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A Revealed Preference Approach**

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The Costs of Carbon Sequestration: A Revealed-Preference Approach

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EXECUTIVE SUMMARY

Increased attention by policy makers to the threat of global climate change has brought with it considerable attention to the possibility of encouraging the growth of forests as a means of sequestering carbon dioxide. This interest has been due, in part, to: suggestions that sufficient lands are available to use the approach to mitigate a substantial share of annual carbon dioxide (CO₂) emissions; and claims that growing trees to sequester carbon is a relatively inexpensive means of combating climate change.

This paper demonstrates a methodology whereby reliable estimates of the costs of carbon sequestration can be developed on the basis of revealed-preference evidence from observations of landowners' behavior when confronted with the opportunity costs of alternative land uses. The 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, the approach employed reflects the actual preferences of landowners, as revealed by landowners' decisions regarding the disposition of their lands in the face of relevant economic signals.

The preliminary results indicate, first, that the marginal costs of carbon sequestration are by no means trivial, despite the claims that have sometimes been made. Second, even putting aside the anticipated responsiveness of land prices to any significant national sequestration program, the heterogeneity of the existing stock of land brings sharply increasing marginal costs of sequestration as higher quality agricultural lands are converted to forested use. Third, there is the somewhat surprising finding that the marginal sequestration cost function shifts upward when periodic harvesting of timber is allowed, despite the fact that opportunity costs for landowners are lowered.

Fourth and finally, there is a striking asymmetry between the marginal costs of carbon sequestration through forestation and those through retarded deforestation. If further research corroborates these findings, this may provide another argument for focusing carbon-sequestration efforts in areas of relatively high rates of deforestation, such as tropical forested regions. 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).

The major advantage of our approach over the models that have dominated the literature on carbon sequestration is that simulations of marginal costs build directly upon revealed-

preference patterns of how landowners have actually responded to the economic incentives they continually face regarding the alternative uses of their lands. This is in contrast with engineering approaches that build up marginal cost functions by aggregating point estimates of how landowners in a particular region or holding a particular type of land *ought* to behave, and in contrast with optimization models that often do much the same thing.

As is well known, landowners tend not to behave as they "ought" farmers are notoriously sluggish in responding to the economic signals they face. Stated otherwise, they are strongly affected by non-pecuniary factors, including a desire to stay on the farm for reasons associated more with quality of life than with financial returns. An econometric model that is based upon an underlying optimization model and then allows for "partial adjustment" or other phenomena can capture, albeit in a crude way, such land-use behavior. Hence, the land-use simulations that come from it, along with the respective estimates of carbon-sequestration costs may be better approximations of reality.

Our approach of linking a dynamic simulation model of carbon sequestration with an econometric model of land use has the potential of adding significantly to our understanding of the costs of this frequently discussed approach to addressing the threat of global climate change. There is a small, but growing literature of econometric analyses of forestation and deforestation. Any can serve as the basis for developing revealed-preference analytical models of the respective marginal costs of carbon sequestration.

THE COSTS OF CARBON SEQUESTRATION: A REVEALED-PREFERENCE APPROACH

Robert N. Stavins*

1. INTRODUCTION

Increased attention by policy makers to the threat of global climate change has brought with it considerable attention to the possibility of encouraging the growth of forests as a means of sequestering carbon dioxide (National Academy of Sciences 1992; Intergovernmental Panel on Climate Change 1994).¹ This approach has, in fact, become an explicit element of both U.S. and international climate policies (U.S. Department of Energy 1991; Clinton and Gore 1993; United Nations General Assembly 1992). This high level of interest has been due, in part, to: suggestions that sufficient lands are available to use the approach to mitigate a substantial share of annual carbon dioxide (CO₂) emissions (Marland 1988; Lashof and Tirpak 1989; and Trexler 1991); and claims that growing trees to sequester carbon is a relatively inexpensive means of combating climate change (Dudek and LeBlanc 1990; National Academy of Sciences 1992; Sedjo and Solomon 1989). In other words, the serious attention given by policy makers to carbon sequestration can partly be explained by (implicit) assertions about respective marginal cost functions.

This paper demonstrates a methodology whereby reliable estimates of the costs of carbon sequestration can be developed on the basis of evidence from observations of landowners' behavior when confronted with the opportunity costs of alternative land uses. The analytical model takes full account of current silvicultural understanding of the intertemporal linkages between deforestation² and carbon emissions, on the one hand, and between forestation and carbon sequestration, on the other. The results support the efficacy and potential value of this analytical approach.

The simplest economic analyses of the costs of carbon sequestration have 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). In a number of cases, it has been assumed, implicitly or explicitly, that land (opportunity) costs are zero (Dixon, *et.al.* 1994, New York

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¹ Alter fossil-fuel combustion, deforestation is the second largest source of carbon dioxide emission, 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). 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 tires for fossil fuels (Richards and Stokes 1995). The model developed in this paper considers the first two pathways.

² 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, Asaduzzantan, _Mintzer, Maya, and Al-Moneef 1995). In our model, there is no reason to make this distinction, and so we singly refer to any *change to* forest use as "forestation." This is in contrast to a change from forest use of land - "deforestation."

State Energy Office 1993; William, Dixon, and Schroeder 1992; Van Kooten, Arthur, and Wilson 1992). Another set of studies -- essentially "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). Related to these is a simulation model of the lost profits due to removing land from agricultural production (Parks and Hardie 1995) and a mathematical programming model of the agricultural sector and the timber market used to estimate the loss of consumer surplus from food price increases due to reduction of agricultural land availability (Adams, *et.al.* 1993). Finally, a recent analysis by Plantinga (1995) adopts land-use elasticities from a previous econometric study to estimate sequestration costs in southwestern Wisconsin.³

Each of these previous analyses has its own comparative advantages, and a number of the studies have absolute advantages along particular dimensions. The research described in the current paper draws on some of the best features of each, including the carbon levelization method of Adams *et.al.* (1993) and Moulton and Richards (1990), and the intertemporal carbon yield curves of Richards, Moulton, and Birdsey (1993). Nearly all of the previous analyses are potentially limited, however, by their inability to reflect the actual preferences of landowners, as revealed -- for example -- by landowners' decisions regarding the disposition of their lands in the face of relevant economic signals.⁴ One aspect of this problem has been described by Richards, Moulton, and Birdsey (1993, pp. 911-912) as follows:

One of the difficulties in conducting an engineering or "least cost" type of analysis is that it assumes that 100 percent of the marginal agricultural land is available for conversion to tree plantations. In fact, that level of participation by agricultural land owners is not likely in the absence of the exercise of eminent domain or public taking powers.

In the words of these same researchers, there has been an observed "tendency of some land owners to hang on to their land longer or more stubbornly" (p. 912) than the simplest economic calculations would suggest.

There are a number of reasons why landowners' actual behavior might not be well predicted by "engineering" or "least cost" analyses: (1) land-use changes can involve irreversible investments in the face of uncertainty (Parks 1995), and so option values -- ignored in engineering and least-cost analyses -- may be important (Pindyck 1991); (2) there may be non-pecuniary returns to landowners from forest uses of land (Plantinga 1995), as well as from agricultural uses; (3) liquidity constraints or simple "decision-making inertia" may mean that economic incentives will affect landowners only with some delay; and (4) there may be private, market benefits or costs of alternative land uses (or of changes from one use to another) of which the analyst is unaware.

³ This brief review of literature is by no means comprehensive. It focuses on studies that have examined U.S. carbon sequestration. Among analyses that have taken an aggregate, global perspective is that of Nordhaus (1991). Furthermore, even for the United States, there have been dozens of engineering models, in addition to the few mentioned above. For recent surveys of the literature, see: Richards and Stokes 1995; and Sedjo, Wisniewski, Sample, and Kinsman 1994. The analytical model of Adams *et.al.* (1993) has the distinction of being the only approach that has included endogenous prices for relevant products. This issue is discussed below.

⁴ The exception is the analysis by Plantinga (1995), which is similar in some respects to the methodology developed in the paper. One major difference is that the former model requires information on land characteristics (quality) *within* counties, and employs these data to carry out separate econometric analyses for individual land productivity classes, whereas the approach developed in the present paper is based upon an econometric model in which the unobserved heterogeneity of land is parameterized and thus estimated simultaneously with other structural parameters. See section 2.1, below.

In the present paper, we seek to address some of these problems by employing an econometric model of actual land-use behavior to derive the costs of carbon sequestration. In Part 2 of the paper, we describe the analytical model, including a brief summary of the structural model of historical land use that is drawn from a previous analysis, the dynamic simulation model of future land use, and the related simulation model of carbon sequestration. In Part 3, we describe the results of simulations for various silvicultural scenarios (of management regimes and tree species) that seem particularly relevant, and we provide a sensitivity analysis of the marginal cost estimates that are derived from the simulations. In Part 4, we compare our results with other estimates of carbon-sequestration costs and with estimates of the cost of abating carbon emissions through fuel switching and energy-efficiency enhancements. We conclude with some comments on promising directions for future research.

2. ANALYTICAL MODEL

We draw upon econometrically-estimated parameters of a structural model of land use, and layer upon it a model of the relationships that link changes in alternative land uses with changes in the time paths of CO₂ emission and sequestration. The major steps in the analysis are as follows. First, a dynamic optimization model of individual landowner decision making is solved with basic control-theoretic techniques. The model focuses on the empirically relevant land-use options of forest and farm.⁵ By allowing for unobserved heterogeneity of land quality, the individual necessary conditions from that optimization model are aggregated into an econometric specification, the parameters of which are estimated with available aggregate time-series and cross-sectional data. These results provide the first building block for the model of carbon sequestration.

The estimated econometric model indicates how land use may be anticipated to change in response to changes in the economic climate, including such relevant factors as expected timber and agricultural product prices, and costs of changing land use. Hence, a properly specified and related simulation model can produce fitted values of land use changes that would take place in response to government policies such as taxes on deforestation or subsidies on forestation. Such simulations yield, in effect, a forest supply function.

Next, a set of models of the various relationships that exist between the time path of deforestation and carbon emissions and the time path of forestation and carbon sequestration are linked with the land-use model, so that we can predict net carbon emissions/sequestration associated with a given tax/subsidy and a given set of background economic variables. Finally, the simulation model is modified so that its results are expressed in terms of marginal costs of carbon sequestration and total annual sequestration. This provides estimates of the key statistic -- the incremental costs of sequestration -- that can be compared with the costs associated with more conventional approaches of carbon abatement, principally fuel switching and increased energy efficiency.

