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

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Discussion Paper 99-31

April 1999

RESOURCES FOR THE FUTURE

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Abstract

The possibility of encouraging the growth of forests as a means of sequestering carbon dioxide has received considerable attention because of concerns about the threat of global climate change due to the greenhouse effect. In fact, this approach is an explicit element of both U.S. and international climate policies, partly because of evidence that growing trees to sequester carbon 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 the management and deforestation regimes, silvicultural species, agricultural prices, and discount rates. We find, somewhat counter-intuitively, that the costs of carbon sequestration can be greater if trees are periodically harvested, rather than permanently established. In addition, higher discount rates imply higher marginal costs, and they imply non-monotonic changes in the amount of carbon sequestered. Importantly, retarded deforestation can sequester carbon at substantially lower costs than increased forestation.

Key Words: climate change policy, forest sinks, land use, carbon sequestration costs

JEL Classification Numbers: Q15, Q23, Q28, D62

CLIMATE CHANGE AND FOREST SINKS: FACTORS AFFECTING THE COSTS OF CARBON SEQUESTRATION

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1. INTRODUCTION

The Kyoto Protocol to the United Nations Framework Convention on Climate Change (1997) 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.[1] Several studies have found that growing trees to sequester carbon could provide relatively low-cost net emission reductions for a number of countries (Bruce, Lee, and Haites 1996), including the United States (Adams, *et.al.* 1993; Callaway and McCarl 1996; Parks and Hardie 1995; Plantinga 1995; Richards, Moulton, and Birdsey 1993; and Stavins 1999).[2]

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

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[1]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 (Houghton 1991; Smith,*et.al.* 1993). 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 (Richards and Stokes 95). The analysis in this paper considers the first two pathways. For further discussion, see Parks et. al. (1997).

[2]There is a range of estimates of the relevant marginal cost function. These various estimates are compared by Stavins (1999), whose own estimates are significantly greater than the others for more ambitious sequestration programs.

as those that promote forestation[3] 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 and deforestation 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 (Stavins 1999). 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.[4]

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[3]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 (Jepma, Asaduzzaman, Mintzer, Maya, and Al-Moneef 1995). 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."

[4]The simplest of previous analyses derived single point estimates of average costs associated with particular sequestration levels (Marland 1988; Sedjo and Solomon 1989; Dudek and LeBlanc 1990; Rubin, *et.al.* 1992; Masera, Bellon, and Segura 1995), sometimes assuming that the opportunity costs of land are zero (Dixon, *et.al.* 1994b; New York State Energy Office 1993; Winjum, Dixon, and Schroeder 1992; Van Kooten, Arthur, and Wilson 1992). "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 (Moulton and Richards 1990; Richards, Moulton, and Birdsey 1993). Simulation models include a model of lost profits due to removing land from agricultural production (Parks and Hardie 1995), a mathematical programming model of the agricultural sector and the timber market (Adams, *et.al.* 1993; Alig *et.al.* 1997), a related model incorporating the effects of agricultural price support programs (Callaway and McCarl 1996), and a dynamic simulation model of forestry (Swinehart 1996). An analysis by Plantinga (1995) 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 1995; Sedjo, Wisniewski, Sample, and Kinsman 1994; and Sedjo, Sampson, and Wisniewski 1997.

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.

In Part 2 of the paper, we describe the analytical model; in Part 3, we carry out simulations for various scenarios and thereby examine the sensitivity of the marginal cost of carbon sequestration; and in Part 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.[5]

2.1 A Structural, Empirical Model of Land Use

In previous work with a different policy motivation, Stavins and Jaffe (1990) 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.[6] 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

[5]In both industrialized nations and in developing countries, nearly all deforestation is associated with conversion to agricultural use (Jepma, Asaduzzaman, Mintzer, Maya, and Al-Moneef 1995).

[6]A detailed description of the dynamic optimization model and the derivation of the econometrically estimatable model is found in Stavins and Jaffe (1990), while Stavins (1990) provides an illustration of the use of the model for environmental simulation.

