean of the unobserved land-quality distribution; σ is the standard deviation of that distribution; α is the effect of weather on conversion costs; β_1 is the effect of government flood-control programs on agricultural feasibility; β_2 is the effect of these programs on the heterogeneity mean; and β_3 is the effect of programs on the standard deviation.

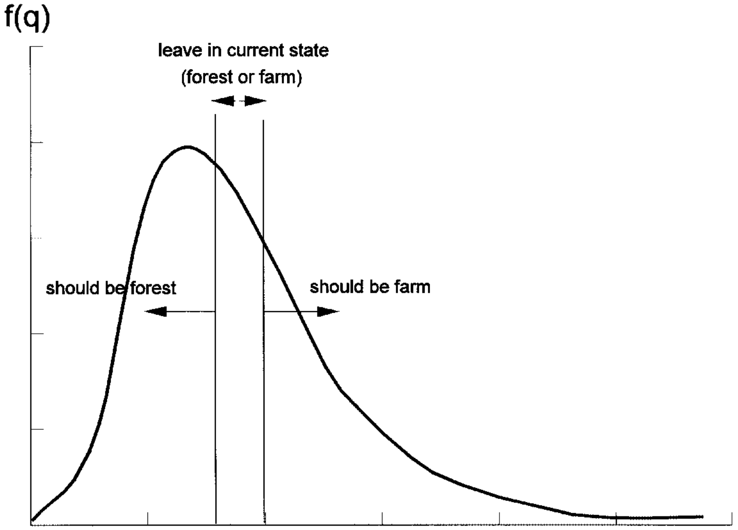

FIG. 3. The distribution of land quality and economic thresholds of forestation and deforestation.

d	probability that agricultural production is feasible;
q^y	threshold value of (unobserved) land quality (suitability for agriculture) below which the incentive for forestation manifests itself;
q^x	threshold value of land quality above which the incentive for deforestation manifests itself; E is an index of the share of a county that has been artificially protected from flooding by Federal programs (by time t);
E	index of share of county artificially protected from periodic flooding;
S	stock (acres) of forest;
F	cumulative, standard normal distribution function;
T	total county area; and
N	share of a county that is naturally protected from periodic flooding.

A simplified, pictorial representation of the model is provided in Fig. 3. The skewed distribution in the figure represents the parameterized lognormal distribution of unobserved land quality; and q^y_{it} and q^x_{it} are the forestation and deforestation thresholds, respectively. Note that each is a (different) function of the benefits and costs of forest production relative to agricultural production. The asymmetries between Eqs. (3) and (4) cause the separation between the two thresholds (where economic signals suggest to leave land in its existing state, whether that be forest or farm). Thus, if expected forest revenues increase, both thresholds shift to the right and we would anticipate that some quantity of farmland would be converted to forest uses. Likewise, an increase in expected agricultural prices means a shift of the two thresholds to the left, and consequent deforestation.

REFERENCES

1. R. M. Adams, D. M. Adams, J. M. Callaway, C. Chang, and B. A. McCarl, Sequestering carbon on agricultural land: Social cost and impacts on timber markets, *Contemp. Policy Issues* **11**, 76–87 (1993).
2. R. Alig, D. Adams, B. McCarl, J. M. Callaway, and S. Winnett, Assessing effects of mitigation strategies for global climate change with an intertemporal model of the U.S. forest and agricultural sectors, *Environ. Resour. Econom.* **9**, 259–274 (1997).
3. J. P. Bruce, H. Lee, and E. F. Haites, "Climate Change 1995: Economic and Social Dimensions of Climate Change," contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge Univ. Press, New York (1996).
4. J. M. Callaway and B. McCarl, The economic consequences of substituting carbon payments for crop subsidies in U.S. agriculture, *Environ. Resour. Econom.* **7**, 15–43 (1996).
5. R. Daniels, personal communication, Mississippi State University, Agricultural Extension Service, Starkville, MS (1994).
6. R. K. Dixon, S. Brown, R. A. Houghton, A. M. Solomon, M. C. Trexler, and J. Wisniewski, Carbon pools and flux of global forest ecosystems, *Science* **263**, 185–190 (1994).
7. R. K. Dixon, J. K. Winjum, K. J. Andrasko, J. J. Lee, and P. E. Schroeder, Integrated land-use systems: Assessment of promising agroforest and alternative land-use practices to enhance carbon conservation and sequestration, *Climatic Change* **27**, 71–92 (1994).
8. D. J. Dudek and A. LeBlanc, Offsetting new CO_2 emissions: A rational first greenhouse policy step, *Contemp. Policy Issues* **8**, 29–42 (1990).
9. M. E. Harmon, W. K. Farrell, and J. F. Franklin, Effects on carbon storage of conversion of old-growth forest to young forests, *Science* **247**, 699–702 (1990).
10. R. A. Houghton, Tropical deforestation and atmospheric carbon dioxide, *Climatic Change* **19**, 99–118 (1991).
11. C. J. Jepma, M. Asaduzzaman, I. Mintzer, S. Maya, and M. Al-Moneef, "A Generic Assessment of Response Options," Draft, Intergovernmental Panel on Climate Change, Report of Working Group III. Geneva, Switzerland (January 20, 1995).
12. J. A. Kershaw, C. D. Oliver, and T. M. Hinckley, Effect of harvest of old growth douglas-fir stands and subsequent management on carbon dioxide levels in the atmosphere, *J. Sustainable Forestry* **1**, 61–77 (1993).
13. G. Marland, "The Prospect of Solving the CO_2 Problem through Global Reforestation," DOE/NBB-0082, U.S. Department of Energy, Washington, DC (1988).
14. O. Masera, M. R. Bellon, and G. Segura, Forestry options for sequestering carbon in Mexico: Comparative economic analysis of three case studies, *presented at* Terrestrial Carbon Sequestration: An Economic Synthesis Workshop, Bergendal, Sweden, May 15–19 (1995).
15. R. J. Moulton and K. R. Richards, "Costs of Sequestering Carbon Through Tree Planting and Forest Management in The United States," GTR WO-58, U.S. Department of Agriculture, Forest Service, Washington, DC (1990).
16. New York State Energy Office, "Analysis of Carbon Reduction in New York State," Albany (1993).
17. W. D. Nordhaus, The cost of slowing climate change: A survey, *Energy J.* **12**, No. 1, 37–65 (1991).
18. P. J. Parks, D. O. Hall, B. Kriström, O. R. Masera, R. J. Moulton, A. J. Plantinga, J. N. Swisher, and J. K. Winjum, An economic approach to planting trees for carbon storage, *in* "Economics of Carbon Sequestration in Forestry" (R. A. Sedjo, R. N. Sampson, and J. Wisniewski, Eds.), CRC Press, Boca Raton, FL (1997).
19. P. J. Parks and I. W. Hardie, Least-cost forest carbon reserves: Cost-effective subsidies to convert marginal agricultural land to forests, *Land Econom.* **71**, 122–136 (1995).
20. A. J. Plantinga, The costs of carbon sequestration in forests: A positive analysis, *presented at* Terrestrial Carbon Sequestration: An Economic Synthesis Workshop, Bergendal, Sweden, May 15–19 (1995).
21. A. J. Plantinga and R. A. Birdsey, Carbon fluxes resulting from U.S. private timberland management, *Climatic Change* **23**, 37–53 (1993).
22. K. R. Richards, R. Alig, J. D. Kinsman, M. Palo, and B. Sohngen, Consideration of country and forestry/land-use characteristics in choosing forestry instruments to achieve climate mitigation goals, *in* "Economics of Carbon Sequestration in Forestry" (R. A. Sedjo, R. N. Sampson, and J. Wisniewski, Eds.), CRC Press, Boca Raton, FL (1997).