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).

2.1 A Structural, Empirical Model of Land Use

In previous work with a distinctly different policy motivation, a dynamic optimization model was developed of a landowner's decision of whether to keep his or her land in its status quo use or convert it to serve another purpose.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,⁷ and on this basis form expectations of future values of respective variables. In particular, landowners observe agricultural prices and production costs, typical agricultural yields for their area, typical timber returns, and the suitability of individual land parcels for agriculture.

Landowners are assumed to 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 revenues in the area (A_{it}); the quality of a specific land parcel for agricultural production (q_{ijt}); agricultural costs of production (M_{it}); typical forestry revenues (f_{it}); and the cost of converting land from a forested state to use as cropland (C_{it}). Thus, a risk-neutral landowner will seek to maximize the present discounted value of the stream of expected future returns.⁸

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

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

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

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

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." The variables are:

⁶A detailed description of the dynamic optimization model and the derivation of the econometrically estimatable model is found in Stavins and Jaffe 1990. An illustration of the use of the model for environmental simulation is found in Stavins 1990. The analysis of carbon sequestration featured in the present paper builds upon results of land-use modeling from those previous studies. The reader is referred there for background details.

⁷For the geographic area of the investigation -- thirty-six counties along the Mississippi River in Arkansas, Louisiana, and Mississippi -- it is empirically reasonable to focus on these two alternative land uses.

⁸Note that the term in the objective function that represents the (discounted present value of) expected future net revenue from agricultural production, $A_{it}q_{ijt} - M_{it}$, is the price of farmland in a competitive market.

⁹This specification implies that all prices and costs are exogenously determined in broader national or international markets, a reasonable assumption in the present application.

- A_{it} = discounted present value of the future stream of typical expected agricultural revenues per acre in county i and time t ;
- q_{it} = 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;¹⁰
- f_{it} = expected annual net income from forestry per acre (annuity of stumpage value);
- S_{it} = stock (acres) of forest;
- r_t = real interest rate;
- W_{it} = windfall of net revenue per acre from a one-time clear cut of forest (prior to conversion to agricultural use);
- D_{it} = expected present discounted value of loss of income (when converting to forest) due to gradual regrowth of forest (first harvest of forest does not occur until the year $t + R$, where R is the exogenously determined rotation length);
- \check{g}_{it} = maximum feasible rate of deforestation; and
- \acute{v}_{ijt} = maximum feasible rate of forestation.

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

$$(\dot{I}_{it} - A_{it} \bullet q_{ijt} + M_{it}) > 0 \quad (5)$$

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

¹⁰ Precipitation and soil moisture influence conversion costs.. Hence, the conversion cost term in equation (1) is replaced below by $C_{it} \exp \{ \alpha P_{it} \} g_{it}$, where α is an estimated parameter and P_{it} is the Palmer Hydrological Drought Index

$$(A_{it} \cdot q_{it} - M_{it} - C_{it} - FN_{it}) > 0 \quad (6)$$

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

Inequalities (5) and (6) imply that all land in a county (of given quality) will be in the same use in the steady state. In reality, of course, counties are observed to be a mix of forest and farmland. Although this may partly reflect deviations from the steady state, it is due largely to the *heterogeneity* of land, particularly in regard to its quality (suitability) for agriculture. Such unobserved heterogeneity can be parameterized¹¹ within an econometrically estimatable model so that the *individual* necessary conditions for land-use changes (equations (5) and (6)) aggregate into a single-equation model, in which the parameters of the basic benefit-cost relationships and of the underlying, unobserved heterogeneity can be estimated simultaneously. In Appendix B, the complete model is derived:

$$FORCH_{it} = FORCH_{it}^a \cdot D_{it}^a - FORCH_{it}^c \cdot D_{it}^c + \lambda_i + \phi_{it} \quad (7)$$

$$FORCH_{it}^a = \gamma_a \cdot \left[d_{it} \cdot \left[F \left[\frac{\log(q_{it}^y) - \mu(1 + \beta_2 E_{it})}{\sigma(1 + \beta_3 E_{it})} \right] \right] + (1 - d_{it}) - \left[\frac{S}{T} \right]_{i,t-1} \right] \quad (8)$$

$$FORCH_{it}^c = \gamma_c \cdot \left[d_{it} \cdot \left[1 - F \left[\frac{\log(q_{it}^x) - \mu(1 + \beta_2 E_{it})}{\sigma(1 + \beta_3 E_{it})} \right] \right] + \left[\frac{S}{T} \right]_{i,t-1} - 1 \right] \quad (9)$$

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

$$q_{it}^y = \left[\frac{\tilde{F}_{it} + M_{it}}{A_{it}} \right] \quad (11)$$

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

¹¹In the current application, a lognormal distribution of land quality was specified, which reflects available information on the actual distribution of quality. Econometric estimates were also made with normal and uniform distributions: the fundamental results are quite robust (Stavins and Jaffe 1990).

where all greek letters are parameters that can be estimated econometrically: $FORCH_{it}$ is the change in forest land as a share of total county area; $FORCH_{it}^a$ is forestation (abandonment of cropland) as a share of total county area; $FORCH_{it}^c$ is deforestation (conversion of forest) as a share of total county area; D_{it}^a and D_{it}^c are dummy variables for forestation and deforestation, respectively; λ_i is a county-level fixed-effect parameter; Φ_{it} is an independent (but not necessarily homoscedastic) error term; γ_a and γ_c are partial adjustment coefficients¹² for forestation and deforestation; F signifies the cumulative standard normal distribution function; q_{it}^y is the threshold value of (unobserved) land quality (suitability for agriculture) below which the incentive for forestation manifests itself; q_{it}^x is the threshold value of land quality above which the incentive for deforestation manifests itself; T_{it} is total county area; N_i is the share of a county that is naturally protected from periodic flooding; E_{it} is an index of the share of a county that has been artificially protected from flooding by Federal programs (by time t); μ is the mean of the unobserved land-quality distribution; and σ is the standard deviation of that distribution.¹³

A simplified, pictorial representation of the model is provided in Figure 1. 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 (11) and (12) 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.

Using panel data for 36 counties in Arkansas, Louisiana, and Mississippi, during the period 1935-1984, the parameters of the model embodied in equations (7) through (12), above, were estimated with nonlinear least squares procedures (Stavins and Jaffe 1990). The basic results are found in Table 1.¹⁴

¹² Conditions (5) and (6) imply that conversion of land to its optimal use (conditional upon prices) will be instantaneous. As suggested above, there are several reasons why this may not be the case, including liquidity constraints, uncertainty about the permanence of price movements, decision-making inertia, and an uneven forest-age distribution. The partial adjustment mechanism allows for gradual movement toward the optimal state. Given the aggregate nature of the analysis, the coefficients indicate the probability that a landowner not in equilibrium in a given nine period will switch to the optimal use within the initial nine period.

¹³ Other parameters to be estimated are: α , 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.

¹⁴ The time dimension of the panel has observations every five years: hence, the time series contains ten periods, and the entire panel contains 360 observations. Estimated parameters are all of the expected sign, and nearly all estimates are significant at the 90, 95, or 99 percent level. Both parameter and standard error estimates are robust with respect to modifications of the specification, and the dynamic goodness-of fit, based upon Theil's (1961) measure, is 0.675.

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.

First, it should be noted that equations (11) and (12) already exhibit two significant asymmetries between forestation and deforestation. Forestation produces a supply of timber (and hence, a 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 (C_{it}) 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 also allow for the possibility of "tree farming," that is, intensive management of the forest, which brings with it significant costs of establishment.¹⁵

Second, there is the silvicultural dimension of choice of species. In the econometric analysis, only mixed stands¹⁶ 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.¹⁷

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.¹⁸ These three sets of silvicultural considerations lead to the following respecification of equation (11):

$$q_{it}^y = \left[\frac{\tilde{F}_{its} + M_{it} - K_{it}}{A_{it}} \right] \quad (13)$$

¹⁵ 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 1991). 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. Table 2 provides descriptive statistics of the major variables used in the simulation analysis.

¹⁶ 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.

¹⁷ 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). A rotation length of 45 years is utilized, also reflecting standard practice (Moulton and Richards 1990).

¹⁸ For permanent stands, no revenue from harvesting is generated, although establishment costs are still incurred for setting up plantations.

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

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

Combining variable values associated with these silvicultural dimensions into logical sets yields four scenarios to be investigated (Table 3):¹⁹ (1) natural regrowth of a mixed stand, periodically harvested; (2) natural regrowth of a "permanent" mixed stand (no periodic harvest); (3) planting of a pine plantation, periodically harvested; and (4) planting of a permanent pine plantation.

As explained above, we have assumed that deforestation brings about not only a loss of future forest revenue, F_{it} , but also a one-time windfall of income, W_{it} , from the immediate sale of timber from the felled forest, the difference being net forest revenue, FN_{it} . In the context of carbon sequestration, it becomes important to allow for another possibility as well, naively that at the time of deforestation, merchantable timber is not sold, but simply burned along with all other on-site material. In this case, FN_{it} , is replaced by F_{it} in equation (12), above (and equation (15), below). This alternative, which becomes quite important when we consider its carbon consequences, yields a set of four additional scenarios, numbered 5 through 8 in Table 3.

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).²⁰ 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 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.²¹

¹⁹ In all four scenarios, the revenue associated with a decision to deforest, FN_{it} is the present value of the one-time windfall from cutting at the time of deforestation minus the opportunity cost associated with the foregone stream of revenues from periodic cutting of an unmanaged mixed stand. This and all forest revenues are in the form of capitalized "stumpage values" and hence are net of harvesting costs.

²⁰ 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.

²¹ As we see below, there is an asymmetry between the amount of net carbon sequestration that is obtained through an acre of forestation, as opposed to an acre of retarded or prevented deforestation. There are other asymmetries associated with differences in costs of monitoring and enforcement and the deadweight loss associated with the two instruments.