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:

$$(F_{it} - D_{it} - A_{it} \cdot q_{ijt} + M_{it}) > 0 \qquad (1)$$

where i indexes counties, j indexes individual land parcels, and t indexes time; upper case letters are stocks or present values; lowercase 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:

$$(A_{it} \cdot q_{ijt} \; - \; M_{it} \; - \; C_{it}^{\alpha P_{it}} \; - \; (F_{it} - W_{it})) \;\; > \;\; 0 \qquad (2)$$

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 (1990), 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 (Stavins and Jaffe 1990). Table 1 provides descriptive statistics of the major variables used in the simulation analysis.

2.2 A Dynamic Simulation Model of Future Land Use

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 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 management 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 equations (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 silvicultural dimension of choice of species. In the econometric analysis, only mixed stands[7] 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.[8]

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 sets of silvicultural considerations lead to the following respecification of equation (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.[9] 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 initial scenarios to be investigated: natural regrowth of a mixed stand, with and without

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[7]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.

[8]The tree-farm revenue streams represent a mix of 80 percent loblolly pine and 20 percent slash pine, based upon practice in the area (Daniels 1994). We use a rotation length of 45 years, also reflecting standard practice (Moulton and Richards 1990).

[9]Forest establishment costs include the costs of planting (purchase of seedlings, site preparation, and transplanting), post-planting treatments, and care required to ensure establishment (Moulton and Richards 1990). We adopt a value of $92/acre ($1990), based upon estimates by Richards, Moulton, and Birdsey (1993) for converted cropland in the Delta (three-state) region.

periodic harvesting; and establishment of a pine plantation, with and without periodic harvesting. Until now we have assumed that deforestation involves the sale of merchantable timber, with an associated windfall of income, W, from the immediate sale of timber from the felled forest. But another possibility is that at the time of deforestation merchantable timber is not sold, but simply burned along with all other on-site material.[10] In this case, the income windfall will be absent (W=0 in equation (4) and in equation (7) below), and there will be important carbon consequences. This possibility yields four additional "deforestation with burning" scenarios, one for each of the four scenarios described above.

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 predictions of future forestation and/or deforestation (Stavins 1990).[11] These results, aggregated across the 36 counties, 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

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[10]This may be thought of as a limiting case with regard to carbon capture in durable goods.

[11]Statistical tests, reported in Stavins and Jaffe 1990, indicate a high degree of structural (and parametric) stability of the model over the fifty-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.

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 (equation (4)) and treating the tax payment as an increment to conversion or production costs in the deforestation part of the model (equation (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 equations (6) and (7) in conjunction with the other equations of the model (see Appendix), in which the variable Z is set equal to zero, 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.[12]

[12]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 1999.

2.3 A Dynamic Simulation Model 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.[13] 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 commence 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*. As will become clear below, the emissions may be instantaneous if the felled forest is burned, or there may be a time-path of emissions if durable wood products are produced from merchantable timber.

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 continually evolving; we attempt to base our modeling of the relationships upon state-of-the-art biological models employing a set of temporal carbon yield curves.[14] Figure 1 provides a pictorial representation of one example of the biological time path of carbon sequestration and emission linked with a specific forest management regime. In the example in the figure, the time profile of cumulative carbon sequestration is for establishing a new loblolly pine plantation. Carbon sequestration occurs in four components

[13]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.

[14]Nordhaus (1991) and Richards, Moulton, and Birdsey (1993) also use carbon yield curves, while many other sequestration cost studies have used point estimates of average flows.

of the forest: trees, understory vegetation, forest floor, and soil (Birdsey 1992).[15] 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 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.[16] Much of the carbon sequestered in wood products is also released to the atmosphere, although this occurs with considerable delay as wood products decay.[17] As can be seen in the figure, in this scenario the forest is replanted, and the same process takes place again.[18]

Although the carbon yield curve with harvesting in Figure 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

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[15]Although 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. Variation in these shares is significant; for some species, soil carbon accounts for nearly 50 percent of total forest carbon.

[16]Our calculations of releases from the understory, forest floor, soil, and non-merchantable timber are based upon Moulton and Richards (1990) and Richards, Moulton, and Birdsey (1993). The share of total forest carbon that actually ends up in merchantable wood varies considerably by species. A reasonable reference point is about 40 percent. Much of the remaining 60 percent 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.