23. K. R. Richards, R. J. Moulton, and R. A. Birdsey, Costs of creating carbon sinks in the U.S., *Energy Conservation Management* **34**, 905–912 (1993).
24. K. R. Richards and C. Stokes, "Regional Studies of Carbon Sequestration: A Review and Critique," Mimeo, Pacific Northwest Laboratory, Washington, DC (June 1995).
25. C. Row, HARVCARB: Modeling forest management and the carbon balance, *presented at* the Western Forest Economics Meeting, Welches, Oregon, May 4–6 (1992).
26. C. Row and R. B. Phelps, Tracing the flow of carbon through the U.S. forest products sector, *in* "Proceedings of the 19th World Congress of the International Union of Forest Research Organizations, Montreal, Canada, August 5" (1990).
27. E. S. Rubin, R. N. Cooper, R. A. Frosch, T. H. Lee, G. Marland, A. H. Rosenfeld, and D. D. Stine, Realistic mitigation options for global warming, *Science* **257**, 148–149, 261–266 (1992).
28. R. A. Sedjo, R. N. Sampson, and J. Wisniewski (Eds.), "Economics of Carbon Sequestration in Forestry," CRC Press, Boca Raton, FL (1997).
29. R. A. Sedjo and A. M. Solomon, Climate and forests, *in* "Greenhouse Warming: Abatement and Adaptation" (N. J. Rosenberg, W. E. Easterling III, P. R. Crosson, and J. Darmstadter, Eds.), Resources for the Future, Washington, DC (1989).
30. R. A. Sedjo, J. Wisniewski, A. Sample, and J. D. Kinsman, "Managing Carbon via Forestry: Assessment of Some Economic Studies," Discussion Paper 95-06, Resources for the Future, Washington, DC (November 1995).
31. T. M. Smith, W. P. Cramer, R. K. Dixon, R. Leemans, R. P. Nelson, and A. M. Solomon, The global terrestrial carbon cycle, *Water Air Soil Pollution* **70**, 19–37 (1993).
32. R. N. Stavins, Alternative renewable resource strategies: A simulation of optimal use, *J. Environ. Econom. Management* **19**, 143–159 (1990).
33. R. N. Stavins, The costs of carbon sequestration: A revealed-preference approach, *Amer. Econom. Rev.* **89**, 994–1009 (1999).
34. R. N. Stavins and A. B. Jaffe, Unintended impacts of public investments on private decisions: The depletion of forested wetlands, *Amer. Econom. Rev.* **80**, 337–352 (1990).
35. S. Swinehart, "Afforestation as a Method of Carbon Sequestration: A Cost–Benefit Analysis," Ph.D. dissertation, Department of Operations Research/Engineering-Economic Systems, Stanford University, Stanford, CA (1996).
36. D. P. Turner, J. Lee, G. J. Koperper, and J. R. Barker (Eds.), "The Forest Sector Carbon Budget of the United States: Carbon Pools and Flux Under Alternative Policy Assumptions," U.S. Environmental Protection Agency, Corvallis, OR (1993).
37. United Nations General Assembly, "United Nations Framework Convention on Climate Change," A/AC.237/18 (Part II)/Add.I and A/AC.237/18 (Part II/Add.1/Corr.1), New York (1997).
38. G. C. Van Kooten, L. Arthur, and W. Wilson, Potential to sequester carbon in Canadian forests: Some economic considerations, *Canad. Public Policy* **18**, 127–138 (1992).
39. J. K. Winjum, R. K. Dixon, and P. E. Schroeder, Estimation of the global potential of forest and agroforest management practices to sequester carbon, *Water Air Soil Pollution* **62**, 213–227 (1992).