We simulate this policy by treating the subsidy as an increment to forest revenues in the forestation part of the model (equation (8)) and treating the tax payment as an increment to conversion or production costs in the deforestation part of the model (equation (9)). Letting Z_{it} represent the subsidy and tax,²² the threshold equations ((11) and (12)) for forestation and deforestation, respectively, become:

$$q_{it}^y = \left[\frac{(\bar{F}_{it} + Z_{it}) + M_{it} - K_{it}}{A_{it}} \right] \quad (14)$$

$$q_{it}^x = \left[\frac{FN_{it} + (M_{it} + Z_{it})}{A_{it} - C_{it}^{\alpha P_{it}}} \right] \quad (15)$$

Thus, a dynamic simulation, based upon equations (7), (8), (9), (10), (14), and (15), in which the variable Z is set equal to zero, will generate a baseline quantity of forestation/deforestation over a given time period.²³ By carrying out simulations for various values of Z over the same time period, and subtracting the results of each from the baseline results, we can trace out a forest acreage supply function, with marginal cost per acre (Z) arrayed in a schedule with total change in acreage over the time period, relative to the baseline.

2.3 A Dynamic Simulation Model of Carbon Sequestration.

For any given 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 (if relative prices are constant over time²⁴). 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. Second, a parcel may continually be in a forested state in both simulations, in which case it sequesters carbon in both simulations (*if* it is periodically harvested, since atmospheric carbon is converted to wood products), but net sequestration due to the policy intervention is again zero. Third, a parcel may continually be in agricultural use in the baseline, but forestation takes place in the policy simulation in year t . Here, the net carbon sequestration due to the policy intervention will be the time-path of (varying) *annual* sequestration (and, in some cases, emissions) that *commence* in year t . Fourth, a parcel may continually be in a forested state in the baseline, but deforestation takes

²² Note that in accordance with equation (7), simulations in a given time period for a specific county will encompass either forestation (equations (8) and (14)) or deforestation (equations (9) and (15)), but *not* both.

²³ The simulated (fitted) values from the model are the set of values that make tip the vector $FORCH_{it}$ for any time t in equation (7). Multiplying these predicted values of $FORCH_{it}$ by county land areas T_{it} and adding these products to the elements of the vector $S_{i,t-1}$ yields predicted values of S_{it} which are in turn fed back into the simulation for the following time period via the term $[S/T]_{i,t-1}$ in equations (8) and (9). The simulation process is actually a two-stage procedure for each time period, in which the values of the dummy variables, D_{it}^a and D_{it}^c in equation (7), are first predicted on the basis of whether this same equation with both dummies set equal to unity yields a positive (forestation) or negative (deforestation) value: then the two dummy variables are adjusted accordingly and the vector $FORCH_{it}$ is simulated for that time period. This two-stage approach mirrors the econometric model that underlies the simulations (Stavins and Jaffe 1990).

²⁴ Will constant relative prices, 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.

place in the policy simulation in year t . Now, the net carbon *emissions* due to the policy intervention will be the time-path of (varying) *annual* emissions that *commence* in year t .²⁵

The next step, conceptually, is to link specific time paths of carbon sequestration (and emissions) with the various types of forestation and deforestation specified. Scientific understanding of these linkages is continually evolving; we base our modeling of the relationships upon state-of-the-art biological models.²⁶ Figure 2 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 depicted in the figure, the time profile is of cumulative²⁷ carbon sequestration associated with establishing a *new* loblolly pine plantation in the study area. Carbon sequestration occurs in four components of the forest: trees, understory vegetation, forest floor, and soil (Birdsey 1992). When the 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 it is assumed that all carbon except for that sequestered in harvested wood is released immediately to the atmosphere.²⁸ Much of the carbon sequestered in wood products is also released to the atmosphere, although this occurs with considerable delay as wood products decay.²⁹ As can be seen in the figure, in this scenario the forest is replanted, and the same process takes place again.³⁰

²⁵ As will become clear below, in this case, 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.

²⁶ We employ a set of temporal carbon yield curves, as do Nordhaus (1991), and Richards, Moulton, and Birdsey (1993). Other sequestration cost studies have used point estimates of average flows.

²⁷ Although the analytical model and the text considers sequestration and emissions in terms of annualized increments, the figure places cumulative net sequestration on the vertical axis simply because this results in a scale in which the effects of interest can most easily be observed.

²⁸ Although the shares vary greatly among forest types, reference points are: tree carbon contains about 80 percent of ecosystem carbon, soil carbon about 15 percent, forest litter 3 percent, and the understory 2 percent. 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).

²⁹ As Sego, 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 or 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).

³⁰ 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 CO₂ 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

Although the carbon yield curve with harvesting in Figure 2 lies everywhere below the yield curve for a "permanent" stand, this is not necessarily the case over longer time horizons. Since the former scenario involves adding more carbon over time as the stock of wood products increases, it is conceivable that the cumulative sequestration is eventually greater. Whether this will indeed be the case at some point in time depends on the share of carbon that is initially sequestered in wood products and those products' decay rate. With a zero decay rate, the peaks in the harvesting yield curve would increase monotonically, but with a positive decay rate, the locus of the peaks approaches a steady-state quantity of sequestration, and that quantity can lie above or below the level associated with the equilibrium level of the "permanent" yield curve.³¹

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? This becomes particularly important if we wish to compare the costs of carbon sequestration with the costs of conventional carbon abatement measures, such as fuel switching and energy-efficiency enhancements. Previous sequestration studies have used a variety of methods to calculate costs in terms of dollars per ton, the desired units for a cost-effectiveness comparison. These approaches have been classified as: flow summation, mean-carbon storage, and levelization. Each has limitations.³²

The first approach is the simplest: the present value of costs is divided by the total tons of carbon sequestered, regardless of when sequestration occurs.³³ 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 divided by the numerical average of annual carbon storage.³⁴ This statistic suffers from the same problems as the first.

The third alternative summary statistic seems most reasonable, and is utilized here: the discounted present value of costs is divided by the discounted present value of tons sequestered.³⁵ 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. We initially use a 5 percent rate, supplemented later by sensitivity analysis.

effects of bringing a new source of wood to the market would also need to be considered.

³¹There 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.

³²Richards and Stokes (1995) provide a useful comparison of the methods.

³³This approach is used by: Van Kooten, Arthur, and Wilson 1993; among others.

³⁴This approach is used by: Moulton and Richards 1990; Dixon, Winjum, Andrasko, Lee, and Schroeder 1994; and Parks and Hardie 1995.

³⁵This approach is used by: Nordhaus 1991; New York State Energy Office 1993; and Richards, Moulton, and Birdsey 1993; and the approach is implicit in the model of Adams, Adams, Callaway, Change, and McCarl 1993.

By developing the constituent intertemporal yield curves for various forest species,³⁶ location, and management conditions, we calculate a set of present-value equivalent carbon-sequestration measures associated with: natural regrowth of a harvested mixed stand³⁷ (43.36 tons); natural regrowth of a permanent mixed stand (50.59 tons); a pine plantation periodically harvested (41.05 tons); and a permanent pine plantation (49.99 tons). 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).³⁸ These values are reported in Tables 2 and 3.

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:

$$PV(SEQ) = \sum_{i=1}^{36} \left[\sum_{t=0}^{90} (FORCH_{it}^a \cdot D_{it}^a \cdot \Omega_t^S - FORCH_{it}^c \cdot D_{it}^c \cdot \Omega_t^E) \cdot (1 + r)^{-t} \right] \quad (16)$$

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

$$\Omega_t^E = \sum_{h=t}^{90} CE_h \cdot (1 + r)^{t-h} \quad (18)$$

and where 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

³⁶ The yield curves provided in Figure 2 are simply examples for one species, loblolly pine. The growth curves that underly 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 CO₂ and induced climate change (Dixon, Brown, Houghton, Solomon, Trexler, and Wisniewski 1994). 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 (Sohngen and Mendelsohn 1995).

³⁷ The carbon paths are weighted averages from hardwood and pine constituents, assuming 55 percent hard woods 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 volumes for pine are based on data used by Richards, Moulton, and Birdsey (1993) for cropland in the Delta region.

³⁸ Given the nature of the model, all deforestation is of mixed stands.

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.

3. THE COSTS OF CARBON SEQUESTRATION

In this part of the paper, we report the results of the simulations of carbon sequestration and emissions, derive estimates of the average and marginal costs of carbon sequestration, and carry out sensitivity analysis of the results.

3.1 Carbon Simulations, 1990-2080

The results of dynamic land-use simulations for the 90-year period³⁹ from 1990 to 2080 of $FORCH_{it}$ from equations (7), (8), (9), (10), (14), and (15) constitute the fundamental inputs into the final carbon simulation model consisting of equations (16), (17), and (18). 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. Respective values of annual forest revenues (f_{its}), establishment costs (K_{it}), present-value equivalent forestation-induced carbon sequestration (Ω_t^s), and present-value equivalent deforestation-induced carbon emissions (Ω_t^E) are summarized in Table 3.

Simulations with the subsidy/tax, Z , set equal to zero (in equations (14) and (15)) generate baseline quantities of carbon sequestration/emissions.⁴⁰ By subtracting these quantities from the results of simulations with positive assumed values of Z , we can trace out a 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 annual⁴¹ carbon sequestration (relative to the baseline).

Table 4 provides the results for one scenario (#3), 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 in the table because it is most directly comparable with the scenarios examined in other studies. The relatively attractive forest revenues associated with this management regime result in a small amount of net forestation taking place in the baseline simulation, a gain of about 52 thousand acres (over the 90-year study period). Baseline net carbon sequestration is approximately 4.6 million tons annually. As can be seen in Table 4, the marginal costs of carbon sequestration increase approximately linearly, until these costs are about \$66 per ton, where annual sequestration relative to the

³⁹ 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.

⁴⁰ 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.

⁴¹ As explained above, both dollars of costs and tons of sequestration (and emissions) are discounted. Hence, annual sequestration refers to an annuity that is equivalent to a respective present value (employing a discount rate of 5 percent).

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 5200 per ton,⁴² 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 3).⁴³ 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.

What happens under the alternative silvicultural 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 result in net deforestation taking place in the baseline simulation, a loss of about 260 thousand acres (Table 5). The marginal cost of carbon sequestration is about \$34 when 5 million tons are sequestered annually.