[17]As Sedjo, Wisniewski, Sample, and Kinsman (1995) 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, Farrell, and Franklin (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 Row (1992), Row and Phelps (1990), and Turner *et.al.* (1993), 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 (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 Nordhaus (1991).

[18]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.

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 fully 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.[19]

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"—each has limitations (Richards and Stokes 1995).

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 has several obvious problems associated with it: first, it 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 sequestration 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

[19]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, Farrell and Franklin (1990) find that old growth forests are superior to periodic harvesting approaches in their ability to sequester carbon, but Kershaw, Oliver, and Hinckley (1993) demonstrate that this is dependent upon specific circumstances.

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 and is utilized here: the discounted present value of costs is divided by the discounted present value of tons sequestered. This approach 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. We initially use a 5 percent discount rate, supplemented later by sensitivity analysis.

We develop the constituent intertemporal yield curves for various forest species, location, and management conditions, and calculate the present-value equivalent carbon-sequestration measures associated with natural regrowth of a mixed stand, both periodically harvested and permanent (43.36 and 50.59 tons, respectively), and a pine plantation, again both periodically harvested and permanent (41.05 and 49.99 tons, respectively).[20] Additionally, we calculate present-value carbon emission measures for deforestation with sale of merchantable timber (51.83 tons) and deforestation with burning of all on-site material (72.64 tons). These values are also reported in Tables 1 and 4.

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[20]The yield curves provided in Figure 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 (Dixon, Brown, Houghton, Solomon, Trexler, and Wisniewski 1994a). 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 carbon paths are weighted averages from hardwood and pine constituents, assuming 55 percent hardwoods and 45 percent southern pine (Daniels 1994). The assumed density of carbon in merchantable hardwoods is from Moulton and Richards (1990) for Delta state hardwoods. In the case of softwoods (pines), density and assumed rotation length are for loblolly pine and slash pine (Moulton and Richards 1990), weighted as being 80 percent and 20 percent, respectively, of total softwoods. Carbon sequestration patterns and merchantable wood volumes for pine are based on data used by Richards, Moulton, and Birdsey (1993) for cropland in the Delta region.

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:

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

where

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

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

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

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, 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 considered here.[21]

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 equations (8), (9), and (10).[22] 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. 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 eight 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 annual[23] carbon sequestration (relative to the baseline). Table 2 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 acres (over the 90-year study period). Baseline net carbon

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

[22]In a prior step, the econometrically estimated parameters were used with newly available data for 1989 to simulate total forested acreage per county in that year. That formed the base-period land use for the 90-year simulations. The 1989 simulations indicate a small (135,000 acre) loss of forests during the previous five-year period, due to a combination of depletion in response to previous Federal programs and increases in relative agricultural prices.

[23]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 (employing a discount rate of 5 percent).

sequestration is approximately 4.6 million tons annually. As can be seen in Table 2 and Figure 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).[24] This is not surprising. Such an implicit limit would be associated in the model 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 36 counties of the study region.[25]

3.1 Alternative Silvicultural Scenarios

The simulated costs of carbon sequestration are given in Table 3, where the alternative scenarios are numbered from #1 through #8. 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 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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[24]Although the assumption of exogenous prices inevitably 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.

[25]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, Figure 2 provides not only a set of point estimates of the marginal cost function, but also the 95 percent 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 now modify the 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 3). 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 does cause a modest decrease in the total amount of induced forestation that occurs. But the time path of carbon sequestration without harvesting is sufficiently favorable to overcome this effect, so that 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.

Our finding that the no-harvesting regimes are more favorable than the harvesting regimes in terms of relative marginal costs contradicts a number of previous carbon-sequestration costs analyses. But, our finding is consistent with the analysis by Van Kooten, Binkley, and Delecourt (1995) who revise a standard Hartman (1976) model to allow for standing trees to have carbon storage value, and find that with some parameter values, permanent stands are more desirable than periodic stands, since carbon valuation overcomes foregone timber valuation.

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 are themselves very similar.