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 5). 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 actually *decrease*. 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 in agreement 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)

⁴² In our partial equilibrium model, this nonlinear part of the marginal cost function is obviously not coming from endogenous impacts on agricultural and forest product prices. Instead, it is a consequence of having forced the forestation and deforestation thresholds into the range of lands of higher (agricultural) quality. i.e. into the long and low right-hand tail of the lognormal quality distribution (Figure 1).

⁴³ 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.

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 (Table 3).

Two of the four 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 the related cases 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 (Table 3). 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 Sensitivity Analysis

There are two reasons for examining the robustness of the simulations to changes in assumed values of underlying variables to provide some check on the reliability of the analysis; and to provide further interpretation of the results. We examine the sensitivity of the results to changes in the discount rate and to changes in relative prices.

3.2.1. Discount Rate

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 net forest revenue, FN_{it} , which embodies the trade-off between foregone future forest revenues and the immediate windfall of revenue from carrying out deforestation. Second, the present-value equivalent tons per acre of sequestration are affected by changing discount rates (Table 6).

In Table 7, 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 and no periodic harvests. 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 greater in that case (Table 6).

3.2.2 The Economic Environment

From an economic perspective, 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.

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 8, increasing agricultural prices in Scenario #3 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 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 8. 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 3) are significantly greater than those associated with a unit of forestation (41.05 tons per acre from Table 3), 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 Scenario #7, in which deforestation results in the burning of all on-site material, rather than the sale of merchantable timber (Table 8). In fact, in the burning scenario, the "carbon efficiency" of retarding deforestation (relative to that of

encouraging forestation) is so great⁴⁴ 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 basecase. From this point on, however, the original pattern returns: higher agricultural prices mean less induced sequestration and higher marginal sequestration costs.

The explanation for this pattern is found in the first line of Table 8, 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

What conclusions can be drawn from these quantitative results? First, the marginal costs of carbon sequestration are by no means trivial, despite the claims that have sometimes been made. Second, even putting aside the anticipated responsiveness of land prices to any significant national sequestration program, the heterogeneity of the existing stock of land brings sharply increasing marginal costs of sequestration as higher quality agricultural lands are converted to forested use. Hence, studies that provide only single point estimates of average costs are likely to be misleading.

Third, there is the somewhat surprising finding that marginal sequestration costs are greater for cases with periodic harvesting of timber. This is despite the fact that opportunity costs for landowners are lowered. Counteracting this effect is the more favorable sequestration pattern provided by permanent stands. Fourth and finally, there is the rather striking asymmetry between the marginal costs of carbon sequestration through forestation and those through retarded deforestation. If further research corroborates these findings, this may provide another argument for focusing carbon-sequestration efforts in areas of relatively high rates of deforestation, such as in tropical forests.⁴⁵ In addition to the fact that these areas are more efficient engines of carbon storage than temperate forests and in addition to the

⁴⁴The volume of *immediate* carbon emissions due to burning is 72.64 tons per acre (Table 3), contrasted with the present value of 41.05 tons of sequestration associated with forestation.

⁴⁵ Wherever market-based policy instruments are employed, this argues for setting the appropriate tax and subsidy, and letting market forces determine the relative amounts of forestation and deforestation that take place.

lower opportunity costs of land that we would ordinarily anticipate to be associated with such areas,⁴⁶ 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).

4.1 Comparison with Other Estimates of Carbon-Sequestration Costs

Because of variations in methodology and differences in geographic area of analysis, it is difficult to make direct comparisons of results among carbon-sequestration studies.⁴⁷ Most studies have not even reported marginal cost functions: instead the vast majority have simply provided a single point estimate of average sequestration costs at some level of total sequestration. If marginal costs are increasing, indeed steeply increasing after some point, as the present study suggests, then such single point estimates of average costs are of only very limited use. Indeed, they can be misleading if improperly applied.

In table 9, we have summarized the results of some of the best and most comparable studies of carbon sequestration. Five of the eight studies provide estimates of a marginal cost function. We summarize the results in the table along three dimensions: total quantity (of land affected and carbon sequestered), average cost, and marginal cost.⁴⁸

The most direct comparison that can be made is with the work of Richards, Moulton, and Birdsey (1993),⁴⁹ who used an engineering approach to develop estimates for the Delta states (of Arkansas, Louisiana, and Mississippi). The comparison is of particular interest because many of the other dimensions of the analyses are quite similar.⁵⁰ Since the present study focuses on just 36 counties in the Delta states, however, it is possible to compare the results only by extrapolating from the study area to the larger tri-state region. The marginal cost function that is thereby developed⁵¹ is significantly

⁴⁶Additionally, 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.

⁴⁷Because of methodological differences, even studies of the same geographic area may yield very different cost estimates. Among the factors that will affect the magnitude of cost estimates are the diverse assumptions, methods, and data that relate to land area, land costs, establishment costs, interest rates, carbon sequestration rates and time paths, scope of the carbon analysis (for example, whether soil carbon is included), and the degree of permanence of wood products. For a comprehensive decomposition of carbon sequestration studies along these and other dimensions, see: Richards and Stokes 1995.

⁴⁸As mentioned above, none of these studies use precisely the same set of methods, and hence none of the results they provide are directly comparable with one another. Where sufficient information is provided in the referenced studies, we have made calculations necessary to render the results more comparable. This is explained in the footnotes to Table 9.

⁴⁹Richarss (personal communication, 1994) provided these detailed results for the Delta states, based upon the methodology employed by Richards, Moulton, and Birdsey (1993).

⁵⁰Thus is not by coincidence: our modeling of the land-carbon linkages follows, to a large degree, the approach of Richards and his co-authors.

⁵¹The 36 counties in the study area represent 13.34 percent of the total area of the three states. If the study area were perfectly representative of the total area, we could multiply our quantity results by 7.5 to compare with the three-state results of Richards. Of course, the study area is not truly representative of the total three-state area along all relevant dimensions. For one thing, it contains better quality (for agriculture) land. On the other hand, there are large areas of government owned lands outside the 36 counties: these would be unaffected by economic signals. These factors work in opposite directions. We use the multiplier of 7.5 simply for the purpose of demonstrating how the results may be related to those of others.

steeper than that of Richards, Moulton, and Birdsey (1993), and lies below it up to about 30 million tons of carbon sequestration (marginal cost of about \$22). In turn, it should be noted that the marginal cost estimates of Richards, Moulton, and Birdsey (1993) for the entire United States are significantly greater than those from other studies. Over the range of values we consider (Table 4), the marginal cost function we estimate (Figure 3) is of similar shape to that of Parks and Hardie (1995), turning steeply upward at about 5100 to \$200 per ton.

We can calculate from Table 9 the net carbon sequestration per acre implied by the various analyses. The figure for the Delta states from Richards, Moulton, and Birdsey (1993) is 2.64 tons per acre annually. Our implicit net sequestration for the equivalent management regime -- Scenario #4, pine plantations with no periodic harvesting -- is considerably less, 1.85 tons per acre annually. Since our carbon yield curves are closely related to those employed by Richards, Moulton, and Birdsey (1993),⁵² why does this significant difference exist?

The answer may provide some insight into the potential advantages and disadvantages of the approach taken in this study. If the model of Richards, Moulton, and Birdsey (1993) were accurate in terms of its structural assumptions (and input data) that landowners behave "optimally" and immediately in response to economic signals and if our analysis were likewise correctly specified, then the marginal cost function simulated from our econometrically-based approach (and hence the implicit annual tons of carbon per acre) ought to be more or less the same as theirs. They are not. One possible explanation brings attention to a central advantage of an econometric approach: landowners do not necessarily respond in the "optimal" and immediate fashion assumed in the engineering models. Indeed, the econometric evidence suggest that landowners have in the past responded to economic signals with considerable delay, particularly when shifting land use from agriculture to forestry. Thus, in our model a given tax/subsidy produces land-use changes, but not only may they be smaller than what is anticipated by Richards, Moulton, and Birdsey (1993) and others, but, more to the point, even if they are of the same magnitude in the steady state, our analysis suggests that those land-use responses will be drawn out over a considerable amount of time. In a world with discounting, this difference can be significant indeed. This is confirmed by our sensitivity analysis; as we decrease the discount rate, the implicit carbon/acre figure approaches the respective figure from Richards, Moulton, and Birdsey (1993).

Overall, the general impression from this study is that the marginal costs of carbon sequestration may be significantly greater than previously reported by authors using other approaches. This is not surprising, given the variety of reasons outlined at the beginning of this paper of why we might anticipate that landowner behavior might be less responsive and hence the marginal costs of carbon sequestration might be greater than are indicated by "engineering" and "least-cost" analyses.

4.2 Comparisons with Estimates of Carbon Abatement Costs

One of the motivations for investigating the costs of carbon sequestration is to compare these costs with "conventional" methods of carbon abatement -- fuel switching and energy-efficiency improvements. There are a wide array of studies from which to draw, and -- as in the case of the carbon sequestration studies -- methodologies vary, as does quality. Because of this variance, we focus first (in Table 10) on cost estimates from one frequently cited source (National Academy of Sciences 1992).

⁵² Note that the annualized value (at a discount rate of 5 percent) of our assumed present-value equivalent sequestration let "permanent" pine is 2.53 tons per acre annually, much closer to the Richards, Moulton, and Birdsey (1993) figure.

In the National Academy of Sciences (NAS) study, one important set of carbon-abatement approaches is associated with substituting alternative fuels for coal in the generation of electricity. The range of costs reported -- \$100 to \$900 per ton of carbon -- are in the same neighborhood as costs suggested by the present and some other studies for carbon sequestration.⁵³ On the other hand, the NAS report suggests that new technologies to increase energy efficiency in some sectors will likely be an order of magnitude more costly than forest sequestration, at least in some regions.

Unfortunately, it is difficult to take these comparisons very seriously, because the NAS report also claims that costs will be *negative* for a wide variety of other energy-efficiency improvements, including residential space heating and industrial use of electricity, despite the fact that analyses by economists of these same options have found significant positive costs.⁵⁴ So, we turn next to some estimates by economists.

One useful source is a survey by Nordhaus (1991) in which he combined results from a number of studies, including those by: Edmunds and Reilly (1983); Jorgenson and Wilcoxon (1991); Manne and Richels (1990); and others. Nordhaus provides a complete schedule of marginal costs associated with percentage reductions in worldwide greenhouse gas emissions,⁵⁵ ranging up to 80 percent of baseline emissions. The Nordhaus global marginal cost function is roughly proportionate to the Richards, Moulton, and Birdsey (1993) function for U.S. carbon sequestration. Their largest simulation is for 340 million tons of carbon sequestered per year, about 31 percent of aggregate 1990 U.S. emissions; at this level, they estimate marginal costs to be \$60 per ton. At a similar percentage reduction in worldwide greenhouse gas emissions, Nordhaus (1991) estimates marginal costs to be \$57 per ton.⁵⁶ On the other hand, Nordhaus' own analysis of *sequestration* suggests that -- on a global basis -- marginal costs increase much more rapidly, reaching \$100 per ton for a percentage reduction of total greenhouse gas emissions of less than six percent.

⁵³ Forestation and retarded deforestation provide a set of secondary environmental benefits, and it has been argued that these should be taken into account in a cost-effectiveness comparison with energy-efficiency enhancements (Sedjo, Wisniewski, Sample, and Kinsman 1994). However, no previous studies of the costs of carbon sequestration have attempted to include these secondary environmental benefits, and it is questionable whether doing so would provide a more useful statistic. In any event, the same would need to be done for calculating the costs of energy efficiency (which may, for example, bring about reduced emissions of sulfur dioxide). The analysis presented in this paper has already gone beyond the bounds of a strict cost-effectiveness analysis into the realm of benefit-cost analysis, since the discounting of tons implicitly involved making assumptions regarding the shape of the marginal benefit function; it is surely desirable not to confuse the two types of analysis any further. On this point, see: Jaffe, Peterson, Portney, and Stavins 1995.

⁵⁴ See, for example: Jaffe and Stavins 1995.

⁵⁵ Greenhouse gases are aggregated by expressing their quantities in carbon equivalents, in proportion to respective radiative -- forcing potential.

⁵⁶ Estimates with the GREEN model (Organization of Economic Co-operation and Development 1994) for the United States in the year 2050 indicate that a 30 percent reduction from baseline could be achieved at a marginal cost of only \$10 per ton of carbon (1985 dollars). The GREEN marginal cost function turns up sharply after 50 percent reductions (\$50 marginal cost).

4.3 Implications for Future Research

Opportunities for future research are plentiful. The model developed here can be improved along a number of dimensions.⁵⁷ Some improvements would represent not just marginal refinements of the current model, but rather improvements in the sense of a new and better model. Primary among these is endogenizing any one of a number of variables that are currently taken as exogenous: agricultural and forestry product prices; the mix of cultivated crops and forest species; and management regimes.⁵⁸ A general equilibrium approach should be possible, both at the econometric stage and in the simulations. This would not simply be desirable, but necessary, if the general approach developed here were to be applied to estimate the carbon sequestration marginal cost function for the United States as a whole.

Finally, we can comment briefly on the methodological implications of this work. The major advantage of our approach over the models that have dominated the literature on carbon sequestration is that simulations of marginal costs build directly upon revealed-preference patterns of how landowners have actually responded to the economic incentives they continually face regarding the alternative uses of their lands. This is in contrast with engineering approaches that build up marginal cost functions by aggregating point estimates of how landowners in a particular region or owning a particular type of land *ought* to behave, and in contrast with optimization models that often do much the same thing.

As is well known, landowners tend not to behave as they "ought;" farmers, in particular, are notoriously sluggish in responding to some of the economic signals they face. For one thing, they are affected by non-pecuniary factors, including a desire to stay on the farm for reasons associated more with perceived quality of life than with financial returns. An econometric model based upon an underlying optimization model and allowing for "partial adjustment" or other phenomena can capture, albeit in a crude way, such land-use behavior. Hence, the land-use simulations that come from it, along with the respective estimates of carbon-sequestration costs may be better approximations of reality.

Linking a dynamic simulation model of carbon sequestration with an econometric model of land use has the potential of adding significantly to our understanding of the costs of this frequently discussed approach to addressing the threat of global climate change. There is a small, but growing literature of econometric analyses of forestation and deforestation (Panayotou and Sungsuwan 1989; Parks and Kramer 1995; Pfaff 1995; Reis and Guzmán 1992; and Southgate, Sierra, and Brown 1991). At least some of these can serve as the basis for developing revealed-preference analytical models of the respective marginal costs of carbon sequestration.

⁵⁷ For example, our revealed-preference approach provides another potential advantage over the engineering approaches : 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. In other words, sensitivity analysis of the results on alternative values of estimated parameters would be of value. A richer description of the marginal cost function can be provided through die use of stochastic (Monte Carlo) simulations. I am currently undertaking this work.

⁵⁸ For example, it would be desirable to allow for the economic endogeneity of the forest rotation length. In this regard, a very different approach to thinking about the carbon supply function is found in a paper by Van Kooten, Binkley, and Delecourt (1995). They examine the sensitivity of the socially optimal rotation length to alternative values of carbon (dollars per ton), and thus develop a supply curve of carbon *per acre*. As timber prices increase, the optimal rotation length decreases; and as carbon value increases, the (socially) optimal rotation length increases.

TABLE 1:
PARAMETER ESTIMATES FOR SIMULATIONS ^a

Parameter	Interpretation	Estimate
γ_a	Forestation partial adjustment	0.36717 ^b (0.184) ^c
γ_c	Deforestation partial adjustment	0.64826 (0.154)
μ	Mean of unobserved quality distribution	1.11650 (0.364)
σ	Standard deviation of unobserved quality distribution	0.43848 (0.067)
α	Weather impact on conversion cost	1.59720 (0.304)
β_1	Federal program impact on agricultural feasibility	8.93700 (2.465)
β_2	Federal program impact on heterogeneity mean	0.77193 (0.774)
β_3	Federal program impact on heterogeneity standard deviation	0.42799
	Goodness of fit ^d	0.6747
	Log likelihood value	791.698
	Degrees of freedom	316

^a For a detailed discussion of the parameter estimation, see: Stavins and Jaffe 1990; and Stavins 1990

^b The model also contains 36 county dummy variables.

^c Robust (heteroscedastic consistent) standard error estimates appear below parameter estimates.

^d The dynamic goodness of fit statistic is equal to 1 - Theil's U statistic, based on comparing predicted and actual net rates of deforestation and forestation, at the county level, across time.

TABLE 2:
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
Fraction of County Naturally Protected from Periodic Flooding	0.614	0.264	0.177	1.000
Index of Artificial Flood Protection	0.371	0.371	0.000	1.418
Palmer Hydrological Drought Index	0.74	0.84	-1.05	1.69
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, with Sale of Merchantable Timber ^e (tons/acre)	51.83	0.00	51.83	51.83
Carbon Emissions due to Deforestation, with Burning of all Material (tons/acre)	72.64	0.00	72.64	72.64
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 percent real rate.

TABLE 3:
ALTERNATIVE SILVICULTURAL SCENARIOS
Discount Rate = 5 Percent

Species Regime	Natural Regrowth of Mixed Stand				Pine Plantation			
Management Regime	Periodic Harvest		No Periodic Harvest		Periodic Harvest		No Periodic Harvest	
Deforestation Regime	Timber Sale ^a	Site Burn ^b	Timber Sale ^a	Site Burn ^b	Timber Sale ^a	Site Burn ^b	Timber Sale ^a	Site Burn ^b
Scenario Number	#1	#5	#2	#6	#3	#7	#4	#8
Deforestation Carbon Emissions ^c (tons/acre) Ω_t^E	51.83	72.64	51.83	72.64	51.83	72.64	51.83	72.64
Forestation Carbon Sequestration ^c (tons/acre) Ω_t^S	43.36		50.59		41.05		49.99	
Annual Forest Revenue (\$/acre/year) f_{its}	19.29		0.00		58.96		0.00	
Establishment Costs (\$/acre) K_{it}	0.00				92.00			

^a If deforestation occurs, merchantable timber is sold; carbon thereby sequestered is partially and gradually released over time.

^b If deforestation occurs, all on-site material is burned.

^c Present value equivalent of life-cycle sequestration and emissions; see text for explanation.

TABLE 4:
SIMULATED LAND CHANGES AND CARBON SEQUESTRATION
Scenario #3: Periodically Harvested Pine Plantation, Sale of Merchantable Timber at Deforestation
Discount Rate = 5 Percent

Baseline Deforestation = + 51,654 acres

Baseline Carbon Sequestration = 4,578,202 tons

Marginal Cos 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 ions/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	10.27
60	3,398	35.96	5,145	39.63	23.76
70	3,893	41.27	5,895	46.24	17.26
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

TABLE 5:
SIMULATED COSTS OF CARBON SEQUESTRATION
FOR ALTERNATIVE SILVICULTURAL SCENARIOS
Annual Carbon Sequestration Relative to Baseline = 5 Million Tons
Discount Rate = 5 Percent

	Alternative Silvicultural Scenarios							
Species Regime	Natural Regrowth of Mixed Stand				Pine Plantation			
Management Regime	Periodic Harvest		No Periodic Harvest		Periodic Harvest		No Periodic 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 acres)	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/Deforestation 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
Average Cost of Carbon Sequestration (\$/ton)	2079	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

**TABLE 6:
PRESENT-VALUE EQUIVALENT
CARBON SEQUESTRATION AND EMISSIONS WITH
ALTERNATIVE DISCOUNT RATES**

Alternative Discount Rates		2.5%	5%	7.5%	10%
Present-Value Equivalent Carbon Sequestration (tons per acre)	Natural Regrowth of Mixed Stand, Periodically Harvested	61.90	43.36	30.63	22.72
	Natural Regrowth of Mixed Stand, No Periodic Harvest	91.48	50.59	32.85	23.52
	Pine, Plantation, Periodically Harvested	54.66	41.05	30.76	23.75
	Pine Plantation, No Periodic Harvest	80.68	49.99	34.33	25.25
Present-Value Equivalent Carbon Emissions (tons per acre)	Deforestation with Sale of Merchantable Timber	54.28	51.83	50.99	50.55
	Deforestation with Burning of all On-Site Material	72.64	72.64	72.64	72.64

TABLE 7:
SENSITIVITY OF RESULTS TO DISCOUNT RATE
Pine Plantation, Sale of Merchantable Timber When/If Deforestation Occurs