Two scenarios where deforestation is assumed to result in complete burning of all on-site material (Scenarios #5 and #6) exhibit somewhat lower marginal costs of carbon sequestration than their two counterparts where deforestation leads to the sale of on-site merchantable timber (Scenarios #1 and #2). This is because retarded deforestation makes important contributions here, and it is retarded deforestation that exhibits such significant differences in carbon emissions between the "site burn" and "timber sale" cases. Of course, there is little or no effect of changing the deforestation activity assumption (sell timber versus burn it) in those cases in which retarded deforestation is small (Scenarios #4 and #8) or absent (Scenarios #3 and #7).

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 interest rate (5 percent). 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 carrying , W. Second, the present-value equivalent tons per acre of sequestration are affected by changing discount rates (Table 4).

In Table 5, 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 percent to 10 percent), 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 Richards, Moulton, and Birdsey (1993), who found that raising the discount rate in their analysis from 3 to 7 percent 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 #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 predicted 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 nineteenth 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 two periodically harvested pine-plantation scenarios —"timber sale" versus "site burn".

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 6, increasing agricultural prices in the "timber sale" scenario 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 (in Scenario #3) as the background agricultural product price level increases. The change, however, is by no means linear. The context of low agricultural prices (30 percent below the base case) increases induced sequestration by 80 percent, whereas the high price context (30 percent above the base case) decreases induced sequestration by only 25 percent.

The same non-linear impact is seen when we observe the effect of agricultural price changes in Scenario #3 on the marginal costs of sequestration, again in Table 6. 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; deceases 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 2) are significantly greater than those associated with a unit of forestation (41.05 tons per acre from Table 2), 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.

This effect becomes even more striking when we consider the “site burn” scenario (#7) in which deforestation results in the burning of all on-site material, rather than the sale of merchantable timber (Table 6). In fact, in the burning scenario, the "carbon efficiency" of retarding deforestation (relative to that of encouraging forestation) is so great[26] that the sensitivity analysis no longer exhibits monotonically increasing marginal costs of sequestration (and monotonically decreasing induced sequestration) as agricultural prices increase. Rather, we now find that once agricultural prices move above the base case level, induced sequestration actually begins to increase (and marginal sequestration costs decrease), up to the point at which agricultural prices are 20 percent above the base case. From this point on, however, the original pattern returns: higher agricultural prices mean less induced sequestration and higher marginal sequestration costs.

[26]The volume of *immediate* carbon emissions due to burning is 72.64 tons per acre (Table 2), contrasted with the present value of 41.05 tons of sequestration associated with forestation.

The explanation for this pattern is found in the first line of Table 6, where baseline forestation and deforestation are presented. As agricultural prices increase from 30 percent below the base case level up to that level, there is only forestation in the baseline and hence only induced forestation in the policy simulations. Hence, the only effect of the agricultural price increase is to reduce the net land-use (acreage) impact of the given ($50) subsidy/tax. Thus, sequestration falls and marginal costs rise. As we move from the base case to 20 percent above it, however, there is deforestation in the baseline, and so the price increase not only reduces the net land-use impact of the subsidy/tax but also increases the net induced carbon sequestration *per acre*, as more and more retarded deforestation is included in the total. The consequence is that net carbon sequestration actually increases (and marginal costs fall). Beyond the 20-percent-above-base-case level, however, both the baseline and the policy simulations exhibit *only* deforestation, and so the impact of increasing agricultural prices is once again only to decrease the net acreage impact of the subsidy/tax; sequestration per acre is constant; and so net sequestration falls and marginal costs rise.

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 are 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 counteracts and overwhelms this effect.[27]

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

[27]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.

intertemporal economic context, retarded deforestation provides carbon conservation at much lower marginal costs than does forestation of the same area.[28]

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 is 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 (Stavins 1999). 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 (Richards *et.al*. 1997). The investigation reported in this paper represents one step along the way to such comprehensive analysis.

[28]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.

TABLE 1:
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 Harvested Mixed Stand	43.36	0.00	43.36	43.36
Natural Regrowth of Permanent Mixed Stand	50.59	0.00	50.59	50.59
Pine Plantation Periodically Harvested	41.05	0.00	41.05	41.05
Pine Plantation, Permanent	49.99	0.00	49.99	49.99
Carbon Emissions due to Deforestation[e] (tons/acre)				
with Sale of Merchantable Timber	51.83	0.00	51.83	51.83
with Burning of all Material	72.64	0.00	72.64	72.64
Interest Rate[f]	5%	0.00	5%	5%

Notes: [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 percent real rate.