		Alternative Discount Rates			
		2.5%	5.0%	7.5%	10.0%
Marginal Cost of Sequestration (\$/ton) when Sequestration = 5 million tons/yr	Scenario #3: Pine Plantation, Periodically Harvested	33	39	58	92
	Scenario #4: Pine Plantation, No Periodic Harvesting	18	27	46	81
Forestation Relative to Baseline (1000 acres) when subtax = \$50/acre	Scenario #3: Pine Plantation, Periodically Harvested	1,467	2,787	4,368	6,131
	Scenario #4: Pine Plantation, No Periodic Harvesting	1,453	2,763	4,336	6,092
Carbon Sequestration Relative to Baseline (1000 tons/yr) [subtax = \$50/acre]	Scenario #3: Pine Plantation, Periodically Harvested	3,271	4,219	4,302	3,928
	Scenario #4: Pine Plantation, No Periodic Harvesting	4,460	5,099	4,832	4,242

TABLE 8:
SENSITIVITY OF RESULTS TO AGRICULTURAL PRICES
Periodically Harvested Pine Plantation
Discount Rate = 5 Percent

		Departures from Base Case Agricultural Product Prices						
		-30%	-20%	-10%	Base Case	+10%	+20%	+30%
Baseline Forestation or Deforestation (1000 acres)		5,968	3,317	1,430	52	-977	-1,758	-2,362
Marginal Cost of Carbon Sequestration (\$/ton) when sequestration = 5 million tons/yr	Scenario #3: Sale of Merchantable Timber at Deforestation	21.93	26.88	32.44	37.91	38.87	39.60	40.94
	Scenario #7: Burning of All 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) when subtax = \$50/acre	Scenario #3: Sale of Merchantable Timber at Deforestation	7,656	6,212	5,094	4,219	3,914	3,669	3,183
	Scenario #7: Burning of All On-Site Material at Deforestation	7,656	6,212	5,094	4,219	4,663	5,019	4,461

**TABLE 9:
COMPARISON WITH RESULTS FROM OTHER STUDIES**

Study	Total Quantity		Average Cost		Marginal Cost	
	Land (mil.acres)	Carbon (mil.tons/yr)	Land (\$/acre/yr)	Carbon (\$/ton)	Land (\$/acre/yr)	Carbon (\$/ton)
This Study ^a	5	7	58	38	≤100	≤66
Moulton and Richards (1990)						
United States ^b	269	690	--	27	≤81	≤37
Delta States Cropland	25	67	50	22	--	--
Richards, Moulton, and Birdsey (1993)						
United States ^c	244	340	--	--	--	≤60
Delta States Cropland ^d	11	29	42	18	≤52	≤22
Adams, et al. (1993) ^e	274	700	--	--	--	≤54
Nordhaus (1991) ^f	248	44	81	64	--	--
Parks and Hardie (1995) ^g	9	22	49	21	--	≤24
Rubin et al. (1992) ^h	71	73	--	23	--	--
Dudek and LeBlanc (1990) ⁱ	14	--	--	38	--	--
Plantinga (1995) ^j	0.65	1.5	--	1	--	6

^a From Scenario # 3, pine plantation, periodically harvested, at a 5% discount rate.

^b Permanent stands on cropland and pastureland only, i.e., not forest land.

^c Figure for total U.S. carbon sequestration is a numerical annual average, rather than an annuity.

^d These figures were used, but not reported, in Richards, Moulton, and Birdsey(1993). Reference is to a permanent pine stand, based on data provided in a personal communication from Richards (1994). Carbon costs and tonnages were annualized over 160 years at a 3% discount rate.

^e Nationwide results for a scenario with harvesting and sale of timber (Table 1, p. 79 and Table 4. p 83).

^f Permanent forestation of "marginal U.S land" (Table 8, p. 60). For this and other studies, we have converted to acres at a rate of one hectare = 2.477 acres and to short tons at a rate of one metric ton = 1.102 short tons.

^g Figures are for U.S. cropland-only scenario (Table 1, p. 127). Marginal costs were computed from marginal cost formula for Figure 4 (p. 131) using 22 million tons per year and annualized using a 4 percent discount rate over 10 years.

^h Nationwide results converted from original study (Table 3, p 261) at a rate of 3.67 tons of carbon dioxide (CO₂) equals one ton of carbon, and into short tons from metric tons.

ⁱ An average permanent stand of U.S. tree species, from Table 3, p 36; CO₂ converted to carbon.

^j Figures are for a 14 -county region of Wisconsin for the scenario assuming a least-cost program at a 4% discount rate and a constant annual sequestration rate of 2.25 tons of carbon per acre (Table II) Average costs computed from data given in original study. Hectares converted to acres.

**TABLE 10:
ALTERNATIVE ESTIMATES OF THE COST OF CARBON ABATEMENT ^a**

Option	Carbon Reduction ^b (million tons/year)	Net cost ^c (\$/ton/year)
Residential and Commercial Energy Use ^d		
Residential Space Heating	22	-130
Commercial & Industrial Space Heating	5	-117
Industrial Energy Use ^e		
Electricity Efficiency	41	-143
Fuel Switching	7	200
Transportation Energy ^f		
Light-Duty Vehicles (Existing Technology)	75	-133
Light-Duty Vehicles (New Technology)	16	1,767
Aircraft Engine Efficiency	4	1,200
Electric Supply Technology ^g		
Advanced Coal	60	933
Natural Gas	255	107
Nuclear	450	163
Hydroelectric	9	127
Wind	9	263
Solar Photovoltaic	120	290
Reforestation ^h	73	23

^a Source- National Academy of Sciences 1992, as reported by Rubin *et al.* (1992) in Tables 2 and 3, pp. 149, 261, See original for explanations of how estimates were developed.

^b Annualized reduction in carbon based on 1989 fuel and electricity use, converted using one metric ton = 1.102 tons and one ton carbon = 3.67 tons of CO₂.

^c Annualized cost (net of any savings from reduced energy consumption), using a 6 percent discount rate.

^d Increased use of existing best-practice technologies, including insulation, window glazing, weather stripping, heat pumps, and solar heating.

^e Electricity efficiency improvements from increased use of existing best-practice motors, electrical drive systems, lighting, and industrial processes. Fuel switching reductions from switching current coal consumption to natural gas or oil where technically feasible.

^f For light-duty vehicles, use existing technology to increase average fuel economy, with no changes in existing fleet and increase fuel economy further through new technology and changes in the existing fleet mix. Increase aircraft engine efficiency, using improved fan jet and other technologies.

^g Replace 1989 coal capacity with advanced pulverized coal, combined natural gas cycle systems, light-water nuclear reactors, hydroelectric plants, and solar photovoltaics.

^h Reforest "economically or environmentally marginal" crop and pastureland and nonfederal forest lands.