TABLE 2:
LAND CHANGE AND CARBON SEQUESTRATION COSTS AND QUANTITIES
Periodically Harvested Pine Plantation, Sale of Merchantable Timber at Deforestation

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
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
1000	9,178	219.53	13,897	664.35	145.01

Notes: Discount rate is 5 percent; baseline forestation is 52 thousand acres; baseline carbon sequestration is 4.6 million tons.

TABLE 3:
COSTS OF CARBON SEQUESTRATION
FOR ALTERNATIVE SILVICULTURAL SCENARIOS

	Alternative Silvicultural Scenarios							
Species Regime	Natural Regrowth of Mixed Stand				Pine Plantation			
Management Regime	Periodic Harvest		No Harvest		Periodic Harvest		No Harvest	
Deforestation Regime	Timber Sale	Site Burn	Timber Sale	Site Burn	Timber Sale	Site Burn	Timber Sale	Site Burn
Scenario Number	#1	#5	#2	#6	#3	#7	#4	#8
Baseline Change in Forestation (1000 acres)	-259	-259	-297	-297	52	52	-69	-69
Baseline Carbon Sequestration (1000 tons)	4,005	3,807	3,931	3,703	4,578	4,578	4,368	4,315
Marginal Cost per Acre ($/acre/yr)	55.80	53.80	49.20	47.10	58.40	58.40	49.10	48.60
Forestation Relative to Baseline (1000 acres)	3,074	2,954	2,662	2,549	3,301	3,301	2,710	2,680
Average Cost per Acre ($/acre/yr)	33.80	32.74	30.31	29.21	35.12	35.12	30.23	29.97
Forestation Carbon Sequestration (tons/acre)	43.36	43.36	50.59	50.59	41.05	41.05	49.99	49.99
Deforestation Carbon Emissions (tons/acre)	51.83	72.64	51.83	72.64	51.83	72.64	51.83	72.64
Average Cost of Carbon Sequestration ($/ton)	20.79	19.33	16.20	14.89	23.20	23.20	16.38	16.07
Marginal Cost of Carbon Sequestration ($/ton)	34.33	31.76	26.30	24.02	38.57	38.57	26.61	26.06

Note: Annual carbon sequestration relative to baseline is 5 million tons; discount rate is 5 percent.

TABLE 4:
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	61.90	43.36	30.63	22.72
No Periodic Harvest	91.48	50.59	32.85	23.52
Pine Plantation				
Periodic Harvest	54.66	41.05	30.76	23.75
No Periodic Harvest	80.68	49.99	34.33	25.25
Present-Value Equivalent Carbon Emissions (tons per acre)				
Deforestation				
w/ Sale of Merchantable Timber	54.28	51.83	50.99	50.55
w/ Burning of all On-Site Material	72.64	72.64	72.64	72.64

TABLE 5:
DISCOUNT RATE SENSITIVITY OF THE COST AND QUANTITY OF CARBON SEQUESTRATION
Pine Plantation, Sale of Merchantable Timber When/If Deforestation Occurs