**FIGURE 1:
THE DISTRIBUTION OF LAND QUALITY
AND ECONOMIC THRESHOLDS OF FORESTATION AND DEFORESTATION**

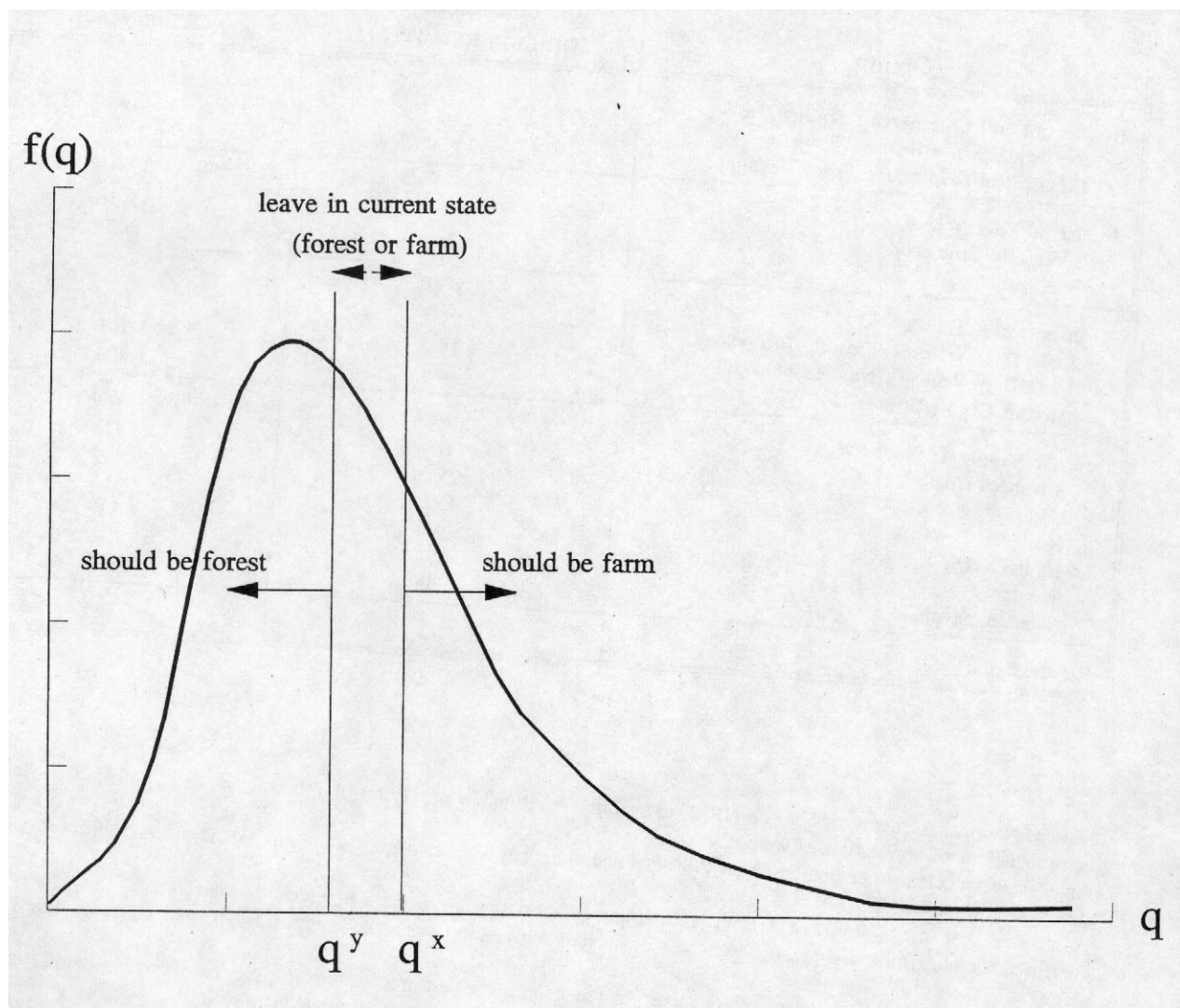
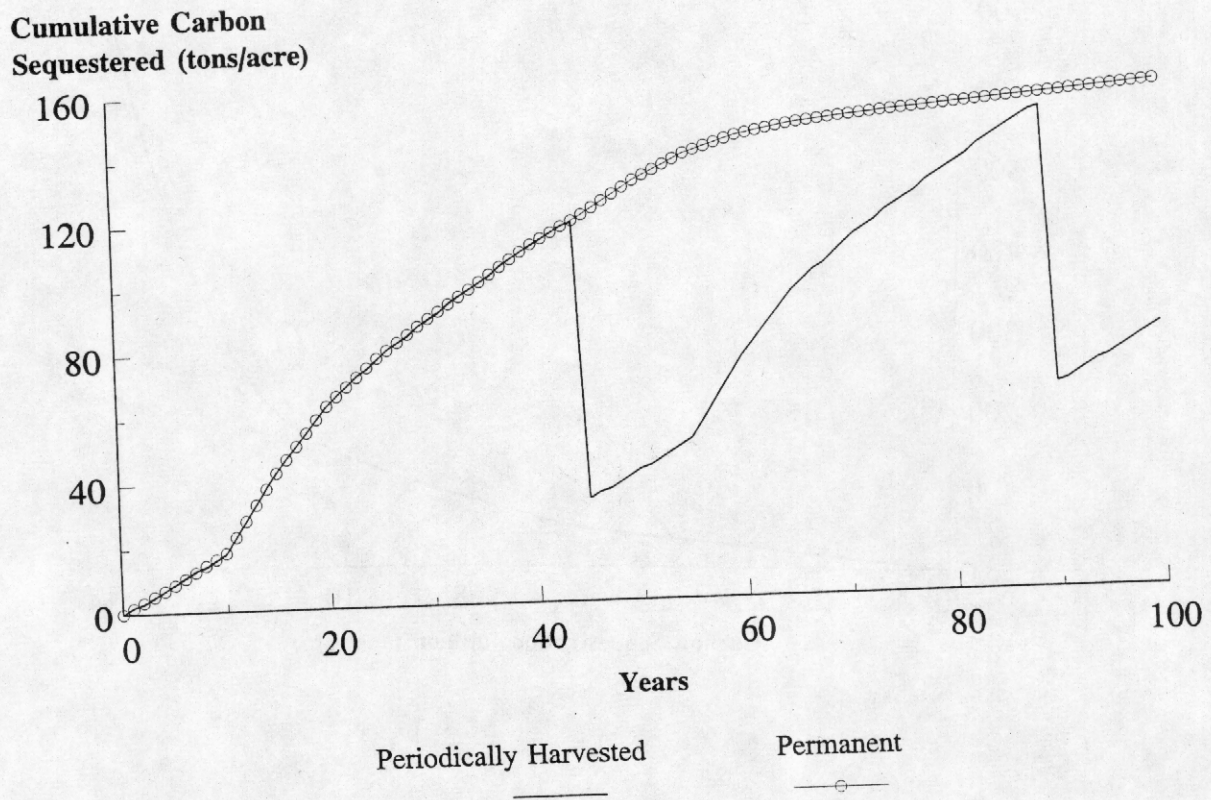
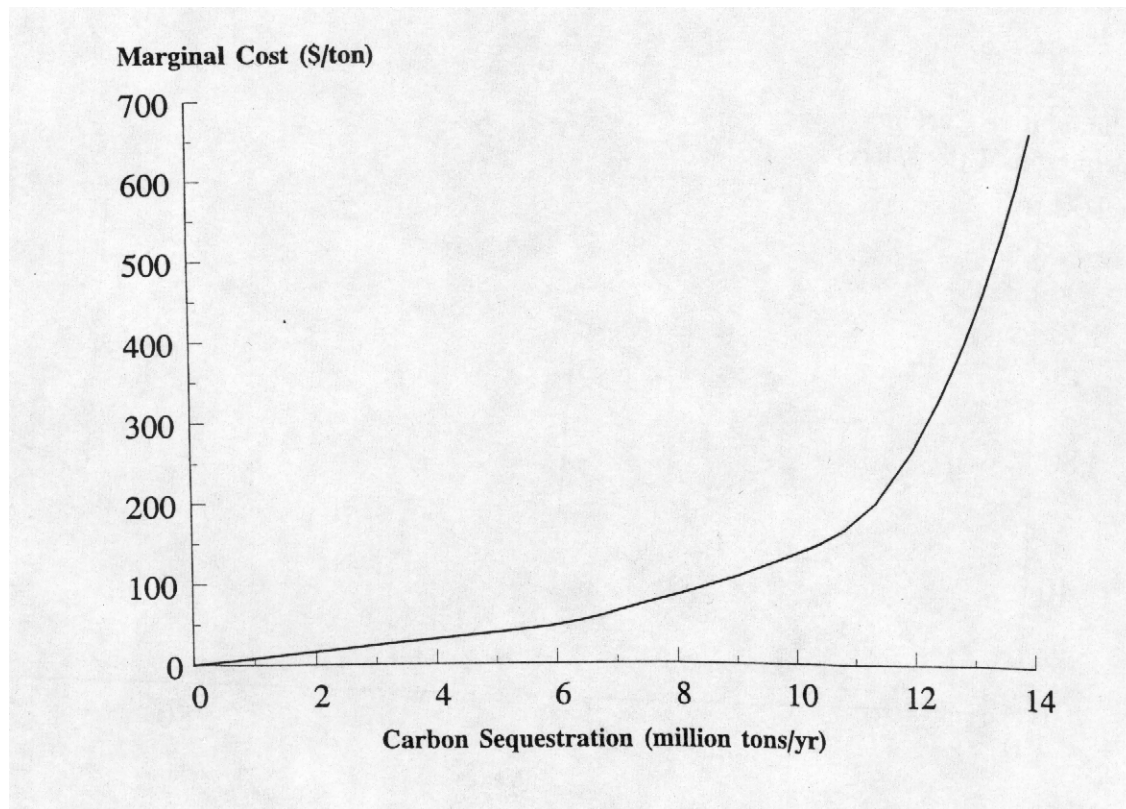


FIGURE 2:
TIME PROFILE OF CARBON SEQUESTRATION
(Loblolly Pine in Delta States Region)



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

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



APPENDIX A: SOLVING THE DYNAMIC OPTIMIZATION PROBLEM

Because of the linear nature of the objective function (equation (1) in the text), the optimal control turns out to have the usual "bang-bang" form. The solution, documented in greater detail in Stavins and Jaffe (1990) and Stavins (1990), proceeds as follows. First, the Hamiltonian equation, with ω_{it} as the costate variable, is:

$$H_{ijt} = \left[(A_{it}q_{ijt} - M_{it})(g_{ijt} - v_{ijt}) - C_{it}g_{ijt} + f_{it}S_{ijt} + W_{it}g_{ijt} - D_{it}v_{ijt} \right] e^{-r_t t} + \omega_{ijt} \cdot [v_{ijt} - g_{ijt}] e^{-r_t t} \quad (A1)$$

According to the maximum principle, the following complementary slackness conditions must hold:

$$g_{ijt}^* = \bar{g}_{ijt} \quad \text{if} \quad \frac{\partial H(\cdot)}{\partial g_{ijt}} > 0 \quad \quad g_{ijt}^* = 0 \quad \text{otherwise} \quad (A2)$$

$$v_{ijt}^* = \bar{v}_{ijt} \quad \text{if} \quad \frac{\partial H(\cdot)}{\partial v_{ijt}} > 0 \quad \quad v_{ijt}^* = 0 \quad \text{otherwise} \quad (A3)$$

An additional necessary condition for the maximization of equation (1) is:

$$\frac{\partial H(\cdot)}{\partial S_{ijt}} = - \frac{d}{dt} [\omega_{ijt} \cdot e^{-r_t t}] \quad (A4)$$

$$\omega_{ijt} = \frac{f_{it}}{r_t} + \frac{\dot{\omega}_{ijt}}{r_t} \quad (A5)$$

Evaluation of the partial derivatives in the first set of necessary conditions yields:

$$g_{ijt}^* = \bar{g}_{ijt} \quad \text{if} \quad [A_{it}q_{ijt} - M_{it} - C_{it} + W_{it} - \omega_{ijt}] > 0 \quad (A6)$$

$$v_{ijt}^* = \bar{v}_{ijt} \quad \text{if} \quad [-A_{it}q_{ijt} + M_{it} - D_{it} + \omega_{ijt}] > 0 \quad (A7)$$

Substituting from equation (A5) into equation (A6),

$$g_{ijt}^* = \bar{g}_{ijt} \quad \text{if} \quad \left[A_{it}q_{ijt} - M_{it} - C_{it} + W_{it} - \frac{f_{it}}{r_t} \right] > \frac{\dot{\omega}_{ijt}}{r_t} \quad (A8)$$

If landowners have static expectations regarding all variables, the necessary condition for *target* deforestation (conversion of forest to farm) reduces to:

$$g_{ijt}^* = \bar{g}_{ijt} \quad \text{if} \quad \left[A_{it}q_{ijt} - M_{it} - C_{it} - FN_{it} \right] > 0$$

$$g_{ijt}^* = 0 \quad \text{otherwise}$$
(A9)

where FN_{it} , net forestry revenue, equals $F_{it} - W_{it}$, and $F_{it} = f_{it}/r_t$.

Likewise, for forestation (conversion of farm to forest), equation (A5) is substituted into equation (A7), yielding the necessary condition for *targeted* forestation:

$$v_{ijt}^* = \bar{v}_{ijt} \quad \text{if} \quad \left[\tilde{F}_{it} - A_{it}q_{ijt} + M_{it} \right] > 0$$

$$v_{ijt}^* = 0 \quad \text{otherwise}$$

where \tilde{F}_{it} , delayed net forest revenue, equals $F_{it} - D_{it}$.