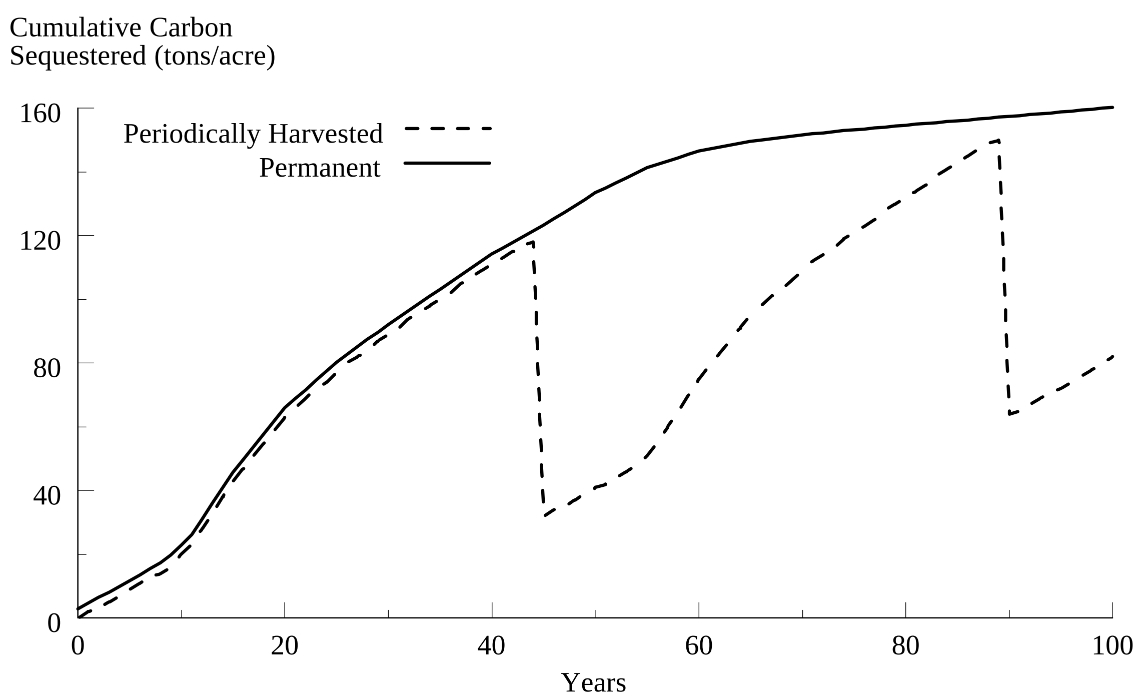
Carbon Sequestration and Forestation Costs and Quantities	Alternative Discount Rates			
	2.5%	5.0%	7.5%	10.0%
Marginal Cost of Sequestration ($/ton)				
(Sequestration = 5 million tons/yr)				
Periodic Harvest (Scenario #3)	33	39	58	92
No Periodic Harvest (Scenario #4)	18	27	46	81
Forestation Relative to Baseline (1000 acres)				
(Subsidy/tax = $50/acre)				
Periodic Harvest (#3)	1,467	2,787	4,368	6,131
No Periodic Harvest (#4)	1,453	2,763	4,336	6,092
Carbon Sequestration Relative to Baseline				
(1000 tons/yr) (Subsidy/tax = $50/acre)				
Periodic Harvest (#3)	3,271	4,219	4,302	3,928
No Periodic Harvest (#4)	4,460	5,099	4,832	4,242

TABLE 6:
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 (1000 acres)	5,968	3,317	1,430	52	-977	-1,758	-2,362
Marginal Cost of Carbon Sequestration ($/ton) (Sequestration=5 million tons/yr)							
Sale of Merchantable Timber at Deforestation	21.93	26.88	32.44	37.91	38.87	39.60	40.94
Burning of On-Site Material at Deforestation	21.93	26.88	32.44	37.91	27.71	19.45	20.66
Carbon Sequestration Relative to Baseline (1000 tons/year) (Subsidy/tax=$50/acre)							
Sale of Merchantable Timber at Deforestation	7,656	6,212	5,094	4,219	3,914	3,669	3,183
Burning of On-Site Material at Deforestation	7,656	6,212	5,094	4,219	4,663	5,019	4,461

Note: Discount rate is 5 percent.

FIGURE 1:
TIME PROFILE OF CARBON SEQUESTRATION
(Loblolly Pine in Delta States Region)



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

FIGURE 2:
MARGINAL COST OF CARBON SEQUESTRATION
(Scenario #3 — Periodically Harvested Pine Plantation)