Equation (A10) indicates that forestation should occur if a parcel is cropland and:

$$(\tilde{F}_{it} - A_{it} \cdot q_{ijt} + M_{it}) > 0$$
(A11)

This is identical to condition (5) in the text. 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. Likewise, equation (A9) indicates that deforestation should occur if a parcel is forested and:

$$(A_{it} \cdot q_{ijt} - M_{it} - C_{it} - FN_{it}) > 0$$
(A12)

This is identical to condition (6) in the text. 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 conversion costs.

APPENDIX B: AGGREGATION OF NECESSARY CONDITIONS

Inequalities (5) and (6) in the text imply that all land (of given quality) 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. Although this may partly reflect deviations from the steady state, it is due largely to the *heterogeneity* of land, particularly in regard to its quality (suitability) for agriculture. Such heterogeneity can be characterized in terms of a probability density function, $\mathcal{F}\{q_{it}\}$ posited as a parametric lognormal relationship, because the general shape of that distribution is reasonable for a distribution of land quality:

$$\begin{aligned} \text{Log}(q_{it}) &\sim N(\mu, \sigma^2) \quad \text{with probability } d_{it} \\ q_{it} &= 0 \quad \text{with probability } (1 - d_{it}) \end{aligned} \tag{B1}$$

where μ and σ^2 are the mean and variance of the normal distribution, and d_{it} is the probability that agricultural production is feasible, such that:

$$d_{it} = \left[\frac{1}{1 + e^{-(N_i + \beta_1 E_{it})}} \right] \tag{B2}$$

where N_i is the share of a county that is naturally protected from periodic flooding; E_{it} is an index of the share of a county that has been artificially protected from flooding by Federal programs (by time t); and β_1 is a parameter that indicates the impact of artificial flood protection relative to the impact of natural flood protection. The logistic specification is used to constrain d_{it} to values between zero and unity, because empirical measures of N_i and E_{it} are only indexes of protection.

As described by Stavins (1990), a more general approach is to allow for the possibility that decisions by the government to protect land from flooding are not made independently from the land's relative potential for agricultural production. Thus, the underlying heterogeneity is itself affected by projects, and the parameters of the lognormal distribution, μ and σ , are themselves functions of E_{it} :

$$\begin{aligned} \log(q_{ijt}) &\sim N \left[\mu(1 + \beta_2 E_{it}), [\sigma(1 + \beta_3 E_{it})]^2 \right] \quad \text{with probability } d_{it} \\ q_{ijt} &= 0 \quad \text{with probability } (1 - d_{it}) \end{aligned} \tag{B3}$$

Denoting the left-hand side of inequality (5) in the text by Y_{ijt} we note that there is an incentive to carry out forestation if $Y_{ijt} > 0$. Hence, there is a threshold value of land quality (q_{ijt}), denoted q_{it}^y below which the incentive for forestation manifests itself:

$$q_{it}^y = \left[\frac{\tilde{F}_{it} + M_{it}}{A_{it}} \right] \quad (B4)$$

Likewise, by denoting the left-hand side of inequality (6) in the text by X_{ijt} we note that there is an incentive to carry out deforestation if $X_{ijt} > 0$. Therefore, there exists a threshold value of land quality (q_{ijt}), denoted q_{it}^x above which the incentive for deforestation manifests itself:

$$q_{it}^x = \left[\frac{FN_{it} + M_{it}}{A_{it} - C_{it}^{\alpha P_u}} \right] \quad (B5)$$

Since there is an incentive to deforest parcel j (in county i at time t) if $q_{ijt} > q_{it}^x$ the (privately) optimal (the desired or target) stock of deforested land, expressed as a fraction of all land available is:

$$\left[\frac{AG}{T} \right]_{it}^* = \left[1 - \left[\frac{S}{T} \right]_{it}^* \right] = d_{it} \cdot \left[\int_{q_{it}^x}^{\infty} [\mathcal{F}_i\{s\}] ds \right] \quad (B6)$$

where $\mathcal{F}\{\cdot\}$ is the lognormal density function. Therefore,

$$\left[\frac{AG}{T} \right]_{it}^* = d_{it} \cdot \left[1 - F_i[q_{it}^x] \right] \quad (B7)$$

where $F_i[\cdot]$ is the cumulative lognormal distribution function, and

$$\left[\frac{AG}{T} \right]_{it}^* = d_{it} \cdot \left[1 - F \left[\frac{\log(q_{it}^x) - \mu}{\sigma} \right] \right] \quad (B8)$$

where $F[\cdot]$ is the cumulative, standard normal distribution function.

There is an analogous equation for forestation, which gives the target stock of forested land as a fraction of the total available land:

$$\left[\frac{S}{T} \right]_{it}^* = d_{it} \cdot \left[F \left[\frac{\log(q_{it}^y) - \mu}{\sigma} \right] \right] + [1 - d_{it}] \quad (B9)$$

where q_{it}^y is the threshold value of q_{ijt} below which the incentive for forestation manifests itself.

As described in detail by Stavins and Jaffe (1990), two specification issues must be addressed before the model embodied in equations (B8) and (B9), above, can be estimated: the possibility that adjustment toward optimal land use is not instantaneous; and combining the deforestation and forestation models into a single equation to be estimated.

As discussed in the text of the present paper, there are various reasons why land-use adjustment may not occur instantaneously. Hence, we allow for the possibility of partial adjustment in each observation period toward the optimal land-use pattern. In the case of deforestation, we have:

$$\left[\frac{AG}{T} \right]_{it} - \left[\frac{AG}{T} \right]_{i,t-1} = \gamma_c \cdot \left[\left[\frac{AG}{T} \right]^*_{it} - \left[\frac{AG}{T} \right]_{i,t-1} \right] + \epsilon_{it}^c \quad (B10)$$

where γ_c is the rate of partial adjustment and ϵ_{it}^c is an error term composed of a county-specific (time-invariant) component, λ_i , and a component, Φ_{it}^c which has mean zero, so that $\epsilon_{it}^c = \lambda_i + \Phi_{it}^c$. Likewise, in the case of forestation, we have:

$$\left[\frac{S}{T} \right]_{it} - \left[\frac{S}{T} \right]_{i,t-1} = \gamma_a \cdot \left[\left[\frac{S}{T} \right]^*_{it} - \left[\frac{S}{T} \right]_{i,t-1} \right] + \epsilon_{it}^a \quad (B11)$$

where γ_a is the rate of partial adjustment and ϵ_{it}^a is an error term composed of a county-specific (time-invariant) component, λ_i and a component, Φ_{it}^a , which has mean zero. Since county-level stocks of forested land and agricultural land are aggregates of individual decisions, these adjustment parameters represent the probability that a landowner not in equilibrium in a given time period will switch to the optimal land use within the initial period.¹

Next, to combine equations (B10) and (B11) into one relationship, we define the net change in the forested fraction of the county between periods $t-1$ and t as:

$$\left[\frac{AG}{T} \right]_{it} - \left[\frac{AG}{T} \right]_{i,t-1} = \left[\frac{S}{T} \right]_{i,t-1} - \left[\frac{S}{T} \right]_{it} = (-1) \cdot FORCH_{it} \quad (B12)$$

Under the assumptions of the model, deforestation and forestation will never occur simultaneously in the same county, and so we can write:

¹ It might seem that a superior approach would be to incorporate adjustment costs or lags into the original optimization problem, but this cannot be done in a way which yields necessary conditions which can be aggregated across heterogeneous parcels to the county level. Am such mechanism must depend on deviations of *individual* parcels from optimality. Estimating a model with adjustment costs requires observing the relationship between the magnitude of deviations from equilibrium and the rate of movement. Since we do not observe individual parcels, this cannot be done, so any adjustment mechanism built into the *individual* model could not be estimated with county data. One could specify a version of equation (1) with adjustment costs at the county level, but that would be equivalent to a representative-firm assumption. Thus, a fully dynamic optimal model can only be implemented with individual data.

$$FORCH_{it} = -D_{it}^c \gamma_c \left[\left[\frac{AG}{T} \right]_{it}^* - \left[\frac{AG}{T} \right]_{i,t-1} \right] + D_{it}^a \gamma_a \left[\left[\frac{S}{T} \right]_{it}^* - \left[\frac{S}{T} \right]_{i,t-1} \right] + \epsilon_{it} \quad (B13)$$

where D_{it}^c and D_{it}^a are dummy variables² for deforestation and forestation regimes; $[AG/T]^*$ and $[S/T]^*$ are the corresponding target stocks from equations (B8) and (B9), respectively; and ϵ_{it} is a composite error term, defined by:

$$\epsilon_{it} = \epsilon_{it}^c + \epsilon_{it}^a = \lambda_i + \phi_{it}^c + \phi_{it}^a = \lambda_i + \phi_{it} \quad (B14)$$

In the econometric estimation, the county-specific components of the error term, λ_i , are treated as fixed-effect parameters and the Φ_{it} are assumed to be independently distributed across i and t , but not necessarily homoscedastic. Thus, equation (B13) leads to a single-equation, fixed-effects model, the parameters of which can be estimated by nonlinear least squares, with county dummy variables employed to eliminate any bias due to the county fixed effect. The final model is thus:

$$FORCH_{it} = FORCH_{it}^a \cdot D_{it}^a - FORCH_{it}^c \cdot D_{it}^c + \lambda_i + \phi_{it} \quad (B15)$$

$$FORCH_{it}^a = \gamma_a \cdot \left[d_{it} \cdot \left[F \left[\frac{\log(q_{it}^y) - \mu(1+\beta_2 E_{it})}{\sigma(1 + \beta_3 E_{it})} \right] \right] + (1 - d_{it}) - \left[\frac{S}{T} \right]_{i,t-1} \right] \quad (B16)$$

$$FORCH_{it}^c = \gamma_c \cdot \left[d_{it} \cdot \left[1 - F \left[\frac{\log(q_{it}^x) - \mu(1+\beta_2 E_{it})}{\sigma(1 + \beta_3 E_{it})} \right] \right] + \left[\frac{S}{T} \right]_{i,t-1} - 1 \right] \quad (B17)$$

where d_{it} , and q_{it}^x are defined, respectively, by equations (B2), (B4), and (B5), above. These six equations make up the complete econometric model and are reproduced in the main text as equations (7), (8), (9), (10), (11), and (12).

² The dummy variables are endogenous. In the econometric estimation, the forestation and deforestation are first estimated separately to predict values for the dummy variables to be used when, in a second stage, equation (B13) is estimated.

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