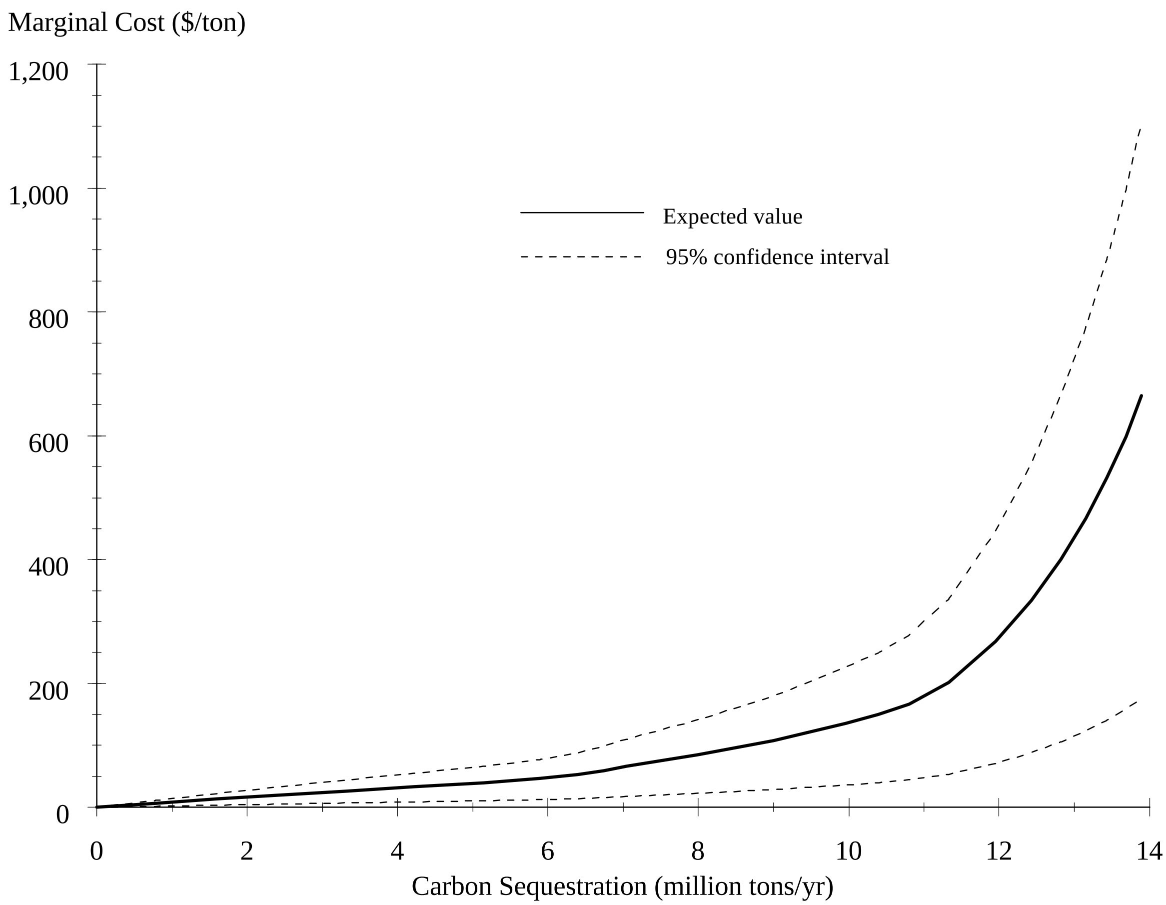
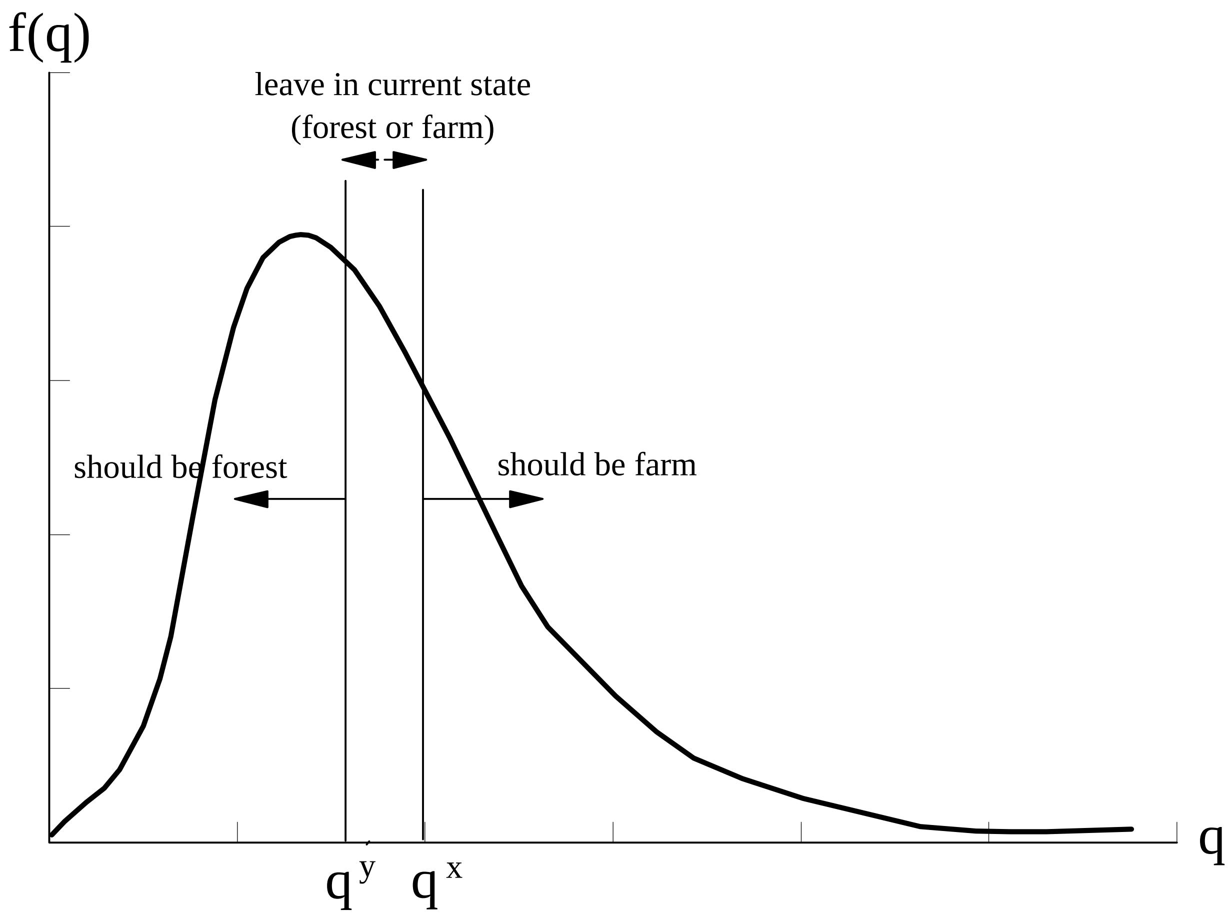


FIGURE 3:
THE DISTRIBUTION OF LAND QUALITY
AND ECONOMIC THRESHOLDS OF FORESTATION AND DEFORESTATION



APPENDIX:
THE DYNAMIC OPTIMIZATION PROBLEM

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

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

$$subject\ to: \qquad \dot{S}_{ijt} = v_{ijt} - g_{ijt}$$

$$0 \leq g_{ijt} \leq \bar{g}_{ijt}$$

$$0 \leq v_{ijt} \leq \bar{v}_{ijt}$$

where *i* indexes counties, *j* indexes individual land parcels, and *t* indexes time; upper case letters are stocks or present values; and lowercase letters are flows.[1] 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);

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

$\bar{g}_{ijt}$ = maximum feasible rate of deforestation, defined such that

$$\int_t^{t+\Delta} [\bar{g}_{ij\tau}]\, d\tau = S_{ijt}$$

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

$$\int_t^{t+\Delta} [\bar{v}_{ij\tau}]\, d\tau = T_{ijt} - S_{ijt}$$

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 (Stavins and Jaffe 1990). Forestation (conversion of agricultural cropland to forest) occurs if a parcel is cropland and if:

$$(F_{it} - D_{it} - A_{it} \cdot q_{ijt} + M_{it}) > 0 \qquad (1)$$

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:

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

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. As shown in Stavins and Jaffe (1990), 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:

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

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

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

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

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

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

where all Greek letters are parameters that can be estimated econometrically;[2]

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;
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 Figure 3. The skewed distribution in the figure represents the parameterized lognormal distribution of unobserved land quality; and q_{it}^{y} and q_{it}^{x} 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 equations (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

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[2]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, the effect of government flood-control programs on agricultural feasibility; β_2, the effect of these programs on the heterogeneity mean; and β_3, the effect of programs on the standard deviation.

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.

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